

# Thermal hydrolysis, anaerobic digestion and dewatering of sewage sludge as a best first step in sludge strategy: full scale examples in large projects in the UK and strategic study including cost and carbon footprint.

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**Abstract** This paper shows that by using thermal hydrolysis process (THP) as a pre-treatment for anaerobic digestion (AD) it is possible to develop a step wise approach to sludge strategy that is cost effective and flexible. By generating a low volume of non odorous, well dewatered and safe digested cake it is possible to recycle sludge directly to agriculture or dry it for fuel use or incinerate/gasify it. In every case the financial cost, carbon footprint and energy balance is better than carrying out the same final processes on undigested or conventionally digested sludges.

The thermal hydrolysis process was first put into practice in Norway in 1995 and is now in application in 20 projects, around the world, for 12 million population equivalent. In simple terms the process relies on pressure cooking sludge cake at 165C for 30 minutes before feeding the liquefied sludge at about 10% DS to conventional digesters. It has the benefits of giving very and rapid digestion, high bioconversion rates – even for secondary sludge and also leads to extremely good dewatering properties – this has been discussed in a number of papers at IWA conferences over the years and can be studied at the following web page ([www.cambi.com](http://www.cambi.com))

The results of a study carried out by Entec UK Ltd for Thames Water Utilities in 2007/8 are discussed. This study was a thorough review of the range of technologies available for treatment of sludge for London and the surrounding area. As such it is relevant for large population centres embarking on new sludge treatment programmes.

The various process/disposal routes were ranked in league tables in terms of whole life costs, energy consumption and greenhouse (GHG) gas emissions.

Numerous tables are included for the individual process/disposal routes and the league tables.

In general process/disposal routes including AD and THP had the lowest whole life cost, energy consumption and GHG emissions. Entec's study shows that advanced digestion with agricultural use was best option for the areas outside of London. Within Metropolitan London then a focus on extreme volume reduction or thermal destruction following THP and AD was more important. Thames Water Utilities has now published its draft 5 year business plan that includes THP plants for the two major London WWTPs as a way of supplementing its incinerator capacity.

Full scale examples are given for 3 projects (Aberdeen, Scotland; Dublin, Ireland and Manchester, England) that have thermal hydrolysis, digestion and dewatering as a first step for projects varying between 0.5 and 3 million population equivalents.

The example for Aberdeen (0.5 million P.E.) is for THP/AD and dewatering that produces a pasteurised cake at 34% dry solids. The plant also produces 1.5 MW of electricity. The biosolids product as proved popular for local farmers and demand exceeds supply as there is only 20,000 tonnes of final product a year. A mass and energy balance is given for this plant that has been in operation 8 years.

In Dublin (1.7 million P.E.) THP and AD is coupled with thermal drying. Compared to conventional digestion the requirement for drying is half because the high solids destruction and high dewaterability halve the water evaporation requirements. A comparison of dryer evaporative capacity is shown in the paper plus an energy balance. The digestion plant is very compact consisting of 3 digesters at 4250m<sup>3</sup> each and was built in 2000.

The Manchester project, planned for 2009/11 will make use of an existing digestion plant at Daveyhume where there are 8 digesters at 7,500m<sup>3</sup> each. The existing sludge from this plant (1.2 million P.E.) is sent to a nearby incinerator – however the sludge does not dewater well and supplementary fuel is required. United Utilities originally planned to build a new incinerator north of Manchester to incinerate sludge from a number of plants – mainly as raw sludge. However a study by their engineering team showed the best option was to retrofit THP at Daveyhume and expand the treatment capacity to about 3 million P.E. by increasing the solids loading to the digesters. The high solids sludge after dewatering will be close to autothermic increasing the effective sludge capacity of the existing incinerator and any remaining cake will be taken to agriculture. In addition electricity production will increase

from 4 MWs to 10 MWs. The upgrade is in the planning/construction phase.

The study and review of these projects demonstrates the flexibility of projects that in THP and AD in combination as the reduced volume of high quality cake makes decisions in sludge use of destruction easier. Furthermore the high solids loading of these digesters (2 -3 times higher than conventional) makes the THP self financing in many cases compared to new digester construction.

**Keywords:** sludge, dewatering, drying, incineration, thermal hydrolysis, strategy

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## THE ENTEC STUDY

Thames Water Utilities Ltd approached Entec UK Ltd in November 2007 to investigate what sludge treatment process technologies are available now or could be available in the medium and long term. This approach was part of Thames Water Utilities Ltd's initiative to review their sludge strategy in the light of external business pressures and internal strategic direction. Indeed, the sludge related parts of their published Strategic Direction Statement could be summarised as;

- Recycling to Land - Improve product quality and minimise solids through enhanced digestion. Extend and secure sludge recycling capacity.
- Energy Recovery - Promote energy recovery where appropriate. Increase the use of renewable energy generation from sludge digestion and Combined Heat & Power (CHP).
- General – Seek sustainable long term solutions

As such, this approach was broadly in line with most other UK water companies and served to illustrate the general recognition that sludge to land is the preferred (on environmental and economic grounds) route for sludge in most circumstances and that sludge has valuable potential as a source of renewable energy.

Coupled with these published direction statements were Thames Water Utilities Ltd's internal goals and targets which, put numbers against these statements to form actual targets. One of these targets was to reduce the carbon footprint of Thames Water Utilities Ltd's activities by a certain amount by a certain date. This combination of strategic direction and internal targets provided the goals that are the driving force behind the shape of Thames Water Utilities Ltd's revision to its sludge strategy.

In order to ensure these goals were realisable, a review of technologies was required that would provide information on the wider aspects of environmental impact, particularly carbon footprint, not just capex and opex. Entec UK Ltd were able to provide all this information and broke the project down into two phases – an initial review of all relevant process technologies and then a more detailed assessment of the preferred technologies when operating in appropriate process routes. Dividing the project in this way enabled a thorough review of technologies to be completed whilst only concentrating on those that would best fit with Thames Water Utilities Ltd's goals and

aspirations.

This paper has been split along similar lines for clarity and presents the results of this investigation.

## Phase one – TECHNOLOGY review

### Purpose and Scope

In order to provide a thorough review of sludge treatment technologies, the first phase of the study looked at all the known technologies in sufficient detail to allow strategic considerations to be made. This provided; an overview of each technology, a selected list of current reference installations, consideration of operational experiences, capex and opex costs (where available from published or internal sources), an assessment of the maturity of each process and a list of suppliers.

### Procedure

In order to structure such an all encompassing review, the sludge technologies were broken down into groups relating the general purpose of the technology. These groups and the technologies studied are listed below.

- 1) **SLUDGE MINIMISATION**
  - a. Cannibal
  - b. Ozonation –Biolysis
  - c. Enzymatic Conditioning
- 2) **SLUDGE PRE-TREATMENT (+ ANAEROBIC DIGESTION)**
  - a. Acid phase hydrolysis
  - b. Thermal hydrolysis
  - c. Enzymic hydrolysis
  - d. Pre-pasteurisation
  - e. Ultrasound hydrolysis
  - f. Homogenisation (ball mills, mechanical shear, macerators)
  - g. Chemical hydrolysis (acid and/or alkali) pre-conditioning
  - h. High pressure hydrolysis (e.g. MICROSLUDGE)
  - i. Electron beam
  - j. Extended solids retention
  - k. Nutrient recovery
- 3) **SLUDGE DEWATERING**
  - a. Electro-dewatering
  - b. Vacuum dewatering/drying
  - c. Drying beds, filter belt, filter press, centrifuge

- d. Screw press
- 4) **AEROBIC DIGESTION**
  - a. Aerobic
  - b. Autothermic Thermophilic Aerobic Digestion (ATAD)
  - c. Reed beds, Facultative lagoons
- 5) **ANAEROBIC DIGESTION**
  - a. Mesophilic Anaerobic Digestion (MAD)
  - b. MAD in Series (Anaerobic Baffled Reactor)
  - c. Thermophilic (ThAD)
- 6) **DRYING**
  - a. Direct Thermal, Indirect Thermal & Hybrid
  - b. High temperature centrifuges
  - c. Solar drying
- 7) **CHEMICAL STABILISATION**
  - a. Lime only (powdered, or liquid (e.g. Kalic)) added to either liquid or sludge cake
  - b. Lime (or other admixtures) with supplementary heating system (e.g. RDP process) added to sludge cake
- 8) **COMPOSTING**
  - a. Static pile (e.g. agitated bay), windrow, co-composting, invessel composting (e.g. TEG), & vermicomposting
- 9) **THERMAL TREATMENTS**
  - a. Raw and Digested Incineration
  - b. Co-combustion (as dewatered cake or dry pellets)
  - c. Wet Air Oxidation / Super Critical Wet Air Oxidation
  - d. Gasification
  - e. Pyrolysis/Oil from sludge/Carbonisation
  - f. Vitrification

In order to investigate these technologies, a number of sources were used that could be grouped as follows;

**Published Literature** – An extensive literature review was performed to identify new technologies being developed in Europe, and to evaluate their performance and applications. Specifically, the review focused on papers presented at the European Biosolids and Organic Resources Conferences and relevant output from the Dutch Foundation for Applied Water Research (STOWA) into commonly used as well as newly developed technologies/techniques in the field of wastewater.

**“Grey” Literature** – Vendor-supplied

information, Internet research, and consultants’ technical reports.

**US Literature** – recent developments in sludge technologies from the United States were reviewed including Water Environment Federation (WEF) conference proceedings and the Environmental Protection Agency (EPA) Technical Report – ‘Emerging Technologies for Sludge Management’, September 2006 ([www.epa.gov/owm](http://www.epa.gov/owm)).

Finally, a key element of any strategic considerations is the timeframe. In broad terms, the strategic review wanted to consider the situation now, in 10 years’ time and in 25 years’ time. This became translated in the technology review as processes that are commercially proven (i.e. available now), developed (i.e. proven to work, but not widely applied) or embryonic (i.e. proven laboratory scale concepts or developed technologies that cannot yet be applied in the UK), respectively.

## PHASE ONE EVALUATION RESULTS

After gathering the information, the details of the 34 technologies investigated were compared against a list of 18 environmental, commercial and technical criteria that were developed from Thames Water Utilities Ltd’s strategic and business drivers. In conjunction with the project stakeholders, each technology was given an indicative score against each criteria to give the results presented in the table below. This analysis was based on qualitative judgement and operational experience from a team drawn from experts across the Thames Water business and from Entec UK Ltd. Professional judgement was applied in each topic area. Some of the scores have been removed to protect Thames Water Utilities Ltd.

The evaluation scoring has been carried out on a scale of 1 to 5, with 1 being the lowest and 5 the highest. Since the basis for scoring each criteria may be different, a symbol legend was also used (not shown in this table) to show the degree of acceptability or preference. So for example under Operating Complexity, this would range from very complex (requiring skilled and experienced operators) at one end of the spectrum to very simple and basic at the other. This would give a score of 1 (i.e. very complex and perhaps more difficult to operate), or a medium score of 3 (i.e. average complexity compared to established technologies) or a score of 5 (i.e. very simple and basic to operate).

Although a ranking is provided this is only for comparative purposes as any actual ranking would be dependent on factors that are site specific and may change over time. Nor is any recommendation implied of one technology over another. The benefit of this ranking, though, is to pick out the ‘best in class’ for Thames Water Utilities Ltd’s requirements and to provide an indication of the relative scores of the technologies. For example, under the anaerobic digestion pre-treatment grouping, although thermal hydrolysis and enzymic hydrolysis are

joint best in class, they are only just ahead of acid phase digestion and pre-pasteurisation. The inference here is that any of these four technologies could be appropriate – the choice will depend upon the site specific weighting of the various criteria. Of interest are the generally low scores of thermal processes in the modern energy conscious environment.

It became clear during this study that there was very little published data regarding the carbon impact of these processes. Therefore this became a key consideration of the next phase of the project.

**Table 1: Technology Scores**

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
		Commercially Proven	Operational Complexity	Plant Maintainable	Flexibility	Plant Footprint	BAT	Process Emissions	Final Product quality	Process consumables	Net energy use	Waste Products Minimised	Waste Hierarchy	Ease of promotion	Minimise Customer Impact	Maximise Energy production	Avoid Landfill	Minimise Carbon Footprint	Minimise Environmental Impacts	Totals	Best in Class
Sludge Minimisation	Cannibal	3	3	4	3	3	2	4	2	5	2	3	4	3	4	1	3	2	3	54	1
	Ozonation –Biolysis																			50	
	Enzymatic Treatment																			51	
Sludge Pre-Treatment + AD	Acid phase hydrolysis																			73	
	Thermal hydrolysis	3	2	2	4	4	5	5	5	4	5	5	3	4	4	5	5	5	5	75	1
	Enzymic hydrolysis	2	3	4	4	3	5	5	4	5	5	5	3	4	4	4	5	5	5	75	1
	Pre-pasteurisation																			72	
	Ultrasound hydrolysis																			65	
	Homogenisation																			62	
	Chemical hydrolysis																			61	
	High pressure hydrolysis																			64	
	Electron beam																			63	
	Extended solids retention																			70	
Nutrient recovery																			65		
Sludge Dewatering	Electro-dewatering																			67	
	Vacuum dewatering/drying																			56	
	Drying beds, filter belt/press, centrifuge																			70	
	Screw press	4	4	4	4	4	4	4	4	4	3	5	4	5	4	2	5	3	4	71	1

**Table 1: Technology Scores (cont.)**

Generic Type	Technology	Technology Considerations						Environmental Compliance						Business Drivers						Scoring	
		Commercially Proven	Operational Complexity	Plant Maintainable	Flexibility	Plant Footprint	BAT	Process Emissions	Final Product quality	Process consumables	Net energy use	Waste Products Minimised	Waste Hierarchy	Ease of promotion	Minimise Customer Impact	Maximise Energy production	Avoid Landfill	Minimise Carbon Footprint	Minimise Environmental Impacts	Totals	Best in Class
Aerobic Digestion	Aerobic Autothermic Thermophilic Aerobic Digestion (ATAD) Reed beds, Facultative Lagoons	4	5	5	4	1	4	3	4	5	5	5	3	4	4	3	5	4	4	60	1
																				52	
																				72	
Anaerobic Digestion	Mesophilic Anaerobic Digestion MAD in Series Thermophilic (ThAD)	5	4	4	4	4	4	4	3	5	5	5	3	4	4	4	5	5	4	76	1
																				71	
																				72	
Drying	Direct Thermal, Indirect Thermal & Hybrid High temperature centrifuges Solar drying Direct Microwave Drying	5	2	2	3	3	2	4	5	4	1	4	4	4	4	1	5	1	4	58	1
																				57	
																				48	
																				51	
Chemical Stabilisation	Lime only stabilisation Lime with supplementary heating	5	4	4	4	4	4	3	2	2	2	5	3	1	1	1	5	2	3	51	1
																				55	
Composting	Static pile, windrow, etc & vermiculture	4	4	4	5	1	3	2	4	3	2	4	3	3	3	1	3	2	3	54	1



## PHASE TWO – PROCESS EVALUATION

### Purpose and Scope

The second phase of this work was carried out to provide a greater level of detail for how those technologies reviewed in Phase 1 would be used together to create process routes. As such, it was designed to be used to inform the development of Thames Water Utilities Ltd’s Sludge Strategy.

The benefit of considering these technologies as part of process routes rather than as isolated stand-alone technologies is that the effects of each technology on the upstream and downstream technologies with which it will actually be applied in reality can be taken into account. This will give a much more accurate assessment of each technology’s impact and enable the fairest possible comparisons to be made.

Thames Water Utilities Ltd were among the first water companies to recognise their impact on the environment through their carbon footprint and began including it as part of their sustainability reporting in 1993. The importance and awareness of climate change has increased manifold in the intervening years and it is now part of the UK water companies’ annual reporting requirements to the regulator, OFWAT. It is now generally considered that carbon footprint is a key environmental and economic consideration in capital schemes and hence the periodic review determinations. It was therefore important to Thames Water Utilities Ltd that the carbon footprint of each of the process routes was calculated in an auditable and standardised manner that would stand the test of time. To maximise the audibility, the calculations of carbon footprint would need to be as closely aligned as possible to the

national reporting requirements as encapsulated in the UKWIR GHG Reporting Tool. However, this tool is aimed at reporting carbon footprint at company level and is not appropriate for use at process level. Entec UK Ltd had previously created and developed a sludge carbon modelling tool that gives auditable results compared to the UKWIR Tool by dint of using the same principles and emission factors (from DEFRA) in the calculations.

### Procedure

Using the best in class technologies that were found from Phase 1, process routes were then populated to manage sludge from raw sludge storage to final outlet. This was carried out at a workshop of key stakeholders for; the current situation, the situation predicted in 10 years time and possible situation in 25 years time. Each stage in the process route was created (shown in the left-most column in the tables below) to provide the key functions of;

- reducing volume (thickening, dewatering and drying),
- providing a treated product (digestion (and pre-treatment), composting),
- defining an outlet (thermal destruction or agriculture).

Other variants on these key functions were discussed but were not considered to be likely to be viable in the timeframes being considered (wet air oxidation, for example).

Table 2 shows process routes that are either currently in use in Thames Water Utilities Ltd or are commercially available and could therefore be applied now.

**Table 2: Appropriate Currently Available Process Routes**

	Process Routes					
Process Component						
Thickening	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums	PFT + Drums
Sludge pre-treatment	Multi tank acid phase	THP		THP		THP
Digestion	MAD	MAD		MAD		MAD
Dewatering	Belt	Belt	Belt	Belt	Belt	Belt
Drying			Direct or Indirect	Direct or Indirect		
Thermal Destruction					Incineration	Incineration
Disposal Route	Land	Land	Land	Land	Landfill	Landfill

In addition to the process routes outlined in Table 2 above, two further process routes were identified at the workshop. These routes, shown in Table 3 below, may become available or more appropriate to the

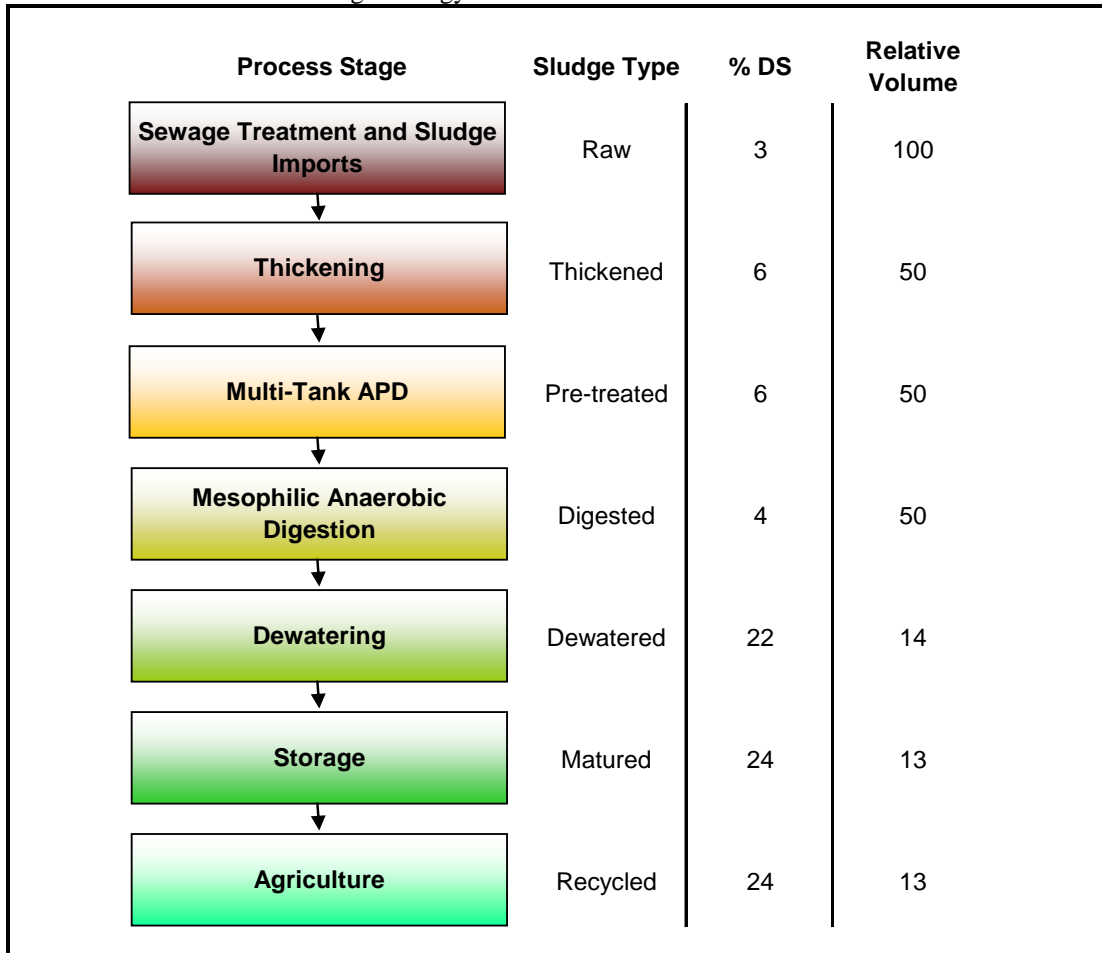
needs of Thames Water Utilities Ltd at some point in the future and would be applied in the sludge strategy in addition to the routes in Table 2.

**Table 3: Appropriate Possible Future Additional Process Routes**

	Process Routes	
Process Component		
Thickening	PFT + Drums	PFT + Drums
Sludge pretreatment	THP	
Digestion	MAD	
Dewatering	Belt+	Belt+
Drying	Direct or Indirect	Direct or Indirect
Thermal Destruction	Incineration	Gasification
Disposal Route	Landfill	Landfill

Of note is the fact that none of the sludge minimisation technologies (i.e. processes that reduce the production of sludge as opposed to its mass or volume) were included in the process routes. They were considered to be too unlikely to become commercially proven in the 25 year timeframe of the Thames Water Utilities Ltd sludge strategy.

The study then considered each of these process routes by first defining the process boundaries and purpose of the routes (to facilitate and legitimise the later comparisons). An example of a process route boundary diagram is shown below. This shows the boundaries of what was included in the considerations pertaining to this route, together with some process information.



**Figure 1: Acid Phase Digestion to Agriculture Process Route**

The environmental impacts were considered in terms of the quantifiable impacts of; carbon footprint (see below), product outlets (traffic, odour and nutrients) and site footprint (area required for the process and product storage). The qualitative impacts

were considered as part of a ‘Pros and Cons’ assessment.

The financial assessment used up to date cost curves from Entec UK Ltd and Thames Water Utilities Ltd. Clearly the use of cost curves will not give actual

costs, but does provide a reliable and quantifiable base for comparing prices as well as a reasonable indication of cost for budgeting purposes.

### Energy and Carbon Calculations

The process route was set up for a standardised 10,000tDSpa plant using Entec’s sludge carbon modelling tool. This tool was created in conjunction with a major UK water company and has been thoroughly tested and validated (where possible) against known results. The data used here was adapted to UK water industry standards in order to protect client confidentiality. The model considers all the inputs (mass and energy) and outputs (mass, emissions, offsets) for each technology in combination with its upstream and downstream technologies or outlets.

The energy balance uses first principles to derive the energy consumed and produced from each stage of the process route. These have been normalised to kWh/year to allow comparisons to be made. The energy productions are net of parasitic heat loads.

The carbon footprint calculations use the same published (primarily collated and endorsed by DEFRA) emission factors as the 2006 UKWIR GHG Workbook, but Entec have applied them more appropriately than the approach born of reporting expediency used in the UKWIR Workbook. In Entec’s view (supported by the Carbon Trust) this gives a more accurate picture of the true impact of these operations and therefore allows a realistic comparison of the processes to be carried out. The Entec model is able to calculate the carbon footprint for processes in common use that cannot be calculated by the UKWIR Workbook because the Entec model includes sufficient detail. It is simply not possible to use the UKWIR Workbook to provide the information delivered in this study.

The specific electricity emission factor used in this study was 0.43kgCO<sub>2</sub>e/kWh, as required by DEFRA for strategic planning studies such as this.

The carbon results were calculated and presented as;

- Direct emissions – i.e. those from sources that are owned or controlled by the water company (e.g. fuels used on sites, process emissions and transport).
- Indirect emissions – i.e. those arising from a company’s activities but occur from sources that are not owned or controlled by the company (e.g. electricity, agricultural activities related to sludge spreading).
- Societal emissions – i.e. those associated with the manufacture and transport

of consumables used by the water industry (e.g. polyelectrolyte production). These are also known as supply chain emissions.

Embedded carbon (i.e. those associated with the manufacture and distribution of materials, especially those for materials of construction, such as concrete and steel, rather than for consumables) is not included as it was not fully developed at that time.

The direct emissions from the transport of sludge are from the diesel fuel used, but also include a factor for the methane liberated during the loading operation. This is based on the presumption of vacuum loading pumps and old sludge, which may not be appropriate to all operations.

The carbon footprint of the digestion pre-treatment plant is included in the digestion plant’s figure as the one is basically part of the other. The direct emissions from the digestion plant are those associated with fugitive emissions and incomplete combustion of methane. The factors Entec has used took account of the real situation regarding secondary digestion (i.e. not always required and sometimes in covered tanks) and the likelihood of leakage and therefore are less than those expressed in the 2006 UKWIR GHG Workbook, but were similar to the latest (Summer 2008) version of the Workbook.

The indirect emissions from digestion arise because of the displacement of electricity production and therefore appear in the results as a negative. Similarly the indirect emissions from the disposal route are caused by the displacement of the need to use chemical fertilisers in the sludge to land route.

## RESULTS

### Quantitative Results

The detailed results from each of the process route sections have been summarised and gathered together in this section to enable the reader to judge the relative merits of each route. The results are presented in descending order of merit to facilitate this judgement.

In considering these tables it is important to keep in mind that the figures presented, whilst based on the best data available, have been calculated from a large number of variables and are therefore subject to considerable variability in their actual values. Taking table 4 as an example, this should be interpreted to say that route 5 is about 4 times more expensive than route 2. In the same vein, route 1 is similar in cost to route 2, and so on.

**Table 4: NPV League Table**

Appropriate Currently Available Route	Appropriate Possible Future Route	NPV (£M)
1. Acid Phase Digestion Cake to Agriculture		22
2. Thermal Hydrolysis Cake to Agriculture		23
4. Enhanced Digested Dried to Agriculture		35

3. Raw Dried to Agriculture		43
	17. Raw Dried Gasification	45
6. Enhanced Digested Cake Incineration		79
	12. Enhanced Digested Dried Incineration	82
5. Raw Cake Incineration		85

**Table 5: Net Energy Consumption League Table**

Appropriate Currently Available Route	Appropriate Possible Future Route	Net Energy Consumption (kWhpa)
2. Thermal Hydrolysis Cake to Agriculture		-20,000,000
4. Enhanced Digested Dried to Agriculture		-18,924,000
	12. Enhanced Digested Dried Incineration	-17,479,000
6. Enhanced Digested Cake Incineration		-16,990,000
1. Acid Phase Digestion Cake to Agriculture		-15,243,000
	17. Raw Dried Gasification	1,703,000
5. Raw Cake Incineration		8,216,000
3. Raw Dried to Agriculture		35,918,000

**Table 6: Total GHG Emissions League Table**

Appropriate Currently Available Route	Appropriate Possible Future Route	Total GHG emissions (tCO <sub>2</sub> epa)
2. Thermal Hydrolysis Cake to Agriculture		730
4. Enhanced Digested Dried to Agriculture		1,010
1. Acid Phase Digestion Cake to Agriculture		1,210
6. Enhanced Digested Cake Incineration		1,230
	12. Enhanced Digested Dried Incineration	1,230
	17. Raw Dried Gasification	1,570

5. Raw Cake Incineration		5,230
3. Raw Dried to Agriculture		9,800

Consistently at or near the top of each league table is process route 2 – Thermal Hydrolysis Cake to Agriculture.

Routes 4 and 1 share second place, with route 1 (Acid Phase Digestion Cake to Agriculture) having better cost results and route 4 (Thermal Hydrolysis Dried to Agriculture) having better energy and carbon footprints.

The lack or minimal quantity of energy production from (respectively) routes 3 (Raw Dried to Agriculture) and 5 (Raw Cake Incineration) are placing these routes at the bottom of the league, with the cost of incineration making route 5 the bottom of the league for costs.

The high cost and relatively poor energy recovery from raw sludge incineration is generally placing those routes that include incineration towards the bottom of the league tables – although it must be noted that this is based on a 10,000tDSpa plant that would be unusually small for an incineration plant. On the other hand, Thermal Hydrolysis can be seen to be particularly beneficial.

Of the thermal destruction process routes, it may be seen that route 6 (Enhanced Digested Cake Incineration) is a good performer as is route 17 (Raw Dried Gasification [Future route]). It is interesting to note that Raw Dried Gasification is, in all cases, better than the current Raw Cake Incineration route, although clearly, gasification is not yet a proven process and this comparison is made using projected performance figures that may be optimistic.

## QUALITATIVE RESULTS

### General

Thickening is a feature that is common to all process routes considered in this study and confers the well understood advantage of reducing the size and hence cost, footprint and environmental impact of all the plant downstream of the thickening stage. The thickening process chosen for energy, carbon and cost analysis is drum thickening. A picket fence thickener (p.f.t) would use considerably less power in itself, but the high solids supernatant normally produced by a p.f.t causes the liquor treatment power consumption to be higher, resulting in only a slightly lower overall power consumption than for the drum thickener. The use of polyelectrolyte gives rise to a small supply chain/societal carbon emission for the drum thickener that does not arise from the p.f.t but this difference may be insignificant if the p.f.t emits more methane than a drum thickener. On balance it is a reasonable assumption that both the drum thickener and the p.f.t have the same carbon footprint.

Instigating routes that produce power at sites where there is inadequate Regional Electricity Company electrical infrastructure will result in high

charges for this infrastructure to be installed. This issue requires the sizing of the CHP plant and hence the quantity of sludge treated by the process route to be carefully considered. This consideration needs to include the relative benefits of changing the sludge importation regime in an operational area – which will consequently have impacts on the recycling costs. This is a complex area of interactions that is best studied using computer modelling.

### *Agricultural Outlet*

Having identified the relative merits of each process route from their position in the league tables it is clear that Thermal Hydrolysis Cake to Agriculture is the process route that most meets Thames Water Utilities Ltd's business needs. However, the limitation of this process to sites where an existing agricultural route is open and the upper capacity limit of around 40,000tDSpa mean that this route may not be suitable for the large works in the major conurbations.

The main reason that Thermal Hydrolysis (THP) appears particularly attractive in this study is because it is able to induce the highest Volatile Solids Destruction (VSD) of all proven advanced digestion processes, thus liberating the most energy from the sludge. Another advantage of THP over other advanced digestion pre-treatment is the improved dewaterability of the digested cake. This enables a lower volume 'soil-like' product to be produced that is attractive to farmers and should assist in keeping the agricultural route open to Thames Water Utilities Ltd. A further advantage of THP is that the process causes more nitrogenous material to be removed from the sludge (at the post digestion dewatering stage) than other processes do. This enables a higher sludge application rate to be attained in areas where the rate is limited by the nitrogen application rate, thus reducing the cost (financial and carbon) of the route. Of course, there is a penalty in the extra energy needed for treatment of these liquors, but in the particular case of Thames Water Utilities Ltd, this is less of an issue than it may be for other companies.

The other advanced digestion technique considered here, multi-tank acid phase digestion (APD) has the advantage over THP of relative simplicity that may be expected to confer a lower whole life cost. However, the most up to date data used in this study (from Thames Water Utilities Ltd, in part) actually shows THP to have a lower capex, opex and hence Net Present Value (NPV) than APD, although the figures are close.

THP also has the advantage that the combination of augmented gas production and dewaterability renders the sludge able to be thermally dried without the need of fossil fuel (and while still maintaining electricity production in a CHP). Hence, if at some point in the future the agricultural route becomes unmanageably restricted, then the dried product could still be recycled, by being sent to outlets as a fuel.

### *Thermal Destruction Outlet - Current*

From this analysis, the large works in the major conurbations may be best served by a thermal destruction process in order to deal with the large quantities of sludge produced. The classic incineration of raw sludge cake as widely practiced in the UK can be seen to give poor results in the context of the parameters analysed. Fundamentally, this is because of the large amount of water in the cake feedstock that is being incinerated. This water has no calorific value and produces a large volume of combustion products to be treated in gas clean-up equipment downstream of the incinerator's combustion chamber. In turn, this results in an occasional requirement for support fuel to be burnt to maintain the incineration and also much larger and therefore more costly plant and equipment. Removing this water will clearly have benefits and all the other thermal destruction routes considered here include for removal of more of this water first.

### *Thermal Destruction Outlet - Future*

The league tables show Enhanced Digested Cake Incineration to have the best energy and GHG figures of the thermal destruction routes. This arises primarily because the digester gas produced by the process can be converted to electricity and heat (both of which may be used on site) and because the improved dewaterability of a thermally hydrolysed digestate reduces the cake's water content. The extra plant required for this route renders it rather more expensive than the next most attractive option - Raw Dried Gasification.

However, Gasification of sewage sludge is not a developed process and has only been considered here as the 25 year option. In developing the gasification process, its costs may increase considerably over the current projected costs used here. In the context of Thames Water Utilities Ltd's business driver to maximise energy recovery from sludge, it may be of interest to know that the combination of thermal hydrolysis, digestion, drying and gasification recovers more energy than any other investigated route. It is therefore suggested that gasification should be investigated as the preferred thermal destruction outlet in the long term and that the incineration of thermally hydrolysed cake should be further investigated as the future preferred route for the large works in the major conurbations.

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## **CONCLUSIONS FROM THE ENTEC STUDY**

1. The first phase of this study investigated thirty four technologies and found that for Thames Water Utilities Ltd's drivers, the highest scoring technologies were those associated with anaerobic digestion.
2. The best-in-class technologies were combined into eight process routes to enable the most appropriate technologies for Thames Water Utilities Ltd to be fairly and comprehensively compared. These routes have been analysed for their advantages and disadvantages along with their impact on the business drivers of cost, energy and carbon footprint.
3. This analysis has required a great deal of data and assumptions to be used as inputs to a fully validated sludge treatment process model. These inputs have been from a variety of sources known to Entec, including; published papers, 'industry standard' figures, Thames Water Utilities Ltd capex figures and recent costings from other Entec clients. It may be concluded that the information is the best available without asking for actual suppliers' quotes, process guarantees, etc. The sheer number of inputs brings with it a certain statistical error that means the numbers quoted from the outputs of the model should only be used to compare one route to another and to give an idea of the likely scale of the actual figures achievable in practice.
4. The most reliable method for calculating the carbon footprint is to start from first principles and work out all the inputs (mass and energy) and outputs (mass, emissions and offsets) for each technology when applied in combination with its upstream and downstream technologies (and outlets).
5. Clearly, for areas outside the major conurbations, advanced digestion in conjunction with dewatering and taking the cake to agriculture offers the most appropriate process route for Thames Water Utilities Ltd. Of the two advanced digestion techniques that have been commercially proven (Thermal Hydrolysis and Acid Phase Digestion), Thermal Hydrolysis offers lower cost, more energy and fewer GHG emissions across the whole process route. Furthermore, Thermal Hydrolysis produces a much superior cake product that should help to maintain the agricultural route (still the Best Practicable Environmental Option in most circumstances) open.
6. The large quantity of sludge produced at the works in major conurbations and the logistical difficulties of moving a sludge product from those works to an un-developed agricultural outlet mean that some form of thermal destruction may be preferred for those sites. The comparatively poor energy balance and high cost of the conventional raw cake incinerator is clear from this analysis when it is compared to the incineration of a sludge containing less water (i.e. after thermal hydrolysis or a thermal drying technology).
7. The benefits of installing a thermal hydrolysis advanced digestion plant prior to a (smaller) conventional incinerator are clearly shown. For the long term, there should be benefits from replacing incineration with gasification once the gasification technology has been developed.
8. By thoroughly assessing sludge technologies along their entire process route from source to final outlet, it is possible to assess the technologies that give the mix of cost, energy

balance and carbon footprint that most suits the business requirements of the water company.

Following this study Thames Water has published its draft business plan for the period 2009-2014. Included in the plan are 5 THP projects. Notably Thames is intending to install THP and AD at both major London WWTPs plants where it currently incinerates raw sludge. The idea is to digest mainly secondary sludge using renovated redundant digesters while continuing to incinerate raw primary sludge. This way both the dewaterability and calorific value of the sludge going to the existing incinerator will be improved.

### THE DUBLIN PROJECT

Dublin's Ringsend WWTP was designed to serve a population of approximately 1.6 million pe with a sludge production of 37,000 dry tonnes per year after upgrading to full secondary treatment. Several technical solutions were put forward as part of a DBFO competition, with the chosen solution being a proposal by Black and Veatch for a combination of SBR technology and anaerobic digestion with Cambi thermal hydrolysis pre-treatment (THP). The THP plant was built by Cambi and handed over to B&V in 2002. The plant is now operated by Celtic Anglian Water. A 2004 performance report has just been

carried out on the mass and energy balance of the plant following 2 years of operation and is detailed in the paper.

Celtic Anglian Water were selected in 2004 for the Sustainable Energy Award out of field of 250 entrants in Ireland. The award recognises a commitment to energy management. Dublin's Ringsend Wastewater Treatment Works was also the winner of the 2004 CIWEM Ken Roberts Award for Technical Innovation in the Water Industry.

Conventional design of anaerobic digestion would have called for about 36,000 m<sup>3</sup> of digestion capacity and at a VS destruction of 50% VS. The Dublin digestion plant has a pre-treatment plant using the Cambi thermal hydrolysis process (THP). The process enables digestion at very high dry solids feed and low hydraulic retention time. The plant was built with 3 digesters of 4,250 m<sup>3</sup> each and is fed with hydrolysed sludge at 11% DS. The net effect is that the plant can produce 3.5m<sup>3</sup>/day per m<sup>3</sup> of digester capacity, which is 350% of the normal situation.

There are 4 no. 1MW Jenbacher engines operating mainly on biogas. Each pair of engines is fitted with a waste heat boiler with a capacity of one tonne steam per hour. These boilers have sufficient capacity to provide 70% of the steam required for the THP, which in turn provides all the heat for the subsequent digestion in the form of hydrolysed feed.

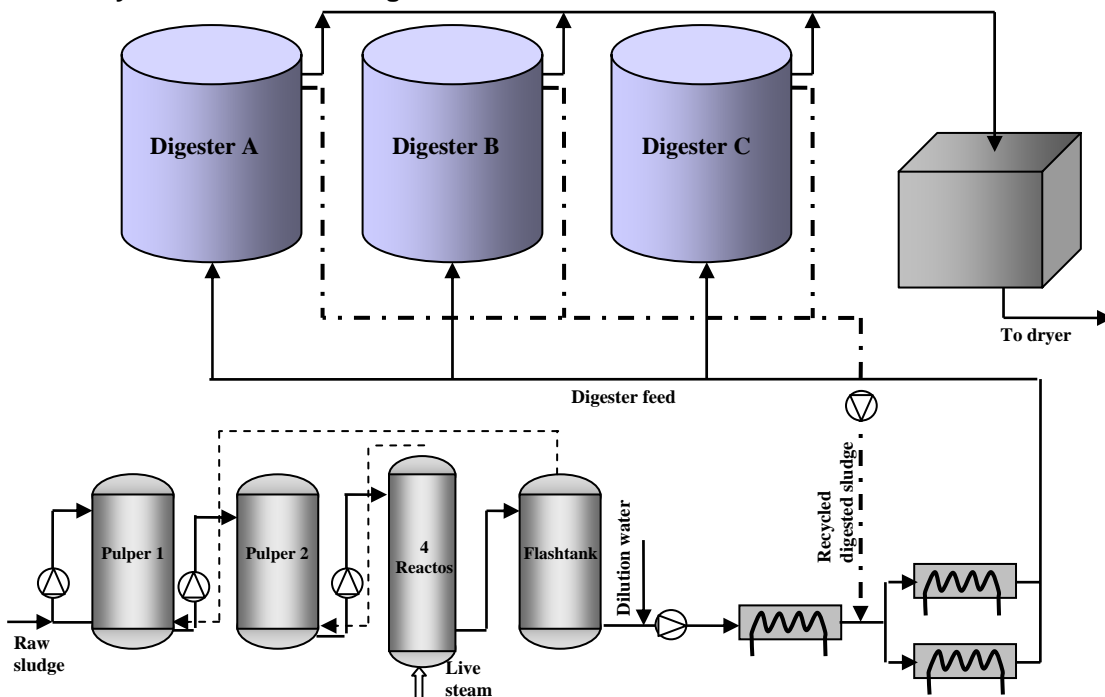
**Table 7 Comparison of digestion performance between conventional and THP**

	Conventional digestion	Cambi THP digestion
DS% feed	5%	12%
Digester volume required	30,500m <sup>3</sup>	12,750 m <sup>3</sup>
VS destruction (15 days HRT)	42%	62%
DS% cake	25%	34%
Tonnes of cake	92,300	54,200
Tonnes Water Evap/hour for drying (MWs energy required)	11.2 t WE	5.7 t WE
Potential MWs generated from Biogas	2.9	4.0

One of the major advantages of this approach was that the plant has two existing 4 tWE thermal dryers for drying raw primary sludge. After the addition of full

secondary treatment and THP and AD the overall water evaporation required did not change despite the doubling of the quantity of raw sludge.

**Figure 2 - Layout of Cambi THP digestion**



The current configuration is capacity to treat about 105 tds of the raw sludge per day. However due to population increase sludge quantities are generally in excess of this and some raw sludge is diverted to the dryers and in addition digested class A digested cake is taken directly to agriculture without drying. So unintentionally the plant has enough capacity to treat up to 150 tds per day by making 2 class A products – Cambi cake and raw dried sludge pellets, i.e. by running the plants in parallel rather than in series.

The success of the Cambi plant and the escalating price of energy have convinced Dublin Corporation to add another line of Cambi THP and add one more digester so that all the sludge can be digested. This work is nearly complete in 2009.

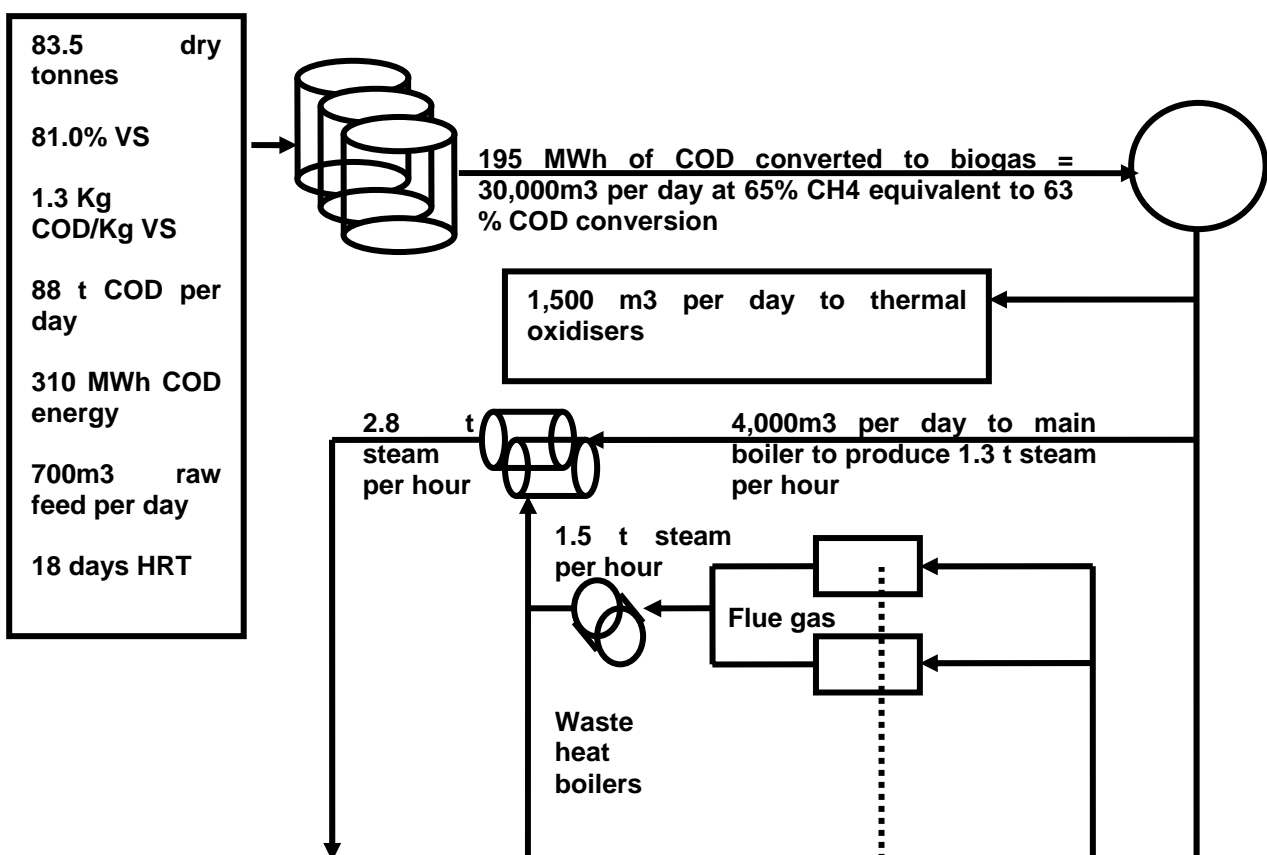
A performance and reliability test was carried out between 20/9/04 and 22/10/04 for the parameters required by the contract guarantees. As a result of the performance test it was noted that biogas production was lower than theoretical. An energy balance was carried out for the month of September 2004 using data from the performance reports and the daily data and is shown in figure 3.

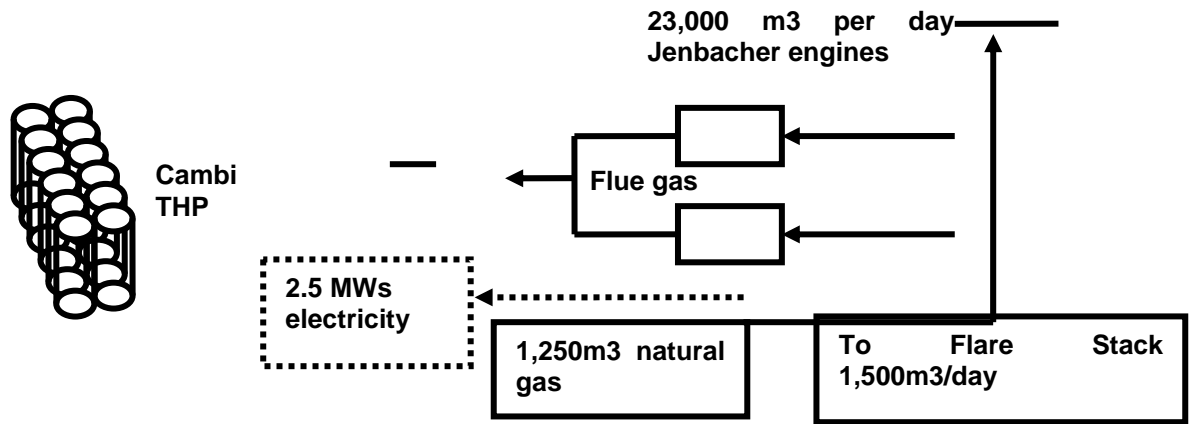
Part of the performance test required CODs to be

carried out on the raw and digested sludge. The Dublin sludge was predicted to have a specific COD of >1.75 Kg COD/Kg VS. In fact the average COD across 10 samples was 1.3 this suggests a high content of carbohydrate and is consistent with the very high fibre content of the sludge. After digestion the average specific COD of the sludge rises to 1.6 which is a typical value of digested biomass. An energy balance using the specific COD of 1.3 fits very well with the measured biogas and power production. It should be noted that the plant is operated with one of the four 1 MW engines on standby for operation of head works pumping station in the event of power failure so that maximum average power production in this mode is just under 3 MWs. This could be achieved with typical COD raw sludge at the VS% conversion demonstrated.

The addition of the extra digester and the third line of Cambi THP will enable greater utilisation of the CHP plant. In addition the replacement of the thermal oxidisers with a gas recompression system will improve the energy balance of the plant.

Figure 3 Approximate daily energy balance based on daily averages from September 2004





**THE ABERDEEN PROJECT**

This section reviews the establishment of a new 50 dry tonne per day biosolids processing facility at a green field site at Nigg Bay, Aberdeen Scotland. Prior to 2001 all sewage had been pumped by long sea outfall into the North Sea. Consequently there was only a minor biosolids operation in the area dealing only with small, rural works. Proposals were sought from a number of consortia for a design, build, finance, operate (DBFO) contract in 1998 by North of Scotland Water Authority (NoSWA) for the Grampian region, which includes new coastal plants at Aberdeen, Peterhead and Fraserburgh as well as many existing smaller plants inland.

NoSWA’s consultant had recommended either thermal drying or incineration for the conforming bid, as there was uncertainty about the agricultural route. A consortium, Aberdeen Environmental Services (AES) including Yorkshire Water, its subsidiary - Grampian Wastewater Services Ltd (GWSL) as operator and EarthTech Engineering Ltd. as designer proposed the CAMBI digestion alternative. The consortium bid was the successful proposal due to a clear financial advantage on capital and operating costs. The inclusion of CAMBI Thermal Hydrolysis was a major contributor to the success of the project.

The advantages of CAMBI for the Aberdeen Project were:

- \* Absolute guarantee of Class A
- \* No dryer was required allowing automatic operations, using a single shift
- \* Digester sizing was 50% of normal.
- \* Ability to receive and treat a variety of imported sludge
- \* Net energy production of 1.5 MW electricity

- \* Simple product to stack and store
- \* Good grassland product
- \* Low volume of product (<30,000 tons per year)
- \* By far the lowest whole life cost

Crucial to the success of the concession was NoSWA’s insistence on the need for a Class A product and the inclusion in the specification of 6 known pathogens that had to be eliminated. Scotland had previously suffered a major E Coli 0157 outbreak with several deaths and this had led to an extreme sensitivity to pathogens. Also, the operator would have to establish a biosolids programme in a region with little history of biosolids use and with a difficult climate. Winters in North of Scotland are long, dark and can be wet or snowy.

GWSL carried out an assessment of data for February and March for the final phase of the EarthTech commissioning which is reported here in Table 8.

The concession bid was based on producing about 30,000 tonnes of cake per year. However, at this stage imports are lower than predicted and there appears to be some drying occurring in the storage shed. The open porous nature of the sludge results in some product curing. Long term stored CAMBI cake develops a growth of mycelia and develops a soil like structure. The cake exits the belt press at about 32-24% DS but actual tonnes removed are lower than predicted because of further VS loss.

Overall input to the system is 18% below forecast and production of CAMBI cake product is 36% below forecast.

**Table 8 . Annual Mass Balance and Average Data Based on February/March 2001**

Indigenous raw dry tonnes	7552
Imported raw dry tonnes	5402
Total raw dry tonnes	12954
Digested dry tonnes	7350
HRT - days	17.5
VS loading- kg VS/m3/day	3.37
VS destruction %	57.5%

VFAs mg/l	432
Ammonia mg/l	2147
pH	7.67
DS% Feed* adjusted for VFA	9.2%
DS% digested sludge	5.12%
DS% of digested cake	32%
DS% of cake* adjusted for drying in shed	38%
Tonnes of cake	19160
Energy Value of Biogas - MWh	31765

**Table 9 . Annual Mass Balance and Average Data Based on April-September 2002**

Indigenous raw dry tonnes	7069
Imported raw dry tonnes	5145
Total raw dry tonnes	12214
Digested dry tonnes	6891
HRT - days	23.5
VS loading- kg VS/m <sup>3</sup> /day	3.29
VS destruction %	56%
pH of digester	7.95
DS% Feed* adjusted for VFA	9.85%
DS% digested sludge	5.55%
DS% of digested cake	32%
DS% of cake* adjusted for drying in shed	36%
Tonnes of cake	18845
Energy Value of Biogas - MWh	30485

showed the product free of the pathogens of concern to NoSWA, even on extended storage.

## Operational Experience and Data

### Data

The plant has been operated directly by GWSL since April 2002. The data shown in Table 9 is based on the average of April to September data. The annual predictions are similar to those given by the February/March data. Dry solids feed has increased to over 9.5% thus raising HRT to 23.5 days. Effective digester volume has been tested using Lithium tracer and is above 95%. Again, there appears to be a loss of solids in the short time in storage. This is confirmed by the ash balance, VS% falls from 61.7% on digester exit to 57.5% on export, tonnes of ash remain constant.

### Establishing the CAMBI Cake Product

The quality of the cake and the service provided to the farmers would be paramount to the success of the whole concession. GWSL showed NoSWA a number of CAMBI installations including the longest established operation in Hamar Norway. Cake has been used here for 7 years and an agricultural programme is well established. Microbiological tests

In the spring of 2001 farmers were invited to witness spreading trials and at the same time a growing trial for spring barley was established. Spring barley is used by the local malsters in the production of Whiskey. It is the predominant crop along with seed potatoes and rotational grassland. The Grampian area has a very short but intense growing season due to very long daylight hours in the summer.

CAMBI cake from Norway was spread at 20 tonne/ha. It was ploughed down in February and sown in March. Grain yield was 7.5 tonne/ha at 85% dry matter. The trial showed that CAMBI cake supplied the entire phosphate requirement of the crop and 40 kg/ha of Nitrogen. The application also supplied 30 kg/ha sulphur and 1.5 kg/ha of copper. CAMBI cake from Norway gave the highest yield response of any of the products tested by SAC, which include lime products and thermally dried products.

The trial results are shown in Figure 4. and the product analysis in Table 9.

Figure 4.

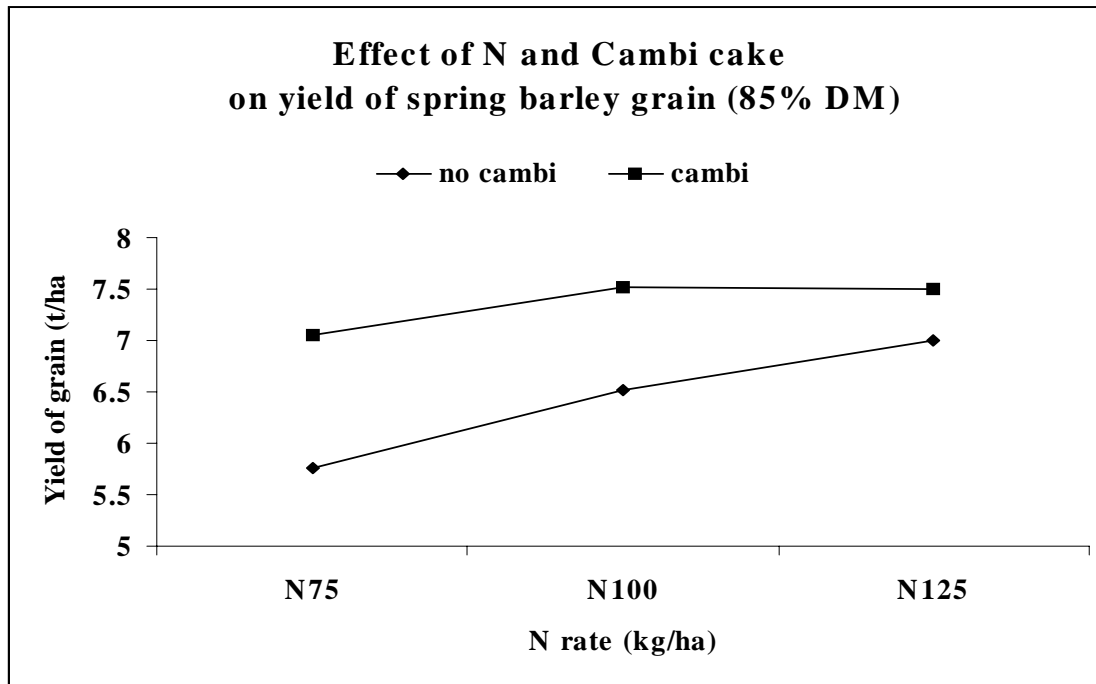


Table 9. Average CAMBI Cake Analysis April –September 2002

Dry Solids	31.7%
Volatile Solids	57.5%
Total Nitrogen	3.82%
Free and Saline Ammonia	0.43%
Total Phosphate as P	3.33%
Potassium	0.21%
Sulphur	1.45%
Copper	325 mg/kg DS
Nickel	45.1 mg/kg DS
Zinc	859 mg/kg DS
Cadmium	3.3 mg/kg DS
Lead	162 mg/kg DS
Mercury	1.5 mg/kg DS
Selenium	3.4 mg/kg DS
Fluoride	163 mg/kg DS

Currently around 1600 wet tonnes per month are being recycled to agriculture. Due to its high dry solids which leads to good stacking properties and the fact that it does not absorb rainwater to any degree we have achieved 12 months of exports from site, with some on field storage prior to spreading. This has left the cake product shed on site practically empty all year round.

The product was tested for long-term stability. No pathogen regrowth occurred. In a long-term storage test the nature of the biosolids changed because of fungal curing to form a soil like product much frequented by rabbits (easy to dig into?). This opens up the possibility of getting into the topsoil market as an adjunct to agriculture.

Since 2002 the agricultural programme has become very well established and demand exceeds supply for the product. One notable fact is that there has never been one complaint about odour or nuisance from the farm spreading operation over these years.

processes on undigested or conventionally digested sludges.

## THE MANCHESTER PROJECT

The Manchester project, planned for 2009/11 will make use of an existing digestion plant at Daveyhume where there are 8 digesters at 7,500m<sup>3</sup> each. The existing sludge from this plant (1.2 million P.E.) is sent to a nearby incinerator – however the sludge does not dewater well and supplementary fuel is required. United Utilities originally planned to build a new incinerator north of Manchester to incinerate sludge from a number of other plants in the north west of England – mainly as raw sludge. However a study by their engineering team showed the best option was to retrofit THP at Daveyhume and expand the treatment capacity to about 3 million P.E. by increasing the solids loading to the digesters. The high solids sludge after dewatering will be close to autothermic increasing the effective sludge capacity of the existing incinerator and any remaining cake will be taken to agriculture. In addition electricity production will increase from 4 MWs to 10 MWs. The upgrade is in the planning/construction phase.

At the time of writing the project has not been awarded but will be decided by time of presentation. It will be the subject of a separate paper presented by Dr W Barber.

## FINA CONCLUSION

This paper shows that by using thermal hydrolysis process (THP) as a pre-treatment for anaerobic digestion (AD) it is possible to develop a step wise approach to sludge strategy that is cost effective and flexible. By generating a low volume of non odorous, well dewatered and safe digested cake it is possible to recycle sludge directly to agriculture or dry it for fuel use or incinerate/gasify it. In every case the financial cost, carbon footprint and energy balance is better than carrying out the same final