TRANSFORMING THE PETRO PROCESS TO PROVIDE FOR BIOLOGICAL NUTRIENT REMOVAL

OV Shipin • PGJ Meiring

WRC Report No. 971/1/07

Water Research Commission

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Report to the
WATER RESEARCH COMMISSION

by

OV Shipin and PGJ Meiring

Meiring Turner and Hoffmann Cons.Eng., PO Box 36693,
Menlo Park, 0102, Pretoria, South Africa

WRC Report No 971/1/07
ISBN No 978-1-77005-527-8

JULY 2007

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EXECUTIVE SUMMARY

Objectives

The project aimed to incorporate biological phosphorus removal into the framework of the PETRO concept. The following aspects of the PETRO system were to be investigated:

a) potential of the PETRO system to incorporate the rationale underlying biological P removal. More than 60% COD removal in the primary pond appears to be counterproductive for downstream P removal since it leaves an insufficient amount of readily biodegradable organics (RBCOD) to meet demands of phosphate accumulating organisms (PAO) in the BNR reactor;

b) full scale plant data on variations of the COD fractionation in the BNR reactor feed (pond effluent) with a view to optimizing availability of RBCOD;

c) potential of the primary pond sludge as RBCOD generator to meet requirements of PAO;

d) sludge production in the PETRO primary pond with a view to optimizing desludging strategies;

e) rationale for the primary pond fermentation pit operated as a novel *RBCOD Generating Pit* (GP) to produce ample quantities of readily biodegradable organics for downstream PAO;

f) impact of recirculation phenomena on the performance of the RBCOD Generating Pit;

g) potential role of microalgae in the P removal in the PETRO system;

Laboratory facilities were kindly offered by Prof W.A. Pretorius (Water Utilization Unit, University of Pretoria).

Research work at the Soshanguve PETRO plant was temporarily terminated. Decommissioning of the old ASP reactor, extension of the plant and lack of operational control made optimisation of aeration and biological P release impossible.

Furthermore, a costly construction of the envisaged pilot plant at Olifantsfontein (ERWAT) was avoided. In the meantime good working relations with the staff at the Newcastle and Sasolburg PETRO plants were established which enabled database collection at the full scale plants.

Towards the PETRO BNR facility

The PETRO system is an appropriate technology equally applicable in the developed and developing world (Fig. 1-2). It combines waste stabilisation ponding as a low tech primary stage and a polishing facility as a secondary stage (Meiring, 1993; Meiring et al., 1996). The system comprises two variants in which the secondary facility can be either a trickling filter (TF) or an activated sludge process (ASP) (Shipin et al., 1999 a, b). Upstream stabilization pond(s) treat up to 60% of incoming organic load. This substantially decreases the size of a costly secondary facility. Hence the system's acronym - PETRO (Pond Enhanced TReatment and Operation).

Incorporation of biological P removal into the PETRO system is a logical development leading to a relatively low tech pond-based treatment facility. It produces final effluent, which compares favourably with the state-of-the-art high-tech BNR plants.

The process of biological P removal requires sophisticated monitoring. Generation of readily biodegradable organics, RBCOD (VFA etc.) is of critical importance for the concept of biological P removal. At the same time supply of readily biodegradable organics to the secondary activated sludge process (trickling filter) is an inherent feature of the PETRO concept. The organics generated in the primary pond boost PETRO activated sludge (TF) microflora and ensure removal of microalgae. On the other hand readily biodegradable organics cause release of phosphate by PAO in the BNR reactor. Thus production of RBCOD plays a crucial role both in the PETRO and biological P removal concepts.

Incorporation of biological P removal into the framework of the PETRO concept would result in an appropriate BNR technology retaining operational simplicity of the PETRO system and achieving a higher degree of treatment. The project sought to improve the performance of the PETRO system using these fortunate similarities of two processes.

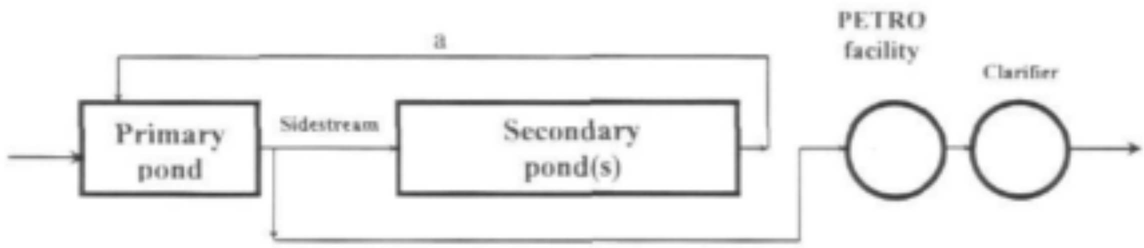

Fig. 1. Basic flow diagram of the PETRO system. a: algae-rich recycle; PETRO facility is either an activated sludge reactor or trickling filter.

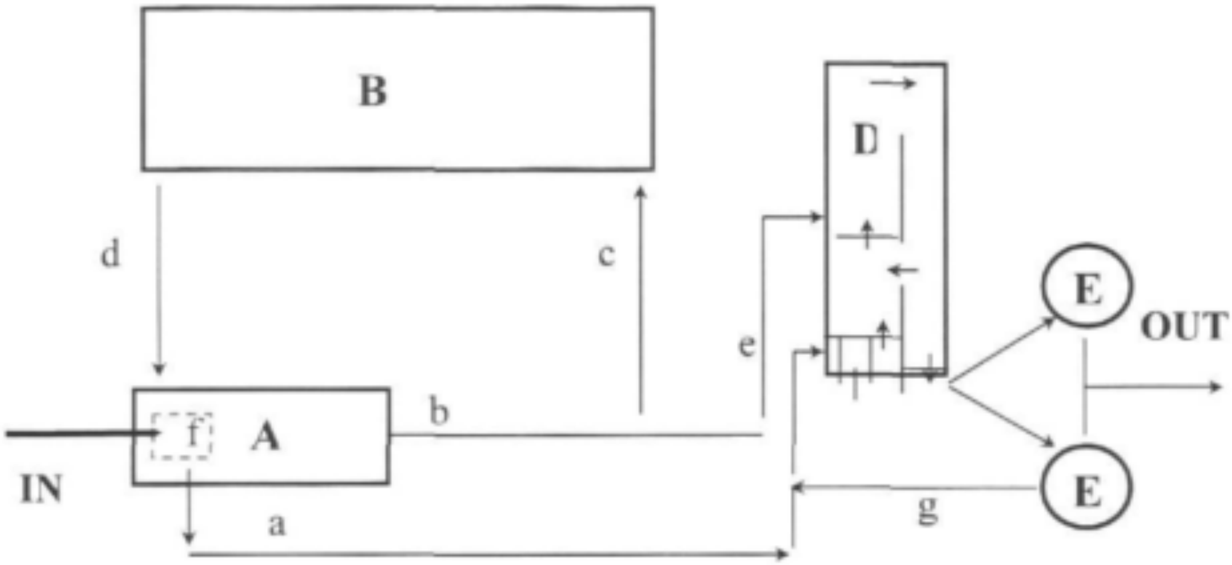

Fig. 2. Basic PETRO BNR flow diagram. A. Primary pond; B. Secondary pond (s); D. PETRO BNR facility; E. Clarifiers; a. Extraction point for BNR anaerobic zone feed; b., e. Primary pond overflow (aerobic zone feed); c. Recycle to secondary pond(s); d. Algae-rich recycle (c : e+a, recycle ratio); f. The RBCOD Generating Pit; g. RAS.

Production of readily biodegradable organics is an issue closely related to sludge production in the primary pond. In this light the desludging strategies require re-evaluation.

Microalgae originating from stabilisation ponds eventually enter the secondary PETRO facility (TF or ASP) where efficient removal of microalgal biomass occurs. Microalgae were shown to play an important role enhancing flocculation and nitrification rates in the activated sludge and trickling filter biofilm. It is known that microalgae take up a portion of phosphate into biomass and facilitate its precipitation as insoluble salts in stabilisation ponds but their role in P removal in the BNR facility downstream of ponds is not certain. This aspect is examined and discussed in relation to chemical precipitation of phosphates in activated sludge.

Overall, integration of ponds with a downstream secondary facility (TF or ASP) into the framework of the PETRO concept allows for substantial capital and operational savings. Incorporation of the biological phosphorus removal into the concept should retain operational simplicity of the PETRO system and achieve an even higher degree of treatment.

In the course of the project it was established that the RBCOD content of the effluent from the primary pond operated under the standard PETRO conditions fully meets only the requirements of the algal removal but not those of the biological P removal.

Observations made at a number of full scale plants strongly suggest that the primary pond used in a particular regime of operation is capable of the RBCOD production at the rates required for biological P removal.

Feasibility of biological P removal in the PETRO context was demonstrated full scale during several experimental periods at the Soshanguve plant. On occasions values below 1 $mg.\ell^{-1}$

were attained for the inorganic P in the final effluent. However, shortage of RBCOD in the ASP reactor feed and excessive aeration were among the factors responsible for inferior P removal for more extended periods. Unfortunately it proved impossible to optimize the process at Soshanguve due to the factors over which there was no control and due to eventual decommissioning of the reactor as a part of the plant extension masterplan.

Sludge production rates in the PETRO ponds and current desludging strategies were reviewed. Sludge production rates under the conditions were found to be intermediate between those reported for acidogenic (0.257 kg $VSS.kg^{-1}$ COD) and methanogenic reactors (0.08 kg $VSS.kg^{-1}$ COD). A preliminary estimate obtained from the full scale primary ponds is 0.18 kg $SS.kg^{-1}$ treated COD. The data require long-term confirmation. The RBCOD generating potential of the primary pond sludge was studied. It was found to correlate with the sludge age and sharply decrease downstream of the primary pond inlet. It continues to decrease further in the secondary ponds.

Pond stratification surveys demonstrated that the RBCOD production increases with an increase of the sludge pool in the pit and *vice versa.*

The PETRO fermentation pit was observed to feature high rate RBCOD production even at relatively long SRT (>15 days) combined with short HRT (<15 hours). Interestingly, SRT in the fermentation pit were significantly higher for the PETRO primary pond than those reported for optimal RBCOD production in acidogenic fermentors.

Recirculation of the algae-rich water from the secondary ponds to the surface of the primary pond is an inherent feature of the PETRO concept. This beneficial phenomenon, still underestimated in the world full scale practice, requires further study. Impact of the recirculation on the PETRO pond performance (particularly RBCOD production) is currently under long-term investigation.

Recirculation rate appears to be at least one of the key factors in the enhancement of the RBCOD production. The tentative data obtained suggest that the enhancement is effected through inhibition of extremely oxygen-sensitive methanogens. This offsets the balance of anaerobic digestion thereby increasing concentration of RBCOD (VFA and other readily biodegradable organics).

High rate recirculation appears to provide an opportunity to significantly increase RBCOD production in an open primary pond. Under these conditions a specific organic loading can be safely increased well beyond the value recommended for ponds without recirculation (0.6 kg $COD.m^{-3}.d^{-1}$).

Even a relatively low rate recycle (0.3 : 1) was shown to be an effective means to avoid a malodorous situation under conditions of high sludge content and enhanced RBCOD production in the pit. It was found permissible for the primary pond sludge to take up to at least 30% of the pond volume without any environmental consequences. Recirculation supplying oxygenated water allows for control of methanogens in the anaerobic microbial consortium. Sludge settleability in the pond appears to increase proportionally to the recycle rate, apparently as a result of a decreased floc buoyancy. Further full scale experiments are required to strengthen the rationale.

As a result of the investigation, the concept of *the RBCOD Generating Pit* located in the primary pond is being developed. It does not involve major structural changes and is based on the existing pond layout. Certain changes in the regime of operation are suggested. Generation of RBCOD in a conventional fermentation pit avoids other high-tech options (e.g. activated primaries, acidogenic fermentors etc.) which are capital cost intensive and more economical for large high-tech plants.

The concept combines a COD removal in the primary pond of up to 60% with a concomitant solubilisation of slowly biodegradable solids. It relies on the generation of RBCOD from the slowly biodegradable organic fraction of the sludge under mildly oxygen-stressed anaerobic conditions. Field observations suggest that the conditions for the enhanced RBCOD production are as follows:

- high specific organic load on the primary pond (0.21- 0.82 kg $COD.m^{-3}.d^{-1}$) and, particularly, on the pit which becomes the RBCOD Generating Pit;

- extensive pool of sludge in the pit;

- short hydraulic retention time (<15 hours);

- short sludge retention time (<15 days) may be beneficial though reasonable volatilization rates are attained even with high SRT (> 30 days);

- high rate recirculation, providing algal oxygenated water from the secondary ponds.

Under these conditions *no pond desludging* option may become feasible: enhanced sludge carryover into the ASP reactor would simplify O & M procedures.

Operational stability and effective attenuation of organic/hydraulic load peaks, which are typical of the primary pond, become features of the envisaged PETRO BNR plant.

Potential role of microalgae in the PETRO system P removal was researched. It was established in the laboratory experiments that apart from the recognized pH-dependent chemical P precipitation in the stabilisation ponds and activated sludge, the PETRO concept features another phenomenon. An *algae-mediated P precipitation* in the activated sludge reactor occurs concomitantly with the EPS-mediated algae removal. It is suggested that the phenomenon is brought about by precipitation of inorganic phosphate in the activated sludge flocs, apparently as calcium/magnesium salts. It appears that without microalgae, chemical precipitation would require much higher concentrations of Ca^{2+} and Mg^{2+}.

Suggested mechanism for the observed pH-dependent enhanced precipitation is the formation of the floc microzones with pH elevated by microalgal photosynthesis. Subsequent removal of waste activated sludge might result in an additional P removal of up to several milligrams per litre. The algae-mediated chemical process may contribute to biological PAO-mediated P removal and thus enhance the system's overall performance. Experiments on a full scale are required to elaborate on the practical importance of the phenomenon.

ACKNOWLEDGEMENTS

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee are gratefully acknowledged.

The Steering Committee of the project consisted of the following persons:

Mr GN Steenveld (Chairman)	WRC
Dr SA Mitchell	WRC
Mr PGJ Meiring	MTH
Prof GvR Marais	UCT
Prof WA Pretorius	UP
Dr AM van Niekerk	WMB
Mr P Gaydon	Umgeni Water
Mr P Herbst	DWAF
Mr D van Tonder	CSIR
Mr HPP Smal	Akasia Municipality
Mrs CM Smit	WRC

Laboratory facilities were kindly provided by Prof WA Pretorius (Water Utilization Unit, University of Pretoria) whose assistance is gratefully appreciated.

The project was made possible due to cooperation of many individuals and institutions. The authors sincerely wish to thank the following:

Dr TD Phillips and Mrs JA Prinsloo (SASTEK R&D, Water Research Division, Sasolburg) for valuable discussions and use of analytical facilities;

Mr M Cronwright (Newcastle PETRO plant) and Mr L Nel (Newcastle Municipality, Town Engineer) for comprehensive analytical data and cooperation in full scale trials;

Mr ML Siebert and Mrs VY Shipina (Water Lab Ltd, Pretoria) for analytical work;

Mr A Batchelor (Environmentek, CSIR) who kindly provided a water sampler.

Mr P Wagener (Sterkwater PETRO plant, Bloemfontein) for analytical data and cooperation;

Mr J Jacobs (Letlhabile PETRO plant, Brits Water Laboratory) for analytical data;

Mr R Phaswana and Mr H Kluever (Soshanguve PETRO plant, Tswaing) for comprehensive analytical data and valuable discussions.

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LIST OF ABBREVIATIONS

ADWF	average dry weather flow
ASP	activated sludge process
BNR	biological nutrient removal (N, P)
COD	chemical oxygen demand
EPS	extracellular polysaccharide
HRT	hydraulic retention time
HT	humus tank
MLD	megalitres per day
MLSS	mixed liquor suspended solids
PAO	phosphate accumulating organisms
PETRO	pond enhanced treatment and operation
RAS	return activated sludge
RBCOD	readily biodegradable COD (S_S)
S_A	fermentation products, considered to be acetate (measured as COD)
S_F	fermentable readily biodegradable organic substrate (measured as COD)
S_S	readily biodegradable soluble COD ($S_A + S_F$)
SBCOD	slowly biodegradable COD (X_S)
SRT	solids (or sludge) retention time
SS	suspended solids
SSV	settled sludge volume
SVI	sludge volume index
TCOD	total COD
TF	trickling filter
VFA	volatile fatty acids
VSS	volatile suspended solids
WSP	waste stabilization pond
WWT	wastewater treatment
X_S	slowly biodegradable substrate, colloidal and particulate

1. INTRODUCTION

1.1 PETRO process

PETRO is an acronym for Pond Enhanced TReatment and Operation. The process is patented in many countries (Meiring, 1992).

PETRO amounts to an integrated pond system, which employs both stabilization ponds as a primary stage and a seemingly conventional process (either activated sludge reactor or trickling filters) as a secondary stage (Shipin et al., 1997; 1999 a,b). These unit processes lined up in a peculiar arrangement have reciprocal obligations that bring about a unique example of synergistic interaction. This is achieved by recirculation, which has proved itself to be indispensable. The basic flow diagram is shown in Fig 1.

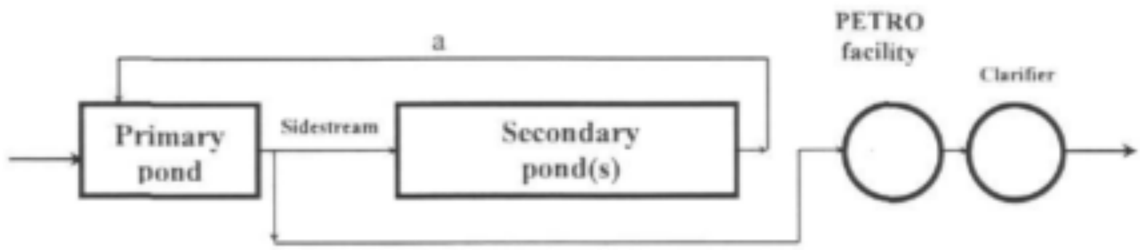


Fig. 1. Basic flow diagram of the PETRO system. a: algae-rich recycle; PETRO facility is either an activated sludge reactor or trickling filter.

1.1.1 Primary stage

Primary (or facultative) pond

Firstly the flow diagram involves a primary pond of specific geometrical design. This relatively low-cost facility makes a major contribution to the biological breakdown of organic matter (60% of COD removed) and therefore to the overall economy of PETRO (Meiring and Hoffmann, 1994).

The primary pond also has other duties to perform. Of importance is the production of an effluent that still contains relatively high levels of readily biodegradable matter, such as volatile fatty acids, which would provide energy to the final unit process - PETRO reactor. This unit process biologically entrains suspended microalgae which are invariably generated in the ponds. This aspect of algae removal from the final effluent is quite unique to PETRO.

Biological Note. Sidestream recirculation via oxidation ponds fulfils a very important role. It illustrates how closely integrated the various unit processes are. Ironically this role involves *suppressing exuberant methanogenic fermentation* which may deplete the volatile fatty acids (and other readily biodegradable matter) in the effluent passing out of the primary pond. These organic compounds provide energy to the mechanism that removes microalgae by means of entrainment/autoflocculation. If correctly employed, the compounds can also facilitate biological phosphorus removal in the downstream PETRO reactor. There is a fortunate similarity between algae and phosphorus removal. Both procedures require a supply of readily biodegradable matter (VFA etc.) in the feed to the activated sludge reactor. It is generally acknowledged that biological phosphorus removal is to involve an external generation of VFA in order to limit the size of the contact zone and facilitate release of phosphorus. The onset of methane fermentation depleting the VFA pool must be kept under control otherwise it would put an abrupt halt to phosphorus removal (but also to microalgae removal) in the PETRO reactor. This explains why methane fermentation taking place in the PETRO primary pond must be kept in check by recirculation of algae-rich oxidation pond effluent. In this manner it introduces oxygen toxicity somewhat suppressing methanogenic fermentation. In its turn this prevents anaerobic degradation to go the full way and thus destroy the biochemical energy required downstream for the removal of both microalgae and phosphorus. Both too much and too little recirculation must be avoided.

Secondary (oxidation) ponds

Secondly the flow diagram involves one or a series of oxidation ponds of adequate surface area located in a sidestream. The oxidation ponds continue the process of biological degradation of residual matter still present in that portion of the primary pond effluent, which is recirculated via the sidestream. Again a relatively large portion of the residual organic matter can be removed in this fashion. It cost-efficiently reduces the load which otherwise would be imposed on the conventional, and normally more expensive, unit process in the secondary stage.

The designer has the opportunity to select the proportional split between (i) the sidestream returning to the primary pond via oxidation ponds and (ii) the rest that proceeds to the secondary stage. On the one hand, the split determines the flow returned via the side sidestream and therefore being treated in the oxidation ponds. On the other hand, it sets the flow to be treated in the PETRO reactor. The split ratio can be optimized to meet site specific conditions.

High recirculation rate concomitantly reduces the organic load to be dealt with in the secondary stage. Note that the hydraulic flow passing out of the ponds and eventually out of the plant via the final unit process will automatically remain equal to the inflow into the plant - a straightforward flow balance. Inversely this means that by increasing the rate of recirculation the organic load handled by the ponds would automatically increase. This would require proportionately larger ponds but the load on the PETRO reactor and reactor's size and cost are reduced accordingly.

A PETRO plant is very site-specific. Topography, availability of land, permeability of soil etc. all play a role in selecting the optimum size and arrangement of the components.

Normally there would be a trade-off whereby the total cost brought about by larger ponds and a higher water volume to be recycled may exceed the alternative - enlarging the size and cost of the PETRO reactor. A costing exercise would be necessary to determine that. Cost of land, suitability and availability thereof, on the one hand, and the cost of civil engineering structures and that of electricity, on the other hand, are factors that would play a role.

Biological Note. Aesthetic phenomena which require special consideration when deciding on the recirculation ratio are the following. Firstly the abatement of odours which emanate from the primary pond. Secondly the formation of an unsightly floating scum which collects on the surface of the pond and causes a nuisance of its own. To combat these phenomena effectively the recirculated sidestream flow should not be less than about 40% of the raw inflow. In very sensitive areas it may be prudent to increase this ratio somewhat although due care should be taken not to upset facultative stratification in the primary pond where acid fermentation is essential. An important outcome of the recirculation is enhancement of algal growth in the ponds which increases oxygenating capacity of the recycle.

1.1.2 Secondary stage

The line-up is concluded by the final unit process - the PETRO reactor. As already mentioned it can be either an activated sludge process (ASP) or a trickling filter (TF).

The PETRO trickling filter variant would normally require a larger capital outlay but less operational and maintenance costs and is very simple to operate. The PETRO activated sludge variant, on the other hand, though inexpensive capital-wise, compared to the trickling filler exerts a larger electricity demand and requires more attention from the staff with skills to run a more sophisticated plant.

The activated sludge variant offers a substantial additional advantage. To with, if necessary it can be extended at little extra cost to facilitate pronounced biological phosphorus removal. As with the removal of microalgae, the initial stage of anaerobic degradation *viz.* acid fermentation produces easily degradable organic molecules which are required in both instances.

Although phosphorus removal through luxury uptake and algae entrainment by autoflocculation and removal with waste activated sludge are two completely different phenomena they occur simultaneously in the same suitably designed activated sludge reactor. The two processes will not inhibit each other but rather does the one process enhance the performance of the other.

Biological Note. The ability of the PETRO reactor (activated sludge or trickling filter) to remove microalgae effectively is based on a remarkable biological phenomenon which until now has not been used in wastewater treatment technology (Meiring et al., 1996, 1997). The problem of cost-efficient removal of microalgae from stabilization pond effluents was intractable before the PETRO system came about. Traditional processes when employed in the customary manner did not remove algae satisfactorily. There is a fundamental difference between the removal of colloidal organic matter still present in settled wastewater and that of microalgae present in a pond effluent. Colloidal organic matter as opposed to algae consists primarily of dead organic material which after being adsorbed by biomass is degraded enzymatically, and then it is sloughed off or removed by way of excess sludge withdrawal. The adsorption seats occupied by the colloids then become vacated and ready for a next round of adsorption. Not so with algae. Even though they are adsorbed and find themselves in the dark, they stay alive in an aerobic and aqueous environment. In the short term the lack of solar irradiation is not fatal and soon their remarkable ability to adapt themselves to the abnormal situation takes over provided that they can draw on an alternative source of energy. Nature has enabled various algal species typical of the PETRO environment, to switch from autotrophic to heterotrophic metabolism - that is provided the necessary readily biodegradable matter (VFA etc.) from the primary pond is available to sustain them. From this source the algae now obtain sustenance and as a result secret polysaccharides which act as coagulants flocculating even more algae. This autoflocculation greatly enhances the normal capacity for coagulation which characterises a standard microbial biomass. It has been well established that algal removal in the PETRO activated sludge reactor likewise draws on the same organic substrate which serves as sustenance for the phosphate accumulating organisms responsible for biological P removal.

1.2 Introducing PETRO BNR

It is ironical that only 5% of the world's wastewater ever receives treatment. Therefore an increase of the percentage is to be seen as a paramount priority of the water establishment. It is particularly important since the remaining 95% of the wastewater come from the developing countries. The current pollution situation in many parts of the world makes upgrading of existing pond-based treatment facilities a serious alternative to construction of new ones based on other technologies (Marais, 1970). Under the circumstances flexible retrofit technologies with a lower capital input are favoured. Thus it is logical that importance of such economical low tech reactors as waste stabilization ponds will grow in the XXI century (Oswald, 1993).

New wastewater discharge legislation is about to be introduced in South Africa (DWAF, 2000). The new discharge requirements are extremely stringent and demand that the state-of-the-art technology is used to upgrade existing WWT plants based on oxidation ponds and trickling filters (employed at the 16 and 23% of the WWT plants, respectively). It is envisaged that to meet these requirements the replacement value of existing municipal treatment infrastructure would amount to R16-billion (van Niekerk, 2000). Obviously the circumstances favour selection of appropriate cost-efficient technologies.

The PETRO system is an appropriate technology equally applicable in the developed and developing world (Meiring et al., 1994). The system comprises two variants in which the secondary facility can be either a trickling filter (TF) or an activated sludge process (ASP). Upstream stabilisation pond(s) treat up to 60% of incoming organic load. This substantially decreases the size of the secondary facility. Hence the system's acronym - Pond Enhanced TReatment and Operation.

Incorporation of biological P removal into the PETRO system is a logical development leading to a relatively low tech pond-based treatment facility. It would produce final effluent which compares favourably with the state-of-the-art high tech BNR plants. Basic PETRO BNR flow diagram is presented in Fig. 2.

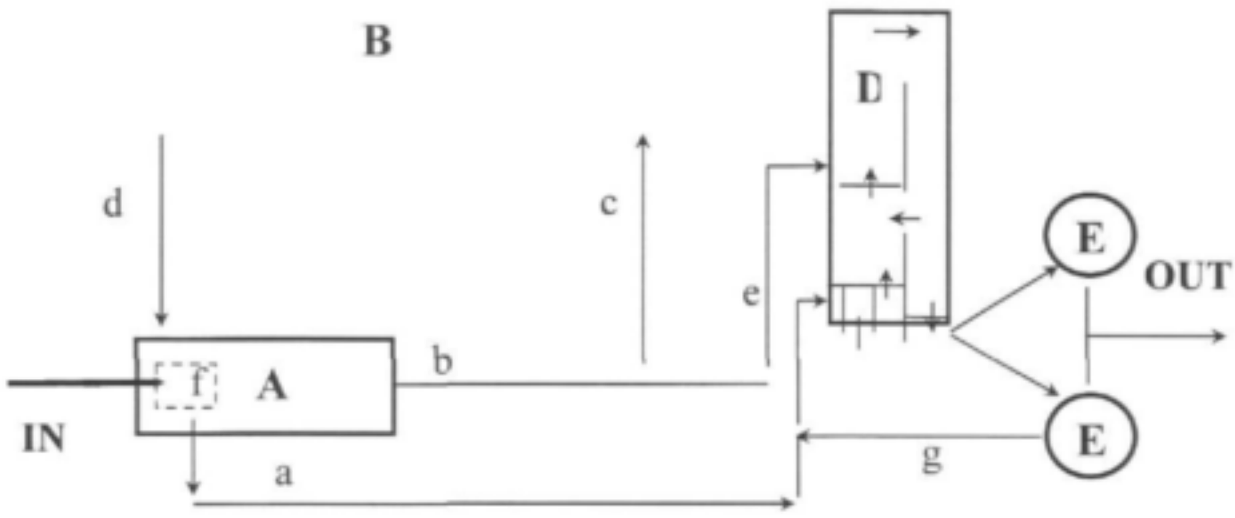


Fig. 2. Basic PETRO BNR flow diagram. A. Primary pond; B. Secondary pond (s); D. PETRO BNR facility; E. Clarifiers; a. Extraction point for BNR anaerobic zone feed; b., e. Primary pond overflow (aerobic zone feed); c. Recycle to secondary pond(s); d. Algae-rich recycle (c : e+a, recycle ratio); f. The RBCOD Generating Pit; g. RAS.

The process of biological P removal requires sophisticated monitoring. Generation of readily biodegradable organics, RBCOD (VFA etc.) is of critical importance in the concept of biological P removal. At the same time supply of readily biodegradable organics to the secondary activated sludge process (trickling filter) is an inherent feature of the PETRO concept. The organics generated in the primary pond boost PETRO activated sludge (TF) microflora and ensure removal of microalgae. On the other hand readily biodegradable organics cause release of phosphate by PAO in the BNR reactor. Thus production of RBCOD plays crucial role both in the PETRO and biological P removal concepts.

The project seeks to dramatically improve the performance of the PETRO system using these fortunate process similarities of the concepts.

Production of readily biodegradable organics (measured as RBCOD) in the framework of the concept is an issue closely related to the sludge production in the primary pond. In this light the sludge removal and disposal strategies require attention.

Microalgae originating from the stabilisation ponds eventually enter the secondary PETRO facility (TF or ASP) where efficient removal of microalgal biomass occurs. Microalgae play an important role enhancing flocculation and nitrification rates in the activated sludge and trickling filter biofilm (Meiring et al., 1998a; Shipin et al., 1996, 1998). It is known that microalgae take up a portion of phosphate into biomass and facilitate its precipitation as insoluble salts in stabilisation ponds but their role in P removal in the BNR facility downstream of ponds is not certain. This aspect is examined and discussed in relation to chemical precipitation of phosphates in the activated sludge.

Several major problems encountered in biological P removal plants were identified as: a) low content of RBCOD in the reactor feed; b) nitrate loading of the anaerobic zone; c) dilution of the reactor feed with storm water; d) suspended solids in the final effluent (inferior flocculation). It is believed that the BNR PETRO offers solutions for at least a, c and d (Henze, 1996). Problem (a) is dealt with in the primary pond pit, problem (c) - in the entire ponding section attenuating hydraulic peaks by the large pond volume and providing reactor feed at a constant rate; problem (d) is dealt with through enhanced flocculation due to involvement of microalgae.

1.3 Growing environmental consciousness and new waste discharge standards

The amount of improperly treated wastewater running into our rivers has reached serious proportions. The current cholera epidemic, and the fact that 7 million people die world-wide from water-related diseases each year, is an urgent reminder of the grim reality (WSSCC, 2001). Furthermore, over 5.8 million cases of diarrhoea are reported globally every day, with 6 people dying for about every 10 thousand reported. Even more depressing is that diarrhoea accounts for about a third of total child deaths under the age of five. Needless to say, the vast majority of them come from the developing communities.

On the other hand, world-wide as well as in South Africa there exists an unfortunate perception by local authorities that water services have to do with the provision of drinkable water only. Treatment of wastewater, which results from the usage of drinking water is not seen as a priority. This in turn leads to the situation when supply and maintenance of the sanitation services is not given proper attention. Department of Water Affairs and Forestry (DWAF) identified that a lack of funds is a major hindering factor for upgrading sewerage networks, of which treatment plants are the most important and critical part (Venter, 2001). The Department reports that quite often sophisticated treatment facilities are installed in the areas which can hardly afford to operate and maintain such complex and expensive systems.

An important development emanating from the new National Water Act, Act 36 of 1998 is that DWAF is about to introduce new effluent (waste) discharge standards (Table 1).

The standards primarily aim at the municipal point source discharges but the whole spectrum of point source and diffuse source pollution, including industrial sector is also being dealt with. If provision of clean water and water-borne sanitation is a *short-term* approach, this move can be seen as a crucial *long-term* statutory solution to the problem of improper treatment of a substantial portion of more than 8 000 mℓ/day of municipal wastewater in South Africa.

Table 1. Comparison of the performance parameters in the light of the new DWAF standards. A state-of-the-art Biological Nutrient Removal (BNR) plant versus an advanced integrated pond system.

Parameter (mg/ℓ)	Proposed new standards	Conventional BNR plant	Advanced integrated pond system (PETRO)
COD	65	40	45
SS	20	10	10
Ammonia-N	3	1	1
Nitrate-N	15	3	5
Inorganic P	1	1	1

According to the proposed standards (DWAF, 2000), wastewater treatment (WWT) plants will be required to comply with considerably tougher limits for carbon, nitrogen and inorganic phosphorus in effluents. Most of the plants will face unprecedented new phosphorus requirements (P< 1 mg/ℓ).

Historically SA has always been in the forefront of research, development and innovation. Water Research Commission, CSIR, WISA, SA Institute of Municipal Engineers, universities and private consultants played a major part in the perfection of main wastewater treatment technologies. Classical work on pathogen removal in the waste stabilisation ponds (WSP) has been done by Gert Marais in the 60-70s. The leading role of CSIR in the development of low tech sanitation should be acknowledged. Departing from the "hole in the ground" approach, the organisation promoted efficient odour-free (due to recirculation of algae-rich water, also of local invention) waste stabilisation pond technology. Maturation ponding was developed in the 50s for bio-filter plants, when their final effluent no longer met more demanding standards and therefore required additional polishing. A concept of integrated wetland treatment systems is also a South African contribution (CSIR). The first steps of the so-called Upflow Anaerobic Sludge Blanket (UASB) approach, currently a widely used technology, were made in Bellville (Cape Town) where the concept of clarigester was perfected. Besides this, the successful marriage of anaerobic digestion and ultrafiltration was also pioneered in the Cape. The world's first full-scale facility incorporating Biological Removal of Phosphorus was designed for Goudkoppies (150 mℓ/day, Johannesburg) by Meiring and Barnard Consultants in the mid 70s (Barnard, 1991). Other Biological Nutrient Removal (BNR) configurations followed, namely, world famous Johannesburg and University of Cape Town processes.

To sum up, the contribution of South Africa to the global wastewater scene is substantial. It ranges from straightforward pit latrines to the state-of-the art activated sludge plants incorporating sophisticated biological removal of nutrients. Nevertheless, it was such traditional low-tech technologies as waste stabilisation ponds and bio-filtration plants that for many decades acted as the backbone of municipal wastewater treatment.

The proposed DWAF effluent (waste) discharge standards were developed in close association with experts in the WWT field (Van Niekerk, 2000). Technologically feasible, they have to be introduced in the current economic climate, which makes it a formidable task for the country facing other serious challenges (housing, AIDS, etc.). It is estimated that R16 billion will be required to replace existing infrastructure and put a country's wastewater treatment facilities into position to reliably meet the standards. Meeting the requirements is not a challenge for modern state-of-the-art activated sludge plants. But what about municipal facilities which presently find it difficult to comply with less stringent carbon and nitrogen standards? Namely, "older" low cost technologies, such as waste stabilisation ponds and bio-filter plants (incorporating ponds for maturation)? These facilities, which faithfully serve the majority of towns, constitute roughly 50% of the country's treatment plants. And are there sufficient financial means to support these measures in the large developing communities in this country, and the continent of Africa for that matter, at the times when health and well-being of people is a vital prerequisite for a successful African Renaissance? Can we turn the wastewater treatment plants, which are failures, into the facilities performing up to the newly required standards? Can we ensure a low-cost conversion followed by a low-cost operation and maintenance? In the light of current and future predicaments faced by the cash-strapped municipalities, it is difficult to overemphasise the importance of existing municipal assets. The currently pressing truth is that waste stabilisation ponds and bio-filters are at the crossroads - either decommission or upgrade. There are two major routes open to municipalities to follow: investment into capacity building and upgrading of the plant on their own or outsource, delegate these issues to a private experienced contractor. It is inevitable that integration of the traditional technologies into innovative systems looms as a major way forward.

But are there processes, which can salvage "older" plants in the current socio-economic situation? That is where the status of South Africa as one of the global leaders in low cost sanitation comes to the fore.

There are basically 4 main players in wastewater treatment: a bio-filter, activated sludge process (ASP), anaerobic digester and waste stabilisation pond. The latter is a unit process incorporating functional elements of the first three. In terms of biological diversity WSP is the most complex of them all. On the other hand, the pond is the simplest system to operate and maintain. Long-term full-scale practice in South Africa shows that traditional wastewater facilities can be successfully introduced into the new cost-effective integrated facilities saving municipalities' existing assets. There is no doubt that technologically feasible performance criteria, on which DWAF standards rest, can be achieved by the advanced integrated pond WWT systems (Table 1). Such integration can be realised through innovative thinking based on known unit processes in new arrangements.

The PETRO system is an example of such a technology, an indigenous process developed by Piet Meiring in collaboration with the Water Research Commission (Meiring and Hoffmann, 1996). A technology of long-standing reputation (prototype plant built in KaNyamazane, Mpumalanga, 1978), it was hailed as "the greatest contribution to low tech wastewater treatment in the 2nd half of the XX century" by the president of the International Water Association.

Generally speaking, an integration of ponds with a bio-filter and/or an activated sludge process may follow a number of directions. However, one crucial condition, as the practice shows, should be always adhered to since it proved to be the most cost-effective. Namely, aerobic treatment is to be preceded by anaerobic digestion. Open deep primary pond with a fermentation pit (3-6 m) is optimal as a primary stage, ensuring up to 85% removal of

1. Integrated pond system involving no secondary ponds (greater odour risks).

2. Standard PETRO system (no odour risks).

3. New prototype PETRO system involving Forced surface aeration instead of secondary Ponds. Dysselsdorp plant (no odour risks).

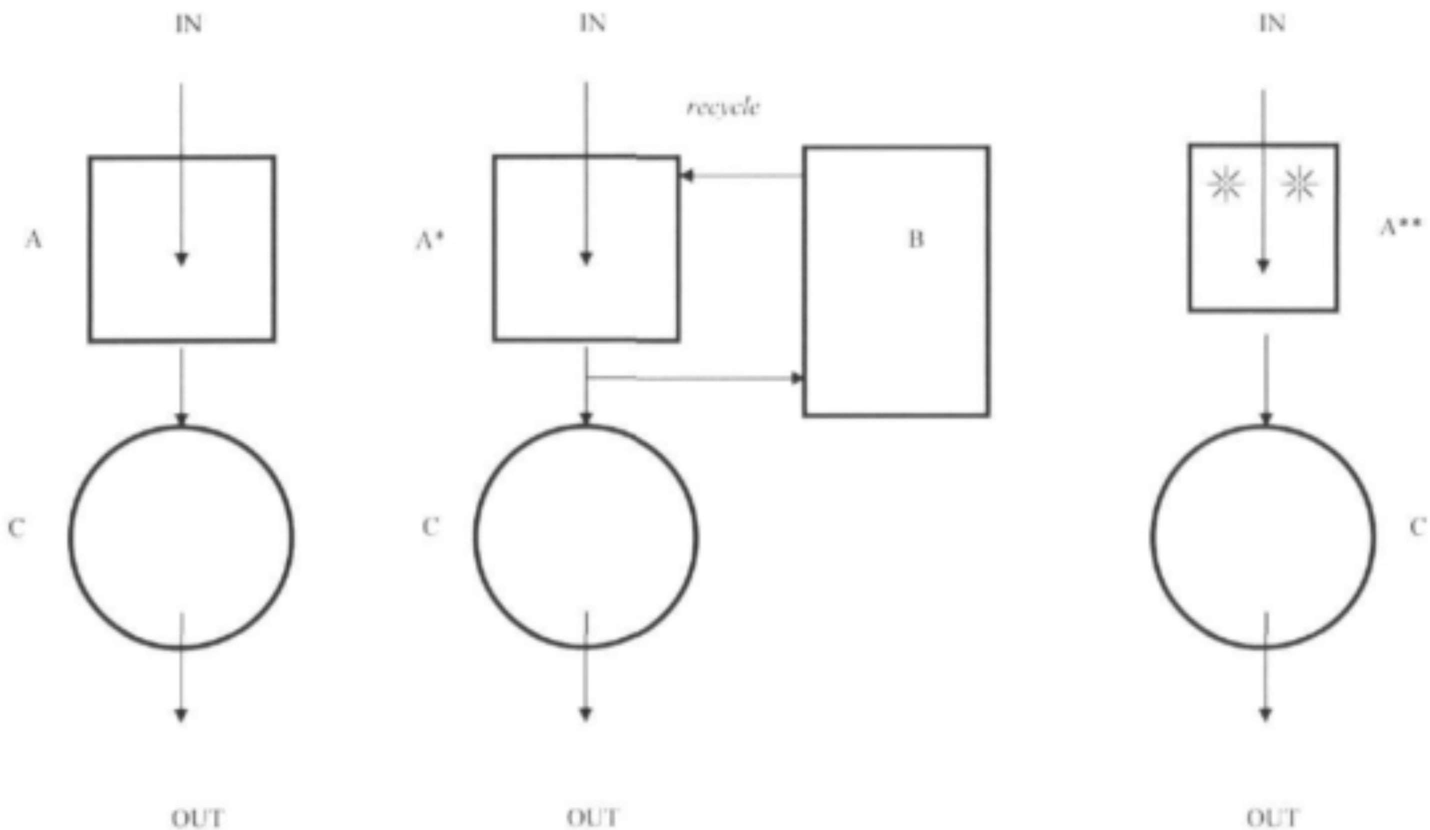


Fig 3. Basic flow configurations of integrated pond systems. A. Primary (anaerobic) pond; A*. PETRO primary (facultative, due to recycle) pond; A. PETRO primary (facultative, due to aeration) pond with forced aeration; B. Secondary (oxidation) pond(s); C. Secondary facility (activated sludge, BNR reactor, or bio-filter); *. Surface low intensity aerator.**

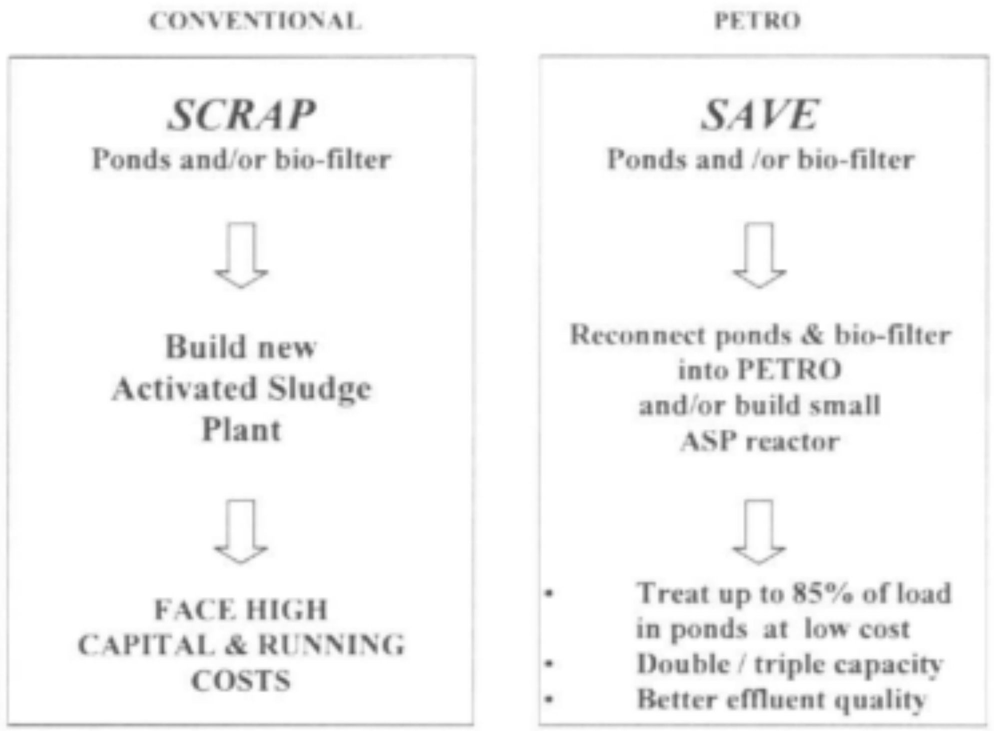


Fig 4. PETRO retrofit overview.

carbonaceous load (COD Odour-free conditions in the primary pond emitting biogas can be effected either through provision of oxygenated water recycled from secondary (oxidation) ponds, or through forced aeration. There are three main configurations of advanced integrated pond systems, which have been extensively proven by the full-scale practice (Fig 3). Low tech and low cost COD removal in the ponds is supplemented by numerous other advantages, of which greater attenuation capacity for hydraulic peaks and greater operational stability are the most prominent. Ponds with interpond recirculation allow application of organic loads, which by far exceed those currently used throughout the world, and this makes the system highly affordable. The ponds enhance efficiency of the entire system. Algae produced in the ponds are efficiently removed downstream by unique microbiological phenomena previously not used in wastewater treatment (Shipin et al., 1997). In some site-specific cases (when land is at a premium) odours can be allayed through forced surface aeration with an intensity low enough not to interfere with an active anaerobic digestion occurring at the lower strata. The secondary stage deals with the remaining carbonaceous and most of nitrogenous load. It incorporates a facility, which can be either bio-filter or/and activated sludge reactor. Since bio-filters, due to the inherent limitations, can not deliver comprehensive N removal and, particularly, biological P removal, new DWAF regulations leave no other choice than to incorporate an activated sludge process as a final polishing stage. In the countries with the discharge standards less strict than SA (and this is most of the world) the bio-filter configuration can be very cost-effective due to simplicity of operation. However bio-filters (particularly in the retrofit situations when they already exist) can play an important role handling significant N loads, thus minimising the size and electricity costs of the ASP reactor. Retrofit options are reviewed in Fig 4.

Constantly being improved, the PETRO concept has been recently enriched with new aspects such as incorporation of stale night soil supplementation for concomitant waste solids disposal and biological P removal, as well as site-specific use of a partially aerated primary pond (Dysselsdorp plant, 2000). The system is highly suitable for phased development in cases when temporary financial problems and issues of capacity building preclude immediate application of the system (Fig 5). Upgrading or green-field construction can be staged at the rate of the availability of resources.

With PETRO South Africa is again at the forefront of development in the water field (Fig. 6). The first PETRO plant built outside SA is an upgrade of existing stabilisation pond (lagoon) system, enhancing its capacity from 90 to 200 mℓ/day and simultaneously providing better final effluent (Melbourne, Australia). Parallel to DWAF, Australian Environmental Protection Agencies are introducing stricter discharge regulations. Selected in a tough competition with other international options on the basis of its simplicity and cost-efficiency the South African technology allows the plant to meet new standards by 2005, without compromising an international bird sanctuary status of the world's biggest pond-based WWT plant. Two other modules of similar capacity are to follow in the near future. Thus conversion of the traditional ponds into a XXI century advanced integrated pond system illustrates another important advantage of any pond-based system, its exceptional *eco-friendliness*. PETRO is a rare example of an *appropriate* technology suitable for a sophisticated modern city, while still applicable for a small developing community with acute capacity building problems (1-2 mℓ/d). Integration of inexpensive artificial wetlands (free surface flow reedbeds) as tailing facility for the systems located in the developing areas further enhances its robustness and safeguards additional polishing in case of power failures and other temporary operational disruptions. Apart from producing sparkling clear effluent of a near-drinking quality, reedbeds, as well as ponds, encourage birdlife. Such are the PETRO plants in Letlhabile (1982, 1998) and Hendrina (1999) (Middelburg Observer, 2000).

Affordability and major economic advantages of the system are illustrated in Fig 7. Economics of the PETRO applications are always site-specific (Municipal Engineer, 1997), but, generalising, it is safe to state that in terms of total treatment costs the system can be responsible for the savings of up to 30% in comparison to conventional WWT systems. PETRO's high standard of treatment is a serious deterrent of pollution and a guarantee against cholera and other infectious water-borne diseases.

Currently municipalities face tremendous challenges in the field of sanitation. In order to survive they have to adapt to the ever-changing economic climate. Needless to say, it must be done in the most cost-efficient way: maximising use of existing assets and minimising expenses. So, if your municipality has ponds, bio-filters or another wastewater treatment just recall that this country is a proud home of many an ingenious technology developed for African conditions and appropriate for upgrading of existing and construction of green-field wastewater treatment facilities.

Fig 5. Typical phased PETRO development - Middelburg (Eastern Cape)

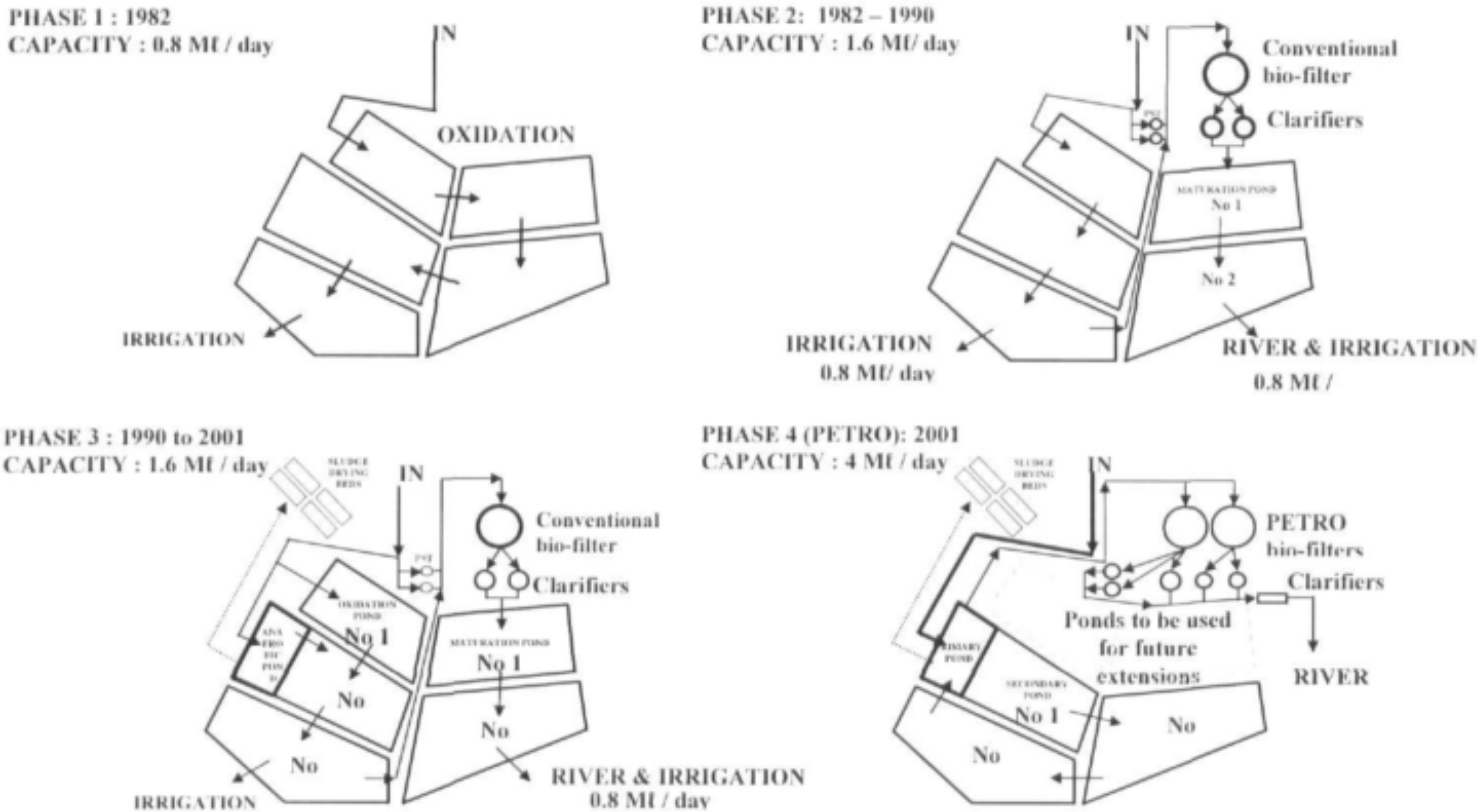


Fig 6. PETRO retrofit involving activated sludge process (ASP). Melbourne (Australia) : Capacity increased from 90 to 200 ML /day.

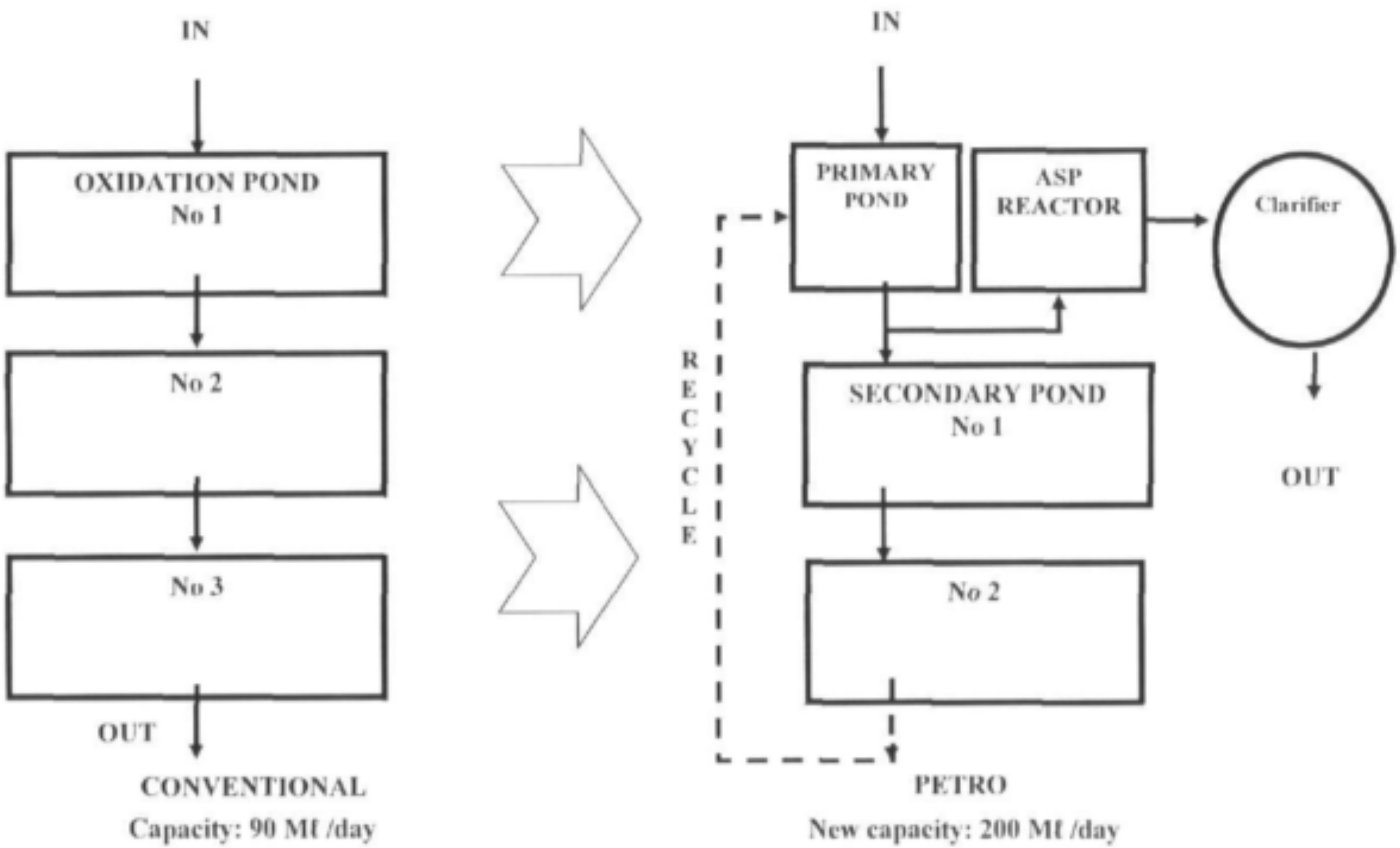
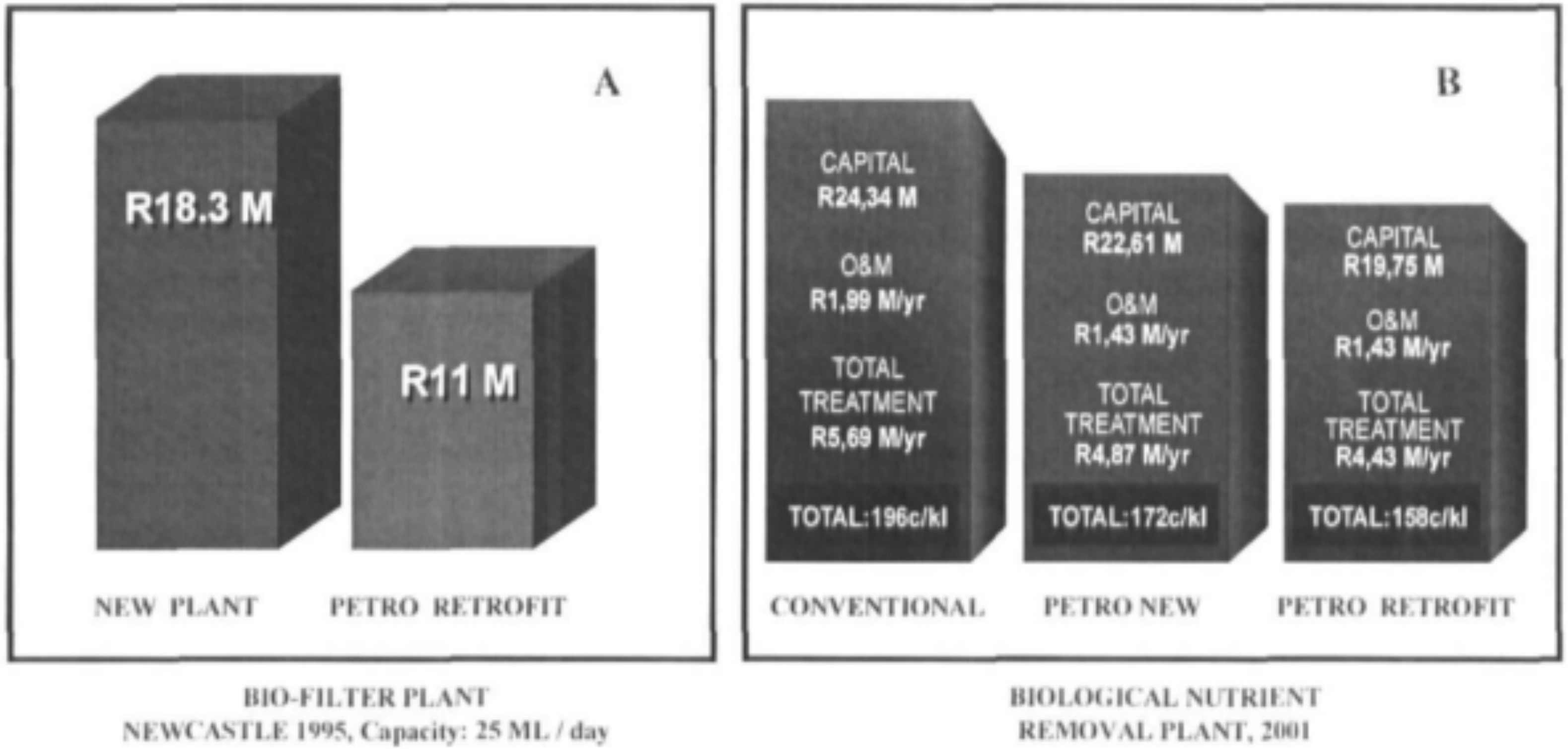


Fig. 7. A. Capital cost comparison. B. Total treatment cost comparison.



2. MATERIALS AND METHODS

COD, ammonia, nitrate, MLSS, SVI, SS, alkalinity, chlorophyll *a*, VFA (distillation method) were determined according to the Standard Methods (APHA,1992). Concentration of $P_{inorganic}$ was determined using the Spectroquant method (Merck). S_S (readily biodegradable soluble substrate, as COD, therefore reported as RBCOD), S_A (fermentation products, considered to be acetate), S_F (fermentable readily biodegradable organics), S_I (non-readily biodegradable soluble organics, as COD) in mg/ℓ^{-1} were determined by the flocculation method (Mamais et al., 1993). $S_S = S_A + S_F$ = RBCOD (Henze et al., 1995).

Empirical ratio VFA : S_S (RBCOD) was established in the present work to be 100 mg/ℓ^{-1} acetic acid : 89 mg O_2/ℓ^{-1} S_S (measures as COD).

Algal concentration was expressed as chlorophyll *a* ($\mu g/\ell$) or cells per ℓ.

Generation of *the Enhanced algal activated sludge* (EAAS) took over 4 weeks. Total duration of each experiment was 9 weeks. Municipal sewage from the Soshanguve PETRO plant, pre-treated under anaerobic conditions, was used as a reactor feed. Organic loading rate on the reactor was 750 mg $COD.\ell^{-1}.d^{-1}$, $COD_{nonalgal}$=250 mg/ℓ^{-1} , COD_{algal} 200 mg/ℓ^{-1}. Non-algal organics were supplemented as separately pre-grown microalgal biomass, consisting of the species typical of the PETRO ponds (*Chlorella, Euglena, Chlamydomonas spp.*), to constitute 2100 200 $\mu g/\ell^{-1}$ as chlorophyll *a* in the reactor feed.

The reactor conditions were similar to those of the full-scale Soshanguve ASP reactor and maintained at: MLSS 3500 200 mg/ℓ^{-1} ; SVI 129 15 $m\ell/g^{-1}$; settleable solids 450 39 $m\ell.\ell^{-1}$; sludge age 15 2 days; pH 7.1 0.2, DO 2 0.5 mg/ℓ^{-1}; chlorophyll *a* 980 160 $\mu g/\ell^{-1}$ in the reactor effluent; chlorophyll *a* in flocs 2300 $\mu g/\ell^{-1}$ (calculated).

Direct measurement of chlorophyll in the EAAS flocs proved impossible due to methodological problems. Pigment extraction with a solvent (acetone, ethanol) yielded a colouring agent from the sludge of which light absorbance at the required wavelengths was several times higher than that of chlorophyll. Therefore the algal biomass in the MLSS had to be evaluated as cells per L and calibrated to chlorophyll *a* $\mu g/\ell^{-1}$.

Laboratory reactor containing EAAS (V=6.5 L) consisted of 3 consecutive zones (anaerobic, anoxic, aerobic) simulating the Soshanguve ASP reactor ($360\ m^3 : 240\ m^3 : 1800\ m^3 = 3 : 2 : 15$). $P_{inorganic}$ concentration in the reactor feed was artificially increased from 6 mg/ℓ^{-1} (Soshanguve primary pond effluent) to 20 mg/ℓ^{-1} by addition of Na_2HPO_4.

Soshanguve primary pond effluent characteristics were: S_I=41 mg/ℓ^{-1}, $COD_{raw\ influent}$ = 568 49 mg/ℓ^{-1}. Letlhabile primary pond effluent: S_I=36 mg/ℓ^{-1}. Sasolburg primary pond effluent: S_I=45 mg/ℓ^{-1}, Newcastle primary pond effluent: 35 mg/ℓ^{-1}. Bloemhof primary pond effluent: S_I=54mg/ℓ^{-1}. Bloemfontein primary pond effluent: S_I=35 mg/ℓ^{-1}.

The RBCOD generation potential as an amount of readily biodegradable organics (measured as COD) generated per 1 g of sludge volatile solids per 1 day (in mg. g^{-1} VS. d^{-1}) was estimated as follows. 100 $m\ell$ original sludge samples were incubated at RT (approx. 18°C) over a period of 7 days, specific amount of RBCOD was estimated as S_S according to Mamais et al. (1993).

Pond stratification surveys at the different PETRO plants were performed from a rubber dinghy, the 1L Kemmerer-type water sampler and flow-through 1L water sampler (Eijkelkamp) was used to sample pond water and sludge from the different depths of the primary and secondary oxidation ponds.

Basic flow diagrams and primary pond geometry of the PETRO plants situated in different regions of South Africa are presented in the APPENDIX FIGURES.

3. RESULTS AND DISCUSSION

3.1 COD fractionation in the primary pond effluent: BNR PETRO versus non-BNR PETRO

Quantity of readily biodegradable organics (RBCOD) available to phosphate accumulating organisms is of the critical importance for efficient biological P removal (Barnard, 1984; Nicolls et al., 1985; Pitman et al., 1992). In order to evaluate the potential of the PETRO system to provide sufficient RBCOD for biological P removal, relative content of readily and slowly biodegradable organics (X_S, SBCOD) in the primary pond effluent (overflow) was evaluated and compared to that of raw sewage influent.

Data on the relative importance of these COD fractions is presented in Table 2-8, Fig. 8-10. As well as Appendix Tables 1-21.It is summarized in Table 9. Data on the COD fractionation in the raw sewage entering the PETRO plants is in agreement with the data reported elsewhere (Nicolls et al., 1985, Ekama et al., 1986; Henze et al., 1995; Wentzel et al., 1995; Mbewe et al., 1998).

Relative amount of readily biodegradable organics in raw sewage varies at different PETRO plants from 11 to 18% of total organics. The percentage of the RBCOD fraction increases up to 28-33% after the treatment in the primary pond as a result of solubilisation of solids due to anaerobic digestion). At the same time relative content of the SBCOD fraction (26-34% of total organics) in the pond effluent (overflow) decreases in comparison to that of the raw influent (43-58%).

Nonetheless, the quantity of readily biodegradable organics is still does not suffice to drive mechanism of biological P removal due to the effect of dilution with the water recycled from the secondary ponds (low in RBCOD).

It is evident from the results presented that the RBCOD content of the effluent (overflow) from the primary pond operated under the standard PETRO conditions fully meets only the requirements of algal removal but not those of biological P removal.

Data on the envisaged COD fractionation in the potential BNR PETRO system is presented in Table 10. Transfer of the primary pond effluent extraction point from the overflow to lower water strata (i.e. immediately above the extensive sludge layer) and operation of the fermentation pit in a different regime (see Section 3.6) is expected to increase relative content of the RBCOD fraction from 26-31% to 56-63%. The values of RBCOD are expected to equal those typical of the conventional BNR reactor feed (Rabinowitz and Barnard, 1997). Enhanced RBCOD concentration is not seen as excessive and detrimental for the secondary PETRO facility. Increase of RBCOD load on the PETRO TF in Newcastle was shown to lead to better performance and quality of the final effluent (Meiring et al., 1998b).

3.2 Production of readily biodegradable organics (RBCOD, S_S) in the PETRO ponds

It is evident from the results of the stratification surveys of the ponding sections at the different PETRO plants presented in Table 9, that the quantity of readily biodegradable organics currently available in the primary and secondary pond (overflow) effluents at the Soshanguve, Letlhabile, Kanyamazane and Bloemfontein plants ranging from 10 to 70 mg/ℓ$^{-1}$ is not sufficient for the downstream biological P removal. The Sasolburg, Newcastle and Bloemhof primary pond (overflow) effluents are characterized by the same RBCOD content despite the presence of extensive pool of sludge. As becomes obvious from 3.3-3.4 this amount of readily biodegradable matter is not sufficient to drive mechanism of biological phosphorus removal in a downstream BNR reactor.

Table 2. Typical performance criteria of the Kanyamazane PETRO system (TF variant).

Parameter, mg/ℓ$^{-1}$	Primary pond outflow	3rd pond outflow	TF inflow	TF outflow	HT overflow	Overall removal[1], %
COD_{TOTAL}	320 (96[2])	208	145	32	16	96.2
S_S	**10**	**5**	**n.d.**	**n.d.**	**n.d.**	**n.d.**
COD_{FILT}	96	n.d.	n.d.	n.d.	n.d.	n.d.
TKN	22.4	25.2	22.4	5.6	5.6	75.0
NH_4^+-N	15.4	14.2	13.8	1.8	1.6	90.0
NO_3^--N	<0.2	<0.2	1.4	12.2	12.8	-
SS	151	98	85	8.4	5.2	96.6
P-total	**5.4**	**5.2**	**4.9**	**4.8**	**4.4**	**48.8**
pH	8.3	8.1	8.1	7.6	7.5	-

[1] - removal assuming the following average data for the raw influent: COD 421 mg/ℓ$^{-1}$; pH 6.9; NH_4^+-N 13.6 mg/ℓ$^{-1}$; NO_3^--N 0.2 mg/ℓ$^{-1}$; SS 150 mg/ℓ$^{-1}$; P total 8.6 mg/ℓ$^{-1}$.

Table 3. Distribution of the readily biodegradable organics ((RBCOD, S_S, mg/ℓ$^{-1}$) in the WSP system of the Soshanguve PETRO plant (6.10.1998, spring). $COD_{raw\ influent}$ = 568 mg/ℓ$^{-1}$ with S_S = 58 mg/ℓ$^{-1}$. Alkalinity (as $CaCO_3$, mg/ℓ$^{-1}$) followed by Settleable Solids (Mℓ$^{-1}$) values are in parentheses.

Depth, m below surface	Primary pond[1] 1st part outflow	Primary pond[1] 2nd part 1st hopper	Primary pond[1] 2nd part 2nd hopper	1st secondary WSP[2] (middle)	2nd secondary WSP (middle)
Overflow			28	26	27
0.5		49	50	20	28
1.0		59	48	n.d.	n.d.
1.7		n.d.	n.d.	32	36
2.0	70(**350**;0)	72	68		
3.0		77	69		
4.0		75(**430**;999)	78		

[1] - The 1st part of the primary pond was covered with a 1 m thick surface sludge layer thus stratified samples were not available; [2] - no recirculation from the secondary ponds to the primary pond at this period.

Table 4. Distribution of the readily biodegradable organics ((RBCOD, S_S, mg.ℓ$^{-1}$) in the pond system of the Letlhabile PETRO plant (21.06.1999, winter). Chlorophyll *a* concentration in the 2nd and 6th WSPs outflow was 89 and 220 µg.ℓ$^{-1}$, respectively. Alkalinity as $CaCO_3$, mg.ℓ$^{-1}$.

Depth, m below surface, meters	1st Primary pond (east)						2nd primary pond			6th (final) pond		
	1st half (middle)			2nd half (middle)			2nd half (middle)					
	S_s	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	50	255	0	53	n.d.	n.d.	51	n.d.	n.d.	n.d.	n.d.	n.d.
1.5 secondary pond bottom	63	280	3	39	n.d.	n.d.	60	n.d.	n.d.	20	259	136
2.0	*89*	*291*	*6*	*59*	*300*	*5*	*60*	*281*	*15*			
2.4 primary pond bottom	95	343	926	100	350	804	58	333	105			
Pond outflow				49	n.d.	0	40	n.d.	0	10	n.d.	0

Table 5. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ^{-1}) in the facultative pond No 1 (southern pond) of the Sasolburg PETRO plant (24.11.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 490 µg.ℓ^{-1}. The only microalgal species present - *Chlamydomonas sp.* * Values for pit No2 are in parentheses.

Depth below surface, meters	Main (1st sump) Fermentation pit			2nd sump pit *			4th sump pit*		
	S_S	alkalinity	settleable solids ml.ℓ^{-1}	S_S	alkalinity	settleable solids ml.ℓ^{-1}	S_S	alkalinity	settleable solids, ml.ℓ^{-1}
0.5	n.d.	160	0	52	108	0	48	153	0
1.0	59	n.d.	0	86	n.d.	10	n.d.	n.d.	n.d.
2.0	80	153	275	80	160	80	79	169	25
3.0	772	469	385						
3.5	918	600	840						
(main pit bottom**)									
Primary pond outflow							69	110	0
1st secondary pond outflow							25	114	0

* - max accessible depth - 2.5 m, due to a dense bottom sludge layer;

** - total pit depth 5 m, pit has a dense bottom sludge layer; it was impossible to obtain a sample from the depth below than 3.5 m.

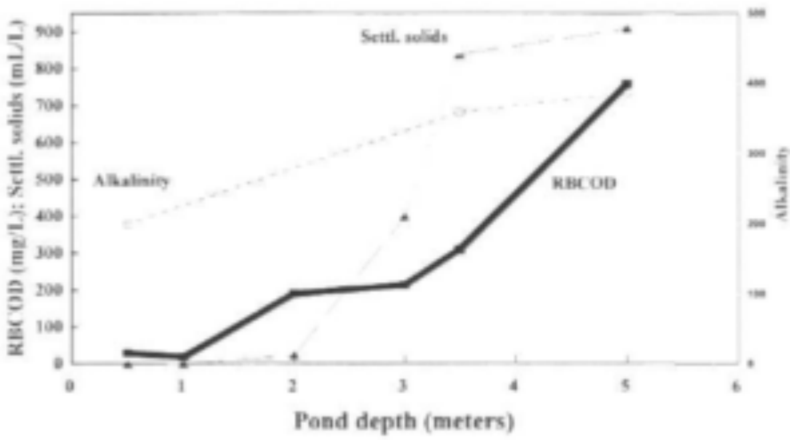


Fig. 8. Typical distribution of readily biodegradable soluble substrates (as RBCOD, solid line) and settleable sludge solids in the fermentation pit of the primary pond. Bloemhof plant.

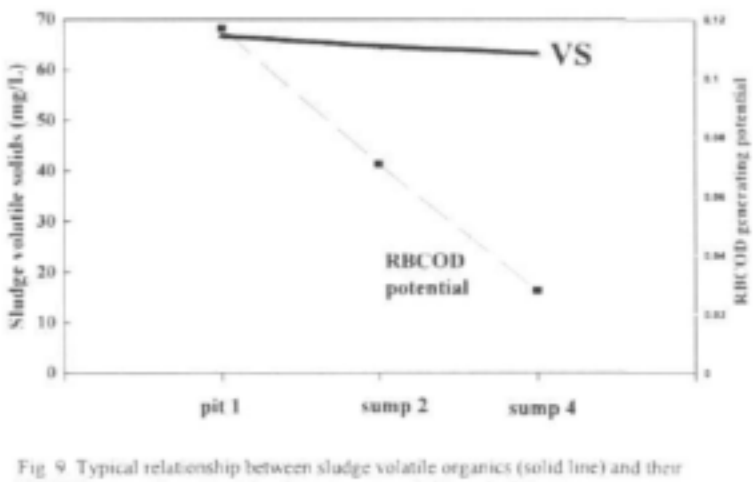


Fig. 9. Typical relationship between sludge volatile organics (solid line) and their RBCOD generating potential in the primary pond. Bloemhof plant.

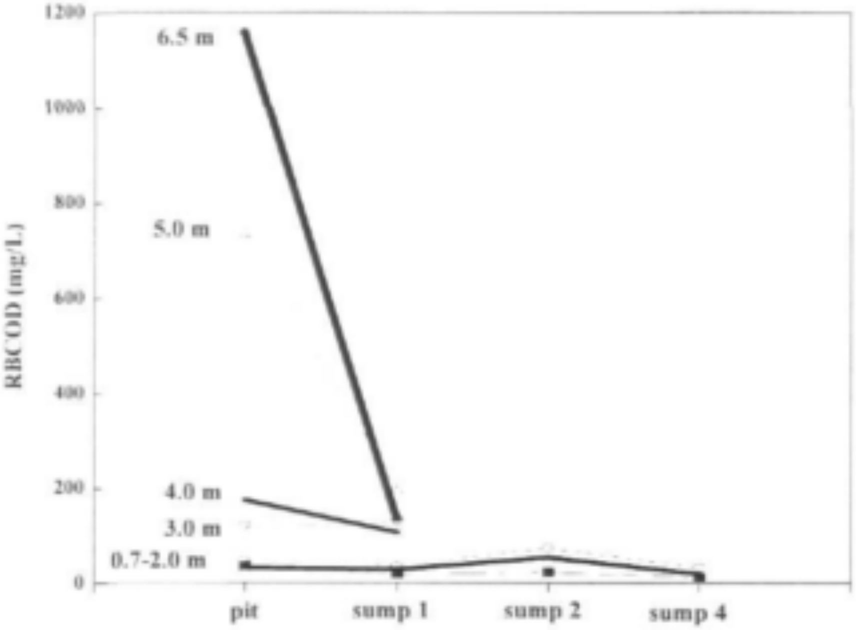


Fig. 10. Typical distribution of readily biodegradable organic substrates (RBCOD) through the pond depth. Sasolburg plant.

Table 6. Distribution of the readily biodegradable organics (RBCOD, S_S, $mg.\ell^{-1}$) in the facultative pond No 1 (southern pond) of the Sasolburg PETRO plant (24.11.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 490 $\mu g.\ell^{-1}$. The only microalgal species present - *Chlamydomonas sp. Values for pit No2 are in parentheses.**

Depth below surface, meters	**Section, functionally representing a primary (facultative) pond**						**Section functionally representing a secondary oxidation pond**					
	Fermentation pit No 1, north (no 2)			1[st] sump pit, middle			2[nd] sump pit, middle			4[th] sump pit, middle		
	S_S	alkalinity	settleable solids $m\ell.\ell^{-1}$	S_S	Alk	settleable solids $m\ell.\ell^{-1}$	S_s	Alk	settleable solids, $m\ell.\ell^{-1}$	S_s	Alk	settleable solids $m\ell.\ell^{-1}$
0.7	60	290	0	12	321	0	10	270	53	12	311	0
1.5	70	312	0	26	315	0	24	280	468	15	326	144
2.0 pond bottom	n.d.	n.d.	n.d.	33	343	0	39	305	980	265	361	840
3.0	53	343	1	81	296	0						
4.0	108	331	0	110	338	0						
4.5	100 (77)	361 (344)	3 (340)	120	320	0						
5.0	128 (130)	346 (313)	100 (168)	129	381	140						
6.5 (pit bottom)	399 (400)	440 (455)	500 (542)	139	546	840						
TF feed (pond outflow)							71	326	0			
Recycle (inlet pipe water)										46	320	0

Table 7. Distribution of the readily biodegradable soluble substrates, RBCOD (S_S, mg.l^{-1}) in the primary pond No 1 of the Newcastle PETRO plant (29.11.1999). S_i=34 mg.l^{-1}. Chlorophyll *a* concentration in recycled water (from the final secondary pond to the surface of the primary pond) was 490µg.l^{-1}. Double recycle since 18.11.99. The only microalgal species present - *Euglena sp.*

Depth below surface, meters	Main (1st sump) Fermentation pit			2nd sump pit (3rd sump pit)			4th sump pit*		
	S_S	alkalinity	settleable solids ml.l^{-1}	S_S	alkalinity	settleable solids ml.l^{-1}	S_S	alkalinity	settleable solids, ml.l^{-1}
0.5	12	340	0	2 (24)	377 (339)	0 (0)	36	366	0
1.0	19	355	0	38 (50)	n.d.	0 (0)	54	n.d.	0
2.0	190	369	18	921 (538)	n.d.	870 (895)	156	n.d.	970
3.0	214	n.d.	215	489 (350)	499 (505)	950 (960)	186	470	980
4.0	310	n.d.	554						
5.0	760	n.d	610						
6.0.	883	414	422						
7.0	800	444	457						
Primary pond outflow							100	320	0
Recycle							23	349	0

Table 8. Distribution of the readily biodegradable soluble substrates (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary pond No 2 of the Newcastle PETRO plant (29.11.1999). S_i=34 mg.ℓ$^{-1}$. No recycle since 18.11.1999.

Depth below surface, meters	Main (1st sump) Fermentation pit			2nd sump pit (3rd sump pit)			4th sump pit*		
	S_S	alkalinity	settleable solids mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	22	365	0	14(10)	310(330)	0 (0)	21	340	0
1.0	14	370	6	15(13)	330(345)	10 (8)	10	366	15
2.0	19	340	148	310(215	480(445)	956(980)	66	406	307
3.0	34	n.d.	293	229(230)	n.d.	970(999)	100	411	995
4.0	210	399	415						
5.0	240	380	430						
6.0	444	410	376						
7.0	606	420	330						
Primary Pond							71	310	0

Table 9. Non-BNR PETRO system. COD fractionation in the primary pond effluent (overflow) vs raw influent (1997-1999). Based on the data presented in Tables 2-8 (See also Appendix Tables 1-21). All values are averages.

PETRO system	**Raw influent**				**Pond effluent (overflow)**			
	RBCOD (S_S)		SBCOD (X_S)		RBCOD (S_S)		SBCOD (X_S)	
	mg.l^{-1}	% of $TCOD_{raw}$	mg.l^{-1}	% of $TCOD_{raw}$	mg.l^{-1}	% of $TCOD_{effluent}$	mg.l^{-1}	% of $TCOD_{effluent}$
ASP variants								
Bloemfontein	70	18	203	50	65	33	61	31
Soshanguve	85	17	290	58	38	15	80	34
TF variants								
Newcastle	110	15	390	56	71	31	70	31
Letlhabile	62	12	225	45	55	29	49	26
KaNyamazane	79	11	352	51	64	30	72	33
Sasolburg	43	14	152	49	70	29	71	30
Bloemhof	240	14	731	43	88	28	99	32

Table 10. Envisaged BNR PETRO system. Envisaged COD fractionation in the primary pond effluent (potential point of extraction - the RBCOD generating pit, water strata immediately over sludge layer). All values are averages.

PETRO system	RBCOD (S_S)		SBCOD (X_S)	
	mg.ℓ$^{-1}$	% of $TCOD_{effluent}$	mg.ℓ$^{-1}$	% of $TCOD_{effluent}$
Newcastle	180	56	106	33
Sasolburg	160	67	46	20
Bloemhof	260	63	185	45

3.3 Sludge production and accumulation of readily biodegradable organics (RBCOD) in the PETRO ponds

The operational data on sludge production and desludging rate from the primary ponds is fragmentary and not complete in many cases.

Nevertheless, the data available from the Newcastle, Sasolburg and Bloemhof plants (Tables 11-14, 17; Appendix Tables 22-31) strongly suggests that the value for the sludge production rate under high rate organic loading (0.4 - 0.8 kg COD.m^{-3} .d^{-1}) combined with the high rate recirculation is greater than that of the conventional sewage anaerobic digestion. It is the latter one that is currently used in the standard PETRO design calculations (0.1 kg SS.kg^{-1} treated COD).

This estimate compares well with the data generated as a result of world-wide re-evaluation of the desludging strategies for stabilization ponds. Sludge production rate in stabilization ponds has shown wide variation. Extensively researched over the last decades, it was reported only for the ponds without recirculation (Schneiter et al., 1983; Iwema et al., 1987; Saqqar and Pescod, 1995b). Sludge production rate values in the anaerobic ponds range from 0.162 to 0.41 kg sludge SS produced per 1 kg COD treated (0.27-0.69 m^3 per 1000 inhabitants equivalent per day , or 0.099- 0.252 m^3 per caput per year, assuming the equivalent is 100 g per caput and sludge content - 6%). This is substantially higher than theoretical values for anaerobic digestion: 0.1 kg SS.kg^{-1} treated COD.

Due to the scarcity of information in literature, it is not possible to correlate organic loading and sludge production rates for stabilisation ponds, though it was reported that efficiency of anaerobic digestion increases (i.e. sludge production decreases) with pond depth (Brockett, 1976).

In the comprehensive overview of the anaerobic pond design parameters, WHO (1987) concluded that a considerable amount of investigation was still needed to achieve acceptable rational design procedure and numerous environmental factors had not been taken into account. Recirculation of algae-rich water is only one of them.

Sludge production rates under the standard PETRO conditions are intermediate between those reported for acidogenic (0.257 mg VSS. mg^{-1} COD, or 0.41 mg SS. mg^{-1} COD) and methanogenic reactors (0.043 mg VSS. mg^{-1} COD, or 0.07 mg SS. mg^{-1} COD (Tanaka and Matsuo,1986).

Attempts to establish a short term material balance of solid deposits in ponds were not successful (Iwema et al, 1987). Detailed long term generalized analysis of the PETRO sludge production is still in progress. The figure which emerged as a preliminary estimate is 0.18 kg $SS.kg^{-1}$ treated COD.

No information on the influence of recycle on sludge production rates is available from literature. This aspect requires further investigation.

Volumes of sludge accumulated and thickness of sludge layers were estimated at different PETRO plants. The data presented in Appendix Tables 22-31. Some aspects of the desludging strategies were reviewed and new recommendations for the plant operators were put forward.

A new parameter termed *the RBCOD generation potential* (RBCOD potential in Fig.9, Tables 11-14, (Appendix Tables 32-34) was introduced in order to estimate potential of sludge accumulated in different parts of the primary and secondary ponds in terms of generation of readily biodegradable organics to be used in downstream P removal. The RBCOD potential is an amount of readily biodegradable organics (measured as COD), generated per g of sludge volatile solids per day (in mg. g^{-1} VSS. d^{-1}).

Pond stratification surveys and full scale experiments at the Sasolburg plant demonstrated that RBCOD production and accumulation of readily biodegradable organics increases with an increase of the sludge pool in the primary pond pit. It gradually decreases with depletion of sludge pool through intensified desludging (Fig. 11; Appendix Table 35). Apparently, additional load of volatile (organic) suspended matter (sludge with a high concentration of readily biodegradable organics) imposed onto anaerobic microbial consortium leads to an increase in intermediary products of anaerobic digestion since methanogenic phase is a rate-limiting component of anaerobic digestion. Once sludge quantity decreases due to routine sludge removal the amount of readily biodegradable matter meets capacity of the methanogenic microflora to process it.

At the same time the RBCOD potential was found to correlate with sludge age (SRT). The highest potential was observed for the fermentation pit sludge. It sharply decreases (from 0.083 to 0.024 mg. g^{-1} VSS. d^{-1}) downstream of the inlet and pit (Fig.9; Tables 11-14; Appendix Tables 32-34). The potential continues to decrease further in the secondary ponds (0.001 mg. g^{-1} VSS. d^{-1}) as the age of the carryover sludge increases while slowly biodegradable fraction (X_S) eventually disappears and volatile solids content decreases from 77% (raw sludge) to 15% (4th sump, Sasolburg).

Table 11. Sludge blanket characteristics of the facultative pond No 2 (northern pond) of the Sasolburg PETRO plant. Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom - approx bottom 50 cm of sludge layer. VSS, % , sludge volatile solids as percentage of total solids; RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VS. d^{-1}.

Section, functionally representing Aprimary A (facultative) pond								Section functionally representing Asecondary≡ oxidation pond							
Fermentation pit no 1				1st sump pit, middle				2nd sump pit, middle				4th sump pit, middle			
Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
									6.07.1999						
65	0.083	67	0.109	66	0.070	65	0.055	60	0.024	54	0.008	47	0.001	15	0.001
									24.11.1999						
67	0.09	66	0.092	66	0.061	64	0.047	61	0.021	52	0.001	35	0.001	23	0.001
									21.12.1999						
68	0.089	69	0.085	67	0.060	66	0.058	60	0.036	60	0.01	51	0.02	19	0.001
									14.03.2000 [1]						
68	0.091	67	0.088	68	0.083	66	0.061	63	0.041	61	0.009	53	0.022	18	0.001

[1]- sump 1 (i.e. Aprimary≡ pond section) was not desludged since 21.12.1999. 63

Table 12. Sludge blanket characteristics of the primary pond of the Bloemhof PETRO plant. Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom - approx bottom 50 cm of sludge layer.

Date	Main (1st sump) fermentation pit				2nd sump pit, middle				4th sump pit, middle			
	Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
	VSS[1]	RBCOD[2]	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
25.5.99	65	0.105	69	0.109	66	0.075	64	0.061	67	0.040	62	0.025
6.8.99	66	0.150	68	0.100	66	0.060	63	0.082	66	0.046	61	0.011
2.12.99	65	0.130	68	0.110	65	0.059	64	0.089	64	0.033	60	0.010

[1] VSS, % , sludge volatile solids as percentage of total solids;

[2] RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VS. d^{-1}.

Table 13. Sludge blanket characteristics of the primary pond No 1 of the Newcastle PETRO plant. Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom - approx bottom 50 cm of sludge layer.

Main (1st sump) fermentation pit				2nd sump pit, middle				4th sump pit, middle			
Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
VSS[1]	RBCOD[2]	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
						3 August 1999					
60	0.066	58	0.070	61	0.067	58	0.045	57	0.001	56	0.001
						29 November 1999					
59	0.065	58	0.071	59	0.066	57	0.044	57	0.001	55	0.001

[1] VSS, %, sludge volatile solids as percentage of total solids;

2 RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VS. d^{-1}.

Table 14. Sludge blanket characteristics of the primary pond of the Bloemfontein PETRO plant

Date	Fermentation pit		Area surrounding the pit	
	VSS[1]	RBCOD potential[2]	VSS	RBCOD potential
26.5.99	69	0.040	67	0.001
6.8.99	70	0.023	69	0.004
1.12.99	69	0.044	66	0.003

1 VSS, % , sludge volatile solids as percentage of total solids;

2 RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VSS. d^{-1}.

Table 15. Influence of algae-rich recycle (490 ug/ℓ chl. *a*) on the RBCOD generating pit. Newcastle primary ponds 1, recycle ratio, c : (c+a) = 0.6:1 and pond 2 (no recycle, c = 0).

Depth m	Pond 1 pit		Pond 2 pit	
	RBCOD	Settl solids	RBCOD	Settl solids
0.5	12	0	22	0
1.0	19	0	14	6
2.0	190	18	19	148
3.0	214	215	34	293
4.0	310	554	210	415
5.0	760	610	240	430
6.0	884	422	444	376
7.0	800	457	606	330

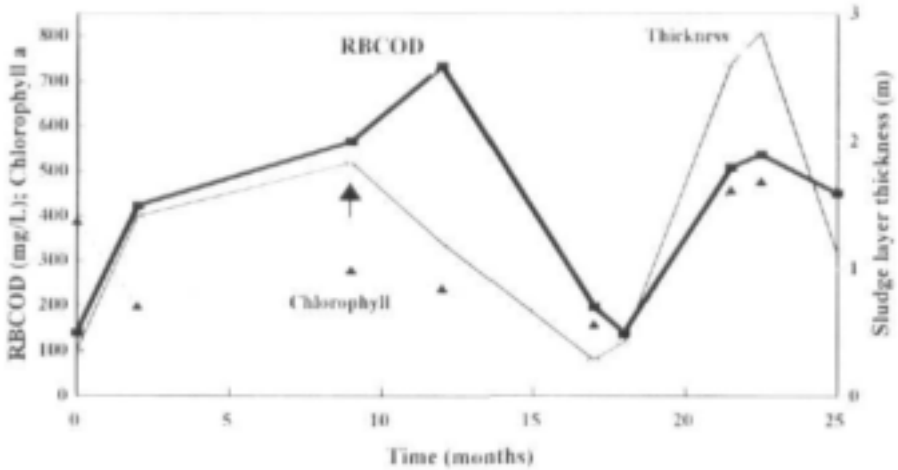


Fig. 11. Correlation between the sludge layer thickness, chlorophyll a and sludge RBCOD in the fermentation pit. Depth 5 m. Sasolburg plant. Arrow indicates gradually enhanced desludging terminated in approx. 6 months.

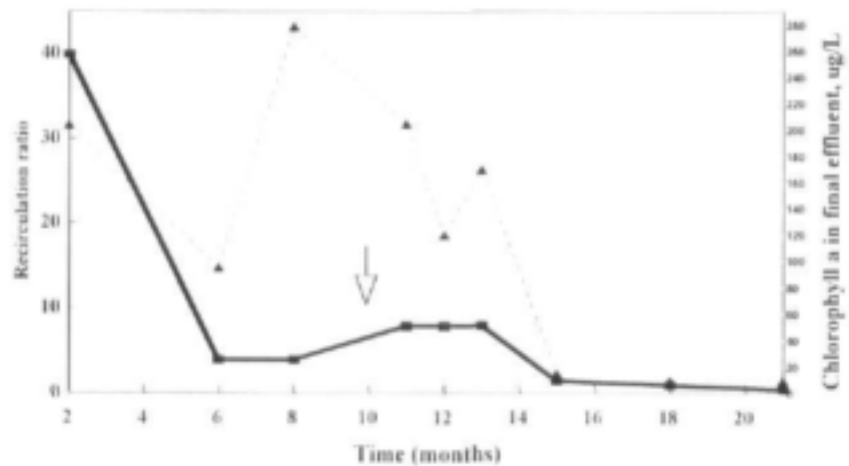


Fig 12. Removal of microalgae at the Sterkwater PETRO plant (Bloemfontein). Impact of pond recycle ratio (solid line) on the removal of algae in ASP (as chlorophyll a in final effluent, broken line). Arrow indicates omission of the direct raw sewage feed to ASP.

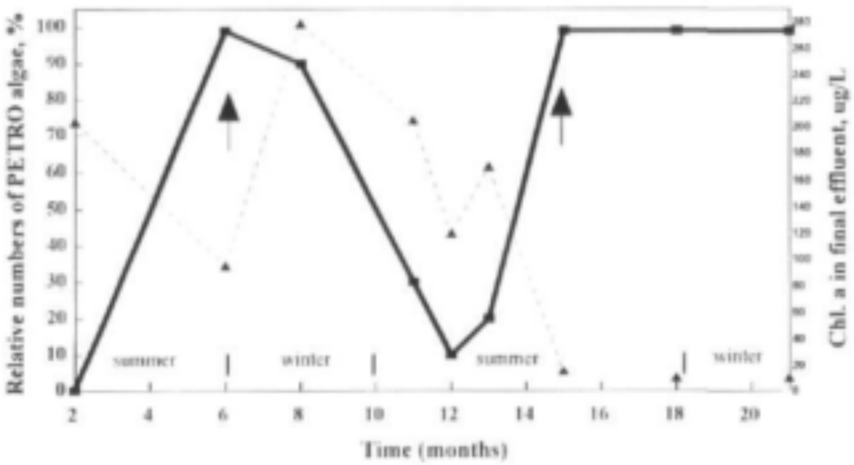


Fig 13. Removal of microalgae at the Sterkwater PETRO plant (Bloemfontein). Relative numbers of "PETRO algae" (solid line) in ponds (as % of total algal numbers) versus chlorophyll a in final effluent (broken line). Arrows indicate consecutive decreases in pond recirculation rate.

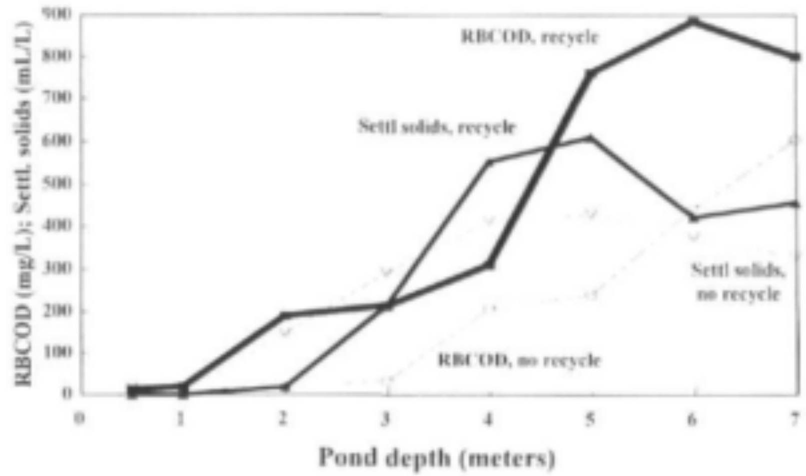


Fig. 14. Influence of the algae-rich recycle on the RBCOD generating pit. Primary pond 1: recycle ratio, 0.6: 1 (solid line). Pond 2: no recycle (dashed line). Newcastle plant.

Table 16. Influence of recirculation rate on the microalgal biomass removal in the ASP reactor and algal specification in ponds. Bloemfontein (Sterkwater) PETRO ASP plant. Note that the names of microalgae typical of a well-balanced PETRO system are in bold.

Date	Recirculation ratio	Algal specification*	Chlorophyll *a* in pond effl **.	COD in pond effl**	RBCOD in pond effl.**	Chlorophyll *a* in final effluent	COD in final effl
22 Jan 1999 (summer)	40 : 1	*Micractinium sp.* (99%) marginal: *Eudorina sp.*, *Microcystis sp.*, ***Euglena sp.*** *Scenedesmus sp.*	688	155	n.d.	204	120
26 May 1999 (winter)	4 : 1	***Chlamydomonas sp.*** (95%) ***Euglena sp.*** (5%) marginal: *Eudorina sp.*, *Micractinium sp.*	105	260	45	95	140
5 Aug 1999 (winter)	4 : 1	***Phacus pyrum*** (90%) *Micractinium sp.*(10%) marginal: *Ankistrodesmus sp*	675	170	94	279	126
25 Oct 1999 (summer)	8 : 1	*Micractinium sp.*(70%) ***Phacus pleuronectes*** (30%) marginal: *Ankistrodesmus sp*	780	165	66	205	91
1 Dec 1999 (summer)	8 : 1	*Micractinium sp.*(90%) ***Phacus pleuronectes*** (10%) marginal: *Ankistrodesmus sp*	190	254	81	120	95

* As approximate cell numbers; ** Primary pond effluent (underflow).

Table 16 (continued).

Date	Recirculation ratio	Algal specification*	Chlorophyll *a* in pond effl **.	COD in pond effl**	RBCOD in pond effl.**	Chlorophyll *a* in final effluent	COD in final effl
6 Jan 2000 (summer)	8 : 1	*Micractinium sp.* (80%) ***Phacus pleuronectes*** (20%) marginal: *Eudorina sp.*, *Ankistrodesmus sp.*	280	n.d.	68	170	82
27 Feb 2000(summer)	1.5 : 1	***Euglena sp.*** (80%), ***Phacus pleuronectes*** (20%) marginal: *Micractinium sp.*	210	215	85	15	49
18 May 2000(autumn)	1 : 1	***Euglena sp.*** (90%), ***Phacus pleuronectes*** (10%)	280	240	60	10	70
25 Aug 2000(winter)	0.5 : 1	***Euglena sp.*** (90%), ***Phacus pleuronectes*** (10%)	190	209	56	10	55

* As approximate cell numbers; ** Primary pond effluent (underflow).

Table 17. Sludge production rates in the PETRO primary ponds (1999).

PETRO systems	Organic load, kg COD. m^{-3}. d^{-1}	Sludge production rate, kg sludge SS.kg^{-1} COD treated	Recycle ratio, (e : e+a)
SASOLBURG	0.21	0.15	0.5 : 1.0
NEWCASTLE	0.59	0.11	0.3 : 1.0
BLOEMHOF	0.34	0.18	0.2 : 1.0
Assumed for high rate anaerobic digesters	>1.0	0.08-0.1	n.a.*

* n.a. – not applicable

3.4 Theoretical RBCOD generation potential of the fermentation pit sludge

It is obvious from the data collected during pond stratification surveys that the sludge produced in the PETRO primary pond as a result of anaerobic digestion in the fermentation pit can be used as an additional source of RBCOD for downstream P removal.

Before comprehensive full scale experimental data are available it is important to evaluate potential amount of the RBCOD produced from the sludge under the conditions characteristic of the PETRO pond.

According to the PETRO design rationale:

the PETRO system with the following parameters:

> organic load of 10 000 kg COD. d^{-1}, inorganic P load 200 kg. d^{-1} (10 kg. m^{-3} @ flowrate 20 Mℓ/d and influent COD 0.5 kg. m^{-3} with at least 50% COD removal in the primary pond

will produce 5000 kg COD. d^{-1} as the BNR reactor feed.

According to the COD fractionation data collected in the field (Table 9) approximately 30% of this COD is RBCOD, i.e. 1500 kg COD. d^{-1}. The figure quoted is for the primary pond overflow effluent. The RBCOD fraction in the pond effluent extracted from deeper pond strata will be substantially higher (up to 56-63%, Table 10, increasing the amount of RBCOD up to 2800 -3150 kg COD. d^{-1}; though the figures are not used in calculations since this aspect is still under investigation).

Literature on P removal in the waste stabilisation ponds (de Oliveira, 1990; Silva et al., 1995) and the Soshanguve plant operational data demonstrate that approximately 30-40% of $P_{inorganic}$ is removed in the primary and secondary ponds providing 120-140 kg P. d^{-1} as the loading on the BNR reactor.

It is generally accepted that 10 mg of RBCOD is required for biological removal of 1 mg P (Wentzel, 1990; Wentzel et al., 1990; Stensel, 1991). Hence 1200-1400 kg RBCOD. d^{-1}

would be required for removal of 120-140 kg $P.d^{-1}$, which is approximately the amount available in the effluent of the PETRO ponding section (BNR feed), i.e. 1500 kg $COD.d^{-1}$.

The PETRO primary pond at the above organic loadings (10 000 kg $COD.d^{-1}$) is estimated to produce approximately 3000 kg sludge $COD.d^{-1}$ (assuming preliminary figure of 0.2 kg SS produced per kg treated COD and SS : COD in sludge as 1:1.5).

Additional amount of RBCOD becomes available with an introduction of *the RBCOD GeneratingPit* (see Section 3.6). RBCOD generating potential of sludge is by far greater than that of soluble slowly biodegradable organics (Gonçalves et al., 1994).

Slowly biodegradable sludge solids (SBCOD) in the pit would produce RBCOD at the rate of 0.16 kg RBCOD per 1 kg sludge COD (Wentzel, 1990; Lilley et al., 1991). Thus 3000 kg sludge $COD.d^{-1}$ is expected to produce 480 kg $RBCOD.d^{-1}$.

To sum up, overall amount of RBCOD available for the P removal in the secondary BNR reactor is 1980 (1500 + 480) kg $RBCOD.d^{-1}$ as against the required 1200-1400 kg $RBCOD.d^{1}$.

3.5 Feasibility of biological P removal in the PETRO system

Due to the nature of the PETRO system, a pond-based facility providing 60% COD removal in the ponds and secondary position of the activated sludge reactor (envisaged BNR reactor), the system=s biological P removal process was considered to be *a priori* fraught with problems of deficiency in readily biodegradable organics for PAO.

Nevertheless feasibility of the efficient biological P removal was demonstrated in the full scale experiments at the Soshanguve PETRO plant (ASP variant, ADWF = 8 MLD).

It has been observed at the plant that for short periods (up to 4 days) after electric power cut-offs efficiency of biological P removal significantly improved. Periods without aeration resulted in creation of anoxic conditions in the reactor and generation of additional RBCOD (S_S). Values around and below 1 $mg.\ell^{-1}$ were attained for the $P_{inorganic}$ in the final effluent (Fig. 15; Table 18).

Lack of readily biodegradable organics as well as excessive aeration were found to be major factors causing poor P release by PAO in the reactor anaerobic zone and, as a result, overall inferior biological P removal. Table 18 presents data of the series of experiments. It is thought that supply of additional readily biodegradable organics from the fermentation pit would remedy the situation.

Unfortunately, the research work at the Soshanguve PETRO plant was terminated. Decommissioning of the old ASP reactor, extension of the plant and lack of operational control made optimisation of aeration and biological P release impossible.

Table 18. Enhancement of biological P-removal in the full-scale ASP reactor. The Soshanguve PETRO plant. Concentration of $P_{inorganic}$ in the reactor feed: 6.3 ∀ 2.0 mg.ℓ$^{-1}$, while $P_{inorganic}$ in the plant raw influent was approximately 10 mg.ℓ$^{-1}$.

Time (days)	1	2	3	4	5	6
P -concentration in the reactor final effluent						
Experiment 1	8.0	1.0	0.6	2.3	4.6	4.3
Experiment 2	6.1	0.7	1.3	2.9	4.1	4.6
Experiment 3	5.6	0.6	n.d.	0.7	1.3	4.2

3.6 Introducing the concept of *the RBCOD Generating Pit*: an approach to tentative design guidelines

Since phosphate accumulating organisms, a driving force behind the process of biological P removal, require readily biodegradable organics to release and subsequently take up $P_{inorganic}$ (Fuchs and Chen, 1975; Abu-ghararah and Randall, 1991; Lotter and Pitman, 1992), various means have been devised to provide RBCOD for the process. An in-line generation of RBCOD in the anaerobic section of the BNR reactor is an option (Barnard, 1984, 1991; Daigger and Polson, 1991). As an alternative, side-stream acidogenic fermenters (or activated primaries) producing VFA and other readily biodegradable organics from settled primary sludge were successfully employed (Pitman et al., 1992; Oldham and Abraham, 1994). The fermentor-based acidogenesis is a high tech approach which requires constant control and extensive optimization (Daigger and Bowen, 1994; Banister and Pretorius, 1998).

The present concept is a simplification of this approach, a development of an appropriate low tech pond-based RBCOD production within the PETRO framework.

Full scale experimentation on the primary ponds at the Sasolburg, Bloemhof and Newcastle plants demonstrated feasibility of an odour-free generation of readily biodegradable organics (RBCOD) in an open highly loaded anaerobic pond.

Sludge slowly biodegradable solids generated in the PETRO primary pond in the course of anaerobic digestion, if left in the pit, serve as a feedback source of soluble organics due to solubilisation of volatile solids (Somiya and Fujji, 1984). The sludge with a short SRT (<5days) contains up to 70% of volatile organics. The enhanced solids solubilisation with VFA and other soluble organics as the end products is expected to occur in the pond. The concept of the BNR PETRO relies on impeded anaerobic digestion with a balance offset towards acidogenic phase. At the same time, as the field data shows, the pond microbial consortium performs a 50-60% COD removal thus complying with the PETRO design criteria.

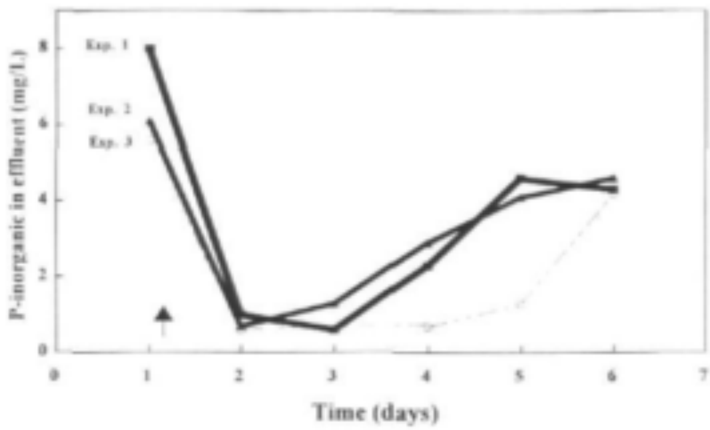


Fig. 15. Enhancement of the biological P removal in the full-scale activated sludge reactor. Three independent experiments. Soshanguve plant. Arrow indicates a short-term period of a decreased aeration.

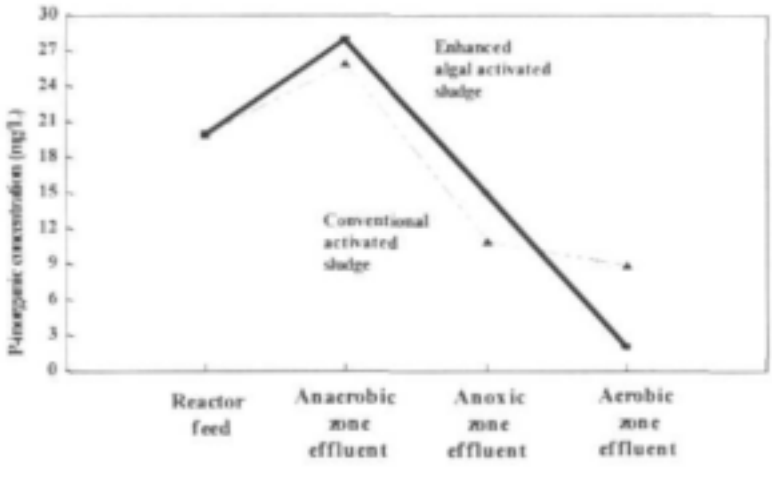


Fig. 16. Algae-assisted chemical P removal in the Enhanced algal activated sludge (solid line) versus the conventional activated sludge (no algae).

This approach runs contrary to the conventional mode of operation of an primary pond or an anaerobic digester when low steady-state amounts of VFA (RBCOD), at the concentration below 100 mg.ℓ^{-1} and VFA: Alkalinity ratio below 0.3, are considered the features of a well-run and balanced anaerobic digestion. Excessive VFA generation is seen as a result of destabilization of methanogenic stage fraught with potential problems of foul odour emission and inferior performance (WPCF, 1987; Mara et al., 1992).

Under certain conditions the PETRO pond in a stable steady-state mode was found to produce quantities of VFA (RBCOD) to the extent of an immature anaerobic pond during a start-up period. Such periods (up to 6 months from the start-up) are well known to be characterized by excessive odour emissions (strong VFA smells) from the ponds. In contrast no excessive odour release was observed from the Sasolburg, Bloemhof and Newcastle primary ponds despite the fact that VFA (RBCOD) concentrations in the sludge were well above 300 mg.ℓ^{-1} (particularly in Bloemhof) while VFA (RBCOD) : Alkalinity ratios were strongly unfavourable from the conventional point of view (Tables 5-8; Fig. 8).

Field observations suggest that the conditions for the enhanced RBCOD production are as follows:

- high specific organic load on the primary pond and, particularly, on the pit which becomes *the RBCOD generating pit*;

- extensive pool of sludge in the pit;

- short hydraulic retention time (<15 hours);

- short sludge retention time (<15 days) may be beneficial though reasonable solubilisation rates are attained even with high SRT (> 30 days);

- high rate recirculation, providing algal oxygenated water from the secondary ponds.

Specific organic loadings on the PETRO primary ponds are among the highest in the world practice (0.21-0.82 kg COD.m^{-3}.d^{-1}). It exceeds that of a conventional anaerobic pond (0.03-0.6 kg COD.$m^{-3}$$d^{-1}$) and a primary facultative pond (0.01-0.03 kg COD.m^{-3}.d^{-1}) (Mara and Mills, 1994; Saqqar and Pescod, 1995a).

It was demonstrated that only the ponds with an extensive pool of sludge featured enhanced RBCOD production, i.e. primary ponds in Sasolburg (before extensive desludging, Table 6; Appendix Tables 7-13, 35; Fig. 10, 11), Bloemhof (Tables 5; Appendix Tables 16-17; Fig. 8) and Newcastle (Tables 7-8, 15; Fig. 14).

It is known that HRT and SRT play important role in acidogenesis (Gerber and Winter, 1984; Elefsiniotis and Oldham, 1994; Skalsky and Daigger, 1995; Henze, 1996). HRT ranging from 5 to 35 hours is thought to ensure efficient VFA production while SRT <10-15 days is recommended to prevent extensive methanogenesis (Cohen et al., 1979; Lilley et al., 1991; Oldham et al., 1992) .

HRT criteria applied to the PETRO ponds are the lowest in the world WSP practice. Actual HRT values in the pit of the PETRO ponds are: Sasolburg - 9 h, Newcastle - 7h, Bloemhof - 9 hours, which lies in the optimal range.

Due to a fragmentary record of desludging at most of the plants evaluation of sludge age is complicated. SRT issue requires further investigation. Though preliminary findings indicate that the sludge age in the studied PETRO pond exceeds 30 days.

It should be pointed out that there is a significant difference between the conventional primary anaerobic pond and the PETRO primary anaerobic pond, also termed an Aerobic-Anaerobic pond. Recirculation of algae-rich oxygenated water from the secondary ponds to the surface of the PETRO anaerobic pond introduces features of a facultative pond. Therefore the PETRO pond is as an intermediate between the conventional anaerobic and primary facultative pond. Recycle containing vehicles of oxygenation in the form of microalgae interferes with anaerobic process in the pond since mixing introduces low amounts of oxygen into deeper pond strata.

Pit design criteria were simplified compared to our latest classical design approach. According to the latter one, a concentric arrangement of the pit was proposed where an internal acidogenic section (receiving raw inflow) separated from the external methanogenic section by the circular wall. New design approach introduces the concept of *the RBCOD Generating Pit* which does not involve major structural changes and is based on the existing pond layout.

Recirculation of the algae-rich water from the secondary ponds to the surface of the primary pond is an inherent feature of the PETRO concept. This beneficial phenomenon, still underestimated in the world full scale practice, requires further study. Impact of the recirculation on the PETRO pond performance (particularly RBCOD production) is a critical aspect.

Recirculation rate appears to be at least one of the key factors in the enhancement of the RBCOD production. Preliminary data obtained suggest that the enhancement is effected through inhibition of extremely oxygen-sensitive methanogens (Fig. 11, 14). This offsets the balance of the anaerobic digestion thereby increasing concentration of RBCOD (VFA and other readily biodegradable organics).

Even a relatively low rate recycle (Fig. 1; 0.3:1=c : e+a, i.e. 30% of the primary pond effluent recycled back through the secondary ponds) was shown to be an effective means to avoid malodorous situation under the conditions of high sludge content and enhanced RBCOD production in the pit (Newcastle). It was found permissible for the primary pond sludge to take up to 30% of the pond volume (Fig 14). Recirculation supplying oxygenated water allows for control of methanogens in the microbial consortium.

Sludge settleability in the primary pond appears to increase proportionally to the recycle rate, apparently as a result of a decreased floc buoyancy (Table 15).

Motility serves as a critical survival adaptation for microalgae typical of the highly loaded primary and secondary ponds integrated into a coherent entity in the PETRO setup (*Chlamydomonas, Euglena, Phacus spp.*). It ensures the highest algal concentration in the surface layer exposed to the sun thus providing an odour-free overlay over the pit area.

Preliminary full scale data from the Sterkwater PETRO plant shows that over-recirculation is detrimental for the downstream removal of algae. Enhanced recycle appears to encourage algal population which is alien to the PETRO microbial system (Table 16; Fig. 12-13). Further full scale long-term observations are required to elaborate on this aspect and put forward design recommendations.

Recycle decreases surface RBCOD (Fig.14; Table 15) but pond stratification data shows that lower strata of the RBCOD generating pit still contain significant amounts of readily biodegradable organics. Due to the impact of recirculation an extraction point of the BNR feed should be situated directly above the sludge layer.

Under these conditions supply of settleable solids from the primary pond to the BNR anaerobic zone, which is negligible in the standard PETRO mode, will be increased. The acidogenic potential of sludge slowly biodegradable organics (X_S) is substantially higher than that of dissolved biodegradable organics. The solid organic matter having undergone pre-treatment in the pit would be readily degraded further in the anaerobic zone. The supply of solid organics in a preconditioned form would greatly enhance pond=s RBCOD generating efficiency. Since recycle of settled sludge in the pit (as in an activated primary) is to be omitted in the PETRO BNR conceptual design, amount of sludge in the pit will be controlled by the flexible hydraulic regime.

High rate recirculation provides an opportunity to significantly increase RBCOD production in an open primary pond. Under these conditions a specific organic loading can be safely increased well beyond the value recommended for ponds without recirculation (0.6 kg COD. $m^{-3}.d^{-1}$).

Overall, operational stability and effective attenuation of organic/hydraulic load peaks, which are typical of a primary pond, become inherent features of the envisaged PETRO BNR plant.

3.7 Potential role of microalgae in phosphorus removal

The role of microalgae in P removal in the PETRO activated sludge reactor was studied in the laboratory reactor containing so called *Enhanced algae-activated sludge* (EAAS) cultures. To obtain the EAAS cultures, activated sludge originating from the full scale PETRO ASP reactor (Soshanguve) was enriched in microalgae. The same cultures were used in the previous experiments when the role of microalgae in exopolysaccharide production in the PETRO activated sludge flocs was investigated (Meiring et al., 1998a).

The approach is not dissimilar to that used by Wentzel et al. (1988, 1989) in the experiments on *the Enhanced polyphosphate organism cultures.* The Enhanced cultures in the activated sludge were enriched in *Acinetobacter sp.* in excess of 90%. It was concluded that they conformed reasonably closely to natural microbial mechanisms characterizing activated sludge removing phosphorus biologically.

Using the same approach the EAAS cultures were enriched in typical PETRO algae, *Euglena, Chlamydomonas, Chlorella spp.*, to the level (2100 $\mu g.\ell^{-1}$ as chlorophyll *a*) substantially exceeding that of actual algal concentration (max 900 $\mu g.\ell^{-1}$) in the sludge of the Soshanguve ASP reactor. The cultures were also expected to conform to microbial mechanisms occurring in the PETRO activated sludge. As the algal concentration influent

$P_{inorganic}$ concentration was increased from 10 mg.ℓ^{-1} (common sewage content) to 20 mg.ℓ^{-1} in order to render the observed effects more pronounced.

Data obtained is presented in Fig. 16 and Appendix Table 36. It was demonstrated that both the EAAS and conventional activated sludge cultures (used as a control) exhibited the same mechanism of biological P removal in the model 3 zone reactor over a period of 9 weeks. At the same time substantial improvement in the final effluent quality was observed in the EAAS cultures in comparison to the control cultures. The difference in performance, particularly pronounced at the stage of aerobic zone, strongly indicated a measure of involvement of microalgae in P removal.

Luxury uptake of inorganic phosphate and subsequent polyphosphate accumulation by various microalgae was reported in literature. The phosphorus-deficient microalgae of different species were shown to commonly possess the ability to incorporate phosphate extremely rapidly if they were provided with this compound. In most cases the incorporated inorganic phosphate exceeded by far the actual need of the cells, so that a surplus amount was stored inside the cell (Kuhl, 1974). In various microalgae this occurs almost exclusively as high molecular inorganic polyphosphates (Kuhl, 1968). Blum (1966) has shown, using ^{32}P-labelled phosphate, that within one minute of uptake at 25°C over 95% of this was converted to organic compounds in *Euglena sp.* (which is a typical PETRO pond alga). This biological mechanism requires further investigation.

The most probable P removal mechanism in this case is *an algae-assisted pH-mediated chemical precipitation* of P in the algal-activated sludge flocs. Algae are well known to increase pH photosynthetically in the algal ponds (Sukenik and Shelef, 1984, Sukenik et al., 1985; Adey et al., 1993; Craggs et al., 1995). $P_{inorganic}$ was actually shown to decrease in a high rate pond by precipitation of Acalcium phosphate≅ in algal flocs (Moutin et al., 1992). They cause formation of insoluble calcium salts, such as apatite, $Ca_3(PO_4)_2$, hydroxyapatite $Ca_5(OH)(PO_4)_3$, etc. It is known that hydroxyapatite is the most thermodynamically stable calcium phosphate solid. Though most of the calcium phosphate precipitates are more soluble and structurally differ from hydroxyapatite (Ferguson et al., 1973). It was suggested that substitution by foreign ions (magnesium, iron) and short precipitation time are responsible for this variability (Ferguson and McCarty, 1970; Corbridge, 1980). It has been shown in experiments with activated sludge that chemical precipitation of P as Aa calcium phosphate≅ was independent of whether the conditions are anoxic, anaerobic or aerobic, provided pH >6.8. At pH <6.5 precipitate formed could redissolve (Hoffmann, 1977).

It is thought that the most probable explanation of the phenomenon observed in the experiment with the EAAS cultures is the following. Being an integral part of the EAAS flocs, microalgae create alkaline microzones where P precipitation is likely to occur. Thus chemical precipitation of P in the activated sludge appears to be facilitated by microalgae.

Furthermore, chemical precipitation without microalgae appears to require higher concentration of Ca^{2+} to precipitate $P_{inorganic}$ present in the influent. Required Ca^{2+} concentration was established to be at least 40 mg. ℓ^{-1} for chemical P precipitation to occur in the activated sludge (Hoffmann, 1977). Under conditions of the reported experiment it took place at a lower concentration: 29 mg. ℓ^{-1}. In general, water supplied for domestic purposes in Pretoria area contains Ca^{2+} : max concentration - 71 mg. ℓ^{-1}, average - 27 mg.ℓ^{-1}, min - 11 mg. ℓ^{-1}; and Mg^{2+}: max concentration 29 mg.ℓ^{-1}, average 7 mg. ℓ^{-1}, min - 1 mg. ℓ^{-1} (Water Lab, 1998).

Overall, it was demonstrated that apart from the recognized pH-dependent chemical P precipitation in stabilisation ponds (Houng and Gloyna, 1984; Surampalli et al., 1993; Cloot and Roos, 1996) and activated sludge (Momberg and Oellermann, 1982), the PETRO concept features phenomenon of *the algae-assisted chemical P precipitation* in the activated sludge. The process occurs simultaneously with the EPS-facilitated algal biomass removal. It results in precipitation of inorganic phosphates in the activated sludge flocs, apparently in a form of calcium/magnesium salts. Subsequent removal of waste activated sludge may result in an additional P removal of up to several milligrams per litre.

Experiments on the full scale are required to confirm practical importance of the phenomenon.

4. CONCLUSIONS

1. Integration of ponds with a downstream secondary facility (TF or ASP) into the framework of the PETRO concept allows for substantial capital and operational savings. Incorporation of the biological phosphorus removal into the concept should retain operational simplicity of the PETRO system and achieve an even higher degree of treatment (Shipin et al., 1999).

2. Production of readily biodegradable organics (RBCOD) plays a crucial role in both the PETRO and biological P removal concepts. The nature of the organic matter is a key factor in the microalgal *heterotrophic autoflocculation* in the secondary facility. At the same time it is the main driving force behind the activity of phosphate accumulating organisms (PAO) in a conventional BNR reactor. The current effort is to use these fortunate process similarities of two concepts in the development of an appropriate BNR technology.

3. It was established that the RBCOD content of the effluent from the primary pond operated under the standard PETRO conditions fully meets only the requirements of algal removal but not those of biological P removal.

4. Observations made at a number of full-scale plants strongly suggest that the primary pond used in a particular regime of operation is capable of the RBCOD production at the rates required for biological P removal.

5. Feasibility of biological P removal in the PETRO context was demonstrated on the full scale during several experimental periods at the Soshanguve plant. On occasions values below 1 $mg.\ell^{-1}$ were attained for the inorganic P concentration in the final effluent. However, shortage of RBCOD in the ASP reactor feed and excessive aeration were among the factors responsible for inferior P removal for more extended periods. Unfortunately it proved impossible to optimize the process in Soshanguve due to the factors over which there was no control and due to eventual decommissioning of the reactor as a part of the plant extension masterplan.

6. Sludge production rates in the PETRO ponds and current desludging strategies were reviewed. Sludge production rates under the conditions were found to be intermediate between those reported for acidogenic (0.257 kg $VS.kg^{-1}$ COD) and methanogenic reactors (0.08 $kg.kg^{-1}$). A preliminary estimate obtained from the full scale primary

ponds is 0.18 kg $SS.kg^{-1}$ treated COD. The data require long-term confirmation.

7. The RBCOD generating potential of the primary pond sludge was studied. It was found to correlate with the sludge age and sharply decrease downstream of the primary pond inlet. It continues to decrease further in the secondary ponds.

8. Pond stratification surveys demonstrated that RBCOD production increases with an increase of the sludge pool in the pit and *vice versa*.

   The PETRO fermentation pit was observed to feature high rate RBCOD production even at relatively long SRT (>15 days) combined with short HRT (<15 hours). Interestingly, SRT in the fermentation pit were significantly higher for the PETRO primary pond than those reported for optimal RBCOD production in acidogenic fermentors.

9. Recirculation of the algae-rich water from the secondary ponds to the surface of the primary pond is an inherent feature of the PETRO concept. This beneficial phenomenon, still underestimated in the world full-scale practice, requires further study. Impact of the recirculation on the PETRO pond performance (particularly RBCOD production) is currently under long-term investigation.

10. Recirculation rate appears to be at least one of the key factors in the enhancement of the RBCOD production. The tentative data obtained suggest that the enhancement is effected through inhibition of extremely oxygen-sensitive methanogens. This offsets the balance of anaerobic digestion thereby increasing concentration of RBCOD (VFA and other readily biodegradable organics).

11. High rate recirculation appears to provide an opportunity to significantly increase RBCOD production in an open primary pond. Under these conditions a specific organic loading can be safely increased well beyond the value recommended for ponds without recirculation (0.6 kg $COD.m^{-3}.d^{-1}$).

    Even a relatively low rate recycle (0.3 : 1) was shown to be an effective means to avoid malodorous situation under conditions of high sludge content and enhanced RBCOD production in the pit. It was found permissible for the primary pond sludge to take up to at least 30% of the pond volume without any environmental consequences. Recirculation supplying oxygenated water allows for control of methanogens in the anaerobic microbial consortium.

    Sludge settleability in the pond appears to increase proportionally to the recycle rate, apparently as a result of a decreased floc buoyancy. Further full scale experiments are required to strengthen the rationale. As a result of the investigation the concept of *the RBCOD Generating Pit* located in the primary pond is being developed. It does not involve major structural changes and is based on the existing pond layout. Certain changes in the regime of operation are suggested. Generation of RBCOD in a conventional fermentation pit avoids other high-tech options (e.g. activated primaries, acidogenic fermentors etc.) which are capital cost intensive and more economical for large high tech plants.

12. The concept combines a COD removal in the primary pond of up to 60% with a concomitant solubilisation of slowly biodegradable solids. It relies on the generation of RBCOD from the slowly biodegradable organic fraction of the sludge under mildly oxygen-stressed anaerobic conditions. Field observations suggest that the conditions for the enhanced RBCOD production are as follows:

    i. high specific organic load on the primary pond (0.21- 0.82 kg $COD.m^{-3}.d^{-1}$) and, particularly, on the pit which becomes the RBCOD Generating Pit;
    ii. extensive pool of sludge in the pit;
    iii. short hydraulic retention time (<15 hours);
    iv. short sludge retention time (<15 days) may be beneficial though reasonable solubilisation rates are attained even with high SRT (> 30 days);
    v. high rate recirculation, providing algal oxygenated water from the secondary ponds.

13. Under these conditions *no pond desludging* option may become feasible: enhanced sludge carryover into the ASP reactor would simplify O & M procedures (Houng and Gloyna, 1984).

14. Operational stability and effective attenuation of organic/hydraulic load peaks, which are typical of a primary pond, become features of the envisaged PETRO BNR plant.

15. The potential role of microalgae in the PETRO system P removal was researched. It was established in the laboratory that apart from the recognized pH-dependent chemical P precipitation in the stabilisation ponds and activated sludge, the PETRO concept features a phenomenon of *an algae-mediated P precipitation* in the activated sludge reactor. It occurs concomitantly with the EPS-mediated algae removal. It is suggested that the process is brought about by precipitation of inorganic phosphates in the activated sludge flocs, apparently as calcium/magnesium salts. It appears that without microalgae chemical precipitation would require much higher concentrations of Ca^{2+} and Mg^{2+}. Suggested mechanism for the observed pH-dependent enhanced precipitation is the formation of the floc microzones with pH elevated by microalgal photosynthesis. Subsequent removal of waste activated sludge might result in an additional P removal of up to several milligrams per litre. The algae-mediated chemical process may contribute to biological PAO-mediated P removal and thus enhance system's overall performance. Experiments on a full scale are required to elaborate on the practical importance of the phenomenon.

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6. TECHNOLOGY TRANSFER

The data obtained is being used in the rationalization of the operation of the existing PETRO plants (Bloemhof, Newcastle, Sterkwater). New design considerations are provided for future installations. The PETRO BNR concept is thought to lay foundation for the retrofit of the existing TF plant in eMbalenhle (Secunda, Sasol). The 15 MLD municipal treatment facility is envisaged to provide comprehensive Biological Nutrient Removal.

Certain aspects of the generated research database are being applied in the ongoing retrofit of the Western Treatment Plant, Werribee, Australia.

The database generated allowed to rationalize pond desludging strategies in the PETRO TF plant in Sasolburg. Occasional malodours present in winter were thereby eliminated.

Enhancement of the PETRO system's potential through incorporation of biological P removal extends spectrum of opportunities for construction of new Agreenfield– and retrofit PETRO plants.

7. PRESENTATIONS AND PUBLICATIONS

The project findings were presented as oral papers for:

The 4th IAWQ International Specialist Conference on Waste Stabilisation Ponds, 20-23 April 1999 in Marrakech, Morocco by Shipin O.V., Meiring P.G.J., Hoffmann J.R. APETRO concept: a tentative approach to biological phosphorus removal incorporating waste stabilisation ponds."

The 6th Biannual WISA Conference, May-June 2000 in Sun City by Shipin O.V., Meiring P.G.J., Cronwright M.Y., Phillips T.D., Prinsloo A.D. Cost-efficient treatment for wastewater from agri-industries: towards comprehensive BNR facility.

The Annual Conference/Exhibition of the Institution of Municipal Engineering of Southern Africa, October 2001 in Rustenburg by Shipin O.V. and Meiring P.G.J. Financial constraints in wastewater treatment: is there a solution?

International Exhibition AFRIWATER 2001, August 2001, Gallagher Estate, Midrand.

The IWA 5th Specialist Conference Exhibition on Waste Stabilisation Ponds. 2002. Auckland, New Zealand, 2-5 April 2002. Shipin O.V., Meiring P.G.J., Hoffmann J.R. Tougher environmental scrutiny: can waste stabilisation ponds withstand it?

Proceedings of the 7th Water Institute of Southern Africa Conference. 2002. Durban, South Africa, 19-23 May 2002. Shipin O.V. and Meiring P.G.J Tightening discharge regulations: can low tech wastewater treatment survive them?

As well as articles:

Water Science and Technology, 40, 10, 223-229. Shipin O.V., Meiring P.G.J., Hoffmann J.R. PETRO concept: a tentative approach to biological phosphorus removal incorporating waste stabilisation ponds.

Water Science and Technology. 2002 (in press). Shipin O.V., Meiring P.G.J., Hoffmann J.R. New environmental scrutiny: can waste stabilisation ponds withstand it?

8. FUTURE RESEARCH AND DEVELOPMENT WORK

A further effort is required to deal with the fundamental and design issues within the framework of the PETRO concept, comprising both the trickling filter (TF) and the activated sludge process (ASP) PETRO variants.

It is to be based on the long-term monitoring of the PETRO plants and full scale plant trials which would provide superior design information in comparison to pilot scale monitoring. A costly stage of pilot plant trials is thereby omitted.

Overall it will substantially enhance potential of the PETRO system.

The following aspects are to be investigated in future:

A) fundamental aspects of the microalgal phenomena in the PETRO system which would pave the way to enhancement of the P removal prior to the BNR reactor:

   i) metabolic patterns of microalgal heterotrophy in the system - role of preconditioning of microalgae in the primary pond;

   ii) potential luxury P-uptake by the typical PETRO microalgae (*Euglena, Chlamydomonas, Chlorella*)

B) development of a comprehensive *full scale* PETRO BNR facility:

   i) design criteria for the RBCOD generating pit;
   ii) primary (sculptured) pond profile configurations;
   iii) RBCOD generating pit impact on pathogen removal downstream;
   iv) inorganic phosphorus flocculated in pond sludge, its fate downstream and impact on overall P removal (Tswaing PETRO plant);
   v) combined P removal model for ponds and ASP

Development of the comprehensive BNR facility is closely related to the following aims.

C) development of a comprehensive sludge handling/disposal strategy (ASP variant) which involves research of the fundamental and applied aspects such as:

   i) dynamics of microbial consortia in the primary pond sludge;
   ii) minimization of sludge production: towards *no pond desludging* option;
   iii) towards no *drying beds* option (surplus of the primary pond sludge carried over into the ASP);
   iv) metabolic patterns of PAO in the PETRO secondary pond and potential for disposal of WAS from the PETRO BNR into the secondary pond pit to stabilize (followed by land application on site)

D) development of the rationale for nightsoil treatment within the framework of the PETRO concept:

   i) impact of nightsoil discharged into the primary pond on major microbial groups and, overall, on P removal in the ponds and ASP.

E) investigation into the issues of site specificity and put forward recommendations on process design flexibility (TF and ASP variants) in the following aspects:

i) major microbial processes underlying inferior performance of the pond and secondary facility (TF, ASP) during a start-up period: minimization of the start-up procedure;
ii) relative primary-secondary pond(s) horizontal and vertical configurations;
iii) *no microalgae in ponds* option;
iv) review limits of process design flexibility

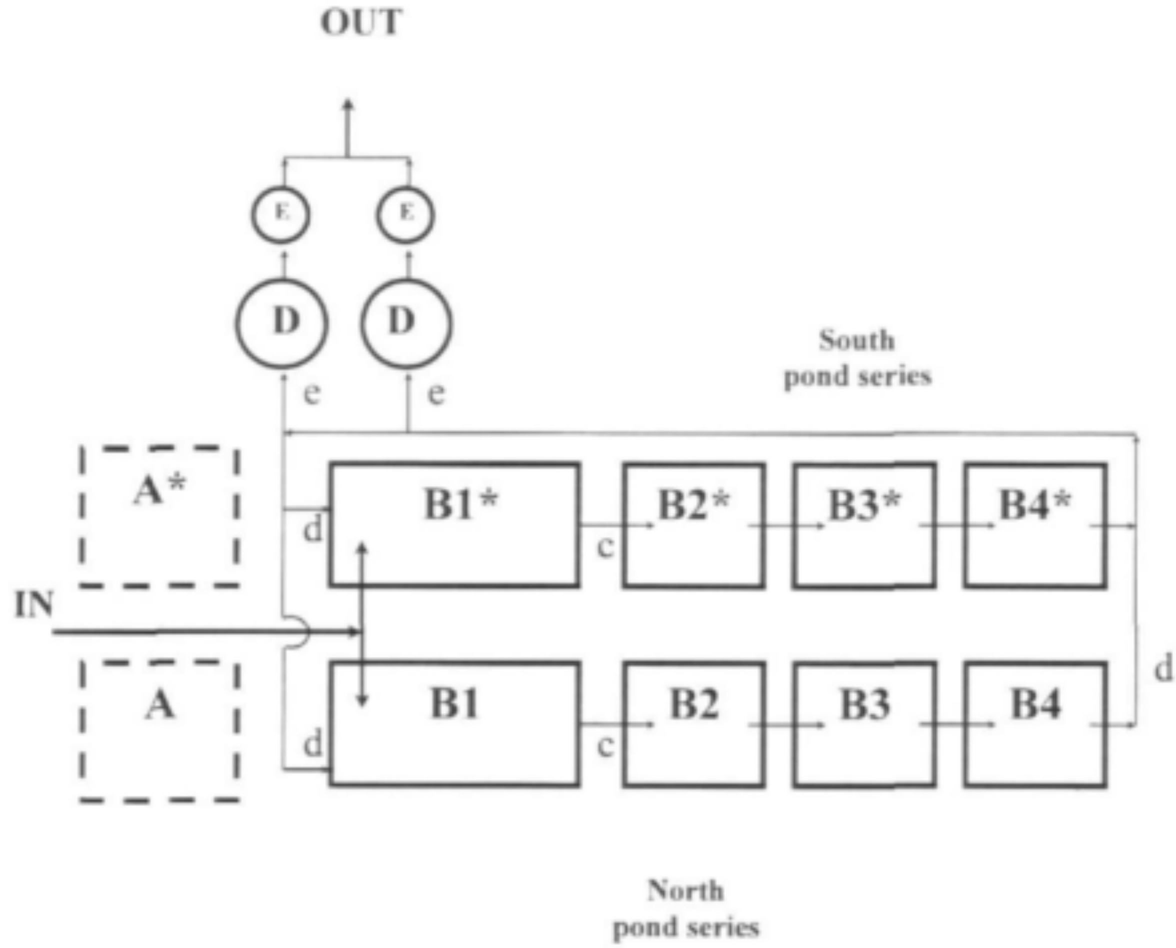
F) development of a microbiological rationale for a potential occurrence of the low F/M filament bulking in the PETRO activated sludge reactor.

G) investigation of the aspects of interpond water recirculation phenomena:

i) impact on the RBCOD generating pit;
ii) impact on long-term stability of the PETRO system;
iii) impact on preconditioning of microalgae in the primary pond (Kanyamazane plant)

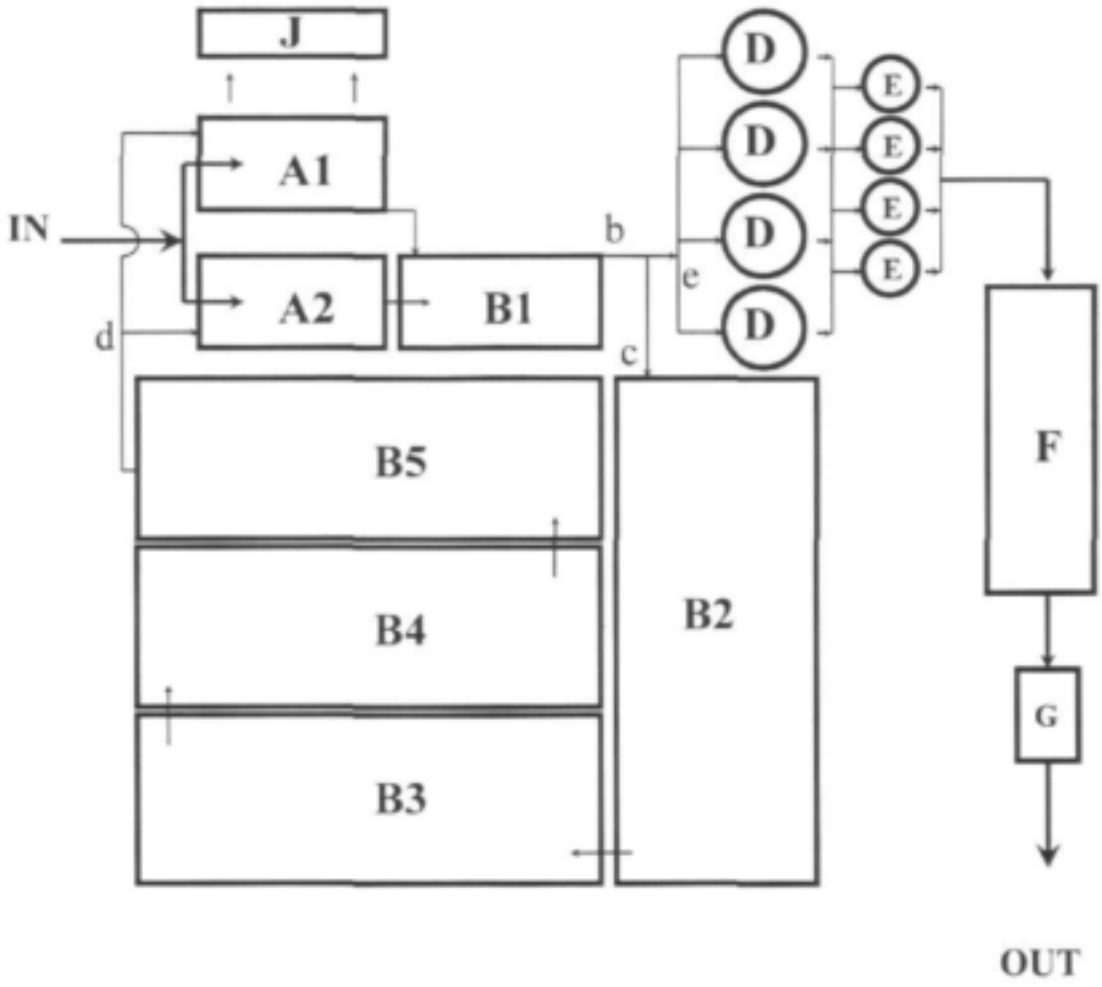
H) preliminary investigation into the feasibility of the BNR facility based on the PETRO Trickling Filter variant.

9. APPENDIX FIGURES



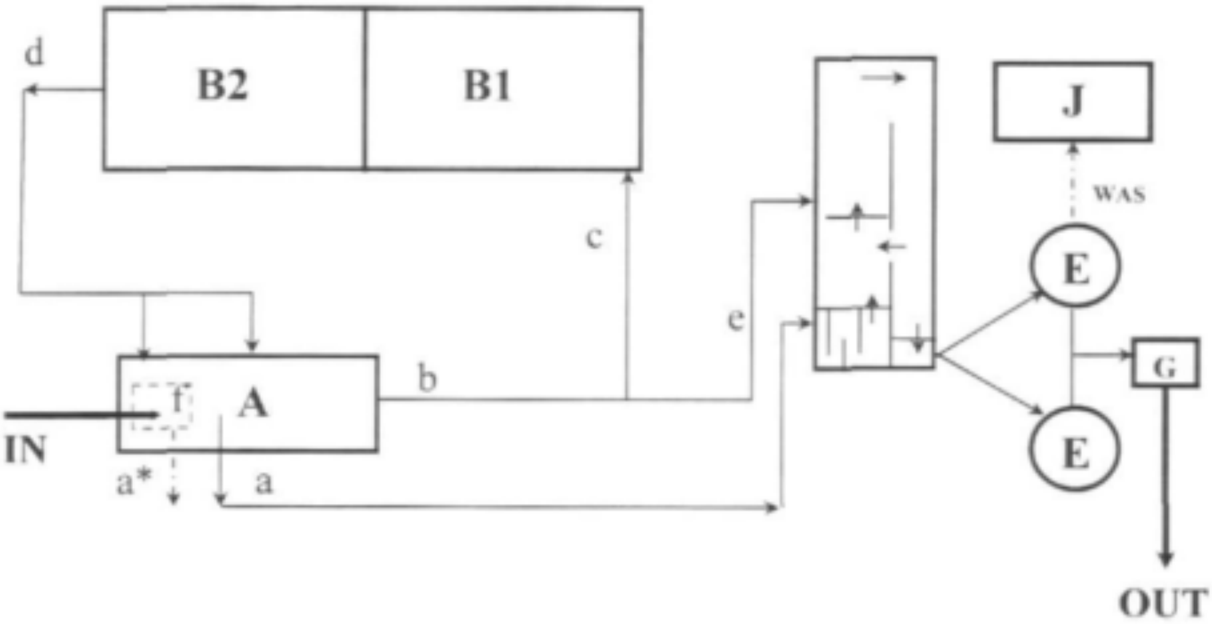
Appendix Fig. 1. Kanyamazane PETRO TF plant. Flow

A-A*. Formal primary ponds (temporarily not operational); B1-B1*.Temporary primary ponds (former secondary ponds). B2-B4. Secondary ponds; D. Trickling filters (secondary PETRO facilities); E. Clarifiers; c. Secondary pond feed; d. Algae-rich recycle from secondary ponds (d : e, recycle ratio); e. TF feed.



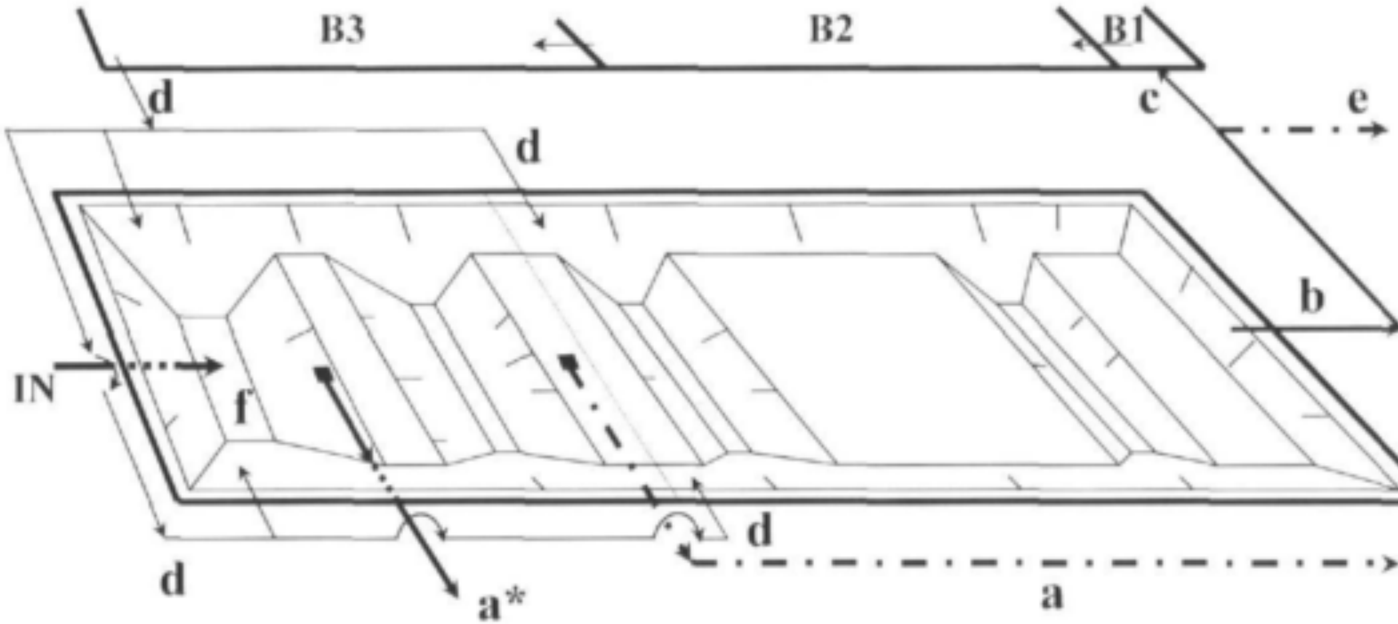
**Appendix Fig. 2. Letlhabile PETRO TF plant.
Flow schematic.**

A1-A2. Primary ponds; B1-B5. Secondary ponds; D. Trickling filters (secondary PETRO facilities); *E. Clarifiers; F. Reedbeds; G. Chlorination channel; J. Sludge drying beds; b. Primary* pond overflow; c. Secondary pond feed; d. Algae-rich recycle from secondary ponds (c : e, recycle ratio); e. TF feed.



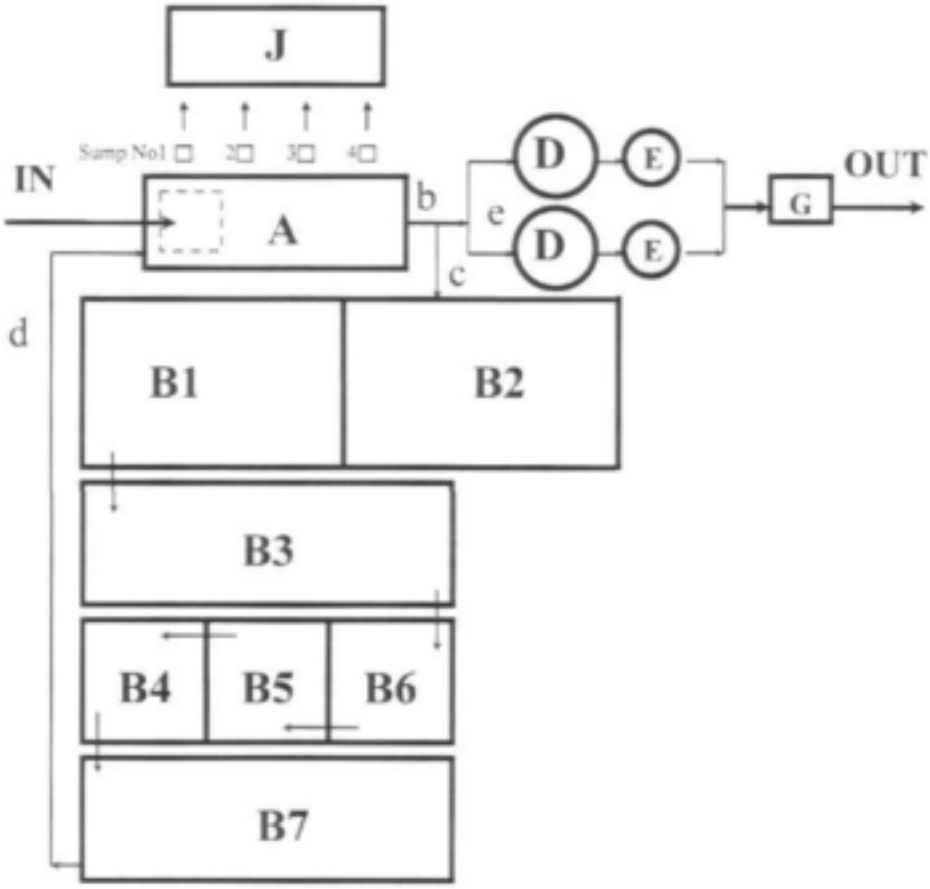
Appendix Fig. 3. Soshanguve PETRO ASP plant.
Flow schematic.

A. Primary pond; B1, B2. Secondary ponds; D. ASP reactor (secondary PETRO facility); E. Clarifiers; G. Chlorination channel; J. Drying beds; a. ASP reactor anaerobic zone feed; a*. Potential extraction point for the ASP reactor anaerobic zone feed; b. Primary pond overflow; c. Secondary ponds feed; d. Algae-rich recycle (c : e+a, recycle ratio); e. ASP reactor aerobic zone feed; f. Proposed RBCOD Generating Pit (current fermentation pit).



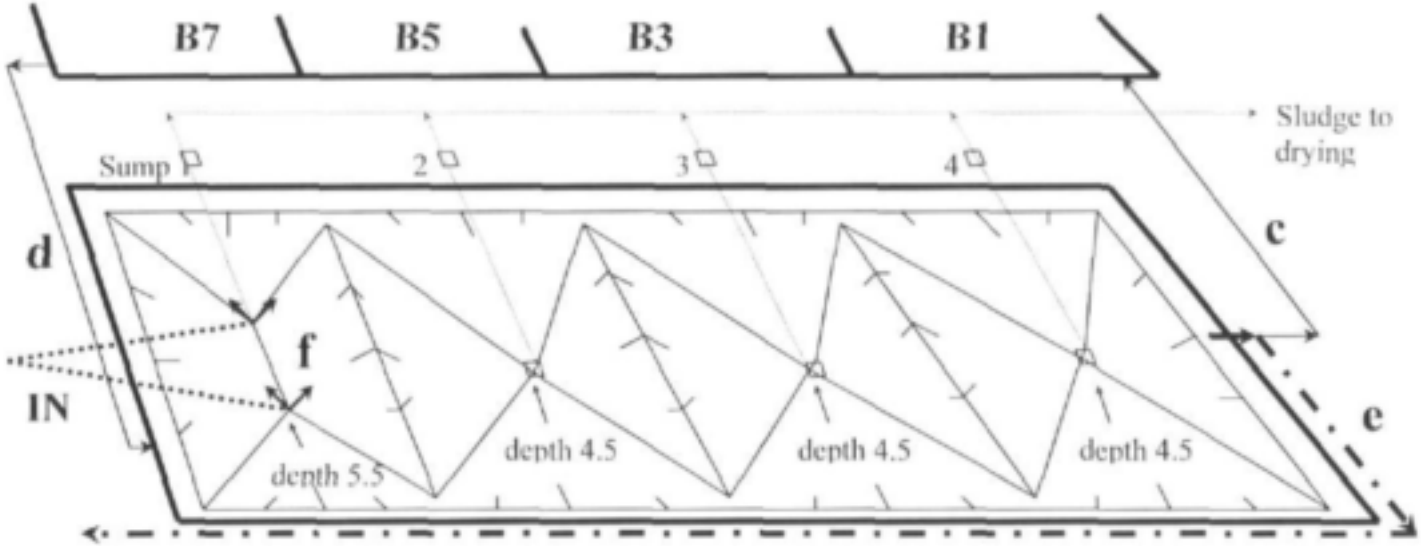
Appendix Fig. 4. Soshanguve PETRO ASP plant Primary pond (0.25 ha; 5.4 Mℓ)

B1-B3. Secondary ponds (total: 1.5 ha; 18.0 mℓ); a. Feed for the ASP reactor anaerobic zone; a*. Potential RBCOD-rich feed for the ASP reactor anaerobic zone; b. Primary pond overflow; c. Secondary ponds feed; d. Algae-rich recycle (c:e+a, recycle ratio); e. feed for the ASP reactor aerobic zone; f. Current fermentation pit (proposed RBCOD generating pit).



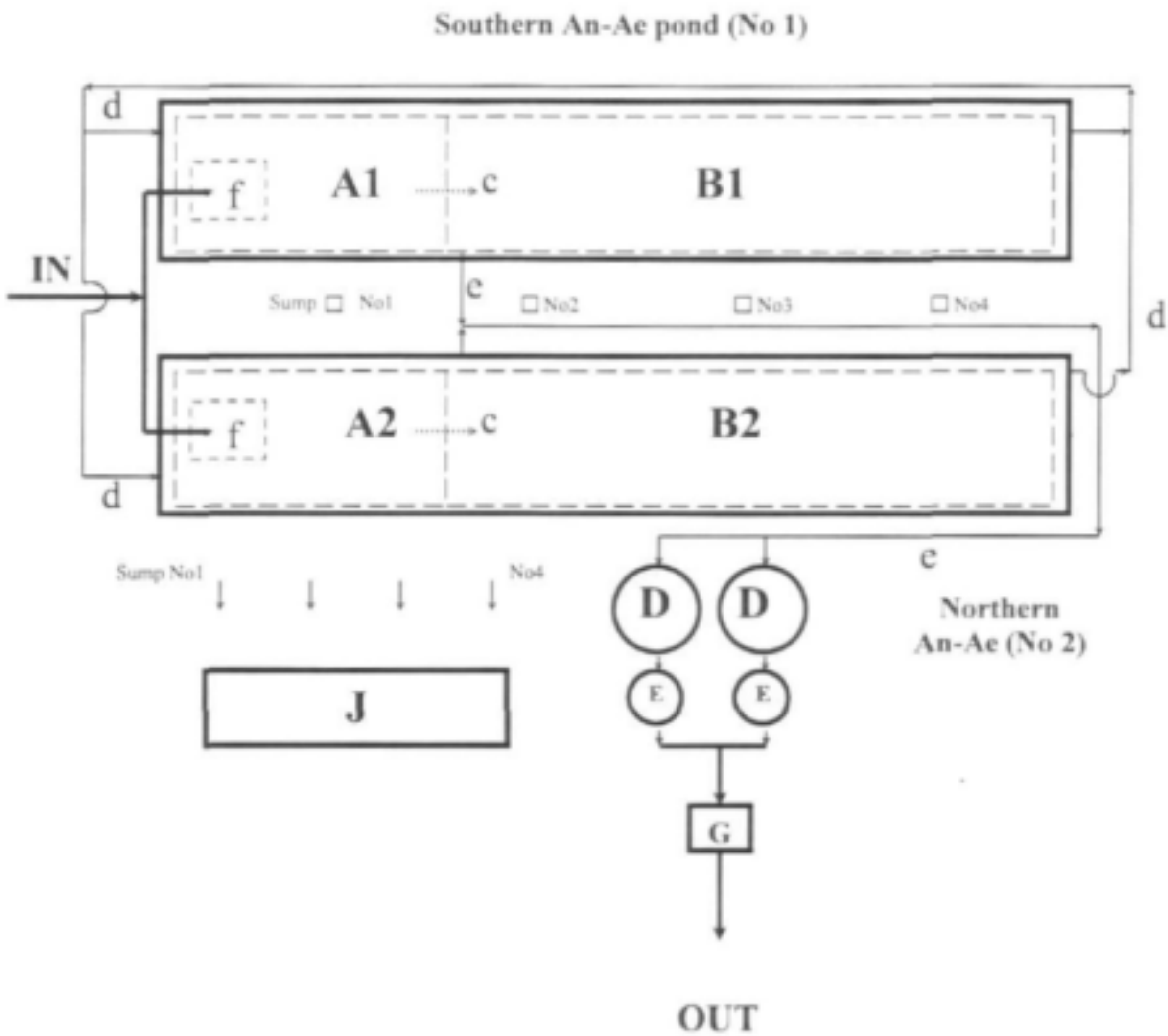
Appendix Fig. 5 Bloemhof PETRO TF plant.
Flow schematic.

A. Primary pond; B1-B7. Secondary ponds; D. Trickling filters (secondary PETRO facilities); E. Clarifiers; G. Chlorination channel; J. Sludge drying beds; b. Primary pond overflow; c. Secondary pond feed; d. Algae-rich recycle from secondary ponds (c : e, recycle ratio); e. TF feed; f. Potential RBCOD Generating Pit (current fermentation pit).



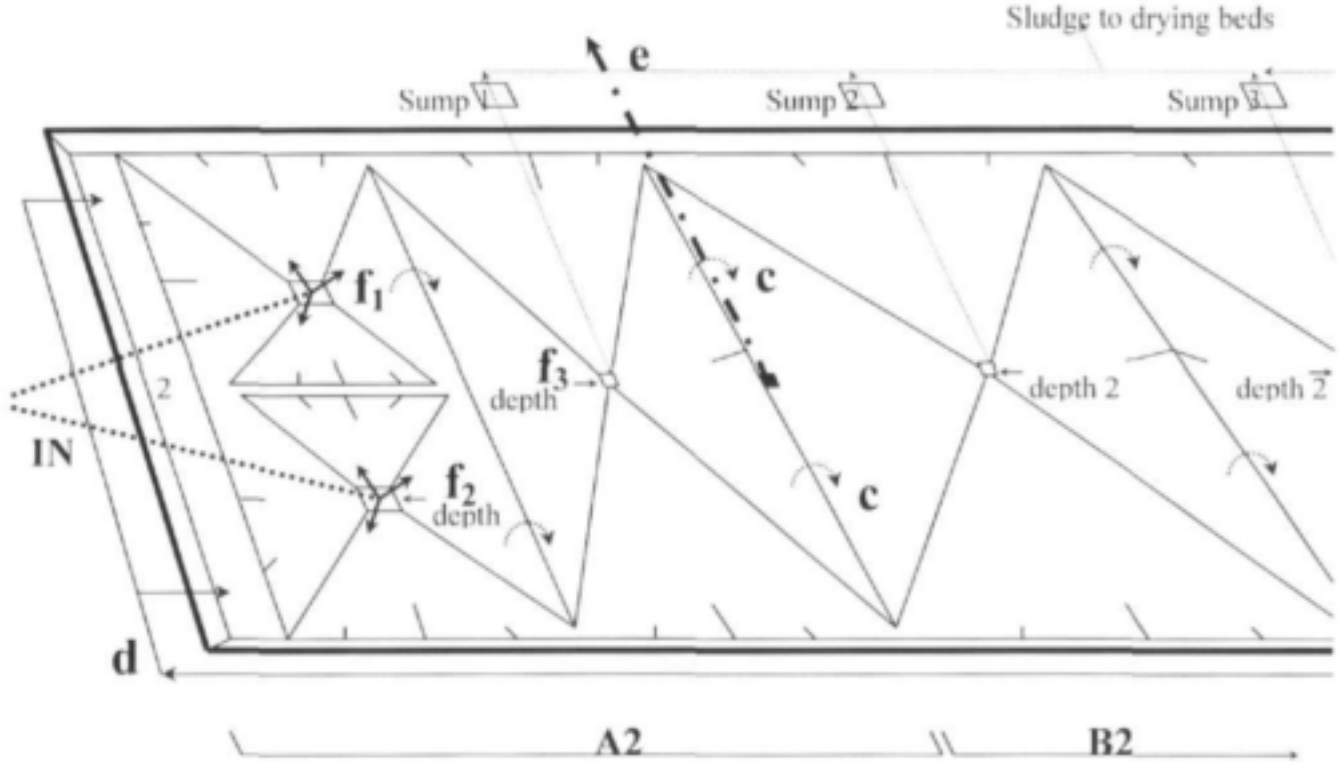
Appendix Fig. 6. Bloemhof PETRO plant. Primary pond (0. 28 ha; 8.7 Mℓ).

B1-B7. Secondary ponds (total: 3.2 ha; 41.7 mℓ); c. Secondary ponds feed; d. Algae-rich recycle (c:e, recycle ratio); e. Primary pond overflow, standard secondary PETRO facility (TF) feed; f. current fermentation pit (proposed RBCOD generating pit).



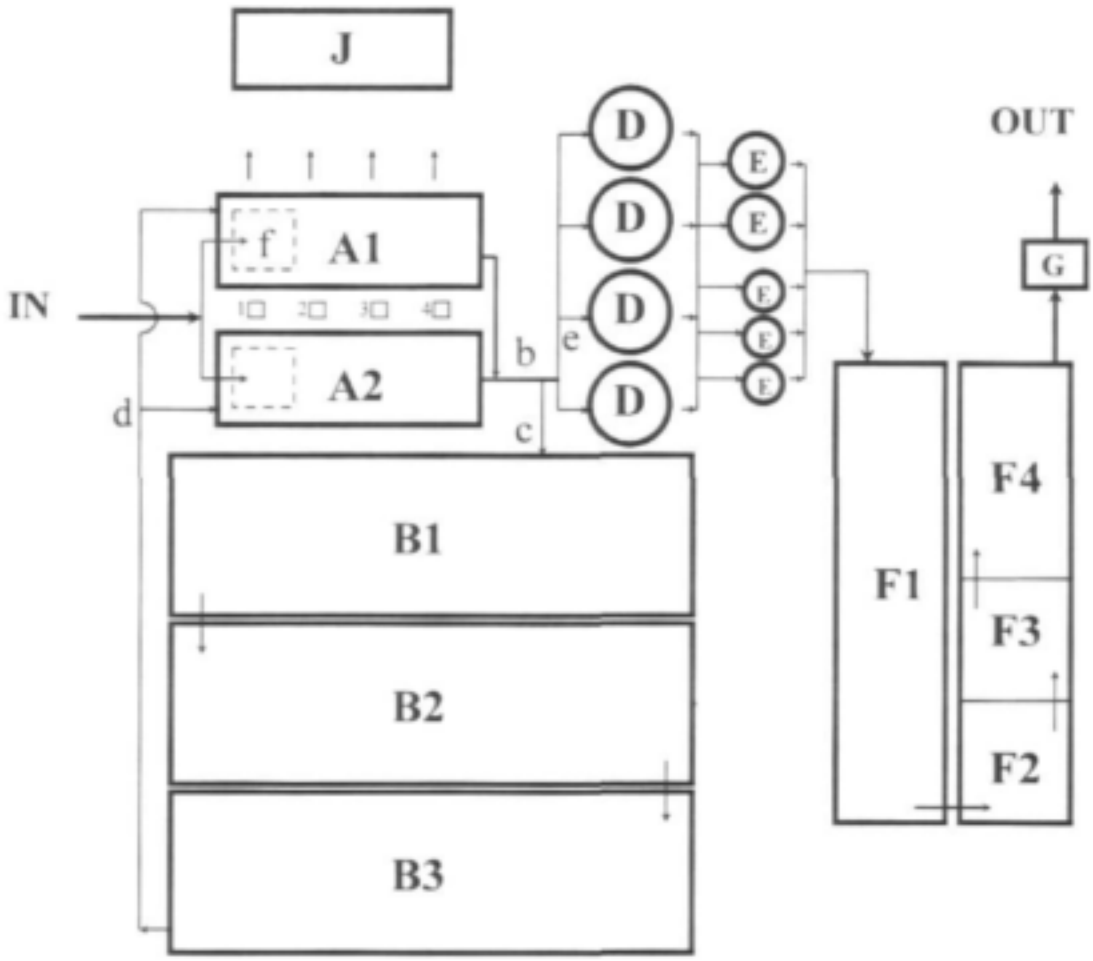
Appendix Fig. 7. Sasolburg PETRO TF plant. Flow schematic.

A1-A2. Primary pond sections of two parallel Anaerobic-Aerobic ponds; B1-B2. Secondary pond sections of the An-Ae ponds; D. Trickling filters (secondary PETRO facilities); E. Clarifiers; G. Chlorination channel; J. Sludge drying beds; c. Secondary pond section feed; d. Algae-rich recycle from secondary pond section (d : e, recycle ratio); e. Primary pond overflow (standard TF feed); f. Proposed RBCOD Generating Pit (current fermentation pit).



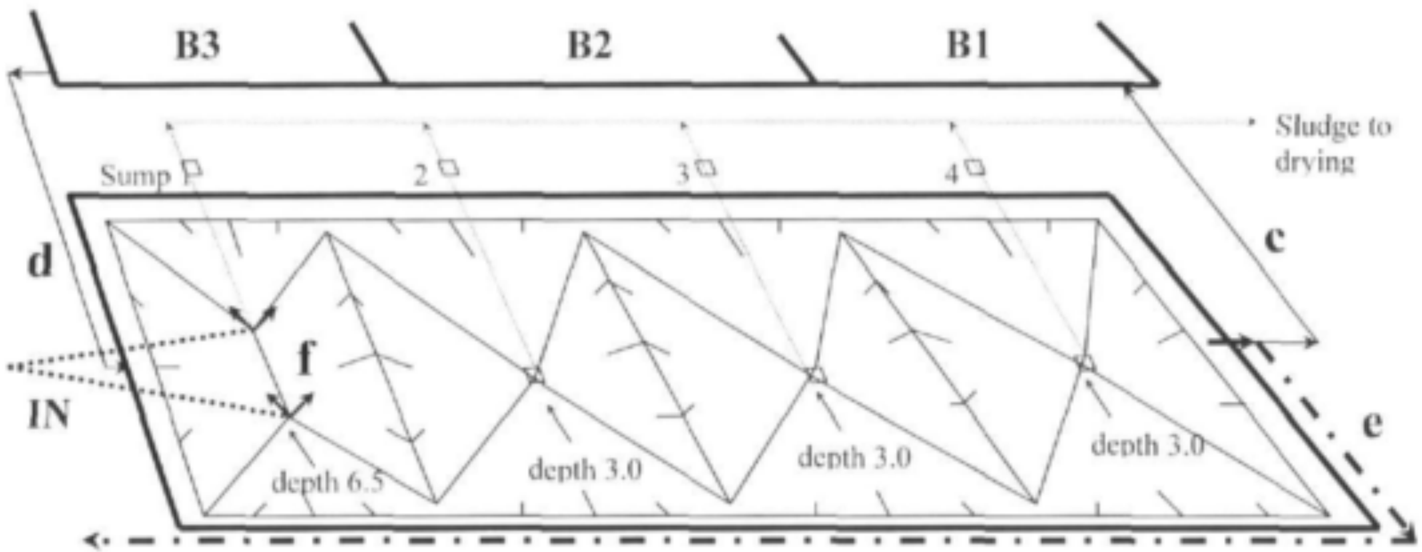
Appendix Fig. 8. Sasolburg *PETRO* plant. Anaerobic-Aerobic (northern) pond.

A2. Primary pond section(0.47 ha; 12.9 Mℓ); B2. Secondary pond section (0.94 ha; 15.1 Mℓ); c. Secondary pond section feed; d. Algae-rich recycle (d:e, recycle ratio); e. Primary pond section overflow, standard secondary PETRO facility (TF) feed; f_1- f_3. current fermentation pits (f_1- f_2 proposed RBCOD generating pits).



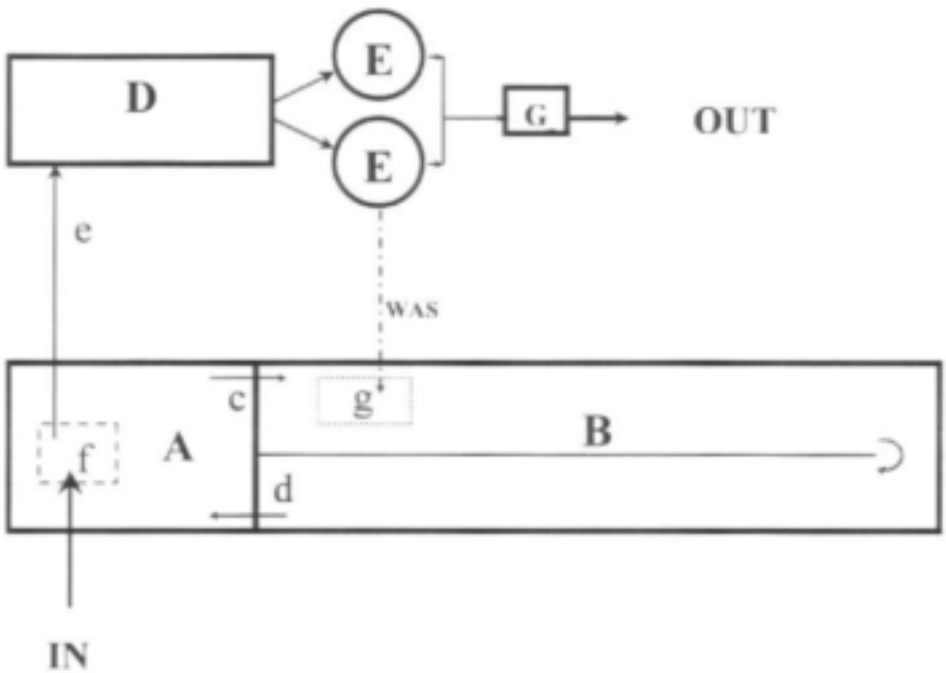
Appendix Fig. 9. Newcastle PETRO TF plant.
Flow schematic

A1-A2. Primary ponds; B1-B3. Secondary ponds; D. Trickling filters (secondary PETRO facilities); E. Clarifiers; F1-F4. Maturation ponds; G. Chlorination channel; J. Sludge drying beds; b. Primary pond overflow; c. Secondary pond feed; d. Algae-rich recycle from secondary ponds (c : e, recycle ratio); e. TF feed; f. Potential RBCOD Generating Pit (current fermentation pit).



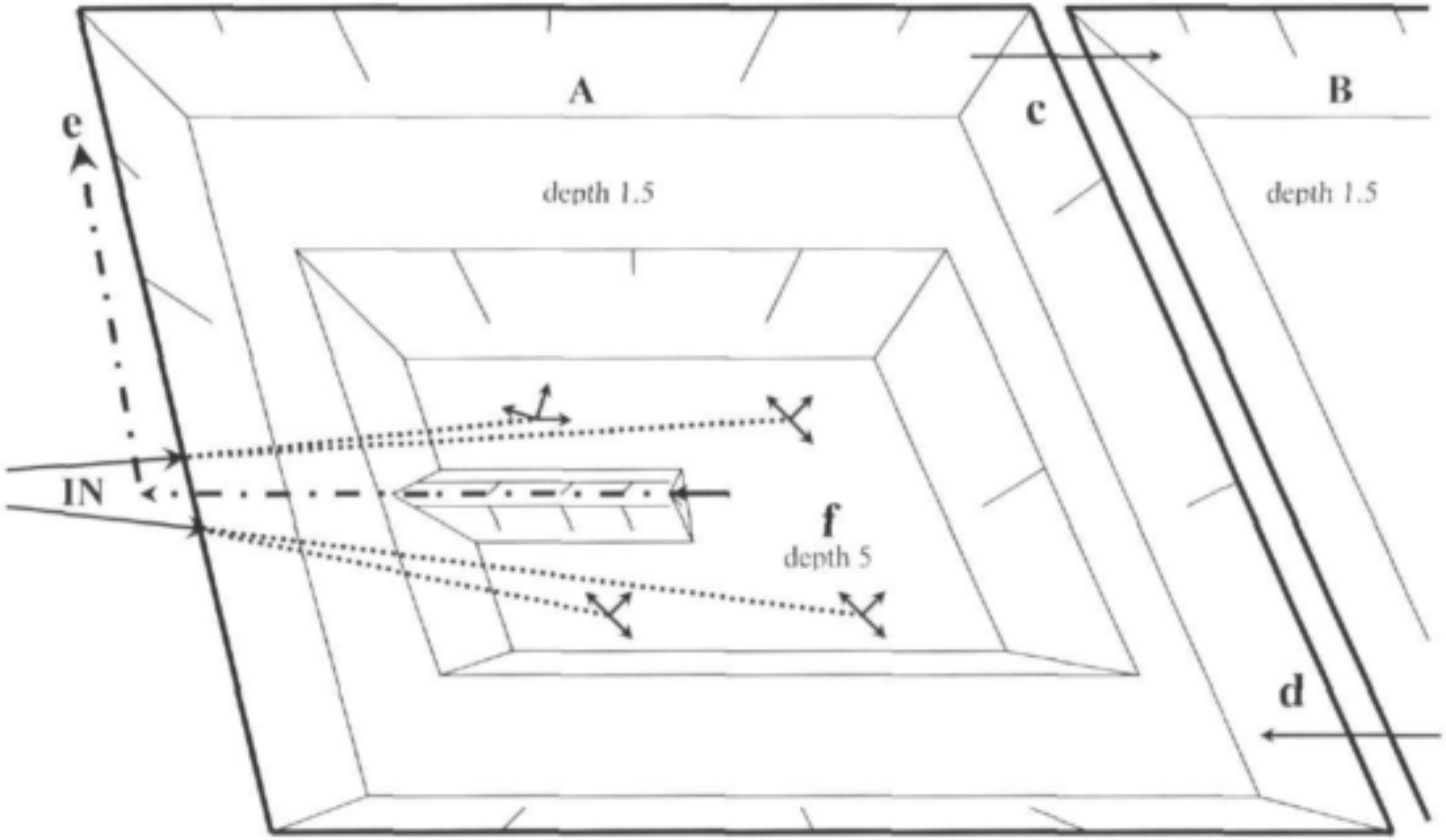
Appendix Fig. 10. Newcastle PETRO plant. Primary pond No 1 (0.63 ha; 13.5 Mℓ).

B1-B3. Secondary ponds (total: 3.3 ha; 49.5 Mℓ); c. Secondary ponds feed; d. Algae-rich recycle (c:e, recycle ratio); e. Primary pond overflow, standard secondary PETRO facility (TF) feed; f. current fermentation pit (proposed RBCOD generating pit).



Appendix Fig . 11. Sterkwater PETRO ASP plant.
Flow schematic.

Fig. . PETRO BNR schematic. A. Primary pond; B. Secondary ponds; D. Activated sludge reactor (secondary PETRO facility); E. Clarifiers; G. Chlorination channel;c., d. Algae-rich recycle (c : e, recycle ratio); e. Primary pond underflow (standard ASP feed); f. The RBCOD Generating Pit (current fermentation pit); g. Pit for WAS stabilisation in the secondary pond.



Appendix Fig. 12. Sterkwater PETRO ASP plant. Primary pond.

A. Primary pond (2.21 ha; 5.31 Ml); B. Secondary pond (5.97 ha ; 90 Ml); c. Secondary pond feed; d. Algae-rich recycle (c:e, d:e, recycle ratio); e. Primary pond underflow 2 m from bottom, standard secondary PETRO facility (ASP) feed; f. proposed RBCOD generating pit (current fermentation pit).

10. APPENDIX TABLES

Appendix Table 1. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the pond system of the Letlhabile PETRO plant (15.10.1998, spring). Chlorophyll *a* concentration in the 2nd and 6th WSPs outflow was 297 and 450 µg.ℓ$^{-1}$, respectively. Alkalinity (as $CaCO_3$, mg.ℓ$^{-1}$) followed by Settleable Solids (mℓ.ℓ$^{-1}$) values are in parentheses.

Depth, m below surface	Primary pond 1st half (middle)	Primary pond 2nd half (middle)	2nd pond, 2nd half (middle)	6 th (final) pond
Overflow		65	45	19(**240**;0)
1.0	64	67	47	n.d.
1.5	n.d.	n.d	n.d.	23(**270**;249)bottom
2.3	116(**305**;849)	107(**328**;465)	84(**339**;149)	

Appendix Table 2. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the pond system of the Letlhabile PETRO plant (22.01.1999, summer). Chlorophyll *a* concentration in the 2nd and 6th WSPs outflow was 330 and 390 µg.ℓ$^{-1}$, respectively. Alkalinity (as $CaCO_3$, mg.ℓ$^{-1}$) followed by Settleable Solids (mℓ.ℓ$^{-1}$) values are in parentheses.

Depth, m below surface	Primary pond 1st half (middle)	Primary pond 2nd half (middle)	2nd pond, 2nd half (middle)	6 th (final) pond
Overflow		47	49	23
0.7	78(**248**;0)	n.d.	52	31(**230**;0)
1.5	69(**256**;0)	51(**250**;0)	n.d.(**296**;0)	25(**246**;140)bottom
2.0	113(**257**;26)	100(**265**;10)	70(**273**;11)	
2.5	129(**350**;999)	127(**356**;844)	91(**366**;153)	

Appendix Table 3. Distribution of the readily biodegradable organics ((RBCOD, S_S, mg.ℓ$^{-1}$) in the pond system of the Letlhabile PETRO plant (25.03.1999, late summer). Chlorophyll *a* concentration in the 2nd and 6th WSPs outflow was 194 and 410 µg.ℓ$^{-1}$, respectively. Alkalinity (as $CaCO_3$, mg.ℓ$^{-1}$) followed by Settleable Solids (mℓ.ℓ$^{-1}$) values are in parentheses.

Depth, m below surface	Primary pond 1st half (middle)	Primary pond 2nd half (middle)	2nd pond, 2nd half (middle)	6 th (final) pond
Overflow		56	56	27
0.7	n.d.	50	67	n.d
1.5	76(**274**;0)	59	n.d.	39(**259**;121)bottom
2.0	100(**310**;36)	77(**253**;15)	73(**381**;0)	
2.4	146(**324**;933)	119(**300**;746)	103(**347**;320)	

Appendix Table 4. Distribution of the readily biodegradable organics ((RBCOD, S_S , mg.ℓ$^{-1}$) in the pond system of the Letlhabile PETRO plant (29.02.2000, summer). Chlorophyll *a* concentration in the 2nd and 6th WSPs outflow was 105 and 350 µg.ℓ$^{-1}$, respectively. Alkalinity as $CaCO_3$, mg.ℓ$^{-1}$.

Depth, m below surface	1st primary pond (east)						2nd primary pond			6 th (final) pond		
	1st half (middle)			2nd half (middle)			2nd half (middle					
	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$
0.7	62	239	0	31	n.d.	0	65	n.d.	0	15	n.d.	0
1.5 secondary pond bottom	71	280	1	52	n.d.	20	53	300.	1	10	259	0
2.0	77	311	358	70	319	288	69	304	79			
2.4 primary pond bottom	64	319	836	67	323	732	65	324	340			
Pond outflow				54	304	0	35	n.d.	0	17	n.d.	0

Appendix Table 5. Distribution of the readily biodegradable organics ((RBCOD, S_S, mg.ℓ$^{-1}$) in the WSP system of the Soshanguve PETRO plant (15.01.1999, summer). $COD_{raw\ influent}$ = 568 ∀ 49 mg.ℓ$^{-1}$ with S_S = 58 ∀ 19 mg.ℓ$^{-1}$. Alkalinity (as $CaCO_3$, mg.ℓ$^{-1}$) followed by Settleable Solids (mℓ.ℓ$^{-1}$) values are in parentheses.

Depth, m below surface	**Primary pond**[1]			**1st secondary**	**2nd secondary**
	1st part outflow	2nd part		WSP (middle)	WSP (middle)
		1st hopper	2nd hopper		
Overflow			20	24	23
0.5		31(**321**;0)	27	15	19
1.0		18	25	n.d.	n.d.
1.7		n.d.	n.d.	30	32(**400**;685)
2.0	44(**357**;0)	45	34		
3.0		43	59		
4.0		86(**390**;880)	89		

[1] - The 1st part of the primary pond was covered with a 1 m thick surface sludge layer thus stratified samples were not available.

Appendix Table 6. Distribution of the readily biodegradable organics ((RBCOD, S_S, mg.ℓ$^{-1}$) in the WSP system of the Soshanguve PETRO plant (29.03.1999, late summer). $COD_{raw\ influent}$ = 568 ∀ 49 mg. ℓ$^{-1}$ with S_S = 58 ∀ 19 mg.ℓ$^{-1}$. Alkalinity (as $CaCO_3$, mg.ℓ$^{-1}$) followed by Settleable Solids (mℓ.ℓ$^{-1}$) values are in parentheses.

Depth, m below surface	**Primary pond**[1]			**1st secondary**	**2nd secondary**
	1st part outflow	2nd part		WSP (middle)	WSP (middle)
		1st hopper	2nd hopper	21	14
Overflow			18	n.d.	n.d.
0.5		35	33	20	20
1.0		34	40	22	56(**395**;91
1.7		57	54		
2.0	56(**320**;0)	n.d.	n.d.		
3.0		56	55		
4.0		93(**376**;786)	90		

Appendix Table 7. Distribution of the readily biodegradable organics ((RBCOD, S_S, $mg.\ell^{-1}$) in the WSP system of the Soshanguve PETRO plant (19.05.1999, autumn). $COD_{raw\ influent} = 568 \forall\ 49\ mg.\ell^{-1}$ with $S_S = 58 \forall 19\ mg.\ell^{-1}$. Alkalinity (as $CaCO_3$, $mg.\ell^{-1}$) followed by Settleable Solids ($m\ell.\ell^{-1}$) values are in parentheses.

Depth, m below surface	**Primary pond[1]**			**1st secondary**	**2nd secondary**
	1st part outflow	2nd part		WSP (middle)	WSP (middle)
		1st hopper	2nd hopper		
Overflow			30	20	24
0.5		49	40	18	21
1.0		47	70	n.d.	n.d.
1.7		68	38	31	44(**390**;564)
2.0	89(**368**;0)	80	57		
3.0		85	76		
4.0		95(**460**;950)	99		

[1] - The 1st part of the primary pond was covered with a 1 m thick surface sludge layer thus stratified samples were not available;

[2] - no recirculation from the secondary ponds to the primary pond at this period.

Appendix Table 8. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 1 of the Sasolburg PETRO plant (6.11.1998). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 280 µg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp.*

Depth below surface meters	**Section, functionally representing Aprimary A (facultative) pond**						**Section functionally representing Asecondary≡ oxidation pond**		
	Fermentation pit no 1			1st sump pit[2]			2nd sump pit		
	S_S	Alk	Settl solids ml.ℓ$^{-1}$	S_S	Alk	Settl solids ml.ℓ$^{-1}$	S_S	Alk	Settl solids ml.ℓ$^{-1}$
0.5	63	278	0	60	311	0	71	302	0
1.0	59	300	0	151	357	105	142	354	156
1.5	69	302	0	269	405	690	214	410	599
pond bottom[1]	67	298	0						
2.0									
3.0	74	313	4						
3.5	132	332	13						
4.0	164	338	319						
5.0	515	546	710						
bottom[1]									
TF feed (pond outflow)							71	328	0
Recycle (inlet pipe water)							50	310	0

* depth at the pit slopes, the actual depth of the fermentation pit - 6.5 m, 1st sump pit - 6.5 m, 2nd sump pit -2 m.
[2] - actually, between the 1st sump pit and fermentation pits 1-2.

Appendix Table 9. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 1 of the Sasolburg PETRO plant (8.02.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 240 µg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp.* Values for the fermentation pit No2 are in parentheses.

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary≅ oxidation pond		
	Fermentation pit no 1, north (no2)			2nd sump pit			4th sump pit		
	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids mℓ.ℓ$^{-1}$
0,7	54 (46)	301	0	23	344	125	55	300	130
1.2 pond bottom	59 (62)	299	0	129	298	1000	77	346	900
3.0	83	336	0						
4.0	79	315	10						
4.5	156 (179)	310 (343)	280 (390)						
5.0	155 (67)	375 (300)	170 (210)						
6.5 pit bottom TF feed pond outflow	387 (315)	560 (510)	938 (730)	65	320	0			
Recycle, inlet pipe water							59	344	0

Appendix Table 10. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 1 (southern pond) of the Sasolburg PETRO plant (30.06.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 170 μg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp. Values for pit No 2 are in parentheses.**

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary≡ oxidation pond					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	50	320	3	34	n.d.	2	49	314	299	39	342	38
1.5	56	316	2	47	326	4	99	290	843	37	360	189
2.0 pond bottom	65	259	0	80	362	0	69	352	990	51	334	910
3.0	n.d.	n.d.	n.d	115	364	4						
4.0	75	354	27	146	366	6						
4.5	100 (87)	360 (309)	0 (10)	130	352	46						
5.0	107 (129)	345 (365)	31 (76)	n.d.	402	102						
6.5 (pit bottom)	299 (287)	484 (500)	999 (980)	389	589	999						
TF feed (pond outflow)							67	336	1			
Recycle (inlet pipe water)										86	367	0

Appendix Table 11. Distribution of the readily biodegradable organics (RBCOD, S_S, $mg.\ell^{-1}$) in the facultative pond No 2 (northern pond) of the Sasolburg PETRO plant (6.07.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 160 µg.◻$^{-1}$. The only microalgal species present - *Chlamydomonas sp.* * Values for pit No2 are in parentheses.

Depth below surface, meters	**Section, functionally representing Aprimary A (facultative) pond**						**Section functionally representing Asecondary≡ oxidation pond**					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, $m\ell.\ell^{-1}$	S_S	Alk	Settl solids, $m\ell.\ell^{-1}$	S_S	Alk	Settl solids, $m\ell.\ell^{-1}$	S_S	Alk	Settl solids, $m\ell.\ell^{-1}$
0.7	49	324	0	29	390	0	46	290	260	36	299	35
1.5	n.d.	n.d.	0	40	n.d.	0	72	297	760	31	337	158
2.0 pond bottom	46	281	0	58	310	0	89	311	999	48	310	900
3.0	71	308	3	106	301	8						
4.0	60	311	5	190	326	7						
4.5	151 (99)	346 (350)	10 (15)	n.d.	n.d.	46						
5.0	70 (90)	333 (310)	25 (30)	125	410	40						
6.5 (pit bottom)	239 (260)	500 (540)	950 (978)	330	570	999						
TF feed (pond outflow)							78	298	0			
Recycle (inlet pipe water)										66	329	0

ctn, functionally representing Aprimary A (facultative) pond Section functionally representing Asecondary≡ oxidation pond

Appendix Table 12. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 2 (northern pond) of the Sasolburg PETRO plant (24.11.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 460 µg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp.* Values for pit No2 are in parentheses.

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary oxidation pond					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	77	311	0	21	346	0	24	340	144	14	287	30
1.5	34	310	0	30	356	0	39	286	530	26	366	200
2.0 pond bottom	49	277	0	37	343	0	76	322	960	33	340	935
3.0	120	300	3	128	322	5						
4.0	176	305	20	108	310	20						
4.5	171 (153)	358 (388)	35 (40)	166	n.d.	n.d.						
5.0	740 (546)	380 (366)	440 (410)	200	410	200						
6.5 (pit bottom)	1160 (833)	498 (591)	640 (589)	136	535	359						
TF feed (pond outflow)							62	320	0			
Recycle (inlet pipe water)										26	302	0

Appendix Table 13. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 1 (southern pond) of the Sasolburg PETRO plant (21.12.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 505 µg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp. Values for pit No2 are in parentheses.**

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary≡ oxidation pond					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	51	330	0	20	340	0	15	n.d.	0	16	n.d.	0
1.5	33	310	0	23	341	0	30	321	460	13	300	100
2.0 pond bottom	26	n.d.	0	30	340	0	43	304	966	21	332	910
3.0	46	n.d.	3	60	318	0						
4.0	110	330	0	51	306	0						
4.5	115 (100)	335 (320)	0 (10)	80	340	0						
5.0	110 (130)	n.d.	100 (115)	129	381	140						
6.5 (pit bottom)	415 (400)	n.d.	450 (510)	156	420	674						
TF feed (pond outflow)							60	n.d.	0			
Recycle (inlet pipe water)										10	n.d.	0

Appendix Table 14. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ^{-1}) in the facultative pond No 2 (northern pond) of the Sasolburg PETRO plant (21.12.1999). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 480 µg.ℓ^{-1}. The only microalgal species present - *Chlamydomonas sp. Values for pit No 2 are in parentheses.**

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary= oxidation pond					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ^{-1}	S_S	Alk	Settl solids, mℓ.ℓ^{-1}	S_S	Alk	Settl solids, mℓ.ℓ^{-1}	S_S	Alk	Settl solids, mℓ.ℓ^{-1}
0.7	61	315	0	38	357	0	29	310	159	21	321	10
1.5	42	300	0	n.d.	n.d.	n.d.	25	299	548	31	340	206
2.0 pond bottom	41	298	2	41	349	4	99	330	975	45	333	917
3.0	129	321	11	153	346	10						
4.0	189	311	54	200	325	10						
4.5	190 (185)	342 (331)	58(87)	281	310	105						
5.0	810 (745)	355 (360)	457 (466)	220	431	340						
6.5 (pit bottom)	940 (910)	461 (580)	690 (687)	124	546	367						
TF feed (pond outflow)							68	340	0			
Recycle (inlet pipe water)										10	311	0

1- sump 1 (i.e. Aprimary= pond section) was not desludged since 21.12.1999.

Appendix Table 15. *Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 1* (southern pond) of the Sasolburg PETRO plant (14.03.2000). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 490 µg.□$^{-1}$. The only microalgal species present - *Chlamydomonas sp. Values for pit No 2 are in parentheses.**

Depth below surface, meters	Section, functionally representing Aprimary A (facultative) pond						Section functionally representing Asecondary≡ oxidation pond					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	15	310	0	18	320	0	n.d.	312	110	24	n.d.	0
1.5	23	n.d.	0	n.d.	n.d.	0	49	258	700	30	324	180
2.0 pond bottom	20	299	0	21	301	0	111	306	999	11	279	980
3.0	n.d.	330	0	n.d.	322	0						
4.0	42	321	2	13	334	1						
4.5	33 (29)	n.d.	0	26	11	6						
5.0	81 (90)	342 (360)	50 (47)	96	340	10						
6.5 (pit bottom)	168 (127)	435 (390)	967 (990)	100	380	999						
TF feed (pond outflow)							43	312	0			
Recycle (inlet pipe water)										35	315	0

Appendix Table 16. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the facultative pond No 2 (northern pond) of the Sasolburg PETRO plant (14.03.2000). Chlorophyll *a* concentration in recycled water (pipe outlet above surface at the beginning of the pond) was 460 µg.□$^{-1}$. The only microalgal species present - *Chlamydomonas sp.* * Values for pit No 2 are in parentheses.

Depth below surface, meters	**Section, functionally representing Aprimary A (facultative) pond**						**Section functionally representing Asecondary≡ oxidation pond**					
	Fermentation pit no 1, north (no 2)			1st sump pit, middle			2nd sump pit, middle			4th sump pit, middle		
	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$	S_S	Alk	Settl solids, mℓ.ℓ$^{-1}$
0.7	10	310	0	11	304	10	26	300	130	12	312	0
1.5	22	360	0	33	321	21	183	325	780	30	343	310
2.0 pond bottom	31	320	6	26	350	30	197	331	999	34	329	999
3.0	125	n.d.	10	230	310	28						
4.0	148	310	20	198	354	176						
4.5	300 (410)	340 (333)	10 (11)	285	319	390						
5.0	320 (290)	379 (397)	69 (100)	410	489	685						
6.5 (pit bottom)	670 699)	534 587)	910 (939)	470	597	999						
TF feed (pond outflow)							79	318	0			
Recycle (inlet pipe water)										91	324	0

[1]- sump 1 (i.e. a primary pond section) was not desludged since 21.12.1999.

Appendix Table 17. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary (facultative) pond of the Bloemhof PETRO plant (6.08.1999). Chlorophyll *a* concentration in recycled water (from the final secondary pond to the surface of the primary pond) was 560 µg.ℓ$^{-1}$. The only microalgal species present - *Chlamydomonas sp.* (in the initial secondary ponds) and *Micractinium sp.* (gradually becoming dominant towards the 8th pond).

Depth below surface, meters	Main (1st sump) fermentation pit			2nd sump pit *			4th sump pit*		
	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	67	n.d.	5	66	157	0	73	188	1
1.0	97	n.d.	1	91	205	19	n.d.	n.d.	n.d
2.0	89	n.d.	200	111	198	162	89	197	43
3.0	654	n.d.	410						
3.5	864	n.d.	930						
4.5 (main pit bottom**)	850	n.d.	1000						
Primary pond outflow							157	148	1
1st secondary pond outflow							40	132	0

* - max accessible depth - 2.5 m, due to a dense bottom sludge layer;

** - total pit depth 5 m, pit has a dense bottom sludge layer; it was impossible to obtain a sample from the depth below than 4.5 m.

Appendix Table 18. Distribution of the readily biodegradable soluble substrates (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary (facultative) pond of the Bloemhof PETRO plant (2.12.1999). S_i=54 mg.ℓ$^{-1}$. Chlorophyll *a* concentration in recycled water (from the final secondary pond to the surface of the primary pond) was 710 µg.ℓ$^{-1}$. The only microalgal species present - *Euglena sp.*

Depth below surface, meters	Main (1st sump) fermentation pit			2nd sump pit *			4th sump pit*		
	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	30	199	0	41	180	0	14	205	0
1.0	60	n.d.	0	45	190	0	30	n.d	0
2.0	149	n.d.	24	74	n.d.	41	70	n.d.	10
3.0	486	n.d.	400						
3.5	600	360	840						
5.0 (pit bottom)	640	388	910						
Primary pond outflow							59	n.d.	0
1st secondary pond outflow							78	150	0

* - max accessible depth - 2.5 m, due to a dense bottom sludge layer.

Table 19. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary pond of the Newcastle PETRO plant (3.08.1999). Chlorophyll *a* concentration in recycled water (from the final secondary pond to the surface of the primary pond) was 94 µg.□$^{-1}$. The only microalgal species present - *Chlamydomonas sp.*

Depth below surface, meters	Main (1st sump) fermentation pit			2nd sump pit *			4th sump pit*		
	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	147	365	0	135(120)	350(355)	0 (0)	125	310	0
1.0	160	380	0	150(144)	360(350)	0 (0)	156	355	0
2.0	380	n.d.	381	330(270)	n.d.	1000(990)	190	n.d	59
3.0	365	435	345	289(300)	490(399)	1000(995)	250	440	000
3.5	500	480	640						
5.0 (*pit* bottom)	*n.d.*	400	540						
6.0	489	410	335						
7.0	520	455	430						
Primary pond outflow							165	340	0
Recycle							42	315	0

Appendix Table 20. Distribution of the readily biodegradable organics (RBCOD, S_S, $mg.\ell^{-1}$) in the primary (facultative) pond of the Bloemfontein (Sterkwater) PETRO plant (26.05.1999). Chlorophyll *a* concentration in recycled water from secondary pond to primary pond (provided for 1 hour per day) was 1130 $\mu g.\ell^{-1}$ (phaeophytin *a* 180 $\mu g.\ell^{-1}$). The concentration in the primary pond (surface) was 105 $\mu g.\ell^{-1}$ (phaeophytin *a* 10 $\mu g.\ell^{-1}$). The only microalgal species present - *Chlamydomonas sp.*

Depth below surface, meters	Fermentation pit			Area surrounding the pit		
	S_S	alkalinity	settleable solids, $m\ell.\ell^{-1}$	S_S	alkalinity	settleable solids, $m\ell.\ell^{-1}$
0.5	21	200	0	18	189	0
1.5	27	188	0	16	205	0
2.0	29	n.d.	0	20	220	15
4.0	69	243	0			
5.0(pit bottom)	121	260	220			
ASP reactor feed (mix of pond effluent and raw influent)				45	190	0
Recycle (under the brush aerator)				13	214	0

Appendix Table 21. Distribution of the readily biodegradable organics (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary (facultative) pond of the Bloemfontein (Sterkwater) PETRO plant (5.08.1999). Chlorophyll *a* concentration in recycled water from secondary pond to primary pond (provided for 2 hours per day) was 940 µg.ℓ$^{-1}$ (phaeophytin *a* - 90 µg.ℓ$^{-1}$).The concentration in the primary pond (surface) was 675 µg.ℓ$^{-1}$ (phaeophytin *a* - 49 µg.ℓ$^{-1}$). The dominant microalgal species present - *Phacus pyrum.*

Depth below surface, meters	Fermentation pit			Area surrounding the pit		
	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	10	210	0	11	176	0
1.5	14	199	0	15	210	0
2.0	19	238	0	21	223	10
4.0	51	210	0			
5.0 (pit bottom)	79	240	82			
ASP reactor feed(mix of pond effluent and raw influent)				94	216	0
Recycle (under the brush aerator)				11	200	0

Appendix Table 22. Distribution of the readily biodegradable soluble substrates (RBCOD, S_S, mg.ℓ$^{-1}$) in the primary (facultative) pond of the Bloemfontein (Sterkwater) PETRO plant (1.12.1999). S_i=35 mg.ℓ$^{-1}$. Chlorophyll *a* concentration in recycled water from secondary pond to primary pond (provided for 24 hours per day, both aerator with only 6 brushes left on each aerator versus 24 brushes on 5.8.99) was 360 μg.ℓ$^{-1}$ (phaeophytin *a* - 170 μg.ℓ$^{-1}$).The concentration in the primary pond effluent (ASP feed) was 190 μg.ℓ$^{-1}$ (phaeophytin *a* - 68 μg.ℓ$^{-1}$). The dominant microalgal species present - *Micractinium sp., Phacus pleuronectes.*

Depth below surface, meters	Fermentation pit			Area surrounding the pit		
	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$	S_S	alkalinity	settleable solids, mℓ.ℓ$^{-1}$
0.5	15	n.d.	0	5	180	0
1.5	20	220	0	10	n.d.	0
2.0	21	225	0	39	230	25
4.0	33	n.d.	0			
5.0(pit bottom)	193	271	170			
ASP reactor feed(mix of pond effluent and raw influent)				81	240	0
Recycle (under the brush aerator)				20	210	0

Appendix Table 23. Bottom sludge thickness in meters (average). Sasolburg PETRO plant . Values for pit No2 are in parentheses.

Date	Section, functionally representing Aprimary A (facultative) pond		**Section functionally representing Asecondary≡ oxidation *pond***	
	Fermentation pit no 1, north (no 2)	1st sump pit, middle	2nd sump pit, middle	4th sump pit, middle
Anaerobic/Aerobic pond No 1 (Southern)				
30.06.1999	1.1 (1.3)	0.8	1.3	1.2
24.11.1999	0.9 (1.0)	1.1	1.1	1.0
21.12.1999	1.0 (1.1)	1.0	1.2	1.1
14.03.2000	1.7 (1.8)	0.8	1.2	0.7
Anaerobic/Aerobic pond No 2 (Northern)				
6.11.1998	2.0	0.9	1.2	n.d.
8.02.1999	2.3 (2.9)	n.d.	1.4	1.4
6.07.1999	0.6 (0.8)	0.6	1.4	1.2
24.11.1999	1.8 (n.d.)	1.5	1.4	1.1
21.12.1999	1.9 (1.7)	1.5	1.2	1.0
14.03.2000 [1]	1.6 (1.7)	3.0	1.1	0.7

[1]- sump 1 (i.e. Aprimary≡ pond section) was not desludged since 21.12.1999.

Appendix Table 24. Estimated combined sludge volume (m^3) in the facultative ponds No 1-2 of the Sasolburg PETRO plant. Average sludge SS content 5% (1-2 sumps). $V_{\equiv PRIMARY\equiv POND}$ = 12900 m^3 ; $V_{\equiv SECONDARY\equiv POND}$ = 14400 m^3 . Combined volume of No 1-2 ponds - 54600 m^3.

Date	**Section, functionally representing Aprimary A (facultative) pond**			**Section functionally representing Asecondary≡ oxidation pond**			
	Fermentation pits no 1-2	1st sump pit	Total	2nd sump pit	3rd sump pit	4th sump pit	**Total per entire pond**
				Pond 1 (Southern)			
30.06.1999	710	605	1315	2099	2030	1970	7414
24.11.1999	530	620	1150	2150	2100	1800	7210
21.12.1999	520	650	1170	2110	2050	1820	7150
14.03.2000	790	510	1300	2100	1900	1720	7000
				Pond 2 (Northern)			
6.11.1998	900	960	1860	2090	2155	1944	8049
8.02.1999	960	990	2050	2380	1980	1879	8189
6.07.1999	690	670	1360	1992	2052	1806	7210
24.11.1999	960	815	1775	2240	2005	1790	7810
21.12.1999 [1]	980	950	1930	2090	2000	1840	7860
14.03.2000 [1]	770	1190	1960	2080	2030	1800	7870

[1]- sump 1 (i.e. A primary≡ pond section) was not desludged since 21.12.1999.

Appendix Table 25. Estimated sludge volume (m^3) in the primary pond of Bloemhof PETRO plant. Average sludge SS content 5.5%. $V_{PRIMARY\ POND} = 8499\ m^3$; $V_{SLUDGE} = 2550 - 2670\ m^3$.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit	Total
25.05.99	1110	510	490	440	2550
6.08.99	1180	540	510	440	2670
2.11.99	710	500	430	400	2040

Appendix Table 26. Bottom sludge thickness in meters (average). Bloemhof PETRO plant.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit
25.05.99	3.3	1.8	1.6	1.6
6.08.99	3.4	1.8	1.7	1.7
2.11.99	2.6	1.4	1.2	1.2

Appendix Table 27. Estimated sludge volume (m^3) in the primary pond no 1 of the Newcastle PETRO plant. Average sludge SS content - 4.8%. $V_{PRIMARY\ POND}$ = 13500 m^3; V_{SLUDGE} = 3450-3900 m^3.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit	Total
3.08.99	2100	800	700	300	3900
29.11.99	1850	700	600	300	3450

Appendix Table 28. Estimated sludge volume (m^3) in the primary pond no 2 of the Newcastle PETRO plant. Average sludge SS content - 4.8%. $V_{PRIMARY\ POND}$ = 13500 m^3; V_{SLUDGE} = 3650-3710 m^3.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit	Total
3.08.99	2000	780	650	280	3710
29.11.99*	2000	750	600	300	3650

* due to the lack of recycle sludge layer is thicker, but solids concentration is lower.

Appendix Table 29. Bottom sludge thickness in meters (average). Newcastle PETRO plant. Primary pond No 1.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit
3.08.99	5.5	1.7	1.6	0.7
29.11.99	4.7	1.5	1.5	1.0

Appendix Table 30. Bottom sludge thickness in meters (average). Newcastle PETRO plant. Primary pond No 2.

Date	Main (1st sump) fermentation pit	2nd sump pit	3rd sump pit	4th sump pit
3.08.99	5.6	1.6	1.6	0.6
29.11.99*	4.9	1.7	1.6	1.0

* due to the lack of recycle sludge layer is thicker, but solids concentration is lower.

Appendix Table 31. Estimated sludge volume (m^3) in the primary pond of Bloemfontein PETRO plant. Average sludge SS content 4.7%. $V_{PRIMARY\ POND} = 53096\ m^3$.

Date	Fermentation pit	Area surrounding the pit
26.05.99	1750	1650
6.08.99	653	1650
1.12.99	2010	1780

Appendix Table 32. Bottom sludge thickness in meters (average). Bloemfontein PETRO plant.

Date	Fermentation pit	Area surrounding the pit
26.05.99	0.4	0.1
6.08.99	0.15	0.1
1.12.99	0.49	0.15

Appendix Table 33. Sludge blanket characteristics of the facultative pond No2 (northern pond) of the Sasolburg PETRO plant (6.11.1998). Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom - approx bottom 50 cm of sludge layer. VSS, % , sludge volatile solids as percentage of total solids; RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VSS. d^{-1}.

Section, functionally representing Aprimary A (facultative) pond						**Section functionally representing Asecondary≡ oxidation pond**					
Fermentation pit no 1				1st sump pit, middle				2nd sump pit, middle			
Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
66	0.075	66	0.090	69	0.060	66	0.041	62	0.013	58	0.003

Appendix Table 34. Sludge blanket characteristics of the facultative pond No 1 (southern pond) of the Sasolburg PETRO plant. Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom – approx. bottom 50 cm of sludge layer. VSS, % , sludge volatile solids as percentage of total solids; RBCOD potential, i.e. an amount of readily biodegradable organics as COD, generated per g sludge volatile solids per day, in mg. g^{-1} VSS. d^{-1}.

Section, functionally representing Aprimary A (facultative) pond								**Section functionally representing Asecondary≡ oxidation pond**							
Fermentation pit no 1				1st sump pit, middle				2nd sump pit, middle				4th sump pit, middle			
Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
30.06.1999															
66	0.087	66	0.086	64	0.068	64	0.057	61	0.031	53	0.009	44	n.d.	19	0.001
24.11.1999															
70	0.088	68	0.080	63	0.049	65	0.050	57	0.022	54	0.001	43	0.002	19	n.d.
21.12.1999															
69	0.079	68	0.077	63	0.058	64	0.046	60	0.032	46	0.005	43	0.001	19	n.d.
14.03.2000															
68	0.089	68	0.090	64	0.050	60	0.053	59	0.033	49	0.01	40	0.003	22	0.002

Appendix Table 35. Sludge blanket characteristics of the primary pond No 2 of the Newcastle PETRO plant. Sludge layer top - approx. top 50 cm of sludge; sludge layer bottom – approx. bottom 50 cm of sludge layer.

Main (1st sump) fermentation pit				**2nd sump pit, middle**				**4th sump pit, middle**			
Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom		Sludge layer top		Sludge layer bottom	
VSS[1]	RBCOD [2]	VSS	RBCOD	VS	RBCOD	VSS	RBCOD	VSS	RBCOD	VSS	RBCOD
29 November 1999											
60	0.066	59	0.069	59	0.065	56	0.044	56	0.001	54	0.001

Appendix Table 36. Correlation between sludge volume (layer thickness) and RBCOD in the PETRO primary pond fermentation pit (5m, V_{pit}=3700 m^3). Sasolburg plant.

Date of survey	Layer thickness, m	RBCOD, mg/ℓ	Chlorophyll *a* in recycle, ug/ℓ
9 February 1998	0.5	100	390
8 April 1998	1.9	405	200
6 November 1998	2.0	515	280
8 February 1999	2.6	341	240
6 July 1999	0.7	80	160
31 August 1999	0.5	115	140
24 November 1999	1.8	740	460
21 December 1999	1.9	810	480
14 March 2000	1.6	320	460

Appendix Table 37. Algae-assisted chemical P removal in the Enhanced algal activated sludge flocs (laboratory experiments). Concentrations in mg l^{-1}. All values are averages of 3 measurements.

Reactor feed*			Anaerobic zone effluent			Anoxic zone effluent			Aerobic zone effluent		
Enhanced algal activated sludge											
P_{inorg}	$N_{ammonia}$	$N_{nitrate}$	P_{inorg}	$N_{ammonia}$	$N_{nitrate}$	P_{inorg}	$N_{ammonia}$	$N_{nitrate}$	P_{inorg}	$N_{ammonia}$	$N_{nitrate}$
Conventional activated sludge (no microalgae)											
20	28	<0.1	28	10	4	15	7	3	<2	2	9
20	28	<0.1	26	12	6	11	4	5	9	3	8

*$[Ca^{2+}]$=29 mg.l^{-1}; $[Mg^{2+}]$=12 mg.l^{-1}

Other related WRC reports available:

External nitrification with the aid of fixed media trickling filters (TF) to increase the capacity of biological nutrient removal (BNR) suspended medium activated sludge (AS) systems.

Hu Z; Sötemann SW; Vermande SM; Moodley R, Little C, Lakay MT, Wentzel MC, Ekama GA

The concept of "external nitrification" (EN) in biological nutrient removal (BNR) activated sludge (AS) systems was investigated in this project as a process configuration aimed at providing nitrification "externally" to the AS reactor in a trickling filter and thereby allowing the sludge age in the AS reactor to be reduced, with a consequent increase in the system capacity for removing organics (COD) and nutrients (N&P). The experimental investigation carried out on laboratory-scale ENBNRAS systems showed that good COD removal was obtained (>90%) and on average about 60% less oxygen was utilised than in an equivalent "conventional" BNRAS system, high (>80 to 90%) removal of N-species was obtained with consequently low (<10 mg N/l) concentrations in the treated effluent, P-removal was lower (30% less) than expected and the settleability of the sludges produced was good (90 to 100 ml/g). Based on these results, the ENBNRAS system generally offers some performance advantages (P-removal being the exception) over conventional BNRAS systems. The economic analysis carried out showed that this translated into a 30% capital cost-saving but only a 5 to 10% total saving when the high proportion of operating vs. capital cost is factored in. In practice though, design decisions would probably be influenced more by the performance benefits offered (better effluent quality) rather than the modest cost-saving estimated.

In this project the kinetic simulation model for all BNRAS (including ENBNRAS) systems was also extended to include anoxic P uptake and denitrification, using literature data for the growth kinetics and stoichiometry of the various organic/nutrient transformations taking place. When tested against experimental data from the project, good correlation was found between the observed and predicted values, auguring well for the use of the model for practical design and implementation of ENBNRAS systems.

Report Number: 970/1/02 **ISBN No: 1 86845 872 5**

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