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A Strategy for Minimisation of Liquid and Gaseous Emissions from the LR Gasification of Dried Sewage Sludge

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Abstract:

Over recent years European legislation has impacted significantly on the waste management strategies of companies responsible for the treatment and disposal of sewage sludge. Many Water Service Companies are looking to make use of the sludge rather than simply seeking the most acceptable disposal route. The main reuse opportunities that are being investigated in the UK are incineration or thermal drying and more recently gasification, although agricultural use is still preferred by some Companies.

Northumbrian Water Limited (NWL) together with their consultants Entec have developed a sludge strategy over the last 5 years which resulted in the building of a regional drying facility at Bran Sands on Teesside. The development of Bran Sands on Teesside, which includes the Effluent Treatment Works and the Regional Sludge Treatment Centre, constitutes a £200 million investment in the heart of one of Europe's main petrochemical centres. The strategy has continued to develop and has now resulted in the proposal for a gasification process to be sited adjacent to the drying plant.

Northumbrian Water Limited (NWL) and its partners Lurgi Umwelt GmbH of Frankfurt have developed an innovative, high-efficiency, energy-positive route for the conversion of wet, raw sewage sludge to electricity via thermal drying and gasification. During the early stages of the project the key technical challenge was identified as the design of a suitable gas cleaning process that would allow the process gas to be used in a gas turbine. During the development of the gasification technology it has been necessary to develop a means of reducing selected raw gas contaminants to ensure compliance with environmental considerations. This paper examines the development process of the Regional Sludge Treatment Centre (RSTC) and the gasification plant as a means of beneficially reusing sewage sludge without placing an unacceptable burden on the environment.

Introduction

What to do with sewage sludge is one of the most pressing questions to have faced water companies over the last few years. The effect of the EU Urban Waste Water Treatment Directive (UWWTD) is to increase sharply the volume of sludge for disposal while, for some companies, removing their main disposal routes through the cessation of sea disposal.

The introduction of the Landfill Tax, which is predicted to rise significantly between now and the year 2005, will bring significant economic pressure to bear on landfilling as a means of sludge disposal. The anticipated introduction of the Landfill Directive and the possibility of a carbon tax will further affect this route. At the same time, the agricultural reuse route remains vulnerable to scare stories, tightening standards and is dependent on the goodwill of others - all of which increase the pressures and risks associated with the agricultural route for utilising sewage sludge.

Entec UK Limited were commissioned to undertake an economic appraisal of the most viable routes for sludge disposal particular to the region. This study covered NWL's existing large sludge producing sewage works and the new coastal works required under UWWTD. These sites together make up 81% of the regions current sludge production. The study investigated the use of digestion and reviewed 10 different dewatering strategies, 17 drying strategies and 15 incineration strategies. As NWL traditionally did not use digestion as a method of treatment, to employ a regional strategy based upon digestion would prove to be uneconomic. In fact the cost of digestion alone was comparable to that of thermal drying.

Therefore, the preferred strategy was to look at thermal drying of undigested sludge as the best and most flexible way of achieving beneficial reuse of the sludge. The dried sewage sludge can be used in a wide variety of ways so offering flexibility to a water company to respond to changes in legislation, public perception, market opportunities, etc. Dried, undigested sludge has the added benefit that the full calorific value (and therefore the energy potential) of the sludge is retained in the product.

The core recommendation of the sludge strategy was to build a single sludge drying centre adjacent to one of NWL's largest sewage treatment works. After the application of an extensive site selection criteria (including size, estuary and road access, planning consent and utilities) the preferred site was nominated as Bran Sands on Teesside, which had already been identified as the site of a new Effluent Treatment Works (ETW) to serve Teesside. The above strategy was formally adopted by NWL in March 1995. Figure 1 shows a photomontage of the fully developed site at Bran Sands.

Figure 1: Photomontage of the Bran Sands Development.

NWL's strategy has been developed in a rigorous step by step approach with the principles of a safe, secure, flexible and economic solution always in mind. This step by step approach, together with a policy of keeping the local authority and the local community informed has, we believe, greatly contributed to the public acceptance of what is, by any standards, a major scheme. The philosophy and strategy adopted by NWL enabled us to meet our obligations of stopping the disposal of sewage sludge at sea. Figure 2 shows the RSTC and ETW under construction during 1998. Both projects were delivered on time and were operation by October 1998.

Figure 2: Bran Sands Development under Construction

As part of this philosophy, and in order to answer questions that might arise, NWL asked Entec to compare the economic, energy and environmental benefits of sludge drying plus gasification with incineration

Sewage Sludge as a Source of Energy

All carbonaceous materials contain energy, and man has learned to harness and utilise this energy for his every day use. Natural gas is used to fire a gas turbine to generate electric power, just as it is used to provide domestic heating for the home in winter. Coal is burnt in a power station to produce steam to drive a steam turbine and also generate electricity. Wood, coke, petroleum products are all used for their energy content in various ways. Can similar use be made of sewage sludge through gasification? The first step is to relate the properties of sewage sludge to those of other carbonaceous materials and identify potential similarities. The following table compares typical data for dried sewage sludge with that of dried brown coal and wood waste, both of which have been gasified on a commercial scale.

Table 1. **Selected Gasification Feedstocks**

Typical Data	Dried Sewage Sludge	Dried Brown Coal (Rheinisch)	Wood Waste Or Biomass	
C	57.0	67.3	54.7	wt % daf
H	8.0	5.0	6.0	wt % daf
O	30.2	26.3	38.9	wt % daf
N	4.2	0.5	0.3	wt % daf
S	0.6	0.9	0.1	wt % daf
	100.0	**100.0**	**100.0**	wt % daf
Volatile Matter	87.0	55.0	>85	wt % daf
Ash	18.6	5.6	1.5	wt % wet
Moisture	7.0	17.1	19.1	wt % wet
Net CV	17.6	19.3	15.4	MJ/kg

LR Thermal Gasification Process

In terms of maximising the fuel gas heating value of the resultant gas it is better to avoid the direct use of partial combustion to provide the gasification heat. The alternative process of thermal gasification achieves this goal either by indirect heat transfer across an exchanger surface or by direct mixing of the dried feed sludge with hot solids. It is this latter approach which sets the LR Gasification Process aside from all other gasification processes, particularly for feedstocks with high volatile matter content such as biomass or dried sewage sludge. The resultant fuel gas has a net calorific value of around 23 MJ/m_n^3 as it is not diluted by combustion products, nor by nitrogen, and the methane content is boosted by the nature of the process. This is compared with 38 MJ/m_n^3 for natural gas and between 10 – 15 MJ/m_n^3 in other forms of gasification.

The basic flow scheme of the LR Thermal Gasification Process is shown in Figure 3. Dried Sewage Sludge in granular form is continuously drawn by screw conveyor from the Feed Bin (A) and metered through rotary valves into the Reactor (B). Immediately it enters the Reactor, the dried sludge comes into direct contact with a continuous stream of hot recirculated sand with a temperature of 900 °C. The two solid streams become mixed as they fall into the bulk of the solids contained in the Reactor. Further mixing takes place within the mass of solids as it is self fluidised by the product gases from the thermal gasification reactions.

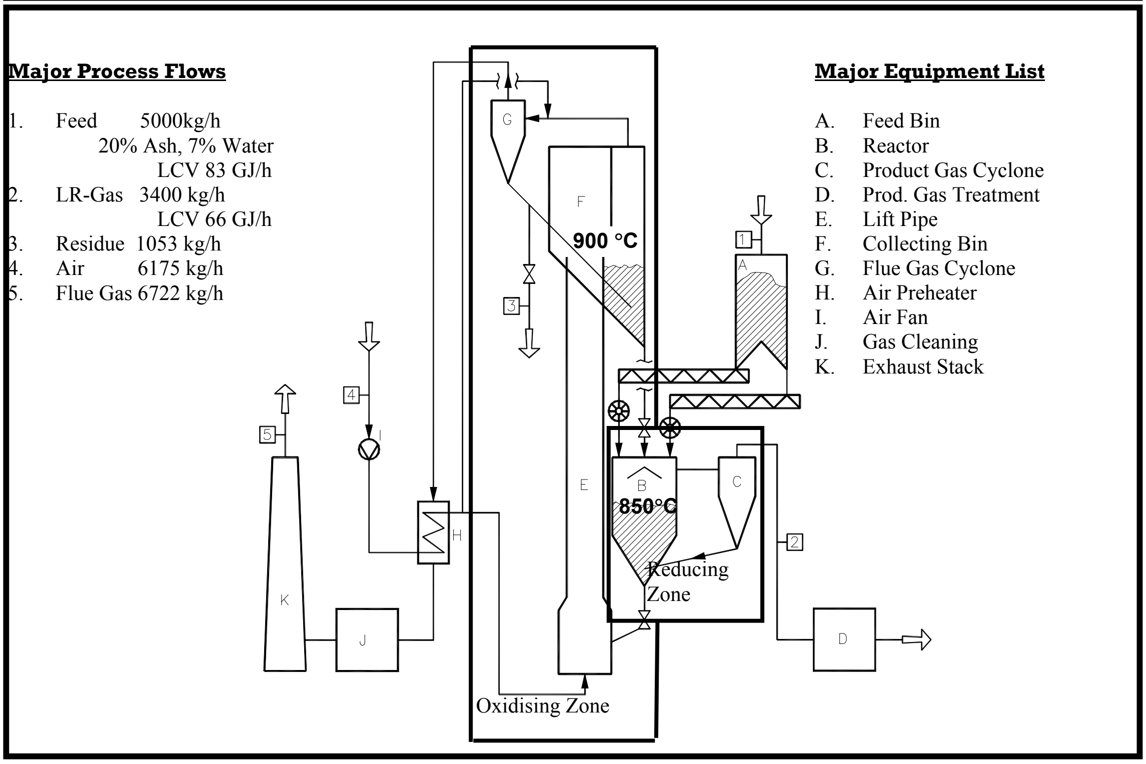
In the first stage of the LR reactor the feed is very rapidly heated (>150 °C/sec) to 850 °C. The organic matter in the feed is thermally cracked to produce a mixture of vaporised liquid and gaseous hydrocarbons as well as a residual carbon/ash that remains behind with the heat carrier sand. In the second, counter-current, stage these gases and liquid vapours come into contact with the hot sand as it enters the reactor, and they are further cracked to shorter length hydrocarbons in the C_1 – C_4 range. Note this secondary phase cracking boosts the calorific value of the LR Product Gas. For example, a hexane molecule has less heating value than its cracked parts. In other words, thermally cracking longer chain hydrocarbons such as hexane using the sensible heat of the hot sand into propane/propene brings about a significant increase in the heating value in the Product Gas. The "cold gas" efficiency of LR Gasification is improved accordingly to values of in the range of 75 – 85%. Note "cold gas" efficiency is the percentage of Net Calorific Value in the feed which is carried through to the Product gas, defined at 0 °C .

The LR Product Gas leaves the Reactor via the Product Gas Cyclone (C) which recovers and returns entrained solids to the Reactor. The gas then passes through Product Treatment (D) that varies depending on the composition of the feed sludge and the quality required by the fuel gas consumer. The char remaining after thermal gasification descend with the sand heat carrier to the base of the Reactor (B) and together they pass down the lower seal leg to the Lift Pipe (E). Positioning the slide valve in the seal leg controls the level of solids in the Reactor. Preheated air is admitted to the bottom of the Lift Pipe and this air pneumatically transports all the solids up the Lift Pipe into the de-entrainment zone of the Collecting Bin (F). En route, the char is burned with the air and the heat generated reheats the solid heat carrier back to 900 °C. Most of the solids gather at the base of the Collecting Bin in readiness for contact with fresh feed sludge in the Reactor. The finer ash from the sludge char is elutriated in the sifting zone of the Collecting Bin before passing with the combustion gases from the Lift Pipe on through to the Flue Gas Cyclone (G). The bulk of the fine ash is collected here and some may be returned to the Collecting Bin while the remainder is discharged as residue.

The flue gases are cooled in the Air Preheater (H) and passed through final Gas Cleaning (J) before being discharged to atmosphere via the Stack (K). Note a slipstream of preheated air is fed upstream of the Flue Gas Cyclone to combust any carbon monoxide which may be present in the flue gases.

A very important feature of the LR Process is the separation of the thermal gasification process, which is a reduction zone, from the residual carbon combustion or oxidation zone (See Figure 3). Thus, the LR Product Gas is not contaminated with the products of combustion and the residual ash is drawn from an oxidation zone not a reduction zone. Ash drawn from the reduction zone would be prone to heavy metal leaching and it would contain a significant amount of reactive carbon, which might exhibit pyrophoric behaviour. On the other hand, ash from the combustion zone of the LR Lift Pipe would contain oxidised heavy metals and only a negligible amount of residual carbon.

Figure 3. LR Thermal Gasification Process



In the conceptual design, the dried sewage sludge is gasified by the LR Thermal Gasification process to produce a fuel gas which when cleaned is burned in a gas turbine. This drives a nominal $6MW_e$ generator, with the hot exhaust gas being fed back to the drying unit. The overall process from wet sludge to electricity will provide a surplus of electrical power corresponding to approximately 1MWh of electricity per tonne of sludge (exclusive of parasitic load), plus 1.5MWh of heat.

The conversion of dried sewage to electricity aspect of the process has already secured 1.5 MECU (circa £1.0 million) demonstration support from the European Commission. The award was made under the THERMIE scheme, towards an estimated total project cost of £13 million (as at December 1998). Detailed process design for the project commenced on 4 January 1999.

Development of a Treatment of Gas Contaminants

Bench-scale gasification trials in the early stages of the project established that ammonia and cyanide concentrations in the aqueous effluent from the process gas clean-up were higher than expected. It became apparent during the conceptual design stage, that conventional pre-treatment options to reduce the toxic effects of the effluent, prior to discharge, could place an unacceptable cost burden upon the project. An innovative solution was required that could meet the technical objectives of reducing fuel bound nitrogen compounds to environmentally acceptable levels, whilst being economically viable.

A study was undertaken to identify and develop an alternative solution to the treatment of fuel bound nitrogen compounds which could be incorporated as an integral part of the overall process. The approach that was developed for treating the effluent streams was to apply a conventional stripping process using air and then thermally decompose the stripped vapours in a low NOx combustion process. In the LR process this is easily achieved by recycling these vapours to the Lift Pipe. In other thermal gasification processes a similar low NO_x combustion process is required. This part of the process represents the major innovative aspect of the approach and proving trials were necessary to confirm the technical viability.

The first stage was a desk study carried out by Lurgi Umwelt GmbH to investigated technical feasibility of the process options, identified a preferred option and estimated investment and operating costs. The second stage involved carrying out proving trials to confirm that thermal decomposition of stripped vapours in the lift pipe would result in acceptable emission levels for release to the environment. Close co-operation with the Environment Agency has been key in selecting the chosen process concept, considered to be BATNEEC (Best Available Technique Not Entailing Excessive Cost), and then developing it into a detailed, fully costed, workable design.

Lurgi Umwelt employed the ASPEN thermodynamic model to initially evaluate the process options available. The ASPEN calculations considered the impact of the various options on the overall integrated gas clean-up process. Two effluent streams were considered in the calculations, a Wastewater 1 stream from the first stage gas clean-up and Wastewater 2 from the final stage gas clean-up.

The ASPEN calculations initially included only one option for Wastewater 1, namely the recirculation of Wastewater 1 stream to the Raw Gas Quench Cooler. This option resulted in minimal production of effluent from the stream enabling this liquid to be injected directly into the lift pipe for thermal decomposition. A second option considered at a later stage, involved stripping of Wastewater 1 stream in a stripping column prior to recirculation, followed by thermal decomposition of only the stripped vapours in the lift pipe.

For Wastewater 2, two options were considered, firstly stripping of Wastewater 2 in an independent stripper column to reduce hydrogen cyanide levels to an acceptable minimum with lift pipe air, before discharging to the Bran Sands effluent treatment works. The second option was a combined Adsorber/Stripper arrangement with the aim to minimise Wastewater 2 effluent production through recirculation of the Wastewater (target zero production of Wastewater 2). In both cases the stripped vapour would be thermally decomposed in the lift pipe.

The thermal decomposition of fuel bound nitrogen compounds in the lift pipe was the cornerstone of this integrated concept for treatment of fuel bound nitrogen compounds. Combustion trials were therefore essential to prove the technical viability of the concept and evaluate the emissions to the environment. The trials were carried out at the research and development facilities of Lurgi Umwelt GmbH on their mini-LR unit.

On completion of the desk study and proving trials, the results were assessed for technical, economic and environmental viability. The environmental assessment was carried out in conjunction with the Environment Agency. The purpose of this assessment was to establish whether the process concept was BATNEEC (Best Available Technique Not Entailing Excessive Cost) and BPEO (Best Practicable Environmental Option) for treatment of fuel bound nitrogen compounds. Following confirmation from the Environment Agency that the process concept was the correct approach, detailed design work to incorporate it into the overall process design was authorised.

Adopted Solution

The desk study results showed that the combined option of stripping Wastewater 1 and using an Adsorber/Stripper arrangement for Wastewater 2 was the preferred option. This option had the advantages of reducing cyanide levels in the effluent by ~99%, reducing ammonia levels by ~40% and removing volatile hydrocarbons, whilst minimising the effluent discharge from the process. The resulting effluent was suitable for discharge to a conventional effluent treatment plant without further pre-treatment. (Refer Figure 4)

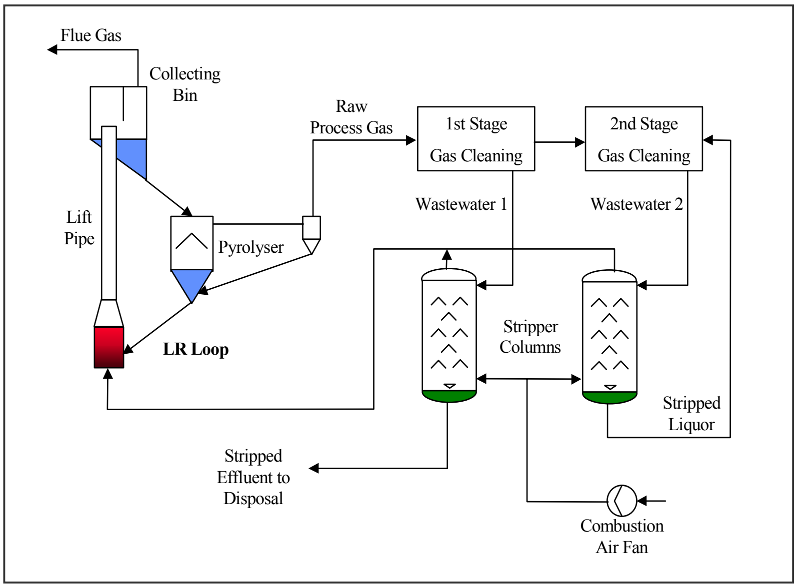


Figure 4: Revised Process Concept

The decomposition of the stripped vapours in the lift pipe was also validated with less than 5% of the fuel bound nitrogen compounds in the stripped vapours being converted to nitrogen oxides. NO_x levels could be further reduced to meet required limits, by the injection of ammonia into the flue gas after the lift pipe in a non-catalytic reduction step (SNCR).

The combustion test carried out on the mini-LR unit measured the extent of nitrogen oxide formation on combustion of fuel bound nitrogen compounds. The results showed that under low excess oxygen conditions, the conversion rate to nitrogen oxide was very low. Initially these tests were planned using an actual mixture of gas liquor and oil from bench-scale gasification of sewage sludge, with hydrogen cyanide then added to the mixture in the correct proportions. However, this was not possible for a number of material and safety reasons. Instead the fuel bound nitrogen compounds were simulated by using acetonitrile (CH_3CN), an easily handled liquid, and ammonia gas as the substitute additives.

A total of 14 combustion tests were conducted at 900°C with sludge residue obtained from a single bench-scale gasification trial. A range of flue gas residual oxygen concentrations (2-5vol%) was used in the tests, with ammonia and acetonitrile added as single components or in combination.

Addition of acetonitrile on its own increases NO_x by up to 10wt%, whilst addition of ammonia on its own hardly increases the background NO_x level for the same residual oxygen values. A possible explanation for this is that small amounts of ammonia remain in the flue gas and react with NO_x in a secondary reaction to form elemental nitrogen.

Estimates of additional investment cost for the process concept were in the range £1.25 million to £1.8 million, while the resultant reductions in operating costs showed a saving of £36000/annum. The additional investment cost is made up of approximately two thirds related to the stripping of Wastewater 1 and 2 and one third related to the increase in size of the lift pipe and flue gas cleaning system. The operating cost indicates a net saving due to the reduced consumption of cooling water and raw water which more than compensated for the increased electrical power consumption of the lift pipe air compressor.

Conclusions

NWL have developed their regional sludge strategy to serve the company for 20 years in a detailed and systematic way over the last 5 years. The dried material produced at the Regional Sludge Treatment Centre can be used in many ways, thus ensuring flexibility in the future to meet legislative, fiscal or political pressures

The gasification project will utilise the dried sludge to produce a gas that will be used to fire a CHP gas turbine to provide energy for the site. By using the sludge in this way NWL will not only benefit from the energy generated but also from the reduction in the volume for ultimate disposal or reuse by others. The company will further benefit by not being reliant on an external body to take the dried material.

The technical viability of this concept for treatment of fuel bound nitrogen compounds has been validated in a desk study and its integrity proved in trial work. The development of the detailed design has confirmed the additional investment cost required to integrate the concept into the overall process design. Environmental assessment has shown this solution to be a Best Practicable Environmental Option for treatment of fuel bound nitrogen compounds. Compared to conventional chemical pre-treatment options this method of treatment has a significant economic advantage due to the lower operating cost.

The main conclusion from the work is that treatment of fuel bound nitrogen in the wastewater streams by air stripping, followed by thermal decomposition in the lift pipe has a technical and economic advantage over conventional chemical based pre-treatment options.

The process concept has the following additional benefits:

- The stripping option for Wastewater 1 improves ammonia removal efficiency in the first stage gas clean-up, due to recirculation of stripped rather than concentrated wastewater.
- Wastewater 1 stripping minimises equipment size increase for the lift pipe and flue gas cleaning system because only stripped vapour was injected instead of the liquid wastewater.
- The Adsorber/Stripper arrangement for Wastewater 2 results in an almost zero production of effluent.
- Although there is an increase in electrical power consumption for the lift pipe combustion air compressor this is more than offset by a substantial reduction in cooling water requirement and raw water input.

Air stripping of the wastewater streams from the gasification process gas clean-up can remove up to 99% of the toxic cyanide compounds and substantially reduce ammoniacal nitrogen in the effluent discharged.

Effluent discharged from the process therefore does not require any further pre-treatment before discharge.

Thermal decomposition under low oxygen combustion conditions results in a low conversion of fuel bound nitrogen to nitrogen oxides.

Application of non-selective catalytic reduction techniques can further reduce emissions of nitrogen oxides from the low NO_x combustion process.

Treatment of fuel bound nitrogen compounds by stripping and thermal decomposition has a negligible environmental impact compared to conventional chemical pre-treatment methods and is considered BPEO by the partners.

Overall operating costs are substantially lower, compared with conventional chemical pre-treatment options.

The strategy developed is regionally specific for the North East of England, however, any strategy must meet the principles of safety, security, flexibility, and economy that NWL have kept in mind throughout the development of their strategy. NWL believe that the strategy adopted is the right one for the region it serves. It meets all the Government's requirements for a sustainable waste management policy and represents the Best Practicable Environmental Option to meet the challenge presented by the UWWTD.

NWL are demonstrating that there are multiple benefits to derived from drying and gasifying sewage sludge and that these benefits are being realised at their RSTC and ETW situated at Bran Sands on Teesside.

Gasification of sewage sludge is likely to become more widely accepted with significant benefits for the water industry as the technologies are developed over the next few years. Indeed, the significance and importance of the technology can be seen in the fact that the EU are prepared to support NWL's Gasification Project by offering a THERMIE grant of 1.5 MECUs (approximately £1.2M).

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