Recovering ammonium and struvite fertilisers from digested sludge dewatering liquors

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Abstract
When sludge dewatering liquors are returned to the head of a wastewater treatment works they can contribute 20% of the total loading of nitrogen and of phosphorus. The loads can be even greater if the works is a regional sludge treatment centre with large quantities of sludges imported from other works. The solids contribution from dewatering liquors is trivial but the N and P loads can be both expensive and, if secondary treatment capacity is limited, decisive in selecting treatment strategies. Dewatering liquors are very concentrated in comparison with sewage, which means there is an opportunity for a radically different approach from the conventional biological methods. This paper describes the results of investigating the potential for stripping N and P from dewatering liquors physico-chemically and the markets for the stripped N and P as fertilisers separate from the biosolids. Experience of full-scale operational plants is included and the paper concludes with a conceptual arrangement for a combined physico-chemical stripping plant to remove 90% and the N and P from dewatering liquors and recover them as fertiliser materials. It is shown that income from selling the recovered fertilisers can offset all or most of the cost of the input chemicals and that the capital cost is competitive with 'conventional' treatment. Recovering some of the P as fertiliser also benefits the biosolids programme.

KEYWORDS
Ammonium sulphate, biosolids recycling, dewatering, fertiliser, nitrogen, phosphate, struvite, sustainability, treatment

INTRODUCTION

Sludge dewatering liquors can impose large loads on wastewater treatment works. Even if the works is only treating its indigenous sludge, the nitrogen (N) and phosphorus (P) in dewatering liquors can constitute at least 20% of the loads of both N and P if the conventional solution of returning the liquor to the head of the works is followed. When a works is a regional sludge treatment centre the load from dewatering liquors can be even greater. Solley (2006) estimated that the nitrogen in digested sludge dewatering liquor for a centralised treatment facility for Brisbane's four WwTWs would be 30% of the N load on the works. The purpose of this paper is to assess whether there is a cost effective alternative to eliminating the N by biological oxidation followed by denitrification and of capturing the P into the sludge. Biological elimination of N is expensive because it involves aeration to nitrify the ammoniacal-N to nitrate and probably adding degradable carbon (e.g. methanol) to feed denitrifying bacteria in an anoxic zone to denitrify the nitrate to nitrogen gas. Some processes aim to halt the nitrification at nitrite and then lose N by denitritation; they are somewhat less energy consumptive, but none the less they use energy to convert potentially useful ammonia to nitrogen gas.

Jarvie et al. (2006) revaluated P inputs to surface waters and concluded that at times of low flow (i.e. when there is least dilution) diffuse inputs are of no consequence and that point discharges (e.g. from wastewater treatment works, WwTW) should still be the focus of concern. They used the elegant technique of monitoring the P:B ratio to fingerprint contribution from WwTW; the B

originating from perbromate whiteners in detergents. They also showed that eroded agricultural soil that had been deposited in surface waters remained a sink for P rather than a source. If these findings are taken up by policy makers there will be more attention to P discharges from WwTW.

P has become one of the limiting parameters for biosolids application to land. Concerns about eutrophication of water have meant that farmers in the European Union are being required to give more attention to nutrient management under the cross-compliance obligations for receiving their single farm payments (Evans, 2005). Water companies are required to have regard to the plant-available P in soil when planning biosolids application. Thus there might be benefit in capturing P from dewatering liquors into a separate stream, rather than back into the biosolids.

There is considerable interest in the UK and many other countries in increasing the solids load fed to anaerobic digestion (AD) and in maximising biogas production. The motivators for this interest (not in any order of priority) are to:
- Increase production of renewable energy [and income from sales]

- Sweat existing AD assets so that they can treat more material [possibly with gate-fee income]

- Increase solids destruction so as to reduce the quantity of digestate for eventual recycling or disposal

- Reduce the difficulty of dewatering and thus increase the dry solids content of the cake to reduce the quantity and increase the stackability

- Improve the confidence in meeting microbiological quality targets

One price of doing this where digestate is dewatered has been the increase in the nutrient loading on the treatment works, which increases the difficulty [and cost] of meeting the existing discharge Consent by "conventional" biological processes.

AD converts the N in proteins that is held in peptide-links into water soluble ammonium ions (NH_4^+). The "conventional" method of wastewater treatment to remove NH_4^+ is biological oxidation to nitrate (NO_3^-) and, if there is a limit on total-N that the works can discharge, biologically denitrify this to nitrogen gas. This process requires considerable energy for pumping and/or aeration and hence cost.

In all probability Consents are going to become even more stringent for works whose effluent is considered to contribute significantly to the nutrient loading of the marine waters that are considered non-dispersing (e.g. North Sea, English Channel, Baltic, etc.). Where biological nutrient removal (BNR) has already been implemented for nitrogen (N) and phosphate (P), the wastewater strength frequently limits BNR by not providing enough food for the microorganisms (F/M ratio) and the return of additional nutrients would most likely require [increasing] supplemental feeding (e.g. methanol) to maintain the process.

Precipitation of struvite (magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6(H_2O)$)) in pipelines carrying dewatering liquor has long been an issue at some works (e.g. Heinzmann, and Engel, 2006). Struvite crystals adhere to pipe walls and have low solubility; the build-up of crystals can block pipes in a matter of weeks. This is particularly an issue in the discharge pipework from dewatering equipment where the ratio of $Mg:NH_4:P$ is correct and dissolved CO_2 is released because of a pressure drop; this causes the pH to rise and struvite forms. A typical cause of pressure drop in the flow of the centrate/filtrate is in the turbulence after a 90° bend or after a flanged-joint where gasket protrudes into the pipe.

P that has been removed into biomass by BNR is held in that biomass as long as it is aerobic but it is released under anaerobic conditions (e.g. in AD). Thus the cycling of P and the cost of dealing with it will be greatest at BNR plants. In the light of Jarvie et al. (2006) it is likely to become an increasing issue as P discharge restrictions are applied to more WwTW. From the above it is obviously desirable to prevent the N and/or P in dewatering liquors from returning to the wastewater treatment stream.

Fortunately dewatering liquors are relatively concentrated compared with wastewater and this has enabled development of examples of inorganic removal processes at operational scale for capturing the N and P and even turning them into saleable products. The more concentrated the feed is to the AD, the more concentrated will be the dewatering liquor; it is not necessarily that the total mass of N and P will be any greater, just that the dilution will be less. In this context the liquor following Cambi thermal hydrolysis is likely to be amongst the most concentrated because the AD is effectively fed at approximately 12%DS i.e. double that of highly loaded AD without Cambi; this dewatering liquor is therefore especially suitable for inorganic stripping. However, inorganic stripping could be applicable to other dewatering liquors as well.

PLANTS WHERE PHYSICO-CHEMICAL STRIPPING OPERATES

As discussed above, phosphate readily precipitates at some works as struvite where it is not wanted, therefore there should be an opportunity to precipitate it in a reactor and recover it; this is already being practised at a few locations.

Part of every foundation chemistry course is volatilising ammonia from ammonium salts by adding alkali either to qualitatively test for its presence or to quantitatively measure its content in the test sample. More than 10 years ago there was a paper in the CIWEM Journal about a pilot plant in Scandinavia that treated liquor with alkali, air-stripped the ammonia and captured it in an acid scrubbing tower.

VEAS Wastewater Treatment Works, Oslo, Norway

VEAS is the larger of Oslo's two WwTW. It serves about 650,000 population equivalents. Sludge treatment comprises acid hydrolysis (1.5 day HRT at 37 °C) followed by mesophilic anaerobic digestion (20 day HRT). 60% organic matter reduction is claimed. The methane content of the biogas is 50 %CH_4 from the acid phase and 70 %CH_4 from the MAD. The liquid digested sludge in the buffer tank before dewatering is 4%DS. Slaked lime is added to condition and sanitise the sludge (approx 40% w/w DS basis); cationic polyelectrolyte is added immediately before the plate and frame press. This membrane press has been adapted to operate as a heated vacuum press. The press cycle is 3 hours, of which 55 minutes is filling. The cake is dewatered at 7 bar pressure. Alternate plates are heated with water at 85 °C and a -0.93 bar pressure is pulled on the filtrate line to reduce the boiling point of the water in the cakes (Sagberg and Berg, 2000 and Sagberg et al. 2006).

Many operational difficulties have been overcome to make this vacuum drying system work, including custom re-designing various elements. Apparently it now works 24/7 automatically. Plates are washed every 14 days to clean the cloths and ensure cake release. Lime scale is removed every 6 weeks with citric acid. Pressures on the vacuum line and the hot water line are monitored to check for leaks, which are a recurrent but manageable feature of operations. The cake is dried to 55%DS. At this dryness the majority of the volume reduction has been achieved; the cake is dry and stackable but there are no issues of dust when it is spread or of explosion. There is a good order book for the cake, which is delivered to farms free of charge; the farmers arrange spreading. The

cake is free of *E. coli* and *Salmonella*. The process has been shown, using microcosms, to kill the eggs of potato cyst nematodes (*Globodera rostochiensis*) and seeds of wild oat (*Avena fatua*).

The phosphate content of the filtrate at VEAS is low because P is precipitated into the cake as calcium phosphate (Ca-P) by the slaked lime. Because of the presence of organic matter and the 'uncontrolled' nature of the precipitation, the Ca-P is probably a poorly crystallised sludge; this lack of crystallisation does not matter at VEAS because the Ca-P is merely incorporated into the digested sludge cake but it is a difficulty if the purpose is to recover P as a Ca-P sidestream. The pH of the filtrate is >10 so most of the ammoniacal-N is as ammonia (Figure 1) and therefore readily stripped by air.
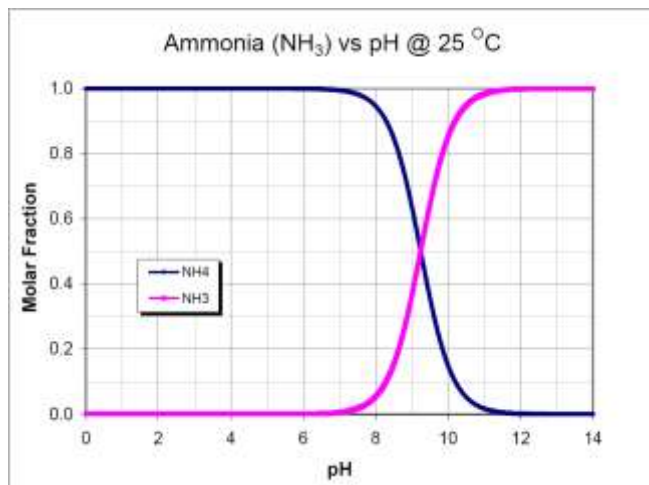

Figure 1 Relationship of ammonia solubility to pH (DiFilippo, 2006)

The alkaline filtrate (1200-1500 mgN/litre) is pumped (via an in-line filter cartridge to remove large sludge solids) to the top of a stripping tower that is packed with plastic media. It is sprayed down the tower against a counter current of air, which is then blown up a second packed tower against a rain of acid (Figure 2).
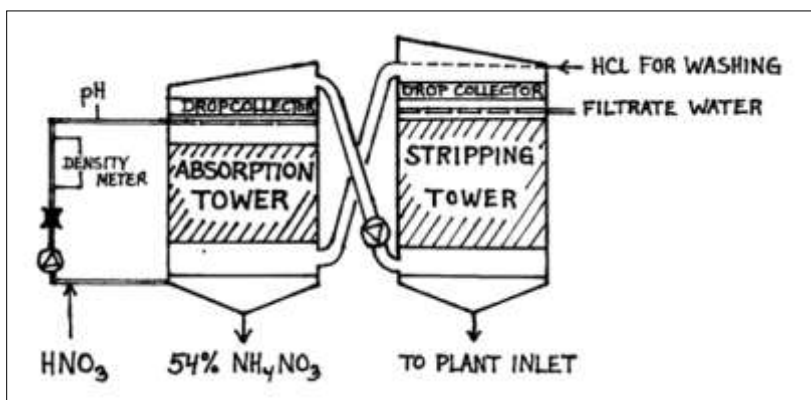

Figure 2 Detail of ammonia stripping at VEAS

The plant was originally designed for sulphuric acid but in 1998 it switched to 55% nitric acid because a) farmers said they did not want ammonium sulphate because of its acidifying effect on soil and b) Norsk-Hydro (now Yara) was prepared to supply nitric acid and purchase the ammonium nitrate, which relieved VEAS of finding customers for its recovered N. Ammonium sulphate acidifies soil because [essentially] nitric acid is formed when ammonium is nitrified to nitrate. In much of the UK, the sulphate in ammonium sulphate is attractive to farmers because sulphur has become a limiting plant nutrient since emissions of S to air have been reduced by clean

air legislation (Figure 3). Ammonium sulphate has actually returned as a commercial agricultural fertiliser. Buying nitric acid from the company that purchases the ammonium nitrate is convenient but it gives that company a strong hand when negotiating prices.

Figure 3 Sulphur fertiliser field experiment [sulphur treatment left, control right] (Rothamsted Research)

The switch from sulphuric to nitric acid at VEAS brought two problems. Firstly, the polypropylene plastic from which the acid stripping tower and pipework were manufactured was attacked by the nitric acid and became brittle. Stainless steel is more suitable for nitric acid and the PP pipework has been replaced with SS. Magnetic drive pumps are used to avoid contact with acid. Secondly, ammonium nitrate is a powerful oxidising agent and in the presence of organic matter is liable to explode [ammonium nitrate fertiliser and diesel was a favourite terrorist bomb] consequently Yara has set a quality limit of 100 ppm total organic carbon. On occasions the TOC-limit has been difficult to achieve, but mostly the product is acceptable to Yara. TOC is not an issue with ammonium sulphate. The whole stripping process has an impressive operational availability of 99.2% up-time and requires very little attendance.

The packing media in the air stripping tower become coated with calcium carbonate because the dewatering liquor is calcium saturated and the stripping air contains CO_2; the media are acid washed bi-monthly.

The nitric acid dosing is controlled by pH and viscosity. The economics of the process lie in this control program and in optimising the air flow. At least 90% of the ammonia is air-stripped and recovered from the filtrate. VEAS produces about 3000 tonnes ammonium nitrate (dry weight) per year. The manager estimates that the cost of replicating this plant (i.e. for 650,000 p.e.) would be £500,000.

Slough Wastewater Treatment Works, UK
Slough operates mesophilic anaerobic digestion and centrifuge dewatering. From the time that biological nutrient removal (BNR) for nitrogen and phosphorus became operational problems of struvite ($Mg(NH_4)PO_4.6H_2O$) scaling in the centrate pipeline were experienced. BNR works well at Slough because of the large amounts of soluble carbon from the confectionary companies on the industrial estate; BNR also works well at Reading because of the soluble carbon from a large brewery. At most other works, supplemental C is needed. When the surplus activated sludge becomes anaerobic in the digester, the P is released from the biomass. Some solubilised P is precipitated by inorganic cations in the digester. At Slough there was sufficient ammonium,

magnesium and phosphate in the centrate that the struvite precipitation potential was large. Some struvite forms in the digesters, but some ammonium, magnesium and phosphate remained in solution because of the pH (and hence were in the centrate). Whenever CO_2 was released from the centrate the pH rose and struvite precipitated. For example CO_2 was released in the pressure-drop zones after 90°-bends in pipes, or after incompletely opened valves or gasket material intruding at flanged joints. Struvite was a nuisance, and a cost, it was therefore decided to crystallise it in a reactor immediately after the centrifuges before it could become a problem. After solving relatively minor development and engineering aspects, the plant operated reasonably satisfactorily for 6 months but Thames Water subsequently decided it was easier to dose iron into the digesters so that the P was precipitated into the biosolids, albeit the operational cost of the iron solution exceeds the combined cost of magnesium chloride and sodium hydroxide and the loss of [potential] income from selling struvite.

Iron dosing into the digester increases the P content of biosolids with consequential effects on application rates, etc. However, reduced sophistication suits the operating paradigm. There is a risk that excessive iron dosing can result in P-deficiency for the microbial biomass in the digester and reduced biogas production, and it can also lead to precipitation of hard calcite. Calcite ($CaCO_3$) crystallisation is inhibited by soluble P. Calcite slush is not a problem but when the concentration of soluble P is small, crystallisation is not inhibited and hard deposits can form that are as much of a problem as struvite.

The reactor of the pilot plant at Slough was a modified lamella clarifier with the plates removed and a central baffle extended to create a settling zone and a reaction zone. It was not ideal but it was available for R&D purposes. It was sandblasted and painted to give smooth internal surfaces (Jaffer and Pearce, 2004).

The specific gravity of struvite crystals is 1.7 so there should be gravity separation of struvite from organic matter. Laboratory studies had shown that maximum P recovery was achieved when the Mg:P ratio was 1.3:1 and the pH was 9; the pilot reactor confirmed the lab results. Struvite crystallised readily.

Operation of the pilot plant was hampered because the control of the dewatering centrifuge was not consistent, which meant that sometimes the centrate was very dirty with sludge solids. There was no sludge screen upstream of the centrifuge or of the digester which meant there were shreds of plastic in the centrate. Because of Fe dosing for P-removal, the phosphate concentration in the centrate was only about 50 mgP/litre. To reduce the cost of the experiment the main pH elevation was achieved by CO_2 stripping, using air. In normal operation of the reactor there was no alkali addition and as a consequence the pH was sub-optimal for struvite recovery to such an extent that the liquor still had a significant struvite formation potential and crystals formed at the overflow. Water was drained from the struvite crystals by gravity; they were then dried in the curing oven of a cement paving-slab manufacturer. They dried easily and the dried material was free-flowing.

Struvite in Japan
Ueno (2004) reported that there are two full-scale struvite recovery plants in Japan; their objectives are to recover struvite for use as a fertiliser because there are no reserves of P in Japan.

Fukuoka City WwTW operates BNR for P-removal. The struvite plant has operated since 1997; it has 6 reactors treating 170 m^3/day. Each reactor is 7 m tall, the nucleation zone is 0.2 m diameter and the separation zone is 0.6 m diameter. Filtrate is continuously metered into the nucleation zone. The reactors are dosed with magnesium chloride solution and the pH is adjusted with sodium

hydroxide solution though Ueno does not specify the pH. All of the struvite is sold to fertiliser companies as raw material for chemical fertilisers.

Shimane Prefecture Lake Shinji East Clean Centre (SECC) commissioned its first struvite recovery plant in 1998 with the objective of reducing the cycling of P within the works (P in dewatering liquors represented 70% of the load on the WwTW) and to produce struvite fertiliser. A second plant was constructed in September 2000. SECC has two reactors each treating 500 m^3/d and a third treating 150 m^3/d. Each of the 500 m^3/d reactors is 9 m tall, the nucleation zone is 1.4 m diameter and the separation zone is 3.6 m diameter. The 150 m^3/d reactor is 5.5 m tall, the nucleation zone is 1 m diameter and the separation zone is 2.6 m diameter. Filtrate (100-140 mgP/litre) is metered into the nucleation zone continuously.   The reactors are dosed with magnesium hydroxide to achieve a Mg:P ratio of 1:1. The pH is adjusted with sodium hydroxide solution to 8.2-8.8. The struvite crystals are growing in a fluidised bed that is maintained by blowing air. Struvite is withdrawn bi-weekly and the crystals are classified, presumably in a cyclone; the smaller crystals are returned to the reactor to nucleate crystal growth. The P removal efficiency is better than 90%, it has also proved to be more consistent than when polyferric sulphate and polyaluminium chloride were used prior to 1998. The influent ammonia is 200-300 mgN/litre: N-removal is about 20%, which is slightly greater than the stoichiometric ratio with P because, at the alkaline pH in the reactor, some ammonia is air-stripped. The plant produces 500-550 kg struvite per day. The analysis is similar to the stoichiometric ratio for struvite. PTEs are negligible in the struvite. All of the production is sold to fertiliser companies who blend it to make a range of fertiliser formulations that are widely used for paddy rice, vegetables and flowers.

Struvite in North America
The Scope Newsletter for September 2006 reported that Edmonton, Alberta, Canada is building a struvite recovery plant to treat 500 m^3 per day of lagoon supernatant and that several other works in Canada and the USA are also doing work in this area.

Struvite in Australia
Solley (2006) reported on the successful construction and operation of a pilot plant for struvite crystallisation. Both solely and Shu et al. (2006) concluded that struvite recovery from dewatering liquors and use as fertiliser was economically and financially preferable to absorbing it by conventional wastewater treatmnent methods (precipitation or biological absorption).

Struvite as a fertiliser
The phosphate industry is concerned that its raw material is running out. Estimates of current reserves range from 100 to 250 years ((European Fertilizer Manufacturers Association, 2000).). Driver et al. (1999) estimate economic reserves at 100 years. For this reason the industry is keen to find sources of recovered P. Rock phosphate is generally calcium phosphate and it would not be practicable to adapt the industry's processes to receive relatively small quantities of struvite. However the majority of phosphate is used as fertiliser and since struvite has been shown (e.g. Johnston and Richards, 2003) to be a satisfactory source of plant-available P it can be used directly. In fact struvite has quite a long history as a fertiliser in the UK and USA as well as its use in Japan. It appears that manufacturers generally granulate struvite (granulation is typical in the mineral fertiliser industry to reduce dust and improve handling) and that the size of the granule affects the rate of N release.

ICI manufactured struvite and sold it under the brand name "N-Mag". It was a slow-release source of N, plus phosphate and magnesium. It was acquired indirectly by Scotts which blends struvite

with potassium and sells it as Scotts N-Mag Lite (N:P_2O_5:K_2O:MgO 3:17:10:5%) a granular fertiliser for use in landscaping and amenity planting.

Struvite also has a long history in the USA where it has been sold under the brand name MagAmp, a 7-40-0 fertiliser that is available in a coarse grade lasting two years and a medium grade lasting one year [for N]. A struvite potassium blend is sold as MagAmp®K Fertilizer.

Some people have abbreviated magnesium ammonium phosphate (struvite) as MAP which is unfortunate because it can lead to confusion with the already established fertiliser product mono-ammonium phosphate. It would be better to avoid such confusion by using the term struvite.

Johnston and Richards (2003) evaluated eleven precipitated phosphates as sources of phosphorus (P) for plant growth by comparing their effectiveness with that of monocalcium phosphate, a source of water soluble P that is generally considered to be fully plant available. The precipitated phosphates comprised struvites recovered from wastewater discharges (mainly magnesium ammonium phosphate), laboratory synthesised struvites, a synthetic iron phosphate and a recovered calcium phosphate. Precipitating phosphates in these forms could be a way for removing P from wastewater before it is discharged to rivers, thus reducing the risk of eutrophication. Application to agricultural land would be one potential use for such phosphates. Evaluation was by pot experiments with a sandy loam soil and with a sandy clay loam soil using perennial ryegrass (*Lolium perenne*) as the test crop. The soils differed in pH (6.6 and 7.1) and in Olsen P (28 and 11 mg/litre). Measured variables were grass dry matter (DM) yield and grass P concentration which were used to calculate offtake of P in the harvested grass. DM yields of ryegrass and P offtakes given by the synthetic and recovered struvites were not significantly different statistically either between themselves or to MCP applied at the same rate. On this basis these struvites could be used to recycle P to similar soils and the effect of the P on crop yield should be similar to that of MCP.

Sulphate of ammonia as a fertiliser
Ammonium sulphate is a classical nitrogen fertiliser (28%N). It was largely superseded in the UK by ammonium nitrate (34.5%N) because it is more concentrated which consequently reduced the time to treat a field. However, ammonium nitrate is banned in some countries because of explosion risk. Urea (46%N) is another concentrated fertiliser but with a risk of losing N as ammonia gas. All ammonia containing fertilisers acidify the soil during their microbial transformation to nitrate; in essence ammonium is hydrolysed to nitric acid by nitrifying bacteria in the soil. Nitrate is readily leached through soil and can also be lost from soil by denitrification so ammonium is the more reliable component of a nitrogen fertiliser, albeit it has an acidifying effect. Sulphate of ammonia has returned to agronomic interest as a fertiliser because it is a source of sulphur, which is now limited in many farming areas and in these areas there is good crop response to S (Figure).

CONCEPTUAL INTEGRATED DESIGN
From all of the information obtained whilst researching the recovery of N and P from dewatering liquors, the best arrangement was concluded to be to combine struvite and ammonium sulphate as illustrated in Figure 4 since they are complementary.

Experience at Slough has demonstrated the importance of having reasonably consistent liquor and with minimum dilution water. This would be an additional benefit of automating polyelectrolyte dosing with real-time data from the filtrate/centrate and/or the feed sludge.

Deposition of carbonates has proved a maintenance issue at VEAS, this could be reduced by scrubbing CO_2 from the air and by recirculating air within the plant because in essence it is only a carrier; the manager at VEAS agreed this would be a sensible and practicable refinement. If CO_2 were not scrubbed, it would also use some of the alkali in the struvite reactor.
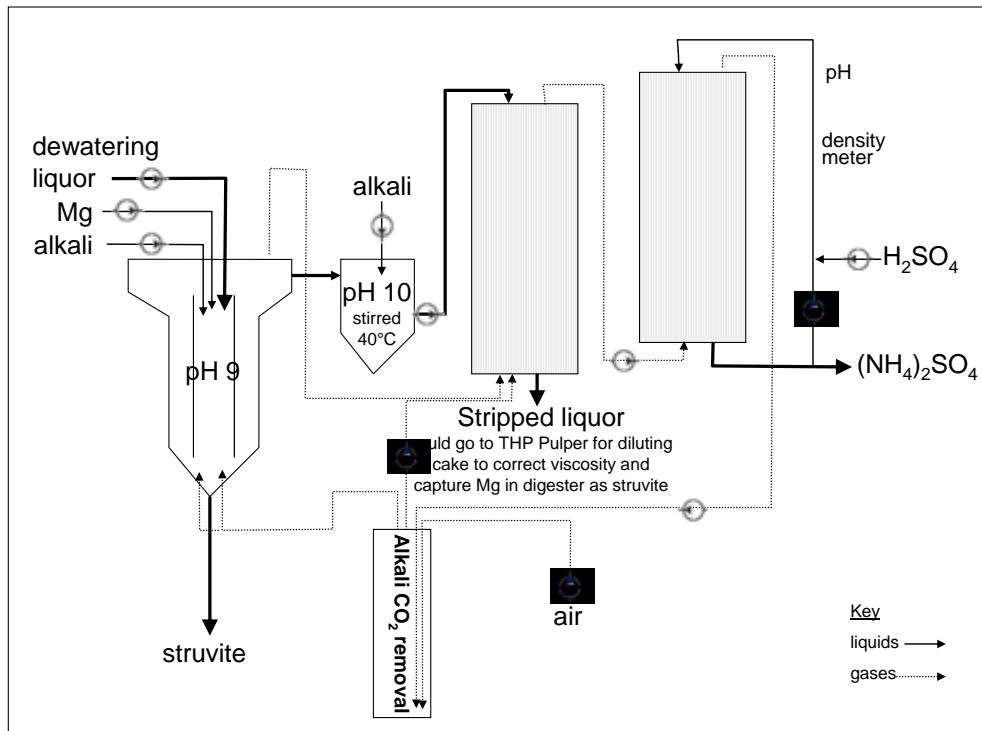

Figure 4 Conceptual schematic design for nutrient recovery from dewatering liquor

The struvite reactor design is similar to the large units operating at SECC (Ueno, 2004). If the design objective is for a plant capable of removing 90% of the P from the dewatering liquor, and since the pH of the liquor will later be raised to 10 for ammonia stripping, the pH in the struvite reactor can be optimised for struvite removal, rather than compromised as was the case at the Slough pilot plant. There is a debate about whether to use the more soluble [and more expensive] magnesium chloride rather than hydroxide but since hydroxide is used at SECC it is worth trying magnesium hydroxide. The struvite crystals will be maintained as a fluidised bed by injecting CO_2-stripped air; crystal size will increase in this fluidised bed. Struvite will be settled alternate weeks and removed via the bottom draw-off.

The pH of the effluent from the struvite reactor will be raised to 10 in a hopper-bottomed stirred tank. The tank will be jacketed with hot water (or a heat exchanger could be used) to raise the temperature, which will decrease the solubility of ammonia. Sodium hydroxide is less expensive than potassium. The warm, pH 10 liquor will be sprayed down the stripping tower against a counter current of air from the struvite reactor and as much additional air as is found necessary to strip the ammonia. Since CO_2 has been stripped from the air, there should be no loss of efficiency as a result of carbonate formation.

The stripped liquor will probably contain some un-reacted magnesium; if it is returned to the as process water the additional magnesium in the digesters will precipitate some of the phosphate as struvite which will make maximum use of the purchased magnesium and save some avoidable load on the struvite plant.

The air-stream from the stripping tower will be blown up the acid tower against a spray of sulphuric acid. The resulting ammonium sulphate solution will be concentrated by re-circulation [as at VEAS] until the optimum/maximum concentration is attained.

Even if the struvite and the ammonium sulphate are sold at a 50% discount to the current prices of fertilisers delivered to farms, the income from their sale will be 75% of the cost of input chemicals, maintenance and manning. This is obviously sensitive to the price of the consumables and to the selling price for the products. The prices of fertilisers have been rising since December 2002 because of the increased cost of energy and because of increased demand for fertiliser for food production and more recently for biofuels. This trend is expected to continue, which will increase the proceeds from selling recovered N, P_2O_5, MgO and SO_3 (these are the units used to express fertiliser in the UK).

The capital cost of a combined plant for 0.5 million p.e. is expected to be not more than £1 million which is competitive with a biological plant. The operating cost would be less than a biological plant and there is the bonus that the P content of the biosolids would be less than if the liquors were returned to the main wastewater treatment plant.

CONCLUSIONS
The concept of physico-chemical stripping appears to be both practicable and financially competitive with biological treatment; it is also more sustainable and has a smaller carbon-footprint. Viability improves as the consistency and concentration of the liquor increases. Struvite precipitates readily, even in dilute liquor. Air stripping to remove ammonia after the liquor has been made alkaline and capturing the ammonia in an acid stripping tower is also straightforward. The products [struvite and ammonium sulphate] have proven fertiliser value and have already drawn expressions of interest from established fertiliser vendors; alternatively these mineral fertilisers could be complementary to a biosolids recycling programme. The proceeds from selling the recovered fertiliser should offset most if not all of the cost of the input chemicals. The capital cost is competitive with biological treatment. Stripping P into struvite is consistent with the principles of sustainability and it reduces the P content of the biosolids which in turn reduces haulage distances and the cost of biosolids recycling. There are two riders to this optimistic picture: is the operator of the WwTW capable of operating such a sophisticated (albeit automated) plant and does it have the confidence to sell the recovered products directly to users or to intermediaries?

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