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Dynamic Modeling
of the High Purity Oxygen
Activated Sludge Process

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by

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ABSTRACT OF THE THESIS

Dynamic Modeling of the High Purity Oxygen Activated Sludge Process

by

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Master of Science in Civil Engineering
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This thesis uses a dynamic model to quantify the capacity of the high purity oxygen activated sludge process. The Joint Water Pollution Control Plant in Carson California was used as an example plant. Data collected in May, 1984 during a full scale test of this facility were used to calibrate the dynamic mathematical model. Following calibration, the model was used to simulate process performance. Specifically, the model was used to determine the treatment capacity of the activated sludge reactors. The results of the computer simulation indicate that the original design capacity can be exceeded by sixty percent (80 million gallons per day maximum) including a twenty percent sinusoidal diurnal flow fluctuation. However, those conditions were achieved during a simulation that included automatic oxygen flow control based on the fourth stage dissolved oxygen concentration. Under those conditions, the fourth stage dissolved oxygen concentration never declined below 3.0 mg/l. It was concluded that, although the Carson plant is currently under loaded, any increase in the influent wastewater flow rate must consider the resulting decreasing sludge age, and the possibility of increased instability from industrial waste.

I INTRODUCTION

During the past several years, the Environmental Protection Agency working under the Clean Water Act has begun to enforce the requirement that all sewage treatment conform to secondary effluent standards. The current favored technology for municipalities is the activated sludge process. The activated sludge process presents two operational options: aeration using air as the oxygen transfer fluid, or a contained vessel using high purity oxygen. The high purity process option presents two distinct advantages. The plant requires a significantly smaller geographic area than an air plant treating the same waste flow. Secondly, the high purity system uses covered reactors. The covered reactors may be advantageous in the control of volatile emissions.

In 1984 the County Sanitation Districts of Los Angeles County began operation of a high purity oxygen activated sludge plant in Carson California. The original plant provided advanced primary treatment for 360 million gallons per day (MGD) of combined industrial and domestic sewage. The secondary system comprised four treatment trains. Each train was designed to treat 50 MGD . A treatment train consists of four 1.315 million gallon complete mix reactors in series. Oxygen is transferred by three surface aerators per reactor. To provide the required oxygen, the County built two 150 ton per day cryogenic oxygen plants. During May of 1984 the County tested the oxygen transfer capability of the secondary treatment system to verify the warranty requirements of the purchase contract. The test results indicated the plant had transferred more oxygen than required by the warranty.

During verification testing, the County collected a significant amount of operational performance data. This thesis uses the historical data provided by the County and applies a dynamic mathematical model to predict operational performance and plant capacity. The model was written in Fortran and CSMP III.[1] CSMP III is a mathematical computer program designed to solve differential equations.

The significance of such a predictive tool is its future application by municipalities and industry to determine if their current activated sludge plants have additional capacity. Additional capacity will be required in the future as the Environmental Protection Agency enforces the Clean Water Act. Additionally, predictive tools of this nature allow design engineers to determine future capitol investment as a function of projected required capacity.

II LITERATURE REVIEW

Early work in mathematical modeling of the activated sludge process involved the application of mass and microbial balances to steady state processes. The model of Mueller, Mulligan, and diToro[2] was based on those conditions. The model described the transfer of oxygen, nitrogen, and carbon dioxide between the gas and liquid phases, but did not account for nitrification. Therefore the total ammonia nitrogen concentration remained constant. Additionally, given the absence of nitrification and the assumption that all biologically produced CO_2 remains as CO_2, eliminated any significant alkalinity source or sink. The model was calibrated to an operating high purity oxygen process. The model was then applied to predict plant performance utilizing several sets of constant (time-invariant) feed conditions.

Gaudy, Srinivasaraghavan, and Saleh developed a steady state algorithm to account for the variabilities in the concentration of the biological solids through control of the return sludge concentration.[3] The Monod growth equation was used to model substrate removal. Gaudy assigned effluent substrate concentration as the basis for plant efficiency evaluation. He concluded that system engineering variables had a greater impact on process dynamics than changes in the biological constants.

The development of a true multicomponent mass transfer model of the gas-liquid interface was presented by McWhirter and Vahldieck.[4] Initial development of the model included coupled equations. However, following the assignment of ideal conditions to the gas phase, and considering the dilute nature of the liquid phase concentrations the equations became non-interactive. Equations for the CO_2 gas/liquid equilibrium were based on the assumption that all non-ionized CO_2 was dissolved rather than in the form of carbonic acid. The equation for alkalinity was developed as a function of system pH and the mole fraction CO_2 in the gas phase. A complete set of equations were presented for gas/liquid component mass transfer. The gas purity predictions were then compared to an operating UNOX plant. The data indicate a very good fit.

Stenstrom and Andrews[5] presented a development of mathematical process control strategies for dynamic activated sludge operations based on SCOUR, the Specific Oxygen Uptake Rate. The model included nitrification and demonstrated variable effluent quality (ammonia basis) as a function of the dynamic state. Various process control strategies were simulated in an effort to maintain constant SCOUR demand irrespective of the time dependent influent parameters.

Hansen, Fiok, and Hovious of Union Carbide developed a statistical model of activated sludge process effluent performance based on linear dynamic modeling of specific operational parameters.[6] The model was based on 21 months of data from an industrial waste water treatment plant. The models operational predictive capability was directed toward effluent suspended solids, effluent soluble chemical oxygen demand, and effluent soluble biochemical oxygen demand. Additionally, the model was utilized to redefine operational strategies.

Clifft and Andrews used a structured model which divides the biomass into sections: active, inert, stored and stored particulate substrate.[7] In their model, substrate removal was limited by its transport into the floc rather than the organisms metabolic rate. The substrate that was not immediately synthesized into active mass was stored for future use. Process simulations using the modified substrate utilization equations successfully predicted O_2 utilization time lag and attenuation of O_2 demand.

In 1986 Clifft and Andrews applied their model to a Houston treatment plant under semi steady state conditions.[8] All influent waste parameters were held constant except the influent flow rate and the influent biochemical oxygen demand. These two parameters were varied sinusoidally at a ratio of 2:1. The specific oxygen uptake rate had been determined at the Houston site in previous work.[7] Following "calibration" they modeled the effects of variable bicarbonate alkalinity, and respiratory quotient on fourth stage pH and dissolved oxygen. Additionally, the effect of varying the gas/liquid volume ratio on the fourth stage dissolved oxygen concentration was simulated.

In 1988 Clifft and Andrews calibrated their dynamic model to a Houston waste water treatment plant.[9] The biological reactions were not modeled theoretically. Rather, the oxygen uptake rates were measured directly in field experiments and inserted into the model as specific rates. The gas phase components included oxygen, nitrogen, carbon dioxide and argon. The model also accounted for gas leaks in the system. Although the leaks had no significant effect in the first two stages, the partial pressure of oxygen in the fourth stage was enhanced due to the leaks. The results of the dynamic modeling evidenced a very close fit between the model and the actual operating conditions. The resulting computer model provided an accurate predictive tool for varying operational conditions.

In 1989 Stenstrom, Kido, Shanks, and Mulkerin developed and applied a dynamic system model to resolve a process warranty dispute.[10] This represented the application of theoretical modeling to actual process verification. The model was designed to determine the oxygen transfer rate under warranty conditions at the Sacramento Regional Water Treatment Plant. Additionally, if the transfer rate was insufficient, the model was to determine under what conditions the warranty specifications could be met. The model considered mass transfer of oxygen, nitrogen, and carbon dioxide in the gas phase. The biological kinetics were based on a modified Monod equation. The alkalinity was considered to be carbonaceous, plus the additional contribution from non-ionized ammonia. The resulting fit was excellent.

III MODEL DEVELOPMENT

The Mathematical model used in this simulation is based upon the work of several previous authors.[2,4,8,9] Specifically, the model follows directly from the model presented by Stenstrom, Kido, and Mulkerin.[10]

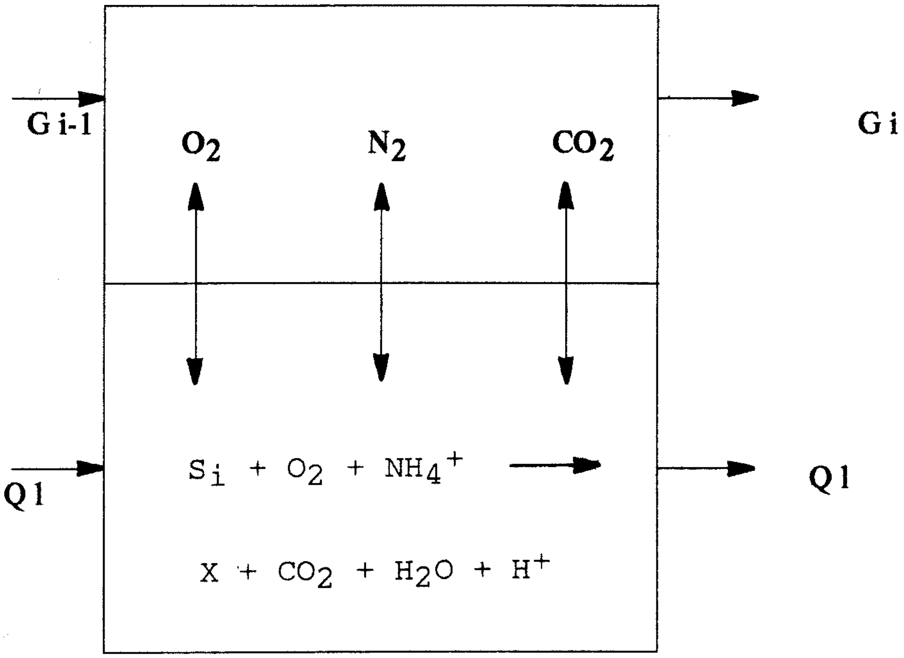

Figure 1

Mass transfer and the basic substrate reaction for Stage(i)

The following equations are use to mathematically represent a dynamic pure oxygen activated sludge process. Initially, all parameters have theoretical values. During calibration, such parameters as the conversion factor for Biochemical Oxygen Demand (five day) to Biochemical Oxygen Demand (ultimate) are used to adjust the waste strength to match the operational process dynamics.

Mu: The Monod specific growth rate. This factor represents the growth rate of the microbiological population as a function of the substrate concentration available for consumption.[10]

Y: The yield coefficient. This parameter is a ratio of the mass of biologically active cells formed to the mass of substrate consumed.

Mu*X(1-Y)/Y: The total substrate converted to oxidation products during growth.

Mu*X(1-Y)*[]/Y:

[A]: Total oxygen consumed by substrate oxidation.

$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$ (1)

$A = [\ Kg\ O_2/Kg\ Substrate\ ] = 1.067$

[YCO_{21}]: Total carbon dioxide produced during substrate oxidation.

$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$ (1)

$YCO_{21} = [\ Kg\ CO_2/Kg\ Substrate\ ] = 1.47$

K_dX: Cells converted to oxidation products during decay.

$K_dX[]$:

[B]: Oxygen consumed during cellular decay.

$$C_5H_7NO_2 + H^+ + 5O_2 \longrightarrow 5CO_2 + NH_4^+ + 2H_2O \quad (2)$$

$B = [\ Kg\ O_2/Kg\ Cells\ ] = 1.42$

$[YCO_{22}]$: Total carbon dioxide produced during cellular decay.

$$C_5H_7NO_2 + H^+ + 5O_2 \longrightarrow 5CO_2 + NH_4^+ + 2H_2O \quad (2)$$

$YCO_{22} = [\ Kg\ CO_2/Kg\ Cells\ ] = 1.95$

The K_{La} values were determined during a clean water test at the manufacturer's location. It is assumed that gas transfer occurs by two film theory and is liquid side limited. The wastewater is presumed to be of low ionic strength. Therefore the K_{La} for CO_2 and N_2 will be a function of the ratio of the molecular diffusivities of CO_2 and N_2 to oxygen.

BIOLOGICAL REACTIONS:

The equations used for the biological mass and substrate balances were based on a glucose model of growth and respiration.[11]

Respiration : $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$ (1)

Synthesis : $5C_6H_{12}O_6 + 6NH_4^+ \longrightarrow$

$6C_5H_7NO_2 + 18H_2O + 6H^+$ (3)

Decay : $C_5H_7NO_2 + H^+ + 5O_2 \longrightarrow$

$5CO_2 + NH_4^+ + 2H_2O$ (2)

Equations 1 to 3 are incorporated into the model in the mass balance equations.

Biological Solids:

$$\frac{dx}{dt} = \frac{Q_L}{V_L}[X_o - X] + [Mu - K_d]^* X \qquad (4)$$

Substrate:

$$\frac{ds}{dt} = \frac{Q_L}{V_L}[S_o - S] - \frac{Mu}{Y} {}^* X \qquad (5)$$

Where Q_L = Liquid Flow Rate

V_L = Reactor Volume

S_o = Influent substrate concentration

S = Reactor substrate concentration

X_o = Influent biological solids concentration

X = Reactor biological solids concentration

Modified Monod Growth Equation:

$Mu = [(Muhat*S)/(K_s + S)]/[DO/(DO + K_{SDO})]$ (6)

The concentration of biological solids in the aeration tank at any time is a function of the flux plus the net growth. The net growth being the difference between Mu (Monod specific growth rate) and K_d (decay rate).

The substrate serves as a food source for the biological solids.

MASS BALANCES:

Liquid Phase

Oxygen:

$$\frac{dO_2}{dt} = \frac{Q_L}{V}[C_{in}-C_{out}] + alpha*K_{La}*[Beta*C^*_{inf} - C] - \frac{A*Mu*X*[1-Y]}{Y} - B*K_d*X \tag{7}$$

Carbon Dioxide:

$$\frac{dDCD}{dt} = \frac{Q_L}{V_L}[DCD_o - DCD] + K_{KLaco2}[DCD_S - DCD] + Mu*X\left[\frac{1-Y}{Y}\right]*Y_{co21} + K_d*X*Y_{co22} \tag{8}$$

Nitrogen:

$$\frac{dDN}{dt} = \frac{Q_L}{V_L}[DN_o - DN] + K_{LAN2}[DN_s - DN] \tag{9}$$

Gas Phase

Oxygen:

$$\frac{dO_2}{dt} = \frac{Q_{Go}O_{2o} - Q_G O_2}{V_G} - K_{Lao2}[DO_s - DO]\left[\frac{V_L}{V_G}\right]\frac{1}{MW_{O2}} \qquad (10)$$

Carbon Dioxide:

$$\frac{dCO_2}{dt} = \frac{Q_{Go}CO_{2o} - Q_G CO_2}{V_G} - K_{LaDCD}[DCD_s - DCD]\left[\frac{V_L}{V_G}\right]\frac{1}{MW_{CO2}} \qquad (11)$$

Nitrogen:

$$\frac{dN_2}{dt} = \frac{Q_{Go}N_{2o} - Q_G N_2}{V_G} - K_{LaN2}[DN_s - DN]\left[\frac{V_L}{V_G}\right]\frac{1}{MW_{N2}} \qquad (12)$$

Where: C_{in} = influent dissolved oxygen concentration

C_{out} = effluent dissolved oxygen concentration

C_{inf}^* = oxygen saturation concentration

C = dissolved oxygen concentration in reactor

DCD_o = influent dissolved carbon dioxide concentration.

DCD = dissolved carbon dioxide concentration in reactor.

DCD_s = dissolved carbon dioxide saturation concentration.

DN_o = influent dissolved nitrogen concentration.

DN = dissolved nitrogen concentration in reactor.

DN_S = dissolved nitrogen saturation concentration.

Q_{Go} = influent gas flow rate.

Q_G = effluent gas flow rate.

V_G = gas volume

O_{2o} = influent gas oxygen concentration

O_2 = reactor gas oxygen concentration

CO_{2o} = influent gas carbon dioxide concentration

CO_2 = reactor gas carbon dioxide concentration

N_{2o} = influent gas nitrogen concentration

N_2 = reactor gas nitrogen concentration

Gas Flow Forcing Function:

$$Q_G = K_{flow}[P_{sp} - P_t] \qquad (13)$$

Partial Pressures:

$$P_{CO2} = CO_2{}^*RT \qquad (14)$$

$$P_{O2} = O_2{}^*RT \qquad (15)$$

$$P_{N2} = N_2{}^*RT \qquad (16)$$

$$P_T = P_{CO2} + P_{O2} + P_{N2} + P_{H2O} \qquad (17)$$

Saturation Concentrations:

He is the Henrys' Law constant. The model adjusts the constant as a function of the reactor liquid temperature.[10,12]

$$DO_S = 5.5555*10^4[\ MWT_{O2} / H_{e\ O2}\ ]*P_{O2}*BETA \quad (18)$$

$$DCD_S = 5.5555*10^4[\ MWT_{CO2} / H_{e\ CO2}\ ]*P_{CO2}*BETA \quad (19)$$

$$DN_S = 5.5555*10^4[\ MWT_{N2} / H_{e\ N2}\ ]*P_{N2}*BETA \quad (20)$$

The alkalinity at the Joint Water Pollution Control Plant is assumed to be primarily carbonaceous in nature. The equation for alkalinity will include the contribution from ammonia.

$$\begin{aligned} ALK = {} & \{HCO_3{}^-\}*Activity_{HCO3}{}^- + 2\{CO_3{}^{2-}\}*Activity_{CO3}{}^{2-} + \\ & \{OH^-\}*Activity_{OH}{}^- + \{NH_3\}*Activity_{NH3} - \\ & \{H^+\}*Activity_H{}^+ \end{aligned} \quad (21)$$

Following from the assumption that the wastewater is of low ionic strength, the activity coefficient will be assigned a value of 1.[13]

$$K_1 = [H^+][HCO_3{}^-]/[H_2CO_3{}^*] \quad (22)$$

$$K_2 = [H^+][CO_3{}^{2-}]/[HCO_3{}^-] \quad (23)$$

$$K_W = [H^+][OH^-] \quad (24)$$

$$ALK = K_1[H_2CO_3{}^*]/[H^+] + 2K_1K_2[H_2CO_3{}^*]/[H^+]^2 + K_W/[H^+] - [H^+] + [NH_3] \quad (25)$$

$H_2CO_3{}^*$ is the total concentration of H_2CO_3 and the fraction of nonionized CO_2 that is dissolved. When the terms are combined the equation becomes cubic in $[H^+]$, and must be solved iteratively. The fraction of the total dissolved CO_2 that is nonionized can be expressed in the following form.

$$f_{CO2} = [H_2CO_3{}^*] \;/\; [H_2CO_3{}^*] + [HCO_3{}^-] + [CO_3{}^{2-}] \quad (26)$$

$$= 1/(\, 1 + K_1/[H^+] + K_1K_2/[H^+]^2 \,) \quad (27)$$

The concentration of dissolved CO_2 that is not ionized equals, DCD^*f_{CO2} .[10]

The fraction of the total ammonia that is NH_3 can be expressed in the following form.

$$f_{NH3} = 1/(\, 1 + [H^+]K_{NH3}/K_W \,) \quad (28)$$

The concentration of ammonia that is NH_3 equals, $[NH_{3Total}]^*f_{NH3}$.

The final alkalinity equation is expressed as:

$$ALK = (K_1[H_2CO_3^*][H^+] + 2K_1K_2[H_2CO_3^*] + K_W[H^+] - [H^+]^3 + [H^+]^2[NH_3])/[H^+]^2 \quad (29)$$

The program solves equation thirty interatively to determine the pH.

$$0 = [H^+]^2 + [H^+][ALK - NH_3] - K_W - (K_1 + 2K_1K_2/[H^+])[H_2CO_3^*] \quad (30)$$

IV MODEL CALIBRATION

During an 8 day period in May of 1984 the County Sanitation Districts of Los Angeles County conducted a process water test at the Joint Water Pollution Control Plant in Carson California. The test was performed on reactor D, one of four parallel trains, of the recently completed high purity oxygen activated sludge plant. The test was to verify that the process could dissolve oxygen at the rate specified under the warranty conditions of the purchase contract. Those specifications are detailed in tables one and two. The results indicated that the process performed beyond expectations and easily achieved the warranty specifications.

The historical data collected during the verification test was used to calibrate a mathematical model to simulate process performance.

Certain fixed process parameters were required for the model. These included:

1) Physical Dimensions
2) K_{La}
3) Alpha Factors

TABLE 1 Warranty conditions

FLOW:	62.5 Million Gallons per Day
OXYGEN UPTAKE RATE:	5625 Lbs. per Day
AVERAGE CONCENTRATION OF DISSOLVED OXYGEN:	6 mg/l none less than 2 mg/l
POWER CONSUMPTION:	809 KWHr

TABLE 2 Operating conditions adjusted to warranty conditions for comparison.

FLOW:	62.41 Million Gallons per Day
OXYGEN UPTAKE RATE:	7600 Lbs. per Day
AVERAGE CONCENTRATION OF DISSOLVED OXYGEN:	14.5 mg/l
POWER CONSUMPTION:	600 KWHr

Table three presents the physical dimensions of the aeration basins.[14] Although most primary effluent parameters are dynamic, the ammonia and alkalinity concentrations were considered to be static do to a lack of available data.

The K_{La} values were determined during clean water testing at the Mixco test facility in September and October of 1979. Table four contains the results of the K_{La} determination from the clean water test report, and the surface aerator placement at the Joint Water Pollution Control Plant.[15]

The actual tests were performed to simulate process conditions. The test tanks had the same liquid depth and 98% of the of the surface area per aerator.

The alpha factors were determined by analyzing the process water test data, and found to be 0.9 for all stages.

The data available for model calibration were historical. The data were collected for process warranty verification, as opposed to process modeling. Unfortunately, this situation presented several shortcomings. The Biochemical Oxygen Demand (five day) were collected at 24 hour intervals. For modeling, the data should be collected at least every 4 hours to indicate fluctuations in waste strength. These fluctuations would be expected at a treatment facility with an influent that is a combination of domestic and industrial wastewater. The influent flow rate during the test period was 62.5 million gallons per day, which is the design peak capacity. There were no indications of any diurnal flow fluctuations during the test period. The dissolved oxygen concentration and head space gas purity data were collected at 3 hour intervals. Unfortunately, no carbon dioxide partial pressure or gas phase concentration data were included in the process verification report. The treatment plant laboratory data did not include influent alkalinity. Therefore,the process alkalinity was set to warranty conditions.

TABLE 3 Physical dimensions of the aeration basins.

UNITS PER TRAIN: 4

LENGTH PER TRAIN: 250 ft.

WIDTH PER TRAIN: 187.5 ft.

WATER DEPTH: 15 ft.

VOLUME PER TRAIN: 5.26 Million Gallons

TABLE 4 Oxygen transfer coefficient for the surface aerators.

STAGE	AERATOR	HP	K_{La20}
1	1 - 3	125	11.875
2	4 - 6	75	6.208
3	7 - 9	75	6.208
4a&b	10-12	75 & 125	7.767

CALIBRATING THE MODEL:

Calibrating any mathematical model to a dynamic system is a challenge unto itself. Fitting a model with data originally collected for another purpose can become quite an undertaking. The data available included:
1) dissolved oxygen concentration 2) partial pressure of oxygen 3) influent and effluent Biochemical Oxygen Demand 4) volatile suspended solids 5) gas and liquid flow rates 6) feed gas purity . It was decided to use the dissolved oxygen concentration and partial pressure data as the basis for the model fit.

Initial computer simulations used theoretical and average values for the biological parameters. Given that the Joint Water Pollution Control Plant receives an unknown portion of industrial waste in the secondary systems influent, the Biochemical Oxygen Demand (five day) to ultimate ratio was adjusted until the oxygen demand on a power weighted average basis matched the plants oxygen demand. Mu and K_d were adjusted to distribute the load through the four tanks to match the oxygen partial pressure and dissolved oxygen concentrations. The alpha factor presented somewhat of a quandary. The values from steady-state analysis ranged from 0.904 to 1.051 depending upon which power weighted basis was used for calculation. Initially, a value of 0.904 was used, but the resulting dissolved oxygen values were too low. The alpha value was then increased to 1.00. The fit improved, but the dissolved oxygen concentrations were still too low. Increasing the alpha factor above 1.00 could not be justified. The County Sanitation Districts of Los Angeles County used an in line flow totalizer to determine gas flow to the process, the accuracy of which is not known. Therefore, the oxygen gas feed rate to the process was increased until an acceptable fit was achieved. This required an increase of 8%.

The model's fit was good but not exceptional. The difference between the model's predicted dissolved oxygen concentration and oxygen partial pressure (P.P.) to the actual process data are presented in table five.

The error between the models predicted values, and the County's data are particularly evident in tanks 1 and 4. The oxygen purity in tank 1 was recorded at 87%. This value was suspect as it was about 10% greater than would be expected from this type of high purity plant. Unfortunately, no carbon dioxide partial pressure data were available. If the carbon dioxide concentration in the gas phase were known, the Y_{CO21} coefficient [kg CO_2/kg substrate] could have been adjusted to fit the operational conditions, rather than using a theoretical value. Given that the Joint Water Pollution Control Plant does treat industrial wastewater, in addition to domestic sewage, it is quite conceivable that the assigned value of Y_{CO21} was too large. If a smaller coefficient had been used, the oxygen purities would have been greater, and the oxygen partial pressure depression would not have been as magnified in stage 4.

TABLE 5 Error in model prediction

TANK	D.O. ERROR mg/l	%	P.P. ERROR atm	%
1	1.25	11	0.1203	14
2	1.63	9	0.0538	7
3	0.94	5	0.0211	4
4	2.72	20	0.1068	25

V PLANT STUDIES

The dynamic model was applied to the Carson plant to determine its maximum treatment capacity. The Carson plant's history of stable performance and removal of the surface aerators blade tips to reduce the oxygen transfer coefficient was sufficient evidence to indicate the plant's capacity was significantly under utilized.

Two types of process simulations were preformed. The first modeled an increased wastewater flow rate with diurnal fluctuations. These fluctuations were based on a sinusoidal function whose amplitude was varied to achieve a predetermined flow variance. To determine if a more economical utilization of the plants' cryogenic oxygen capacity could be achieved, additional simulations were preformed with the oxygen feed rate based on the influent sewage flow rate and the dissolved oxygen concentration in stage four. The dissolved oxygen set point was 6.0 mg/l. This was based on the operational warranty conditions.

It was stipulated that the plants' capacity was exceeded if the dissolved oxygen concentration in tank four fell below 3.0 mg/L. This was based on the warranty condition that no dissolved oxygen would be below 2 mg/L. The 1.0 mg/L buffer was included to minimize the effect of any oxygen production time lag resulting from unforeseen fluctuations in waste strength that might consume excessive amounts of oxygen in stage one. The operational parameters assigned to the model's influent variables were based on a seven day average during the verification period. These parameters included: 1) oxygen feed rate 2) feed gas purity 3) wastewater strength based on Biochemical Oxygen Demand {five day} 4) wastewater influent flow rate. The base influent parameters are presented in table six.

The first simulation was based on an operating strategy of constant influent wastewater flow rate and constant oxygen feed rate. The data are presented in Figure 2. At 90 MGD the stage four dissolved oxygen concentration did not drop below 3.0 mg/l. The initial part of the graph shows the initial condition of the transients. As the simulation proceeds, the process parameters reach steady-state condition.

TABLE 6 Steady state influent parameters for capacity simulation

Oxygen Feed Rate:	52.55 ton/day
Feed Gas Purity:	97%
Waste Strength:	127 (BOD5)
Influent Sewage Flow Rate:	62.5 MGD

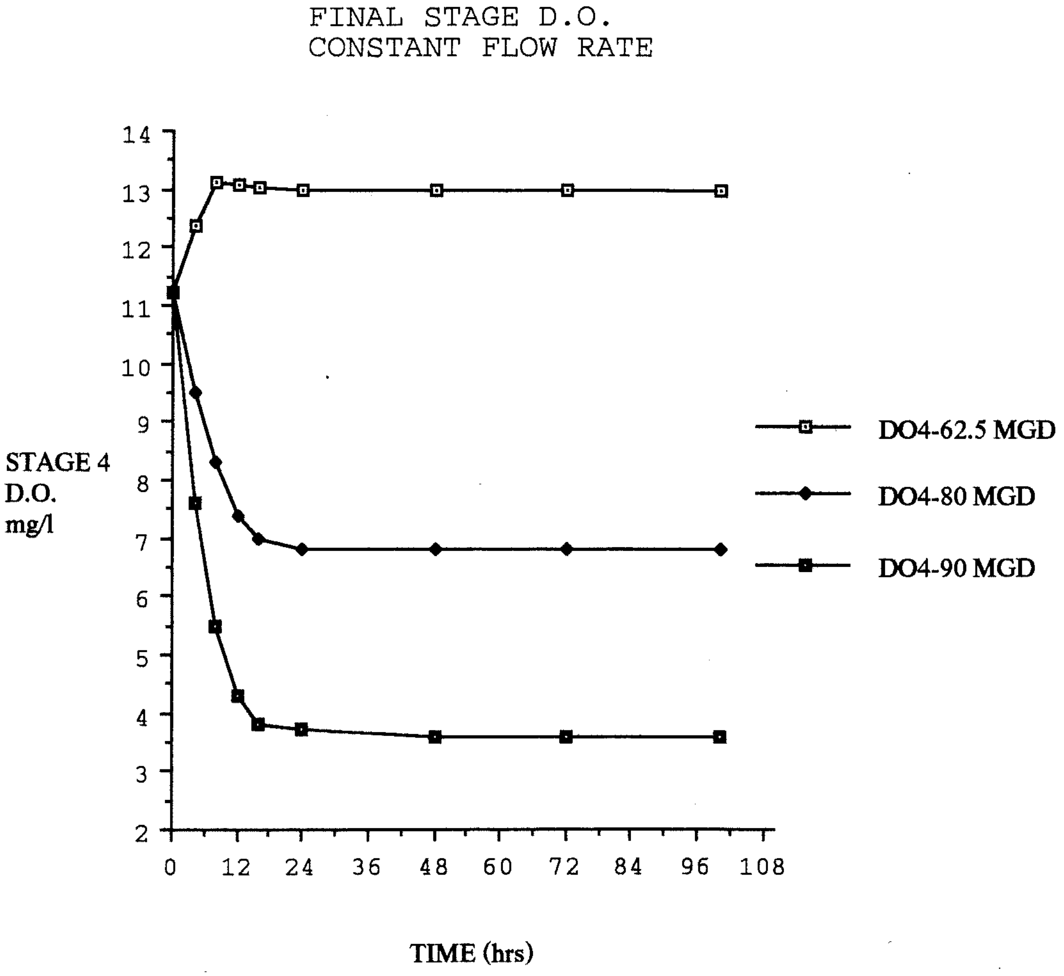

Figure 2 Final stage dissolved oxygen concentration, constant liquid and gas flow rates

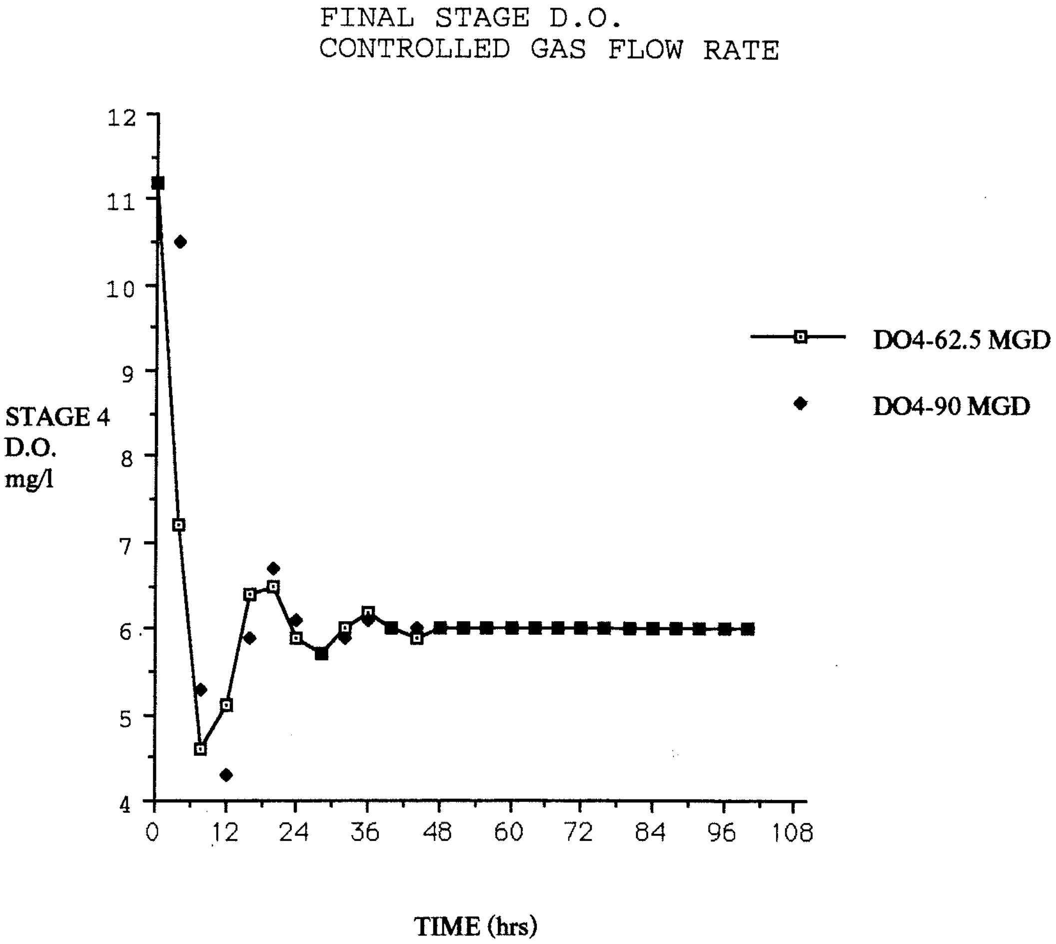

Figure 3 Final stage dissolved oxygen concentration, controlled gas flow rate.

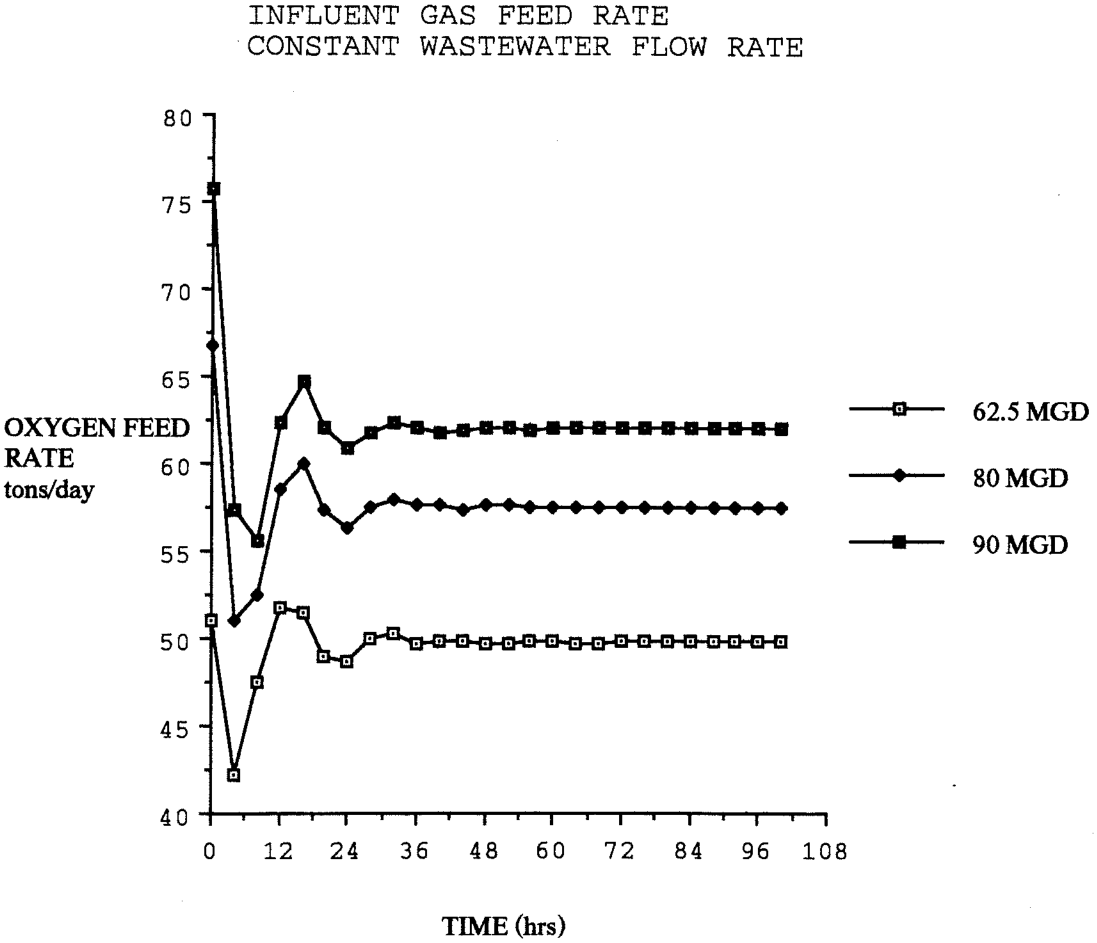

Figure 4 Influent gas feed rate, constant liquid feed rate.

The second simulation case was based upon a constant sewage influent rate while the oxygen feed rate was a function of the fourth stage dissolved oxygen concentration. Figure 3 presents the fourth stage dissolved oxygen concentration as a function of time. Steady state was achieved within 48 hours. Figure 4 shows the oxygen feed rate in tons per day as a function of time and influent wastewater flow rate. The maximum oxygen production rate of 75 tons per day-train was never exceeded by demand even at 90 MGD.

The third simulation involved a variable wastewater influent flow rate, while the oxygen feed rate was keep constant. This type of model simulates the behavior of a high purity plant with minimal or nonexistent turn down ability afforded by the oxygen plant. The magnitude of sinusoidal (diurnal) flow fluctuation was 16 and 32 percent. A third run set the influent sewage base rate to 80 MGD and 20 percent sinusoidal fluctuation. The data are presented in Figure 5. At no time did the dissolved oxygen concentration drop below 3.0 mg/l. However, when the fluctuation was increased to 40 percent, the model failed due to insufficient dissolved oxygen concentration.

The final simulation involved both diurnal fluctuation and a controlled variable oxygen feed rate. This case represents process control, and real world feed conditions. Figure 6 presents the fourth stage dissolved oxygen concentration as a function of time for three cases of flow fluctuation. To determine the maximum plant capacity, the influent wastewater flow rate was steadily increased until the fourth stage dissolved oxygen concentration dropped below 3.0 mg/l. The maximum treatable capacity is 80 MGD with 20 percent diurnal fluctuation. However, the model predicts that 90 MGD could also be treated as the minimum dissolved oxygen concentration was 2.9 mg/l, only 0.1 mg/l below the cut off value. These data are presented in Figure 7.

The model was used to determine the required dynamic oxygen feed rate when the influent wastewater rate was 62.5 MGD with 16, 20, and 30 percent diurnal fluctuation. Figure 8 presents the required oxygen feed rate to maintain a dissolved oxygen concentration of 6.0 mg/L in tank four. At no time was the oxygen plants' capacity exceeded.

An example of a failure condition is presented in Figure 9. The gas flow rate was fixed, and the wastewater flow was 90 MGD with 20 percent diurnal fluctuation.

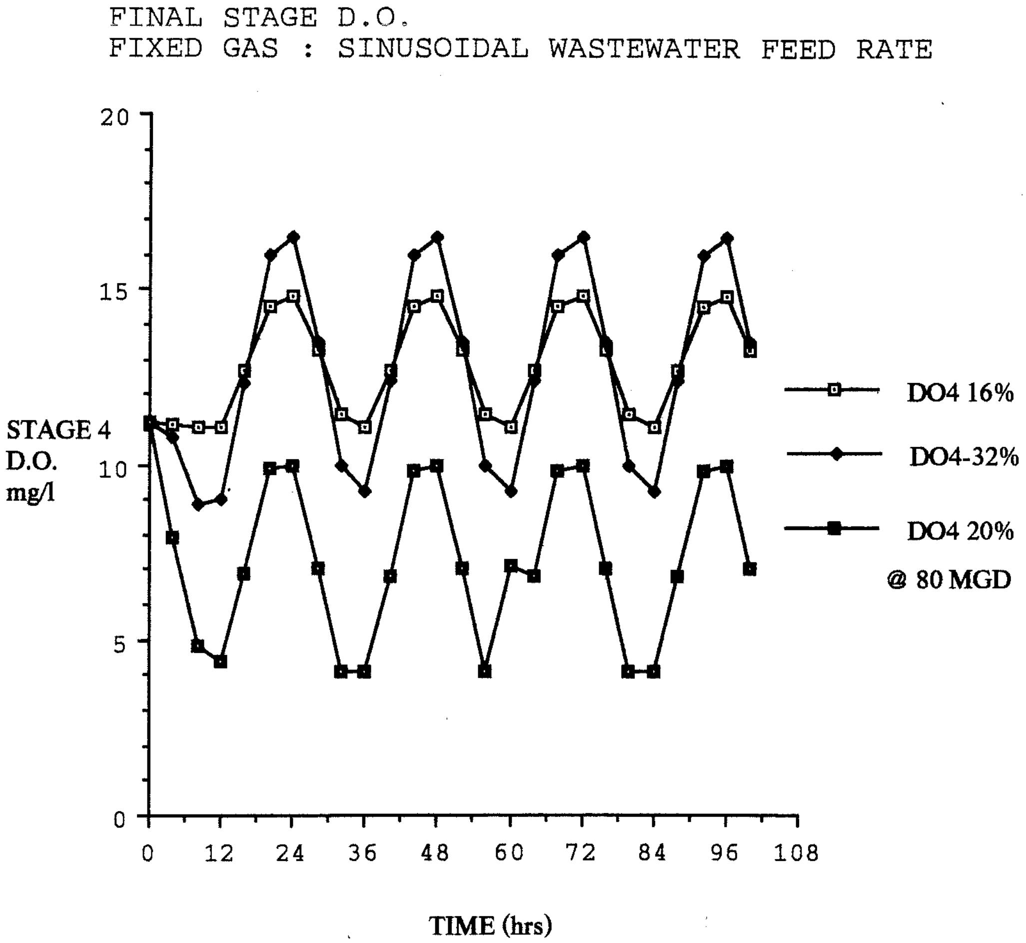

Figure 5 Final stage dissolved oxygen , fixed gas feed rate, sinusoidal liquid feed rate.

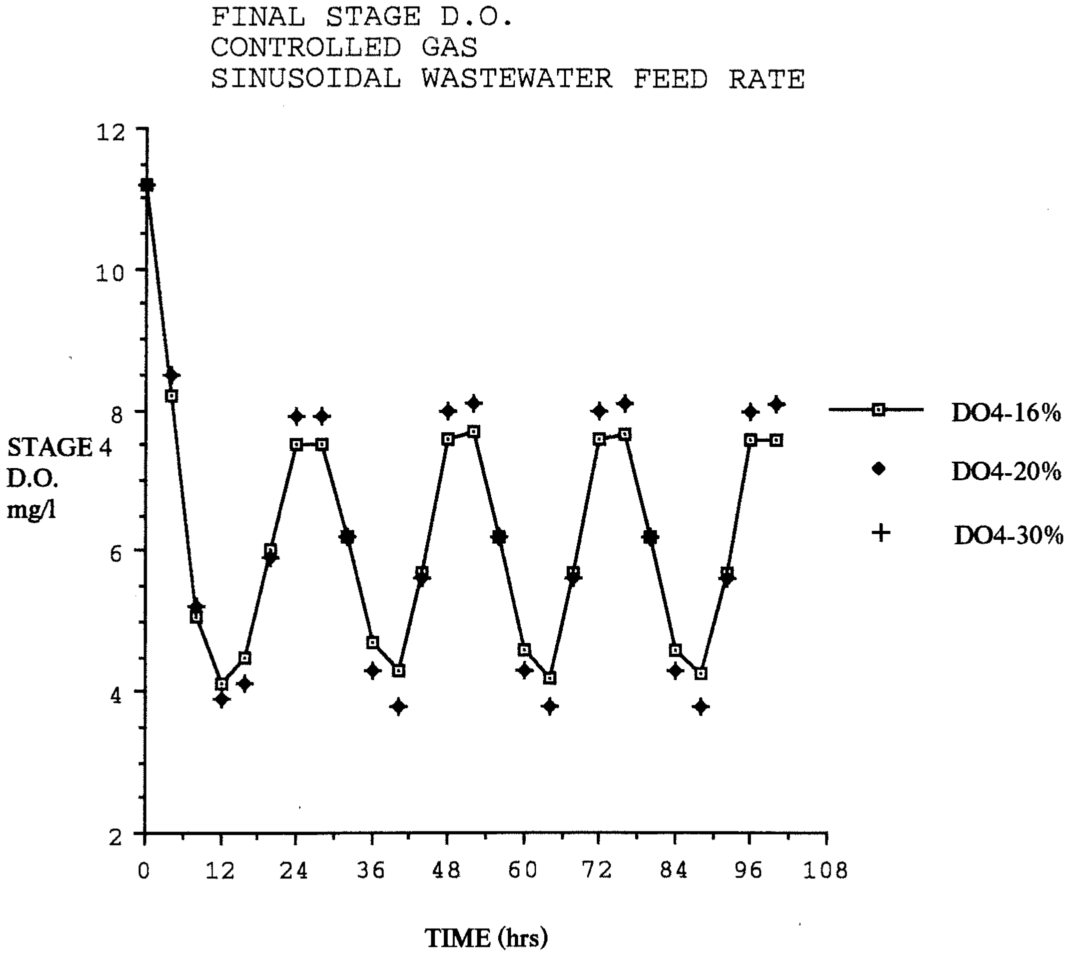

Figure 6 Final stage dissolved oxygen , controlled gas feed rate, sinusoidal liquid feed rate.

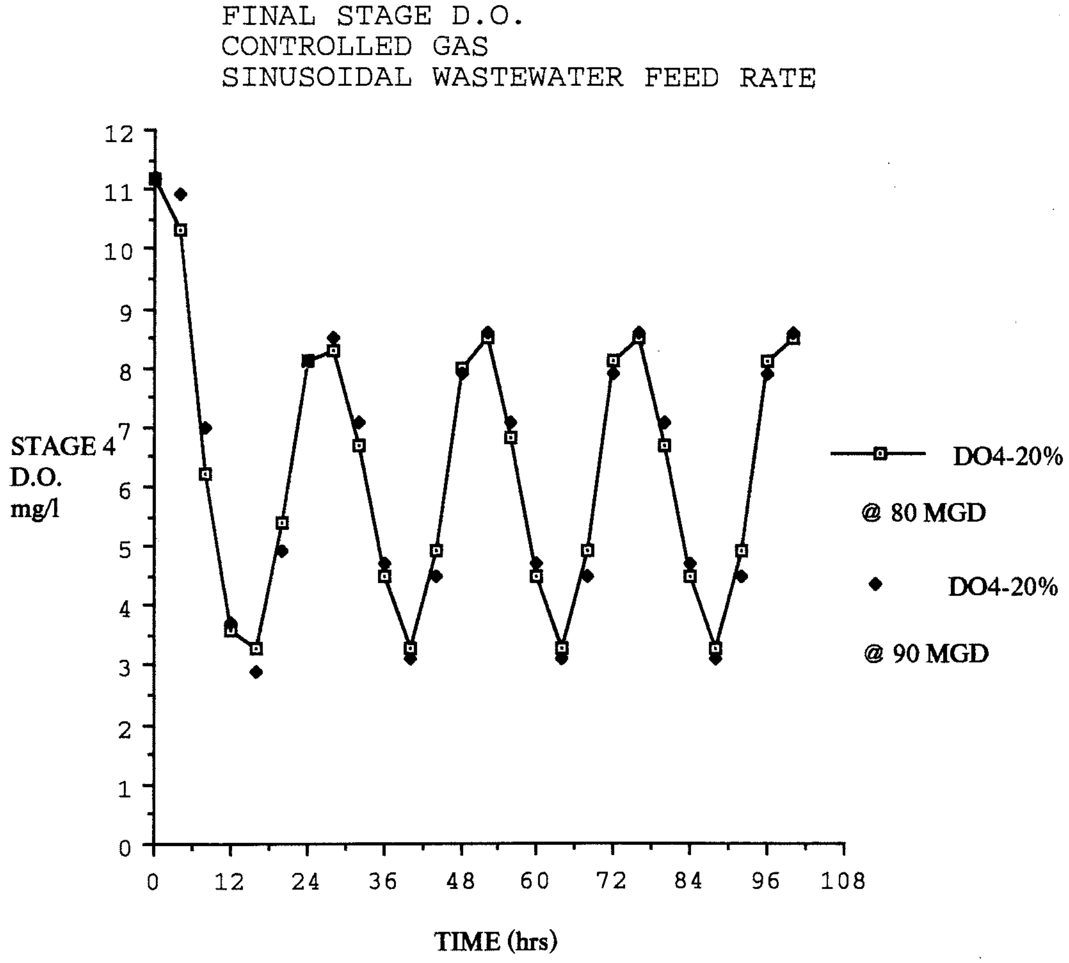

Figure 7 Final stage dissolved oxygen, controlled gas feed rate, sinusoidal liquid feed rate.

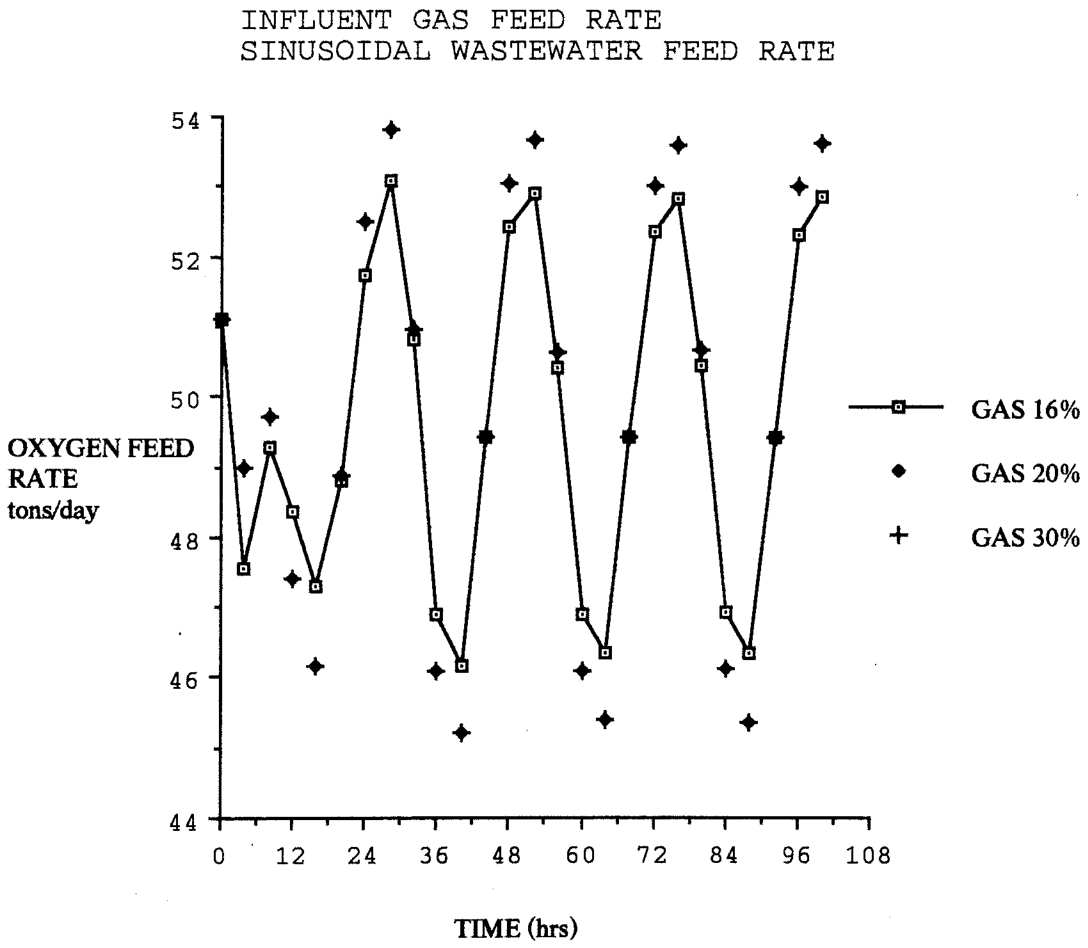

Figure 8 Influent gas feed rate with sinusoidal liquid feed rate.

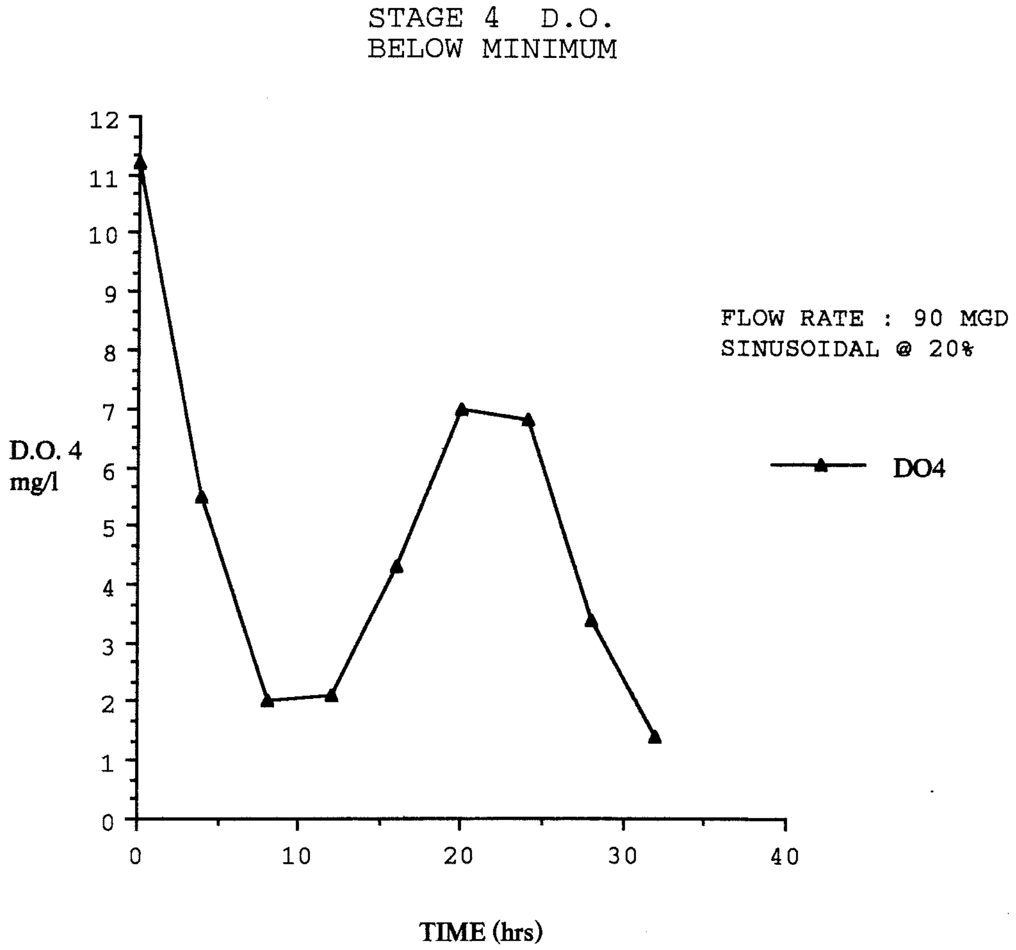

Figure 9 Final stage dissolved oxygen below the established minimum.

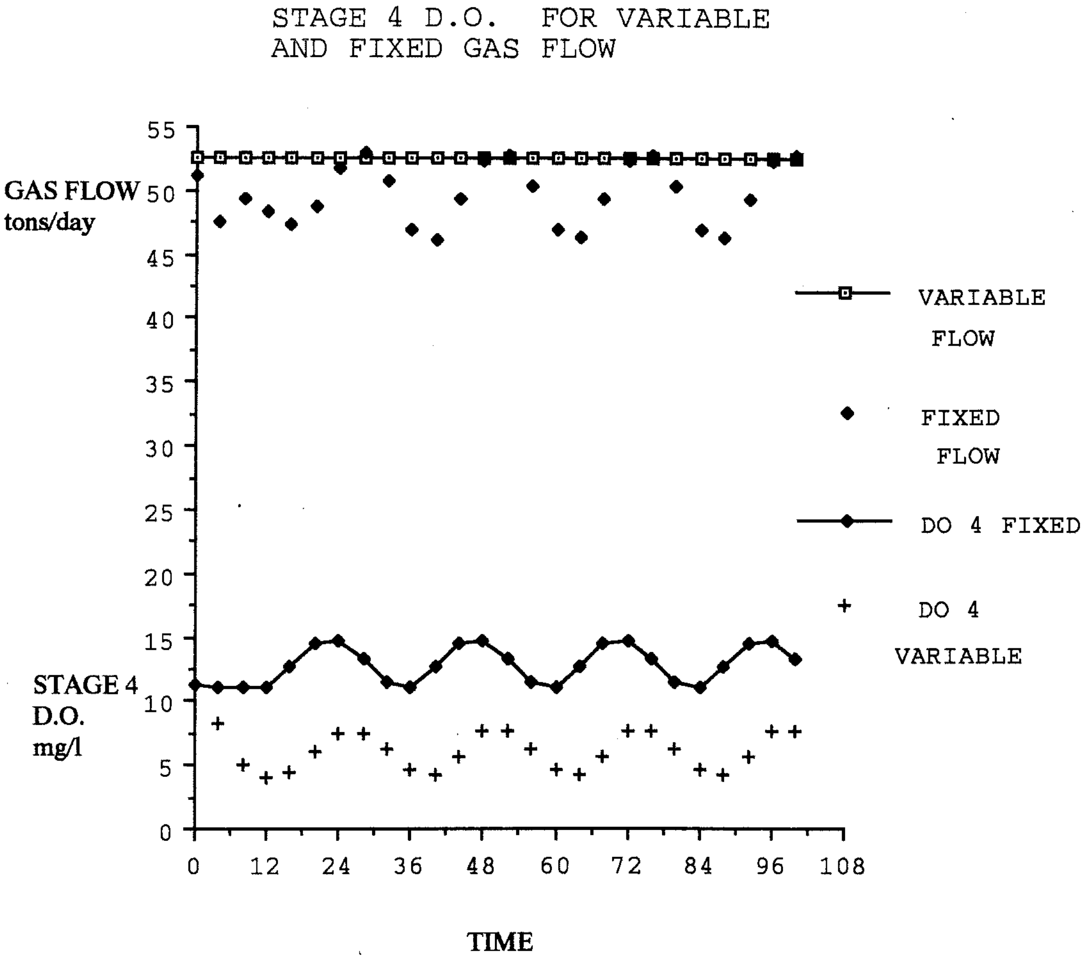

Figure 10 Final stage dissolved oxygen for variable and fixed gas flow.

To determine if any reduction in oxygen usage could be realized through flow control, the operating condition of 62.5 MGD with 16 percent diurnal fluctuation was selected. The standard feed condition used 54.18 tons of oxygen per day, while the flow controlled system used 49.71 tons of oxygen per day. A savings of 4.47 tons of oxygen per day. The data are presented in Figure 10.

VI CONCLUSIONS

The application of a dynamic mathematical model to the County Sanitation District of Los Angeles Counties' high purity oxygen activated sludge treatment plant produced two distinct conclusions: 1) The computer model's applicability is a function of the quality and quantity of the calibration data. 2) The Carson plant is significantly under loaded.

The computer model was stable and flexible during the simulations. However, any model is only as strong as its weakest link. In this case, that link is the calibration data. The calibration data were originally collected during a warranty verification experiment of the oxygen transfer capability, shortly after the initial start up. For modeling, the Biochemical Oxygen Demand samples should have been taken every four hours. The dissolved oxygen concentration, oxygen and carbon dioxide partial pressure, and influent gas and wastewater flow rates should have been collected hourly. Had the data been acquired more frequently, the model's calibration would have been better, although, the fit was good.

The conclusions based upon simulation results about the operation of the Carson plant are straightforward. The plant is operating significantly below capacity as a function of oxygen transfer capability. The plant has a design load capacity of 50 MGD, with peak flow capacity of 62.5 MGD. The warranty conditions were specified for the peak operational conditions. The data from the simulations indicate that each stage could treat as much as 90 MGD under ideal constant flow conditions. Each stage has a capacity of 80 MGD with the inclusion of sinusoidal diurnal flow, if the oxygen feed rate is coupled to the fourth stage dissolved oxygen concentration, and influent sewage flow rate. Although, as the influent flow rate increases, the predicted sludge age decreases. To maintain a sludge with good settling characteristics, a balance must be struck between capacity and stability. The conclusions drawn from the simulation data are strictly based on oxygen transfer capability, and Biochemical Oxygen Demand (five-day) removal. Process hydraulics and secondary clarifier performance are untested. Actual operational conditions may significantly restrict any increase in treatment capacity. Additionally, the model does not account for sludge production, which may also limit any increased treatment rate.

The plants current under loading provides the County with a situation wherein the plant has an extensive degree of industrial waste shock capacity. A stable plant does not provide the impetus to drastic operational change. However, a new operational strategy might be to balance the ratio of flow to capacity against industrial waste shock stability as a function of the industrial waste feed fraction.

Finally, older cryogenic oxygen production plants have limited ability to modulate oxygen production. Therefore, if flow control is instituted, the plant could operate at the average rate of the sinusoidal demand curve. During the decreasing demand portion of the curve, the excess oxygen could be stored for use during the peak portion of the curve, which would reduce the overall operating costs.

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APPENDIX

A : MODEL PARAMETERS

B : COMPUTER PROGRAM LISTING

SECTION A:

Model Parameters

Muhat = 0.25 hr^{-1}

Y = 0.62

Y_{O21} = 1.07

Y_{O22} = 1.42

Y_{NH31} = 0.039

Y_{NH32} = 0.1239

K_{SDO} = 2.5 g/M^3

K_S = 50 g/M^3

Y_{CO21} = 1.37

Y_{CO22} = 1.95

K_D = 0.0127 hr^{-1}

BETA = 0.985

K_{LaCO2} = $0.836K_{LaO2}$

K_{LaN2} = $0.943K_{LaO2}$

THETA = 1.024

BOD5TOU = 0.52

SECTION B:

Computer Program Listing

```
MACRO
XJ,SJ,DOJ,DN2J,DCDJ,HIJ,FCDJ,QGJ,PCO2J,PO2J,PN2J,CO2J,N2J,O2J,...
DNH3J,ALKJ=REACT(THETAJ,XOJ,SOJ,DOOJ,DN2OJ,DCDOJ,HIOJ,QGOJ,CO2OJ,.
..
N2OJ,O2OJ,ICXJ,ICSJ,ICDOJ,ICDN2J,ICDCDJ,ICCO2J,ICO2J,ICN2J,CKLAOJ,
...
VLJ,TPRESJ,TPRESI,DNH3OJ,ALKOJ)
**********  LIQUID PHASE MASS BALANCES ***************
* CORRECT FLOW FOR PRESSURE CHANGE
  QGNJ=QGOJ*TPRESJ/TPRESI
* MICROBIAL MASS BALANCE
DXDT = (XOJ - XJ)/THETAJ + (MUJ - KD*O2LIM) * XJ
XJ   = INTGRL(ICXJ,DXDT)
* ORGANISM GROWTH RATE
* MUJ  = MUHAT*SJ*DOJ/((SJ +KS)*(DOJ+KSDO))
* COMMENT OUT THE ABOVE EXPRESSION FOR MU AND SUBSTITUTE WITH THE
* FOLLOWING EXPRESSION WHICH IS MORE CONVENIENT FOR PREFORMANCE
CALCS.
  O2LIM=(DOJ/KSDO) / (1.+(DOJ/KSDO))
  MUJ  =MUHAT*SJ/(SJ+KS)*O2LIM
* SUBSTRATE BALANCE
DSDT = (SOJ - SJ)/THETAJ -MUJ*XJ/Y
SJ   = INTGRL(ICSJ,DSDT)
* AMMONIA BALANCE
DNH3RJ=(YNH32*KD*O2LIM + YNH31*MUJ/Y - YNH32*MUJ)*XJ
DDNH3J=(DNH3OJ-DNH3J)/THETAJ+DNH3RJ
DNH3J=INTGRL(ICNH3J,DDNH3J)
* CALCULATE THE ALKALINITY INCREASE FROM AMMONIA INCREASE
ALKJ=ALKOJ+(DNH3J-DNH3OJ)/14.E+03
* SET THE MASS TRANSFER COEFFICIENTS FOR NITROGEN AND CARBON
DIOXIDE
* TO THE SOME FRACTION OF THE VALUE FOR OXYGEN
CKLANJ=CKLAOJ*FKLAN2
CKLACJ=CKLAOJ*FKLACO
* DISSOLVED OXYGEN
O2UPJ=MUJ*XJ*YPO21 + KD*XJ*YO22*O2LIM
```

```
DODT= (DOOJ - DOJ)/THETAJ + SDOJ - O2UPJ
DOJ  = INTGRL(ICDOJ,DODT)
* DISSOLVED NITROGEN
DN2DT=(DN2OJ - DN2J)/THETAJ +SDN2J
DN2J  = INTGRL(ICDN2J,DN2DT)
* DISSOLVED CO2
*DCDR=MUJ*XJ*YPCO21 + KD*XJ*YCO22*O2LIM
DCDRJ=O2UPJ*1.375
DCDDT=(DCDOJ-DCDJ)/THETAJ+SDCDJ + DCDRJ
DCDJ  = INTGRL(ICDCDJ,DCDDT)
********** GAS SATURATION CONCENTRATIONS  ****************
* OXYGEN
DOSJ=PO2J/HEO2
* NITROGEN
DN2SJ=PN2J/HEN2
* CARBON DIOXIDE
DCDSJ=PCO2J/HECO2
********** PH AND FRACTION OF DISSOLVED CARBON DIXOIDE WHICH IS
*                    H2CO3  (USE FUNCTIONS TO SIMPLIFY)
FCDJ =FCO2(HIJ,CK1,CK2)
HIJ=PHCAL(ALKJ,DCDJ,DNH3J,CK1,CK2,CKW,CKNH3)
************** GAS SIDE  BALANCES************************
* STRIPPING RATES
* CO2
SDCDJ=CKLACJ*(DCDSJ - DCDJ*FCDJ)
* DO
SDOJ =CKLAOJ*(DOSJ - DOJ)
* NITROGEN
SDN2J =CKLANJ*(DN2SJ - DN2J)
* VOLUMETRIC GAS PRODUCTION
  QGJ=LIMIT(0.,10000.,(KFLOW*((VPH2O+PCO2J+PO2J+PN2J)-TPRESJ)))
* CO2 BALANCE
CO2DT = (QGNJ*CO2OJ - QGJ*CO2J)/VG -SDCDJ*VLJ/(VG*MWCO2)
CO2J   = INTGRL(ICCO2J,CO2DT)
* N2 BALANCE
N2DT  = (QGNJ*N2OJ  - QGJ*N2J)/VG -SDN2J*VLJ/(VG*MWN2)
```

```
N2J     = INTGRL(ICN2J,N2DT)
* O2 BALANCE
O2DT   =(QGNJ*O2OJ - QGJ*O2J)/VG -SDOJ*VLJ/(VG*MWO2)
O2J    =INTGRL(ICO2J,O2DT)
* PARTIAL PRESSURES
* CO2
PCO2J = CO2J*RT
* N2
PN2J  = N2J*RT
* O2
PO2J = O2J*RT
ENDMAC
************************************************************
INITIAL
*  THIS SECTION DESCRIBES THE INITIAL CONDITIONS AND INPUTS TO THE
*  REACTORS.
** FIRST THE BIOX PARAMETERS
PARAM MUHAT=0.250, Y=0.62, YO21=1.07,YO22=1.42,YB5TOU=0.52
PARAM YNH31=0.039,YNH32=0.1239
PARAM KSDO=2.50, KS=50., YCO21=1.37,YCO22=1.95,KD=0.01270,NPRINT=2
* PARAMETERS FOR SLUDGE RECYCLE
PARAM ALKR=5.76E-03,DCDR=120.,DN2R=10.
PARAM DTIME1=0.,DTIME2=100.0,OFFSET=0.,O2LAG=0
PARAM MWCO2=44.009,MWN2=28.013,MWO2=31.998,R=8.2056E-05
* ALPHA AND BETA FACTORS; EFFECTIVE SATURATION DEPT
********* MODIFY FOR COUNTY **************
PARAM
ALPHA1=1.000,ALPHA2=1.000,ALPHA3=1.000,ALPHA4=1.000,BETA=0.985
PARAM CFCONV=0.58858
* RATIOS OF NITROGEN AND CO2 KLA'S TO OXYGEN
PARAM FKLACO=0.836,FKLAN2=0.943,BKLA1=11.875
* CSD'S KLAS FROM CLEAN WATER TANK TEST
PARAM BKLA2=6.208,BKLA3=6.208,BKLA4=7.767
* FIT O2 FEED RATE TO MATCH ORIGINAL OPERATIONAL PERFORMANCE
PARAM O2ERR=1.08
* OPERATIONAL SIMULATION AND OPTIMIZATION PARAMETERS
```

```
PARAM MGDMOD=1.0
PARAM FPMOD=1.0
PARAM KLAMOD=1.0
PARAM BOOST=0.0
FEDFLX=(1+BOOST*SIN(0.2618*TIME))
PARAM DOSP=6.0,KERR=1.0,KINTER=1.0
DOERR=(DOSP-DO4)
GASMOD=DOERR*KERR+KINTER*INTGRL(0.0,DOERR)
* SET THE CONTROLLER PARAMETERS
PARAM RSETS=0.,RSETI=0.0,SRTSP=7.,RO2GP=0.,RO2GI=0.0
* TOTAL PRESSURES. LET THEM VARY BY 2 INCHES
PARAM TPRES1=1.006,TPRES2=1.0045,TPRES0=1.006
PARAM TPRES3=1.0030,TPRES4=1.0015
** INITIAL CONDITIONS
PARAM ICS1=120.,ICDO1=11.0,ICNH3J=24.0
PARAM ICS2=90.,ICDO2=16.4
PARAM ICS3=60.,ICDO3=16.3
PARAM ICS4=30.,ICDO4=11.2
* INITIAL PURITY PROFILES IN FRACTIONS (SAME AS PARTIAL PRESSURE)
PARAM FPO21=.905,FPO22=0.7202,FPO23=0.5888,FPO24=0.4106
PARAM FPCO21=0.01,FPCO22=0.01,FPCO23=0.01,FPCO24=0.01
PARAM ICPH1=7.5,ICPH2=7.5,ICPH3=7.5,ICPH4=7.5
* INLET GAS PURITY (% O2) AND OXYGEN FLOW IN TONS PER DAY.
PARAM ZWSCFM=0.056
* CHECK INTO CSD'S WATTAGE DRAW PER STAGE
PARAM ZWM1=286.0,ZWM2=183.0,ZWM3=176.0,ZWM4=207.0
** INFLUENT PARAMETERS
PARAM BOD5IN=153.,PHO=7.6,DOO=0.,DNH3I=13.5,XPEFF=0.
PARAM ACACO3=275.
PARAM QMGDA=63.,QRRAT=0.35,NBASIN=1
QMGDI=QMGDA*MGDMOD
* LIQUID VOLUMES
PARAM VLCF1=175781.,VLCF2=175781.,VLCF3=175781.,VLCF4=175781.
* GAS VOLUMES
PARAM KFLOW=80000.
PARAM VGCF1=58594.,VGCF2=58594.,VGCF3=58594.,VGCF4=58594.
```

```
*  HEAD SPACE VOLUME
FIXED NPRINT
** NOW THE FUNCTIONS FOR ION PRODUCTS OF WATER, CARBONIC ACID,
*AMMONIA,
*  AND VAPOR PRESSURE OF WATER.
FUNCTION
FPKW=(0.,14.944),(5.,14.734),(10.,14.535),(15.,14.346),...


(20.,14.167),(25.,13.996),(30.,13.833),(35.,13.680),(40.,13.535),.
..
   (50.,13.262)
* AMMONIA
FUNCTION FPKNH3=(0.,10.081),(5.,9.904),(15.,9.564),(20.,9.4),...
   (25.,9.245),(30.,9.093),(35.,8.947),(40.,8.805),(50.,8.539)
* CARBON DIOXIDE PK1
FUNCTION
FPK1=(0.,6.58),(10.,6.46),(15.,6.42),(20.,6.38),(25.,6.35),...
   (30.,6.34),(35.,6.332),(40.,6.325),(45.,6.3215),(50.,6.320)
* CARBON DIOXIDE PK2
FUNCTION FPK2=(0.,10.63),(10.,10.49),(15.,10.43),(25.,10.33),...
   (40.,10.22),(50.,10.17)
* VAPOR PRESSURE OF H2O IN MM HG
FUNCTION FVPH2O=(0.,4.579),(5.,6.543),(10.,9.209),(15.,12.788),...
   (20.,17.535),(25.,23.756),(30.,31.824),(35.,41.175),...
   (40.,55.324),(50.,92.51)
* SET THE MEASURED VARIABLES FOR THE INITIAL SECTION
** LOAD CARSON DATA INTO FILES FOR COMPARISON TO MODEL
      PO21D=GDATA(TIME,1)
      PO22D=GDATA(TIME,2)
      PO23D=GDATA(TIME,3)
      PO24D=GDATA(TIME,4)
      DO1D=GDATA(TIME,5)
      DO2D=GDATA(TIME,6)
      DO3D=GDATA(TIME,7)
      DO4D=GDATA(TIME,8)
      FPURO2=GDATA(TIME,9)*FPMOD
```

```
*      TGASM1=GDATA(TIME,10)
*      TGASMU=TGASM1*O2ERR
       TGASMU=0.9*QMGD+GASMOD
       QMGD=GDATA(TIME,11)*MGDMOD*FEDFLX
       TEMP=AFGEN(TEMPF,TIME)
       BOD5IN=GDATA(TIME,12)
       BOD5OD=GDATA(TIME,13)
       XSETA=GDATA(TIME,18)-OFFSET
** LATER USE OFFSET TO  ADJUST MODEL WASTE RATE TO MATCH MLVSS
***** CALCULATE THE CONSTANTS
   PK1=NLFGEN(FPK1,TEMP)
   CK1=1./(10**PK1)
   PK2=NLFGEN(FPK2,TEMP)
   CK2=1./(10**PK2)
   PKNH3=PKW-NLFGEN(FPKNH3,TEMP)
   CKNH3=1./(10**PKNH3)
   PKW=NLFGEN(FPKW,TEMP)
   CKW=1./(10**PKW)
* WATER VAPOR PRESSURE (CONVERT TO ATMOSHPHERES)
   VPH2O=NLFGEN(FVPH2O,TEMP)/760.
***** HENRY'S LAW CONSTANTS.
* OXYGEN (* 10 E-04 )
FUNCTION FHO2=(0.,2.5410),(5.,2.903),(10.,3.279),(15.,3.66), ...
   (20.,4.052),(25.,4.434),(30.,4.869),(35.,5.07),(40.,5.35)
* NITROG (* 10E-04 )
FUNCTION
FHN2=(0.,5.29),(5.,5.97),(10.,6.68),(15.,7.38),(20.,8.04),...
   (25.,8.65),(30.,9.24),(35.,9.85),(40.,10.4),(50.,1.13)
* CARBON DIOXIDE (* 10 E-03 )
FUNCTION FHCO2=(0.,0.728),(5.,0.876),(10.,1.04),(15.,1.22),...

(20.,1.42),(25.,1.64),(30.,1.86),(35.,2.09),(40.,2.33),(50.,2.83)
***** CALCULATE THE CONSTANTS INCLUDING THE MW OF EACH SPECIES AND
**
***    THE MOLE FRACTION OF WATER
   HEO2=NLFGEN(FHO2,TEMP)/(55555.*MWO2*1.E-04*BETA)
```

```
   HEN2=NLFGEN(FHN2,TEMP)/(55555.*MWN2*1.E-04*BETA)
   HECO2=NLFGEN(FHCO2,TEMP)/(55555.*MWCO2*1.E-03*BETA)
***** GAS TRANSFER COEFFICIENTS
* FIRST STAGE
* FUNCTION FKLA1 PREVIOUSLY A FUNCTION OF GAS RECIRCULATION RATES
*** TEMPERATURE FOR THE FIRST TEST
FUNCTION
TEMPF=(0.,27.0),(8.,27.0),(32.,27.0),(56.,27.0),(80.,27.0),...
(104.,27.0),(128.,27.0),(152.,27.0),(168.,27.0),(200.,27.0),...
(300.,27.0),(408.,27.0)
**** CALCULATE THE COEFFICIENTS
* CALCULATE THE VALUE OF R * T
   RT=R*(TEMP+273.15)
* CALCULATE THE INLET HYDROGEN ION CONCENTRATION FROM PHO
   HIO=1./(10**PHO)
* CALCULATE THE INLET AMMONIA CONCENTRATION IN G/MOLES
*    NH3I=CNH3I/14.E+03
* CONVERT THE VOLUMES TO M**3 AND CALCULATE THETAS.  FOR THE
   Q=QMGDI*1.E+06*0.003875/(24.*NBASIN)
   QR=QRRAT*Q
   QT=Q+QR
   XR=XSETA*QT/QR
   VL1=VLCF1*0.02832
   VL2=VLCF2*0.02832
   VL3=VLCF3*0.02832
   VL4=VLCF4*0.02832
   VG=VGCF1*0.02832
   THETA1=VL1/(Q+QR)
   THETA2=VL2/(Q+QR)
   THETA3=VL3/(Q+QR)
   THETA4=VL4/(Q+QR)
   ALKI=ACACO3/(50.E+03)
* CALCULATE THE INITIAL PARTIAL NITROGEN PRESSURE BY DIFFERENCE
* INDICATED AS %
   FPN21=TPRES1-VPH2O-FPO21-FPCO21
   FPN22=TPRES2-VPH2O-FPO22-FPCO22
```

```
     FPN23=TPRES3-VPH2O-FPO23-FPCO23
     FPN24=TPRES4-VPH2O-FPO24-FPCO24
*  INITIAL  GAS  HEADSPACE CONCENTRATIONS FROM ABOVE CONVERTED TO
*  MOLES
     ICO21=TPRES1*FPO21/RT
     ICN21=TPRES1*FPN21/RT
     ICCO21=TPRES1*FPCO21/RT
     ICO22=TPRES2*FPO22/RT
     ICN22=TPRES2*FPN22/RT
     ICCO22=TPRES2*FPCO22/RT
     ICO23=TPRES3*FPO23/RT
     ICN23=TPRES3*FPN23/RT
     ICCO23=TPRES3*FPCO23/RT
     ICO24=TPRES4*FPO24/RT
     ICN24=TPRES4*FPN24/RT
     ICCO24=TPRES4*FPCO24/RT
*  INITIAL MLVSS CONCENTRATIONS
     ICXS=XR*QR/(QR+Q)
     ICX1=ICXS
     ICX2=ICXS
     ICX3=ICXS
     ICX4=ICXS
*  CALCULATE THE INLET DISSOLVED GAS CONCENTRATIONS
     DN2I=0.791/HEN2
     DOI=0.
     DCDI=(ALKI- (DNH3I/14.E+03)/(1. + HIO * CKNH3/CKW)) *
MWCO2*1.E+03
*  INITIAL PH CALCULATIONS
     HI1=10**(-ICPH1)
     HI2=10**(-ICPH2)
     HI3=10**(-ICPH3)
     HI4=10**(-ICPH4)
*  INITIAL CONDITIONS FOR DISSOLVED GASSES.  CALCULATE FROM
*  PARTIAL PRESSURES. ASSUME SATURATION
     ICDCD1=TPRES1*FPCO21/(HECO2*FCO2(HI1,CK1,CK2))
     ICDN21=TPRES1*FPN21/HEN2
```

```
   ICDCD2=TPRES2*FPCO22/(HECO2*FCO2(HI2,CK1,CK2))
   ICDN22=TPRES2*FPN22/HEN2
   ICDCD3=TPRES3*FPCO23/(HECO2*FCO2(HI3,CK1,CK2))
   ICDN23=TPRES3*FPN23/HEN2
   ICDCD4=TPRES4*FPCO24/(HECO2*FCO2(HI4,CK1,CK2))
   ICDN24=TPRES4*FPN24/HEN2
* CALCULATE THE INLET VOLUMETRIC GAS FLOW RATE
   TGASB=TGASMU*2000./(24.*NBASIN)
   QGO=TGASB*RT*454./(MWO2*(TPRES1-VPH2O))+TGASB*(1.-  ...
   FPURO2)/FPURO2  *RT*454./(MWN2*(TPRES1-VPH2O))
   O2O=(TPRES1-VPH2O)*FPURO2/RT
   N2O=(TPRES1-VPH2O)*(1.-FPURO2)/RT
   QGOCF=QGO*CFCONV
   CO2O=0.
* CALCULATE THE FOLLOWING COMBINATIONS OF PARAMETERS TO IMPROVE
* SPEED.
   YPO21=(1.-Y)*YO21/Y
   YPCO21=(1.-Y)*YCO21/Y
   YPNH31=YNH32-YNH31
* CONVERSION FACTOR FOR GLOBAL BALANCES
   CFTON=NBASIN*24./(454.*2000.)
* CALCULATE THE LEAK FLOWS
** QLK1= NOT FOR CSD
   SOI=BOD5IN/YB5TOU
* CALCULATE INITIAL CONDITIONS FOR SRT AND FMR
   SODIFF=(Q+QR)*(SOI-ICS4)*CFTON
   SMASS=NBASIN*(ICX1*VL1+ICX2*VL2+ICX3*VL3+ICX4*VL4)/9.098E+05
   XMDIFF=LIMIT(0.004,1000.,((ICX4*(Q+QR)-QR*XR)*CFTON))
***************************************************************
DYNAMIC
NOSORT
CALL DEBUG(NPRINT,DTIME1)
CALL DEBUG(NPRINT,DTIME2)
SORT
PROCEDURE DO1D,DO2D,DO3D,DO4D,PO21D,...
PO22D,PO23D,PO24D,TGASM1,FPURO2,TEMP,BOD5IN=INDATA(TIME)
```

```
*      IF(KEEP.NE.1) GOTO 90
       PO21D=GDATA(TIME,1)
       PO22D=GDATA(TIME,2)
       PO23D=GDATA(TIME,3)
       PO24D=GDATA(TIME,4)
       DO1D=GDATA(TIME,5)
       DO2D=GDATA(TIME,6)
       DO3D=GDATA(TIME,7)
       DO4D=GDATA(TIME,8)
       FPURO2=GDATA(TIME,9)*FPMOD
*      TGASM1=GDATA((TIME-O2LAG),10)*O2ERR
       TGASM1=0.9*QMGD+GASMOD
       QMGD=GDATA(TIME,11)*MGDMOD*FEDFLX
       TEMP=AFGEN(TEMPF,TIME)
       BOD5IN=GDATA(TIME,12)
       BOD5OD=GDATA(TIME,13)
       XSETA=GDATA(TIME,18)-OFFSET
90     CONTINUE
ENDPROCEDURE
   DOERR=(DOSP-DO4)
   GASMOD=DOERR*KERR+KINTER*INTGRL(0.0,DOERR)
   TFAC=1.024**(TEMP-20.)
   RT=R*(TEMP+273.15)
   TGASB=TGASMU *2000./(24.*NBASIN)
   QGO=TGASB*RT*454./(MWO2*(TPRES1-VPH2O))+TGASB*(1.- ...
   FPURO2)/FPURO2 *RT*454./(MWN2*(TPRES1-VPH2O))
   O2O=(TPRES1-VPH2O)*FPURO2/RT
   N2O=(TPRES1-VPH2O)*(1.-FPURO2)/RT
   QGOA=QGO
* INFLUENT PARAMTERS
   FEDFLX=(1+BOOST*SIN(0.2618*TIME))
   Q=QMGD*1.E+06*0.003875/(24.*NBASIN)
*  QR=QRRAT*Q
   QT=Q+QR
   THETA1=VL1/(Q+QR)
   THETA2=VL2/(Q+QR)
```

```
   THETA3=VL3/(Q+QR)
   THETA4=VL4/(Q+QR)
   SOI=BOD5IN/YB5TOU
   DCDI=(ALKI- (DNH3I/14.E+03)/(1. + HIO * CKNH3/CKW)) *
MWCO2*1.E+03
* CALCULATE THE RESULTS OF MIXING RECYCLE AND INFLUENT FLOWS. MOVE
* IT TO THE DYNAMIC SECTION FOR TIME VARYING FLOW RATE.
PROCEDURE SO,DNH3O,ALKO,DCDO,DN2O,SOA,XOA = INPUT(Q,QR,QT)
   XO=(Q*XPEFF+QR*XR)/QT
   SO=(Q*SOI+QR*S4)/QT
   DNH3O=(Q*DNH3I+QR*DNH31)/QT
   ALKO=(Q*ALKI+QR*ALKR)/QT
   DCDO=(Q*DCDI+QR*DCDR)/QT
   DN2O=(Q*DN2I+QR*DN2R)/QT
   XOA=XO
   SOA=SO
ENDPROCEDURE
*   CKLA2L=NLFGEN(FKLA2,GAS2) --- KLA AS A FUNCTION OF GAS
*  RECIRULATION RATIO NOT APPLICABLE TO CARSON
CKLA1=BKLA1*TFAC*ALPHA1*KLAMOD
CKLA2=BKLA2*TFAC*ALPHA2*KLAMOD
CKLA3=BKLA3*TFAC*ALPHA3*KLAMOD
CKLA4=BKLA4*TFAC*ALPHA4*KLAMOD
X1,S1,DO1,DN21,DCD1,HI1,FCD1,QG1,PCO21,PO21,PN21,CO21,N21,O21,...
DNH31,ALK1=REACT(THETA1,XOA,SOA,DOO,DN2O,DCDO,HIO,QGOA,CO2O,N2O,..
.
O2O,ICX1,ICS1,ICDO1,ICDN21,ICDCD1,ICCO21,ICO21,ICN21,CKLA1,...
VL1,TPRES1,TPRES0,DNH3O,ALKO)
* MIX THE FLOWS FOR SLUDGE REAERATION. PROCEDURE DROPPED FOR CSD
** STAGE #2 **
X2,S2,DO2,DN22,DCD2,HI2,FCD2,QG2,PCO22,PO22,PN22,CO22,N22,O22,...
DNH32,ALK2=REACT(THETA2,X1,S1,DO1,DN21,DCD1,HI1,QG1,CO21,N21,...
O21,ICX2,ICS2,ICDO2,ICDN22,ICDCD2,ICCO22,ICO22,ICN22,CKLA2,...
VL2,TPRES2,TPRES1,DNH31,ALK1)
** STAGE #3 **
X3,S3,DO3,DN23,DCD3,HI3,FCD3,QG3,PCO23,PO23,PN23,CO23,N23,O23,...
```

```
DNH33,ALK3=REACT(THETA3,X2,S2,DO2,DN22,DCD2,HI2,QG2,CO22,N22,...
O22,ICX3,ICS3,ICDO3,ICDN23,ICDCD3,ICCO23,ICO23,ICN23,CKLA3,...
VL3,TPRES3,TPRES2,DNH32,ALK2)
** STAGE #4 **
X4,S4,DO4,DN24,DCD4,HI4,FCD4,QG4,PCO24,PO24,PN24,CO24,N24,O24,...
DNH34,ALK4=REACT(THETA4,X3,S3,DO3,DN23,DCD3,HI3,QG3,CO23,N23,...
O23,ICX4,ICS4,ICDO4,ICDN24,ICDCD4,ICCO24,ICO24,ICN24,CKLA4,...
VL4,TPRES4,TPRES3,DNH33,ALK3)
*********************************************************
   BOD5OC=S4*YB5TOU
   PH1=-ALOG10(LIMIT(1.E-14,1.,HI1))
   PH2=-ALOG10(LIMIT(1.E-14,1.,HI2))
   PH3=-ALOG10(LIMIT(1.E-14,1.,HI3))
   PH4=-ALOG10(LIMIT(1.E-14,1.,HI4))
   SR=S4
NOSORT
* THIS SECTION CONTROLS THE SLUDGE AGE
*  CONSIG=INSW((TIME-3.),0.,(SRTSP-SRT))
*  XSET1=RSETS*(CONSIG)+RSETI*INTGRL(0.,CONSIG)+XSETA
   XSET=LIMIT( 500.,3200.,XSETA)
   XR=QT/QR*XSET
*  CONP=LIMIT(0.,1.0,PUTILU)
TGASMU=TGASM1
SORT
* CALCULATE THE GLOBAL BALANCE INFORMATION AFTER STEADY-STATE
* HAS BEEN REACHED.  MOVE THIS SECTION TO TERMINAL TO INCREASE
SPEED.
   MLSS=(X1+X2+X3+X4)/4
   XMDIFF=LIMIT(0.004,1000.,((X4*(Q+QR)-QR*XR)*CFTON))
   SODIFF=(Q+QR)*(SO-S4)*CFTON
   N2MIN=(QGO*N2O*MWN2+Q*DN2I+QR*DN2R)*CFTON
   O2MIN=QGO*O2O*MWO2*CFTON
   CO2MIN=(CO2O*MWCO2+Q*DCDI+QR*DCDR)*CFTON
   O2MOUT=(QG4*O24*MWO2+(Q+QR)*DO4)*CFTON
   CO2MOU=(QG4*CO21*MWCO2+(Q+QR)*DCD1)*CFTON
   N2MOUT=(QG4*N21*MWN2+(Q+QR)*DN24)*CFTON
```

```
   O2UTIL=O2MIN-O2MOUT
   PUTIL=O2UTIL/O2MIN
   O2MOUC=QG4*O24*MWO2*CFTON
   O2UTIU=O2MIN-O2MOUC
   PUTILU=O2UTIU/O2MIN
   O2CONS=O2UTIL/SODIFF
   CO2PRO=(CO2MOU-CO2MIN)/SODIFF
   CO2CHK=SODIFF*(1.-Y)*YCO21+(SODIFF*Y-XMDIFF)*YCO22
   SMASS=NBASIN*(X1*VL1+X2*VL2+X3*VL3+X4*VL4)/9.098E+05
   ERRDO1=ABS(DO1-DO1D)
   ERRDO2=ABS(DO2-DO2D)
   ERRDO3=ABS(DO3-DO3D)
   ERRDO4=ABS(DO4-DO4D)
   ERRPO1=ABS(PO21-PO21D)
   ERRPO2=ABS(PO22-PO22D)
   ERRPO3=ABS(PO23-PO23D)
   ERRPO4=ABS(PO24-PO24D)
   ERRDOT=ERRDO1+ERRDO2+ERRDO3+ERRDO4
   ERRPOT=ERRPO1+ERRPO2+ERRPO3+ERRPO4
   IERRDO=INTGRL(0.,ERRDOT)
   IERRPO=INTGRL(0.,ERRPOT)
* ENERGY CALCULATIONS
*    MIXERS -- USE THE POWERS MEASURED IN THE GILBERT REPORT
  ZWMIX=NBASIN*(ZWM1+ZWM2+ZWM3+ZWM4)
*  GAST=(GAS1)*NBASIN
* ZWBLOW=ZWSCFM*GAST
   ZWALL=ZWBLOW+ZWMIX
*  ZWS1=NBASIN*(ZWM1)
* POWER WEIGHTED DO, PURITY, AND ALPHA
DOAVI=INTGRL(0.,((DO1*ZWM1+DO2*ZWM2+DO3*ZWM3+DO4*ZWM4)/ZWALL))
PO2AVI=INTGRL(0.,((PO21*ZWM1+PO22*ZWM2+PO23*ZWM3+PO24*ZWM4)/ZWALL)
)
ALPHAI=INTGRL(0.,((ALPHA1*ZWM1+ALPHA2*ZWM2+ALPHA3*ZWM3+ALPHA4*...
ZWM4)/ZWALL))
* O2 CONSUMTION BY STAGE
   O2COI1=INTGRL(0.,(QGOA*O2O-QG1*O21)*CFTON*MWO2)
```

```
   O2COI2=INTGRL(0.,(QG1*O21-QG2*O22)*CFTON*MWO2)
   O2COI3=INTGRL(0.,(QG2*O22-QG3*O23)*CFTON*MWO2)
   O2COI4=INTGRL(0.,(QG3*O23-QG4*O24)*CFTON*MWO2)
   O2COI5=INTGRL(0.,(QGOA*O2O-QG4*O24)*CFTON*MWO2)
* O2 PURITY AVERAGE
   PUTAVI=INTGRL(0.,PUTILU)
   DO1I=INTGRL(0.,DO1)
   DO2I=INTGRL(0.,DO2)
   DO3I=INTGRL(0.,DO3)
   DO4I=INTGRL(0.,DO4)
   PO21I=INTGRL(0.,PO21)
   PO22I=INTGRL(0.,PO22)
   PO23I=INTGRL(0.,PO23)
   PO24I=INTGRL(0.,PO24)
   ENDT=TIME
NOSORT
   FMR=YB5TOU*(SODIFF/SMASS)
   SRT=LIMIT(0.,100.,(SMASS/XMDIFF))
TERMINAL
* POWER WEIGHTED DO, PURITY, AND ALPHA
   DOAVG=DOAVI/ENDT
   PO2AVG=PO2AVI/ENDT
   ALPHAA=ALPHAI/ENDT
* O2 CONSUMPTION BY STAGE
   O2CON1=O2COI1/ENDT
   O2CON2=O2COI2/ENDT
   O2CON3=O2COI3/ENDT
   O2CON4=O2COI4/ENDT
* O2 TOTAL CONSUMPTION
   O2CON5=O2COI5/ENDT
* O2 PURITY AS A FUNCTION OF TIME
   PUTAVE=PUTAVI/ENDT
   DO1A=DO1I/ENDT
   DO2A=DO2I/ENDT
   DO3A=DO3I/ENDT
   DO4A=DO4I/ENDT
```

```
    PO21A=PO21I/ENDT
    PO22A=PO22I/ENDT
    PO23A=PO23I/ENDT
    PO24A=PO24I/ENDT
* WRITE OUT THE RESULTS WITH FORTRAN WRITES
             WRITE(6,1004)
1004  FORMAT(' STAGE   RECIRCULATION    DO     PO2   O2 UPTAKE  PH
KW')
      WRITE(6,1005)
1005  FORMAT(' (NO)    (SCFM / STAGE) (MG/L)   (FRAC)   (TON/DAY)')
      WRITE(6,1010) GAS1,DO1A,PO21A,O2CON1,PH1,ZWM1
      WRITE(6,1020) GAS2,DO2A,PO22A,O2CON2,PH2,ZWM2
      WRITE(6,1030) GAS3,DO3A,PO23A,O2CON3,PH3,ZWM3
      WRITE(6,1040) GAS4,DO4A,PO24A,O2CON4,PH4,ZWM4
      WRITE(6,1050) GAST,DOAVG,PO2AVG,O2CON5,ZWALL
1010  FORMAT(1X,'  1 ', 8X,F5.0,4X,F6.2,4X,F5.2,F8.1,4X,F3.1,F6.0)
1020  FORMAT(1X,'  2 ', 8X,F5.0,4X,F6.2,4X,F5.2,F8.1,4X,F3.1,F6.0)
1030  FORMAT(1X,'  3 ', 8X,F5.0,4X,F6.2,4X,F5.2,F8.1,4X,F3.1,F6.0)
1040  FORMAT(1X,'  4 ', 8X,F5.0,4X,F6.2,4X,F5.2,F8.1,4X,F3.1,F6.0)
1050  FORMAT(/,'   T ', 6X,F7.0,4X,F6.2,4X,F5.2,F8.1,6X,F7.0)
      WRITE(6,1060) PUTAVE,ALPHAA,NBASIN
1060  FORMAT(//,' FRACTION OXYGEN UTILIZATION=',F5.3,/,...
              /,' POWER WEIGHTED ALPHA FACTOR=',F5.3,/,...
              /,' NUMBER OF BASINS IN SERVICE=',F4.0,///)
      WRITE(6,1070)
1070  FORMAT('1')
METHOD STIFF
PRINT
X1,S1,DNH31,DO1,DN21,DCD1,PH1,ALK1,FCD1,QG1,PCO21,PO21,PN21,...
X2,S2,DNH32,DO2,DN22,DCD2,PH2,ALK2,FCD2,QG2,PCO22,PO22,PN22,...
X3,S3,DNH33,DO3,DN23,DCD3,PH3,ALK3,FCD3,QG3,PCO23,PO23,PN23,...
X4,S4,DNH34,DO4,DN24,DCD4,PH4,ALK4,FCD4,QG4,PCO24,PO24,PN24,...
XR,XSET,SRT,FMR
OUTPUT
QMGD,BOD5IN,BOD5OD,BOD5OC,DO1,DO1D,DO2,DO2D,DO3,DO3D,DO4,...
DO4D,PO21,PO21D,PO22,PO22D,PO23,PO23D,PO24,PO24D,S1,S4,MLSS,...
```

```
FMR,SRT;PUTIL,O2CONS,XMDIFF,ERRDO1,ERRDO2,ERRDO3,ERRDO4,ERRDOT,...
IERRDO,ERRPO1,ERRPO2,ERRPO3,ERRPO4,ERRPOT,IERRPO,PUTILU
OUTPUT DO1,DO2,DO3,DO4,DO1D,DO2D,DO3D,DO4D,TGASM1
OUTPUT PO21,PO22,PO23,PO24,PO21D,PO22D,PO23D,PO24D,QGO
TIMER FINTIM=100.0,PRDEL=24.,OUTDEL=4.,DELMIN=1.68E-06
END
STOP
      FUNCTION SDIV(A,B)
C.. THIS FUNCTION GIVES YOU A "SAFE" DIVISION
      SDIV=-1.
      IF(ABS(B).GT.1.E-20) SDIV=A/B
    RETURN
      END
      FUNCTION PHCAL(ALK,CO2,CNH3,CK1,CK2,CKW,CKNH3)
C.. THIS FUNCTION CALCULATES THE PH OF A DILUTE SOLUTION IN A
CLOSED
C   BIOX REACTOR.  THE CALCULATION IS IMPLICIT
      REAL*8 DK1,DK2,DCO2,DPH,DNH3,DALK,B,C,ZGESS,DKNH3
C.. SET THE FIRST GUESS EQUAL TO THE OLD PH
      ZGESS=1.D-06
C.. CONVERT THE SINGLE PRECISION ARGS TO DOUBLE PRECISION
      DK1=CK1
      DK2=CK2
      DKW=CKW
C.. ALSO CONVERT CO2 AND NH3 TO MOLAR CONCENTRATION.
      DCO2=CO2/44009.
      DALK=ALK
      DKNH3=CKNH3
      DNH3=CNH3/14.E+03
C.. QUADRATIC COEFFICIENTS
      B=DALK-DNH3/(1.+DPH*DKNH3/DKW)
      ITER=0
10    C=-DKW- (DK1 + 2.D0 * DK1*DK2/ZGESS)*DCO2
C.. CALC THE PH
      DPH= (-B+DSQRT(B**2 - 4.D0*C))/2.D+00
      IF(DABS(DPH-ZGESS).GT.1.D-12) GOTO 20
```

```
C.. NORMAL CONVERGENCE
        PHCAL=DPH
        RETURN
20    IF(ITER.GT.10 ) GOTO 30
        ZGESS=DPH
        B=DALK-DNH3/(1.+DPH*DKNH3/DKW)
        ITER=ITER+1
        GOTO 10
C.. NO CONVERGENCE
30      WRITE(6,1000) ZGESS,DPH,ITER
1000    FORMAT(' NON CONVERGENCE IN PH CALCULATION.',/,
     1  1X,' EXECUTION STOPPING',/,' FINAL GUESS FOR PH =',D17.6,
     2  /,' FINAL CALC FOR PH =',D17.6,/,' ITERATION NUMBER=',I5)
        PHCAL=DPH
      RETURN
      END
      FUNCTION FCO2(PH,CK1,CK2)
C.. THIS FUNCTION CALCULATES THE FRACTION OF THE TOTAL CARBON
WHICH
C   IS IN THE H2CO3 FORM.
      REAL*8 DK1,DK2,DPH
C.. CONVERT TO DOUBLE PRECISION FOR THE CALCULATION
      DK1=CK1
      DK2=CK2
      DPH=PH
      FCO2=1.D+0/((DPH*DK1*DK2/DPH+DK1)/DPH+1.D0)
      RETURN
      END
      FUNCTION GDATA(TIM,ITYPE)
      REAL*4 MLFGEN,MLSS(10)
      DIMENSION TIME(85),TF1(85),TF2(85),TF3(85),TF4(85),
     1GP1(85),GP2(85),GP3(85),GP4(85),DO1(85),DO2(85),DO3(85),
     2DO4(85),O2FPUR(85),O2FTON(85),QMGD(85),O2OTON(85),O2VENT(85)
      DIMENSION TIME2(85),QMGD2(10),BODIN(10),BODOUT(10),RAS1(10),
     1RAS2(10),CODIN(10),CODOUT(10),WAS(10)
      DIMENSION TIME3(7),XM1(7),XM2(7),XM3(7),XM4(7),TIME4(85)
```

```
      DIMENSION AX1(5),AX2(5),AX3(5),AX4(5),AX5(5),AX6(5),AX7(5),

1AX8(5),AX9(5),AX10(5),AX11(5),AX12(5),AX13(5),AX14(5),AX15(5),
     2AX16(5),AX17(5),AX18(5),AX19(5),AX20(5),AX21(5),AX22(5)
      DATA AX1 /5*0./,AX2 /5*0./,AX3 /5*0./,AX4 /5*0./,AX5 /5*0./,
     1AX6 /5*0./,AX7 /5*0./,AX8 /5*0./,AX9 /5*0./,AX10 /5*0./,
     2AX11 /5*0./,AX12 /5*0./,AX13 /5*0./,AX14 /5*0./,AX15/5*0./,
     2AX16 /5*0./,AX17 /5*0./,AX18 /5*0./,AX19 /5*0./,AX20/5*0./,
     3AX21/5*0./,AX22/5*0/,JUMP/0/
      IF (JUMP.GT.0) GOTO 25
      DO 10 I=1,8
      READ(16,*,END=15)
TIME(I),CODIN(I),CODOUT(I),BODIN(I),BODOUT(I)
10    N=I
15    CONTINUE
      DO 16 I=1,200
      READ(17,*,END=17)
TIME2(I),O2FTON(I),O2VENT(I),O2OTON(I),O2FPUR(I)
16    N2=I
17    CONTINUE
      N3=8
      DO 18 I=1,N3
      READ(18,*,END=19)
TIME3(I),XM1(I),XM2(I),XM3(I),XM4(I),RAS1(I),
     1RAS2(I),MLSS(I),QMGD(I)
18    N4=I
19    CONTINUE
      DO 20 I=1,200
      READ(20,*,END=21)
TIME4(I),DO1(I),DO2(I),DO3(I),DO4(I),GP1(I),
     1GP2(I),GP3(I),GP4(I)
20    N5=I
C.. CONVERT THE GAS PERCENTS TO GAS FRACTIONS
21    DO 23 I=1,N5
      GP1(I)=GP1(I)/100.
      GP2(I)=GP2(I)/100.
```

```
      GP3(I)=GP3(I)/100.
23    GP4(I)=GP4(I)/100.
C..  CONVERT OXYGEN FLOW RATES TO GAS FLOW RATES
      DO 24 I=1,N2
      O2FPUR(I)=O2FPUR(I)/100.
      O2OTON(I)=O2OTON(I)/1004.
24    O2FTON(I)=O2FTON(I)/O2FPUR(I)
      JUMP=1
25    GOTO(70,80,90,100,110,120,130,140,150,160,170,
     1180,190,200,210,220,230,240,250,260,270,280), ITYPE
70    GDATA=MLFGEN(AX1,N5,TIM,TIME4,GP1,56)
      GOTO 950
80    GDATA=MLFGEN(AX2,N5,TIM,TIME4,GP2,56)
      GOTO 950
90    GDATA=MLFGEN(AX3,N5,TIM,TIME4,GP3,56)
      GOTO 950
100   GDATA=MLFGEN(AX4,N5,TIM,TIME4,GP4,56)
      GOTO 950
110   GDATA=MLFGEN(AX5,N5,TIM,TIME4,DO1,56)
      GOTO 950
120   GDATA=MLFGEN(AX6,N5,TIM,TIME4,DO2,56)
      GOTO 950
130   GDATA=MLFGEN(AX7,N5,TIM,TIME4,DO3,56)
      GOTO 950
140   GDATA=MLFGEN(AX8,N5,TIM,TIME4,DO4,56)
      GOTO 950
150   GDATA=MLFGEN(AX9,N2,TIM,TIME2,O2FPUR,85)
      GOTO 950
160   GDATA=MLFGEN(AX10,N2,TIM,TIME2,O2FTON,85)
      GOTO 950
170   GDATA=MLFGEN(AX11,N3,TIM,TIME3,QMGD,8)
      GOTO 950
180   GDATA=MLFGEN(AX12,N,TIM,TIME,BODIN,8)
      GOTO 950
190   GDATA=MLFGEN(AX13,N,TIM,TIME,BODOUT,8)
      GOTO 950
```

```
200    GDATA=MLFGEN(AX14,N3,TIM,TIME3,RAS1,8)
       GOTO 950
210    GDATA=MLFGEN(AX15,N3,TIM,TIME3,RAS2,8)
       GOTO 950
220    GDATA=MLFGEN(AX16,N,TIM,TIME,CODIN,8)
       GOTO 950
230    GDATA=MLFGEN(AX17,N,TIM,TIME,CODOUT,8)
       GOTO 950
240    GDATA=MLFGEN(AX18,N3,TIM,TIME3,MLSS,8)
       GOTO 950
250    GDATA=MLFGEN(AX19,N3,TIM,TIME3,MX1,8)
       GOTO 950
260    GDATA=MLFGEN(AX20,N3,TIM,TIME3,MX2,8)
       GOTO 950
270    GDATA=MLFGEN(AX21,N3,TIM,TIME3,MX3,8)
       GOTO 950
280    GDATA=MLFGEN(AX22,N3,TIM,TIME3,MX4,8)
950    RETURN
       END
       FUNCTION MLFGEN(AX,N,X,ARRX,ARRY,M)
C**************************************************************
C.. THIS FUNCTION GENERATES AN ARBITRARY FUNCTION DEFINED BY PAIRS
OF
C   DATA POINTS CONTAINED IN THE ARRAIES ARRX AND ARRY, WITH THE
C   NUMBER OF POINTS = N.
C   NOTE THAT THE FUNCTION CHECKS FOR PROPER DATA ENTRY ON THE
FIRST
C   CALL, AND CHECKS TO SEE IF X IS IN THE RANGE DEFINED  IN THE
DATA
C   ARRAY. QUADRADIC INTERPOLATION IS USED.
C**************************************************************
       REAL*4 MLFGEN
       DIMENSION ARRX(M),AX(5),ARRY(M)
C.. CHECK FOR INITIAL ENTRY
       NW=6
       IF(AX(1)) 10,10,90
```

```
10     AX(1)=1
       IF(N-2) 20,20,30
20     WRITE(NW,1000) N
1000   FORMAT(//,' LESS THAN THREE DATA POINTS (',I6,
      1' WERE SUPPLIED FOR AN MLFGEN  FUNCTION',//,
      2' EXECUTION TERMINATING')
       STOP 20
30     AX(4)=0
C.. CHECK TO SEE IF THE DATA WAS ENTERED CORRECTLY IN ASCENDING
ORDER
       DO 40 I=2,N
       IF(ARRX(I-1).GT.ARRX(I)) GOTO 50
40     CONTINUE
       GOTO 60
50     K=I-1
       WRITE(NW,1010) I,ARRX(I),K,ARRX(K)
1010   FORMAT(//,' THE INDEPENDENT VARIABLE FOR A MLFGEN FUNCTION
HAS ',
      1'NOT BEEN',/,' ENTERED IN ASCENDING ORDER',/,' THE',I3,'TH
POINT='
      2,2X,E17.6,2X,'WHILE THE',I3,'TH POINT=',2X,E17.6,/,'
EXECUTION TER
      3MINATING')
       STOP 30
60     AX(3)=0.
       IF(X.LT.ARRX(1)) AX(3)=-1.
       IF(X.GT.ARRX(N)) AX(3)=1.
       IF(AX(3)) 70,80,70
70     WRITE(NW,1020) X,ARRX(1),ARRX(N)
1020   FORMAT(' THE INITIAL ENTRY TO A MLFGEN FUNCTION IS OUT OF
RANGE',    1/,
      1/,' THE VALUE OF THE INDEPENDENT VARIABLE IS',E17.6,' WHILE
THE',
      2/,' MINIMUM VALUE OF THE FUNCTION IS',E17.6, ' AND THE
MAXIMUM',
      3/,' VALUE OF THE FUNCTION IS',E17.6)
```

```
      IF(AX(3)) 240,80,210
80    AX(2)=1
C.. NORMAL ENTRY FOR MLFGEN
90    IF(X-ARRX(1)) 220,100,110
100   AX(2)=1
      AX(4)=0
      MLFGEN=ARRY(1)
      GOTO 300
110   IF(X-ARRX(N)) 120,115,190
115   AX(2)=N
      AX(4)=0
      MLFGEN=ARRY(N)
      GOTO 300
120   I=IFIX(AX(2)+0.5)
130   IF(X.LT.ARRX(I)) GOTO 140
      I=I+1
      IF(I.GT.N) GOTO 190
      GOTO 130
140   I=I-1
      IF(I.LT.1) GOTO 220
150   IF(X.GE.ARRX(I)) GOTO 160
      GOTO 140
160   I=I+1
      IF(I.GT.N) GOTO 190
      AX(2)=I
      IF(I-2) 170,170,180
170   MLFGEN=ARRY(I-1)+(X-ARRX(I-1))*(ARRY(I)-ARRY(I-1))/
     1(ARRX(I)-ARRX(I-1))
      AX(4)=0.
      GOTO 300
180   A1=ARRX(I-1)-ARRX(I-2)
      A2=ARRX(I)-ARRX(I-1)
      A3=ARRX(I)-ARRX(I-2)
      A4=X-ARRX(I-1)
      A5=X-ARRX(I)
      A6=X-ARRX(I-2)
```

```
      MLFGEN=ARRY(I-2)*A4*A5/(A1*A3)-ARRY(I-1)*A6*A5/(A1*A2)+
     1ARRY(I)*A6*A4/(A3*A2)
      AX(4)=0.
      GOTO 300
190   IF(AX(4)) 210,200,200
200   WRITE(NW,1030) X,ARRX(N)
1030  FORMAT(' INDEPENDENT VARIABLE FOR MLFGEN FUNCTION ABOVE
RANGE',/,
     1' INDEPENDENT VARIABLE=',E12.6,' MAXIMUM FOR THIS MLFGEN
FUNCTION'
     2,'=',E12.6)
210   MLFGEN=ARRY(N)
      AX(4)=-1
      AX(2)=N
      GOTO 300
220   IF(AX(4)) 230,230,240
230   WRITE(NW,1040) X,ARRX(1)
1040  FORMAT(' INDEPENDENT VARIABLE FOR MLFGEN FUNCTION BELOW
RANGE',/,
     1' INDEPENDENT VARIABLE=',E12.6,' MINIMUM FOR THIS MLFGEN
FUNCTION'
     2,'=',E12.6)
240   AX(2)=1
      AX(4)=+1
      MLFGEN=ARRY(1)
300   RETURN
      END
```