ACTIVATED SLUDGE AERATION SYSTEM EFFICIENCY UNDER DIFFERENT PROCESS CONDITIONS IN WASTEWATER TREATMENT PLANTS

M. Zermeño[1], R. Iranpour[1*], A. Magallanes[1], T. Montgomerry[1], P. Weston[1], M. Williamson[1], R. Reeves[1]
[1*]Applied Research, Terminal Island Plant, Bureau of Sanitation, City of Los Angeles

[1*] Hyperion Plant / Applied Research
12000 Vista Del Mar
Playa Del Rey, CA 90293

ABSTRACT

Offgas analyses of oxygen transfer efficiency (OTE) at the Terminal Island Treatment Plant (TITP) of Los Angeles document changing performance of fine-pore diffusers in an activated sludge plant over a number of years. Although this plant treats an especially challenging waste stream, the operation of the aeration tanks is little different from many other plants, so these results have wide potential relevance.

Recent sessions with larger number of measurements per day and revisiting tanks after a few days or weeks provided improved time resolution, compared to previous work. Samples were more closely spaced, and some samples were taken in the intervals between the aeration grids, at the ends of the tanks, and near the edges of the grids. Tests were also made in which the hood was left in the same position for an hour or two, to determine whether the measurements were subject to significant temporal variations on time scales of a few minutes to an hour or more.

Analysis of the full set of measurements made at TITP since 1991 shows detectable effects of changing process conditions, and indicates that the recently measured efficiencies were at the level of systems without diffusers which is a major problem with many aeration systems in activated sludge plants in USA and other countries, in particular plants running under nutrient removal with selector processes. This is probably explained by deterioration of the air distribution system that has now been remedied by a refurbishment program. Also, as in other activated sludge plants in the US, a blower system that lags behind the diffuser technology and that has limited flexibility has made overaeration difficult to avoid in the past. It would have limited the economic benefits of repairs that were limited to the air distribution and diffusion system. Offgas testing can provide evidence of aeration system deterioration when leaks and fouling are large enough to affect local OTEs, but usually the full extent cannot be verified until tanks are dewatered.

The recent measurements not only demonstrate variations in tank efficiency, but show the degree to which efficiency losses may develop without being recognized if OTE measurements are not done. Hence, there may be value in similar measurement programs at other plants, for which this study may serve as a prototype.

KEYWORDS

Offgas, aeration, oxygen transfer efficiency, selectors, blowers, anoxic

INTRODUCTION

Improving oxygen transfer efficiency (OTE) in aeration tanks has substantial potential economic significance. For example, the potential savings from improved aeration efficiency at the Los Angeles plants have been roughly estimated at over a hundred thousand dollars per year, and comparable savings may be possible at other large municipal treatment plants.

The importance of OTE in activated sludge plants follows from two simple considerations. First, although the actual fraction varies from roughly a half to as much as nine tenths, typically around two thirds of the electricity consumed at such a plant goes for blowing air into the aeration basins. Second, the amount of air that must be blown for any treatable biological load is inversely proportional to OTE.

This inverse relationship is seen from the need to transfer enough oxygen to maintain equilibrium with biological consumption, so that airflow is manually or automatically adjusted by feedback from dissolved oxygen sensors in the tanks. Since the mass of oxygen transferred per unit time is the product of OTE and the mass of air supplied in this time (Allbaugh, et al., 1985), this gives the inverse proportionality for any specified mass transfer rate.

OTE is affected by many aspects of the environment in a tank. First, there are easily recognized influences of quantities such as temperature, pressure, and the concentration of the oxygen that is already dissolved in the water (Redmon, et al., 1981, 1983; ASCE, 1992; Ewing Engineering, 1984; Babcock and Stenstrom, 1993), so that it is routine to adjust the raw OTE measurements to what they would be under standard conditions. Second, deeper tanks tend to provide higher OTEs, because there is more time for oxygen transfer as the bubbles rise, but the benefits of very deep tanks are limited (Huibregtse, et al., 1983). Third, OTE is always lower in dirty water than in clean, which is typically represented by an adjustment factor denoted by α. It has long been widely believed that α resulted largely from surfactants in the water (e.g., Masutani and Stenstrom, 1991), but Hwang and Stenstrom (1985) found that bacterial oxygen uptake (OUR) rate was better correlated with α in their experiments than surfactant concentration was. As surfactant concentration and OUR are influenced by the bacterial population in a tank, Fisher and Boyle (1999) looked for evidence that the differing bacterial populations in tanks with and without anoxic or anaerobic selector zones might influence α, but found no evidence of a significant effect. Iranpour, et al (1999) wrote a discussion on this work. Theoretical developments are discussed in Newbry (1998), and Iranpour (1999). Advanced and micro-bubble aeration are discussed in *Science* (Iranpour, et al. 1999) and Semmens, et al. (1999a & b).

Since 1991 the Bureau of Sanitation of Los Angeles has occasionally assessed air flow and diffuser performance at its plants to gain insight into power consumption and the relative value of differing types of diffusers and cleaning methods. Recently, additional work has been done at the Terminal Island Treatment Plant (TITP). The new work has been done with some innovations in sampling. The recent samples were more closely spaced and comprehensive than in previous research, such as the earlier studies at TITP, which are included in the graphs and tables below, or the measurements at Site A in Redmon, et al. (1983). The new observations show aspects of aeration system performance that were not evident with more widely spaced samples.

Some of the tanks that were unused at the time of these measurements have gone back into service, and the plant has undergone extensive refurbishment. Thus, further measurements planned at this and other Los Angeles plants are expected to provide additional information for the Bureau's cost reduction efforts. However, the work done to date provides illustrations of the value of both the measurement methods and the results.

EXPERIMENTAL SETUP

Terminal Island Treatment Plant: TITP has a capacity of approximately 30 million gallons per day (MGD) of wastewater. The secondary treatment system that is the subject of this study has been in operation since 1977. (Primary treatment at the site began in 1933). TITP receives some domestic wastewater, but historically 40%-60% of its influent has been industrial, including irregularly timed large discharges of wastewater from metal plating, fish canning, the Long Beach Naval Shipyard, several oil refineries, and chemical plants. Usually around 10% of the influent is seawater. Thus, the plant always has had to cope with high levels of sulfide and salinity in the influent, and the pH, BOD, SS, and NH_3-N levels have tended to be highly variable, reaching frequent extreme values. Often, heavy metals and oil and grease have also been above what is common in municipal wastewater.

Figure 1a shows a plan view of a typical basin. There are nine rectangular aeration tanks, 300 feet in length, 30 feet in width, with an average side water depth of 15 feet. The aeration system is an Aercor fine pore system, with 9-inch ceramic domes and hard rubber gaskets. Stainless steel bolts are used to hold down the diffusers. These diffusers were installed at TITP around November, 1990, so by the end of this study they had been in service for nearly eight years, and were approaching the halfway point of their planned service life. In each tank the diffusers are arranged in four grids, designated as Grids A, B, C, and D. The aeration system is designed to provide tapered aeration to meet an anticipated greater oxygen demand at the influent end of the tank.

During much of the period since the first OTE measurements, the plant was operated with a high mean cell residence time, and with six of its nine tanks in two step-fed serpentine series of three tanks each to obtain a high hydraulic retention time. These were efforts to nitrify the plant's high load of ammonia nitrogen. Starting in the late 1980s, this mode of operation was adopted because previous operation in other modes had led to a prolonged period of frequent violations of discharge standards (Wada and Fan, 1990). The nitrification measures were effective, since the number of discharge standard violations decreased drastically in the early 1990s, and after 1994 there were three consecutive years with no violations.

In recent years, with changing economic conditions and installation of some wastewater treatment equipment at the factories, the ammonia nitrogen load has decreased and become more stable, so it has been more common for only one serpentine series to be used, with the other operating tanks acting as plug-flow reactors. Moreover, in early 1998 it was decided that partial nitrification would now be acceptable, so the process was changed to reduce air consumption.

Evidently, meeting the discharge standards has been the priority, but efforts to minimize costs have been made where possible. For example, as full nitrification reduces the pH of the secondary effluent and mixed liquor to the range 6.8-7.1, this counteracts diffuser fouling, and so operation without cleaning the diffusers was considered satisfactory. The last cleaning performed on the aeration basins at TITP during the period of this study was water hosing of the diffusers in Tank 3 at the beginning of 1993. Once partial nitrification operation began in early 1998, the pH rose again, and this is suspected to have contributed to additional fouling. However, in the past year the plant has been undergoing extensive refurbishment as it converts to full reclamation of its effluent, and this includes new valves, improved monitoring instruments and control equipment, and replacement of many iron or steel air distribution pipes with fiberglass.

Offgas Instrument: The analyzer uses the same principles as the commercially available Ewing Mark V instrument (Ewing Engineering, 1984). The measurements used the established method: offgas is collected by a hood floating on the surface of the tank, and after removal of CO_2 and water vapor from the sample stream the O_2 partial pressure is measured by a fuel cell. The depletion of O_2 relative to the ambient air is then computed, from which one derives the raw OTE, as described in (Redmon, et al., 1983, Campbell, 1983, Iranpour, et al 1998, 1999, 2000). In using this method it is important for the readings to stabilize every time the hood is transferred. Sample contamination by ambient air leads to underestimation of oxygen depletion in the offgas, and hence of OTE. Once the seal between the hood and the water is reestablished, the air contamination dissipates and the O_2 partial pressure declines to its level in the offgas.

EXPERIMENTAL PROCEDURE

Table 1 summarizes the procedures used in the measurements. Before 1998, samples were taken at the positions shown in Figure 1b. The midlines of the grids were avoided because leaks from the main pipes, which run along the midlines, could distort the results. Likewise, measurements in the interiors of the grids were expected to be most nearly characteristic of average performance. For the recent experiments, the sampling patterns (Figure 1c) are less uniform than those previously used, but cover larger percentages of tank surfaces, since the tanks were subdivided into a larger number of partitions. Another sampling method (Figure 1d) was to leave the hood in the same place for an hour or two to determine whether the samples were subject to significant temporal variations during these periods. This was done once in each grid.

The operation of the instrument produces a number of parameters that are recorded as the fundamental data from which results are derived. These include sensor pressure, hood pressure, sensor voltage, gas flow rate and others. Once the local OTE values are computed from the oxygen depletion derived from these quantities, an average OTE weighted by flow and area is computed by the following equation:

$$\overline{OTE} = \frac{\sum_{i=1}^{m} A_i Q_i OTE_i}{\sum_{i=1}^{m} A_i Q_i},$$

where i is the hood location sample number; A_i is the area associated with hood location i ; Q_i is the air flux associated with hood location i (gas flow rate divided by hood area); OTE_i is the oxygen transfer efficiency measured at hood location i ; and $\overline{OTE}$ is the overall average OTE.

Correcting for departures from the standard atmospheric pressure and temperature, and for nonzero DO in the wastewater, gives the standardized OTE parameter, αSOTE, which provides the most uniform basis for comparing aeration efficiencies observed at different times and places. A mercury thermometer and a DO meter were used to measure temperature and DO at the point of OTE measurement to convert the raw OTE values inferred from oxygen depletion into αSOTE according to the following formula:

$$\alpha SOTE = \frac{OTE \cdot C^{*}_{\infty 20}}{\left(\Omega \beta C^{*}_{\infty T} - DO\right)\theta^{T-20}} \; ,$$

where $C^{*}_{\infty 20}$ is the equilibrium DO concentration at 20°C, 760 mm barometric pressure, and zero salinity; $C^{*}_{\infty T}$ is the equilibrium DO concentration at temperature T, 760 mm barometric pressure, and zero salinity; Ω is the barometric pressure correction factor; α is the salinity correction factor (C^{*}_{∞} process water/ C^{*}_{∞} clean water); α is the temperature correction factor (1.024 is the ASCE standard); and T is the water temperature, in °C.

In addition, data were obtained from the control room that included wastewater flows, RAS flows, air flows, and DOs of the tanks. Readings from instruments in the field (connected to the control room) were also recorded for comparison with the control room data.

The α parameter, which measures the reduction in OTE caused by dirty process water, is computed by α = αSOTE / SOTE, where SOTE is the standardized clean water OTE, a quantity that is estimated from a formula fitted to clean water laboratory measurements by the manufacturer. For the Aercor ceramic dome diffusers in the tanks studied here, SOTE = 45.346 - 22.005 QD + 5.903 QD^2, where QD is the airflow per diffuser in scfm. This quadratic formula only applies over a modest range of QD, so that for feasible QD values SOTE declines with increasing QD.

OBSERVATIONS

Figure 2 presents the results from the 1991 and 1994 sessions for Tank 3, and Figure 3.presents the corresponding data for Tank 4. The plots for January 19, 1994 begin at 100 feet because by this time these tanks were being operated with Grid A as an anoxic selector zone. Figures 4 through 7 present the data from the four measurement sessions conducted in the summer of 1998, including both the data recorded by the measurement crew and the corresponding control room data. Figure 8 shows the efficiencies at the fixed hood positions as a function of time in September and October, 1998.

Table 2 summarizes the results from all the measurement sessions. These are tank averages derived by weighting the individual measurements by observed airflow and the partition area surrounding the measurement location. The "Grid interiors" columns allow comparing the recent results to those from 1991 and 1994, since they are all based on data recorded at similar positions. The "Overall" columns include the data from the recent measurement sessions that were obtained in the grid interiors, at the edges of the grids, and in the gaps between the grids. Table 3 summarizes the plant control room data for the measurement sessions.

ANALYSES

1991-1994 Results: Figures 2a and 3a show that during the April 12, 1991 measurement session the αSOTE readings in Tank 3 were relatively high in Grid A, lower in Grid B, and generally higher, but highly variable, in Grids C and D, while Tank 4 had lower efficiencies in Grid A, a higher first point in Grid B that was followed by a steady decline to the end of Grid C, and then a rise in Grid D. The α factor plots in Figures 2b and 3b show very similar behavior, while the general decline of the air flux values in Figures 2c and 3c is as would be expected from the tapered aeration system design. The DO in Figures 2d and 3d rises toward the effluent end of each tank, and is unusually high at the end of Tank 4.

During the September 3, 1991 measurements the detailed profiles of the measured quantities were different, and the efficiencies for Tank 3 were generally lower, as reflected in the averages in Table 2(a). The efficiency decline for Tank 4 was smaller, and the sizes of the standard deviations in Table 2(a) raise the question whether the change is significant. However, Figure 3a shows that five of the eight individual September measurements are below the corresponding April measurements, and only two September measurements are higher, so this is evidence that the lower mean indicates a modest genuine decline. As before, the α factor variations in Figures 2b and 3b follow variations in the αSOTE readings closely, although the absolute α values are little changed from April. The general trend of the air flux values in Figures 2c and 3c is as before, although the absolute values are higher, as would be expected from the need to maintain approximately the same oxygen transfer rate with diminished efficiency. The DO concentration in Tank 3 in Figure 2d showed a different profile along the tank from April, but the average was little different, while Figure 3d shows that the DO concentration in Tank 4 was much lower, especially near the effluent end.

The January 19, 1994 results include a much smoother trend in the αSOTE and α factor results in Tank 3, as well as lower efficiencies in both tanks. Again, the α factors vary with the αSOTE readings, and this time the α for Tank 3 in Figure 3b is persistently lower than it was in September, 1991. Furthermore, the air fluxes in Figures 2c and 3c are substantially higher than in 1991, and the flux in Tank 3 reverses the trend expected from the tapered aeration design. Likewise, Figure 2d shows that the DO in Tank 3 rises steeply toward the effluent end of the tank, unlike the lower DO in Tank 4 in Figure 3d.

1998 OTE instrument results: The salient characteristic of the 1998 results for all three tanks is the low mean efficiencies, as shown in Table 2(a). The mean αSOTEs are in the range 3-8%. Comparison with data from other similar plants shows that similar performance range has been observed.

Further examination shows that the especially low mean for Tank 5 (Figure 6) is the result of nearly uniformly low efficiencies in Grids C and D. By contrast, the efficiencies in the corresponding grids of the other tanks are much more variable, and many of them are higher.

The large variations in the individual measurements in Tank 4 (Figures 4 and 5) and Tank 6 (Figure 7) are the reason that the mean efficiencies for these tanks have standard deviations that are at least half the sizes of the means. Thus, the statistical significance of the means is poor.

Large changes in the Tank 4 readings between July 16 (Figure 4) and August 12 (Figure 5) are another potentially significant aspect of these data. The large efficiency reading at 150 feet on July 16 was not duplicated in August, but between 200 and 275 feet the values were low in July and higher in August. Hence, although the means for the two days are within one quarter of a standard deviation of each other, and so are not significantly different by established statistical standards, the near constancy of the means obscures the changes in the local values.

The low OTE in most of Tank 5 is matched by a nearly uniform high air flux, while the higher OTEs in Grids C and D of Tanks 4 and 6 correspond to more or less irregularly decreasing air fluxes. These data show the expected anticorrelation between air flux and OTE, since bubble size usually increases with air flux, and hence the average surface/volume ratio of the bubbles decreases.

Figure 8 shows the means and standard deviations of the measurement sessions conducted with the hood positions left fixed for an hour or two in each grid for September 10 and October 12, 1998. These observations agree relatively well with the tank scan data at corresponding positions in Figures 5 and 6, but show substantial variability.

1998 control room results: Control room data from times that are as close as possible to the times of the offgas measurements have also been tabulated, and are summarized in Table 3. Tank influent flow and RAS flow show no surprises. Each was very stable during the measurement sessions with RAS flow approximately a third to less than a half of the influent flow on each day. The airflow data in Figure 6c on August 25 show very stable airflow to the tank, except for a brief but large dip at around 10:20 AM. This is reflected in the large standard deviation in the table entry for this day, and the air flux data (Figure 6b) recorded during the offgas measurements agree well with this. The agreement is not as good for the sessions at Tank 4 (Figures 4b and 5b), which may in part be due to the greater temporal variation of the air supply to this tank, as shown by the control room data in Figures 4c and 5c. However, much of the disagreement must be attributed to the greater degree of local variation in diffuser behavior, displayed in the OTE measurements in Figures 4a and 5a.

Plant DO measurements, made at a fixed detector in Grid D of each tank, also show considerable temporal variation, as displayed in Figures 4c through 7c. These variations raise the possibility that the assumption of local equilibrium, implicit in the conversion from OTE to αSOTE, is not strictly valid. However, the low solubility of oxygen and the high bacterial metabolic rate make the residence time for dissolved oxygen a very few minutes, which is much shorter than the time scales of most of these fluctuations. Hence, the conversion to αSOTE remains valid for the precision of these measurements.

DISCUSSION

Operation Effects: Careful examination makes it possible to separate some of the effects of the changing operation methods, described in the Experimental Setup section, from the decline of diffuser efficiency due to fouling. Thus, the sawtooth appearance of the αSOTE plots for both

1991 measurements of Tank 3 (Figure 2) and the September 1991 measurements of Tank 4 (Figure 3) appears to be explained by recalling that these are the times when these tanks were being step fed as part of the nitrification process. At the beginning of each grid there was an additional infusion of dirty water, which tends to reduce αSOTE, either by its surfactant content (Masutani and Stenstrom, 1991) or by some effect associated with its high oxygen uptake rate (Hwang and Stenstrom, 1985). As the water progresses to the downstream side of the grid some of the food is consumed. In this way each grid reproduces on a small scale the behavior observed in plug-flow tanks, where efficiencies tend to rise from the beginning to the end of the tank.

On the other hand, the smoother appearance of the αSOTE plots for 1994, especially for Tank 3 (Figure 2), reflects the abandonment of step feeding with the establishment of the anoxic selector zones at the influent ends of these tanks to suppress the growth of *Nocardia* species and the foaming that they cause. Before the anoxic zones were established, the conditions were ideal for *Nocardia* growth, since the food/mass (F/M) ratio was usually low as the operators maintained a high mass to consume shock loadings, and the sludge age was high to promote nitrification. (For example, during the measurement sessions in 1991 the mean cell residence times were around 13 days, and in late 1988 they had been raised near 50 days (Wada and Fan, 1990). However, obligate aerobes like *Nocardia* are starved by feeding the influent into the anoxic zones, since these conditions allow facultative anaerobes to absorb most of the food before the aeration region is reached.

Both Tanks 3 and 4 had anoxic zones in 1994 because one serpentine series consisted of Tanks 3, 2, and 1, in that order, while the other sequence was 4, 5, and then 6. In 1998, Tanks 4, 5, and 6 were operated as plug-flow tanks, so each was being fed with primary effluent through an anoxic zone, and hence the biological environment in these tanks was similar to the conditions in Tanks 3 and 4 in 1994. Thus, the 1994 and 1998 data are more directly comparable to each other than either is to the 1991 step feed data.

Fouling, Leaks, and Blowers: Making allowances for the differences in operation over the years at TITP, it is clear that in Table 2 the reductions in the average tank efficiencies from April to September, 1991, and then to January, 1994, represent losses in diffuser performance. The cleaning in Tank 3 in February, 1993, may have done some good, but overall the efficiency of this tank declined more than the efficiency of Tank 4 from September, 1991, to January, 1994. By 1998, a further decline had occurred in the efficiency of Tank 4, and similar low efficiencies were observed in Tanks 5 and 6. Hence, if Tank 3 had been measured, similar results probably would have been obtained.

Stenstrom and Masutani (1989) found that when a tank at the Whittier Narrows Plant was dewatered for cleaning, broken diffusers, blown gaskets, and loose pipes were quite widespread. At TITP, in adjacent tanks that were dewatered for the refurbishment program that was in progress at the plant, the measurement team observed some of these forms of deterioration of the air distribution systems, so leakage and fouling on both sides of the diffusers were probably present in Tanks 4 through 6 during the OTE observations. Operational experience shows that all the diffusers become fouled after a long enough time, and that a power failure would cause much more rapid fouling than normal operation.

Another aspect of the overall technical and economic situation is the limited output range of the blowers, which are now more than 20 years old. Each blower can put out a maximum of 40,000 scfm, and the minimum output level in operation has been about 20,000 scfm because unacceptable surges occur in their power supplies when the output is decreased to around 17,500 scfm. Hence, the expense of improving the condition of the diffuser system might not have been fully repaid by savings in electrical consumption while it was impossible to reduce blower output to match improved OTE. Introducing more flexible aeration system design depends not only on the blowers but on the control systems and distribution systems, in which there have been many advancements in the past twenty years.

The refurbishment program has now installed new air pipes and valves and rebuilt pipes for feeding the influent into the tanks Preliminary work is also being done on modernizing the blowers and their power and control systems for greater adaptability.

Costs and Energy Conservation: Combining the results of this study with those of Stenstrom and Masutani (1989) suggests that diffuser fouling and air distribution system damage may be widespread in many other large activated sludge wastewater treatment plants. They may be performing below what is expected from, for example, the design recommendations in USEPA (1989), which recommends design assumptions for fine-pore diffuser OTE that are much more conservative than the performance of relatively new diffusers, such as was observed in April, 1991. The recent OTE observations are below the recommended design assumptions. Thus, it is possible that many plants might be able to take actions that would realize substantial savings in energy consumption if they were alerted to tank efficiency problems by offgas OTE measurements.

CONCLUSIONS

1. Offgas measurements at TITP from 1991 to 1998 show substantial variations of OTE.
    a. The efficiencies in Tanks 3 and 4 in April, 1991, not long after the diffusers had been installed, were very high.
    b. Significant losses in efficiency, presumably due to fouling, had occurred by September, 1991.
    c. Although the diffusers of Tank 3 were cleaned by water hosing in February, 1993, by January, 1994 the average efficiency in this tank had declined below the level of Tank 4.
    d. By 1998 the efficiencies in Tanks 4, 5, and 6 had declined to the level of systems without fine-pore diffusers. These low efficiencies are attributed to past operational changes over several years.
    e. Measurements in 1998 with the hood left in the same place for 1-2 hours also showed relatively short-term variations.
    f. These measurements also confirmed the low efficiencies seen at some points in the tanks during the scans a few weeks before .
2. The earlier measurements show evidence of the changes in tank operation between 1991 and 1994.
    a. The September, 1991 αSOTE and α results show sawtooth variations that probably reflect the step feeding that was practiced at that time.

   b. The January, 1994 αSOTE and α results show smoother variations that probably reflect the change to feeding through an initial anoxic zone.
3. Innovations in OTE sampling, with increased tank coverage and more frequent measurement sessions, provided increased detail in 1998 compared to the earlier observations.
4. The α values derived from these data may be influenced by the nitrification occurring in these tanks, but additional measurements would be necessary to verify this.
5. Although several aspects of the operation and aeration system conditions probably contributed to the low efficiencies observed in the summer of 1998, many of them have now been improved by an extensive refurbishment program.

As the research program has progressed, the operators and management at the Los Angeles plants have become strongly interested in regular monitoring of the OTE in their tanks. The authors believe that the experiments reported here demonstrate the general value of more frequent and comprehensive OTE measurements in providing guidance for decisions about maintaining, repairing, and replacing aeration systems.

REFERENCES

Allbaugh, T.A., Benoit, D.J., Spangler, J. (1985). Aeration system design using offgas oxygen transfer testing. Report prepared for the City of Lansing, Michigan.

ASCE. (1992) "Measurement of Oxygen Transfer in Clean Water," *Standard Am. Soc. Cov. Eng.* Committee on Oxygen Transfer, New York, NY.

Babcock, R. W., Jr., Stenstrom, M. K. (1993) "Precision and Accuracy of Off-Gas Testing for Aeration Energy Cost Reduction," *Proceedings of 66th WEF annual conference*, Anaheim, Ca.

Campbell, Jr., H.J. (1983). Oxygen transfer testing under process conditions. Proc. of workshop on Aeration System Design, Operation, Testing and Control, EPA/Environment Canada, Madison, Wisconsin.

Brindle, K., Stephenson, T., Semmens, M. J. (1999) "Pilot-Plant Treatment of a High-Strength Brewery Wastewater Using a Membrane-Aeration Bioreactor," *Water Envir., Res.*, **71** (6), 1197-1204

Ewing Engineering Company (1994). *Operating manual for aerator-rator offgas analyzer*. 6200 N. 39th St., Milwaukee, WI 53209.

Fisher, M. J., and Boyle, W. C.(1999) "Effect of Anaerobic and Anoxic Selectors on Oxygen Transfer in Wastewater," *Water Env. Res.*, V. 71, N. 1, pp. 84-93.

Huibregtse, G. L., Rooney, T. C., and Rasmussen, D.C. (1983) "Factors affecting fine bubble diffused aeration," *J. WPCF*, 55 (8), 1057-1064.

Hwang, H.J., Stenstrom, M.K. (1985) "Evaluation of Fine-bubble alpha factors in near full-scale equipment," *J. WPCF*, 57 (12), 1142-11151.

Iranpour, R., Magallanes, A., Zermeno, M., Patel, D., Garnas, G., Stenstrom, M. (1998) "Assessment of Aeration Basin Performance Efficiency," *Proceedings of WEF 71st Annual Conference & Exposition*, Orlando, Fl.

Iranpour, R., Magallanes, A., Zermeno, M., Mayer, R., Patel, D., Oh, S., Moghaddam, O., Garnas, G., Langley, J., Stenstrom, M. (1999) "An OTE Prototype to Optimize Maintenance and Air Consumption: Full Scale Analyses at City of Los Angeles' Wastewater Treatment Plants." *Proceedings of WEF 72nd Annual Conference & Exposition*, New Orleans, Louisiana.

Iranpour, R., et al. (1999) "Of: Oxygen-transfer efficiency of fine-pore diffused aeration systems: energy intensity as a unifying evaluation parameter," *J. Water Envir. Res.*, **71** (4), 506-509.

Iranpour, R., et al. (1999) "Of: Effect of Anaerobic and Anoxic Selectors on Oxygen Transfer in Wastewater," *J. Water Envir. Res.*, in press.

Iranpour, R., Stenstrom, M., Tchobanoglous, G., Miller, D., Wright, J., Vossoughi, M. (1999) "Environmental Engineering: Energy Value of Replacing Waste Disposal with Resource Recovery," *Science*, July 30, 1999, Vol. 285, pp. 706-711.

Iranpour, R., et al. (2000) "Assessment of Aeration Basin Performance Efficiency: Sampling Methods and Tank Coverage," IAWQ, *Water Res.*, in press.

Iranpour, R., et al. (2000) "Assessment of Aeration Basin Performance Efficiency: Frequent Sampling For Damage Detection," *J. Water Envir. Res.*, **72** (3), 363 – 376.

Masutani, G., Stenstrom, M.K. (1991) "Dynamic Surface tension effects on oxygen Transfer," *J. Envir. Engrg.* 117 (1), 323-333.

Newbry, B. W. (1998) "Oxygen-transfer efficiency of fine-pore diffused aeration systems: energy intensity as a unifying evaluation parameter," *J. Water Envir. Res.*, **70** (3), 323-333.

Redmon, D., and Boyle, W.C. (1981). Preliminary findings: offgas analysis. Report presented to the ASCE Oxygen Transfer Standard Committee, Detroit, MI.

Redmon, D., Boyle, W.C. and Ewing, L. (1983) "Oxygen transfer efficiency measurements in mixed liquor using off gas techniques," *J. WPCF*, 55 (11), 1338-1347.

Semmens, M. J., Gulliver, J.S., Anderson, A. (1999a) "An Analysis of Bubble Formation Using Microporous Hollow Fiber Membranes," *Water Envir., Res.*, **71** (3), 307-315

Stenstrom, M.K., and Masutani, G. (1989) "Fine bubble diffuser fouling: The Los Angeles Studies," A final report to the ASCE and the USEPA.

US EPA (1989). *EPA/ASCE design manual on fine pore aeration*. Cincinnati, OH. EPA/625/1-89/023.

Wada, F., and S. Fan. (1990) "Innovative Secondary Treatment Process Control Using High MCRT, Low F/M, and Complete Nitrification to Treat High Industrial Loads," *CWPCA*

TABLE 1 - Summary of Experimental Parameters for Tanks at TITP

Date (Time) (1)	Tank (2)	Portions (3)	No. of hood locations in: Grid interior (4)	No. of hood locations in: Gaps and edges (5)	No. of samples in: Grid interiors (6)	No. of samples in: Gaps and edges (7)	Pattern (8)	Comments (9)
04/12/91 (8:00AM-11:30AM)	3	8	8	–	8	–	transverse	serpentine, 1st pass; 8 months service
	4	8	8	–	8	–	transverse	plug flow; 4 months service
09/03/91 (8:00AM-11:30AM)	3	8	8	–	8	–	transverse	serpentine, 1st pass; 13 months service
	4	8	8	–	8	–	transverse	serpentine, 1st pass; 9 months service
01/19/94 (8:00AM-11:30AM)	3	6	12	–	12	–	transverse	serpentine, 1st pass
	4	6	12	–	12	–	transverse	serpentine, 1st pass
07/16/98 (8:00AM-3:00PM)	4	13	13	4	17	6	transverse	plug flow
08/12/98 (8:00AM-3:00PM)	4	13	13	4	21	7	transverse	plug flow
08/25/98 (8:00AM-3:00PM)	5	14	14	4	23	7	transverse	plug flow
08/26/98 (8:00AM-3:00PM)	6	13	13	4	20	6	transverse	plug flow

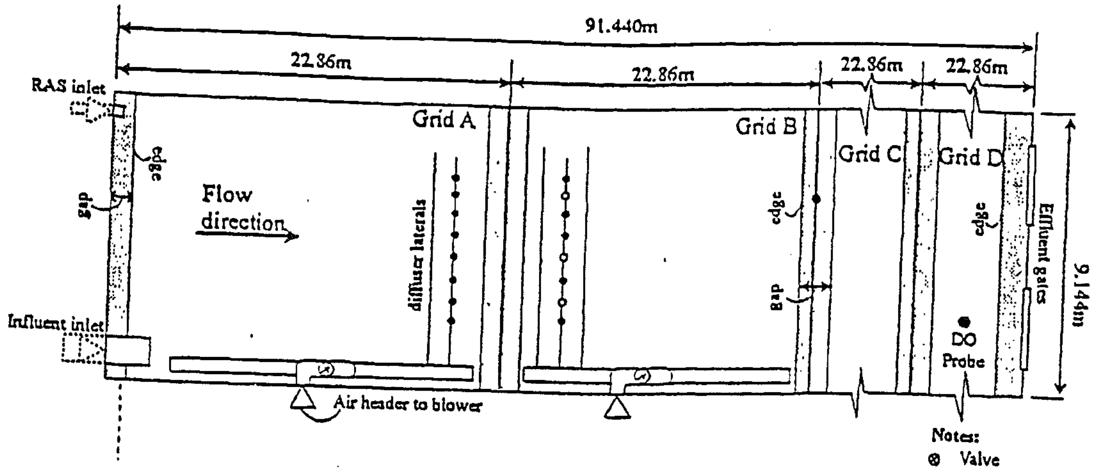
TABLE 2 - Oxygen Transfer Efficiencies for Tanks at TITP

Date (1)	Tank (2)	Efficiencies (average ± standard deviation): Grid interiors OTE (3)	Grid interiors aSOTE (4)	Overall (grid interiors, gaps, & edges) OTE (5)	Overall (grid interiors, gaps, & edges) aSOTE (6)
04/12/91	3	18.00 ± 2.75	20.00 ± 3.87	*not available*	*not available*
04/12/91	4	12.50 ± 6.13	16.60 ± 3.87	*not available*	*not available*
09/03/91	3	14.3 ± 2.94	15.60 ± 3.18	*not available*	*not available*
09/03/91	4	13.70 ± 2.90	15.10 ± 2.96	*not available*	*not available*
01/19/94	3	10.90 ± 0.50	11.40 ± 1.03	*not available*	*not available*
01/19/94	4	12.50 ± 2.41	13.60 ± 3.37	*not available*	*not available*
07/16/98	4	4.40 ± 3.67	5.42 ± 4.21	5.54 ± 4.95	6.60 ± 5.34
08/12/98	4	4.57 ± 2.14	7.44 ± 4.11	4.95 ± 2.47	8.06 ± 4.52
08/25/98	5	2.47 ± 1.06	3.35 ± 0.94	2.42 ± 1.37	3.30 ± 1.24
08/26/98	6	5.83 ± 4.57	7.77 ± 6.39	6.21 ± 4.30	8.23 ± 6.06

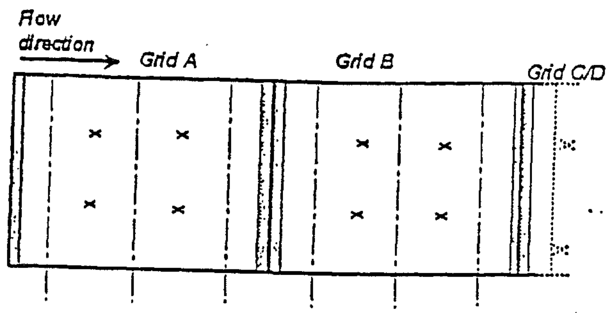
TABLE 3 - Control Room Data Corresponding to Dates of Measurement Sessions at TITP

Date (Time) (1)	Tank (2)	RAS (3)	Q (4)	Total Air flow (5)	DO Sensor in Grid D mg/L (6)
		average ± standard deviation (m^3/min)			
04/12/91	3	*not available*	*not available*	*not available*	*not available*
04/12/91	4	*not available*	*not available*	*not available*	*not available*
09/03/91	3	*not available*	*not available*	*not available*	*not available*
09/03/91	4	*not available*	*not available*	*not available*	*not available*
01/19/94	3	*not available*	*not available*	*not available*	*not available*
01/19/94	4	*not available*	*not available*	*not available*	*not available*
07/16/98 (9:30AM- 3:00PM)	4	7.73 ± 0.47	17.56 ± 0.53	110 ± 8.60	3.35 ± 0.33
08/12/98 (8:45AM- 12:00PM)	4	6.81± 0.26	15.38 ± 0.45	114 ± 1.20	2.99 ± 0.06
08/25/98 (8:45AM- 1:00PM)	5	4.52 ± 0.42	17.56 ± 0.63	144 ± 13.00	5.11 ± 0.22
08/26/98 (9:20AM- 1:00PM)	6	4.68 ± 0.21	18.27 ± 0.60	149 ± 2.50	3.66 ± 0.52

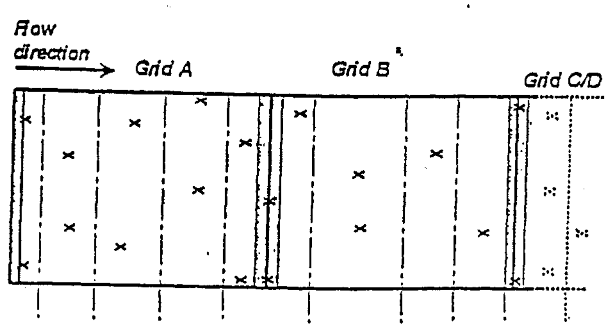
Figure 1 - Plan Views of Experimental Setup and Procedures



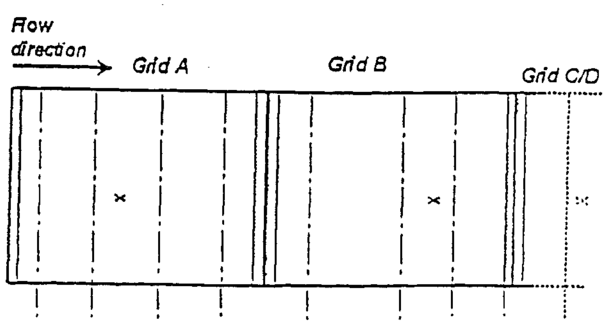
(a) tank structure



(b) sampling locations; uniform transverse pattern (91-94)

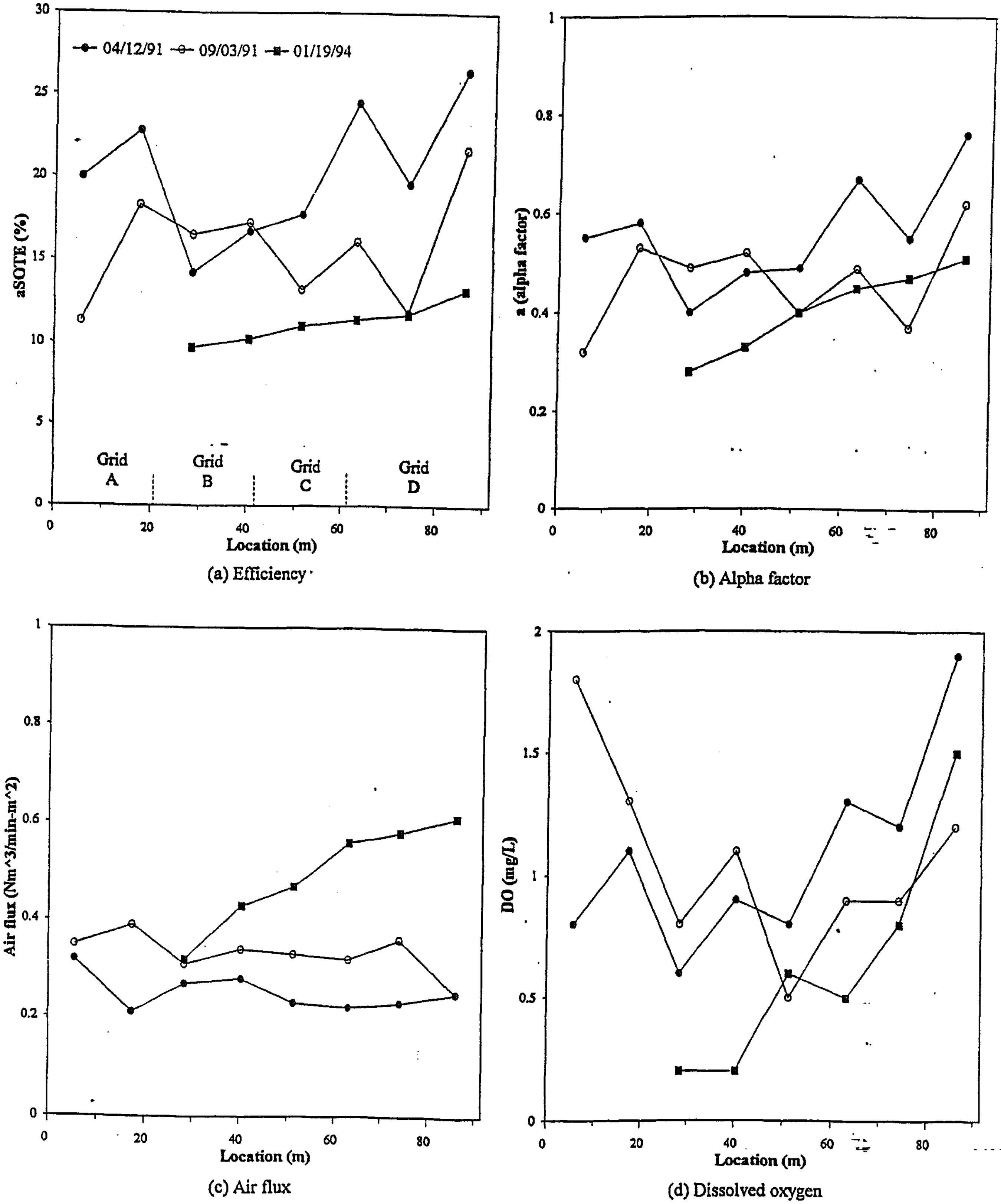


(c) sampling locations; random transverse pattern (98)



(d) sampling locations; fixed positions (99)

Figure 2 - Offgas Data for Grids A, B, C and D (interiors only) of Tank 3 at TITP, 91-94 (7:00AM - 5:00PM) (reorganized from Stenstrom reports)



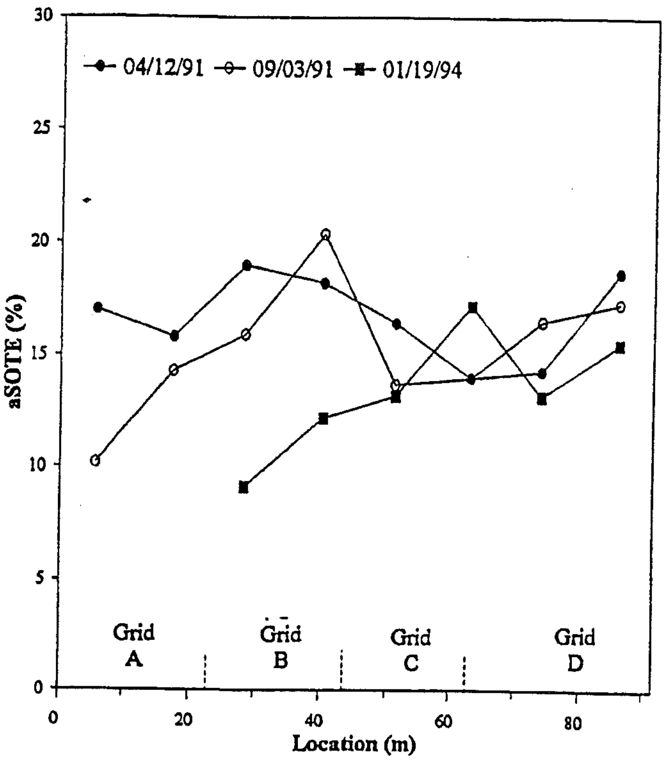
(a) Efficiency

(b) Alpha factor

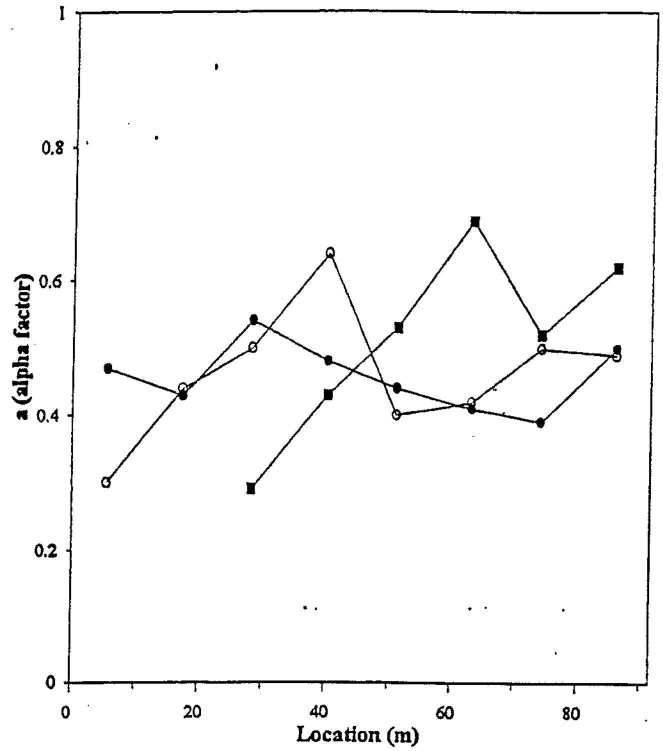
(c) Air flux

(d) Dissolved oxygen

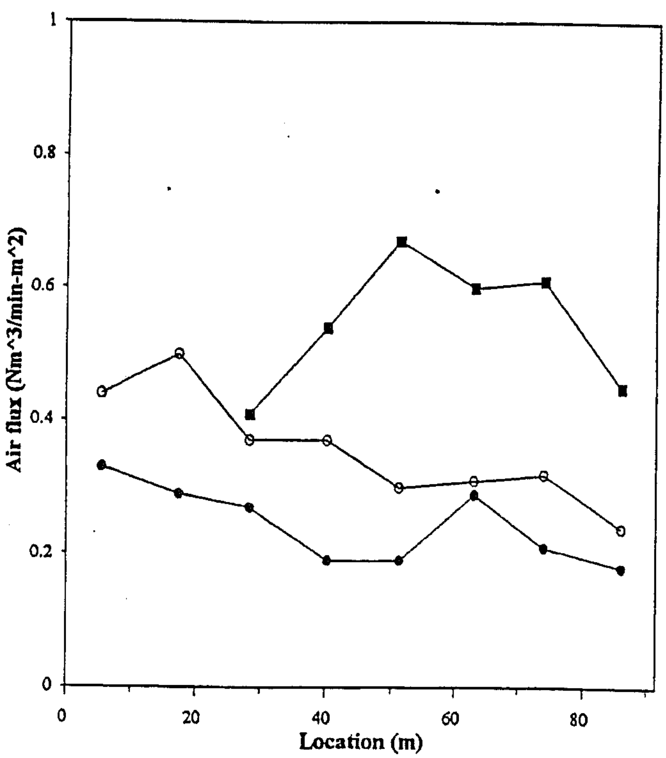
Figure 3 - Offgas Data for Grids A, B, C and D (interiors only) of Tank 4 at TITP, 91-94 (7:00AM - 5:00PM) (reorganized from Stenstrom reports)



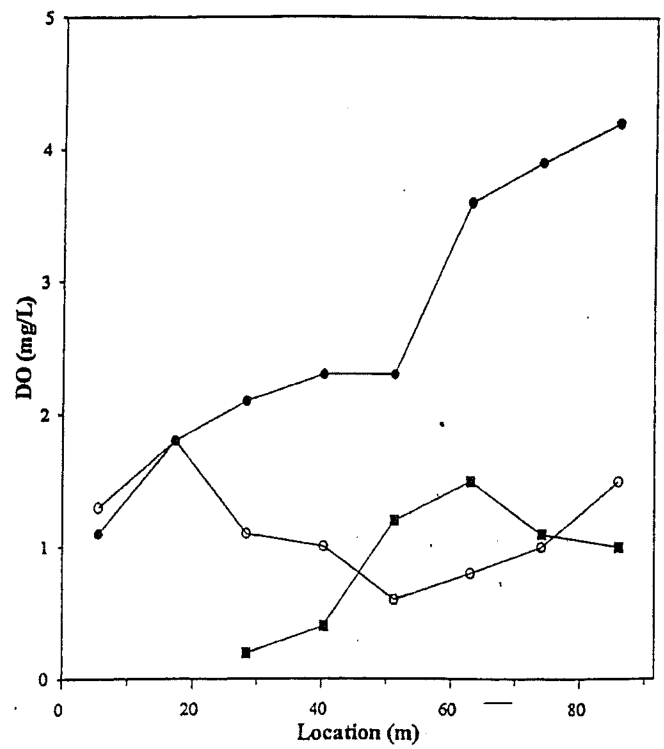
(a) Efficiency



(b) Alpha factor

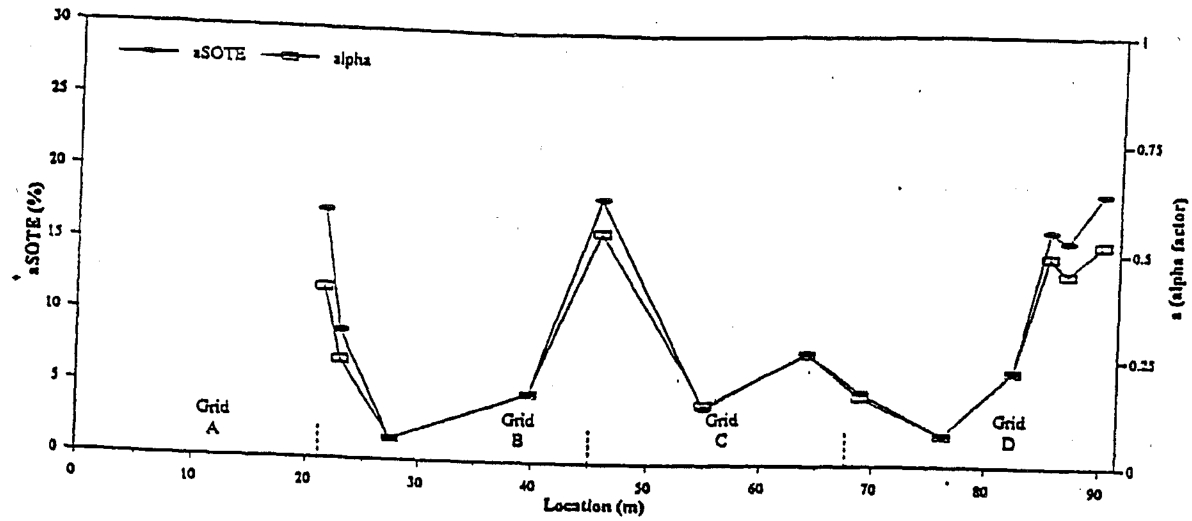


(c) Air flux

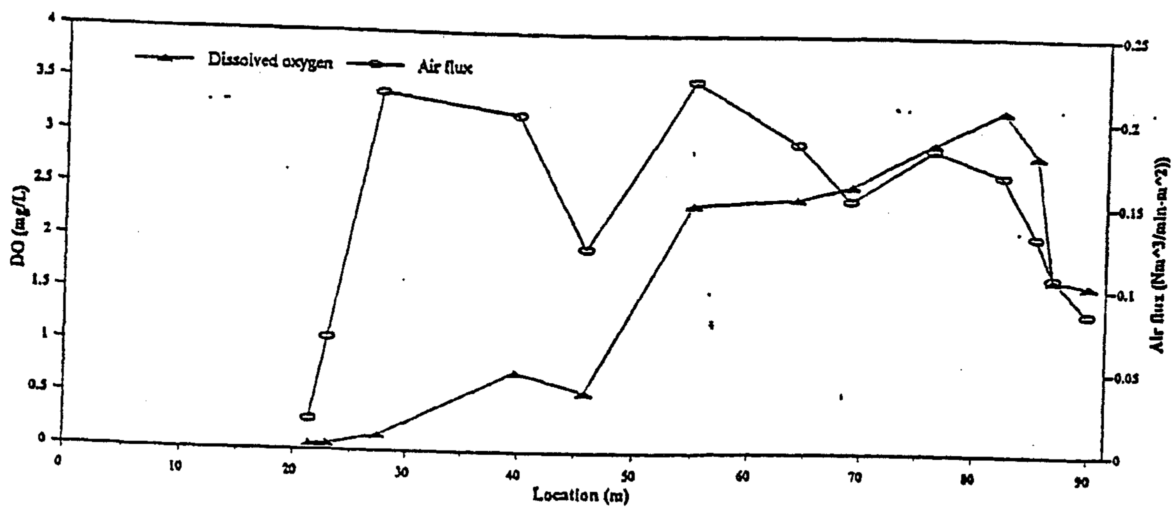


(d) Dissolved oxygen

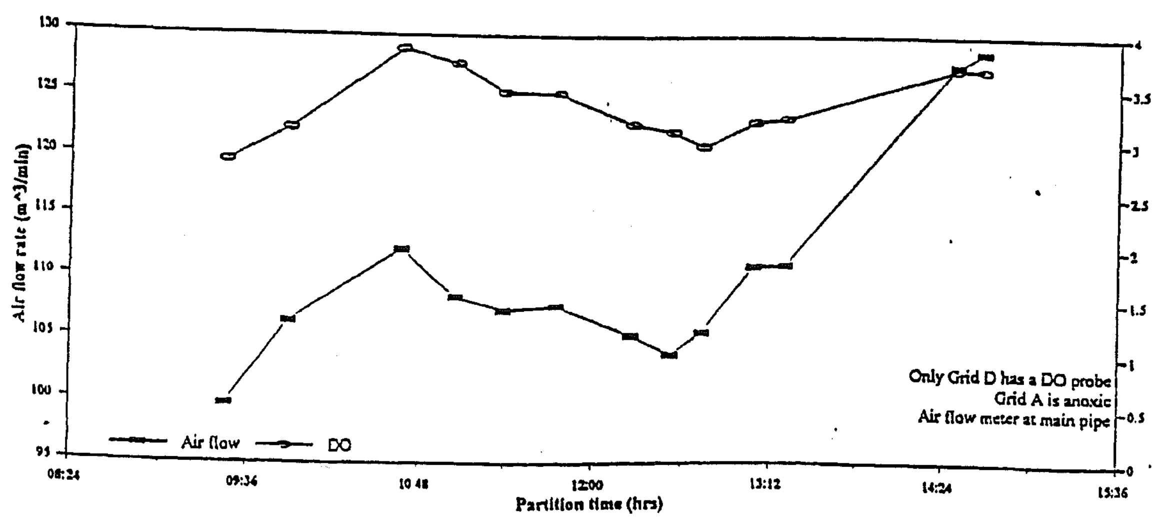
Figure 4 - Offgas Data for Grids A, B, C and D (interior & gaps and edges) of Tank 4 at TITP, 07/16/98, (7:00AM-5:00PM)



(a) Efficiency and alpha factor

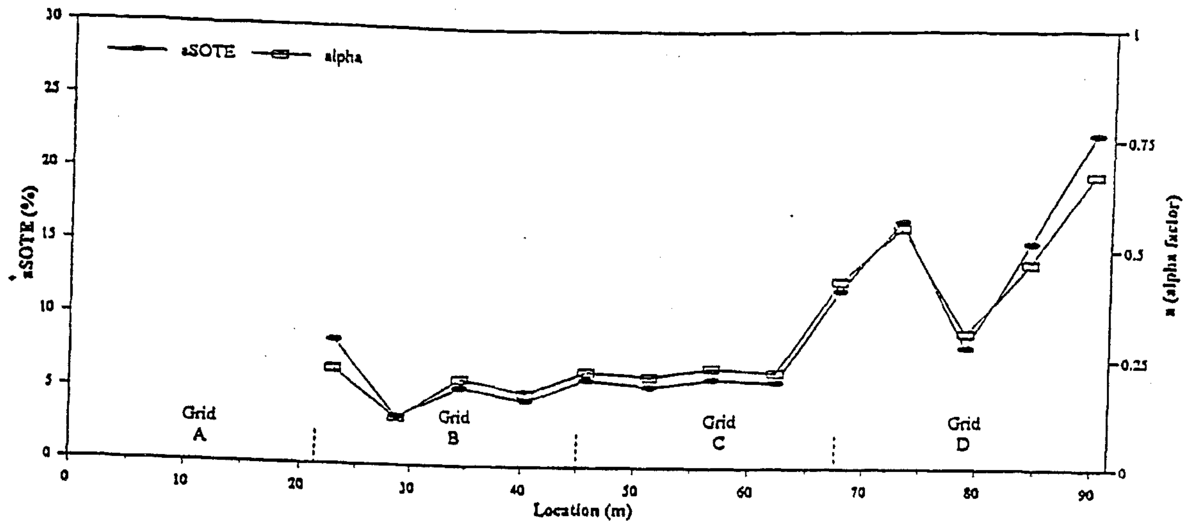


(b) Dissolved oxygen and air flux

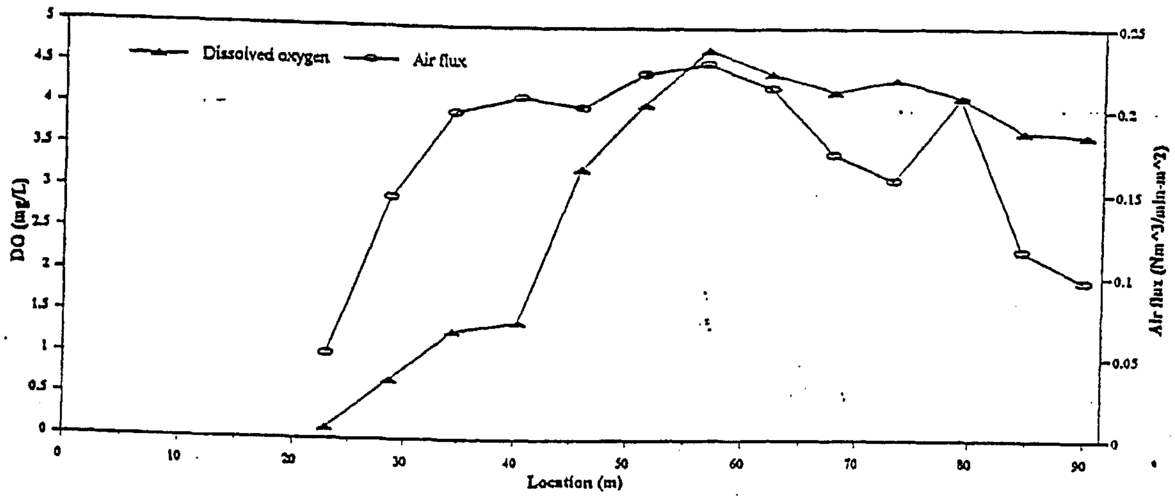


(c) Air flow rate and DO as functions of time averaged over partions

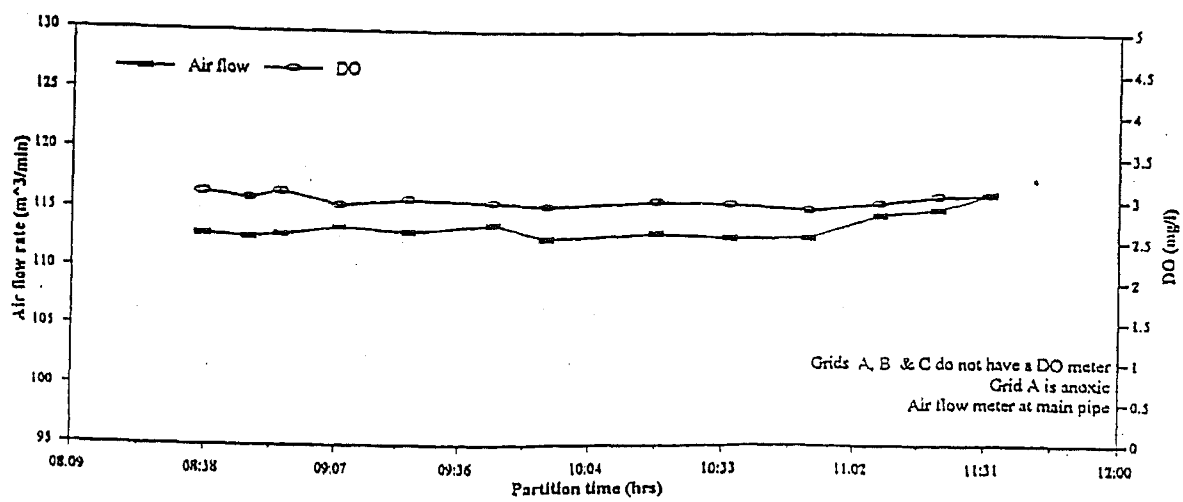
Figure 5 - Offgas Data for Grids A, B, C and D (interior & gaps and edges) of Tank 4 at TITP, 08/12/98, (7:00AM-5:00PM)



(a) Efficiency and alpha factor

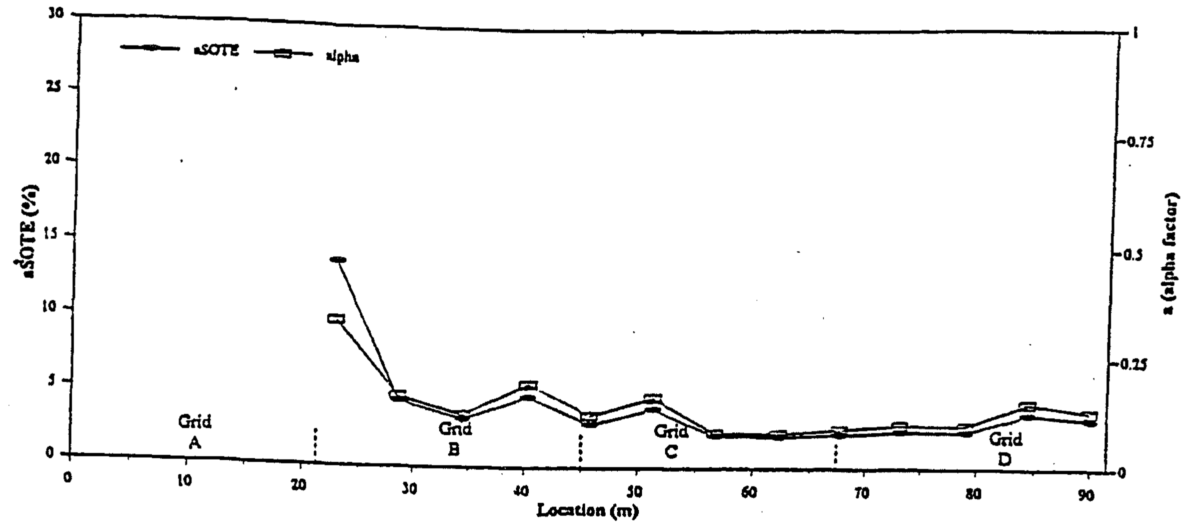


(b) Dissolved oxygen and air flux

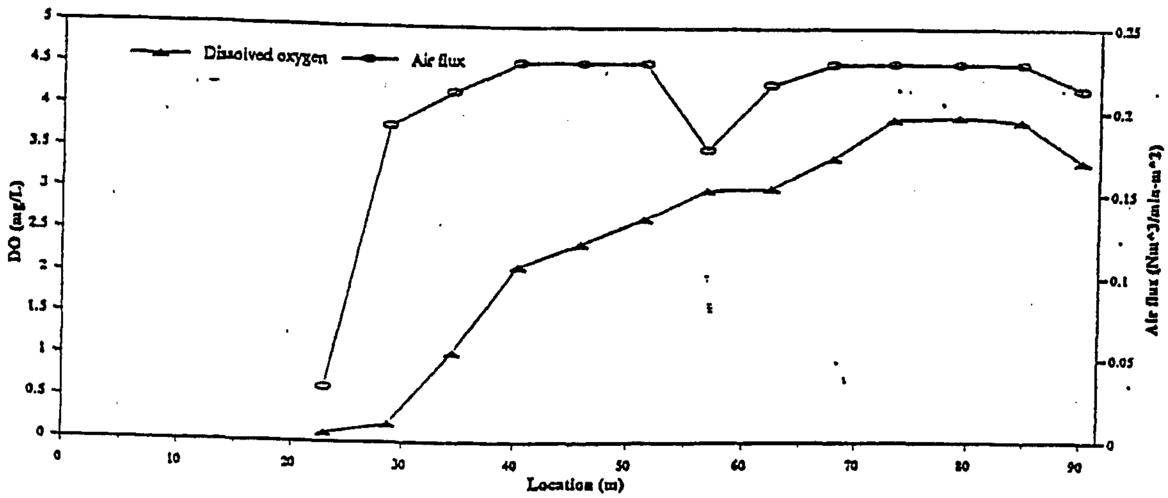


(c) Air flow rate and DO as functions of time averaged over partions

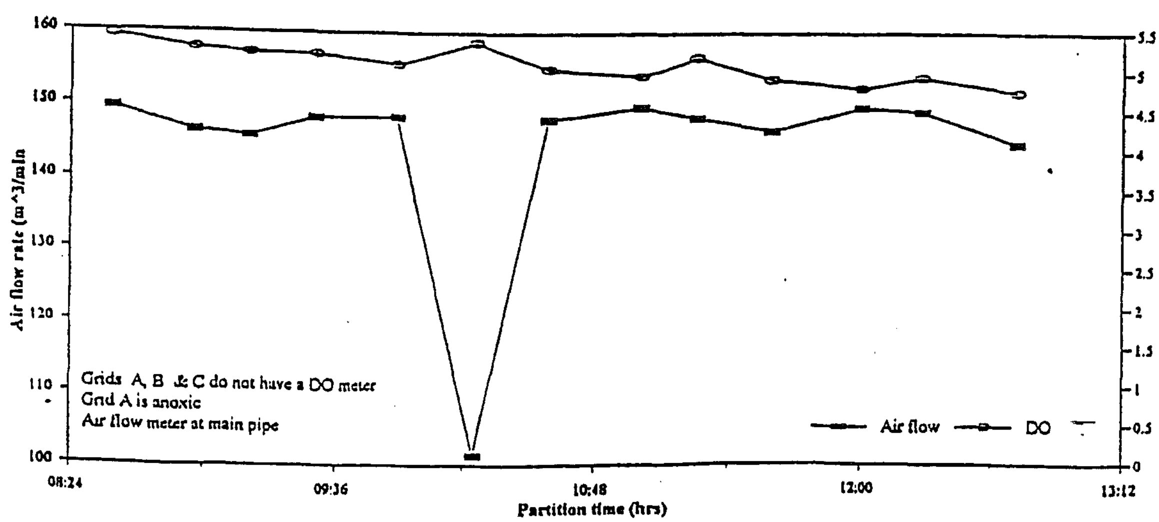
Figure 6 - Offgas Data for Grids A, B, C and D (interior & gaps and edges) of Tank 5 at TITP, 08/25/98,(7:00AM-5:00PM)



(a) Efficiency and alpha factor

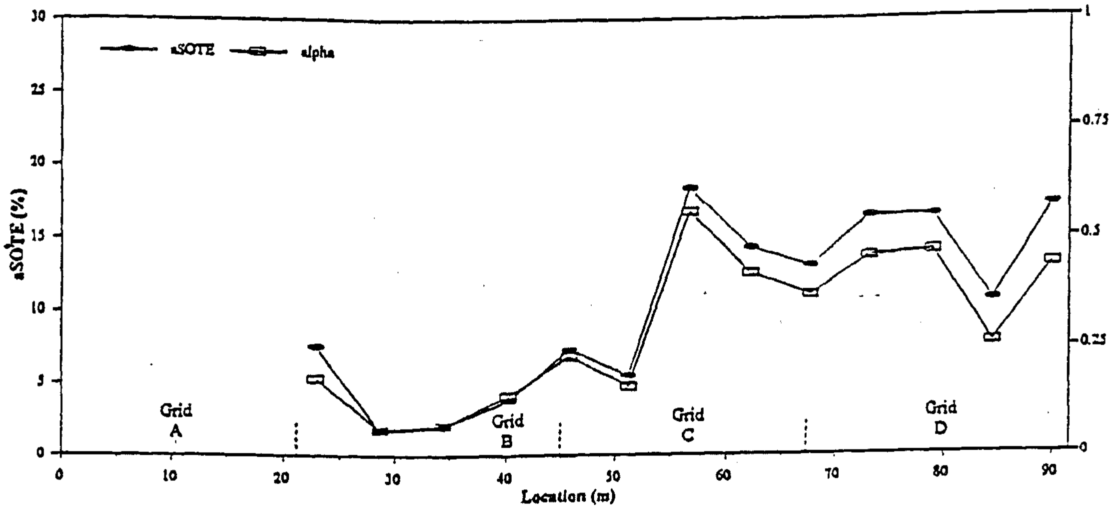


(b) Dissolved oxygen and air flux

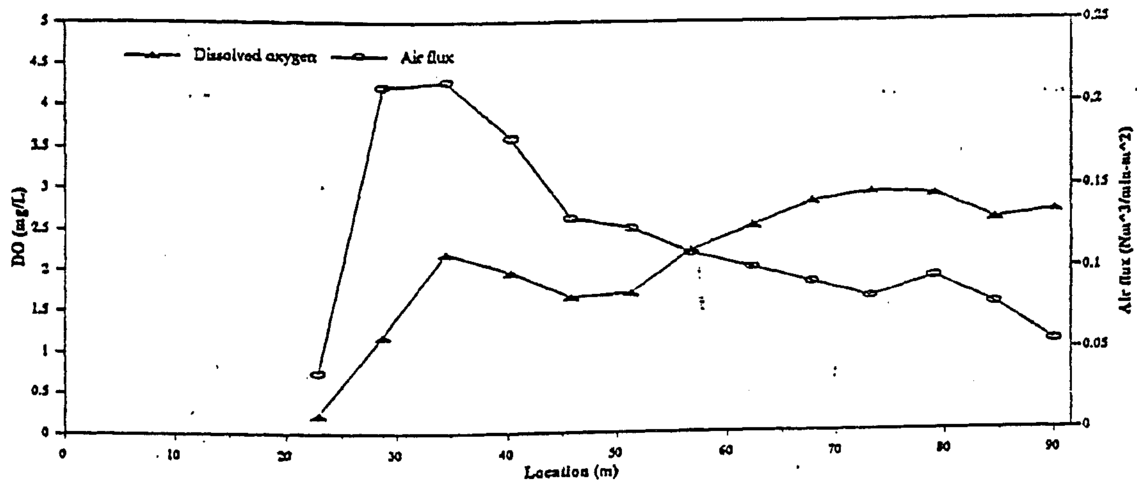


(c) Air flow rate and DO as functions of time averaged over portions

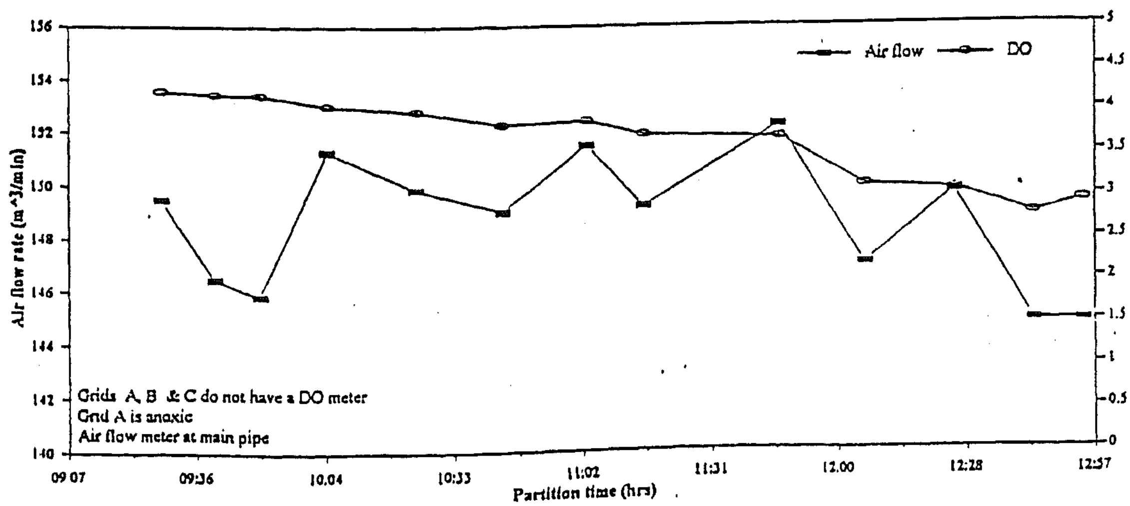
Figure 7 - Offgas Data for Grids A, B, C and D (interior & gaps and edges) of Tank 6 at TITP, 08/26/98, (7:00AM-5:00PM)



(a) Efficiency and alpha factor

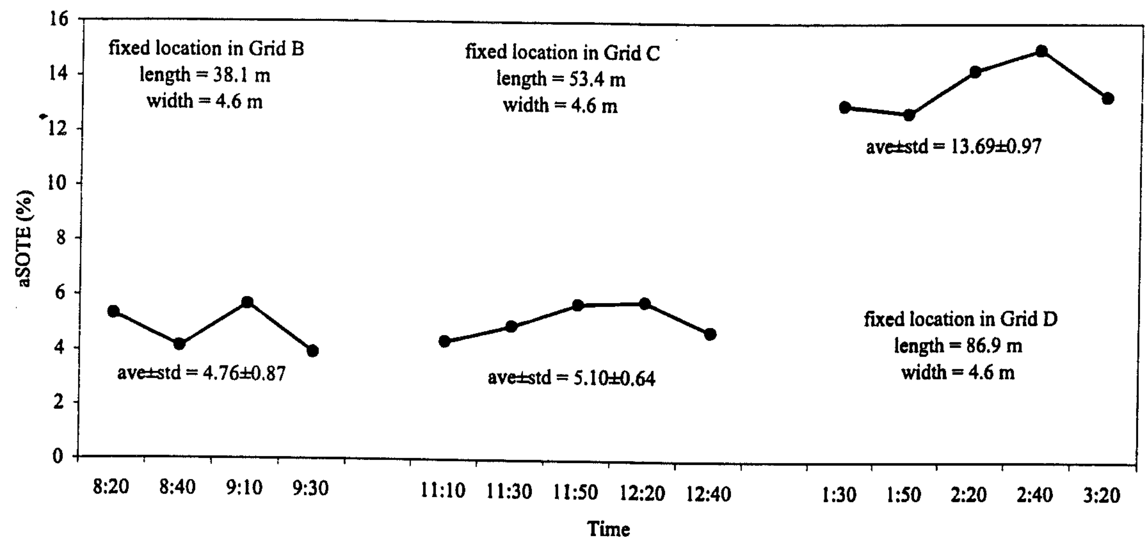


(b) Dissolved oxygen and air flux

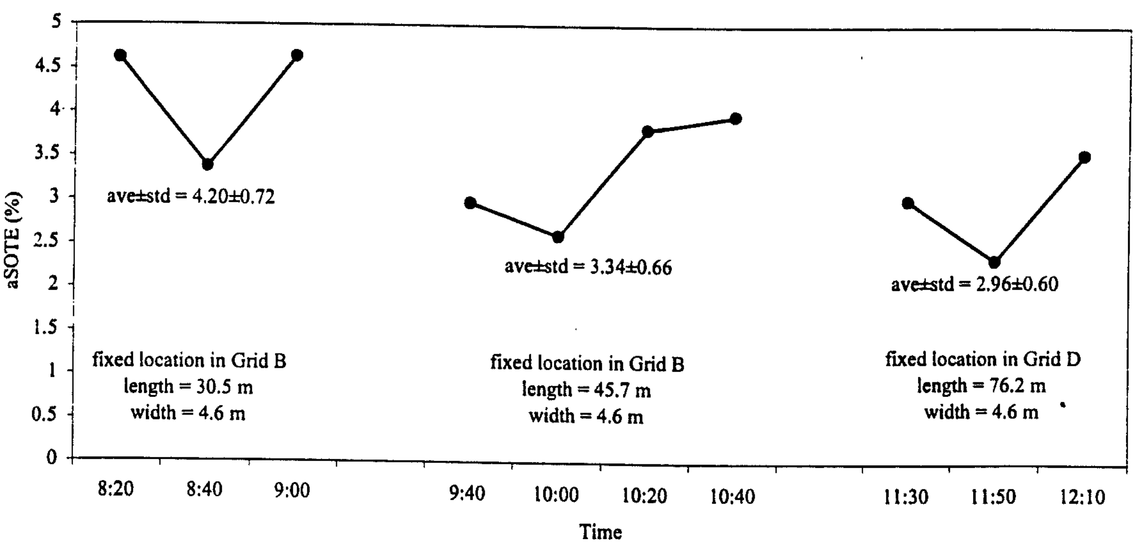


(c) Air flow rate and DO as functions of time averaged over partitions

Figure 8 - Offgas Data for Fixed Hood Locations



(a) Efficiency, Tank 4, 9/10/98



(b) Efficiency, Tank 5, 10/12/98