Experimental Evaluation of Sub-Surface Aeration Systems

by

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More stringent effluent requirements combined with decreasing land availability (at an ever increasing cost) presents a unique design problem to those engineering industrial and municipal wastewater treatment plants. Where treatment plants exist but expansion is required, land surrounding the existing treatment plant is either unavailable or carries a prohibitively high price tag. For these reasons, biological treatment plants are being constructed on smaller land areas utilizing deeper aeration basins.

As the available surface area decreases, the use of surface aerators may become objectionable because the application of sufficient power at the surface to provide the required oxygen transfer can yield an esthetically unpleasing plant due to surface turbulence. Where the ratio of energy input to available surface area must be high in order to provide the design oxygen transfer, the resultant high turbulence with surface aerators produces a colloidal liquid particle termed "mist". This material can become objectionable when it is blown by the wind outside the property boundary of the sewage treatment plant. Additionally, closely confined aerators may create a noise problem by their pumping action as they pump large quantities of liquid through the air.

Sub-surface aeration systems eliminate many of these problems in that high power inputs beneath the surface of the aeration basin can be utilized with minimal surface turbulence. This reduces the noise level substantially in the sewage treatment plant and produces minimal colloidal "mist". Submerged turbine aeration devices provide additional benefits in that 100% process flexibility is obtainable. Systems are designed to run with no air supplied to the mixing turbines and at this design point total solids suspension is obtainable with no oxygen transfer. As the air is

turned from 0 to 100% of the design capacity of the system, oxygen transfer is increased up to the maximum design point. 100% flexibility with constant mixing is obtained while simultaneoulsy reducing the air quantities that would otherwise be required with diffused air type systems. Reduction in air quantities reduces mist production and provides minimal surface turbulence for the quietest possible operation. Additionally, dissolved oxygen levels can be controlled during periods of low loading thereby preventing problems with denitrification in the final clarifier. These systems can be designed to handle any uptake rate and industrial biological treatment systems with uptake rates substantially exceeding 200 mg/L/hr have been installed and operated satisfactorily. There is no maximum size to the units that can be applied and 300 HP units are becoming a more common occurrence. (1)

Since the submerged turbine systems can satisfy any design uptake rate without relying on the surface area of the basin for oxygen transfer, extremely deep aeration tanks can be provided which means minimal use of land area. Installations with 30' liquid depths are now in operation and depths two and three times this value are totally plausible.

As the use of submerged turbine aeration devices gained in prominence, testing of this type equipment become more commonplace. Little information has been published concerning the evaluation of these type aeration systems and a complete spectrum on the data analysis procedure has been used. The so-called surface aerator mathematical model was initially used in analyzing submerged systems because the surface aerator model was simple to use and readily available. Unfortunately the surface aerator model is totally inadequate for this type data analysis and error exceeding 50% are not uncommon.

This inadequacy has been noted by numerous investigators [2] and various mathematical models have been proposed in an attempt to compensate for the incorrect method of data analysis. Additionally, testing procedures vary widely and simple modifications to the so-called un-steady state re-aeration test can cause additional errors in evaluationg submerged turbine systems. One may have a tendency to rely on BOD removal information rather than clean water testing of sub-surface aerations systems. This is a dangerous practice that can lead to gross errors and totally inadequate plant design.

The solution to the problem is a correct test procedure designed to eliminate errors caused by improper sampling, chemical effects, oxygen concentration gradients, etc. Secondly, the data must be evaluated properly in order that correct conclusions regarding performance are drawn. A further method for minimizing problems in the field is to test full scale units rather than relying on "scale-up". If testing is impossible, a detailed review of past data is imperative and a re-evaluation of the data submitted should be undertaken using an appropriate mathematical model.

Sub-surface aeration is defined as oxygen transfer that results when an oxygen containing gas is continuously released below the free surface of the liquid to be aerated. Because of turbulence, bouyancy, and interfacial tension[3,4] the gas becomes the discontinuous phase and assumes the form of bubbles. Mass transfer takes place from each bubble as it rises to and breaks the free surface of the liquid.

Superscript numbers throughout the text refer to bibliography.

DETERMINATION OF OXYGEN CAPACITY

The performance of surface aeration devices is usually determined by the standard non-steady state or transit re-aeration of tap water. This procedure has been discussed in detail by Landberg, et al.[5] In order to discuss the evaluation of sub-surface aeration systems, using the same experimental test, a brief review of the model and in particular the assumptions used when evaluation surface aeration systems is in order.

The basic equation used in this model is:

$$\frac{W}{10^6}\ \frac{dc}{dt} = K_L'a(T)\ (C^* - C) \qquad \ldots\ldots(1)$$

The assumptions that are implicitly made when this equation is used to describe the re-aeration process are as follows:

1. The non-convective mass transfer takes place in a zone where the partial pressure and the concentration of the gas being transferrred remains constant is the gas phase. i.e. C* remains constant during the experiment and will only change when the water temperature and/or atmospheric pressure changes.
2. The major resistance to mass transfer resides in the liquid film and therefore the $K_L'a(T)$ depends only on the liquid properties.
3. The total mass of liquid being aerated is instantaneously at the uniform concentration C. (Convective mass transfer rate much greater than mass transfer rate due to turbulent diffusion at gas-liquid interface.)

When these assumptions are satisfied, equation (1) can be integrated to

the usual logarithm of the dissolved oxygen deficit proportional to time form. Use of this form allows the $K_L a$ to be determined from the slope of the semi-log plot of deficit versus time.

When the method of aeration is sub-surface and a non-steady state re-aeration experiment is conducted, how are these assumptions modified? Of the three assumptions listed above, the first is the one that must be be relaxed for application to sub-surface aeration. This can be easily understood by recalling that oxygen obeys Henry's Law which says that the equilibrium concentration of a solution of gas dissolved in a liquid at a given temperature is proportional to the partial pressure in the mixture above the liquid.(6)

$$C^*(T) = H(T)\, M_{02}\, P_T \qquad \text{.....(2)}$$

When applied to an aeration system in which the mass transfer occurs only at the free liquid surface at a constant water temperature, the three factors on the right hand side of equation (2) are all constant since H(T) depends only on gas-liquid pair and the liquid temperature. The mole fraction, M_{02}, oxygen in the atmosphere is constant at .209. This in effect, assumes the atmosphere is an infinite supply of oxygen and replenishment of atmospheric oxygen in the region of the interface occurs much faster than the rate at which it is depleted. The diffusion coefficient of oxygen in air is approximately 10^4 times the diffusion coefficient of oxygen in water so for all intents and purposes depleted atmospheric oxygen is instantaneously replaced. And P_T, the atmospheric pressure, does not usually change over the time period of an experimental run.

Now let's examine what takes place when the gas phase is present in the form of a bubble submerged and rising in an oxygen depleted liquid. At the point of bubble release M_{02} is .209 assuming atmospheric air is used for the gas supply. The absolute pressure in the bubble at a depth Z_b below the free liquid surface is:

$$P_T = P_0 + \rho Z_b$$

It is assumed that the characteristic bubble size $r_b \gg 2\sigma/P_T$ so there are no interfacial effects influencing the internal pressure.(7) As the bubble rises it will transfer oxygen (we assume here that the liquid is saturated with nitrogen and the gas is saturated with water vapor so the only species being transferred is oxygen) and therefore both P_T and M_{02} will be decreasing. Decreases in P_T are caused by the movement of the bubble toward the free surface and hence regions of lower hydrostatic pressure. Decreases in M_{02} are caused by transfer of oxygen from the gas inside the bubble to the liquid. A gas bubble, unlike the atmosphere, cannot be considered as representing infinite supply of oxygen.

It is clear that C* for the sub-surface aeration system is no longer a simple constant. The bubble, the basic mass transfer element, "sees" a constantly changing equilibrium concentration in the liquid depending on where it is with respect to the free surface and how much oxygen is being depleted or the mass transfer rate. At the beginning of a re-aeration experiment when the dissolved oxygen concentration is approximately zero, the mass transfer rate is high and the depletion is rapid. Conversely, after an extended period of aeration, the mass transfer rate approaches zero and in some regions (upper portions) of the basin oxygen

is transferred from the liquid to the gas and in other regions (lower portions) oxygen is transferred from the gas to the liquid. Here we have a dynamic steady state situation in which absorption and desorption are occurring simultaneously such that the net transfer rate of oxygen approaches zero.

Under these conditions the dissolved oxygen concentration no longer changes with time and assumes a value intermediate to C*(T) at the surface and C*(T) at the point of air introduction. The exact steady state level will depend on the design of the equipment used and provides an important experimental clue to where and how the mass transfer takes place.

The conclusion that can be drawn from this discussion is that equation (1) is not, in principle, applicable to data obtained from a sub-surface aeration system since it does not reflect, physically, what we know regarding gas-liquid equilibrium. Therefore, characteristic parameters such as $K_L a(T)$ or mass transfer rates obtained from the surface model are not subject to physical interpretation.

In practice, if the liquid depth is one or two feet and the maximum percentage absorption, E, is less than 10%, the effects discussed above will be negligible when compared to experimental variability. However, in a full scale system where the liquid depths range from 8 to 30 feet and absorption efficiencies as high as 40%, the effects must be accounted for if a realistic characterization of the equipment at standard condition is to be determined. Standard conditions for aeration equipment in North America are taken to be: water temperature of 20°C, 1 atmosphere (14.7

psi) pressure and 0.0 mg/ℓ dissolved oxygen. The oxygen mass transfer rate at standard conditions is commonly referred to as the SOR (standard oxygen rate). In practice, it is usually not possible to measure the oxygen transfer rate at standard conditions. The quantity that can be determined experimentally, however, is the overall mass transfer coefficient $K_L a(T) Z_s$.

When $K_L a(T) Z_s$ has been obtained, use of the model presented here enables one to calculate the oxygen absorption efficiency (E(T)). The mass transfer coefficient can then be corrected to 20°C and the absorption efficiency and oxygen transfer rate at standard conditions obtained. These calculations are simplified by the use of a single curve, derived from the model, that relates the oxygen absorption efficiency to a dimensionless mass transfer number μ.

SUB-SURFACE AERATION MODEL - THEORY

In order to quantitatively account for the effects discussed above, a mathematical model has been developed[8,9] that incorporates these complexities The resulting expression indicates how the changing gas phase composition and pressure are related to the mass transfer rate. The model is shown schematically in Figure 1.

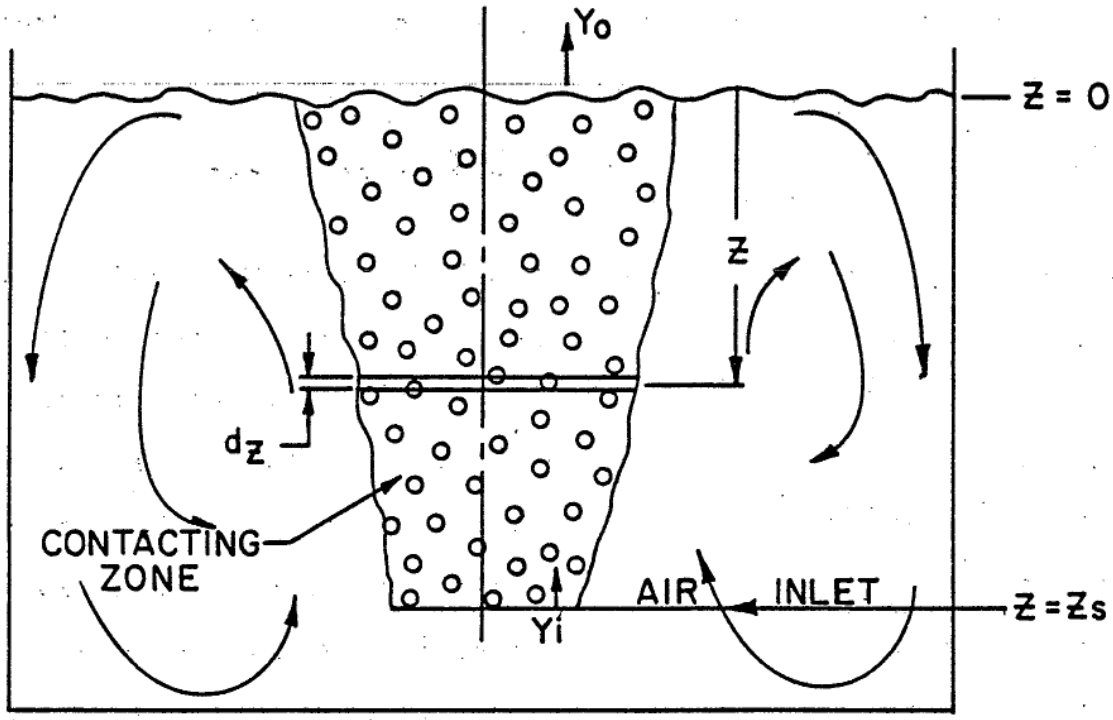

Figure 1.

The assumptions made here are:

1. Plug flow of gas and liquid through the contacting zone
2. Mass transfer coefficient independent of position in the contacting zone
3. No transfer of nitrogen

An overall mass balance at a given time results in the following relation:

$$G(Y_i - Y_o) = \text{mass transfer rate} \qquad .....(3)$$

A mass balance around a differential section dZ provides:

$$\frac{dY}{dZ} = \frac{K_L a(T)}{G} (C^*(Y,Z,T) - C) \qquad .....(4)$$

The functional dependence of C* on the gas phase composition Y and the pressure, depth Z, has been explicitly shown. Assuming a perfectly mixed basin we have:

$$\frac{W}{10^6} \frac{dC}{dt} = K_L a(T) \int_0^{Z_s} (C^*(Y,Z,T) - C)dZ \qquad .....(5)$$

This model is a generalization of the surface aerator model. The driving force for mass transfer is still the difference between equilibrium partial pressure and actual partial pressure. It relates the increase in dissolved oxygen with time to the changing conditions in the contacting zone through equation (5), and relates the changing conditions in the contacting zone to the increase in dissolved oxygen concentration through equation (4). In this way we have expressed the coupling that exists between the mass transfer rate and gas phase composition in a sub-surface aerator.

Equation (5) can be written as:

$$\frac{W}{10^6} \frac{dC}{dt} = K_L a(T) Z_s \langle \Delta C \rangle$$

where:

$$\langle \Delta C \rangle = \frac{1}{Z_s} \int_0^{Z_s} (C^*(Y, Z, T) - C)dZ$$

is the mean driving force.

The mole fraction oxygen can be expressed in terms of the weight ratio, Y, of oxygen to nitrogen, as:

$$M_{02} = \frac{Y}{Y+J}$$

The weight ratio, Y, is used because in a non-steady state re-aeration test the tap water is, or can be, saturated with nitrogen and therefore changes in gas phase composition are most easily characterized by Y. The nitrogen flow rate G, can be obtained from the standard cubic feet per minute inlet air flow rate (SCFM) as:

$$G = 3.47 \times SCFM$$

Henry's Law can now be expressed as:

$$C^*(Y,Z,T) = \frac{C^*(T)}{3.09} \frac{Y}{Y+J} (P_0 + \rho^Z)$$

Two interesting relationships can be derived from the above equations. The first is a prediction of the steady state dissolved oxygen concentration, $C\infty$ Steady state is reached when $\frac{dC}{dt} = 0$. When this occurs the overall mass transfer rate is zero. From equation (3) we see that $Y_o = Y_i$ under these conditions. Y is no longer a function of Z and can therefore be removed from the integrand in equation (5). Putting these conditions in equation (5) gives:

$$\int_0^{Z_s} \left(\frac{C^*(T) \quad (.209)}{3.09} \right) (P_0 + \rho^Z) - C\infty) dZ = 0$$

Evaluating the integral and solving for C_∞ gives:

$$C_\infty = C^*(T)\left(\frac{PO + \frac{1}{2}\rho Z_s}{14.7}\right) \qquad \ldots\ldots\ldots(6)$$

which says that the steady state dissolved oxygen concentration is the average of the equilibrium dissolved oxygen concentration taken at the free surface and at the point of air introduction. This result is a direct consequence of assuming that the mass transfer coefficient is independent of position (Z) in the contacting zone.

Experiments have shown (see Figure 3.) that when a mechanical sub-surface aerator is used the steady state value reached is that given by equation (6). Preliminary evidence indicates that equation (6) does not hold for certain non-mechanical sub-surface aerators. This is a direct indication that the mass transfer coefficient is dependent on position in the contacting zone.[9] In systems that approach a steady state concentration different than that given by equation (6), considerations should be given to generalizing the model presented here.

It has been our experience that there does not exist a universal model for the evaluation of sub-surface aerators. Models must be developed, from general principles, that incorporate the operating characteristics of the system under study. This requires extensive experimental work usually full scale (10 - 30 ft. deep tanks). It is only on scales of this magnitude that it is possible to obtain reliable measurements of the effects described here.

In the limiting case when the point of air introduction is very close to the free surface as is the case for a surface aerator $C\infty$ becomes:

$$C\infty = C^*(T)_1 \frac{PO}{4.7}$$

which is the value used when evaluating a surface aerator. Thus this model reduces to the conventional surface model as a limiting case.

The second relationship is particularly useful for evaluating experimental results. It provides the connection between the absorption efficiency E and the overall mass transfer coefficient $K_L a(T) Z_s$ at 0.0 mg/ℓ dissolved oxygen concentration. The derivation starts with equation (4) with C=0.0.

$$\frac{dY}{dZ} = \frac{C^*(T)\ K_L a(T)}{3.09\ G}\ \frac{Y}{Y+J}\ (P_O + \ell Z)$$

If we let $\gamma = \frac{C^*(T)\ K_L a(T)}{3.09\ G}$ and separate the variables Y and Z we have

$$\left(1 + \frac{Y}{J}\right)dY = \gamma(P_O + \ell Z)dZ$$

Integrating both sides of this equation and using the boundry values at:

$$Z = Z_s \qquad Y = Yi$$

$$Z = 0 \qquad Y = Yo$$

gives:

$$Y_i - Y_o + J\ \ln\left(\frac{Yi}{Yo}\right) = \gamma Z_s\ (P_O + \tfrac{1}{2}\ell Z_s) \qquad \text{.....(7)}$$

The absorption efficiency, E, is related to Y_i and Y_o as:

$$E = 1 - \frac{Yo}{Yi}$$

Using this in equation (7) gives:

$$Y_i E + J \ln\left(\frac{1}{1-E}\right) = \gamma Z_s \left(P_o + \tfrac{1}{2}\ell Z_s\right)$$

This equation cannot be solved in closed form for E in terms of the other variables. However, Figure 2 shows a graph of E x 100 as a function of the dimensionless group:

$$\mu = \frac{C^*(T)\ K_L a(T) Z_s}{3.09\ G}\ \left(P_o + \tfrac{1}{2}\ell Z_s\right) \qquad \text{.....(8)}$$

Concentration versus time data can be used to obtain $K_L a(T) Z_s$. μ can then be calculated from equation (8). Using this value of μ and the graph, Figure 2, a corresponding value for E can be obtained. The $K_L a(T)$ is then corrected to standard conditions by the relation:

$$K_L a(20) = K_L a(T)\ 1.024^{20-T}$$

and setting:

$$C^*(20) = 9.2 \text{ mg/}\ell$$

$$P_o = 14.7 \text{ psi}$$

A value for μ at standard conditions can be calculated. This can be used with the graph in Figure 2 to obtain an efficiency, E(20) at standard conditions. The SOR can then be computed from:

$$SOR = G\ Y_i\ \frac{E(20)}{100}$$

When determining the dissolved oxygen concentration by using the Winkler method for measuring dissolved oxygen concentrations, corrections should be made for cobalt interference which has been discussed by Kalinski, et al[10] before a comparison with equation (6) can be made. We have found

that the cobalt effect results from a chemical precipitate that titrates as if it were dissolved oxygen when analyzed by the Winkler procedure. This effect is a complex function of cobalt ion CO^{++}, Na_2SO_4, pH, and other dissolved salts in the test water. This chemical precipitate is an additive to the true value of dissolved oxygen when analyzed by the Winkler procedure and this erroneously high dissolved oxygen level (chemical addition plus the true dissolved oxygen) interfers with correct data analysis providing results which appear high.

The addition of this chemical blank (the titrated chemical precipitate) to each dissolved oxygen level measured during a non-steady state re-aeration test produces an error in the evaluation of surface aeration equipment that can exceed 50%. It is important that this chemical effect be understood and accounted for in the evaluation of any test data for all types of aeration systems, even though the degree of error is less with sub-surface systems.

The amount of precipitate formed is extremely dependent upon pH. For any fixed cobalt concentration the quantity of precipitate increases at a pH greater than 7 and will not form at all at a pH less than 5. With all of these variables interacting, it is difficult to predict in advance the quantity of chemical precipitate that will be involved in a test. In order to determine oxygen transfer only, all oxygen transfer guarantees should be based upon test results from which the chemical effects have been removed. Some investigators[10] propose running at very low cobalt levels to obtain chemical free test results. Low cobalt concentrations do not necessarily eliminate the chemical effect and the

parameters of pH, duration of aeration, quality of the test water, etc, can still provide significant chemical effects. A more accurate procedure is to use sufficient cobalt, (2ppm cobalt) to produce a measurable chemical precipitate, to measure the resulting blank, and deduct this from each dissolved oxygen measurement. The blank can readily be measured by titrating a sample of the test water directly without the addition of manganous sulfate ($MnSO_4$) or alkali-iodide azide reagent but with the addition of potassium iodide. This effectively measures the blank and when data are analyzed with the blank removed from each dissolved oxygen measurement, chemically corrected test results are obtained indicating true oxygen transfer. This has been cross-checked in conjunction with the dissolved oxygen probes with excellent agreement.

Two examples are presented to illustrate 1) the use of the proposed model and 2) the misleading results that can be obtained when the data are analyzed using the surface model.

The concentration versus time data for the first example is shown in Figure 4. A smooth curve has been drawn through the points. If we now re-write equation (5) as:

$$\frac{W}{10^6}\ \frac{dc}{dt} \quad - \quad K_L a(T) Z_s C \quad = \quad K_L a(T) \int_0^{Z_s} C^*(Y,Z,T)\,dZ$$

and recall that as $\frac{dc}{dt} \rightarrow 0 \qquad C \rightarrow C\infty$, which is independent of time, then for low absorption rates (toward the end of a non-steady state experiment) the right hand side of the above equation tends to a constant value. This implies that there is a linear relationship between $\frac{W}{10^6}\ \frac{dc}{dt}$ and C in this range.

The data were used to, manually, obtain an approximation to $\frac{dc}{dt}$ by taking differences in concentration over short time intervals. Numerical curve fitting techniques can and should be used for this step. We have done

this step manually to show that it can be done quickly (10-15 mins.).

A plot of $\frac{W}{10^6} \frac{dc}{dt}$ versus C is shown in Figure 8. The error bars show the range of variation due to the precision in the concentration measurements. As can be seen from an examination of Figure 5, a linear relationship does exist between $\frac{dc}{dt}$ and C when the absorption is below about 10%. The slope of this line was used to obtain an estimate of the overall mass transfer coefficient. This value was used to calculate μ at the conditions of the test and a corresponding absorption efficiency from Figure 2. The AOR was then calculated, plotted, and labeled in Figure 5 at 0.0 mg/ℓ dissolved oxygen.

The calculated AOR seems to be in line with the measure rates. In fact, if the line drawn to obtain the mass transfer coefficient is extrapolated back to C=0 it intercepts the $\frac{W}{10^6} \frac{dc}{dt}$ axis about 5% higher than the value obtained by calculation. This is reasonable since the absorption efficiency is only 17% at C = 0 and a large difference would not be expected.

The AOR, using the same data set, was then obtained by the conventional surface model. The standard deficit versus time plot is shown in Figure 6. This AOR was then plotted and labeled on the graph in Figure 5. The surface model, in this instance, gave a 26% higher value.

Example 2 (Figures 7, 8 & 9) shows the result of the same analysis using another set of data. These data were selected to show the effect of a rather large absorption rate. This was accomplished by keeping the

same power level (as Example 1) on the aerator turbine and reducing the gas flow rate by a factor of approximately 2.8. Referring to Figure 8, we see that the SOR determined by the proposed method is in line with the measured rates. In this case extrapolating the line used to determine the mass transfer coefficient to C = 0 resulted in a 23% higher value for the SOR.

The results of a surface model analysis of this set of data is plotted and labeled in Figure 8. A 65% higher SOR is obtained with the surface model. A summary of the results for these two examples at standard conditions is shown in Table I.

This illustrates the magnitude of errors we believe are made when the changing gas phase composition and the effect of depth is not accounted for in any manner.

TABLE I

Comparison of Methods
At Standard Conditions

Example 1

	Surface Model	Proposed Model	% Difference
$K_L a(20)$	74.87	51.95	44.1
SOR	688.8	538.9	27.8
E(20)	23.0	18.0	27.8

Example 2

	Surface Model	Proposed Model	% Difference
$K_L a(20)$	58.31	33.76	72.7
SOR	536.50	324.9	65.1
E(20)	51.2	31.0	65.1

ALTERNATE METHODS

Various other mathematical models have been used to evaluate test data obtained from sub-surface aeration systems. The following is a brief description of some of the commonly used models.

LOG MEAN DRIVING FORCE

This method of data analysis has been successfully used as both a correlating tool and a method of data analysis. In a manner similar to the procedure just discussed, oxygen transfer per increment of time is developed from a plot of dissolved level vs. time as shown in Figures 7 and 8. The absorption efficiency per time interval thereby allows the saturation value of dissolved oxygen to be determined at the surface. The saturation value of dissolved oxygen at the point of air introduction is known and therefore the driving force at this point and at the surface of the liquid can be determined for each time interval.

It is then a simple matter to determine the log mean driving force for each time interval (dissolved oxygen data closer than 1 mg/ℓ to the equilibrium value at the surface should not be used) and plot this against oxygen transfer in pounds per hour. The slope of this line on arithmetic paper passing through the origin provides the $K_L a$ under test conditions. This $K_L a$ can then be converted to standard conditions and a trial and error solution is then used to determine the standard oxygen rate (SOR). This procedure provides excellent results since it corrects for both pressure and changing gas concentration on the rising bubbles.

LOG MEAN SATURATION VALUE

In a like manner, the data analysis can be accomplished using a log mean saturation value rather than a log mean driving force. The two logarithmic averaging procedures yield results quite close as long as the air introduction depths remain less than approximately 20 ft.

AVERAGE SATURATION VALUE - ASSUMED OXYGEN TRANSFER EFFICIENCY

Some investigators have promoted the use of a constant saturation value determined as the average saturation value between the surface and the sparge. This has been further modified by assuming a nominal oxygen transfer efficiency of 10-20% in determining saturation value at the surface of the liquid. For a low uptake rate system in tank depths no greater than 20 feet, this method yields a good approximation (though sometimes optimistic) of the oxygen transfer capability of a submerged device. The saturation value is held constant throughout the calculation and data analysis is accomplished on semi-log paper using the surface aerator procedure but substituting the corrected saturation value for handbook values.

SURFACE MODEL

The surface aerator model was briefly covered at the beginning of this article. The degree of error obtained by utilizing this method of analysis can be significant. No correction is made for pressure or oxygen concentration of the rising gas bubble and therefore the surface model is totally inadequate.

The two previous examples have been worked out using the above procedures and the results are tabulated on Table II.

TABLE II

SOR#/hr of Various Mathematical Models

	Proposed Model	Log Mean Driving Force	Log Mean Saturation Value	Average Saturation Value	Surface Model
Example I	538.9	518	504	598	688.8
Example II	324.9	342	374	365	536.5

SUMMARY AND CONCLUSIONS

Significant errors result when data obtained from submerged aeration devices are mathematically analyzed with no correction being made for tank depth and changing oxygen concentration of the rising gas bubbles. Various procedures have been presented to correct for these effects. Our findings are that as long as reasonable corrections are made, with the surface model the notable exception, the various procedures provide comparable results.

The following conclusions can be drawn:

1. It is necessary to include both depth and the absorption efficiency of the rising gas bubbles in any analysis of submerged turbine aeration systems.
2. The surface model is totally inadequate and erroneously high ratings of submerged aeration systems can be obtained. For instance, Example 2 indicates an oxygen transfer efficiency of 537 pounds per hour for data analyzed by the surface model. We believe actual oxygen transfer is closer to 350 pounds of oxygen per hour.
3. Testing surface or submerged devices with no correction for the effects of chemicals can artificially inflate the "true" oxygen transfer capability of the system tested. Any data analysis procedure should include the removal of all chemical effects prior to data analysis.
4. A reasonable correction for pressure and absorption efficiency utilizing the first three data analysis procedures discussed will provide oxygen transfer values that agree within experimental error.
5. The mathematical model presented appears to fit submerged aeration systems utilizing mechanical agitation to contact oxygen bearing gasses with clean water.

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FIG. 2

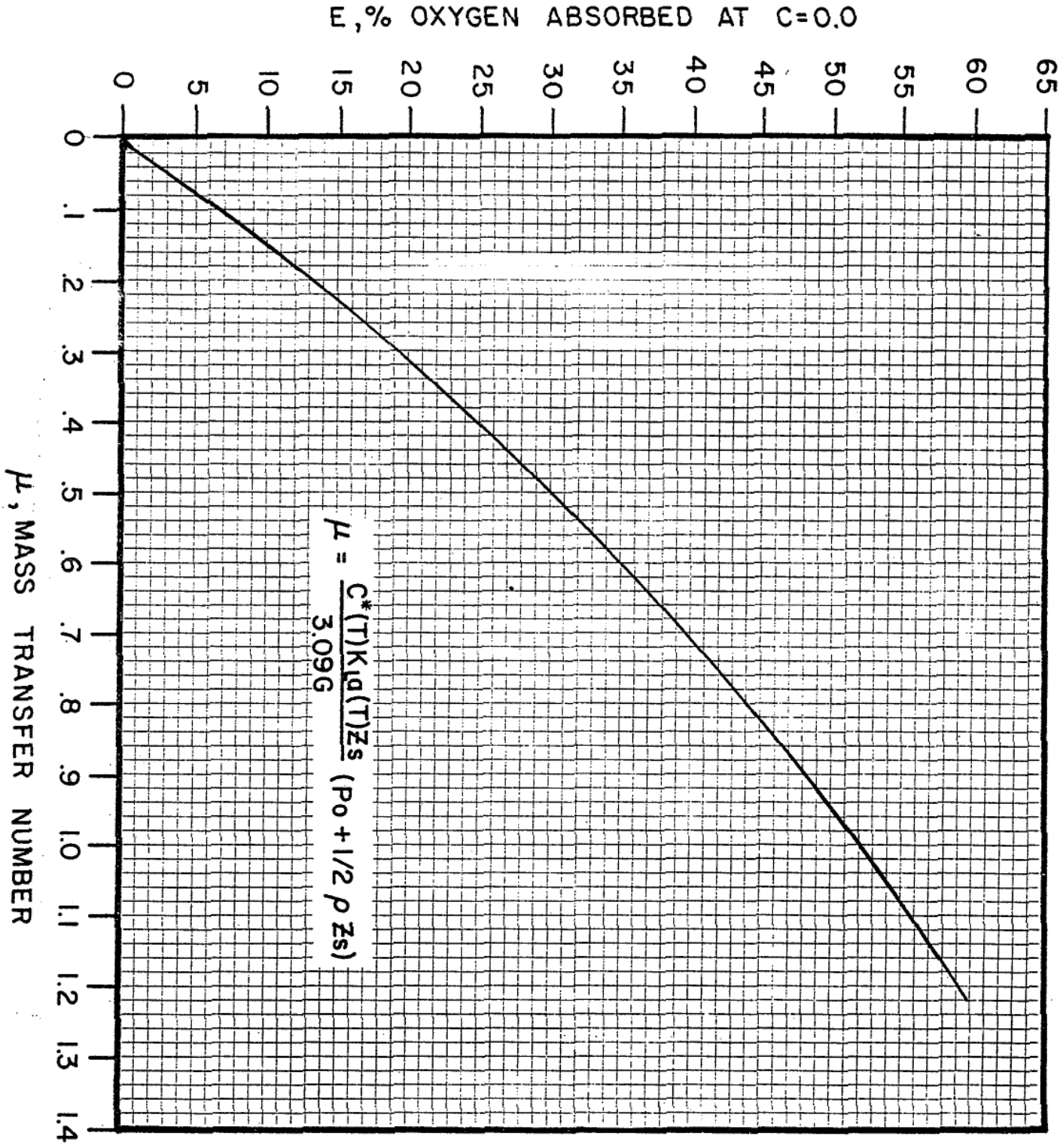
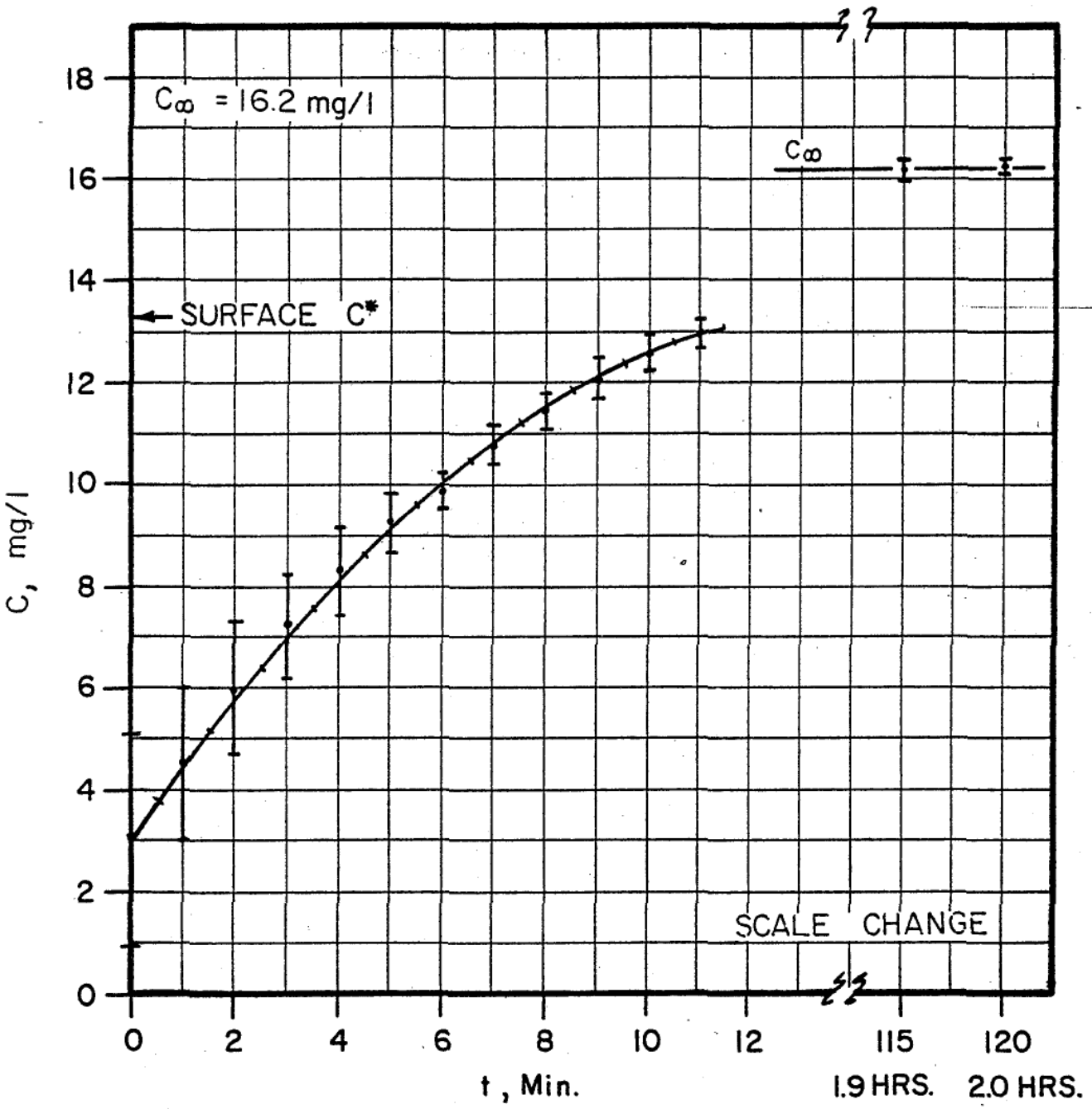
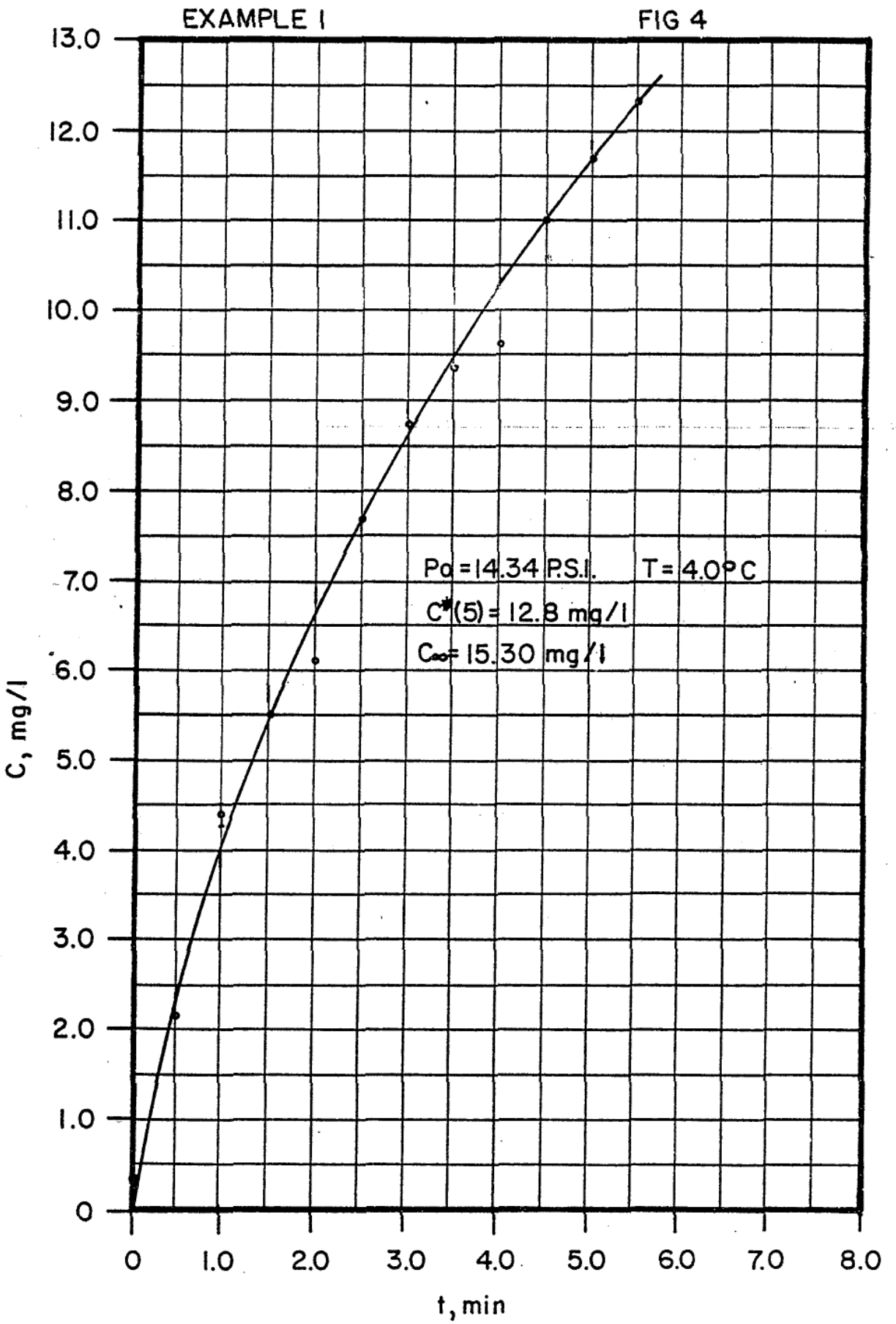

E, % OXYGEN ABSORBED AT C=0.0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
μ, MASS TRANSFER NUMBER
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
$\mu = \frac{C^*(T)K_g(T)Zs}{3.09G}(Po + 1/2\ \rho\ Zs)$

FIG. 3


C_∞ = 16.2 mg/l
C_∞
SURFACE C*
SCALE CHANGE
C, mg/l
t, Min.
1.9 HRS.
2.0 HRS.
0
2
4
6
8
10
12
14
16
18
115
120


EXAMPLE 1
FIG 4
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
C, mg/l
Pa = 14.34 P.S.I.
T = 4.0°C
C*(5) = 12.8 mg/l
C∞ = 15.30 mg/l
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
t, min

EXAMPLE I

FIG. 5

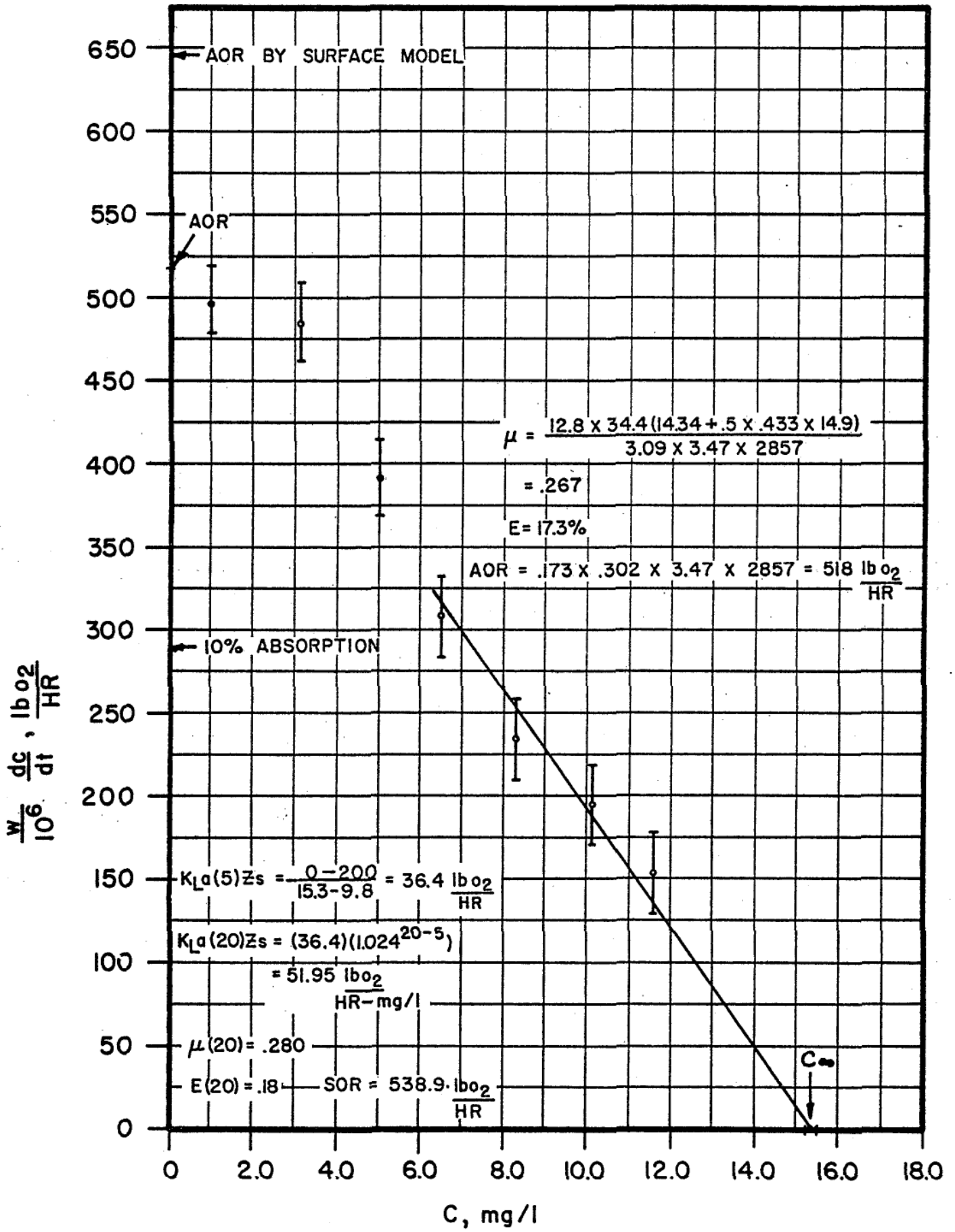
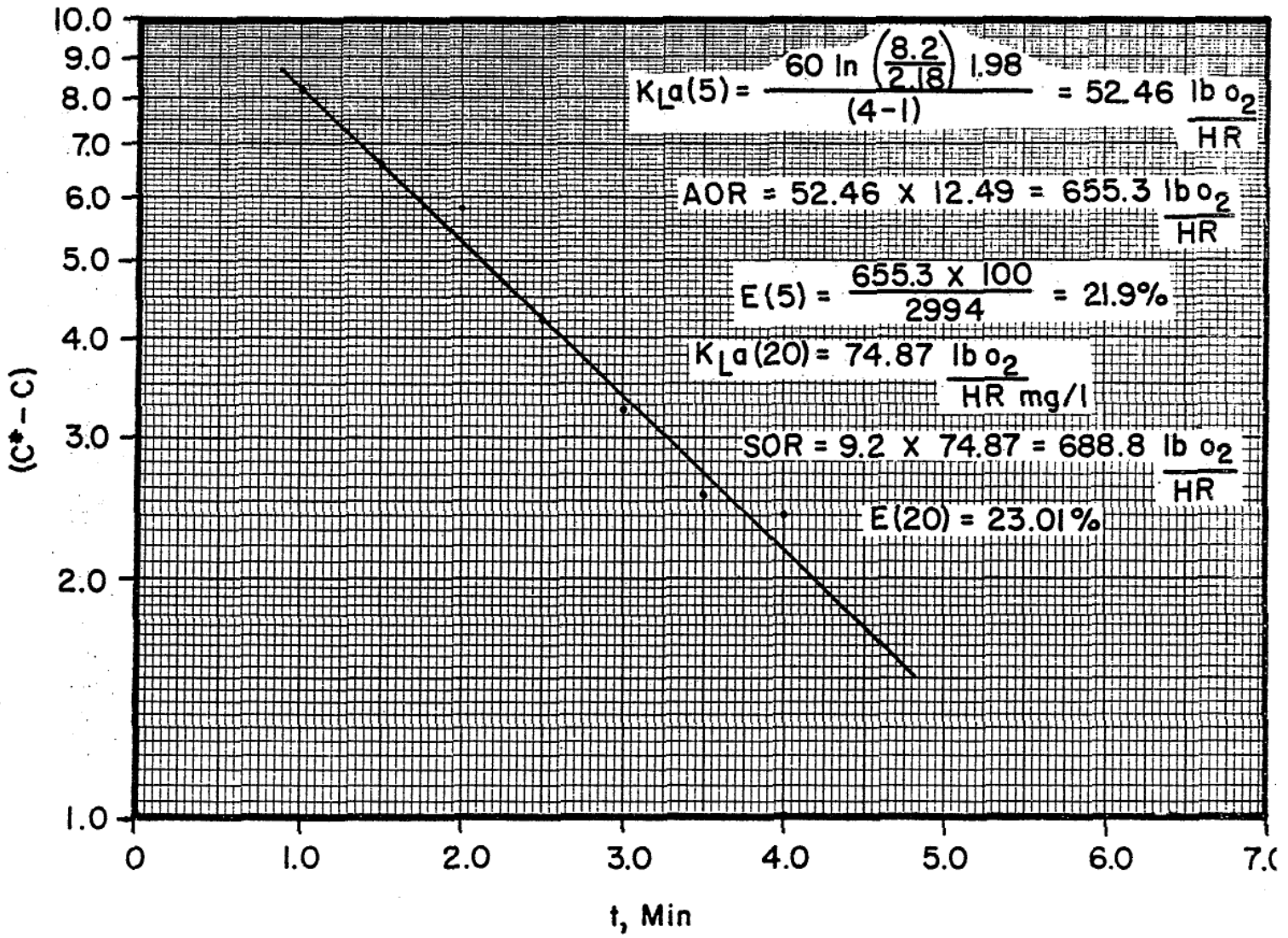


FIG. 6

EXAMPLE I

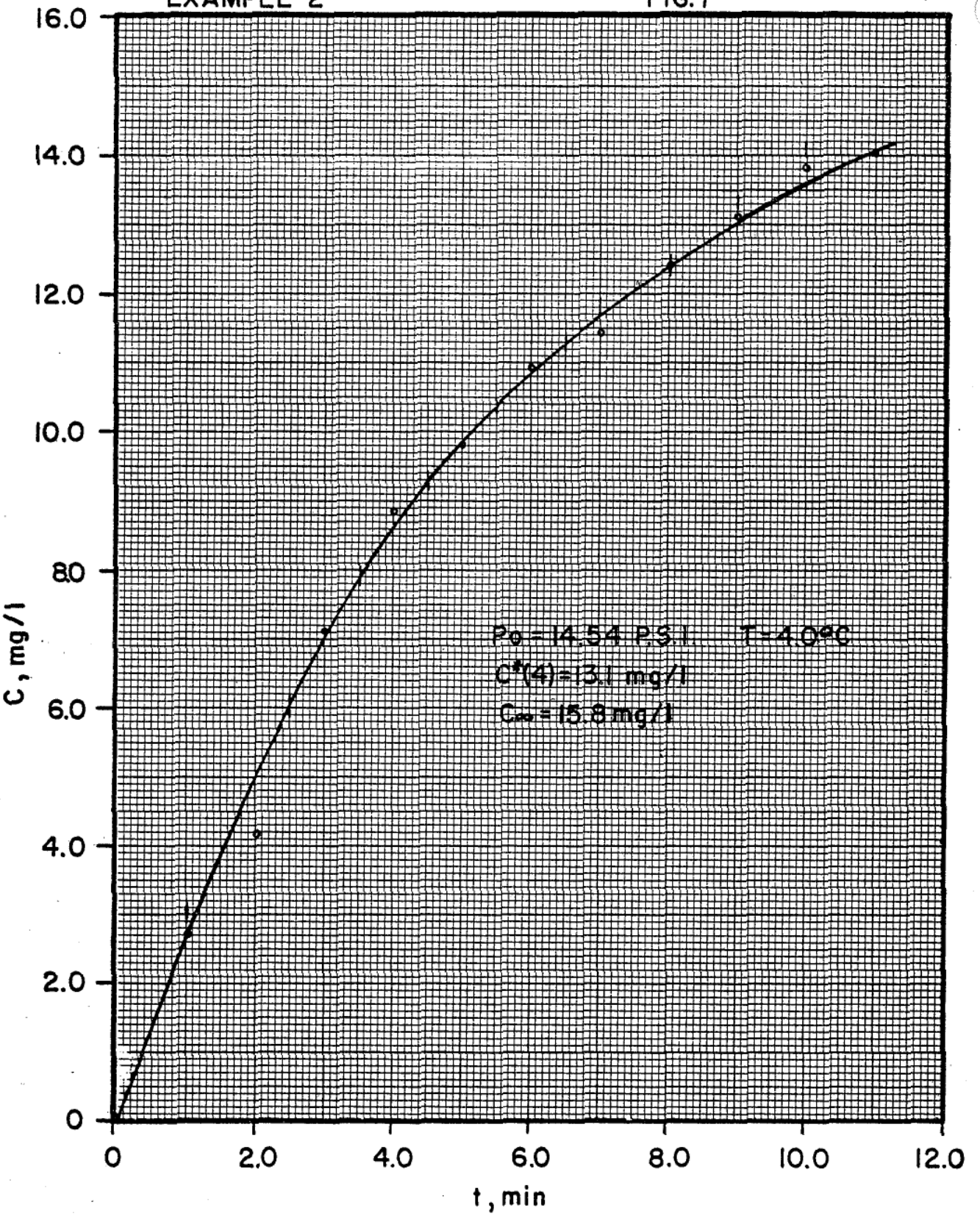
ANALYSIS OF SUB-SURFACE AERATION DATA WITH SURFACE AERATOR MODEL

SCFM = 2857 $Ft.^3$/Min.
AIR INTRODUCTION DEPTH = 14.9 Ft.
VOLUME = 237,770 GAL.
C_∞ = 12.49 Po = 14.34 PSI



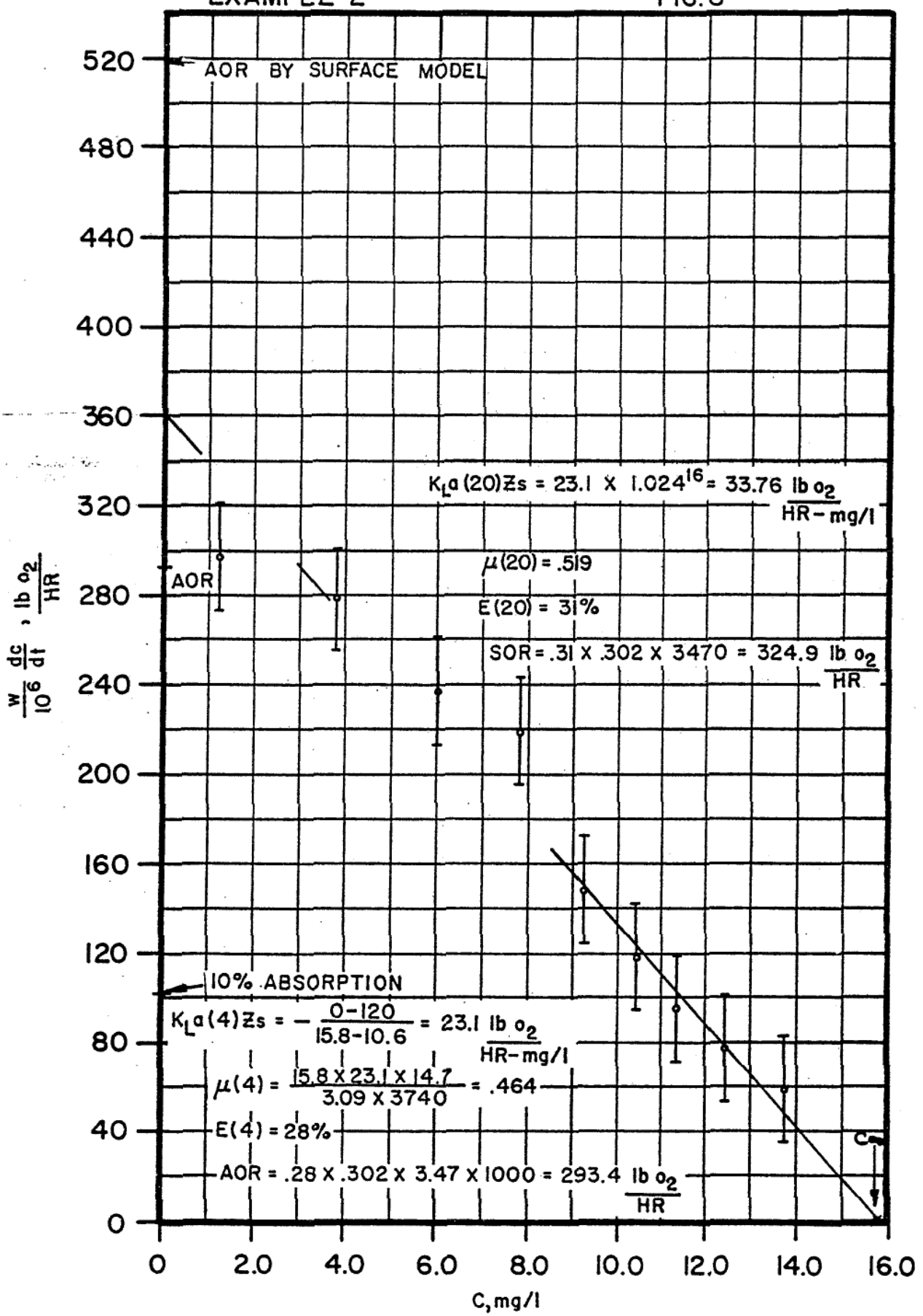
EXAMPLE 2

FIG. 7



EXAMPLE 2

FIG. 8



EXAMPLE 2

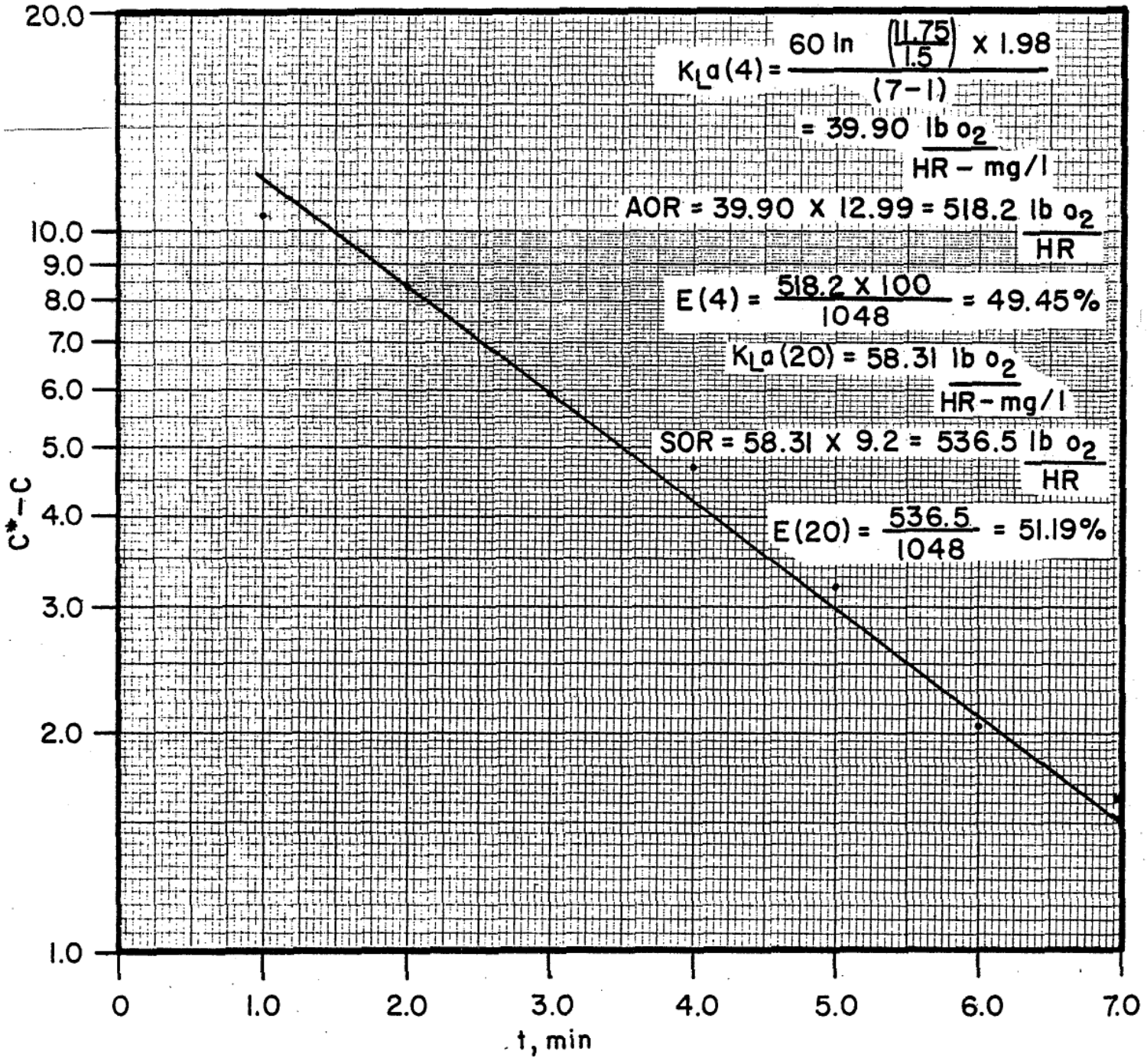
SCFM = 1000 FT^3/MIN

AIR INTRODUCTION DEPTH = 14.9 FT.

VOLUME = 237,770 GAL.

C_∞ = 12.99 mg/l Po = 14.54 P.S.I.

FIG. 9



NOMENCLATURE

W	Weight of water in test basin (Lb.)
$\frac{dc}{dt}$	Time rate of change of dissolved oxygen concentration (mg/ℓ-hr)
C	Dissolved oxygen concentration
$C^*(T)$	Dissolved oxygen concentration is equilibrium with air (21% O_2 79% N_2) at 1 atmosphere total pressure and T°C (mg/ℓ)
T	Test water temperature (°C)
t	Time (hrs. or mins.)
$K_L\acute{a}(T)$	Overall mass transfer coefficient at temperature T°C. (Lb 02/hr-mg/ℓ)
$H(T)$	Henry's Law constant (mg/ℓ /Lb/in^2)
P_T	Absolute pressure in gas phase (Lb/in^2)
P_o	Atmospheric pressure (Lb/in^2)
Ps	Standard Atmosphere 14.7(Lb/in^2)
ℓ	Hydrostatic pressure of water per foot of depth $\left(\frac{\text{Lb}}{\text{in}^2\text{-ft}}\right)$
σ	Interfacial tension (Lb/in)
r_b	Bubble size (in)
M_{02}	Mole fraction oxygen
M_i	Mole fraction in inlet gas
E	Fraction oxygen absorbed (E = 1-Yo/Yi)
AOR	Oxygen transfer rate at test temperature and pressure and 0.0 mg/ℓ dissolved oxygen concentration $\left(\frac{\text{Lb 02}}{\text{hr}}\right)$
SOR	Oxygen transfer rate at 20°C and 1 atmosphere barometric pressure and 0.0 mg/ℓ dissolved oxygen concentration (lb 02/hr)
Y	Gas phase concentration (Lb 02/Lb N2)
G	Nitrogen weight flow rate (Lb N2/hr)

Z	Distance from free liquid surface to plane in contacting zone (ft)
Z_s	Distance from free liquid surface to plane of air introduction (ft)
dZ	Differential segment of contacting zone (ft)
$\frac{dY}{dZ}$	Rate of change of gas phase concentration with respect to depth (ft^{-1})
$K_La(T)$	Mass transfer coefficient per foot of contacting zone at temperature T. (Lb 02/hr-mg/ℓ -ft)
$C^*(Y,Z,T)$	Equilibrium concentration of oxygen in water at gas concentration Y, depth Z, and temperature T. (mg/ℓ)
J	Ratio of molecular weights 02 to N2 (32/28)
SCFM	Volumetric air flow rate into liquid at 1 atmosphere pressure and 20°C (FT^3/min)
$C\infty$	Steady state dissolved oxygen concentration (mg/ℓ)
μ	Mass transfer number
Yi	Gas phase concentration of inlet air (.302 for atmospheric air) (Lb 02/Lb N2)
Yo	Gas phase concentration of air leaving contacting zone (Lb 02/Lb N2)

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