The role of respirometry in maximising aerobic treatment plant efficiency

Dr P. Spencer Davies (psd@strathkelvin.com) and Dr Fiona Murdoch (fm@strathkelvin.com)
Strathkelvin Instruments Ltd, 1.05 Kelvin Campus, W of Scotland Science Park, Glasgow G20 0SP

Wastewater treatment plants are coming under increasing pressure to increase their efficiency of operation. There are two objectives in this. The first is to reduce the cost of treatment. The second is a response to new legislation aimed at reducing the carryover of toxic materials to receiving waters. In order to achieve this, it is necessary to focus on the pivotal role of bacterial respiration in the aerobic treatment process. The importance of respiration in this context is that it is quickly and easily measurable. Using new technologically advanced respirometers it is possible to use respiration measurements for modelling the treatment process, for management of toxicity, and for measuring short term BOD, nitrification capacity, readily degradable BOD treatment capacity, and aeration requirements. Major increases in efficiency are most likely to come from more efficient process control and from the introduction of toxicity management plans for plants that treat industrial wastes.

INTRODUCTION

Pressure to increase the efficiency of operation of biological wastewater treatment plants is coming from two sources. Firstly, there is increasing awareness that the economic costs of treatment can be reduced if the plant is operating at full efficiency. Computer modelling of treatment processes is making some progress, and this will lead to a better understanding of the underlying costs. Secondly, there is increasing pressure to improve the quality of effluents that are discharged, and in particular to minimise the carryover of toxic chemicals, which have not been removed in the course of treatment. Respirometry is an essential tool for both efficient process control and for managing the toxicity of those plants that treat toxic industrial wastes.

In the highly regulated environment in which the wastewater industry operates, changes in operating procedures often follow from changes in legislation. The Water Framework Directive (2000) seeks to improve the quality of receiving waters. In addition to regulating the discharge of BOD, COD, ammonia etc, which can directly influence eutrophication, toxic substances in effluents will be more tightly regulated. In particular IPPC licences will, in future, include provision for measuring the toxicity of the effluent to the actual organisms of the receiving waters. This will involve use of the new Direct Toxicity Assessment (DTA) tests that have recently been approved by the Environment Agency and SEPA. Clearly if toxicity entering a treatment works is not removed by the activated sludge bacteria, there will be failed discharge consents. The main reason for failure to remove toxicity, is that the bacteria themselves have been poisoned by the toxic chemicals, and are unable to function effectively. Legislation to regulate the discharge to public sewer of substances that will harm the functioning of a biological treatment works is contained in schedule 4 of the Urban Wastewater Treatment (England & Wales) Regulations, 1998. However, although effective procedures to measure influent toxicity and its effects upon the bacteria, are now available, the regulations are still not being effectively applied.

Exceptionally, treatment works operated by some of the larger manufacturing companies do regulate influent toxicity in order to maximise process control and minimise treatment costs. By so doing, they are also able to ensure that their discharged effluents are of high quality, and therefore to not attract the unwelcome publicity associated with failed consents.

Probably the most sensitive indicator of toxicity is inhibition of the respiration rate of the activated sludge. As will be shown below, when respiration is inhibited, the rate of biodegradation of the sewage is reduced. Respirometry therefore has an important role to play in detecting toxicity and in process control.

BIOLOGICAL PROCESSES OF ACTIVATED SLUDGE

Activated sludge is a flocculent mixture of micro-organisms, mainly bacteria, which degrade multiple substrates in order to grow. They consume oxygen, and this is conventionally referred to as respiration. Respiration is intimately linked to both growth of the activated sludge and to biodegradation.

Respiration. The bacteria of the activated sludge are of two types. These are the chemiautotrophs (mainly nitrifiers, which take in ammonia) and the heterotrophs (which consume the organic carbon of the BOD). The ways in which they use oxygen is quite different. The nitrifying bacteria, chiefly Nitrosomonas and Nitrobacter, oxidise ammonia to nitrate and then to nitrite. The stages are:

$$\mathbf{NH_3 + O_2} \quad \underset{\textit{Nitrosomonas}}{\text{®}} \quad \mathbf{NO_2 \;+\; O_2} \quad \underset{\textit{Nitrobacter}}{\text{®}} \quad \mathbf{NO_3}$$

This process is not strictly speaking, respiration. True respiration is only displayed by the heterotrophic bacteria. Respiration involves the breakdown of simple organic carbon molecules, and the end product is carbon dioxide and water. (However, the combined rates of oxygen uptake by the both types of bacteria, is usually referred to as the respiration rate of the activated sludge.) What both processes have in common is that they yield energy. Some of this energy is used in keeping the bacteria alive.

Growth. The major use of the energy made available in respiration is for the biosynthetic chemical reactions involved in growth. These require a supply of organic carbon molecules (and others such as nitrogen and phosphate -containing molecules) in addition. There is a proportional link between the carbon and energy, and if either is limiting, growth is restricted accordingly.

Biodegradation. For both respiration and growth, the bacteria need to take in carbon and other nutrients. In nitrifiers, the carbon is taken up as inorganic carbon dioxide, and organic carbon compounds are synthesized inside the bacteria. Heterotrophs need to take in organic carbon compounds. Small molecular weight compounds are taken in quickly. These are the so-called readily biodegradable compounds of the sewage. Other larger molecules need to be broken down outside the bacteria into small compounds in order to be taken up. This is a slow process, often taking many days to accomplish. These large and often complex molecules are the less readily biodegradable compounds. The process of breakdown and uptake of these carbon compounds, (and of ammonia by nitrifiers), is biodegradation.

Respiration rate as a predictor of biodegradation rate. In heterotrophic bacteria, the carbon taken up is divided between that which is broken down in respiration and that which is built up into macromolecules for growth. The relationship between respiration, growth and total carbon uptake (which equals biodegradation) is shown in Figure1 below:

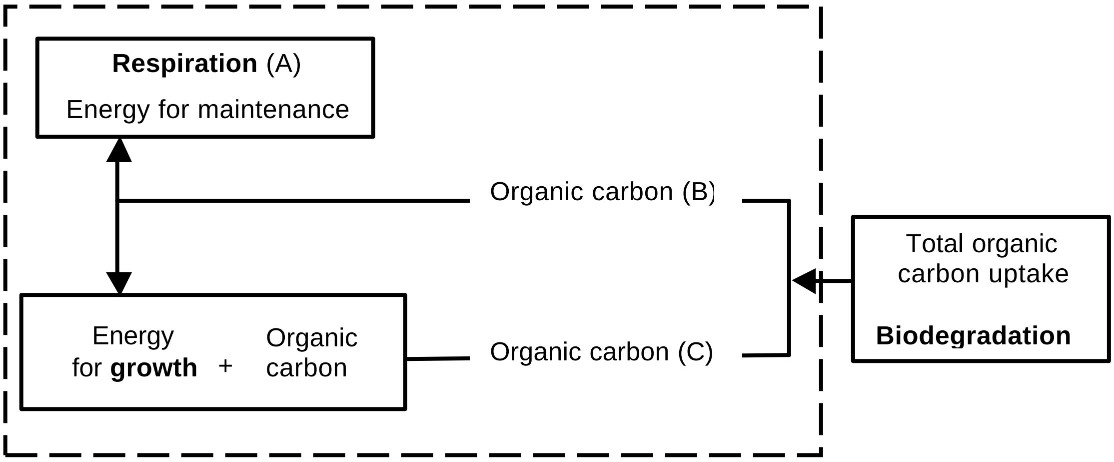


Figure 1 Simple model showing the relationship between respiration, growth and biodegradation in heterotrophic bacteria.

By measuring the respiration rate (A), it is possible to calculate the amount of organic carbon (B) that is being used to provide energy. A can therefore be used to predict B. Respiration rate (A) can also be used to predict the energy used in growth. It can be assumed that there is a proportional relationship between this energy and the amount of carbon being used in growth (C). A can therefore be used to predict C also. B + C equals the total carbon uptake, which equals the rate of biodegradation. Since Respiration rate (A) predicts B and C, it can be used to predict rate of biodegradation.

The situation in nitrifiers (Figure 2) is simpler, since oxygen uptake rate provides a direct measure of ammonia biodegradation.

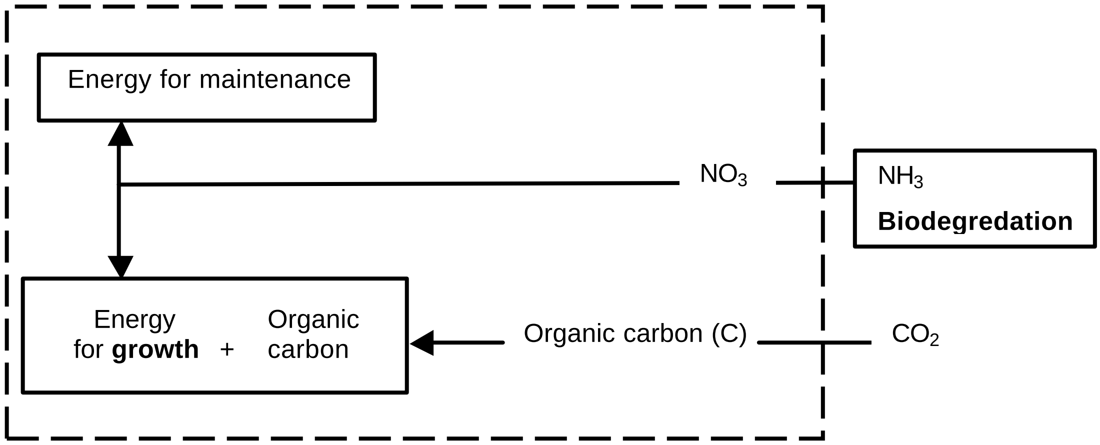


Figure 2 Simple model showing the relationship between oxygen uptake rate and biodegradation of ammonia in nitrifying bacteria.

These two models serve to show the central role of respiration rate (or more strictly, oxygen uptake rate) in the aerobic breakdown process.

Effects of toxicity. In heterotrophic bacteria, toxic compounds in wastewater can inhibit either growth or respiration. Because of the tight linkage between respiration, growth and biodegradation indicated in the model (Figure 1), it can be seen that if growth is inhibited, the requirement for energy will decrease, and the respiration rate will be reduced. Since less carbon will be required for respiration, the rate of carbon uptake or biodegradation will decrease. At the same time, the amount of carbon which is incorporated in growth will be reduced. This will also lead to reduced biodegradation. Conversely, if the toxin inhibits respiration, the amount of carbon for respiration will be reduced, leading to reduced biodegradation. A decreased supply of energy from respiration will result in a reduced growth rate, and hence a lowered rate of carbon uptake or biodegradation. From this it is seen that wherever the toxicity acts, there is inhibition of both respiration rate and rate of biodegradation.

Nitrifiers are particularly prone to inhibition by toxic substances. Again from the model (Figure 2), it can be seen that inhibition of either growth or the energy yielding oxidation reactions, will result in a decrease in both oxygen uptake rate and in rate of uptake biodegradation of ammonia.

Substrate availability and respiration rate. From Figure1 it can be seen that with heterotrophic bacteria, availability of organic carbon in the sewage can limit the rates of both respiration and growth. Sometimes in the course of aerobic treatment the heterotrophic bacteria may completely remove the biodegradable organic carbon or BOD. In this situation, the bacteria are not growing, and therefore are not using energy for growth. Not unexpectedly, they have a low respiration rate. This is called the Endogenous Respiration Rate, and represents the energy requirement for maintenance of the living bacteria. The carbon to provide this energy comes initially from storage compounds. When these are exhausted, it is obtained by autodigestion of internal cell components.

When activated sludge that is in the endogenous state comes into contact with sewage, the respiration rate rises rapidly, over a matter of minutes, to a higher level (Figure 3). The bacteria are now taking up the readily biodegradable molecules and growing at their maximum rate. The respiration rate is a measure of the rate at which they are using energy for growth. This rate of respiration is the *Maximum Respiration Rate* and has two underlying components: the endogenous rate and the growth-stimulated respiration rate. The carbon for the endogenous component of the respiration rate is now simply a part of the total organic carbon uptake. For completeness, it should be mentioned that if ammonia is present, and there are nitrifying bacteria in the sludge, part of the increased oxygen uptake is due to the oxidation processes of nitrification.

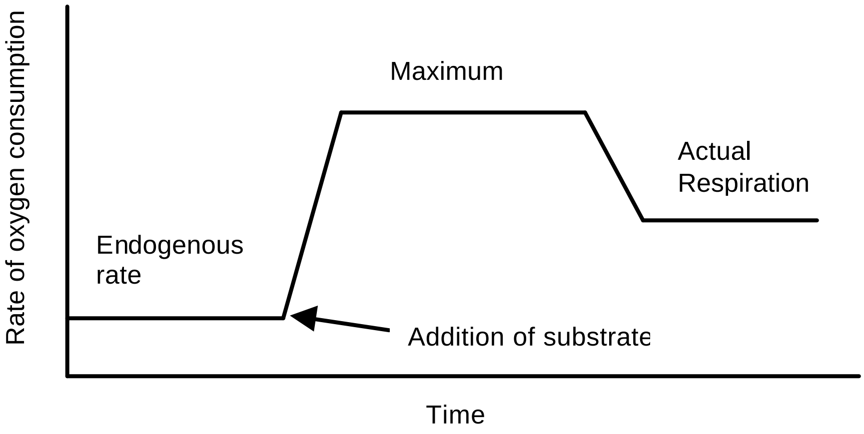


Figure 3 Graph showing the rapid increase in respiration rate, from the endogenous rate to maximum rate, when activated sludge is exposed to substrate (sewage).

When the readily biodegradable carbon compounds have been exhausted, the respiration rate will reduce, but to a higher level than the endogenous rate. The rate-limiting step now is the rate at which the bacteria can break down the less readily degradable compounds in the sewage into the smaller molecules that can be taken up. At any given time, in an aeration basin, the respiration rate of the sludge will be somewhere between endogenous and the maximum, depending on the concentration of biodegradable substrate available. This rate of respiration is sometimes referred to as the *Actual Respiration Rate.*

APPLICATION OF RESPIROMETRY AT SEWAGE TREATMENT PLANTS

The oxidative processes of respiration and nitrification that underlie the breakdown and removal of organic carbon and ammonia can be measured by respirometry. In process control, oxygen uptake rates can be used to model the aerobic treatment process and to manage toxicity. In addition, respirometry is used to calculate short term BOD, to predict BOD treatment capacity, aeration requirements and nitrification capacity.

Modelling. Respiration rate is used as the most sensitive variable in detailed modelling of activated sludge process theory (1,2,3). An example of this is presented to model the effects of toxicity on the effluent quality of a wastewater treatment plant. The model uses the Activated Sludge Model No. 1 (4) and process layout and influent pattern of the COST 624 simulation benchmark (5,6,7). The treatment plant comprises completely mixed aeration tanks and a secondary settlement tank. The toxic substance, two concentrations of which are investigated, is non-biodegradable and causes inhibition of the respiration rate.

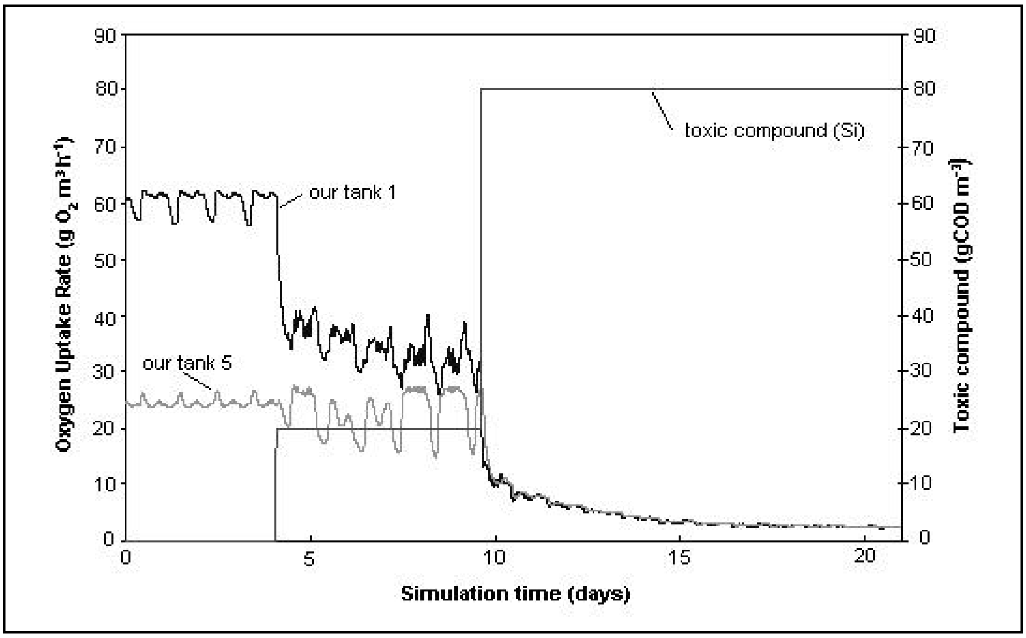


Figure 4 Computer model simulation of the effect of influent toxicant on respiration rate in 1st and 5th aeration tank (7).

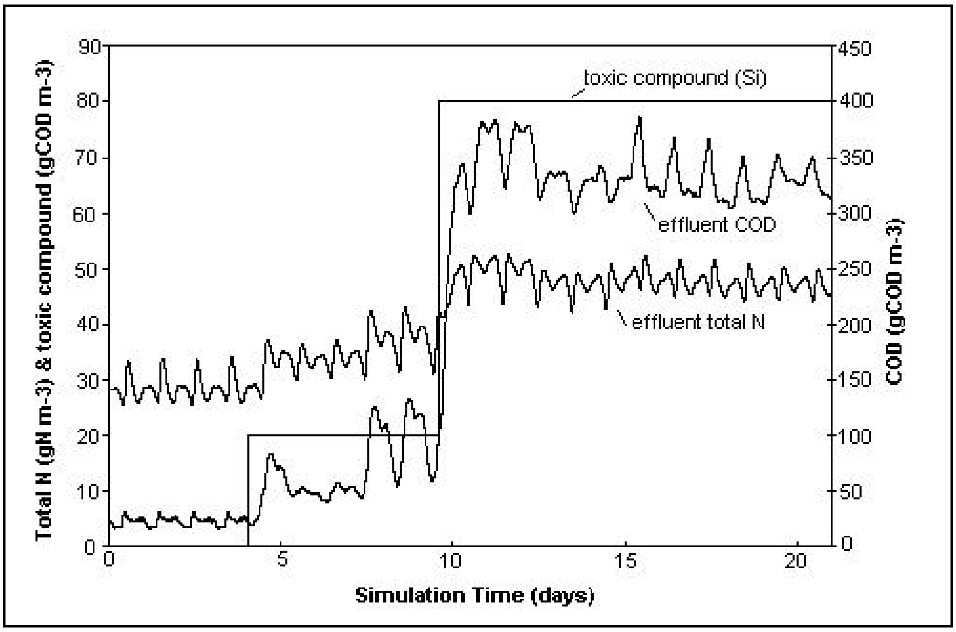


Figure 5 Computer model simulation of the effect of influent toxicant on effluent N and COD concentrations (7).

The model predicts that at the lower concentration of the toxin, there would be a 50% decrease in respiration rate which would result in a 3-4 fold increase in the effluent COD (Figures 4, 5). If the toxin concentration is increased 3-fold, the respiration rate would be inhibited by 80%, resulting in a consequential increase in effluent COD of 150%. The computer model may be used to simulate other causes of changes to the respiration rate of the activated sludge, and offers a lot of potential for improved process management.

Short term BOD. Measures of respiration rate may also be used as an indicator of short term BOD (BOD$_{st}$)(7). The traditional measurement of BOD (BOD$_5$) involving a 5-day incubation period of the wastewater in the presence of bacteria, was originally introduced to minimise eutrophication in receiving waters (8). However, BOD measurements over such a long time-frame are not useful in assessing the biodegradability of organic matter passing through a wastewater treatment works. BOD$_{st}$ uses activated sludge biomass of the treatment plant and aims to measure the biodegradable BOD. It is carried out by measuring the increase in oxygen consumption when a small amount of influent wastewater is added to activated sludge in the endogenous state, in a closed chamber(7). BOD$_{st}$ measures oxygen uptake due to both nitrifiers and the heterotrophic bacteria as in the BOD$_5$ test. Attempts at correlating BOD$_{st}$ and BOD$_5$ are futile, since the discrepancy is simply an indication of the relative amount of non-readily degradable material in the wastewater (7). BOD$_{st}$ should, therefore, be viewed as a tool for use in process control, rather than as a cost-saving predictor of BOD$_5$.

Loading predictions. Laboratory measurements of maximum respiration rate will quickly establish the maximum rate of readily degradable BOD breakdown achievable with the biomass in the tanks at any one time. Heavily increased loading can swamp the ability of the biomass to take this up within the retention time available. Prior knowledge of the rates of biodegradation of BOD with the biomass available can therefore be used to optimise process control.

Other uses. Measurement of maximum respiration rate of activated sludge has been used for monitoring and process control (9), for determination of maximum aeration capacity (10), and for estimation of biomass viability and concentration(9,10,11). However, it has been argued that a better estimation of biomass concentration is obtained by using the endogenous, rather than maximum rate of respiration (12). New developments in instrumentation will allow rapid measurement of nitrification capacity of activated sludge.

Finally, for those treatment works that accept industrial effluents, respiration rate measurements can be used as the basis of a toxicity management plan. This may offer immediate returns in maximising aerobic treatment plant efficiency, when implemented. This is discussed in more detail below.

RESPIROMETRY IN TOXICITY MANAGEMENT

Until recently, the effects of toxicity on process control, has not received a great deal of attention. That is probably because of the unavailability of suitable instrumentation for measuring toxicity. A contributing factor has also been that evidence for the effects of toxicity has been largely anecdotal. However a major study on the effects of industrial toxicity on plant performance at the Antwerp sewage treatment works has recently been published(13). It was found that there was almost continuous respiration inhibition over a 10-day monitoring period. The average inhibition was about 10%, with peaks of up to 30%. In a second study on the plant, peaks of up to 43% inhibition were observed, and this was accompanied by a substantial washout of solids. Studies on toxicity effects at other plants have also been published (14,15,16).

With increasing pressure from the regulators to ensure that toxicity is not discharged in treatment plant effluents, it is opportune for managers to introduce formal toxicity management plans within the operational procedures for sewage treatment. There are four stages to any such toxicity management plan:

Prevention. This is particularly important for plants that receive discharges by sewer from multiple industrial sources. Even if tightly regulated there is still the possibility of a highly concentrated slug entering the tanks. The only way to guard against this, is by the installation of an early-warning device such as an on-line respirometer. Ideally, the device should sound an alarm and divert the flow into a storage tank for the duration of the flow of the toxic slug. At the present state of technological development, early warning devices of this sort are relatively costly and are prone to giving false positives(17).

Prevention is also important for treatment works that accept tankered waste. Here the problem is simpler, since a sample of the waste can be taken at point of delivery and its toxicity measured with a laboratory respirometer. Ideally, if the tanker contains a concentrated toxic waste, it should be discharged initially to a storage tank. From here it can be fed into the plant at a rate determined by the level of its toxicity. This approach would enable plant managers to devise a treatment-charging scheme that would take into account the actual toxicity of the waste and any additional costs of treatment.

Toxicity Monitoring. Even with an early-warning device in operation, and certainly in the majority of cases where these are not deployed, toxic compounds may find their way into the aeration tanks. Here, chronic toxicity will reduce the rate of respiration and the rate of biodegradation. Balanced against a possible saving in aeration costs, in a well controlled system, is the problem of failure to remove the BOD within the allotted flow time, resulting in breach of consent limits. Monitoring the respiration rate of samples of sludge on a daily basis in the laboratory of the treatment works, will alert the plant manager to problems with treatability, which may enable some remedial action to be taken.

Identification of toxic streams. If, as a result of toxicity monitoring, toxic wastes are found to be affecting treatment processes, it is necessary to try to find where it is coming from. This involves toxicity tracking, by sampling at various places in the sewer line, to locate the source of the toxic streams. These samples would be analysed with a laboratory respirometer using the sludge of the receiving works. Tracking may be extended into the offending manufacturing plant in order to locate the process stream containing the toxic compounds. Armed with data of this sort, the receiving treatment plant manager has the ability to impose a toxicity-based consent, and/or to revise the tariff for treatment. The Mogden formula is deficient in that it makes no allowance for the additional costs of treatment of toxic waste.

Toxicity Reduction. When the source of the toxicity in a manufacturing plant has been identified, toxicity reduction procedures can be instigated at source. These would initially be carried out on a pilot scale. The effectiveness of the procedures can be quickly tested alongside the pilot operations, using a laboratory respirometer.

RESPIROMETERS: ON-LINE AND LABORATORY

On-line and laboratory respirometers have complementary roles in toxicity management. Laboratory respirometers have an additional role to play in process control and management.

On - line respirometers and other early warning devices. A review of available early warning devices and their efficiency has been published recently in the USA by a WERF working party, together with recommendation for further developments(17). Ideally, on-line respirometers should be continuous, taking measurements in real time. However, a number of systems, by the nature of the measurement principles, are discrete sampling systems. At the time of installation of on-line monitors, storage facilities need to be built, in order to contain the diverted toxic waste. Such waste is normally treatable. However, the extent of the toxicity has to be determined, using a laboratory respirometer, in order to calculate the rate at which it should be fed into the treatment tanks, to achieve a dilution at which it will no longer cause a toxic effect. Currently, on-line systems are prone to generating false positives, and they require some care in their operation. Examples of on-line monitors which are in use in European countries are Rodtox, Stiptox, Minworth and Manotherm, whilst Amtox measures nitrification inhibition only.

Laboratory respirometers. The earliest laboratory respirometers (18) attempted to replicate aerobic tank conditions on a pilot scale, and involved open containers of activated sludge. The problems associated with diffusion of oxygen through the air/water interface were subsequently overcome by using closed containers for the sludge. As the bacteria respire, the decrease in oxygen is sensed either by a manometric device in the air space above the liquid, or by an oxygen electrode inserted into it. Oxygen electrodes have the advantage that they do not require an air space. As a result, the sludge can completely fill the respirometer chamber, so reducing the total amount of oxygen present at the start (since there is approximately 30 x as much oxygen in a given volume of air in comparison to water) and increasing the sensitivity of the measurements. Respirometers that are used for long term studies on biotreatability require to have the respired oxygen replenished. This may be achieved either by electrolytic generation of oxygen or by bleeding in small quantities of the compressed gas.

The earliest oxygen electrode-based respirometers, used a single electrode. In order to obtain replicate respiration rate values, or to measure respiration rates under different treatments, these respirometers require a re-aeration phase to return the sludge to the starting oxygen concentration, at the end of a respiration run. The consecutive cycles of depletion and re-aeration are usually referred to as respirograms.

In order to reduce the time taken to obtain data, Strathkelvin Instruments developed a 6 - electrode activated sludge respirometer (Figure 6). With associated software and protocols, it was designed to offer speed, simplicity and accuracy in operation. The six oxygen electrodes are precision microcathode Clark-type electrodes. They are housed inside special electrode holders, which seal the 20ml sludge samples from the atmosphere. Despite the heterogeneous flocculent nature of activated sludge, variation in respiration rates between 6 samples from the same batch is small. Furthermore, the respiration rates measured on these small sample volumes are almost identical to those measured in 1litre samples of sludge.

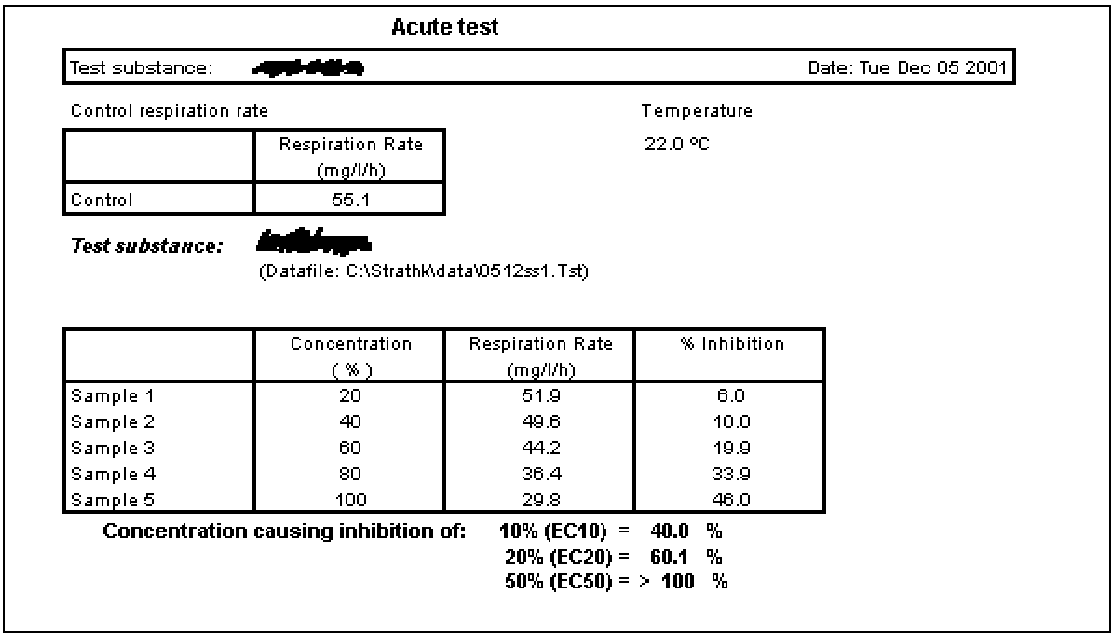
Figure 6 The Strathkelvin Activated Sludge Respirometer which utilises 6 oxygen electrodes connected via an interface to the pc loaded with dedicated respirometry software.

As the sludge respires, the decrease in oxygen in the respirometer cells is displayed on the computer screen. A complete respiration run occupies no more than 5 - 10 minutes, after which, the software analyses the data and produces a detailed report in spreadsheet format. By developing a suite of protocols, each supported by dedicated software, it has been possible to develop the full versatility of respirometry in process and toxicity management at wastewater treatment works. For instance, the respirometry program may be used for monitoring of sludge health or for calculating the maximum treatable BOD, whilst the toxicity test programs can be used for measuring total or percentage respiration inhibition. A recent development has been the addition of procedures and software to produce rapid measures of nitrification inhibition and inhibition of the heterotrophic BOD-degrading bacteria caused by industrial wastewaters.

In nitrification inhibition and respiration inhibition tests, the Report which is produced, is a fully audited locked spreadsheet, showing values for the EC_{50}, EC_{20} and EC_{10} i.e. the concentrations of wastewater which produce a 50%, 20% or 10% inhibition of the oxygen uptake rate. These values can be used by the treatment plant manager to determine the rate at which the wastewater should be allowed to enter the plant.

CASE STUDY: RESPIRATION INHIBITION TOXICITY TEST

Respiration inhibition tests are particularly important for managers of treatment facilities that accept contract tankered wastes. This is because a test, using activated sludge of the treatment works can be quickly carried out, upon arrival of the tanker.



Acute test

Test substance: [redacted]	Date: Tue Dec 05 2001

Control respiration rate

	Respiration Rate (mg/l/h)
Control	55.1

Temperature

22.0 °C

Test substance: [redacted]

(Datafile: C:\StrathK\data\0512ss1.Tst)

	Concentration (%)	Respiration Rate (mg/l/h)	% Inhibition
Sample 1	20	51.9	6.0
Sample 2	40	49.6	10.0
Sample 3	60	44.2	19.9
Sample 4	80	36.4	33.9
Sample 5	100	29.8	46.0

Concentration causing inhibition of: **10% (EC10) = 40.0 %**
20% (EC20) = 60.1 %
50% (EC50) = > 100 %

Figure 7 An example of a test report page, showing the EC_{50}, EC_{20} and EC_{10} values that are used to predict the effects of waste streams on plant performance.

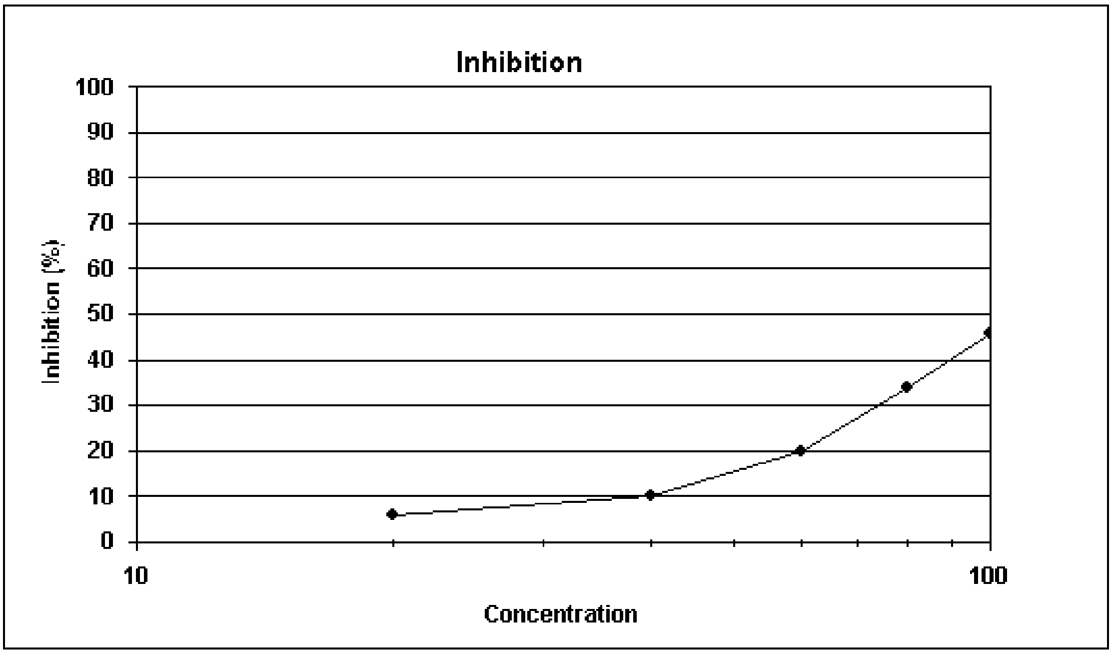


Figure 8 The plot of respiration inhibition v wastewater concentration, from the Report.

In the extract of the Report shown above (Figure 7, 8), it can be seen with a 100% concentration of the wastewater, the respiration rate is inhibited by 46% relative to the control. The EC_{50} is >100%, EC_{20} is 60% and EC_{10} is 40%. These values show that the wastewater is toxic. The plant manager can then use these data, together with knowledge of the dilution that would be achieved when added to the aeration tanks, to work out the rate of discharge to achieve a minimal and acceptable level of inhibition. In the study carried out at Antwerp sewage treatment works, a 10% inhibition did not appear to affect the quality of the effluent. At the present state of knowledge, it is not possible to tell what level of inhibition is acceptable. In the future, it is possible that the application of respirometry in association with process control models, such as that shown above, will be used to make a more informed decision.

Because of its close relationship to both biodegradation and growth of biomass, respiration rate is a key parameter in process control at treatment works. Paradoxically, it has not been widely use. This is partly because respirometry has been a slow and fiddly technique. However, with the advent of technically advanced computerised respirometers the procedures are now fast, accurate and with wide applications. Respirometry is now being used in procedures ranging form short term BOD measurements and toxicity management, to nitrification capacity checks. It is clear that in the future it will have a significant role to play in the optimisation of process control, in order to increase the efficiency of sewage treatment plant operation.

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