Synopsis

Biological nutrient removal (BNR) activated sludge systems (designed and operated with an additional function of biologically removing nitrogen and phosphorus) produce a waste activated sludge (WAS) that is rich in nitrogen (N) and phosphorus (P). When digested, this nitrogen and phosphorus are released, producing a dewatering liquor high in ammonia or nitrate and phosphate. Not only does this dewatering liquor need to be treated, but the phosphate also precipitates in the digester and surrounding pipework, resulting in loss of digester capacity and pipe blockages.

This investigation studies anoxic-aerobic digestion (aerobic digestion with intermittent aeration), as an alternative digestion of BNR WAS. Aerobic digestion is simple to operate – being an extension of the activated sludge process, requiring aeration and limited recycling. This compared with anaerobic digestion which is complex to operate requiring airtight containers with fire risk, heating and much recycling. In anoxic-aerobic digestion, the nitrogen is removed by nitrification-denitrification, which has the added advantages of reducing the digester's oxygen demand and recovering some of the alkalinity lost in nitrification. Phosphate is precipitated in the digester - a convenient location. This results in a digester dewatering liquor low in nitrogen and phosphorus (<5 $mgNH_4$-N/ℓ, <15 $mgNO_3$-N/ℓ and 20 to 30 $mgPO_4$-P/ℓ) that can be returned to the activated sludge plant without overloading it.

Biological excess phosphorus removal (BEPR) is conducted by a group of bacteria known as polyphosphate accumulating organisms (PAOs) who have a cyclic behaviour with phosphate. They take up orthophosphate (PO_4^{3-}) in an aerobic environment, to store it in long inorganic polyphosphate chains (PO_3^-), counterbalanced by cations Mg^{2+}, K^+ and Ca^{2+} and release it in an anaerobic environment. Therefore, the WAS withdrawn from these systems, coming from the aerobic zone, will have a high P content, that it will release as soon as conditions turn anaerobic (not only anaerobic digestion, but also in pipework and settlers where the sludge has gone from anoxic to anaerobic). This released P precipitates with available co-released Mg^{2+} and Ca^{2+}. Besides the release of P, another problem in digestion is the nitrogen (ammonia in anaerobic and nitrate in aerobic), which cannot be released with the effluent and, if returned to the activated sludge plant, can overload it.

Anoxic-aerobic digestion was studied by Warner *et al.* (1983) before the practice of BEPR, and they found an aeration cycle of 2h air on, 2h air off, to effectively remove the nitrogen (a dewatering liquor low in both ammonia and nitrate), with a saving in oxygen demand of about 40%. Mebrahtu (2007) studied batch aerobic digestion of BNR WAS at high concentration (total suspended solids, TSS of 1.5 to 2%, 15 to 20gTSS/ℓ) and found the released P to precipitate. He developed a steady state model for batch and continuous aerobic digestion based on the activated sludge model of Marais *et al.* (1976) that Warner *et al.*

(1983) used, and the BEPR model of Wentzel *et al.* (1990). In this investigation Mebrahtu's model is further developed and fine-tuned, particularly to include weak acid-base chemistry to assess what phosphate minerals are precipitating in the digester dewatering liquor. Initially, a dynamic model is done in Aquasim (Reichert 1994), whose results showed that mineral precipitation did indeed occur. Laboratory results from this investigation are assessed with steady state and batch models – further dynamic modelling will be done in a subsequent report.

In this investigation, an effective BNR activated sludge system was operated for two years – a labscale UCT system with submerged panel membranes for solid-liquid separation and added acetate, P, Mg and K to the influent settled sewage to increase the P removal. This UCT system of 75ℓ total reactor volume, fed 150ℓ/d real settled sewage, was operated at a sludge age of 10 days with WAS of concentration 8 to 10 gTSS/ℓ. This WAS (P content 0.15 to 0.19 mgP/mgVSS, volatile suspended solids) was fed to two anoxic-aerobic digesters (12ℓ each, sludge age 20 days, on an intermittent aeration cycle of 3h air on, 3h air off), operated at different TSS concentrations. One was fed concentrated WAS (16 to 20gTSS/ℓ), to observe mineral precipitation of phosphate, as well as the nitrogen removal at high concentration and the other at low TSS (3gTSS/ℓ) to observe the orthophosphate (OP) release from BEPR WAS without mineral precipitation. After 6 months a pH controller, sodium bicarbonate was added due to the loss of alkalinity and drop in pH from P precipitation. pH was maintained between 7.2 and 7.6 for the remainder (18 months) of operation. A year into the anoxic-aerobic digesters' operation, the pH controller was changed to hydroxide. Magnesium was also added to the high TSS digester to increase the precipitation of orthophosphate, and the low TSS digester was taken off intermittent aeration (turned fully aerobic) to observe the build-up of nitrate without denitrification. During the last 6 months of the two years of operation, hydroxide remained the pH controller, the low TSS digester remained fully aerobic and calcium was added to the high TSS digester in place of magnesium, enough Ca to precipitate P to concentrations low enough for recycle to the influent of the AS plant (20 to 30 mgP/ℓ – equivalent of 0.5 to 1 mgP/ℓ influent sewage).

However, it was found that precipitation of OP occurred even in the low TSS digester. Therefore, several long-term (20 to 40 days) aerobic batch tests were conducted on BNR WAS (from the UCT system) and digester sludge to observe the rate of P release from polyphosphate, which had been assumed to be at the PAO endogenous rate b_G = 0.04/d. In dilute aerobic batch digestion of WAS (2 to 3gTSS/ℓ), the P release from BNR WAS was seen to be linear. A polyphosphate release rate of 2.5 times the expected rate (b_G = 0.04/d) was found, b_{GP} = 0.1/d. This rate was fitted to three separate batch tests on dilute WAS (P content 0.15 to 0.19 mgP/mgVSS), to show its independence of sludge characteristics and concentration. At this rate the polyphosphate is entirely released within 15 to 20 days of batch digestion and two thirds released in steady state digestion at a retention time of 20 days. This continued release was confirmed in a long term batch test on high TSS digester waste.

Short-term batch tests were also conducted on continuous digester waste to observe the nitrification and denitrification capabilities of anoxic-aerobic digester waste, which were significant. (A parallel study by Motlomelo *et al.* 2010, who added source-separated urine to an anoxic-aerobic digeseter fed UCT system WAS of 16-20gTSS/ℓ, found the digester capable of removing double the nitrogen released from the WAS). The high TSS digester sludge also showed release of its remaining polyphosphate and absorbance of acetate when tested under anoxic and aerobic conditions with added acetate. This confirms the remaining active PAO biomass after 20 days continuous digestion, due to its slower endogenous rate (0.04/d) compared with that of ordinary heterotrophic organisms (OHOs, 0.24/d), upon which digestion time is typically calculated for sludge stability. However, this lesser stability of BNR WAS is made up for by most of the polyphosphate having been released, therefore the digested sludge is less of a threat for P precipitation.

The weak acid base chemistry of the dewatering liquors was studied – of the long-term aerobic batch digesters and anoxic-aerobic digesters – to observe what orthophosphate minerals precipitate, particularly struvite [$MgNH_4PO_4.6H_2O$] which is blamed for phosphate precipitation in many studies of digester dewatering liquor. However, in this investigation into aerobic and anoxic-aerobic digestion of BNR WAS, struvite was not found to precipitate as ammonia was readily nitrified. KMP was also not found to precipitate – K^+ remained dissolved, an indicator of the rate of polyphosphate released. Magnesium phosphate, particularly newberryite [$MgHPO_4.3H_2O$] and bobierite [$Mg_3(PO_4)_2.8H_20$] were found to precipitate, as well as calcium phosphate [TAP, $Ca_3(PO_4)_2.xH_2O$]. Dissolved calcium remained low from UCT system effluent to digester dewatering liquor (10 to 20 mg/ℓ, even in the high TSS anoxic-aerobic digester). When added to the high TSS anoxic-digester WAS feed, calcium was found to be a more successful precipitator of phosphate than magnesium which either remained in dissolved form or precipitated with carbonate at pHs above 7.4. This shows lime [$Ca(OH)_2$] as an effective additive to an aerobic (or anoxic-aerobic) digester of BNR WAS as it will serve a dual purpose of precipitating P and raising the pH and alkalinity lost in P precipitation. However, with WAS of high P content, lime will precipitate more P than the available hydroxide and a further addition of e.g. NaOH may be required to maintain pH.

In conclusion, this investigation has shown the effectiveness of anoxic-aerobic digestion of BNR WAS in producing a digester dewatering liquor (DWL) low in N and P (<10 mgTN/ℓ and 20 mgP/ℓ), that can be returned to the activated sludge plant. Nitrogen is removed by nitrification-denitrification, P is precipitated with available co-released Mg^{2+} and Ca^{2+} cations, but can be augmented by the addition of lime. .