Monitoring and control of anaerobic digestion*

WR Ross** and JM Louw

National Institute for Water Research, P.O. Box 109, Sanlamhof 7532, South Africa

Abstract

Digesters treating industrial wastes are frequently subjected to fluctuations in both waste composition and organic load, thus necessitating special precautions on the part of the operator to prevent metabolic overloading of the micro-organisms. This paper describes various sensitive indices of digester stability relevant to effective process control and operating reliability at high load rates.

Introduction

Anaerobic treatment of soluble organic industrial wastes is often regarded as an unstable process by engineers, especially when compared with aerobic sewage treatment. Given the particularly complex, concentrated and fluctuating nature of anaerobic substrates and the higher space loading rates required by these systems, it is clear that anaerobic digestion will be a sensitive process. However, it need not be unreliable if properly controlled.

Aside from mechanical failure, the two principal causes of digester failure are:

- metabolic overloading of the micro-organisms and consequent pH drop; and
- loss of biomass.

Whatever the cause of failure, the ultimate result is a retardation or even complete cessation of gasification. Subsequent reactivation is often time-consuming owing to the slow growth rate of rate-limiting bacteria, such as the methanogens. The onus therefore rests both on the designer to provide reliable control arrangements and on the operator to devise overall control strategies to minimise an overload risk.

The present paper examines a number of sensitive indices of imminent overload and consequent performance loss. These parameters have proved effective for process control. While the emphasis has been laid upon suspended-growth systems for soluble waste treatment, the concepts discussed are also of relevance for anaerobic systems treating solid wastes such as sewage sludge and manures.

Relationship between cation availability and substrate buffer potential

The degree of process control required for treating a given industrial waste is largely governed by its chemical composition. Cation availability is particularly important since it determines the alkalinity of pH of the digester system. Thus, e.g. nitrogenous compounds are decomposed and reduced to ammonia, a proportion of which is metabolised by the process organisms while the remainder is combined with the liberated carbon dioxide to produce stable inorganic compounds which act as buffers, e.g. NH_4HCO_3.

The influence of cation availability on buffer potential is illustrated in Figure 1 which gives data from anaerobic studies on various wastes of different COD. Thus, e.g. the low availability of nitrogen and other cations in brewery wastes (total cations, 2 me/ℓ) results in a digester effluent of low buffer capacity – insufficient to allow an acceptable safety factor for a high-rate process. Addition of alkali for pH control is therefore essential for systems with a natural alkalinity below 1 000 mg/ℓ as $CaCO_3$. If a sodium salt is used for pH control care must be taken not to exceed the reported sodium-ion inhibitory concentration of 3 500 to 5 500 mg/ℓ Na (McCarty, 1964).

In contrast, digesters treating wine distillery wastes (total cations, 160 me/ℓ) develop an alkalinity of 6 000 mg/ℓ as $CaCO_3$. This is due to the high potassium bitartrate feed concentrations and consequent release of potassium ions, available for buffering during digestion.

Volatile acid: alkalinity: pH ratios for digester control

As mentioned above, ammonium ion concentration plays an important part in determining the bicarbonate alkalinity or buffering capacity of the digester system. Increasing volatile acid levels are neutralised by the bicarbonate alkalinity and give rise instead to, as it were, 'volatile acid-salts' alkalinity. Under these conditions bicarbonate alkalinity can be approximated by means of the following formula (McCarty, 1964):

$$BA = TA - (0{,}85)(0{,}833)\,VA$$

Where:

BA = bicarbonate alkalinity (mg/ℓ $CaCO_3$)
TA = total alkalinity (mg/ℓ $CaCO_3$)
VA = volatile acid (mg/ℓ CH_3COOH)
0,85 = Only 85% of volatile acid-alkalinity is measured by titration of total alkalinity to pH 4.
0,833 = Convert volatile acid units to equivalent alkalinity units.

An increase in volatile acids over and above the available cation component of the alkalinity results in the formation of free volatile acids and partial destruction of buffering potential, accompanied by pH drop and decreased gas production.

The relationship between volatile acid level, alkalinity and pH determined in the course of a recent study on anaerobic digestion of brewery waste is illustrated in Figure 2 (Ross, 1985). It will be seen that a bicarbonate alkalinity deficit occurs at pH less than 5,8. Although probably the principal parameter governing the stability of the digestion process, pH is not a sensitive indicator since by the time the pH falls, alkalinity has already declined. Digester pH should if possible be held within the 6,8 to 7,2 range.

Relationship between pH and volatile acids dissociation index

A pH-dependent equilibrium exists between the ionised and un-

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**To whom all correspondence should be addressed.

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ionised volatile acid fractions in accordance with the equation

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+ \quad \ldots\ldots (1)$$

A drop in pH results in a leftward displacement of this equilibrium and a rise in un-ionised volatile acid concentration. The equilibrium relations described by Equation 1 are shown graphically in Figure 3. Kroeker *et al.* (1979) report data from the literature which reveal a definite increase in the likelihood of digester failure at un-ionised volatile acid concentrations above 10 mg/ℓ as acetic acid. Operators should generate their own instability data for process control purposes.

Measurement of micro-organism activity

Monitoring of the rate of gas production in the digester provides an immediate indication of the intensity of the digestion process. Under favourable conditions, any change in feed load should be reflected by a corresponding change on the gas recorder/integrator within the space of one hour. Figure 4 illustrates how micro-organism activity may be gauged from response of gas production to feed interruptions (Stander *et al.*, 1968). In an actively gassing system, angle θ_1 is small and equals angle θ_2, i.e. cessation of feed results in an immediate decrease in gas production. Likewise, recommencement of feeding results in an immediate increase in gas production. Overload situations on the other hand are characterised by bigger angles and a slower response to feed interruptions.

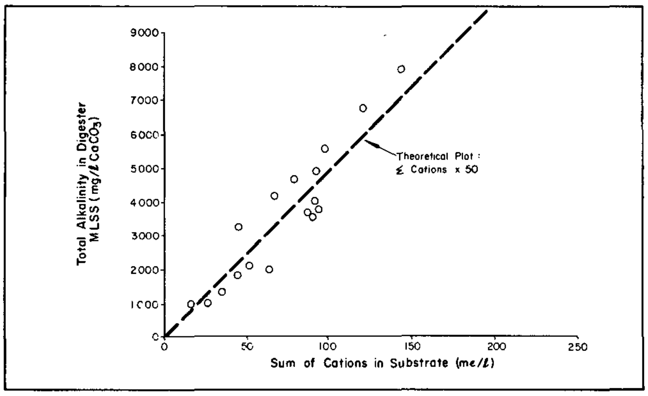

Figure 1
Relationship between available cations and buffer potential of substrate

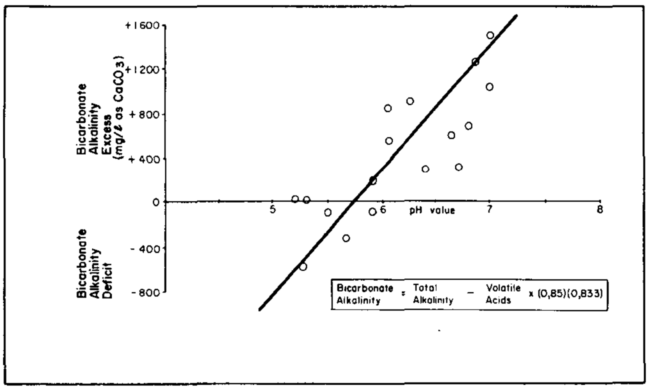

Figure 2
Relationship between alkalinity, volatile acid and pH value for anaerobic digestion of brewery waste

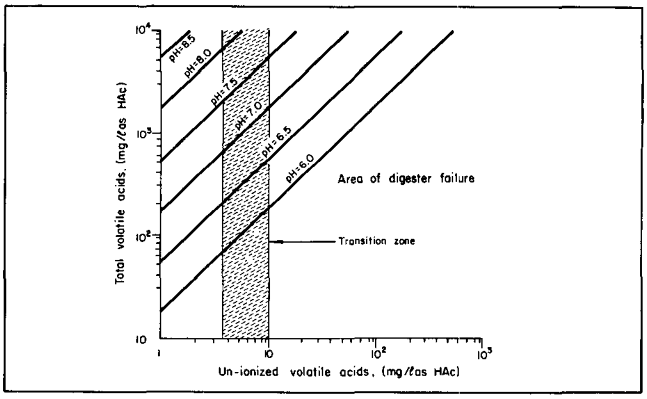

Figure 3
Relationship between pH and dissociation of volatile acids (after Kroeker et al., 1979)

Relationship between gas production and mass of COD utilised

The theoretical percentage daily conversion of organic matter (as reflected by COD) to gas has been shown to be a most useful biomass activity indicator, providing an early warning of incipient problems. A typical COD balance for an anaerobic digester (Ross *et al.*, 1981) indicates that percentage gas conversion is commonly in the 65 to 75% range for good digestion (biodegradable wastes) but falls below 50% whenever the volatile fatty acids exhibit an upward trend in excess of 500 mg/ℓ (steam distillation method). The residual COD of the filtered anaerobic effluent also affords a measure of the efficiency of the process.

Relationship between temperature and loading rate

Temperature is one of the principal factors affecting the metabolic activity of organisms and hence also the permissible load rate. Previous research (Stander *et al.*, 1968) confirmed that a temperature rise of 10°C results in a doubling of biological activity and hence also in permissible load rate over the mesophilic temperature range of 15 to 35°C and, conversely, a sharp decline in activity at 45°C (Figure 5). A sudden temperature drop in a high-rate system will result in an immediate overload with a concomitant increase in volatile acids. Under such conditions the feed rate must be reduced appropriately to compensate for the reduced metabolic activity of the organisms.

It is recommended that mesophilic digesters be operated continuously at a temperature as close as possible to 35°C. Heating and mixing of sludge must occur simultaneously because uniform heating of the digester contents is essential. Localised overheating or underheating zones are aggravated by inadequate mixing and should be avoided because the micro-organisms are

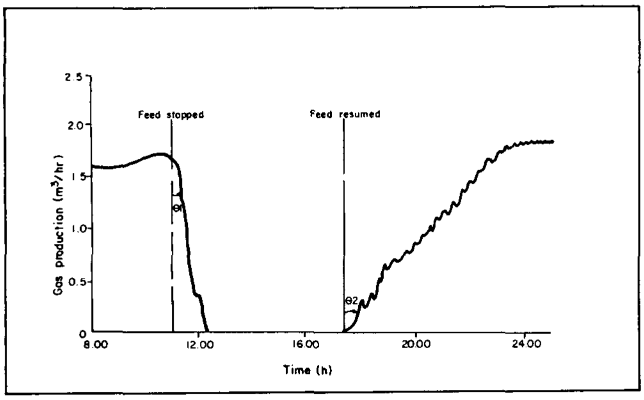

Figure 4
Gas production with temporary cessation of feed

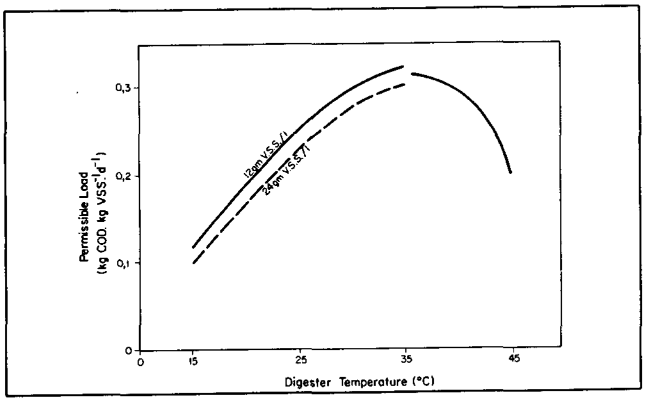

Figure 5
Relationship between temperature and permissible load rate

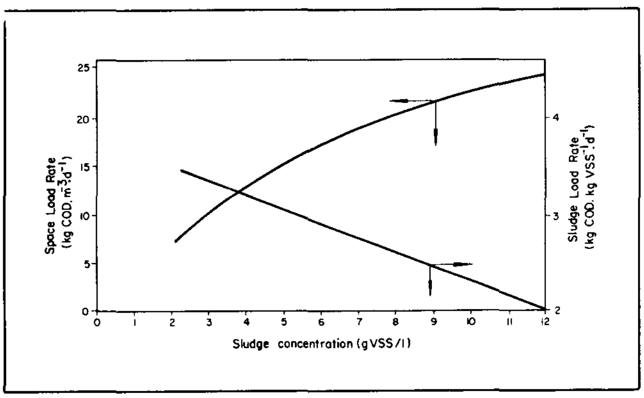

Figure 6
Relationship between sludge concentration and loading rates

sensitive to temperature changes. Indirect heating, e.g. by means of hot water coils or tubes is preferable.

Heating of the digester should not be dependent on digester gas as fuel and standby alternative fuel sources must accordingly be provided in order to ensure that adequate heating can be maintained even in the event of digester gas being unavailable, e.g. at start-up or during periods of interrupted feeding.

Relationship between sludge concentration and load rate

The load rate which is of economic interest to the designer is the space load rate (kg $COD.m^{-3}.d^{-1}$), governing the capacity of the digestion chamber. Recent research by Ross *et al.* (1981) indicated an increase in space load rate with increasing VSS concentration in the 3 to 12 g/ℓ range (see Figure 6). Space load rate is thus governed by both temperature and sludge concentration; both these parameters should accordingly be specified for comparative evaluation of different digestion systems.

Digester loading can also be expressed in terms of sludge load rate (kg $COD.kgVSS^{-1}.d^{-1}$). This parameter provides a measure of biomass activity level and is similarly dependent on sludge concentration. It will be seen from Figure 6 that the reverse is true of sludge load rate; higher values being observed at lower sludge concentrations.

The conclusion may therefore be drawn that higher sludge concentrations are desirable provided always that mixing efficiency and settling characteristics are not impaired. The crucial factor to be determined for sludges with inferior settling characteristics is the maximum solids concentration which will permit effective solids separation without impairing economical biological purification.

Indices for sludge settling characteristics

The weak point of anaerobic processes treating soluble organic wastes has generally been the inferior MLSS settling characteristics. Sludge settling characteristics govern not only maximum permissible MLSS concentration but also load rate and clarifier surface area. Whereas in conventional sewage sludge digestion the population of active organisms is continually replenished via the raw feed, industrial effluents seldom contain the biota necessary for digestion. Moreover if sludge synthesis is less than the sludge lost in the effluent, arrangements must be provided for efficient separation and return of active cell material from the effluent. Formation of dense, active sludge with good settling characteristics is thus a prime requisite for successful operation of a high-rate anaerobic system. Such sludges have been developed in unmixed plants, e.g. the Bellville glucose-starch clarigester (Hemens *et al.*, 1962) and the UASB beet-sugar process in operation in Amsterdam (Lettinga *et al.*, 1979)

Flux settling curves (Figure 7) and more periodic stirred-specific-volume tests have proved to be useful indicators of fluctuations in clarifier sludge settling characteristics for purposes of operational control (Ross *et al.*, 1981).

Relationship between load rate and sludge settling characteristics

Operational guidelines are required in order to optimise the biological and physico-chemical parameters governing load rates and sludge settling characteristics. Figure 8 schematically il-

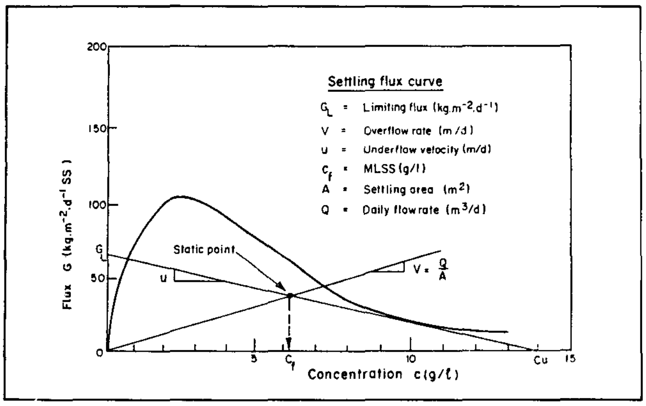

Figure 7
Flux curve as indice for sludge settleability

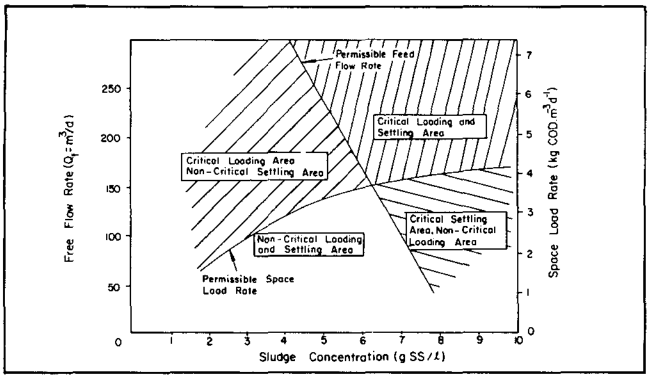

Figure 8
Operational guidelines for digester and clarifier

lustrates the interrelationships between daily feed rate, sludge concentration and permissible space loading rates for both digester and clarifier. The point of intersection of the two curves, based on the type of data reproduced in Figures 6 and 7, represents optimum operating conditions.

Sensory evaluation

An immediate indication of the efficiency of the anaerobic digestion process may be obtained by visual and organoleptic inspection. The final effluent should be clear and free of objectionable odour. The degree of gasification occurring in the digester and clarifier indicates whether or not digestion has proceeded satisfactorily.

A major control parameter is sludge depth in the clarifier, readily measured by means of a sample bottle on a calibrated rod. A rise in sludge level indicates inefficient digestion and/or overloading.

Sludge appearance is another important parameter. A skilled operator soon learns to distinguish an active sludge from a declining one. Active sludge has a lustrous, tarry appearance and is free of noxious odour whereas declining sludge is characterised by a dull, lifeless appearance and a pungent, putrescent smell.

Discussion

The ease of operation of a digester and the degree of monitoring and control required are governed by such factors as:

- type of waste;
- plant design;
- load rates envisaged;
- operator experience; and
- monitoring and control facilities.

Experience indicates that no single parameter is sufficiently sensitive to permit reliable forecasting of incipient overloading or digester failure, particularly at high load rates. Effective monitoring requires a combination of physical, chemical and biological indices, notably interrelationships such as that between loading rate and biomass retention.

Digester monitoring – e.g. volatile-acidity determination by steam distillation – is readily effected by a technician using inexpensive apparatus and is moreover essential as a back-up against potential failure of more complex equipment such as e.g. gas chromatography systems. It is recommended that a weekly report sheet be kept incorporating daily test results, together with an ongoing graphical record of sensitive stability indicators to enable the operator to discern digester trends and institute early corrective measures.

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