BIOLOGICAL NUTRIENT REMOVAL (BNR) TECHNOLOGY IN NEW AND UPGRADED WWTP'S

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ABSTRACT

Although much progress has been made in the past 30 years, BNR wastewater treatment plants do not always live up to expectation. This paper reviews key features of BNR plant design, basic microbiology behind nutrient removal and discusses some problems and process requirements operators should be aware of, when trying to operate and optimise BNR plant performance.

KEY WORDS
Nitrification, Denitrification, EBPR, BNR

1.0 INTRODUCTION

A farmer's specification for a work vehicle would, by default suggest four wheel-drive, high ground clearance and a strong chassis. The only decision would be manufacturer and model. Similarly ordering a wastewater treatment plant forty years ago, the choice would have been straight forward – trickling filter or activated sludge, maybe a lagoon. Nowadays, letting a tender for a biological nutrient removal (BNR) plant, one will have to choose from a range of designs for what seem to be fairly uniform operational requirements.

Consulting wastewater engineering textbooks, reveals about two dozen BNR plant designs that claim to remove organic carbon, bCOD (mostly carbohydrates, fats, protein and reduce levels of other organics such as drugs and detergents), suspended solids, nitrogen (N), and phosphorous (P), to levels set by regulatory agencies.

These different BNR designs after thirty years of practice and experience have contracted to fewer, more efficient variants or configurations, including oxidation ditches, membrane bioreactors (MBRs) and sequencing batch reactors (SBRs). All have anaerobic (no oxygen O), anoxic (oxygen only available from nitrite and nitrate) and aerobic zones (or phases). Often the tanks are subdivided into a number of stages or sections per zone (Tschobanoglous G et al 2003). Primarily the differences setting all these plant configurations apart are plug flow/mixed, the location of the zones in the plant and specifics of the one to three recycling arrangements provided. On the inflow side plants typically have an anaerobic zone, followed by an anoxic zone(s), an aerobic zone(s) and a clarifier. Primary sedimentation tanks and digesters are usually omitted.

2.0 DISCUSSION

Why after all these years are some BNR plants (design and performance) not more reliable? It is possible that local wastewater composition/flow rates are too variable. Retrofitting existing plants to a tight budget and then modifying again after a time of operation is not unusual. A greater problem is that many designers treat the bacteria involved like a chemical catalyst, something that will behave exactly as predicted in plant operational modelling.

Successful plants should combine excellent modelling and design, reliable pumps, valves, aerators, probes and instruments, a stable influent composition, flow rate and steady prevailing temperatures - with highly trained and vigilant operators monitoring, testing and controlling every aspect of operation. However, no one can guarantee that biological processes will always behave in a totally predictable manner and so some plants underperform despite best efforts.

The BNR anaerobic, anoxic and aerobic zones are designed to optimise metabolic activity (activities that produce energy and/or cell growth i.e. new cells) of groups of bacteria that will carry out the removal of carbon C, nitrogen N, and phosphorous P. Who are these bacteria and what are the basics of the reactions they carry out?

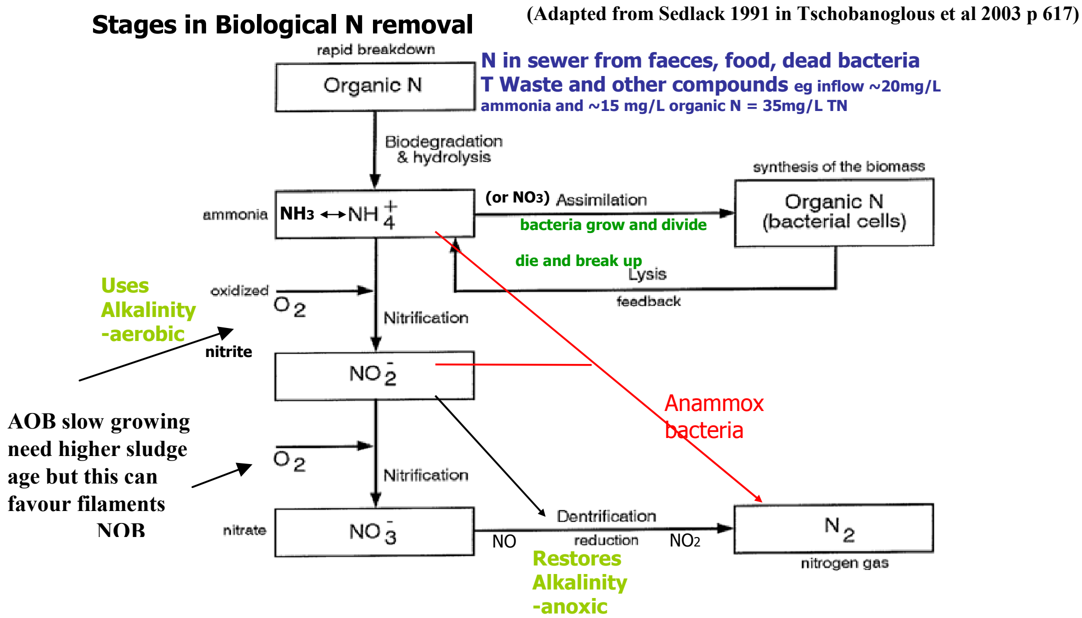
Recent research has shown that the Nitrosomonas, Nitrobacter, Acinetobacter and Nocardia previously attributed as the responsible agents, are at best bit players (Seviour R Nielsen PH eds 2010). Instead groups of related bacterial species were discovered who carry out these transformations. To keep a discussion of this topic manageable it is easier to describe six groups of bacteria that are of interest in BNR operations. (Noting that there may be up to a billion bacteria and up to a million protozoa comprising thousands of microbial strains in 1ml of activated sludge);

1. The large group of heterotrops or heterotrophic organisms (**HOs**) are the primary agent of carbon (as BOD or bCOD) removal. Many ferment carbon compounds CHO in the absence of O2 to volatile fatty acids VFA (or rbCOD as they do in digesters and sewer pipes) such as acetate. In the presence of O2 they respire and break down carbon compounds further, releasing CO2. Some of these bacteria produce enzymes which cut (hydrolyse) large polymer molecules such as starch or protein into glucose and amino acids, which are used as food source i.e. carbon and energy source, by most microbes present. They are also major floc formers in activated sludge systems. The HO can be used to produce VFA in anaerobic static fermenters to feed the rbCOD requiring bacteria in BNR. It should be noted that all microbes in the BNR system (bacteria, protozoa and fungi) that are removed via WAS or effluent will remove C, N and P.

2. The ammonia (NH3 or depending on pH, $NH4^{+}$) oxidising* bacteria **AOB** oxidise ammonia to nitrite (NO2) - slow, and then the nitrate oxidising bacteria **NOB** oxidise nitrite to nitrate (NO3) - fast. The overall process "**Nitrification**" is the rate limiting process of BNR systems. Nitrifiers grow slower (15-20 times) than the HO, use up alkalinity 7.1 mg for every mg of NH4, and work faster as temperatures increases but become inhibited after 30°C. They need a higher sludge age, prefer pH 7.2-8, a high DO level and slow down if DO < 2mg/L.

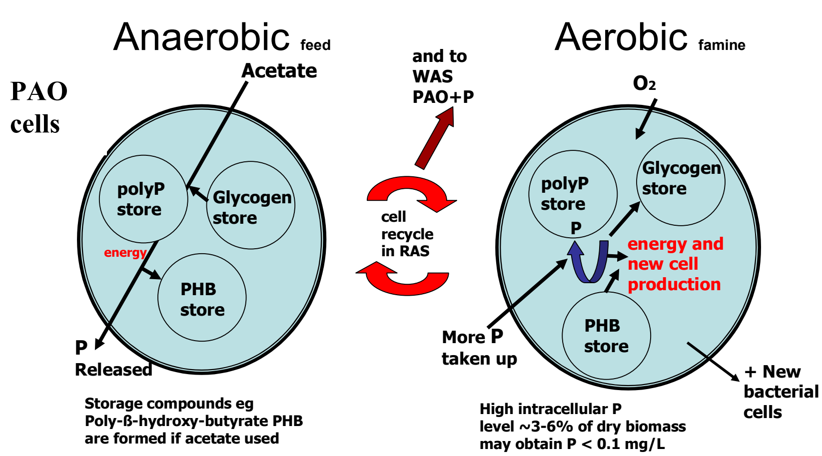
3. **Denitrifiers**, are HOs but can get their O from O2 **or** from NO3. They reduce* nitrite and nitrate in an anoxic environment to nitrogen gas N2, which is released to the atmosphere. They preferably grow on readily biodegradable COD (rbCOD) such as acetate or methanol. They restore some of the alkalinity (but there is a net loss) and release some oxygen (O) back into the culture medium.

***Oxidation or reduction means taking away or adding electrons to an ion or molecule this allows bacteria to break up or reassemble molecules gaining or using energy in these processes.**



The above flowchart shows key chemical transformations carried out by nitrifying and denitrifying bacteria in BNR. The currently experimental ANAMMOX process provides a route for N removal using another group of slow growing bacteria that can change NH3 and NO2 into N2 gas without aeration.

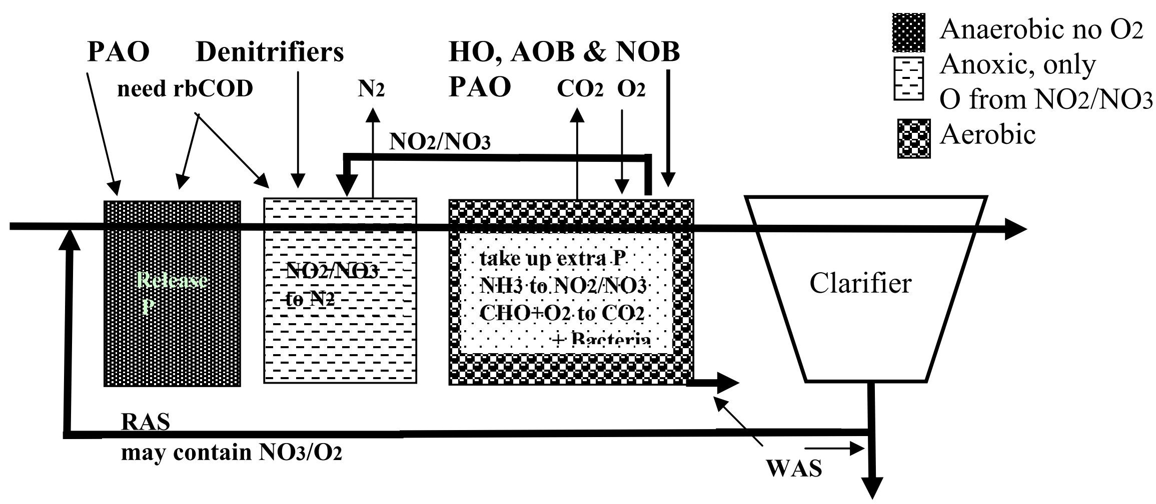
4. The phosphate accumulating organisms **PAO** can, if fed rbCOD such as acetate under anaerobic conditions (no O available) create an energy store in the cell and in so doing release P into the medium. In aerobic conditions they use the stored energy to divide (reproduce) taking up more P then previously released. This P is kept in the cells and stored as PolyP. The P goes out with the WAS fraction to remain in the dewatered sludge. But the bacterial cells must be in an aerobic environment until dewatered and return water (centrate, filtrate) must be checked for P to avoid extra P being recycled to the plant. P may be released in the aerobic reactor, or the clarifier - secondary P release - if sludge retention times SRT are to long or if the culture is over aerated. The PAO are sensitive to O and NO3 being recycled to the anaerobic zone (s) of the reactor. PAO can take out about twice the P up to 6% dry weight, compared to other bacteria wasted from the system. PAO have a lower temperature optimum then the other BNR groups they also have a competitor in the anaerobic zone the glycogen accumulating organisms GAO who may outgrow the PAO under certain conditions such as a lower pH, but do not take up extra P.



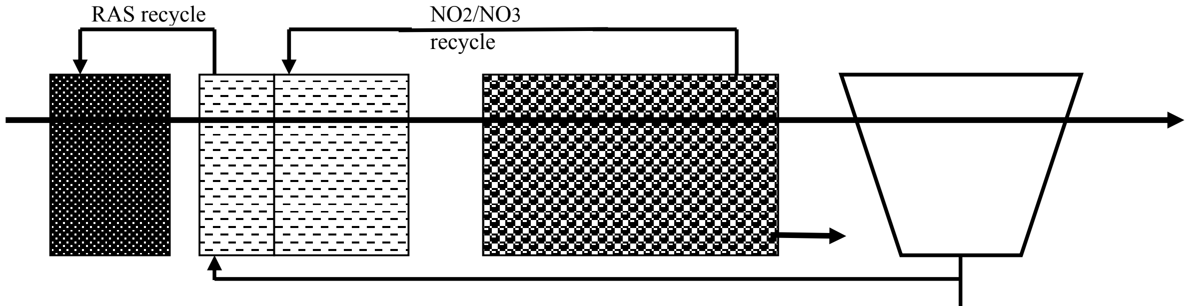
PAO cycling between aerobic and anaerobic conditions, taking up extra P (luxury uptake)
(Adapted from Mino 1987 in Seviour R Nielsen PH eds 2010 p 499)

5. The final group of microbes of interest in BNR are nuisance filamentous bacteria that may cause sludge bulking or foaming. Conditions that contribute to bulking or foaming include, low RAS and MLSS, poor dewatering, hydraulic overload, or rbCOD not used up rapidly in anaerobic and anoxic zones. In addition to chlorination, water spray or use of skimming devices, operators can create conditions that favour floc formers over filaments by introducing selectors that produce a substrate (food) gradient in the tank. The difficulty is that some strains of filamentous bacteria have different preferences for food sources or for certain reactor parameters such as DO, pH, temperature, or hydraulic retention time HRT.

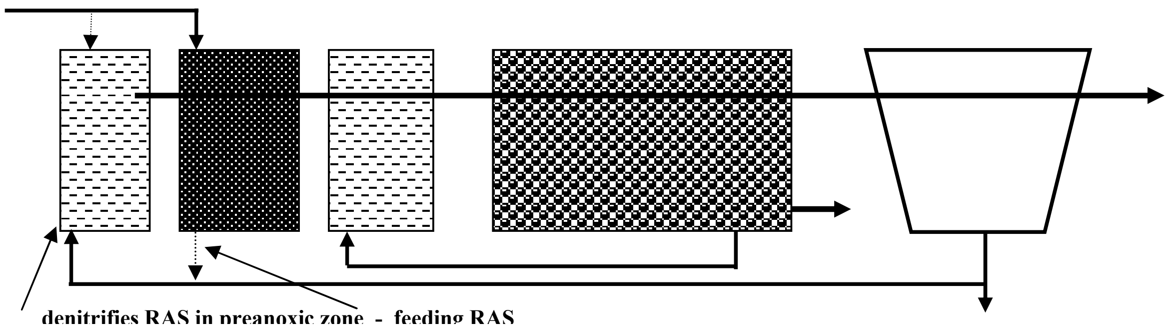
The three stage Bardenpho or A^2O process, below, has the required anaerobic, anoxic and aerobic zones and NO2/NO3 recycle from the aerobic to the anoxic zone needed for BNR.



The flowcharts below show the modified university of Cape Town MUCT and Modified Johannesburg MJB BNR plant designs. They are further developments of the 3 stage Bardenpho process and progressed from an initial design to the modified version shown below, which offers more control and flexibility. It is suggested that these plant configurations more reliably remove N and P because there is less chance of O2 or NO2/NO3 being recycled to the wrong zone. Each one of the zones may have a number of sections that in the aerobic zone could provide staged O2 supply.



Modified UCT configuration, the rbCOD is used where needed most



Modified Johannesburg configuration, increases size of anoxic sludge fraction

In addition there are SBR, MBR, MBBR, UASB and extended aeration plants often oxidation ditches with high hydraulic retention times, sludge age and MLSS that reliably remove N and P. (These would be the subject of another presentation).

Plant influent contains the various pollutants to be removed and a constant inflow of a vast range of bacterial species. They come from the digestive tract of animals and from many other sources as well, some sloughing of from biofilms in collection networks others originating with trade waste or during storm water events. This ensures that the BNR reactors are constantly reseeded with the same and sometimes different species of microbe e.g. new competitors. It is assumed that the environment in the plant will select and give a growth advantage to the wanted species and inhibit nuisance and other undesirable microorganisms.

3.0 CONCLUSIONS

Having considered aspects of the designs and operation of BNR plants, what might cause a plant to suddenly or slowly loose the ability to remove P or N?
Principal causes include:

- Insufficient or less desirable rbCOD to support N/P removal - add pre-fermenter or supplement - if possible trial different supplements
- Recycling of O2 or NO2/NO3 no true anaerobic or anoxic conditions, some POAs denitrify - should avoid aerating influent, consider M Johannesburg process
- Fluctuations in flow rate – changing HRT – affecting sludge ages of the bacteria
- Changes in the concentration of sewage and its constituents e.g. TW changing, new source, or source going off line, one off toxic release
- Release of hot/caustic TW water close to small plant (Laundry, food processor)
- Bacteria are inhibited by heavy metals or certain organics (including some polys,

antibiotics, alcohols/solvents, detergents, farming/horticulture/pesticides)

- Low alkalinity inflow may need to dose NaCO3
- Difficulty maintaining DO e.g. diffusers cracked, torn, blocked (as temperature increases DO will go down, but simultaneously some bacteria increase activity (up to a point), causing low DO, and aeration system overload
- Bacterial populations change without obvious reason e.g. replaced by a competitor, possibly caused by a specific toxin to that strain, also bacteria have viruses (phage) sudden phage attack could decimate a population. Lastly bacteria can shift their metabolism in response to altered conditions.

In general terms; have the best pre-treatment for grit, rags, SS, oil, grease/scum removal and air diffusers your money can buy. Have backup alum or FeCl3 for P precipitation, and additional O2 supply in reserve. Investigate possibilities to even out influent flows. Know your trade waste officer. Be aware bacteria can exchange genetic material and so acquire/loose capabilities, this variability and competition from other strains is difficult to include in computer modelling software. If discharging into a sensitive environment consider (with great caution) upgrading with microfiltration unit (MBR), and/or advanced oxidation AOP/BAC if persistent problems. Lobby regulators to lower detergent P further. Considering the vulnerabilities of automated systems trained operators must have the ability and the necessary resources to respond to alarms and control all aspects the process.

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