BIOLOGICAL TREATMENT OF COAL CONVERSION CONDENSATES

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Abstract

Biochemical oxidation is an important way to remove organic contamination from foul condensates in coal conversion plants. The design considerations are discussed; oxygen is recommended in preference to air, and a test with mutated bacteria is recommended. Reactor configurations are also discussed. When the organic contamination is high, the use of oxygen requires forced cooling and a combined cooling tower/trickling filter is suggested for the test. Preliminary plant designs are given for two situations in a Hygas plant: one when lignite is fed and one when a bituminous coal is fed.

Waters that condense and are removed from a coal conversion plant will often be highly contaminated with organic matter. The level of contamination depends on the process and on the coal. Condensate from Solvent Refined Coal, Synthoil, or H-Coal can be expected to be very dirty. From gas plants the contamination seems to be higher from a lower temperature and a shorter residence time. Thus Lurgi and probably Synthane will give quite dirty water, Hygas will give less dirty water, and Bigas the least dirty. The coal rank is very important. Condensate from a Hygas plant fed lignite is many times more contaminated than condensate from the same plant fed a bituminous coal.

Dirty condensate will have to be treated for reuse. Reuse possibilities include makeup to a wet flue gas desulfurization system, use for dust control, and makeup to a cooling tower. The first in line of the commonly assumed treatments is solvent extraction. If the extractable concentration is high enough that its value as a fuel or as crude phenol can partially offset cost, then solvent extraction, or a treatment accomplishing the same result, should be used. For lower levels of contamination solvent extraction will probably not be economically justifiable. Most condensates will next have to be treated to remove ammonia and many will require removal of hydrogen sulfide. After ammonia separation the next treatment in series will often be biological oxidation. The contamination in many waters seems to be biodegradable. Phenol, a common, high level contaminant, is biodegradable.

It is the purpose of this paper to put forward preliminary designs for biological oxidation plants for these waters. Biological oxidation and solvent extraction are both treatments to accomplish the same objective, to remove organic contamination. They are not mutually exclusive. If solvent extraction is not economic and is not used, biological treatment will usually be required. But if solvent extraction is used its cost is quite dependent on the level of contamination acceptable in its effluent and it may pay to follow solvent extraction with biological oxidation. When treated condensate is to be used as makeup to a cooling tower, biological treatment has some disadvantages. Phosphorus will have to be added and will not be all used up in the treatment. Dissolved CO_2 and suspended solids are increased by biological treatment. Possibly residual ammonia, which is necessary as a nutrient in biological treatment, will be higher than need be left after ammonia stripping. We are not, at the moment, able to say whether biological treatment should be reserved for situations where solvent extraction is not used, or whether biological treatment will be useful subsequent to solvent extraction.

DESIGN CONSIDERATIONS

Major design considerations for biochemical oxidation include:

- A. Reactants
  - a. Phenols and other organics
  - b. Other required nutrients
  - c. Oxidants
- B. Biological Agents
- C. Reactor Configurations

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A. Reactants

During biological treatment the organic constituents of wastewaters, such as phenols, are oxidized and utilized as the sources of carbon and/or energy while the reaction is mediated by biological agents. Phenol is usually considered biodegradable. However, if the phenol concentration exceeds a certain threshold level, phenol itself can inhibit the bio-oxidation. This threshold concentration of phenol has been reported to be 500 mg/l[1] and 1,000 mg/l;[2] these concentrations are unlikely to be exceeded in the completely mixed bioreactor of an activated sludge system. Should the phenol concentration become inhibitory, a proper scheme of dilution may be needed. Dilution can be achieved by internal recirculation of treated water or by adding an external dilutant.

Other organics, particularly those refractory in nature, may significantly affect the performance of biological treatment and consequently the dilution requirement. Although this category of organics may be measured by the difference between COD and BOD, its effect on bio-oxidation appears to be poorly understood and requires pilot testing with the specific wastewater to be treated.

To satisfy nutritional requirements of the biological agents responsible for bio-oxidation, certain inorganic macro and micro nutrients may have to be provided. Macro nutrients such as nitrogen and phosphorus are required in proportion to phenol content. A typical weight ratio as used at Bethlehem Coke Plant[3] is phenol:N:P $\doteq$ 70:5:1. Excess N is available in the condensates, so the ammonia concentration will be reduced to the required nutritional level by proper ammonia recovery prior to biological treatment. Phosphorus will have to be supplied by adding phosphoric acid or equivalent. Various trace nutrients such as manganese, copper, zinc, and other metals might not be available in the wastewater but are required by biological agents.[4]

For the ultimate oxidant for bio-oxidation, molecular oxygen is the most common choice, whether it comes from compressed air or high-purity oxygen gas. The use of high purity oxygen rather than air has gained increasing acceptance in aerobic biological treatment. In addition to certain advantages in treatment performance,[5] it has been reported that the use of high purity oxygen appears to be more energy-effective in the transfer of oxygen.[6] The total energy required to separate oxygen from air, and then dissolve the oxygen in water, is less than the energy required to dissolve directly in water the same amount of oxygen from air.[6] Othmer[6] reported that normal aeration under 1 atmosphere required about 0.5 kW-hr of energy to dissolve 1 pound of oxygen from air, whereas this requirement dropped to less than 0.05 kW-hr to dissolve 1 pound of commercial oxygen. For the high purity oxygen activated sludge plant designs given later, the energy for dissolution is 0.09 kW-hr/lb O_2. For oxygen production the energy is about 0.165 kW-hr/lb O_2,[11] totaling about 0.26 kW-hr/lb O_2. Furthermore, since oxygen is required and produced in many coal conversion plants, it can be made available for biological treatment at the cheapest possible price. Approximately 3,000 tons per day of oxygen will be needed in a standard size SNG plant, and the amount of oxygen required for the high purity oxygen activated sludge (HPOAS) system may be about 10 percent or less of that required for coal conversion, depending on the amount of BOD to be removed in the biological treatment.

B. Biological Agents

The use of specially prepared bacteria for more effective biological treatment of certain industrial wastes has been recently publicized.[7] These bacteria are prepared from the parent strain through induced mutation, which may involve exposing the parent strain to programmed radiation, and subsequently through proper enrichment allowing for the buildup of a large population of mutant bacteria. The mutant baceria so produced are far more efficent in degrading certain pollutants than the parent strains occurring in nature or the mixed culture commonly used in activated sludge process. For instance, the mutated *Pseudomonas sp.*, commercially marketed as PHENOBAC, could increase the rate of degradation by about twofold. When parent strains and mutant strains were exposed to 500 mg/l of phenol in a laboratory test, the time for 100 percent degradation (as measured by ring disruption) was 25 hours and 8 hours respectively.[8]

In another laboratory study simulating the treatment of aqueous effluents (using a synthetic solution of phenol with other additives) from coal conversion processes,[2] the acclimated activated sludge from the Bethlehem Coke Plant and PHENOBAC were used as the biological agents. In terms of phenol degradation, the efficiency of the mutated bacteria was noted to be about two times that of the acclimated sludge.[9] It was also found convenient to handle the predried and packaged mutant bacteria which could be reactivated by immersion in 100° F water for about an hour.[2,7] The cost of PHENOBAC, which comes in 25-100-lb. packages, is about $16 per pound.

In addition to the laboratory tests reported above, mutant bacteria have also been found useful in certain full-scale High Purity Oxygen Activated Sludge (HPOAS) facilities. In the treatment of a number of petrochemical and refinery wastewaters, the performance of PHENOBAC was compared in parallel with that of ordinary activated sludge, and PHENOBAC was found to achieve:[10]

1. better process stability;
2. enhanced removal of TOC; and
3. reduction of foaming in bioreactors and liquid-solids separators.

In view of the above information available from various independent sources, the use of mutant bacteria warrants serious consideration in the future pilot facilities treating coal conversion wastes. A side-by-side comparison on the performance of mutant bacteria, acclimated sludge, and ordinary activated sludge would be highly desirable.

C. Reactor Configurations

The most common configurations of bioreactors include: trickling filters, where fixed biological growth is maintained, and activated sludge systems, where suspended growth is utilized. In general, trickling filters have been used for their simplicity and low cost of operation, resilience to shock loads and toxic substances, while activated sludge has been known for its high treatment efficiency, better control and reliability.

It is not a new idea to combine the desirable attributes of trickling filter and activated sludge processes into the most cost-effective system by use of dual biological processes (using a combination of trickling filter and activated sludge) for industrial wastewater treatment.[12] Success in the treatment of wastewaters form organic chemical manufacturing, petrochemical refining, and meat processing industries has been reported.[12,13] In most of the reported cases, the water contaminants of primary concern have been phenols and BOD.

Since the use of HPOAS (high purity oxygen activated sludge) appears to have significant advantages at coal conversion plants, it is essential to consider the control of water temperature in the covered bioreactors. Oxidation of hydrocarbons are exothermic reactions. The oxidation of C, CH, and CH_2 can theoretically lead to 1° F temperature rise per 184, 170, and 161 mg/l BOD removed, assuming 100 percent biodegradability. For phenol, this temperature rise will be about 1° F per 165 mg/l BOD removed. Therefore, considering the various heat losses in the bioreactors, it may be reasonably assumed that the removal of 200 mg/l BOD will cause an increase in water temperature of 1° F.

Biological agents are known to be temperature sensitive. It has been recommended[14] that the water temperature in the aerobic biological treatment of coke plant wastes be 95-100° F throughout the year. Consequently, when a high level of BOD removal is to be achieved by HPOAS, the temperature rise may become excessive and a means of cooling may become necessary.

To take the advantages of dual biological treatment processes and to satisfy the cooling requirement, we suggest merging a trickling filter with a cooling tower as an integral unit when HPOAS is used. In the treatment of refining wastes it has for more than two decades been found economical and desirable to achieve bio-oxidation and water cooling in a cooling tower structure.[15] Functionally, the cooling tower in this case is analogous to the trickling filter in terms of organic removal. Whether this unit should be designed as a trickling filter or a cooling tower depends on which function will be limiting.

EXEMPLARY WASTEWATER CHARACTERISTICS

Two examples will be used in the following design studies, based on Hygas plants using a lignite and a bituminous coal feed. Details are given on Table 1.

ALTERNATIVE PROCESS TRAINS

1. *Air Activated Sludge*

The air activated sludge (AAS) system is probably the most common treatment system used for wastewaters with constituents similar to coal conversion wastewaters, e.g., coke plant wastes. An extensive literature review on the biological oxidation of coke plant wastes was reported by Barker and Thompson[18] in 1973. Among the treatment systems discussed, AAS is the predominant treatment system of success. Laboratory studies[27] abroad have also indicated that AAS systems can satisfactorily treat the coal conversion wastes with the following characteristics:

Total ammonia	~ 1,500 ppm
Total phenols	~ 300 ppm
Thiocyanate	~ 150 ppm
Chloride	~ 2,500 ppm

Among the full-scale AAS facilities treating coke plant wastes, the one at Bethlehem Coke Plant, Bethlehem, Pennsylvania, has been in operation since 1962, and seems to have the most complete data available in the literature.[3] Since there has been no pilot tests for the treatment of coal conversion wastes by AAS in the United States, we begin by basing a preliminary design on the data available from the Bethlehem AAS system and essentially scale up from this existing treatment facility.

The scaled design is based on the assumption that the biodegradability of coal conversion wastewaters is identical with that of the coke wastewater. This assumption is open to question. No data on COD of the coke wastewater is available in Reference 3. However, an analysis of an average coke plant waste indicated that the theoretical oxygen demand due to phenols, which are readily biodegradable, constitute about 68 percent of the measured COD while for coal conversion

TABLE 1

WATER ANALYSES AND FLOWS FROM TWO HYGAS PLANTS

	Lignite feed	Bituminous coal feed
BOD_5 (mg/l)	13,000 - 18,000	2,000 - 3,000
COD (mg/l)	25,000 - 30,000	~ 3,000
Phenol as C_6H_5OH (mg/l)	3,000 - 5,000	300 - 500
NH_3 as N (mg/l)	~ 290	~ 30
Flow, 10^3 lb/hr	295	535
10^6 gals/day	0.85	1.5
m^3/sec	0.037	0.066

Analysis from References 5 and 16. Ammonia is reduced to the listed level by prior treatment. Flow for the lignite feed from Reference 5 and for the bituminous feed from Reference 17.

wastewater phenol averaged about 40 percent of the COD.[19] Although the question of biodegradability can only be fully answered by pilot testing, the above comparison indicates certain differences in chemical composition between coke plant and coal conversion wastewaters. It is essentially unknown at this point whether and how this will affect the design of biological treatment. Should the assumption of biodegradability become invalid to any extent, there would be corresponding limitation on the usefulness of the preliminary design.

One of the most important design considerations regarding biological treatment of coke plant wastes is to determine if the waste contains any inhibitory constituents which may render the biological treatment system totally or partially unfunctional. If these constituents exist, it is essential to determine their threshold concentrations and thus the dilution required for the influent to the biological treatment system. Some inhibitory constituents and their threshold concentrations found in our literature search include:

Phenol = 500[1] - 1,000[2] mg/l
Ammonia = 1,200[18] - 2,000[3] mg/l
Chloride = 2,000[18] mg/l

Phenol will normally be kept at a low enough level in the mixed reactor. Ammonia will have to be reduced by prior treatment. Chloride will not usually reach toxic level.

The following rules were used to produce the scaled design. Most numerical values came directly from the Bethlehem AAS experience[3] while the four biokinetic coefficients, k, K_s, Y, and k_d were evaluated by us on the basis of data from Reference 3.

Nutrients such as nitrogen and phosphorus are essential for biological treatment. The required weight ratio is assumed to be invariant and is phenol:N:P = 70:5:1. Excess N is available in the wastewater, and the ammonia nitrogen concentration will be reduced to the proper level by ammonia recovery prior to biological treatment. Phosphorus will have to be supplied by adding phosphoric acid or equivalent.

The design of bioreactors was based on a biokinetic model developed by Lawrence and McCarty.[20] This model is based on an empirically developed relationship between the rate of growth of microorganisms and the rate of consumption of degradable contaminants. Degradable contaminants are called "substrate" as they are "food" for the microorganisms. The relationship is

$$\frac{dX}{dt} = Y\frac{dS}{dt} - k_d X \qquad (1)$$

where

X = concentration of microorganisms
t = time
Y = growth yield coefficient; weight of microorganisms produced per weight of substrate removed
S = concentration of substrate or degradable contaminant
k_d = microorganism decay coefficient, time^{-1}.

If Eq. (1) is divided by X we obtain

$$\frac{1}{X}\frac{dX}{dt} = \frac{Y}{X}\frac{dS}{dt} - k_d \qquad (2)$$

In Eq. (2) each term has the dimension (time^{-1}) and compatible units must be used. The left hand side of Eq. (2), which is the rate of increase of concentration of microorganisms per unit concentration, may also be written $1/\Theta_c$, where Θ_c is called the mean cell residence time or sludge age. The first term on the right hand side of Eq. (2) includes the quantity $\frac{1}{X}\frac{dS}{dt}$ which is the rate of decrease of concentration of substrate per unit concentration of microorganisms. This quantity is a function of the concentration of substrate and the Lawrence and McCarty model assumes the function

$$\frac{1}{X}\frac{dS}{dt} = \frac{k_s S}{K_s + S} \qquad (3)$$

In sum, the model can be written

$$\frac{1}{\theta_c} = \frac{YkS_1}{K_s + S_1} - k_d \qquad (4)$$

The rest of the major design equations are:

$$XV = \frac{YQ\theta_c(S_0 - S_1)}{1 + k_d\theta_c} \qquad (5)$$

$$r = \frac{q}{Q} = \frac{1 - (V/Q)/\theta_c}{(X_r/X) - 1} \qquad (6)$$

$$P_x = \frac{XV}{\theta_c} \qquad (7)$$

$$w = \frac{P_x}{X_r} \qquad (8)$$

The meaning of all symbols used is shown in the schematic flow diagram in Figure 1. The four basic coefficients were evaluated from information given in Reference 3. In this reference are tabulated experimental values of (lb phenol removed)/(lb microorganisms)(day), which is $\frac{1}{X}\frac{dS}{dt}$, as a function of the phenol concentration, S. These values are plotted in Figure 2 and the curve so obtained is fitted to Eq. (3) by noting that k is the value of $\frac{1}{X}\frac{dS}{dt}$ when S is large and K_s is the value of S when $\frac{1}{X}\frac{dS}{dt} = k/2$. Also from Reference 3 the $\frac{1}{X}\frac{dX}{dt}$ can be calculated. On Figure 3 is plotted $\frac{1}{X}\frac{dX}{dt}$ against $\frac{1}{X}\frac{dS}{dt}$ from which the coefficients Y and k_d are determined.

The values of the coefficients determined in this way are:

$k = 0.9$ lb C_6H_5OH/lb MLSS•day = 2.14 lb BOD/lb MLSS•day
$K_s = 0.17$ mg/l C_6H_5OH = 0.4 mg/l BOD
$Y = 0.4$ lb sludge/lb C_6H_5OH processed = 0.17 lb sludge/lb BOD processed
$k_d = 0.17\ (\text{day})^{-1}$

These coefficients were evaluated in terms of phenol removal and then converted to BOD based on the theoretical oxygen demand of 2.38 units per unit of phenol.

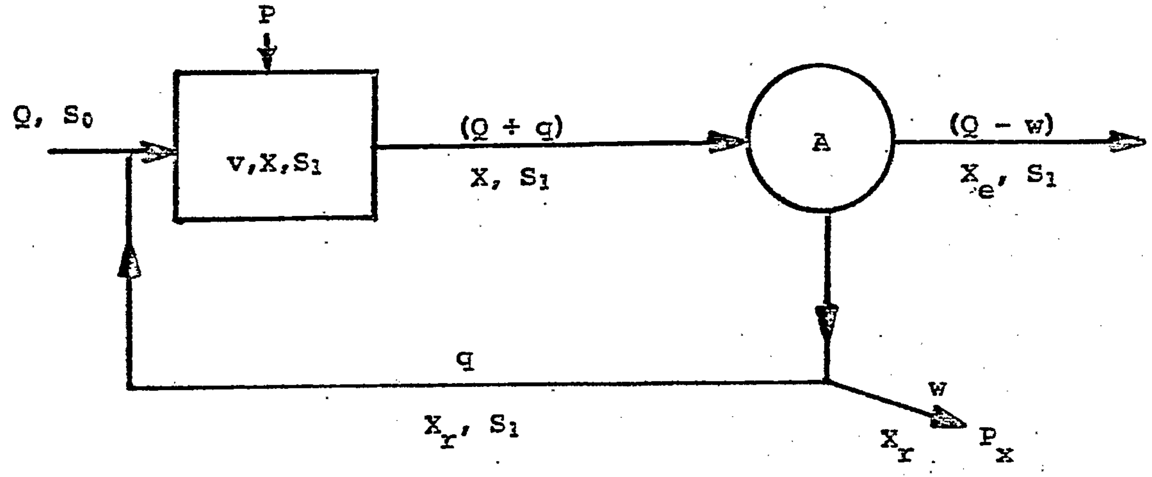
The aerator power requirement is taken to be proportional to the BOD or phenol removed. At Bethlehem Coke Plant the power requirement is based on 18.2 lb phenol removed/(day)(hp) or 43.3 lb BOD/(day)(hp), which compares closely with typical values in the literature of 45-50 lb BOD removed/(day)(hp).[21]

The best way to size the clarifier is to determine experimentally the relationship between initial settling velocity and suspended solids concentration.[22,23] This typically takes the form shown in Figure 4.[24] The aeration vessel volume and solids separator volume can then be determined for series of concentrations of microorganisms, X, and the optimum concentration of microorganisms determined. We have no data to plot Figure 4 and have, therefore, used the one available point from Reference 3, namely X = 2,600 mg/l and the clarifier overflow rate is 685 gal/(day)(ft^2). For use in Eq. (6) we also assumed the same value of $X_r/X = 3.44$. The value of X_r/X is a function of the performance of the solids separator.

Subsequent treatment of waste sludge depends on the means of ultimate disposal and the method of transport to the disposal site. Sludge is beneficial when added to coal ash and this seems to be an attractive means of ultimate disposal as the nutrient content of waste sludge will be conducive to the revegetation process. The sludge may be transported by tank truck or pipeline, and the final selection is dictated by the economics of these operations. The method of transport will in turn determine whether any sludge treatment is desirable. The objective of sludge treatment in our designs is primarily volume reduction. For assumed transportation by tank truck, dissolved air flotation (DAF) thickening followed by vacuum filtration is included. These sludge treatment processes are sized according to the following criteria: 20 lbs dry solids per square foot per day for the DAF thickener, and 120 lbs dry solids per square foot per day for vacuum filters. These values are assumed,[25] not scaled, because Bethlehem Coke Plant discharges its sludge to a sewage plant and provides no sludge treatment.

The results of the calculations for the two exemplary waste waters described on Table 1 are given on Table 2. For each water calculations are presented for a two-stage process with 95 percent removal in each stage and an equivalent single stage process with 99.75 percent removal. The volumes are insignificantly different, showing that the reaction is zero order in the range of concentrations of BOD of interest. Complete calculations are, therefore, presented for 95 percent and 99.75 percent removal, in single stages, for each water. The results for the lignite at 99.75 percent removal are also shown in Figure 5.

Some preliminary comments can be made. The clarifier diameters are small and with very little increased investment larger diameters can be used and the somewhat high overflow rate



Q = flow rate of liquid waste to be treated biologically, volume/time;

q = flow rate of recycled sludge, volume/time;

w = flow rate of wasted sludge, volume/time;

S_0 = influent substrate concentration, mass/volume;

S_1 = effluent substrate concentration, mass/volume;

X = microbial mass concentration, mass/volume;

X_e = microbial mass concentration in the clarified overflow from the solids separator, mass/volume;

X_r = microbial mass concentration in the underflow from the solids separator, mass/volume;

P = power requirement for aeration, energy/time;

P_x = excess microorganisms production rate, mass/time.

Figure 1. Air activated sludge model.

assumed can be reduced. The hydraulic residence times listed are not unreasonable. The quantity called F/M on Table 2 is $\frac{1}{X}\frac{dS}{dt}$ in Eq. (2) and is calculated from the equation

$$F/M = (\frac{1}{\theta_c} + k_d)/Y \qquad (9)$$

The listed quantities are very much higher than usual practice. It should be noted, however, that the BOD of phenols has been calculated as 2.38 times of phenol concentration, i.e. we have assumed BOD to be equivalent to the theoretical oxygen demand of phenol. The calculated F/M in terms of BOD may thus be on the high side.

The major problem with the biokinetics limited design presented on Table 2 is the high rate of BOD removal and the consequent high rate of oxygen transfer required. In all designs

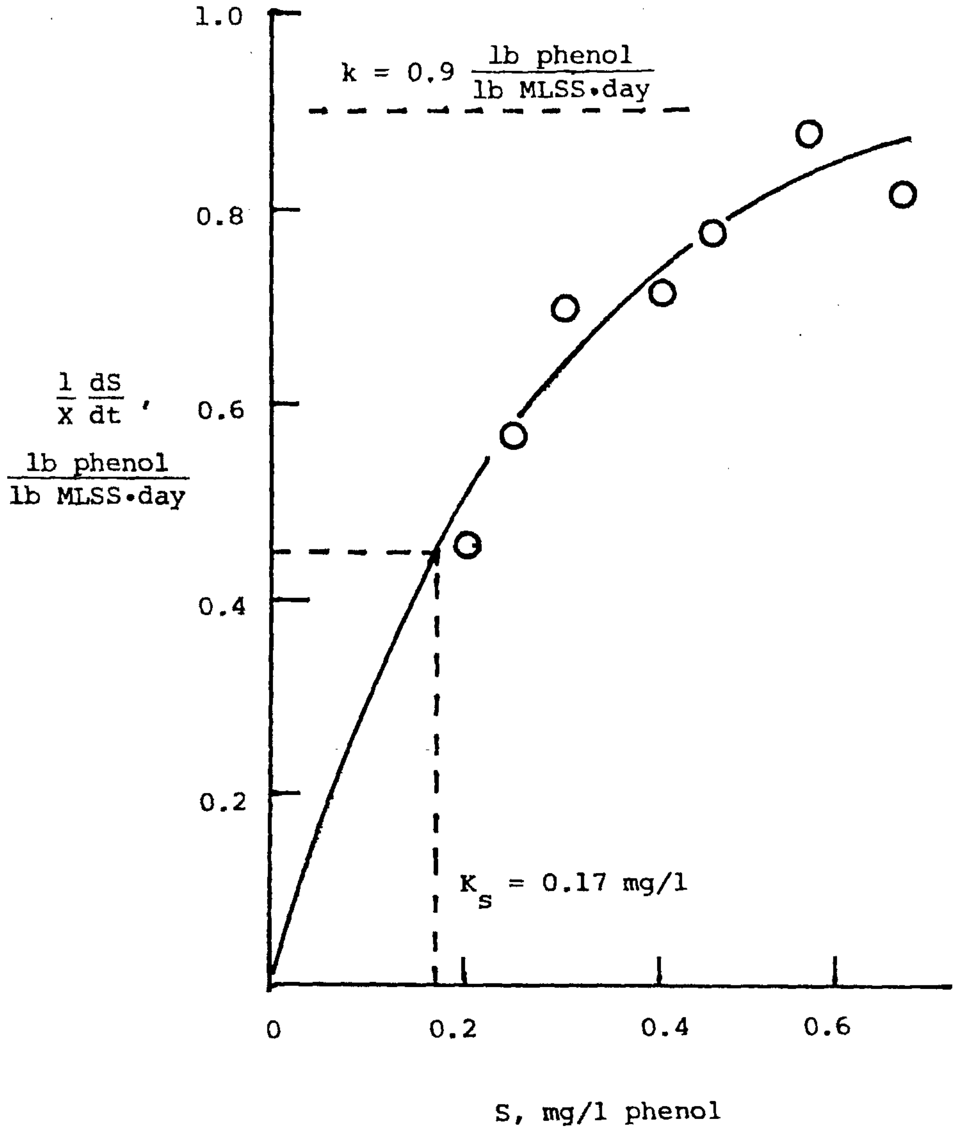


Figure 2. Substrate utilization vs. substrate concentration (based on data from Ref. 3).

this exceeds 200 mg/(l)(hr). Suppose, first, that surface aerators are used and that the aeration basins are made 15 ft deep. The horsepower for the aerators is found to be applied at a rate of about 120 hp/10^3ft^2. If power were to be applied at this rate the energy to transfer each pound of oxygen would probably increase unacceptably. Potential remedial measures include: (1) use of shallower basins, such as a basin depth of 9 feet instead of 15 feet, this will lead to an energy application of less than 75 hp/10^3ft^2; (2) use of oxygenation systems which are more efficient than surface aerators, such as submerged aerators or using high purity oxygen rather than ordinary air as the source of oxygen.

2. High Purity Oxygen Activated Sludge (HPOAS)

As discussed previously HPOAS has the advantages of energy effectiveness and the ready availability of high purity oxygen at most coal conversion facilities. The following preliminary HPOAS design for lignite feed is based on the information supplied by Union Carbide Corporation.

No kinetic coefficients were used in the design of HPOAS. Instead, an empirical approach using F/M ratios and MLVSS data based on past experience with similar industrial wastewaters was followed. It is felt that in the treatment of high stength industrial wastewaters the process design may frequent-

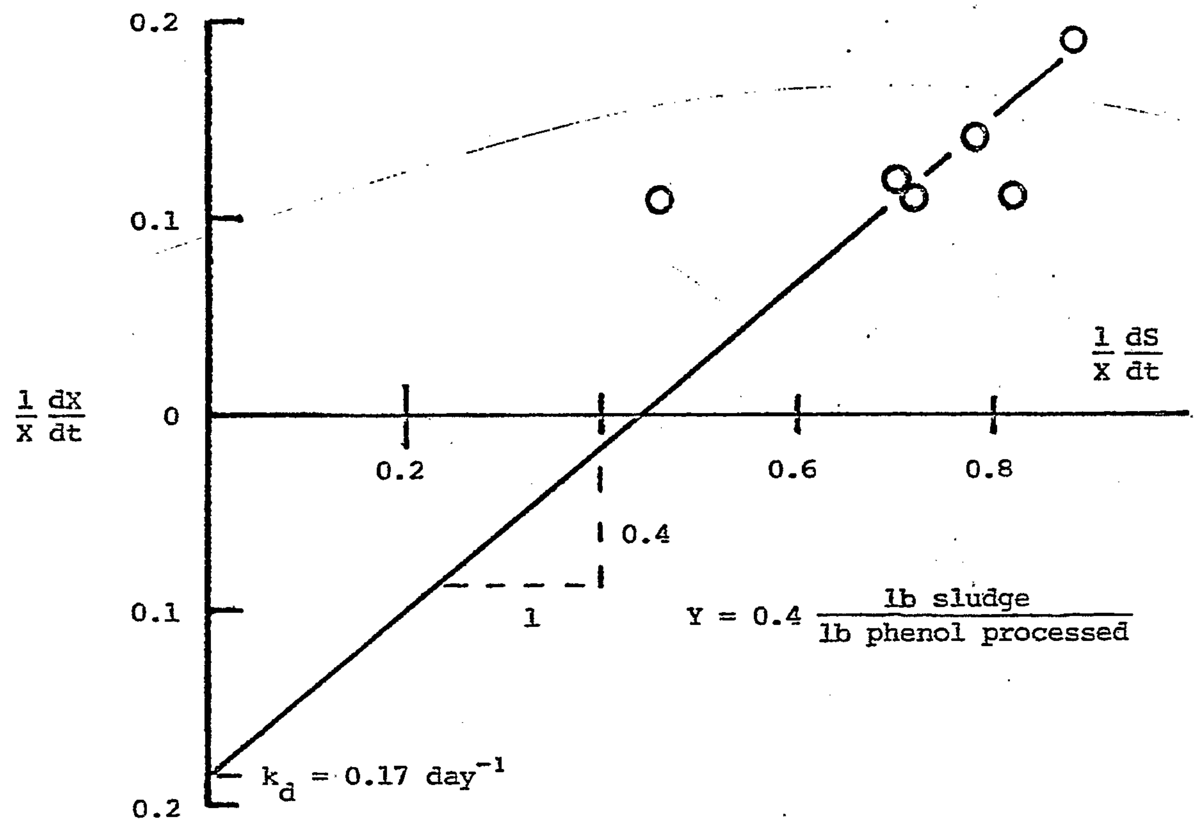


Figure 3. Sludge growth rate vs. substrate utilization rate (based on date from Ref. 3).

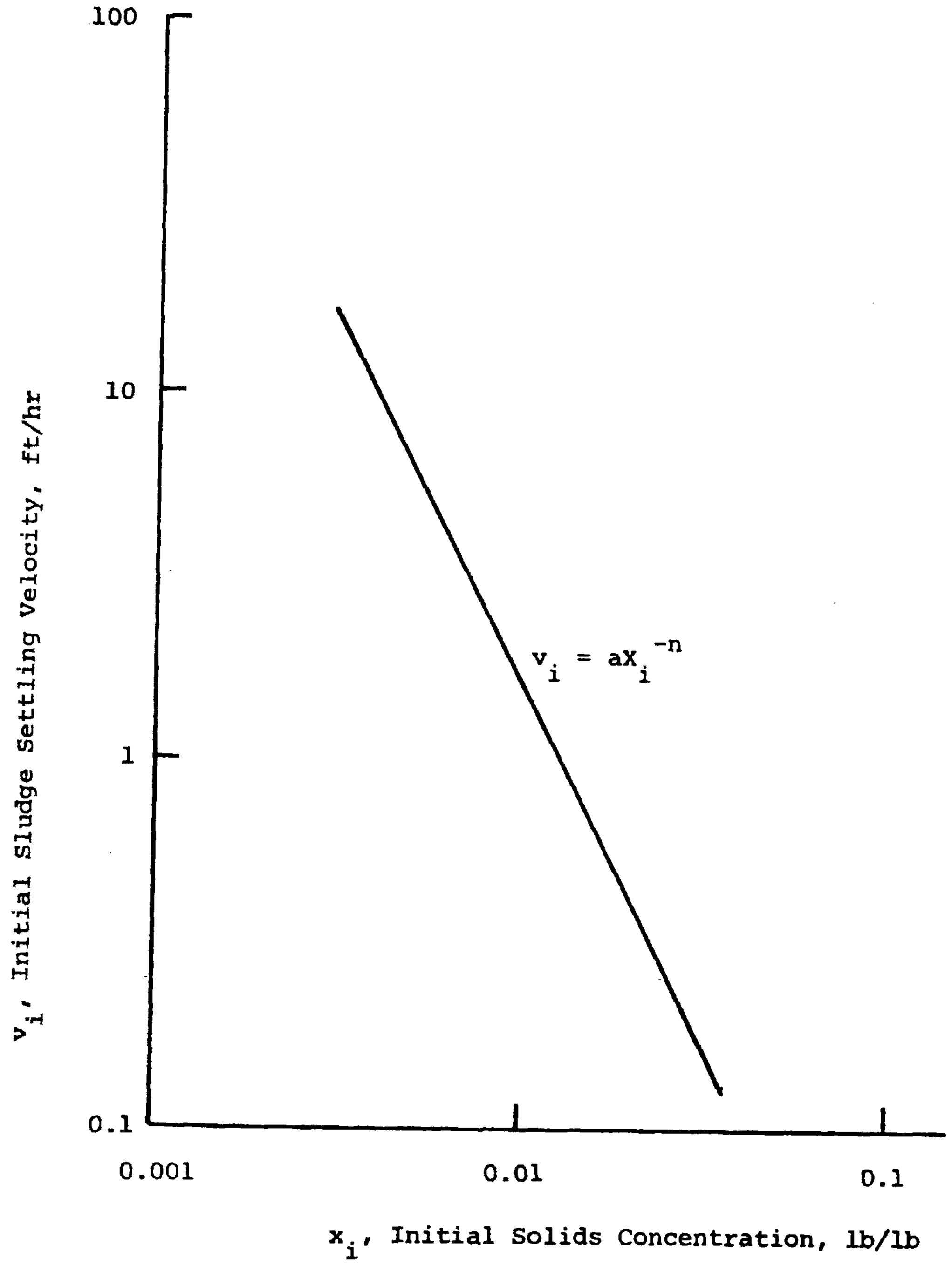


Figure 4. Typical settling velocity vs. solids concentration.

TABLE 2

CALCULATIONS ON AIR ACTIVATED SLUDGE PLANTS

	Lignite Feed			Bituminous Coal Feed		
	First 95%	Second 95%	99.75%	First 95%	Second 95%	99.75%
S_0, mg/l	18,000	900	18,000	3,000	150	3,000
Q, 10^6 gal/day	0.85	0.85	0.85	1.5	1.5	1.5
S_1, mg/l	900	45	45	150	7.5	7.5
θ_c, days	5.16	5.25	5.25	5.19	5.70	5.70
XV, 10^9 (mg)(gal)/l	6.80	0.34	7.20	2.00	0.11	2.21
V, 10^6 gals	2.61	0.13	2.77	0.77	0.04	0.85
Total V, 10^6 gals	2.75			0.81		
r	0.17		0.16	0.37		0.37
q, 10^6 gal/day	0.14		0.13	0.55		0.55
P_x, 10^3 lb/day	11.0		12.6	3.2		3.2
w, 10^6 gal/day	0.15		0.17	0.043		0.043
P, hp	2800		2940	820		860
D, hw	2080		2190	610		640
Clarifier area, ft^2	1240		1240	2190		2190
Clarifier dia., ft	40		40	53		53
DAF thickener, ft^2	550		630	160		160
Vacuum filter, ft^2	96		110	28		28
Residence Time, days	3.1		3.3	0.51		0.54
F/M, $\frac{\text{lb BOD}}{\text{(lb sludge)(day)}}$	2.1		2.1	2.1		2,0

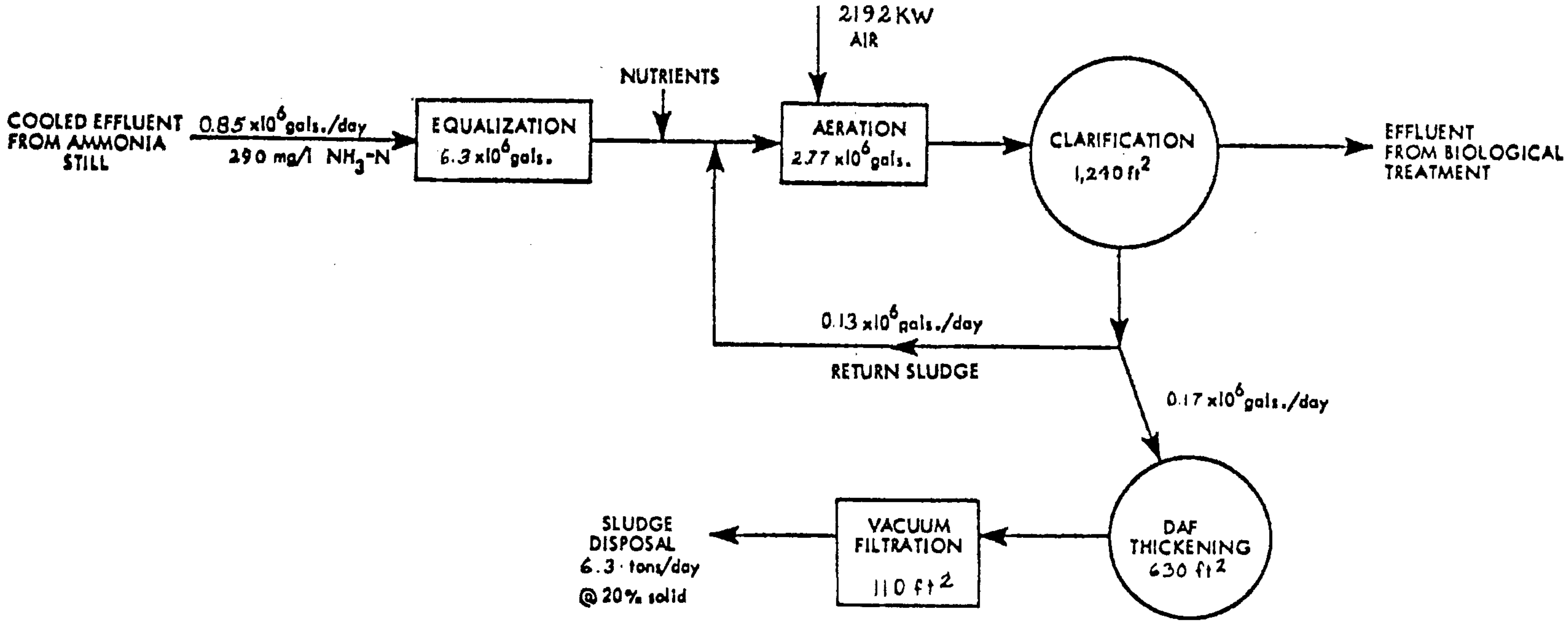


Figure 5. Air activated sludge system (AAS) for Hygas plant with lignite feed (from Table 2).

ly be dictated by considerations other than biokinetics, such as oxygen transfer and/or solids separation. However, if biokinetic data can be obtained and compiled properly by using an appropriate reaction model, we should be able to expand our data base and make rational designs easier in the future.

The HPOAS system design consists of multitrains in parallel, with each train consisting of multistages to obtain a quasi-plug flow condition. High purity oxygen is fed to the space above the liquor level in each stage of the oxygenation basin, and oxygen transfer is accomplished by use of surface aerators or equivalent. The dissolved oxygen concentration in the mixed liquor will be maintained at about 5 mg/l rather than 2 to 3 mg/l as commonly used in the AAS system. As with the AAS system, two steps of HPOAS treatment are used with each step achieving about 95 percent removal of BOD.

Two key parameters for the design of activated sludge systems are mean F/M (food to microorganism) ratio and MLVSS (mixed liquor volatile suspended solids). The F/M ratios for step 1 and step 2 differ because of the difference in BOD loading; F/M is 0.8 in step 1 and 0.3 in step 2. The MLVSS will be substantially larger than that for the AAS system because of improved settling velocities of the oxygen sludge, and the MLVSS in this case is assumed to be 7,300 mg/l in step 1 and 4,500 mg/l in step 2. The clarifiers are designed on the basis of an overflow rate of 400 gals/(day)(ft^2) in step 1 and 300 gals/(day)(ft^2) in step 2. These overflow rates are expected to give low suspended solids concentration in the overflow. The design is summarized on Table 3.

The oxygen requirement, pounds of oxygen required per pound of BOD removed, is a function of F/M and COD/BOD ratios.[26] The effect of COD/BOD ratio may be particularly significant in this case as the fate of COD in the biological treatment of coal conversion wastes is unknown at present. The oxygen requirement is assumed to be 1.03 lb/lb BOD removed in step 1 and 1.21 lb/lb BOD removed in step 2. Whenever COD needs to be evaluated in the biological treatment, the removal of COD is assumed to be equal to that of BOD; this assumption is conservative and should lead to a design on the safe side.

The average oxygen utilization in the oxygenation basin depends on the purity of the oxygen in the gaseous mixture which essentially consists of feed oxygen and the carbon dioxide produced as a result of the biochemical oxidation. Therefore the average oxygen utilization percentage will increase as the feed BOD concentration decreases and is assumed to be 79 percent in step 1 and 80 percent in step 2. Based on the oxygen requirement and average oxygen utilization efficiency, the amount of oxygen to be transferred can be calculated.

The energy requirement is estimated as follows. The surface aerators consume about 1 hp-hr for 7.8 lb oxygen supplied, or 0.0956-kW-hr/lb oxygen supplied. Air separation consumes about 0.165 kW-hr/lb oxygen.[11]

A major design consideration is the control of water temperature in the oxygenation basin. As discussed previously, the removal of 200 mg/l BOD will cause an increase in water temperature of 1° F. Since the removal of BOD in step 1 is 95 percent of 18,000 mg/l, this will result in a temperature rise of about 85° F. To maintain the temperature at 95-100° F in the oxygenation basin, it will be necessary to recycle 3.4 x 10^6 gal/day of the mixed liquor at a temperature of about 97° F and to reduce its temperature to 80° F in a cooling tower, as shown in Figure 6. The temperature of the 0.85 x 10^6 gal/day feed is assumed maintained at 80° F from the equalization basin. The broken line in Figure 6 shows the recycling of the clarified water through the cooling tower for more flexible operation.

3. *Activated Trickling Filter-High Purity Oxygen Activated Sludge (ATF-HPOAS)*

In Figure 6, showing the HPOAS system, the cooling would usually be accomplished by passing the return flow through coils situated in a spray tower. Water from the clarifier overflow can be sprayed onto the outside of the coils and a forced air draft used to evaporate some of the water and so cool the return flow. It would be convenient to simply spray the return flow itself into the spray cooling tower, achieving

TABLE 3

DESIGN OF THE HPOAS SYSTEM[a]

Design Basis	
Flow, 10^6 gal/day	0.85
BOD_5, lbs/day	127,600
BOD_5, mg/l	18,000
COD, mg/l	28,000
COD/BOD_5	1.56
Wastewater temperature, °F	80°F
pH	Adjusted as required
Nutrients	Phosphorus to be added

System Design	Step 1	Step 2
Flow, Q (10^6 gal/day)	0.85	0.85
Retention time, hrs (based on feed flow)	74	16
MLSS, mg/l	7,800	5,100
MLVSS, mg/l	7,300	4,500
Sludge Recycle Rate, %Q	35	35
Mean biomass loading, lbs BOD_5/(lb MLVSS)(day)	0.8	0.3
Volumetric organic loading, lbs $BOD_5/(10^3 ft^3)$(day)	364	84
Average D.O. level, mg/l	5.0	5.0
Oxygen supplied, tons/day	79.0	4.6
Average oxygen utilization efficiency, %	79	80
Secondary clarifier overflow rate, gal/(day)(ft^2)	400	300
Recycle suspended solids concentration, wt %	2.0	2.0
Effluent Soluble BOD_5,[b] mg/l	900	45

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[a] Preliminary information supplied by Union Carbide on the basis of assumptions provided by WPA.

[b] Used as basis for determining oxygen requirement.

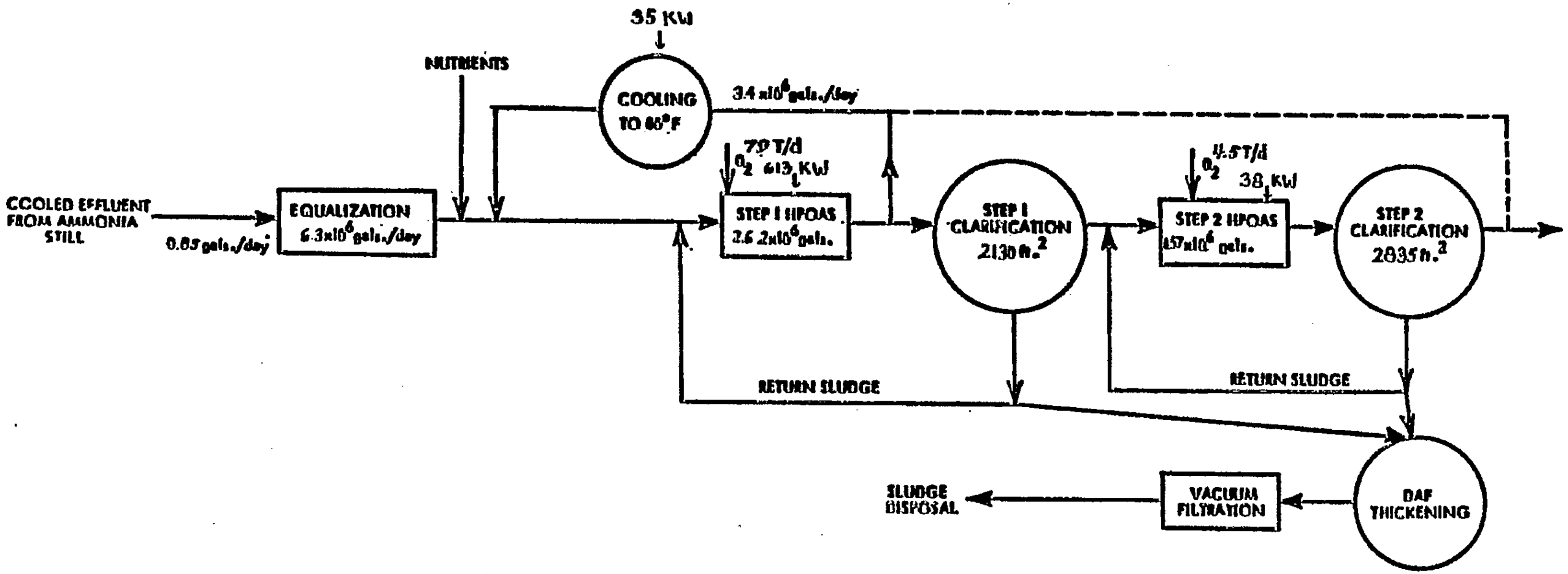

Figure 6. High purity oxygen activated sludge (HPOAS) system for Hygas plant with lignite feed.

cooling by forced evaporation. The unanswered question is whether spraying will also break up and damage the biological flocs. This requires testing. Even if spraying to make droplets proves not satisfactory, it may be possible to distribute the return flow over a fill placed in the tower. This fill may be a type of cooling tower fill called "film type" (as distinct from "splash type") over which the descending water flows in a film. Most manufacturers of cooling towers make film type fill. Such a filled tower will inevitably turn into a trickling filter. Munters Corporation makes a plastic fill that has been used, in separate situations, in a cooling tower and in a trickling filter.

In Figure 7 is shown a possible scheme with a combined cooling tower/trickling filter. The new unit will be designated as an activated trickling filter (ATF). An activated trickling filter as used here is a trickling filter of plastic medium loaded continuously with the mixed liquor from the HPOAS units, as shown in Figure 7. The ATF is expected to achieve the following objectives:

1. Reduce BOD by about 30 percent as a pretreatment to the HPOAS system;
2. Reduce the temperature of the recycled mixed liquor from the HPOAS system from about 95° to 80° F;
3. Strip off the excessive carbon dioxide from the recycled mixed liquor.

Qualitatively, the use of an ATF-HPOAS system may be expected to have the following advantages over the use of an HPOAS system alone:

1. Less energy required. The energy required to pump water and drive the air fans in the ATF may be lower than that to transfer the large quantities of air or to generate and transfer adequate oxygen for the activated sludge process;
2. Less capital and operating costs;
3. Less system upsets and higher treatment reliability. This is due to the fact that fixed biological growth is less susceptible to loss of the biota activity through shock loadings of either hydraulic feed, BOD concentration, or toxicants. Recycling of the mixed liquor may also contribute to the treatment reliablity.

In the design of ATF we used the BOD removal relationship for trickling filters of plastic medium, and the details of calculation have been reported elsewhere.[5] However, the use of ATF in combination with an HPOAS system in the manner shown in Figure 7 results in an extremely high organic loading of about 8,000 lb BOD/(10^3ft^3 of medium)(day) compared to current practice of having high organic loadings in the range of 1,000-1,400 lb BOD/(10^3ft^3)(day). This occurs because the BOD concentration in the feed water is high and, also, because the recirculation rate is determined by the cooling requirement of step 1 of the HPOAS sysem and is not adjusted to control the BOD loading of the trickling filer. Also, there are contaminants in the coal conversion wastewater other than phenol which may inhibit biochemical oxidation in the ATF to some extent. For these reasons, the usual trickling filter design equation has been modified by assuming that the reduction in BOD obtained is only 30 percent instead of the 80 percent found by use of the standard design equation. Furthermore, forced ventilation is used to avoid oxygen transfer limitation. In our preliminary design modular units of ATF designed for ease of counter-flow ventilation, each 20 feet in diameter and 18 feet in height, have been used.

According to B.F. Goodrich General Products, who manufactures plastic medium for trickling filters, no difficulty is anticipated in running the mixed liquor through the filter medium as long as the MLSS does not exceed 10,000 mg/l and the diameter of solid particles is less than 0.5 inches. Nevertheless the detailed configuration of ATF remains to be better defined in the future pilot tests. The critical considerations may be how to prevent plugging of the filter medium by excessive biological growth and how to avoid the anaerobic condition when oxygen transfer becomes limiting. In spite of these uncertainties we strongly recommend experimenting with ATF as successful

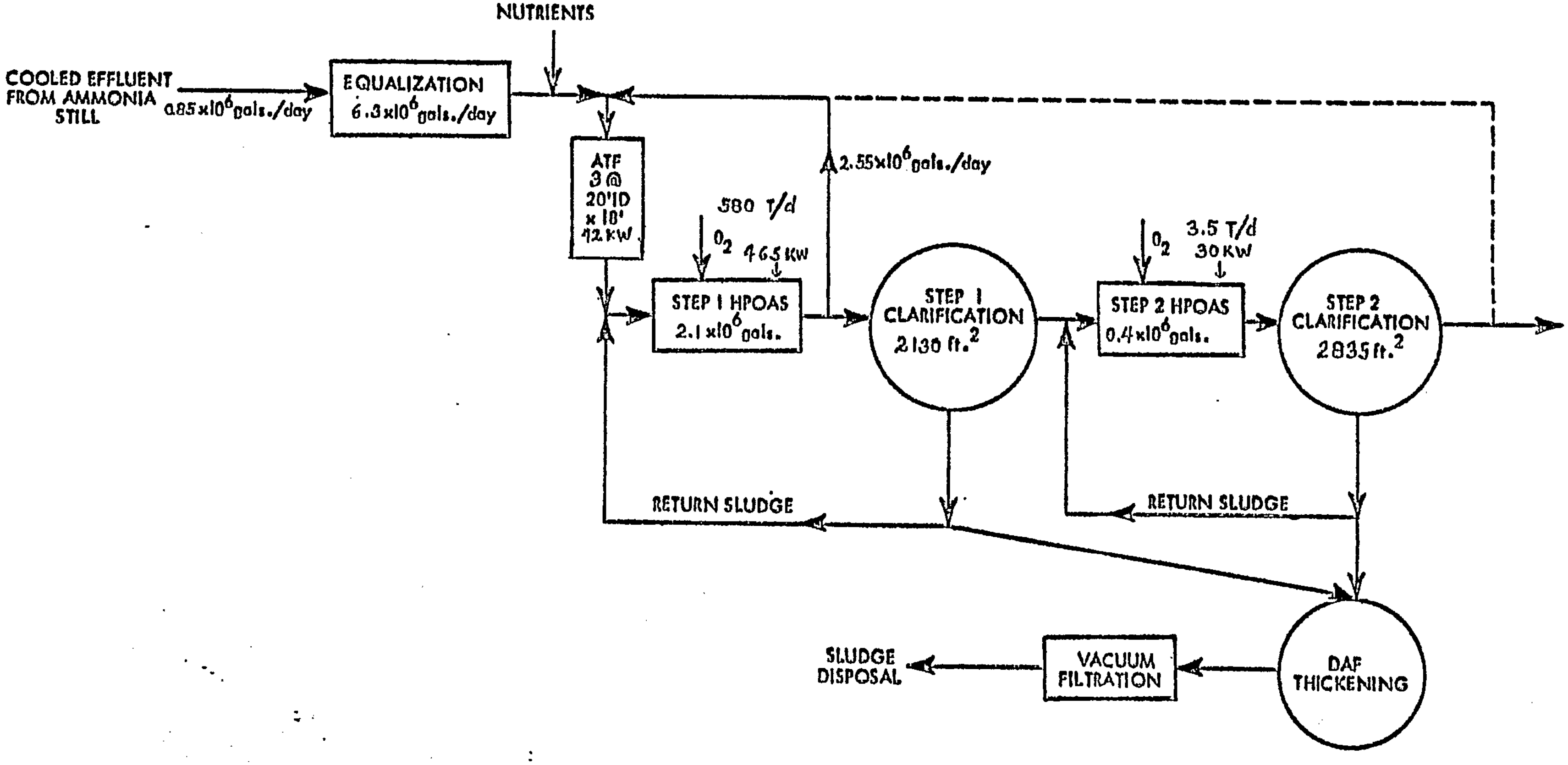

Figure 7. Activated trickling filter-high purity oxygen activated sludge system (ATF-HPOAS) for Hygas plant with lignite feed.

applications of a similar system have been reported.[15]

CONCLUSIONS

Among the three preliminary designs described above, the ATF-HPOAS system appears to be the most cost-effective and energy-effective[5] for treating high-strength wastes, such as those from Hygas plants using lignite feed. With bituminous coal feed the BOD concentration will be much smaller, and the cooling of mixed liquor from step 1 of the HPOAS becomes unnecessary. The use of HPOAS may be preferred to AAS where oxygen is also utilized in the coal conversion process. The use of mutated bacteria and experimenting with ATF are recommended for future pilot tests.

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