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TECHNICAL REPORT TR124

THE USE OF POWDERED ACTIVATED CARBON IN THE ACTIVATED-SLUDGE PROCESS: A TECHNICAL AND ECONOMIC ASSESSMENT

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by

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Price: Free to WRC Members; £5.00 to non-Members

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SUMMARY

Biological treatment and activated-carbon adsorption may be regarded as complementary processes, since the former oxidises small soluble organic molecules which are poorly removed by activated carbon, while activated carbon tends to remove some of the more refractory, slowly biodegradable, material. One method of utilising the complementary functions of biological and activated-carbon treatment is to add powdered activated carbon (PAC) to the aeration basin of an activated-sludge plant.

The effects of PAC addition on effluent quality, sludge settling and other aspects of works operation are reviewed, and mechanisms are discussed in the following pages.

It appears that the adsorptive capacity of PAC increases directly with the period of retention of carbon in the aeration tanks, and that operation at a relatively high solids retention time of about 15-20 d would be necessary for the adsorptive capacity to approach the values (about 0.40 kg COD/kg AC) obtained in the treatment of secondary effluent by granular activated carbon (GAC).

The relative costs of treatment by PAC addition to activated sludge, and by sequential activated-sludge and granular activated-carbon processes are estimated for design flows in the range 11 000-110 000 m^3/d. Numerous assumptions have necessarily been made; but, without some means of regenerating the added PAC, it seems unlikely that the addition of PAC to activated sludge will be the cheaper alternative except for design flows of about 25 000 m^3/d or less. Regeneration of the PAC by the wet-air oxidation process would perhaps lead to some cost-savings, but more information about the process is needed before its viability can be assessed.

The use of PAC in the activated-sludge process for treating some industrial effluents, especially those containing toxic adsorbable compounds, may be economically viable; but it seems unlikely that its use in the treatment of domestic sewage will be.

Prospective users of the process, whereby powdered activated carbon is added to mixed liquor in the activated-sludge process, should note that it is the subject of UK Patent No. 1 335 464.

CONTENTS

SYMBOLS USED

a = empirical constant in equation C4

a_1 = empirical constant in equation C5

b = endogenous respiration coefficient

BOD = biochemical oxygen demand

C = concentration of PAC in aeration tanks

C_o = PAC dose based on influent flow rate

C_e = concentration of PAC in overflow from final settlement tanks

C_r = concentration of PAC in underflow from final settlement tanks

CAP = capacity of a furnace for regenerating activated carbon

CC = initial capital cost of civil engineering works

CM = initial capital cost of mechanical equipment

CO = annual operating cost

COD = chemical oxygen demand

DWF = dry-weather flow

E = efficiency of treatment = $\frac{S_o - S_1}{S_o}$

F = fractional operation time for a furnace

F_L = maximum solids loading that final settlement tanks can tolerate

F/M = organic loading on microbial solids in the aeration tanks = $\frac{Q\ (S_o - S_1)}{VX}$

GAC = granular activated carbon

GACT = treatment by granular activated carbon

I = concentration of inert solids (not microbial and not PAC) in aeration tanks resulting from return of WAO liquors

k = empirical constant in equation C1

k_1 = empirical constant in equation C4

k_2 = empirical constant in equation C5

k_3 = empirical constant in equation C6

k_4 = empirical constant in equation C7

$K_{r.ref}$ = regeneration rate constant at a temperature β_{ref}

$K_{r.\beta}$ = regeneration rate constant at a temperature β

Kj-N = Kjeldahl-nitrogen

l = empirical constant in equation B1

LOAD = apparent adsorptive capacity of PAC at equilibrium with effluent

$LOAD_{max}$ = apparent adsorptive capacity of PAC at equilibrium with influent

$LOAD_{\delta}$ = deviation of adsorptive capacity from a reference value

m = empirical constant in equation B1

MLSS = concentration of mixed-liquor suspended solids

n = empirical constant in equation C1

n_1 = empirical constant in equation C4

n_2 = empirical constant in equation C5

NH_3-N = ammoniacal-nitrogen

NPV = net present value

p = empirical constant in equation B1

PAC = *powdered activated carbon*

PACAST = treatment by powdered activated carbon in activated sludge

PO_4-P = phosphate-phosphorus

q = flow rate at which underflow from final settlement tanks is recycled to aeration tanks

Q = flow rate of influent wastewater to aeration tanks

r = volumetric recycle ratio = $\frac{q}{Q}$

r_1 = dimensionless constant in equation A4 = $\frac{W(Q+q)}{Q(q+W)}$

r_2 = dimensionless constant in equation A9 = $(\frac{Q-W}{Q})\ (1-\frac{W}{q+w})\ \frac{X_e}{X}$

r_3 = dimensionless constant in equation A9 = $r_1 + r_2$

S_o = concentration of substrate in influent wastewater

S_1 = concentration of substrate in overflow from final settlement tanks

SCOD = chemical oxygen demand of a filtered liquor

SLR = sludge loading rate

SO_4-S = sulphate-sulphur

SSVI = stirred specific volume index

t = *time*

t* = time from start-up needed for C to reach a given value

TOC = total organic carbon

u = maximum underflow rate from final settlement tanks

V = aeration tank volume

W = flow rate at which underflow from final settlement tanks is wasted

WAO = wet-air oxidation

X = concentration of microbial suspended solids in mixed liquor

X_e = concentration of microbial suspended solids in overflow from final settlement tanks

X_r = concentration of microbial suspended solids in underflow from final settlement tanks

Y = yield coefficient

α = temperature coefficient

β = temperature

β_{ref} = temperature at which peak bacterial uptake of substrate occurs

ΔBOD = reduction in BOD of settled sewage on passing through aeration tanks

θ = nominal hydraulic retention period

θ_c = biological solids retention period, or sludge age

θ'_c = retention period for powdered activated carbon in aeration tanks

1. INTRODUCTION

Numerous studies of the application of activated carbon in wastewater treatment have been made in recent years. These have been primarily concerned with the use of columns of granular activated carbon as tertiary units to remove by adsorption the organic compounds remaining in solution after biological treatment(1-4), and to act as the final stage of a physico-chemical treatment (PCT) process(5-10). As an alternative to columnar operation using granular carbon, powdered activated-carbon (PAC) slurry contactors have also been tested(11-17).

Dissolved organic substances in sewage and industrial wastewaters are not equally adsorbed, the adsorbability of any one compound being dependent on several intrinsic properties such as molecular weight and configuration, polarity and solubility(18-22), and also on the nature and concentrations of other compounds present(22-24). Low molecular weight polar substances which are easily biodegraded, e.g. carbohydrates and volatile fatty acids, tend to be less readily adsorbed than are refractory materials(10,25).

This selectivity limits the extent by which the organic concentration of a wastewater may be reduced by physical adsorption, and therefore it is unlikely that physico-chemical treatment of sewage of organic strength normal to the UK will provide the same degree of treatment as that of biological methods(9,10,25). This is despite the biological activity which proceeds in any adsorption system(1,8,9,17,26). It is likely therefore that, if the employment of activated carbon is found to be necessary in the UK for the treatment of wastewater, its use for polishing effluents after biological treatment will be emphasised.

The addition of PAC to the reactors of plants treating wastewater with activated sludge may be viewed as an alternative method of achieving high quality effluents. Added stability in treatment efficiency might also be possible. The purpose of this review is to assess the technical and economic viability of this process, and to discover where more information is needed.

Prospective users of the process where powdered activated carbon is added to mixed liquor in the activated-sludge process should note that it is the subject of UK Patent No. 1 335 464.

2. PROCESS DESCRIPTION

In the system using powdered activated carbon in activated-sludge treatment (PACAST), PAC is added continuously or intermittently to the settled sewage, or directly to the aeration tanks. The carbon is recycled with the biological sludge solids and, once an equilibrium level of carbon has been achieved in the reactor, a constant PAC dose and sludge wastage results in the carbon solids retention time being approximately equal to the biological sludge age θ_c*.

The process flow diagram in Fig. 1 illustrates the use of PAC on a throw-away basis. This might not appear to be economically attractive because of the replacement cost of PAC (£160-£320/tonne, prices for second quarter of 1978). However, the absence of capital plant for contacting the biologically oxidised liquor with activated carbon and for activated-carbon regeneration is an attractive feature, especially if enhanced treatment efficiencies would be required for only relatively short periods. Simplicity of operation might also make the process attractive for a small works, particularly for one treating wastewater of predominantly industrial origin.

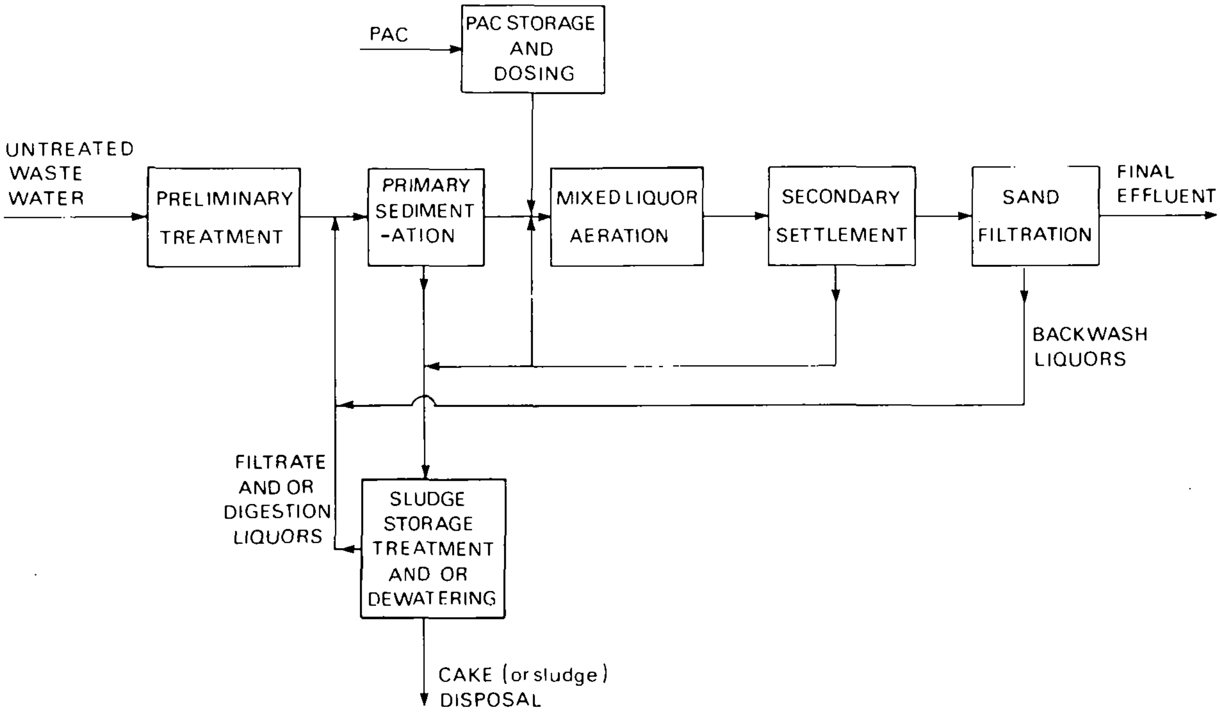

Fig. 1. Simplified flow diagram showing the use of PAC on a throw-away basis

Plant combining PAC regeneration with oxidation or carbonisation-activation of biological solids must also be considered. A flow diagram showing the incorporation of such a unit process is given in Fig. 2. However, it is shown in Section 5 that several fundamental drawbacks are inherent in the two processes. These include those of recycling a high proportion of inert (non-activated) material

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* Appendix A.

and, in the case of wet-air oxidation at least, the imposition of increased organic and nitrogenous loads at the aeration stage.

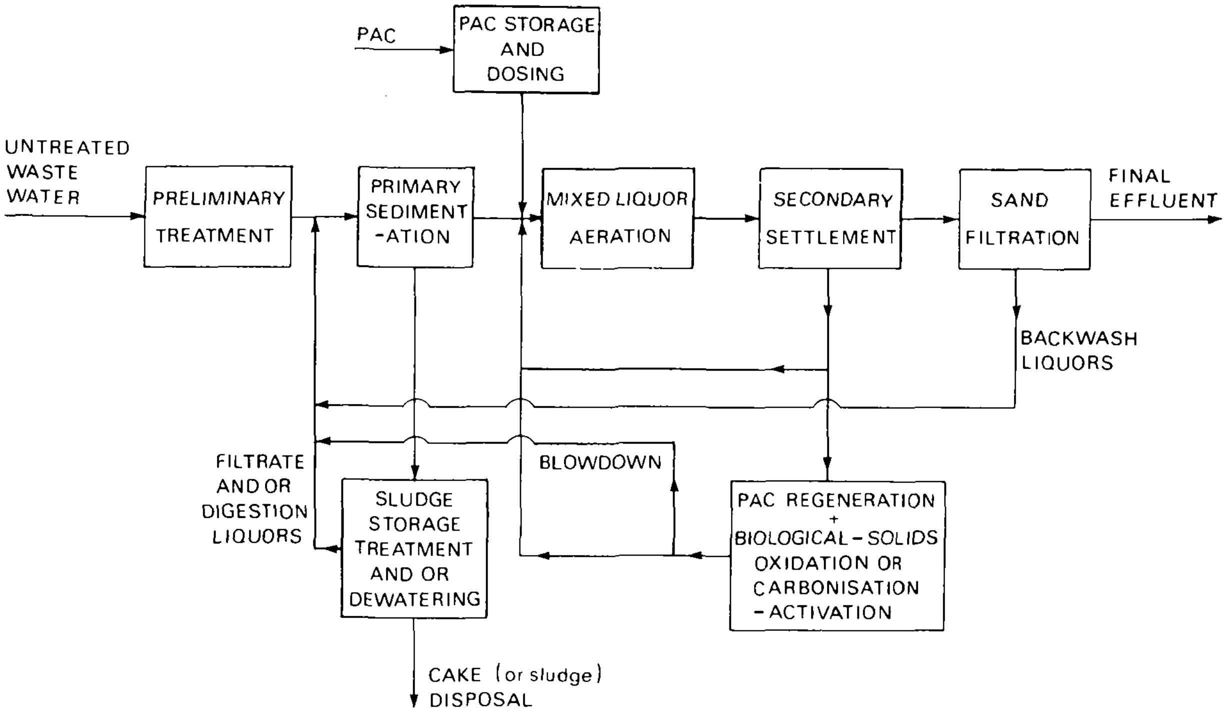

Fig. 2. Simplified flow diagram showing the use of PAC with some means of regeneration

3. THE EFFECTS OF ADDING PAC TO ACTIVATED-SLUDGE REACTORS

Forming part of an appraisal of the use of PAC in the treatment of sewage, a summary of some of the more recent studies of PAC addition to biological reactors was given by Shuckrow and Culp(27). They concluded that the process was attractive, compared with others employing powdered and granular carbon, because it could be incorporated into existing biological plant.

A critical evaluation of these studies was not provided, however, and a more comprehensive review has been made by DeWalle and others(28). This indicated that improved treatment is achieved at reactor equilibrium concentrations as low as 50 mg PAC/l. They observed that effluent COD and BOD values varied inversely with reactor PAC concentrations, but that the effectiveness of any given concentration varied widely between studies. For example, a 25 per cent COD reduction over control unit effluents was effected by PAC concentrations ranging from 250 to 5750 mg/l.

Unfortunately, a comparison of some of the data cited by DeWalle and others(28) with the originals(29-30) reveals discrepancies, and the origin of data ascribed to Robertaccio and others(31) is obscure. Because of the unsatisfactory nature of these reviews, a reappraisal of the currently available literature was made.

3.1. EFFECT ON EFFLUENT QUALITY

The principal effects of PAC dose and equilibrium reactor concentration on effluent quality are broadly summarised in Table 1. Clearly, the treatment of a great variety of wastewaters, using a number of activated carbons, has been examined over a wide range of PAC doses, treatment scale, and operating conditions - though the last have often been poorly defined, particularly with respect to temperature. Because of this and the lack of analytical consistency between studies, meaningful comparison of results is difficult. Examination of the data does suggest, however, that the studies may be considered to fall into two main categories:

(i) those that have attempted to up-rate activated-sludge treatment systems that are either overloaded or subjected to highly variable, and occasionally toxic, influents (Studies 1-8 and 11);

(ii) those that have attempted to up-grade the quality of secondary effluent to that normally associated with polished effluents (Studies 7, 9, and 10).

It may also be noted that the wastewaters treated in Categories (i) and (ii) have tended to be industrial and domestic in character, respectively, but that the treatment of a purely domestic sewage has not been investigated.

Table 1. Summary of enhanced steady-state removals achieved by PACAST units

Study No.		1	2	3	4*	5	6*	7*	8	9*	10*	11*
Reference No.		29	32, 33	32, 33	32	34	35, 36	37	38	28	39	40
Wastewater type		Glucose	Industrial	Industrial	Industrial	Industrial	Industrial	Industrial	Domestic + industrial	Domestic + glucose	Domestic + glucose	Industrial
Wastewater flow rate (m^3/h)		1.0-2.0 x 10^{-3}	15.6	17.4	103	347	72.1	1.2 x 10^{-3}	221	0.078 x 10^{-3}	0.78 x 10^{-3}	2.45 x 10^{-3}
Reactor Temperature (^{o}C)		22.2	-	-	-	-	-	21-23	-	-	-	14-31
Sludge age (d)		-	-	-	-	52.3	5.3-6.5	6.2-8.8	3.7	5-10	3-15	20-60
Hydraulic retention time (d)		0.10-0.20	-	-	-	0.55	0.55	0.26	0.092	1.05	1.07	0.64
PAC dose (mg/l)		-	-	85	-	20	308	51-657	22.5	5.25-63.0	3.57-357	25-200
PAC concentration in the reactor (mg/l)		1000-2000	1000	1700	500	1900	2970	1670-21700	900	50-300	50-1000	2340-9380
Control effluent (mg/l)	BOD	-	544	-	-	308	20	2-7	42	-	-	-
	COD	125-210	1760	-	-	1180	292	140-171	-	17-25	35-41	58-73
	TOC	-	-	-	-	420	146	34-45	-	-	-	22.0-26.5
	SS	-	-	78	-	230	207	-	26	-	-	-
Increased removals compared to control units (mg/l)	BOD	-	289	-	-	278 236†	9	0-3	25	-	-	-
	COD	100-170	800	-	-	- 830†	53	28-126	-	3-6	2.1-11.9	8-44.5
	TOC	-	-	-	-	- 320†	6	2.6-32	-	-	-	0-17.5
	SS	-	-	48.53	-	- 110†	128	-	-	-	-	-
Other information		DO kept at 6.0 mg O_2/l and MLSS at 2500 mg/l. Organic loading was in the range 1.10-1.15 mg COD/mg MLSS d.	Ambient temperatures during the test period were much less than in the control.	F/M ratio varied from 0.09 to 1.43.	Increased colour removal of 260 APHA units. Colour of control was 580 APHA units.	Plant upsets were greatly reduced with carbon in the reactor.	BOD of unfiltered effluent was reduced from 77 to 34 mg/l.	Increased colour removal of 313-702 APHA units.	Variations in effluent quality were reduced	The reactors simulated plug-flow conditions.	The reactors simulated plug-flow conditions.	Nitrification was enhanced, particularly at the lower temperatures.

* Samples were filtered before analysis.

† Increased removals over the entire dosing period.

With particular reference to the uprating of overloaded and/or stressed activated-sludge plants, the addition of PAC effects reductions in effluent colour and phenolic compounds, and in all parameters usually considered indicative of effluent quality. However, because of the factors previously mentioned and the inter-relationship that exists between the carbon dose and equilibrium concentration, the hydraulic retention time, and the sludge age, plots of treatment efficiency against the two carbon variables (Figs 3 and 4) are of specific value only (see Appendix A).

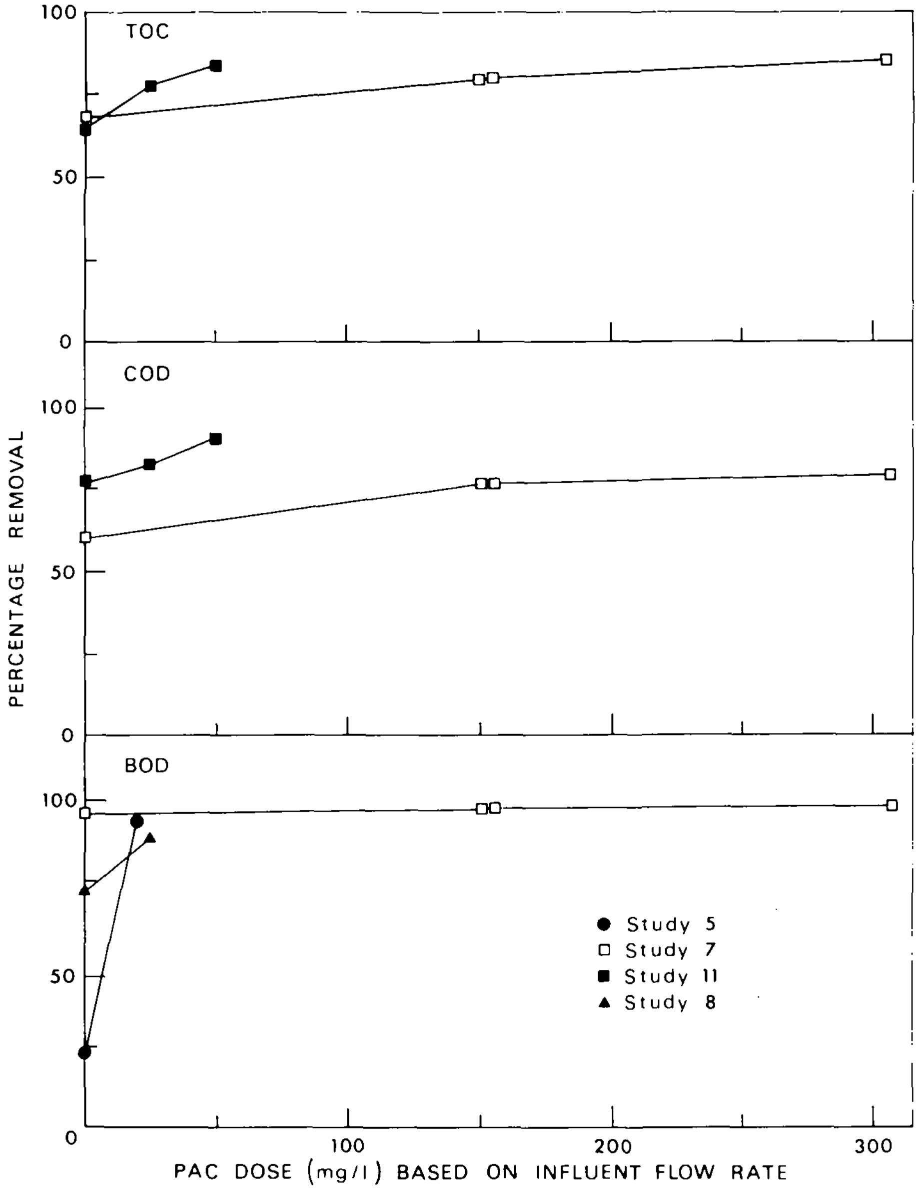

Fig. 3. Steady-state treatment efficiencies as functions of PAC dose

Somewhat unexpectedly, perhaps, PAC addition is reported to enhance nitrification (40-44), this being particularly noticeable at lower temperatures(40). Their observation of a total nitrogen imbalance around the carbon system led Spady and Adams(41) to postulate that denitrification was also enhanced. Pilot-scale trials by Zimpro, Inc.(42) appear to support this.

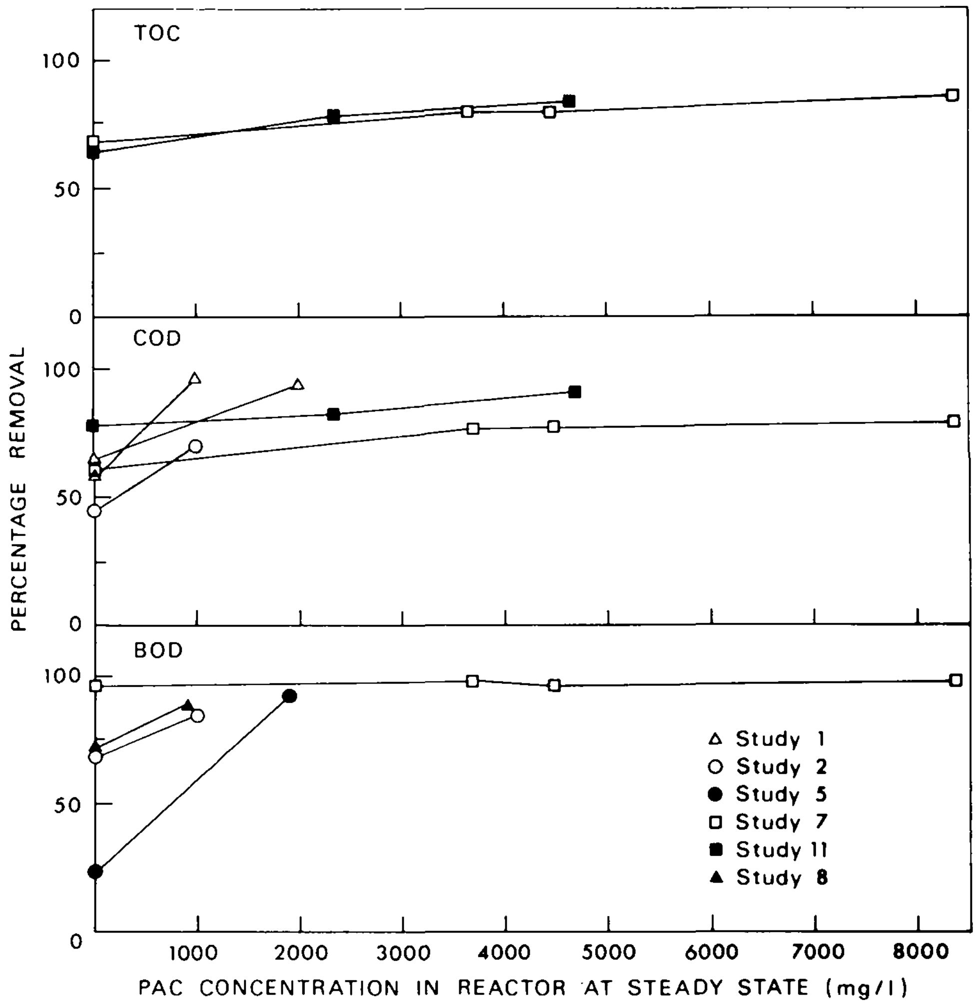

Fig. 4. Steady-state treatment efficiencies as functions of concentration of PAC in reactor

3.1.1. Optimisation of the carbon dose

In upgrading an activated-sludge reactor to produce effluent of a quality equivalent to that produced by a granular carbon adsorption stage, minimisation of costs seems to depend on optimising the powdered carbon dose. Grieves and others(40) were the first to appreciate this. Their data indicated that the enhanced treatment efficiency obtained at a sludge age of 20 d could be retained at reduced carbon dose by increasing the sludge age - thus maintaining high concentrations of PAC in the reactor (even taking into account the lower reactor temperatures during operation at the higher sludge age of 60 d).

The dependence of effluent quality on sludge age and carbon dose - two of the primary control parameters - is more clearly illustrated by a transformation of the data obtained by DeWalle and Chian(39). Their data for soluble COD (SCOD) in the effluent are presented in Fig. 5 as a function of the equilibrium concentration of PAC in the reactor and of sludge age. From these data, and from Equation 1 derived in Appendix A, the PAC dose C, required to achieve a given effluent SCOD at a set value of θ may be plotted as a function of θ_c:

$$C = \frac{\theta_c}{\theta} . \qquad (1)$$

Choosing an arbitrary value for the effluent SCOD of 30 mg/l, such a relationship is illustrated in Fig. 6. This also depicts the variation with sludge age of the apparent organic loading on the carbon (mg SCOD/mg PAC), and clearly indicates that the cost-effectiveness of carbon addition is greatly improved by operating the reactor at relatively high sludge ages.

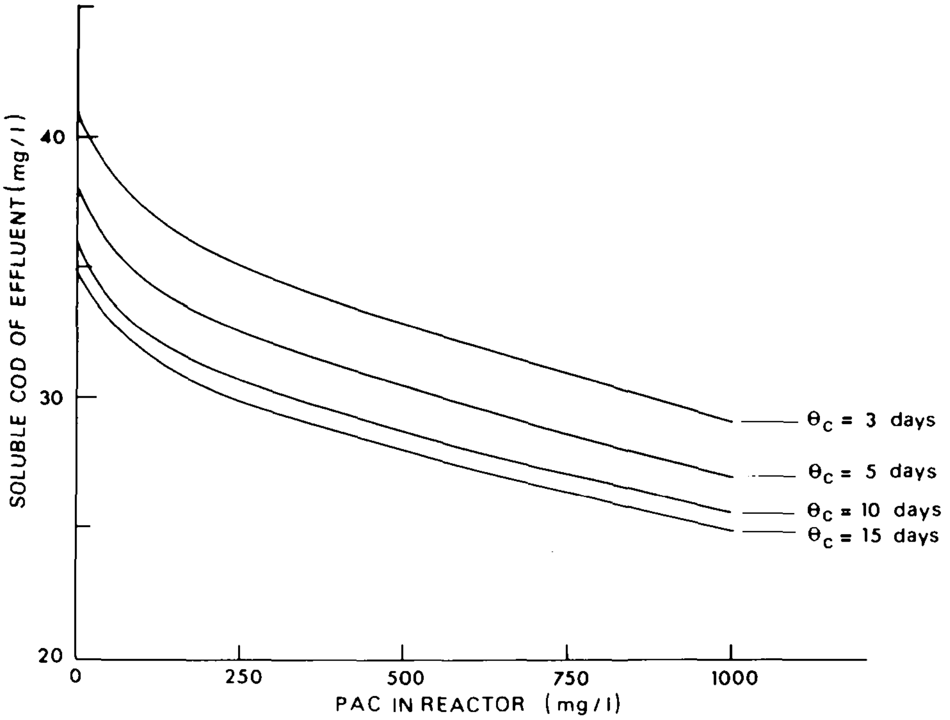

Fig. 5. The influence of sludge age and concentration of PAC in the reactor on effluent SCOD at steady state. (After Reference 39)

For a given value of θ, however, practical limitations imposed by the settling characteristics of the suspended solids in the mixed liquor may be considered to govern an upper limit to the sludge age adopted(45). This limitation may be expressed by Equation 2:

$$r\left(\frac{X_r}{X} - 1\right) = 1 - \frac{\theta}{\theta_c} , \qquad (2)$$

a rationalised form of that originally put forward by Lawrence and McCarty(45) from a mass balance for microbial solids around the solids separator. The ratio X_r/X is a function of the efficiency of the solids separator and of the settleability of the mixed liquor, and Equation 2 suggests that modification of an existing activated-sludge plant, to one employing low PAC doses and operated at a higher sludge age, might not be feasible. However, data described in the succeeding section indicate

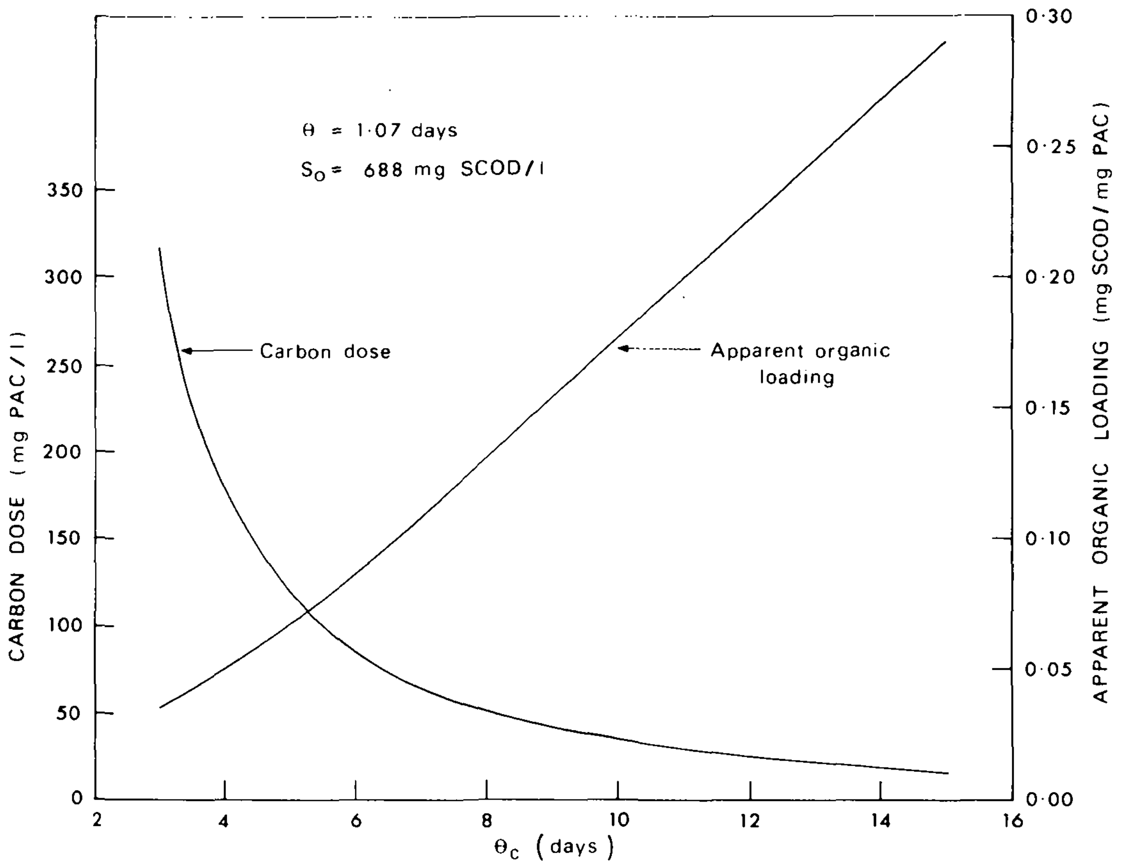

Fig. 6. Carbon doses resulting in an effluent SCOD of 30 mg/l, and the apparent organic loading at these doses, as functions of sludge age. (Derived from Reference 39)

that the addition of PAC produces thicker, more easily settleable sludges. Thus operation at a higher sludge age might be possible with need only of a relatively small increase in aeration-tank volume or settlement-tank area.

From published data it is not possible to give a confident estimate of the carbon doses which might be needed to produce a given effluent quality under optimal conditions. But if an apparent organic loading of 0.25 mg SCOD/mg PAC is assumed, then improvement of the effluent quality of an activated-sludge plant from, say, 35 to 15 mg SCOD/l would require a PAC dose of 80 mg PAC/l. That loadings of this magnitude can be achieved at such low effluent concentrations has yet to be convincingly demonstrated, however, and this and the optimal carbon dose would have to be determined in pilot-scale trials.

3.2. EFFECT ON SETTLED-SEWAGE QUALITY

It is general UK practice to co-settle wasted secondary sludge with the screened and degritted crude sewage. Thus contact of the waste PAC (at quasi-equilibrium with the final effluent) with influent wastewater of high organic strength might significantly reduce the dissolved organic load on the aeration stage, and reduce still further the inhibitory effects of (adsorbable) toxic substances on secondary treatment stability and efficiency. A crude estimate of the maximal reduction in load of dissolved organic material that could be expected may be made by assuming that adsorption is described by a Freundlich isotherm. Using typical data, and assuming an effective PAC dose of 80 mg/l and the achievement of equilibrium, a maximal loading reduction of 20 per cent may be calculated. Allowing for the contribution to the organic load made by the non-settleable solids, and other factors, a total reduction in organic loading of some 5 per cent might thus be possible.

3.3. EFFECT ON SLUDGE PRODUCTION AND PROPERTIES

Rather less attention has been paid to the effects of PAC addition on the production rate and properties of sludge than has been addressed to its effects on effluent quality. However, it seems that PAC addition to industrial wastewaters results in lower effluent suspended-solids concentrations, thicker sludges, reduced volumetric wastage rates and, where polymers are used to aid settlement of solids, reduced polymer doses (Table 2). The yield of vacuum filters may also increase as a result of PAC addition to sewage(41), and sludge-conditioning doses may be lower(41,46). Only a limited number of measurements of specific resistance to filtration of sludges containing PAC have been made(47), however; hence the dewatering characteristics of these sludges are not well defined.

Table 2. Effects of PAC addition on effluent suspended solids and sludge settleability at plants treating industrial wastes

Reference	PAC dose (mg/l)	Concentration of suspended solids in effluent		Percentage reduction in volumetric sludge-wastage rate	Comments
		Control	Test		
(32,33)	22.5	-	-	-	Sludge-wasting practice unaltered. Solids settling improved but data either not obtained or not published.
	85	78	25-30	-	-
	30	-	-	68	Unthickened sludge solids increased from 3-5% to 8-10% dry solids content.
(34)	20	230	120	65	Polymer dose to aid solids settling reduced from 20 mg/l to 10 mg/l.
	100	-	-	20	Effluent suspended solids decreased by 25%.
	15	-	-	70	Effluent suspended solids decreased.
(38)	19	-	-	-	Solids settling in the 20% overloaded plant was improved. For the first time it became possible to concentrate solids in the clarifier for effective sludge return.

When considering the economic feasibility of the process, these limitations in data are rather unimportant since over 80 per cent of total costs can be attributed to those of PAC addition (see Section 6 and Appendix E).

3.3.1. Settleability of PAC

Early trials by the DuPont Co. indicated that as much as 45 mg/l PAC might be carried over in the effluent from the final settlement tanks(36). In order to minimise losses, a cationic polyelectrolyte was added to the mixed liquor before final settlement(48). The use of high-density (>640 kg/m^3), rapidly-settling lignite carbons is recommended by ICI of America, as an alternative to polymer addition; they claim that, once a system has become acclimated to the carbon, the addition of polymer or inorganic coagulant is unnecessary for the settlement of carbon particles(32-34,38).

Another solution to the problem of PAC carry-over would be to modify the production process to yield powdered activated carbons of larger particle size.

3.4. EFFECT ON ANAEROBIC DIGESTION OF SLUDGES

Where wasted secondary sludge, mixed with primary sludge, is anaerobically digested, improved digester performance may occur as a result of PAC addition to the secondary reactor. Confirming earlier work(49) on the beneficial effects of PAC, laboratory studies of Adams(50) indicated that an optimal carbon dose of 5 per cent on total sludge-solids feed enhanced the breakdown of volatile sludge solids and the formation of methane. These claims were supported by the results from several full-scale studies(46,50-52). Filter yields were also enhanced and digester operation was reported to be less susceptible to upset. Principally through a reduction in sludge handling costs(46,51), but also through elimination of the need for deodorant chemical(52), PAC addition (to the digester) was reported to be self-financing in some instances.

More recent work, however, has shown that the addition of PAC would have little effect on the performance of a well-operated digester under design loading rates, and that the main value of activated-carbon addition lies in its ability to sustain gas production rates during stress conditions caused by toxic materials present in the influent sludge(53,54).

3.5. EFFECT ON FOAMING AND AERATION

Reduced effluent detergent concentrations and problems of foam formation, in both the reactor and receiving stream, have also been reported(32-34,38). In some cases, cost-savings from the reduced use of defoaming chemicals more than offset the cost of the added PAC.

The oxygenation efficiency of fine-bubble diffused-air systems can be highly sensitive to the presence of detergents and surface-active agents in the liquid(55). A potentially significant effect of the adsorption of such substances onto PAC might, therefore, be an increase in oxygenation efficiency, and some compensatory reduction in aeration costs. This would especially apply to plug-flow reactors, though any cost-benefits cannot be quantified at present.

4. MECHANISMS BY WHICH PAC IMPROVES TREATMENT

Several mechanisms have been proposed to account for enhanced treatment resulting from PAC addition. These are fully discussed in Appendix B, as are attempts(37,39) which have been made to model the increased removal of slowly-biodegradable but adsorbable organic substances. These model studies have not been completely successful, though empirically it does appear that the adsorptive surfaces on the carbon are biologically regenerated, and that apparent adsorptive capacities increase directly with the retention time of the solids in the reactor. Removal of organic compounds by purely physical adsorption does not appear to be generally significant.

The adsorption of material inhibitory to bacterial activity is also apparently important, especially in the processes of nitrification and anaerobic digestion.

Improvements in solids settling and sludge thickening probably result from PAC acting as a weighting agent, and as nucleation sites for floc formation.

5. REGENERATION OF WASTED PAC

5.1. THE WET-AIR OXIDATION (WAO) PROCESS

Several processes for the regeneration of PAC have been the subject of development in recent years. The more important of these include the fluidised-bed furnace(14,56), the Westvaco transport reactor(56-58), and the Zimpro wet-air oxidation process(13,16, 42,56,59); but only WAO is reported to be capable of combining oxidation of secondary solids with PAC regeneration.

A simplified flow diagram of the WAO process is shown in Fig. 7. The wasted sludge containing PAC is first thickened to about 8 per cent dry solids, at which concentration it is claimed that subsequent treatment is autothermic(27,59). It is then pressurised to about 50 bar(27,59,60), a controlled amount of air added, and heated to a temperature of 204-243°C(42,59,60). Under these conditions, Zimpro Inc. claims(27,42) that PAC losses in the WAO unit are about 6 per cent. Additional losses are incurred, however, because of the need to limit the accumulation of inert (non-activated and non-biological) suspended solids in the aeration basin by wasting a fraction of the oxidised PAC sludge. Zimpro advocates(27) a wastage (blowdown) rate of 5 per cent, the wasted fraction being returned to the head of the works.

Before return to the aeration basin the oxidised PAC sludge is flash-evaporated over a pressure-reducing valve, and the mixture, including combustion gases, is further cooled by the settled sewage in a mixing channel. It is claimed(59) that problems of odour from the combustion gases and stripped volatiles are not generally experienced. n the partial WAO of non-PAC-containing sludges, however, the concentration of organic volatile substances (mainly carboxylic acids, aldehydes, ketones, and hydrocarbons) in the off-gases may be such that a catalytic after-burner has to be installed(61). Thus the installation of an after-burner may be required in practice for PAC regeneration.

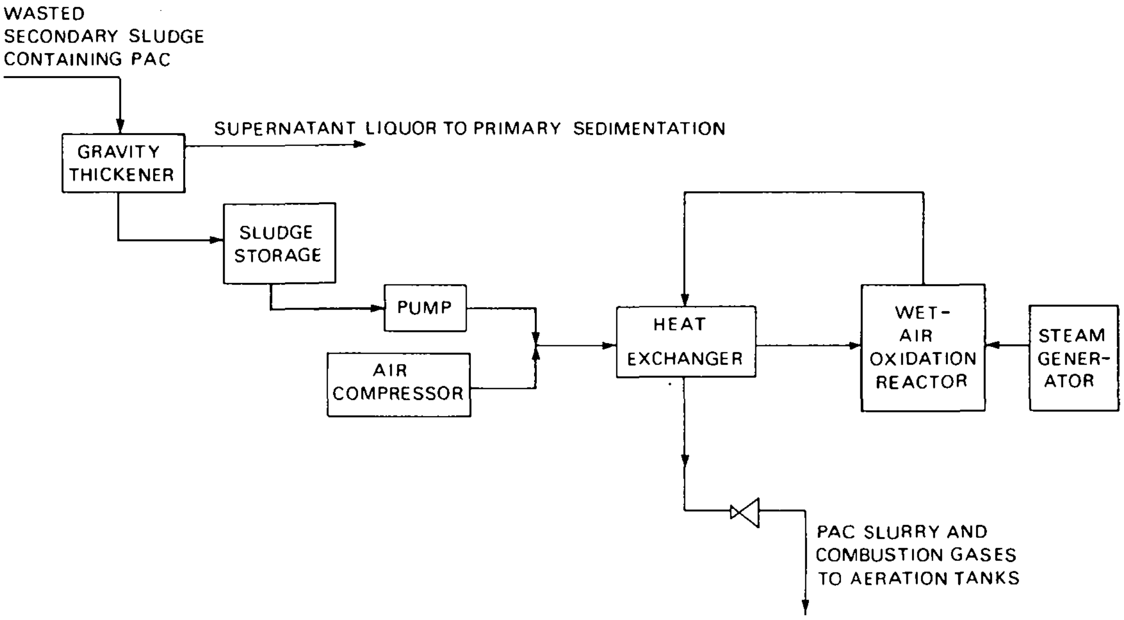

Fig. 7. Simplified flow diagram of the wet-air oxidation process. (Adapted from Reference 42)

It is well known that a significant fraction of the particulate organic material is solubilised in WAO (see Table 3). Thus WAO of the wasted secondary sludge imposes an additional carbonaceous and ammoniacal load on the secondary treatment stage(60,63-65), and concern has been expressed about the treatability of the organic fraction(65). There is also evidence to suggest that aluminium and some heavy metals (Cu, Zn, Ni, Cr) in sludges are solubilised to some extent(66,67). Because of these factors, and because of the undesirability of forming inert mixed-liquor suspended solids from the primary sludge solids, it is most probable that separate primary sludge disposal plant would also have to be installed.

In view of the severe maintenance problems that can result from scale formation(66), it is essential that pilot-scale trials precede the installation of any full-scale WAO units. Sommers and Curtis(66) reported that carbonate and sulphate scale rapidly formed on heat-exchanger and reactor surfaces respectively, when anaerobically digested sludges were treated. A hot nitric acid wash had negligible effect on the sulphate scale, and removal had to be done manually with a chipping hammer. It is conceivable that such problems of scale formation might occur after plant shutdown, e.g. for maintenance, when thickened PAC sludge, held in storage for a week or more, would be treated. Problems of corrosion and mechanical blockage might also be expected.

Table 3. Typical properties of filtrate liquors after wet-air oxidation of sewage sludge. (After Teletzke(62))

Property	Raw sludge	Filtrate liquors after 45% reduction in sludge COD	Filtrate liquors after 80% reduction in sludge COD
Percentage volume of raw sludge recovered	-	92	95
Total solids (mg/l)	50 000	8 910	6 320
Volatile solids (mg/l)	33 300	7 280	4 840
BOD (mg/l)	-	9 000	6 500
COD (mg/l)	60 000	21 700	12 400
NH_3-N (mg/l)	300	1 200	1 320
PO_4-P (mg/l)	326	11	10
SO_4-S (mg/l)	-	272	263

Cost information for the WAO process under UK conditions is not readily available, but estimates of capital and operating costs in the USA have been provided by Shuckrow and Culp(27,68). They compared the costs of PACAST and WAO of the PAC sludge with those of several other processes employing activated carbon, but the case of sequential activated-sludge and activated-carbon treatment was not considered. Nor was identical effluent quality specified as a design criterion. Some of the design specifications for the WAO process have been used in Section 6, however, for the economic evaluation of the PACAST-WAO process.

5.2. THERMAL REGENERATION COMBINED WITH THE CARBONISATION AND ACTIVATION OF THE BIOLOGICAL SLUDGE SOLIDS

In the USA a project to develop a regional residues treatment system using activated carbon made by pyrolysis of organic sludges has been briefly reported(69). But, though the principle of making activated carbon from sewage-works sludges is theoretically attractive, practical work on these lines has been mainly at laboratory scale(47) and small pilot scale(70-72).

The limited data which have been published(47,70,71) indicate that the yield of activated carbon is no higher than 40 per cent on a carbon recovery basis, and that the product has a high ash content of perhaps 55 per cent. Allowing for the ash content, though, the surface area and adsorptive capacity of the activated carbon so made are comparable with those of commercially-available powdered carbons. The data of Bosch and others(47) may be used to derive a value of 410 m^2/g for the surface area of activated carbon produced from activated sludge under conditions providing maximal surface area per mass of dry sludge. And the adsorption capacity for methylene blue of an activated carbon made from fungal mycelium was 0.31-0.71 times that of a standard, high-surface-area carbon, Filtrasorb 400(71).

Though Bosch and others(47) found the surface area of carbon made from primary sludge to be less than that of carbon made from activated sludge, the potential yield of activated carbon from mixed sewage-works sludges could be quite high. Assuming a sludge-solids production of 0.5 kg dried solids/m^3 crude sewage, a fractional volatiles content of 0.80, a fractional carbon content of the volatile solids of 0.5, and an activation yield of 0.40, a yield of about 80 mg/l of low-grade activated carbon might be realised. The settling characteristics of mixed activated sludge and activated carbon made from sludge appear to be superior to those of activated sludge alone(47). Thus recycle to the aeration basin of the activated carbon made from sludge has some limited appeal. The high ash content of the activated product would result in a higher degree of PAC wastage than in the Zimpro WAO process, but it is possible that the wasted carbon could be sold as a by-product, or used on a throw-away basis at nearby sewage works or water-treatment works.

5.3. THERMAL REGENERATION COMBINED WITH INCINERATION OF THE BIOLOGICAL SLUDGE SOLIDS

The DuPont Co. have installed a full-scale multiple-hearth furnace for PAC regeneration, a furnace in which biological solids are simultaneously incinerated(31,73,74). Few details have been published but it is stated that carbon losses are greater than those obtained in GAC regeneration (5-10 per cent), and that the regenerated PAC requires washing with concentrated hydrochloric acid to reduce the build-up of inert solids in the aeration basin.

Thermal regeneration of PAC combined with incineration of the biological solids in a completely-mixed furnace has been practised by a Japanese company with similar results. A British Patent(75) has been issued for this process.

6. PROCESS ECONOMICS

6.1. PROCESSES TO BE COMPARED

The addition of PAC to activated sludge would seem to be most applicable for the treatment of industrial wastewaters and of sewage having a large industrial component. However, the process operating conditions and PAC dose necessary to obtain effluent of the specified standard are likely to be unique to each case considered. The composition of sewage comprising predominantly domestic waste is less variable and, if the aim of the process were to produce a high-grade effluent suitable for some form of re-use, its operational characteristics would probably be more predictable.

In the remainder of this section, therefore, the costs of PACAST, with and without WAO of wasted PAC sludge, are estimated for works designed to treat sewage dry-weather flows (DWF) of 11 000, 33 000, and 110 000 m^3/d, and compared with those of sequential treatment by activated sludge and granular activated carbon.

Flow diagrams for the processes using PAC have essentially been given previously, see Figs. 1, 2, and 7. A simplified flow diagram for the GAC process for treating filtered conventional effluent is shown in Fig. 8. For all processes, comminution of the crude sewage, detritus removal, and storm tanks are specified. After final settlement, all effluents are filtered in rapid gravity sand filters. All sludges for disposal are dewatered in filter plate presses, after storage, and the cake transported to tip.

6.2. DESIGN CRITERIA

It is assumed that the wastewater to be treated is a typically domestic sewage, the BOD and ammoniacal nitrogen contents of the conventionally settled sewage being 200 mg/l and 25 mg/l, respectively, and that the final effluent is to be fully nitrified with a soluble COD (SCOD) of 15 mg/l. All other design criteria for the three processes are listed in Appendix D. Most are based on performance data published in Technical Report TR 61(55), but other sources(3,27,76-78) have also been used. The assumptive nature of many of the design criteria is emphasised in Appendix D also, and it is recommended that this be consulted.

6.3. COST ESTIMATES

6.3.1. Results

The net present values (NPV) of works providing treatment over a period of thirty years have been estimated. In anticipation of the adoption of a test discount rate (TDR) of 5 per cent in the water industry, results using this rate are presented. Table 4 summarises the data, while a more detailed breakdown of total costs is provided in Appendix E. The cost of conventional works producing a fully-nitrified effluent, and providing sand filtration, is taken as a base-line, with which the additional costs of the processes using activated carbon are compared. Since the capital and operating costs have largely been estimated with the aid of Technical Report TR 61, all costs are expressed at levels for the third quarter of 1976 (1976 Q3).

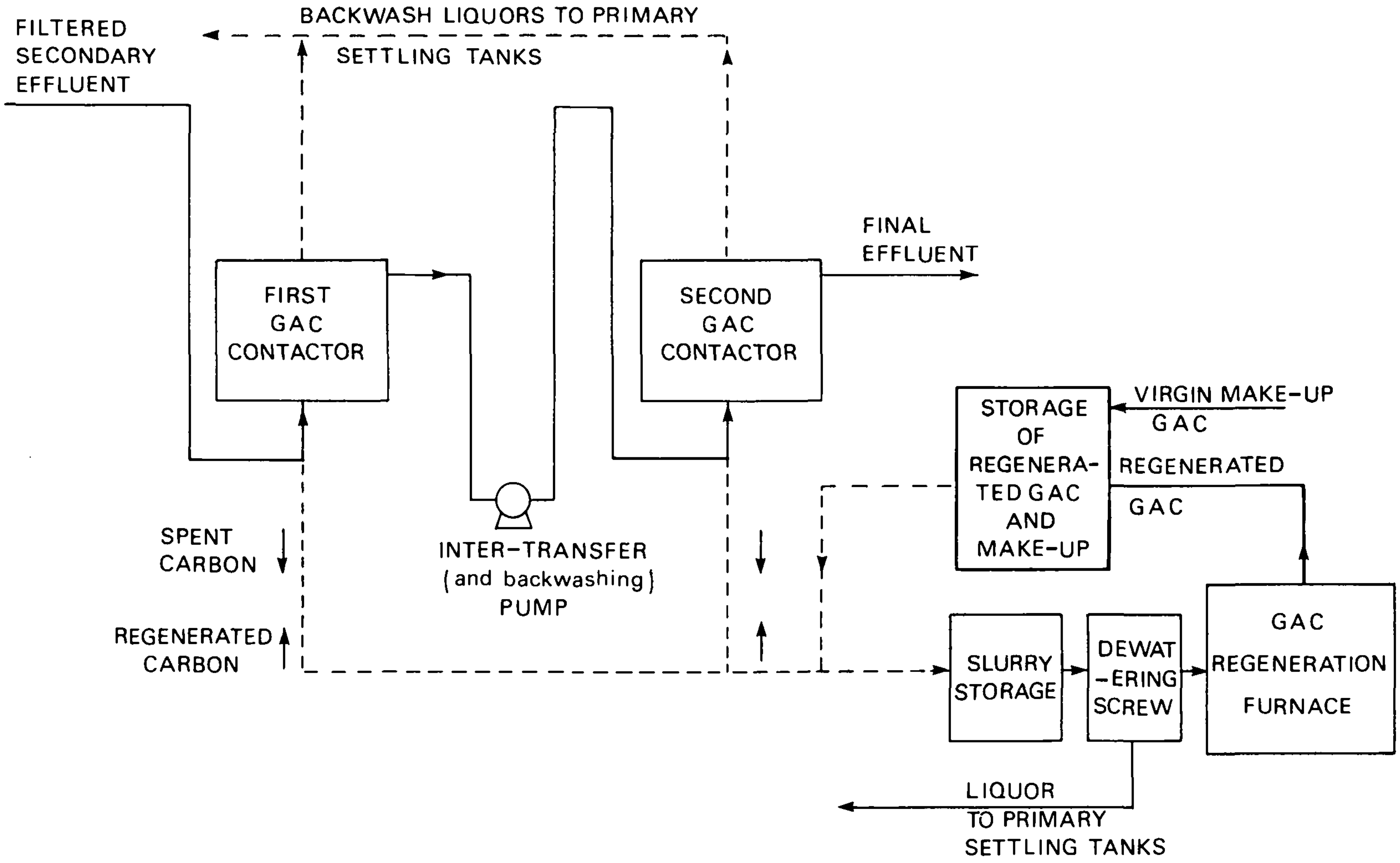

Fig. 8. Simplified flow diagram for the treatment of effluent by granular activated carbon (GAC)

Table 4. Summarised cost data

Works size (m^3/d)		11000	33000	110000
NPV of conventional works (£'000)		3120	7640	21200
Activated-carbon process	Organic loading (kg SCOD/kg AC)		ADDITIONAL NPV (£'000)	
PACAST	0.10	2990	8860	28600
	0.15	1970	5780	18400
	0.20	1480	4260	13600
	0.25	1150	3340	10600
	0.30	962	2720	8650
	0.35	802	2280	7170
PACAST + WAO	0.225	1840	3050	7970
GACT	0.25	1920	4340	11500
	0.40	1640	3520	8960
	0.55	1510	3130	7660

For PACAST it should be noted that over 83 per cent of total additional costs can, in each case, be attributed to the costs of PAC addition. An example of the distribution of costs for PACAST and GACT is given in Fig. 9.

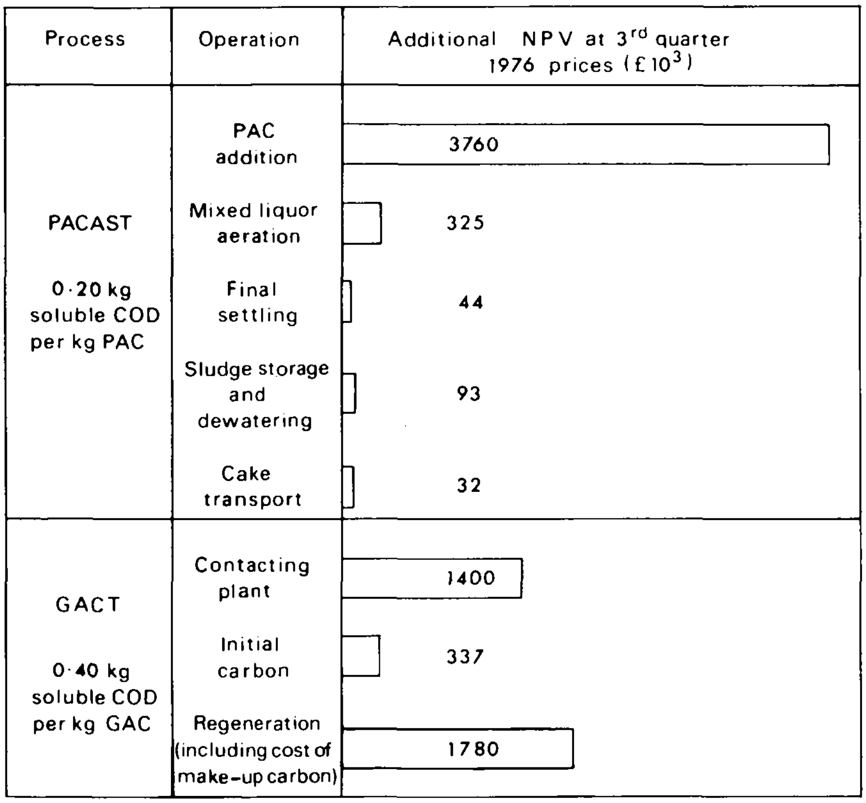

Fig. 9. A breakdown of the additional net present values (NPV) of works employing PACAST and GACT for organic loadings of 0.20 and 0.40 kg soluble COD/kg activated carbon, respectively, for a dry-weather flow of 33 000 m^3/d

The dependence of the additional NPV of PACAST, and of granular activated-carbon treatment (GACT), on the apparent organic loading on the carbon is illustrated in Figs 10-12 for each works size. Adopting mid-range values for the organic loading, Fig. 13 depicts the variation in costs with works size over the range examined. The additional cost of PACAST with regeneration of the added PAC by wet-air oxidation is also displayed.

In estimating the costs of the activated-carbon processes, sources(27,78-81) other than Technical Report TR 61 have also been consulted. Full details are provided in Appendix F. It should be noted that as the use of activated carbon for sewage treatment has not been adopted at full scale in the UK, there exists a degree of uncertainty about some of the capital-cost relationships that are used, and some of the operating resources specified. Uncertainty is especially attached to the estimation of capital costs of GAC contacting plant and WAO units.

Details of the unit operating costs employed are given in Appendix G.

6.3.2. Discussion

In view of the many assumptions made, judgement of the relative costs of the three processes must necessarily be provisional until more information is available. However, one conclusion can be drawn immediately from these results: that the costs of activated-carbon treatment are high for all processes, the results suggesting that the use of activated carbon would increase the NPV of a works by about 40 per cent at least, over the whole range of works sizes considered.

In interpreting the cost-estimates it must be remembered that the costs are estimated to be those of works built on green-field sites. The economies of scale thus act in favour of the basic PACAST process since the provision of additional aeration tank capacity, etc. does not result in a proportionate increase in costs. If an extension to an existing works were considered, these same economies of scale would not apply and PACAST would become relatively more expensive.

Restricting discussion to that of works constructed on green-field sites, therefore, the results indicate that, without some means of regenerating the added PAC, the addition of PAC to the activated-sludge process is likely to be more expensive than sequential treatment by activated sludge and GAC at works treating average flows in excess of about 25 000 m^3/d. Within the organic loading ranges appropriate to the two activated-carbon processes, it is also apparent that the costs of PACAST are much more sensitive to the organic loading on the carbon. This reflects the penalty incurred in the throw-away use of PAC. Nevertheless, if loads of about 0.20 kg SCOD/kg AC or more can be sustained by PAC under the assumed conditions, PACAST could prove to be the marginally cheaper alternative for the smallest works sizes, especially if enhanced treatment were only required for part of the year, e.g. during periods of drought.

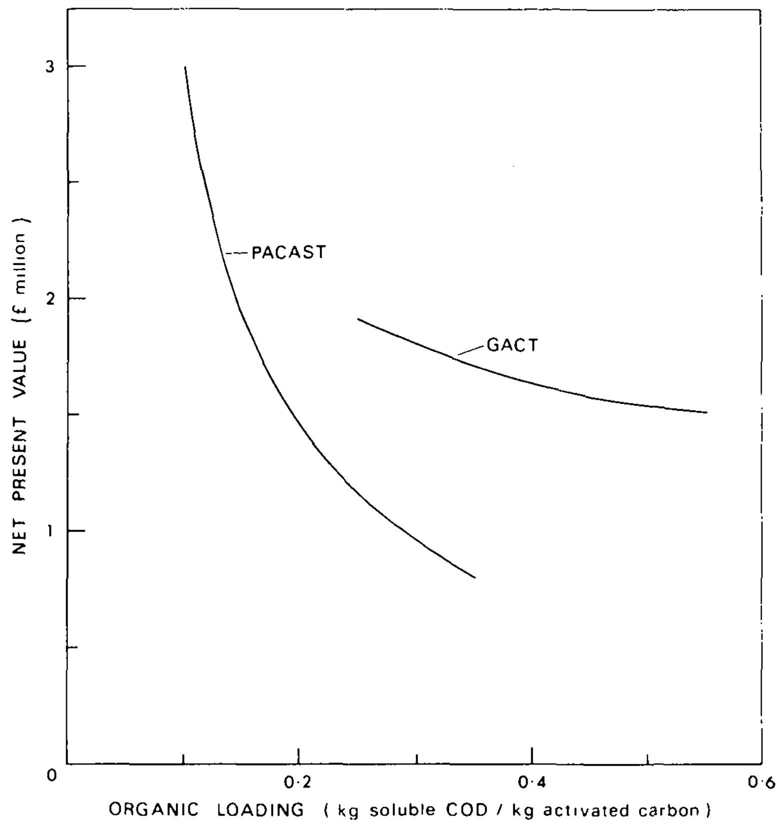

Fig. 10. Comparison of the estimated NPV of GAC treatment with that of PACAST for a DWF of 11 000 m^3/d, using a value of 5 per cent for the TDR. All costs are additional to those associated with the base-treatment works

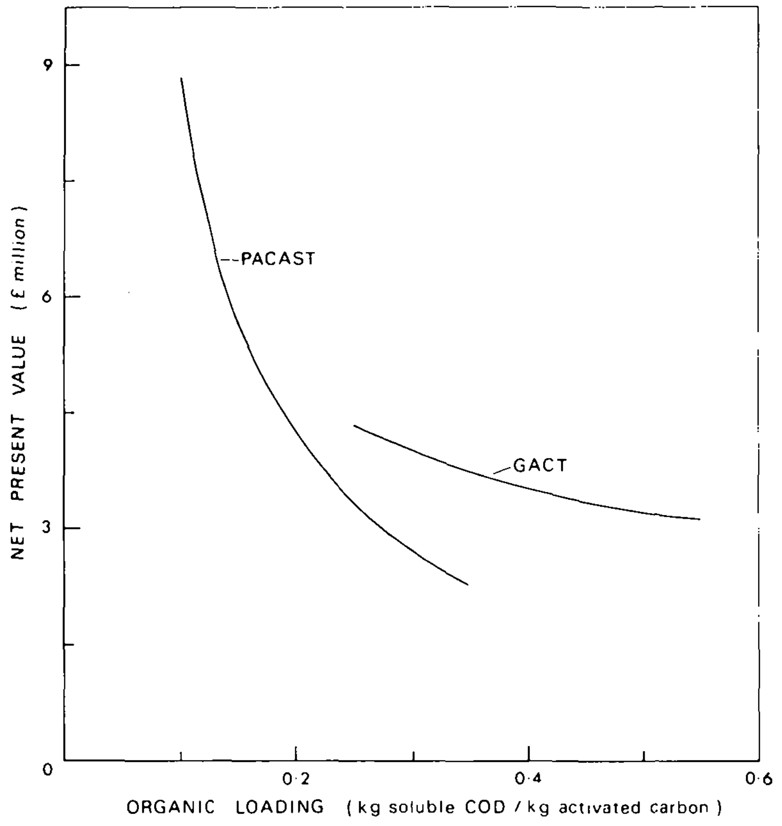

Fig. 11. Comparison of the estimated NPV of GAC treatment with that of PACAST for a DWF of 33 000 m^3/d, using a value of 5 per cent for the TDR. All costs are additional to those associated with the base-treatment works

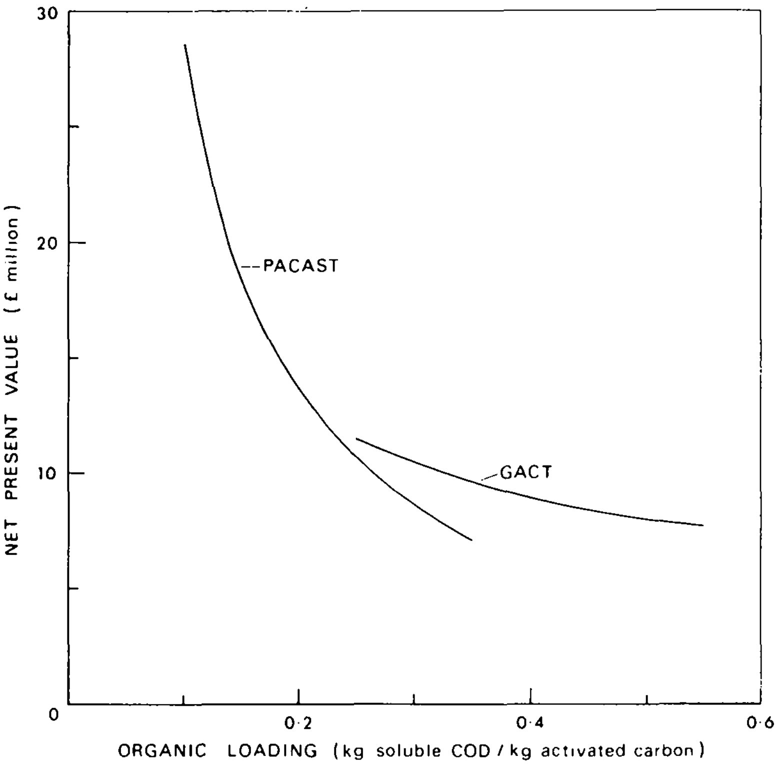

Fig. 12. Comparison of the estimated NPV of GAC treatment with that of PACAST for a DWF of 110 000 m^3/d, using a value of 5 per cent for the TDR. All costs are additional to those associated with the base-treatment works

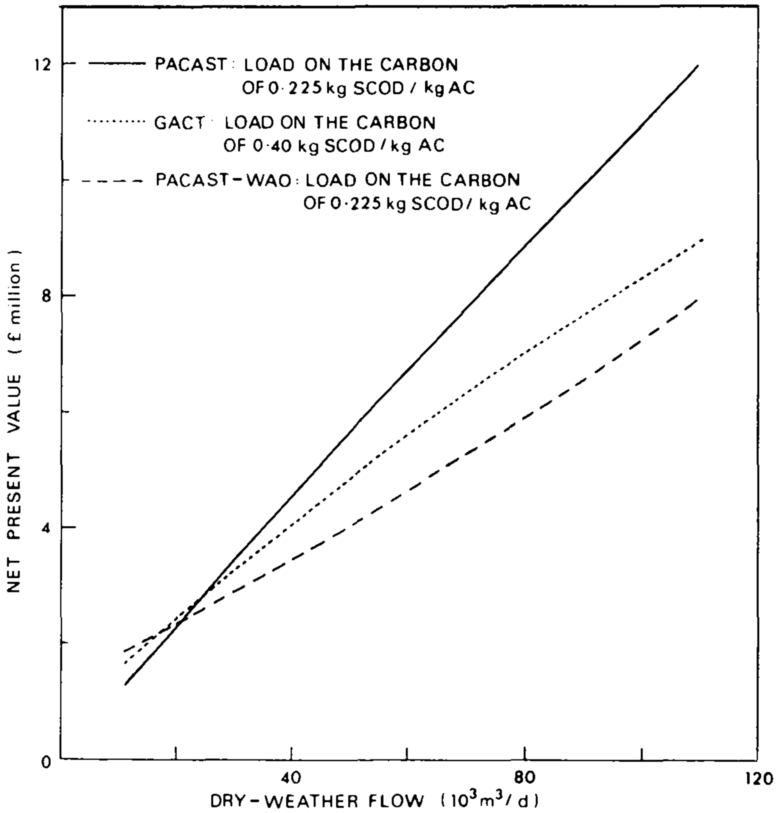

Fig. 13. Comparison of the estimated additional costs (3rd quarter 1976 prices) for works designed to treat dry-weather flows in the range 11 000 - 110 000 m^3/d

Dependence on an uninterrupted external supply of PAC would be a serious disadvantage though, as would the preponderance of operating costs over which no control could be exerted, and for the more general case the viability of PACAST would seem to depend on the provision of plant for regenerating the PAC. At the lower end of the range of works sizes considered, however, wet-air oxidation of secondary sludge containing PAC appears to result in increased costs, and it is only at works treating average flows in excess of about 22 000 m^3/d that net savings result. In view of the doubts concerning the treatability of the wet-air oxidation liquors and the reliability of the WAO process, the apparent cost-competitiveness of PACAST-WAO at the medium-to-larger works sizes must be viewed with some caution.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. SEWAGE TREATMENT

With information currently available, the conclusion is that treatment of sewage by adding PAC to the activated-sludge process is unlikely to be viable, in general, compared with sequential treatment by activated sludge and GAC. There might be some scope for the process at the smallest-size works constructed, but additional information is needed to confirm this. Information is needed in the following areas:

(i) the organic loading on the carbon that can be attained,
(ii) the effect of added PAC on the oxygenation efficiency of aeration equipment,
(iii) whether polymer addition is necessary to prevent PAC carry-over from the final settlement tanks,
(iv) the settleability of activated sludge containing PAC,
(v) the dewatering characteristics of sludges containing PAC,
(vi) the effects on the anaerobic digestion process.

It is improbable though that the process will be of general interest. Hence pilot-scale trials to supply the deficient data are of low priority.

For medium and large-sized works it appears that PACAST with WAO of the secondary sludge containing PAC might be cheaper than sequential treatment by activated sludge and GAC. But doubts exist concerning the treatability of the WAO liquors and the reliability of the WAO process, and it is unlikely that the process will be employed.

Though the ash content of activated carbon made from sewage sludges appears to be high, development work in this area seems to be warranted. Taking into consideration the effects of scale, however, the production of carbon would probably be feasible only for a large works where a potential problem of sludge disposal existed. A sludge-disposal problem could thereby be largely eliminated, and the activated carbon used at the works itself or one nearby to improve effluent quality, or at nearby water-treatment works.

7.2. INDUSTRIAL WASTEWATER TREATMENT

In theory, the process might be suitable for the treatment of industrial wastewaters containing a large proportion of biodegradable material but for which conventional activated-sludge treatment is not suitable, because of the intermittent presence of (adsorbable) toxic or inhibitive substances, or because of widely-fluctuating hydraulic and organic loads. The merits of PACAST would, however, need to be assessed for each individual case.

APPENDIX A PAC MASS FLOWS FOR A FULLY-MIXED REACTOR

A.1. PAC BUILD-UP IN THE REACTOR

A.1.1. Assuming zero PAC carry-over from the final settlement tank

Consider the system shown in Fig. A1, and assume PAC carry-over from the final settlement tank. Ignoring the rate of accumulation of carbon solids within the settlement tank, a mass balance for PAC around the whole system gives:

$$Q\ C_o - W\ C_r = V\ \frac{dC}{dt} \qquad \text{(A1)}$$

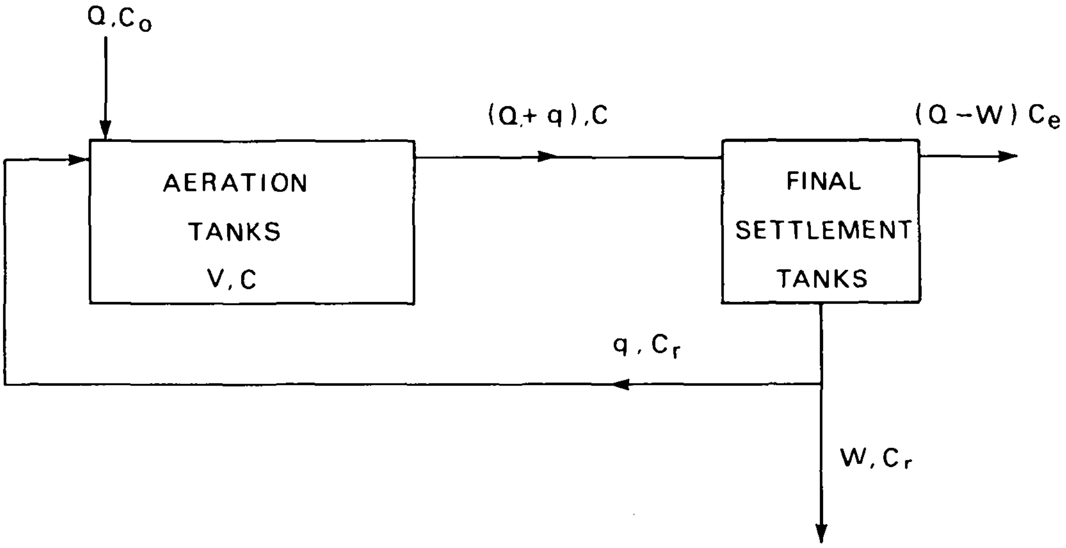

Fig. A1. Mass flows of PAC

and a similar balance around the reactor gives;

$$Q\ C_o + q\ C_r - (Q + q)\ C = V\ \frac{dC}{dt}\ . \qquad \text{(A2)}$$

Combining Equations A1 and A2 leads to:

$$C_r = \frac{(Q + q)}{(q + W)}.C. \qquad \text{(A3)}$$

Also, combining Equations A1 and A3 may be shown to give:

$$r_1.C + \theta.\frac{dC}{dt} - C_o = 0, \qquad \text{(A4)}$$

where $r_1 = \frac{W(Q + q)}{Q(q + W)}$.

Assuming constant flow rates, separation of the variables and integrating yields:

$$\mathrm{Ln}\frac{\left\{\frac{C_o}{r_1} - C_1\right\}}{\left\{\frac{C_o}{r_1} - C_2\right\}} = \frac{r_1}{\theta}\ (t_2 - t_1), \qquad \text{(A5)}$$

where C_1, C_2 = the values of C at times t_1 and t_2, respectively, as a solution to Equation A4.

One aim of the process may be to keep a given concentration of PAC in the reactor. The dose to maintain this concentration at equilibrium is given by setting dC/dt = 0 in Equation A4, i.e.

$$C_o = r_1 . C. \qquad \text{(A6)}$$

In practice, the reactor concentration would be brought up to the desired level by dosing at greater rates initially. And the time taken (t*) is given by:

$$t^* = \frac{\theta}{r_1}\ \mathrm{Ln}\frac{\left\{\frac{C_o}{r_1}\right\}}{\left\{\frac{C_o}{r_1} - C\right\}}. \qquad \text{(A7)}$$

A.1.2. Assuming that the ratios of PAC to biological solids concentrations in the mixed liquor, effluent and return sludge are the same

From mass balances around the whole system and the final settlement tank, a set of equations can be derived that are similar to those in Section A.1.1. An additional term is involved, however, because C_e is no longer presumed to be zero. A solution is made possible by assuming that

$$\frac{X}{C} = \frac{X_r}{C_r} = \frac{X_e}{C_e}. \qquad \text{(A8)}$$

It can thus be shown that the build-up of PAC in the reactor is described by

$$r_3\ C + \theta . \frac{dC}{dt} - C_o = 0, \qquad \text{(A9)}$$

where $r_3 = r_1 + r_2$,

r_1 = as before,

$$r_2 = \left(\frac{Q - W}{Q}\right)\left(1 - \frac{W}{q + W}\right)\ \frac{X_e}{X}$$

Assuming constant flow rates, as before, equations similar to A5-A7 are formed by substituting r_3 for r_1 in each case.

A.2. EQUALITY OF SLUDGE AGE AND CARBON SOLIDS RETENTION TIME

At equilibrium the sludge age is defined by

$$\theta_c = \frac{V\,X}{(Q - W)\,X_e + W\,X_r}, \qquad \text{(A10)}$$

while the carbon solids retention time is defined by

$$\theta'_c = \frac{V\,C}{(Q - W)\,C_e + W\,C_r} = \frac{V\,C}{Q\,C_o} = \theta\,\frac{C}{C_o}. \qquad \text{(A11)}$$

For θ'_c to be equal to θ_c, Equation A12 must be satisfied:

$$\frac{X}{(Q - W)\,X_e + W\,X_r} = \frac{C}{(Q - W)\,C_e + W\,C_r} \qquad \text{(A12)}$$

when

$$C_o = \frac{\theta_c}{\theta}.\ C. \qquad \text{(A13)}$$

Two solutions to Equation A12 may be proposed. The first rests on the assumption that C_e is equal to zero. Equation A12 may then be recast as:

$$\frac{X}{C} = \frac{X_r}{C_r} + \left(\frac{Q}{W} - 1\right)\frac{X_e}{X_r}. \qquad \text{(A14)}$$

The second solution is given by Equation A8, that is,

$$\frac{X}{C} = \frac{X_r}{C_r} = \frac{X_e}{C_e}.$$

By substituting representative values for X, X_r, X_e, and Q/W into Equation A8 and Equation A14 it may be demonstrated that the two solutions are approximately equivalent for values of C up to 1000 mg/l. However, at the higher concentrations which will probably be needed in practice, the derived values of X_r/C_r increasingly diverge. This has significant implications for the control of sludge age. And, while this need not be an all-important factor in the operation of a full-scale works, a fundamental investigation of the process at pilot scale would have to take this into account. This is especially true where reactors are to be operated in parallel, at the same sludge age, with one operated as a PACAST unit and one as a control.

Thus analytical techniques will have to be developed to allow the differentiation of the carbon and microbial solids. These techniques may include microscopic analysis, radioactive labelling, and volatile solids analysis. DeWalle and others(28) have pointed out problems with the last technique, however - approximately 79 per cent by weight of virgin PAC being lost when heated for 1 hour at 540°C.

APPENDIX B DISCUSSION OF THE MECHANISMS BY WHICH PAC ENHANCES ACTIVATED-SLUDGE TREATMENT

B.1. IDENTIFICATION

Many mechanisms have been proposed to account for the benefits derived from PAC addition. These may be categorised as:

(i) Enhancement of the biological degradation processes,
(ii) Removal by physical adsorption,
(iii) as a seed and weighting agent for the biological solids.

Though each is here considered separately, it will become evident that interaction is likely to exist between the three mechanisms.

B.2. ENHANCEMENT OF THE BIOLOGICAL DEGRADATION PROCESSES

B.2.1. Fundamental mechanisms

From their comparative studies of the enhancement of activated-sludge treatment by the addition of PAC and spent fluid catalytic-cracking catalysts, Schwartz and McCoy(82,83) concluded that the activated carbon (or catalyst) functioned as a nucleation centre for the microbial solids, providing a surface on which the microbial population can grow, and promoting solids settling and compaction.

Such a mechanism, in which PAC provides a support for biomass growth, depends on the provision of external rather than internal surface area. However, Perrotti and Rodman(84) observed that aerated reactors, fed with a glucose and phenol mixture, removed twice as much TOC overall when activated carbon was added, as did identical units to which sand of the same mesh size as the carbon was added. Since approximately the same total external surface areas for bacterial growth were provided, it was postulated that the increased TOC removal was due to the large internal surface area of the carbon. Hutton(35) came to the same conclusion and Grieves and others(40) obtained data which provide further support for this view - an activated carbon of high internal surface area (3099 m^2/g) giving greater organic carbon removal, even at lower doses, than that given by carbons of less internal surface area (514-717 m^2/g).

Perrotti and Rodman(84) suggested that bacteria cannot physically migrate into the micropore structure of activated carbon owing to size limitations, but that exoenzymes secreted by the organisms and functioning independently of them, could easily diffuse into and out of the carbon microstructure and, through their action, effect the breakdown and desorption of the adsorbed compounds. They further postulated that an enzyme-substrate relationship is possible within the carbon structure, controlled ultimately by the bacteria. Toxic materials might thus be desorbed at a rate slow enough to allow degradation or removal without harmful effects to the bacteria.

This model differs considerably from that proposed by Kalinske(29), and others(32-34,38,41,85), based on observations of increased rates of COD reduction rates in batch laboratory units fed with glucose, and reports(86) that some forms of carbon selectively adsorb oxygen from gases in solution. This postulates that activated carbon within an aerated microbial suspension provides extensive "concentration sites" for the dissolved organic compounds, oxygen, and bacteria, thus accelerating the rate of biological oxidation. .

Similar reasoning was used by Weber and Ying(87) to account for the large apparent adsorption capacities of GAC in aerobic expanded beds. Though it was acknowledged(87,88) that bacteria are probably too large to effect significant biological growth in the internal pore structure of activated carbon and that biological growth is, therefore, largely confined to the external particle surface, this mechanism was stated to differ from that in which the carbon merely acts as a support medium. The principal difference is a sharper liquid-solid phase separation, for both oxygen and organic compounds, that results from adsorption onto carbon, replacing absorption into the biomass as the main partitioning factor.

None of the workers who have proposed a "concentration-site" mechanism appear to have considered, though, the nature of oxygen adsorption onto activated carbon, the rate of adsorption, and the adsorption capacity of activated carbon for oxygen. The limited data available(89) may be taken to indicate that the concentration effect for oxygen is not as significant as has been imagined. Prober and others(89) observed oxygen sorptions of only 3-16 mg O_2/g AC for the adsorption of dissolved oxygen from aerated water at 6-40°C onto several types of activated carbon. Only 2-5% of the oxygen was reversibly adsorbed, moreover; sorption of the remainder being attributed to the formation of carboxylic acid groups and other oxidation reactions. Rates of adsorption conformed to an intra-particle diffusion limiting model, though it was suggested that they could be limited by very slow reactions. Puri and coworkers(90) demonstrated that the nature of the surface-oxide complexes affects the adsorption of phenol on sugar charcoal and carbon black.

B.2.2. Removal of slowly-biodegradable compounds

Koppe and others(91,92) noted that the addition of activated carbon to an activated-sludge unit treating the slowly-degradable substrate pentaerythritol resulted in more rapid acclimation and increased removal compared to a control unit. It has been suggested(32-34,37-41,87,93) that the enhanced removal of such substrates (material that, in general, is measured by the COD and TOC tests but not to any great extent by the BOD test) results, initially, from its adsorption onto carbon. The retention time of the substrate in the reactor is thus extended from the hydraulic retention time θ to the sludge age θ_c, and renders the substrate more liable to biodegradation by one of the previously described mechanisms.

Following preliminary experiments(93) which indicated that the apparent SCOD loading on added activated carbon increased with increasing sludge age, Flynn(37) developed a semi-empirical model with the aim of confirming that the removal of slowly-degradable substances was achieved as previously mentioned. Reference SCOD and STOC loading lines (adsorption isotherms) were first determined for operation at a relatively constant temperature and sludge age. Apparent SCOD and STOC loadings were then computed from a series of trials in which several values of sludge age (θ_c), temperature (β) and reactor PAC concentration were adopted. It was postulated that the deviation of the appparent from the reference loading would be related to these variables, and that the data could be fitted to an empirical equation of the form:

$$\text{LOAD}_\delta = 1 + m\,\theta_c + p\beta \qquad \text{(B1)}$$

where 1, m and p are constants.

From a multiple linear regressional analysis of the data, it was concluded that biodegradation of the more refactory organics was confirmed. However, this conclusion cannot be drawn from these data since:

(i) operation under only seven sets of condtions was examined, and thus the significance of the statistical analysis must be open to considerable doubt;

(ii) the temperature range employed spanned the temperature (24°C) at which peak substrate utilisation by the bacteria occurred;

(iii) whilst the regression coefficient m was positive for the regression of STOC loadings on θ_c and β, it was negative for the SCOD regression.

The units operated by DeWalle and Chian(39) were in parallel; thus, temperature effects may be neglected in evaluating their study. The computed loadings plotted in Fig. 6 pertain to PAC in contact with effluent of the same SCOD concentration, i.e. 30 mg/l, and these data provide strong support for the hypothesis that the adsorptive surfaces are biologically regenerated. The size of the apparent loadings (Table B1) calculated from other data agree with this, and the biological regeneration of spent activated carbons has been reported as being partially effective(56).

It may be noted from Fig. 6 that the increase in apparent capacity with sludge age is non-linear for a sludge age of up to 5 days, but that within the range $5 \leqslant \theta_c \leqslant 15$ d the apparent SCOD capacity is given approximately by:

$$\text{LOAD} = 0.065 + 0.0225\,\theta_c \qquad \text{(B2)}$$

where the constant of value 0.0225 may be regarded as a regeneration rate constant having the dimensions T^{-1}. The initial non-linearity may reflect a necessity for the carbon solids retention time to be of a certain value for the biomass to become firmly attached to the carbon particles. Support for this is provided by the experience of Shell and Burns(14) in operating a pilot-scale PAC slurry contactor system. Though adsorption equilibrium could be attained after approximately 30 min contact time, a solids retention time of 2-3 d was recommended in order to gain the benefits of microbial activity without the problems of sulphide production. The latter is unlikely to be a factor in the operation of an aerated reactor, however.

The effect of temperature on the regeneration rate constant is not known, nor, except for the study by Flynn(37), has it been considered. If the regeneration is a biological process, though, one might anticipate that within the temperature range of general interest, and at a constant sludge age, the degree of regeneration would increase with increasing temperature according to the equation:

$$K_{r.\beta} = K_{r.ref} \exp\left(\alpha(\beta - \beta_{ref})\right). \qquad \text{(B3)}$$

DeWalle and Chian(39) developed a semi-empirical model to predict the effluent quality that could be achieved by PACAST units. The model was based on observations of apparent adsorptive capacities increasing linearly with increasing sludge age, and on data(17,28,39) which indicated that apparent adsorptive capacities varied directly with influent substrate and mixed liquor suspended-solids concentrations. It was proposed that the apparent capacity is a function of sludge age and the ratio of microbial solids concentration to PAC concentration in the reactor. However, though the basic tenets of the model are of interest, its development and attempted verification are open to extensive criticism, as given in Appendix C.

Neither the reactor concentration of microbial solids, nor the ratio of microbial solids to PAC concentrations, alone appear to determine the rate of adsorptive capacity regeneration in a PACAST unit.

B.2.3. Indirect enhancement by the adsorption of inhibitors

It has been suggested that activated carbon may enhance biological treatment indirectly by adsorbing materials that are toxic to the microbial organisms. This is perhaps most dramatically illustrated by the extremely high apparent organic loadings observed by DeJohn and Adams(34) (see Table B1). Without PAC addition, materials present in the wastewater apparently inhibited microbial activity and resulted in poor removal of biodegradable compounds. Adsorption of these inhibitory substances, such as zinc, onto activated carbon might be expected to reduce their toxicity and result in greater BOD removal.

It is generally recognised that the nitrifying autotrophic bacteria of the general *Nitrosomonas* and *Nitrobacter*, which oxidise ammonia to nitrite, and nitrite to nitrate respectively, demonstrate much slower growth rates than do the heterotrophic bacteria which oxidise carbonaceous material, and are more sensitive to environmental factors such as temperature and pH value. Their response to inhibitory materials present in the wastewater to be treated is complex, and depends considerably on the pattern of occurrence of these substances in the wastewater(94-96). However, their relatively slow growth rates result in the process of nitrification being more vulnerable to upset, since all that is necessary to prevent nitrification

Table B1. Apparent organic loading data

Reference	Study No.*	PAC dose (mg/l)	Sludge age (d)	Apparent loadings (mg/mg PAC) BOD	COD	TOC	Additional information
34	5	20	52.3	13.9	-	-	At equilibrium.
				11.8	41.5	16.0	Over the whole dosing period.
37	7	51.1	$\overline{8.5}$	0.004	0.548	0.071	Temperature 21-23°C
		148		0.001	0.423	0.124	
		657		0.003	0.192	0.048	
		151	$\overline{7.2}$	0.015	0.444	0.095	
		154		0.021	0.448	0.105	
		306		0.011	0.252	0.076	
38	8	22.5	3.7	1.11	-	-	-
28	9	10.5	5	-	0.381	-	-
		63.0		-	0.095	-	
		5.25	10	-	0.571	-	
		31.5		-	0.127	-	
40	11	100	20	-	0.445	0.095	Carbon A; Temperature 31°C
		100		-	0.250	0.045	Carbon B
		100		-	0.290	0.035	Carbon C
		100		-	0.080	-0.010	Carbon D
		200		-	0.205	0.088	Carbon A; Temperature 26°C
		200		-	0.170	0.065	Carbon B
		200		-	0.150	0.055	Carbon C
		25	60	-	0.624	0.380	Carbon A; Temperature 14°C
		50		-	0.768	0.270	Carbon B
		100		-	0.256	0.095	Carbon C

* See Table 1.

from being achieved consistently is for the rate of growth of the organisms to be reduced to a point at which their wash-out becomes inevitable(97). Thus the process of nitrification might be expected to be particularly enhanced by the adsorption, and removal from solution, of inhibitory materials. Enhanced nitrification due to PAC addition has been observed by Suschka(43), and Stensel and others(98).

In view of the susceptibility of anaerobic bacteria, particularly those responsible for conversion of lower fatty acids to methane, to inhibition by toxic substances, including anionic detergents in sewage(64), this indirect mechanism would also appear to be significant in the anaerobic digestion process.

Tacit support for an indirect mechanism is also given by the results of fish toxicity tests carried out by Robertaccio and others(31), who showed that the effluent from a conventional activated-sludge unit treating an industrial waste was lethal to fish, while that from a PACAST unit was not.

B.2.4. Denitrification

Increased denitrification resulting from PAC addition has been regarded as a consequence of more efficient solids settling (see Section B.4). An alternative explanation may be offered, however, that this stems from the anoxic degradation of organic material adsorbed on the activated carbon, as has been observed in columns of GAC used to treat wastewaters(1,8,87). If this is so, the apparent nitrate loading on the activated carbon might be expected to increase with sludge age concomitant with the increase in apparent organic loading.

B.3. REMOVAL BY PHYSICAL ADSORPTION ALONE

Few workers have considered that solely physical adsorption plays a major role in pollutant removal by PACAST units, except in removal of colour and dye molecules, detergents, heavy metals and various inorganic and organic toxicants. Even in this sphere, though, it is probable that some degree of biodegradation of the adsorbed compounds takes place. Voorn(99), for example, observed that activated carbon in an aerated reactor removed colour five times more efficiently than activated carbon in contact with the conventional effluent.

It has been tentatively suggested that physical adsorption onto PAC is of more general significance(30). These conclusions, however, have been based on somewhat limited data, which failed to show any increase in MLSS concentration and oxygen uptake rate of units dosed with PAC.

Based on data obtained from laboratory units operated at sludge ages of 5 and 10 d, and from column adsorption studies of the control unit effluents, DeWalle and others(28) tentatively concluded that the enhanced organic removal by the 10-d unit resulted more from physical adsorption, while that by the 5-day unit was more biologically mediated (but see Section B.4.). It was suggested that columns containing PAC removed a much greater amount of SCOD (by physical adsorption) from the 10-d control unit effluent, though similar percentage SCOD removals were observed for the 5- and 10-day test units. However, their data indicate that on passing 75 bed-volumes of effluent through the columns (equivalent to 2½ hours flow), the percentage SCOD removal was essentially independent of control unit sludge age (Fig. B1).

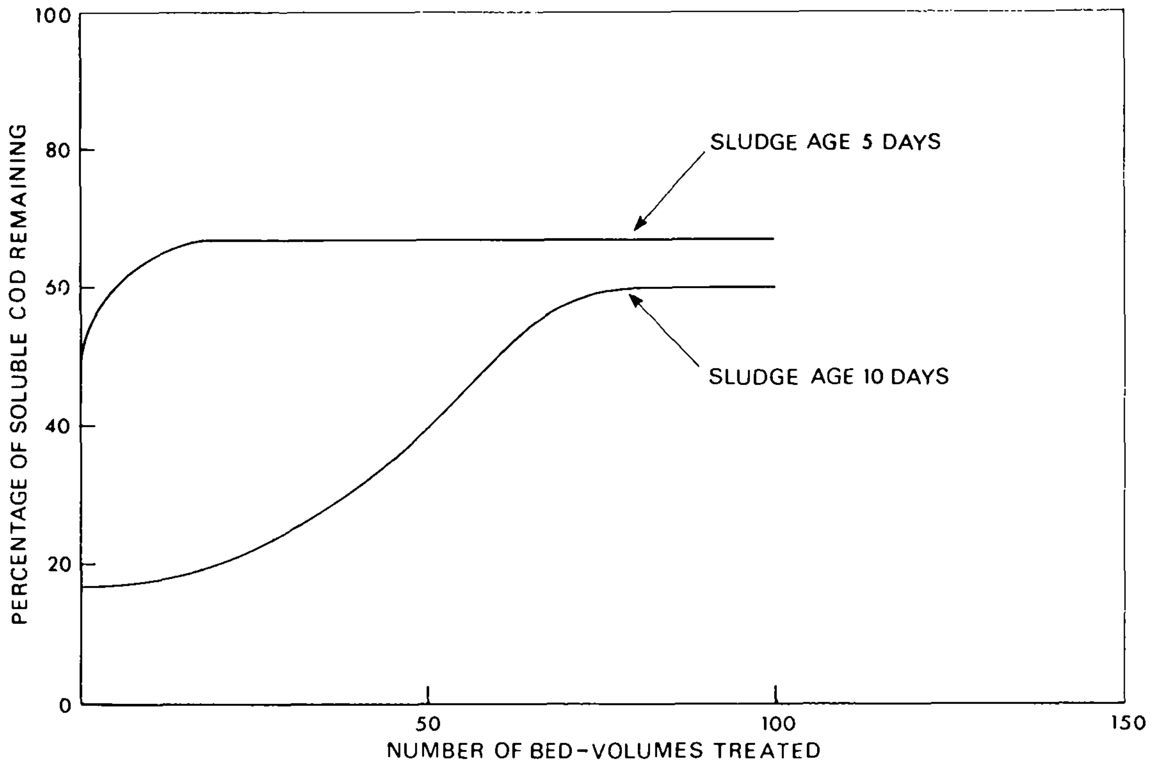

Fig. B1. Reduction in SCOD of the effluents from control activated-sludge units by upflow PAC columns. (After Reference 28)

The different characteristics of the breakthrough curves may perhaps be ascribed to the influence of sludge age on the concentration of poorly adsorbed material in the unit effluents. Kim and others(100) demonstrated that higher values of θ_c result in lower effluent concentrations of such material. On start-up of column operations, this component is adsorbed to some extent but, as the adsorption zone passes through the column, is later displaced by compounds possessing higher energies of adsorption(23,49). This can occur shortly after start-up and may have resulted in the observed partial breakthrough curves. If so, the hypothesis of DeWalle and others(28) is not sustained.

B.4. IMPROVED SOLIDS SETTLING

Adams and co-workers(32-34,38-41) suggested that high-density PAC improves solids settling by acting as a weighting agent, keeping the microbial solids in the system under high organic load conditions which would normally lead to sludge bulking; and by providing sites for floc formation under low organic loadings which normally result in a dispersed biofloc and loss of solids. Enhanced phosphorus and nitrogen removals could be expected to stem from the reduction in effluent suspended solids, improved nitrogen removal resulting from the maintenance of a greater mass of denitrifying organisms in the activated sludge. If an anoxic zone is not provided, however, and denitrification takes place in the final settlement tank, it is possible that the sludge may still float, despite the evidence of more rapidly settling sludges.

DeWalle and others(28) observed that more compact sludge flocs resulted from PAC addition. From a group organic analysis of the effluents from units operated at a sludge age of 5 d, it was postulated that the enhanced SCOD removal resulted from the formation of these denser flocs. Organic intermediates released by the bacteria during substrate utilisation would thus diffuse less readily from these flocs, while their subsequent uptake would be more rapid. If this is the case, however, it might be thought that this effect would be balanced by lower rates of substrate diffusion into the flocs. They ascribed the formation of the more compact sludge flocs to the adsorption of high molecular weight humic material of high carbohydrate content. Previous studies(101) had apparently shown that its adsorption on cellular material aided flocculation and resulted in more settleable sludges.

APPENDIX C A CRITICAL EVALUATION OF THE MODEL PROPOSED BY DeWALLE AND CHIAN

In this model, apparent adsorptive capacities were plotted against effluent SCOD concentrations for a number of values of sludge age, and the curves extrapolated to the effluent SCOD concentrations of the control units. The extrapolated capacity values ($\mathrm{LOAD}_{\max}$) were plotted against sludge age, and the gradient of the assumed linear curve was termed the daily regenerated capacity. It was proposed that this could be related to the microbial solids concentration in the reactor by a power function of the influent wastewater substrate concentration, that is, S_o,

$$\frac{\partial\ \mathrm{LOAD}_{\max}}{\partial\ \theta_c} = k\ S_o^{\ n}, \qquad \text{(C1)}$$

where k and n are constants.

In determining values for the constants k and n (0.0025 and 0.55 respectively), literature data were also used. However, the daily regenerated capacities determined from these data were not derived in a similar fashion. Those based on the data of Wallace and Burns(17), for example, were determined from the plots of apparent adsorptive capacity (for a range of PAC doses) against solids retention time.

It was admitted that the model was crude and lacked precision: at any given influent substrate concentration, the daily regenerated capacity exhibited a 2-fold variation about the predicted value. The authors suggested that the model could be refined through replacement of the influent COD data with BOD data, and by incorporation of a yield factor. However, this model suffers from other short-comings. In addition to using extrapolated data values which, in the context of this process, have no real physical meaning attached to them, the authors appear to have overlooked a basic fact of adsorption - namely, that the adsorptive capacity of an adsorbent is directly related to the original concentration of adsorbate. Thus, the use of adsorptive capacity values estimated to be those of activated carbon at equilibrium with a variable influent adsorbate (or substrate) concentration is mistaken. Indeed, it can be shown that their model does not adequately describe their own data(39). Suppose that, in addition to its dependence on θ_c, the apparent adsorptive capacity of activated carbon is dependent on the concentration of biological MLSS or on the ratio of the concentrations of the biological and PAC MLSS. Adopting the sludge-age approach(45) to describing activated-sludge treatment kinetics, the microbial solids concentration in the reactor at steady state can be given by:

$$X = \frac{Y\ \theta_c\ (S_o - S_1)}{\theta\,(1 + b\ \theta_c)}. \qquad \text{(C2)}$$

This reduces to:

$$X = \frac{Y\,\theta_c\,E\,S_o}{\theta\,(1 + b\,\theta_c)}. \tag{C3}$$

At steady state the concentration of PAC in the reactor may be given approximately by Equation A13, that is,

$$C = C_o\,\frac{\theta_c}{\theta}\ .$$

Adopting the approach of DeWalle and Chian, therefore, the apparent organic loading on the added PAC is given at steady state by

$$\mathrm{LOAD} = a + k_1\ \theta_c\ X^{n_1} \tag{C4}$$

or by

$$\mathrm{LOAD} = a_1 + k_2\ \theta_c\ \left(\frac{X}{C}\right)^{n_2} \tag{C5}$$

where a, a_1, k_1, k_2, n_1 and n_2 are constants.

Referring to the transformed data of Fig. 6, the parameters θ, E, S_o, and Y may be regarded as constant. Also, the constant b is typically small ($\approx 0.05\ d^{-1}$) such that, within the range $5 \leqslant \theta_c \leqslant 15$, the factor $(1+b\ \theta_c)$ is essentially constant.

Equations C4 and C5 may be approximately reduced, therefore to:

$$\mathrm{LOAD} = a + k_3\ \theta_c^{\ 1+n_1} \tag{C6}$$

and

$$\mathrm{LOAD} = a_1 + \frac{k_4\ \theta_c}{C_o^{\ n_2}} \tag{C7}$$

respectively, where k_3, k_4 are constants.

In Fig. 6, the load variations are linear with respect to θ_c. This implies that the factors X and $\frac{X}{C}$ are not significant in determining the rate of regeneration of adsorptive surfaces.

APPENDIX D DESIGN CRITERIA

D.1. COMMON OPERATIONS

Table D1. Criteria common to all processes

DWF	11 000, 33 000, and 110 000 m^3/d
Preliminary treatment	
Maximum flow rate	6 DWF (m^3/d)
Storm tank volume	0.25 DWF (m^3)
Primary sedimentation	
Retention time at 1 DWF	6 h
Rapid gravity sand filtration	
Hydraulic loading at 3 DWF	250 $m^3/m^2 d$
Filter-cake transport to tip	
Cake dry solids	30% w/w
Distance per round trip to tip to tip	5, 10, and 20 miles for DWFs of 11 000, 33 000, and 110 000 m^3/d respectively

D.2. SEQUENTIAL TREATMENT BY ACTIVATED SLUDGE AND GRANULAR ACTIVATED CARBON

Table D2. Criteria for the activated-sludge stage

DWF	11 000, 33 000, and 110 000 m^3/d
Aeration tanks	
Δ BOD	190 mg/1
Effluent SCOD	45 mg/1
SLR	0.15 kg BOD/kg MLSS d
θ_c	10 d
Hydraulic retention time at 1 DWF	0.25 d
MLSS	3800 mg/1
Installed duty power for aeration*	1.5, 1.35, and 1.2 kW/kg BOD respectively
Oxygen requirement*	1.8 kg O_2/kg BOD
Final settlement tanks	
SSVI	100 ml/g
u	0.6 m/h
F_L	6.3 kg/m^2 h
Maximum flow-rate of return sludge	11 000, 33 000 and 110 000 m^3/d respectively

* Fine-bubble diffused-air system provided. The duty power and oxygen requirement is specified for the average rate of BOD reduction.

Table D3. Criteria for the sludge-dewatering stage

DWF	11 000, 33 000, and 110 000 m^3/d
Production of sludge solids	0.5 kg/m^3
Sludge dry solids (DS) content	4.5% w/w
Sludge holding tanks	
Capacity	5 d
Filter-plate presses	
Maximum number of pressings per week	10, 10, and 15, respectively
Dose of aluminium chlorohydrate	1.5% w/w (Al_2O_3/DS)
Cake dry solids content	32.5% w/w

Table D4. Criteria for the activated-carbon treatment stage

DWF	11 000, 33 000, and 110 000 m^3/d
Organic loading	0.25, 0.40, and 0.55 kg SCOD/kg AC
Activated-carbon contactors	
Feed SCOD	45 mg/l
Number of contactors in series	2
Hydraulic loading at 3 DWF	590 m^3/m^2 d
Total hydraulic retention time at 1 DWF	0.5 h
Total bed depth	4.1 m
Bulk density of GAC	0.45 $tonne/m^3$
Activated-carbon regeneration furnace	
Furnace capacity	1.75 times the average rate of GAC exhaustion
Hearth loading	0.404 tonne GAC/m^2 d
Total GAC losses	7% w/w
Furnace temperature	900 °C

The concentration of mixed liquor suspended solids in the aeration tank may be estimated from Equation D1* using an assumed value of 0.15 for the sludge loading rate (SLR).

$$SLR = \frac{Q \ \Delta BOD}{V \ MLSS} \qquad (D1)$$

where ΔBOD = effected reduction in BOD of the settled sewage. This value for MLSS is used to size the final settlement tanks by a method described by

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* This does not take into account the sludge solids present in the final settlement tank.

White(76), based on the observed relationship between the maximum expected stirred specific volume index (SSVI) of the sludge and the maximum underflow rate (u) from the tanks, and the maximum solids loading (F_L) that the tanks can tolerate, that is,

$$F_L = 307\ (\mathrm{SSVI})^{-0.77}\ u^{0.68}. \qquad \text{(D2)}$$

Though no full-scale activated carbon plants for the treatment of sewage effluent have been built, it is anticipated that sand-filtered effluent would be contacted with GAC in plant similar to upflow sand filters. Several contactors are presumed to act in parallel, each consisting of two units in series. The hydraulic loading (590 m/d) specified at the maximum design flow lies at the upper end of the range recommended by the Environmental Protection Agency of the United States(77).

For each design flow, the size of the multiple-hearth furnace for GAC regeneration is dependent on three variables:

(i) the hearth loading, for which the value of 0.404 tonne GAC/m^2 d given by Hutchins(78) is adopted,

(ii) the furnace downtime, for which it is assumed that the furnace is on standby at weekends and is down for planned and unplanned maintenance for periods of three and five weeks per year, respectively,

(iii) the loading of adsorbed organic material on the exhausted GAC, for which values within the range 0.25 to 0.55 kg SCOD/kg GAC are assumed, based on a review of pilot-plant data(3).

D.3. TREATMENT BY ACTIVATED SLUDGE WITH ADDED PAC

D.3.1. With no regeneration of PAC

Table D5. Criteria for the activated-sludge stage

DWF	11 000, 33 000, and 110 000 m^3/d
Aeration tanks	
Δ BOD	195 mg/l
Effluent SCOD*	35 mg/l
SLR	0.1 kg BOD/kg MLSS d
θ_c	20 d
MLSS	7000 mg/l
Installed duty power for aeration†	1.6, 1.45, and 1.3 kW/kg BOD respectively
Oxygen requirement†	1.9 kg O_2/kg BOD
PAC dosing	
Organic loading	0.10, 0.15, 0.20, 0.25, 0.30, and 0.35 kg SCOD/kg AC
Capacity of dosing equipment	3 times the average PAC dose
Final settlement tanks	
SSVI	50 ml/g
u	0.6 m/h
F_L	9.3 kg/m^2 h
Maximum flow rate of returned sludge	11 000, 33 000, and 110 000 m^3/d

* Assumed to be that if PAC was not present.

† Fine-bubble diffused-air system provided. The duty power and oxygen requirement is specified for the average rate of BOD reduction.

Table D6. Criteria for the sludge-dewatering stage

DWF	11 000, 33 000, and 110 000 m^3/d
Production of sludge solids	0.70, 0.633, 0.60, 0.58, 0.567, and 0.557 kg/m^3 for organic loadings of 0.10, 0.15, 0.20, 0.25, 0.30, and 0.35 kg SCOD/kg AC respectively
Sludge dry solids content	4.5% w/w
Sludge holding tanks	
Tank capacity	5 d
Filter-plate presses	
Maximum number of pressings per week	10, 10, and 15 for DWFs of 11 000, 33 000, and 110 000 m^3/d respectively
Dose of aluminium chlorohydrate	1.0% w/w (Al_2O_3/DS)
Cake dry solids content	32.5% w/w

To gain the benefits from biological regeneration of the carbon adsorptive surfaces, it is assumed that the activated-sludge process would be run at a sludge age of 20 d. Assuming a sludge growth index of 0.5 kg solids/kg BOD removed, this is equivalent to a sludge loading of 0.1 kg BOD/kg d.

Neglecting any influence that adsorption of surfactants on the added PAC might have on the oxygenation efficiency of the aeration equipment (fine-bubble diffused air), additional aeration capacity would have to be provided to meet the respiratory oxygen demand of the suspended biomass. Any relationship between hydraulic retention time and oxygen requirement is neglected, and it is assumed that the additional oxygen requirement could be met by installing an extra 0.1 kW of duty power per kg BOD removed per hour.

It is assumed that commercially-available, high-density (>640 kg/m^3) PAC having a surface area of 400-600 m^2/g is added to the aeration tanks as a slurry; that the apparent loading on the carbon would lie in the range 0.10-0.35 kg SCOD/kg AC; and that the capacity of the dosing equipment is three times the average rate. As the use of high-density PAC is specified, it is assumed that the use of polymers to aid solids settling in the final settling tank is not necessary.

Although secondary sludges containing PAC are said to settle much more rapidly than conventional sludges, no reliable quantitative measurements of their settleability have been made. It is assumed, therefore, that the stirred specific volume index of the sludge would not exceed 50 ml/g, and that the maximum solids loading on the final settlement tanks can be predicted by use of Equation D2 as before. Taking into consideration the greater mass of suspended solids in the aeration and settlement tanks (compared with the conventional nitrifying plant), adoption of this criterion implies that additional aeration-tank and/or settlement-tank capacity has to be provided. Trial calculations indicated that it would be cheaper to provide greater aeration-tank capacity than install additional settlement tanks. Consequently, no additional settlement capacity is specified. This condition can be approximately satisfied by assuming a mixed-liquor suspended-solids concentration of 7000 mg/l. Note that at the maximum PAC dose considered (200 mg/l), this would result in a hydraulic retention time of over 20 h: the alternative of providing additional settlement capacity would result in the need to maintain a mixed-liquor solids concentration of about 18 000 mg/l.

Any reduction in BOD of the settled sewage resulting from the discharge of waste secondary sludge containing PAC to the primary settlement tank is discounted, and it is assumed that the dry solids content of the co-settled sludge would be unchanged at 4.5 per cent.

Assuming also that the rate of sludge dewatering, and the cake solids content, would be unaffected, increased dewatering capacity would need to be installed. It is assumed, however, that less aluminium chlorohydrate sludge conditioner would be needed on a w/w basis, and that the dose could be cut from 1.5 to 1.0 per cent (w.Al_2O_3/w. dry solids).

D.3.2. With regeneration of PAC by wet-air oxidation

Table D7. Criteria for the activated-sludge stage of PACAST-WAO

DWF	11 000, 33 000, and 110 000 m^3/d
Aeration tanks	
Δ BOD [a]	211 mg/l
Effluent SCOD [b]	35 mg/l
Δ SCOD [c]	3 mg/l
Kj-N content of sludge produced from the oxidation of settled sewage	5% w/w (Kj-N/DS)
Δ NH_3-N [d]	5 mg/l
SLR	0.1 kg BOD/kg MLSS d
Y	0.5 kg solids/kg BOD
θ_c	20 d
MLSS Total	7000 mg/l
Microbial	3240 mg/l
PAC	3120 mg/l
Inerts	640 mg/l
Installed duty power for aeration [e]	1.65, 1.50, and 1.35 kW/kg BOD respectively
Oxygen requirement [e]	1.0 kg O_2/kg BOD
PAC dosing	
Organic loading	0.225 kg SCOD/kg AC
Capacity of dosing equipment	1 times the average total PAC dose
Final settlement tanks	
SSVI	50 ml/g
u	0.6 m/h
F_L	9.3 kg/m^2 h

[a] Allows for the additional BOD of the returned WAO liquors.

[b] Assumed to be that if PAC was not present and WAO liquors were not returned.

[c] Assumed to be the additional residual (after biochemical oxidation) SCOD resulting from the return of WAO liquors.

[d] Effective increase in ammoniacal nitrogen concentration in the feed due to the returned WAO liquors.

[e] Fine-bubble diffused-air system provided. The duty power and oxygen requirement are specified for the average rate of BOD reduction, allowing for the return of WAO liquors.

Table D8. Criteria for the wet-air oxidation stage of PACAST-WAO

DWF	11 000, 33 000, and 110 000 m^3/d
Solids production (microbial + PAC + inerts)	0.225 kg DS/m^3
Sludge thickeners	
Solids loading	50 kg/m^2 d
Solids content of thickened sludge	8% w/w
Holding tanks for thickened sludge	
Capacity	21 d
Wet-air oxidation	
Unit capacity	2.11, 1.75, and 1.75 times the average rate of flow of thickened sludge
Operating pressure	50 bar
Operating temperature	230 °C
Blowdown rate	5% v/v
PAC losses	
Total losses from the process	15% w/w
Losses in the final effluent	4% w/w
Losses in the WAO unit	6% w/w
Blowdown losses	5% w/w

Table D9. Criteria for the primary sludge dewatering stage of PACAST-WAO

DWF	11 000, 33 000, and 110 000 m^3/d
Solids production	0.40 kg/m^3
Sludge dry-solids content	4.5% w/w
Sludge holding tanks	
Capacity	5 d
Filter-plate presses	
Maximum number of pressings per week	10, 10, and 15 respectively
Dose of aluminium chlorohydrate	1.5% w/w (Al_2O_3/DS)
Cake dry-solids content	32.5% w/w

For the sake of simplicity, and because of the nature of the additional assumptions that have to be made, only one value for the apparent organic loading on the carbon is specified, the value of 0.225 kg SCOD/kg AC lying in the middle of the range considered for the throw-away use of powdered carbon. Any effects of regeneration on the adsorptive capacity of the carbon are neglected. Plant for adding virgin carbon (make-up) is specified so that, operating at capacity, the average total carbon dose could be supplied.

In the design of the aeration and settlement tanks, assumptions similar to those in the preceding section have to be made. Additionally, the solubilisation of a fraction of the biological component of the waste sludge and the formation of inert suspended solids must be taken into account.

Assuming a sludge-growth index of 0.5 kg solids/kg BOD removed, a reduction in BOD of the settled sewage of 195 mg/l results in the formation of approximately 100 mg solids/l. If the Kjeldahl-nitrogen content of the solids is 5 per cent (w/w), complete conversion to ammoniacal nitrogen in the WAO unit would result in an increased load on the activated-sludge tanks equivalent to 5 mg NH_3-N/l.

Taking the ratio of the COD to volatile sludge solids for the biological fraction of the sludge to be 1.67, and the volatiles to comprise 80 per cent of the biological total solids, the COD of the sludge solids produced will be about 131 mg/l on a works design flow basis. Assuming that 20 per cent of the sludge is solubilised by WAO and that the BOD-to-COD ratio of the resultant liquor is 0.55(62), the return of this liquor to the aeration tanks will result in the production of more sludge solids, a fraction of these again being solubilised. If the returned liquors can be regarded as equivalent to settled sewage, the net result may be estimated to be an increased loading on the activated sludge of 16 mg BOD/l.

For the provision of a fully-nitrified effluent, it is assumed that the oxygen requirement could be met by the installation of an additional 0.05 kW of duty power per kg BOD removed per hour.

Because of the return of WAO liquors to the aeration tanks, more PAC would be needed to adsorb any residual SCOD. Assuming the liquors to be equivalent to settled sewage, in terms of treatability, a 15 per cent increase in the total PAC dose would be needed to adsorb the extra residual SCOD, estimated as being 3 mg/l. Note that this assumption may seriously underestimate the PAC dose required and hence the capacity and costs of the WAO unit.

Assume that the production of inert suspended matter in the WAO unit is directly proportional to the BOD of the settled sewage. Using data given by Shuckrow and Culp(27), the concentration of inert suspended solids in the aeration tanks, I, may be estimated from Equation D3.

$$I = 21 \frac{\theta_c}{\theta}. \qquad (D3)$$

Sludge wasted from the final settlement tanks is continuously thickened to an assumed dry-solids content of 8 per cent in a gravity thickener, which is operated at an assumed solids loading of 50 kg/m^2 d(27). This is a considerably higher loading than could be tolerated for the thickening of activated sludge alone. Duplicate thickeners are specified to ensure process stability.

The thickened sludge is held in storage tanks. These are assumed to have a capacity of 21 d so that PAC would not be wasted from the system during a lengthy shut-down of the WAO unit.

The capacities of the WAO units are based on their down-time being identical to that of multiple-hearth furnaces, subject to an apparent limitation on the smallest size unit (65 m^3/d) commercially available(27).

APPENDIX E ESTIMATED PROCESS COSTS

Table E1. Net present values of works producing a filtered nitrified effluent

DWF (m^3/d)	11 000				33 000				110 000			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
Preliminary treatment	304	51	1	429	656	91	1	879	1528	238	3	2098
Primary settling	129	14	0	164	322	24	0	391	1134	178	1	1539
Mixed liquor aeration	261	154	18	817	581	363	54	2074	1400	935	181	5910
Final settling	158	20	0	205	431	32	1	540	1437	106	2	1777
Sand filtration	111	110	2	325	270	233	5	739	717	528	18	1898
Sludge storage and dewatering	283	252	22	1057	605	646	66	2732	1127	1286	221	6800
Cake transport	0	0	2	32	0	0	10	161	0	0	58	936
Pumping station	52	24	-	94	65	32	-	121	127	85	0	272
TOTAL	1298	625	45	3120	2930	1421	137	7640	7470	3356	484	21200

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded. NPV is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost.

Table E2. Additional net present values of works employing PACAST, for a DWF of 11 000 m^3/d

Organic loading (kg SCOD/kg AC)	0.10				0.15				0.20			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	16	32	154	2554	13	26	102	1700	11	23	77	1291
Mixed liquor aeration	173	11	1	223	113	11	1	157	82	11	1	123
Final settling	9	1	0	12	9	1	0	12	9	1	0	12
Sludge storage and dewatering	65	75	0	187	42	48	-2	88	29	35	-3	38
Cake transport	0	0	1	16	0	0	1	16	0	0	1	16
TOTAL	263	119	156	2990	177	86	102	1970	131	70	76	1480

Organic loading (kg SCOD/kg AC)	0.25				0.30				0.35			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	10	20	62	1043	9	19	52	878	9	17	45	762
Mixed liquor aeration	63	11	1	102	50	11	1	88	40	11	1	77
Final settling	9	1	0	12	9	1	0	12	9	1	0	12
Sludge storage and dewatering	20	26	-4	-3	15	21	-4	-16	12	17	-5	-42
Cake transport	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	102	58	59	1150	83	52	49	962	70	46	41	809

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded. NPV is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost.

Table E3. Additional net present values of works employing PACAST, for a DWF of 33 000 m^3/d

Organic loading (kg SCOD/kg AC)	0.10				0.15				0.20			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	28	55	470	7702	23	45	308	5066	20	39	228	3762
Mixed liquor aeration	386	36	4	546	253	36	4	399	185	36	4	325
Final settling	34	7	0	48	34	7	0	44	34	7	0	44
Sludge storage and dewatering	150	196	2	501	99	127	-5	224	72	92	-8	93
Cake transport	0	0	4	65	0	0	3	48	0	0	2	32
TOTAL	598	294	480	8860	409	215	310	5780	311	174	226	4260

Organic loading (kg SCOD/kg AC)	0.25				0.30				0.35			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	17	35	180	2978	16	32	148	2457	15	29	125	2080
Mixed liquor aeration	141	36	4	276	111	36	4	243	90	36	4	220
Final settling	34	7	0	44	34	7	0	44	34	7	0	44
Sludge storage and dewatering	52	71	-10	6	46	57	-11	-40	37	47	-12	-81
Cake transport	0	0	2	32	0	0	1	16	0	0	1	16
TOTAL	244	149	176	3340	207	132	142	2720	176	119	118	2280

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded. NPV is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost.

Table E4. Additional net present values of works employing PACAST, for a DWF of 110 000 m^3/d

Organic loading (kg SCOD/kg AC)	0.10				0.15				0.20			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	50	101	1574	25616	41	82	1023	16683	36	71	762	12449
Mixed liquor aeration	929	91	14	1389	611	91	14	1039	441	91	14	852
Final settling	100	9	0	124	100	9	0	124	100	9	0	124
Sludge storage and dewatering	317	405	5	1057	219	266	-20	330	139	196	-28	5
Cake transport	0	0	23	371	0	0	15	242	0	0	11	178
TOTAL	1396	606	1616	28600	971	448	1032	18400	716	367	759	13600

Organic loading (kg SCOD/kg AC)	0.25				0.30				0.35			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
PAC addition	32	64	600	9818	29	58	492	8063	27	54	413	6780
Mixed liquor aeration	341	91	14	742	271	91	14	665	211	91	14	599
Final settling	100	9	0	124	100	9	0	124	100	9	0	124
Sludge storage and dewatering	108	154	-34	-191	90	126	-38	-319	74	105	-42	-434
Cake transport	0	0	9	145	0	0	7	113	0	0	6	97
TOTAL	581	318	589	10600	490	284	475	8650	412	259	391	7170

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded. NPV is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost.

Table E5. Additional net present values of works employing PACAST with regeneration of PAC by WAO, for an organic loading of 0.225 kg SCOD/kg AC

DWF (m^3/d)	11 000				33 000				110 000			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
Raw sludge storage and dewatering	-49	-49	-4	-195	-97	-124	-13	-509	-174	-237	-44	-1268
Cake transport	0	0	0	0	0	0	-2	-32	0	0	-12	-194
PAC dosing equipment	16	23	1	70	30	39	1	109	53	72	2	202
Mixed liquor aeration	165	29	4	292	367	73	10	678	885	200	35	1849
Final settling	9	1	0	12	34	7	0	48	100	9	0	124
Gravity thickening	41	23	-	81	87	34	-	149	204	70	-	333
Thickened sludge storage	49	7	-	65	87	12	-	115	240	33	-	315
Wet-air oxidation†	286	292	46	1510	407	414	87	2494	1081	1099	230	6604
TOTAL	517	326	47	1840	915	455	83	3050	2389	1246	211	7970

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded from all treatment stages except that of WAO. NPV is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost.

† Includes the cost of carbon make-up.

Table E6. Additional net present values of works using granular activated carbon

A. DWF of 11 000 m^3/d

Organic loading	0.25 kg SCOD/kg AC				0.40 kg SCOD/kg AC				0.55 kg SCOD/kg AC			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
Contacting plant	294	199	1	647	294	199	1	647	294	199	1	647
Initial carbon	126	0	0	131	108	0	0	112	100	0	0	104
Regeneration†	69	76	59	1146	50	56	46	884	41	46	40	762
TOTAL	489	275	60	1920	452	255	47	1640	435	245	41	1510

B. DWF of 33 000 m^3/d

Organic loading	0.25 kg SCOD/kg AC				0.40 kg SCOD/kg AC				0.55 kg SCOD/kg AC			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
Contacting plant	620	420	4	1398	620	420	4	1398	620	420	4	1398
Initial carbon	378	0	0	393	324	0	0	337	300	0	0	312
Regeneration†	146	155	133	2547	106	114	92	1781	86	93	73	1419
TOTAL	1144	575	137	4340	1050	534	96	3520	1006	513	77	3130

C. DWF of 110 000 m^3/d

Organic loading	0.25 kg SCOD/kg AC				0.40 kg SCOD/kg AC				0.55 kg SCOD/kg AC			
Cost component*	CC	CM	CO	NPV	CC	CM	CO	NPV	CC	CM	CO	NPV
Contacting plant	1405	953	13	3233	1405	953	13	3233	1405	953	13	3233
Initial carbon	1261	0	0	1311	1080	0	0	1124	1002	0	0	1042
Regeneration†	326	342	374	6926	238	250	245	4605	192	203	187	3383
TOTAL	2992	1295	387	11500	2724	1203	258	8960	2599	1156	200	7660

* All costs are expressed to the nearest £'000 at 1976 Q3 prices. Labour costs are excluded from all treatment stages except that of GAC regeneration. NPV of all items except the initial carbon is calculated from NPV = 1.10 CC + 1.55 CM + 16.14 CO, where CC is the total initial civil costs, CM is the total initial mechanical costs, and CO is the annual operating cost. The initial carbon is assumed to have been bought in the final year of a 3-year construction programme and a factor of 1.04 is therefore used to calculate CC.

† Includes the cost of carbon make-up.

APPENDIX F DETAILS AND DISCUSSION OF SOME COST-RELATIONSHIPS USED AND RESOURCES SPECIFIED

F.1. GRANULAR ACTIVATED-CARBON CONTACTORS

Costs for GAC contactors are assumed to be similar to those of up-flow sand filters, and the appropriate cost-relationship in TR 61 has been employed. These costs include that of the sand medium, but no correction for this has been made since it will be negligible compared to the cost of GAC.

Sufficient contact area should be provided so that two contractors are always spare - one for the removal of spent carbon, and one for recharging with regenerated and make-up carbon. However, as the limitations on plan area and aspect ratio are not sufficiently known, the precise number of contactors and total plan area cannot be specified with confidence. An arbitrary 10 per cent additional area, therefore, has been assumed in estimating the capital costs. The civil and mechanical components of these costs are each assumed to be 50 per cent.

Though no estimates of the effect on costs of flow-balancing have been made, it would seem that the provision of flow-balancing plant could reduce the capital costs of both the contacting vessels and the initial charge of GAC.

In specifying the amount of carbon that would be required for plant start-up, an additional amount has been included to allow for prolonged down-time of the regeneration furnace. Extra carbon equivalent to 21 d supply at average rates of GAC exhaustion has been specified. It has been assumed that all of the initial carbon would be brought on-site in the final year of the 3-year construction and commissioning programme, and an appropriate factor used to calculate its contribution to the additional NPV of the works. This carbon has been considered an item of civil costs.

F.2. MULTIPLE-HEARTH REGENERATION FURNACE

The cost-curves for multiple-hearth incinerators in Technical Report TR 61 have been considered appropriate to use for costing the regeneration furnace. Additional costs for a carbon slurry dewatering screw were estimated by an up-dated cost-curve given by Burley and Short(79).

The sources required to operate the furnace have largely been given by Hutchins(78), and are listed in Table F1. It has been assumed, however, that for all furnaces an additional 1 man per shift would be required. The fuel oil needed for re-heating the furnace after shut-down for maintenance (assumed to be 3 times per year) and the maintenance of a 'soaking' temperature at weekends have been estimated graphically from data given by Hoyland(80).

Table F1. Resources required to operate the regeneration furnace

Make-up carbon	7% w/w
Fuel oil* (excludes that needed for steam generation, and for re-heat and stand-by)†	$2.34.F.CAP^{0.811}$ 10^{9} J/year
Electricity*	$2.34.F.CAP^{0.315}$ 10^{3} kWh/year
Steam	0.6 kg/kg AC
Operating labour	1 man/shift
Operating supplies	10% of maintenance costs/year
Laboratory + supervision	45% of operating labour and 25% of maintenance costs/year
Maintenance	6% of mechanical capital costs/year

* Where CAP = furnace capacity kg GAC/d,
F = fraction of total time for which the furnace is operated = 0.56 for a furnace capacity of 1.75 times the average rate of GAC exhaustion.

† Fuel oil needed to provide re-heat and stand-by heat is approximately 1.0-1.5% on an annual basis of that needed for furnace operation (F = 0.56).

F.3. WET-AIR OXIDATION REACTOR

The estimated capital costs of the WAO units and the resources required for operation are both largely based on graphical data supplied by Shuckrow and Culp(27). Their estimate of the capital costs contained a 25 per cent allowance for contractor's overheads and profit. This allowance was subtracted, the resultant cost converted to pounds sterling using the conversion rate current for 1975 Q4, and this cost up-dated to 1976 Q3 levels by use of average NCI and EAI cost-indices. It is assumed that the mechanical and civil components would be 60 per cent and 40 per cent respectively. An allowance of 47.5 per cent was added to the civil costs, as in the other estimates, to cover interprocess pipework, site works, contractor's overheads and site allowance.

Maintenance material costs were taken to be 1 per cent of the total capital cost per year(27).

The power consumption of the high-pressure pumps and air compressors was taken to be directly proportional to the duration of operations, and graphical data supplied by Shuckrow and Culp(27) were used accordingly.

Fuel consumption will be sensitive to the sludge thickness, i.e. to the energy released per unit volume of sludge in the oxidation of the organic material. At a solids concentration of 8 per cent w/w, Zimpro is quoted as stating(27) that oxidation should be an autothermic reaction. Assuming this to be true, and that heat is only needed for start-up after the weekend and after maintenance, an approximate value for the fuel-oil requirement may be estimated. It is assumed that the annual fuel-oil requirement is equivalent to that used in heating up 2 hours' flow of sludge from a temperature of 20 °C up to one of 230 °C, at an overall efficiency of 33 per cent, 49 times per year. The specific heat of sludge is assumed to be the same as that of water and the effect of pressure (on specific heat) is neglected.

Operating labour, operating supplies, and laboratory and supervisory staff are all specified on the same basis as for the multiple-hearth regeneration furnace.

APPENDIX G UNIT OPERATING COSTS

PAC	£190/tonne
GAC	£690/tonne
Fuel oil	£1.36/10^9 J
Electricity	£0.02/kWh
Labour (for GAC regeneration furnace and WAO unit)	£13000/man-shift year
Steam* (for GAC regeneration furnace)	£13/tonne of steam
Aluminium chlorohydrate (15% Al_2O_3 solution w/w)	£90/tonne of solution

* It is assumed that steam would be generated by the direct injection into the furnace of water preheated to 80 °C. Additional fuel oil would be required, and it is assumed that the production of steam by this means would be 60 per cent efficient.

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Printed in Great Britain by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset