final report

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1. INTRODUCTION

The Australian Red Meat Industry is seeking alternatives to traditional rendering and landfilling practices for solid waste. Towards this end it was desirable to define the current state-of-the-art in anaerobic digestion technology as disposal option for solid "Non Manure and Paunch" (NMP) waste with high lipid (fat) and protein contents. Anaerobic digestion of wastewaters from abattoirs and food processing industries is well developed but solid waste digestion is a relatively new technology used mainly for disposal of the organic fraction of "Municipal Solid Waste" (MSW) with high cellulose and plant fibre and low lipid and protein contents. Therefore published information on anaerobic digestion of solid NMP waste with high protein and lipid contents is scarce. Many full scale anaerobic digestion plants for solid waste in Europe are currently under construction or have recently been commissioned but not for "pure" NMP waste.

Waste Solutions Ltd was commissioned by the Meat Research Corporation in the MRC **Project M.737: Solid Anaerobic Digestion Technology Review** to define the current state-of-the-art in anaerobic digestion technology for solid "Non Manure and Paunch" (NMP) waste from meat processing industries by

i) obtaining unpublished information through interviews of experts,
ii) conducting a literature survey to describe the relevant process microbiology,
iii) defining current process technology through a:
   - literature survey,
   - patent search and
   - the analysis of pilot scale anaerobic digestion studies of solid NMP waste,
iv) and identifying key issues, research gaps and potential bottlenecks for implementation of anaerobic digestion technology by the red meat industry.

The first progress report of this project covered in detail digestion of solid wastes in Europe with emphasis on solid agricultural wastes, industrial wastes, energy crops and the organic fraction of MSW [1].

The second progress report [2] constituted a survey of the published literature about the Anaerobic Digestion (AD) microbiology for solid wastes with special emphasis on microbial degradation of high protein/ high lipid Non Manure and Paunch (NMP) wastes from the red meat processing industry. Major microbiological journals and the Waste Solutions literature data base were screened for the period 1990 - 1995 +

major key references from the years prior to this period were retrieved, analysed and interpreted.

The third progress report [3] defined the state-of-the-art in AD technology for abattoir wastewaters including critical process parameters and anaerobic digester design criteria for solid NMP waste. Waste handling, composition of liquids and solids from the digesters and issues specifically relating to solid NMP waste digestion were addressed and order of magnitude costs for three different possible NMP waste digestion options were given.

The main outcome of this analysis was that state-of-the-art AD technology could provide for economical NMP waste disposal only in combination with other NMP-byproduct processing steps or as codisposal (codigestion) with other solid organic wastes such as the organic fraction of MSW. Stand-alone and seasonally operated anaerobic NMP solids digesters in small rural abattoirs would face unattractive process economics due to the necessary waste dilution, long residence times and low COD removal rates and efficiencies. While the AD of soluble organic wastes has been developed to a high standard [4 -7] dedicated AD technology for solid high lipid, high protein content wastes is a gap in digestion technology research and development. Therefore in this final report we outline and recommend a list of necessary developments and measures that should be taken to integate dedicated anaerobic NMP solids digestion systems into abattoir operations.

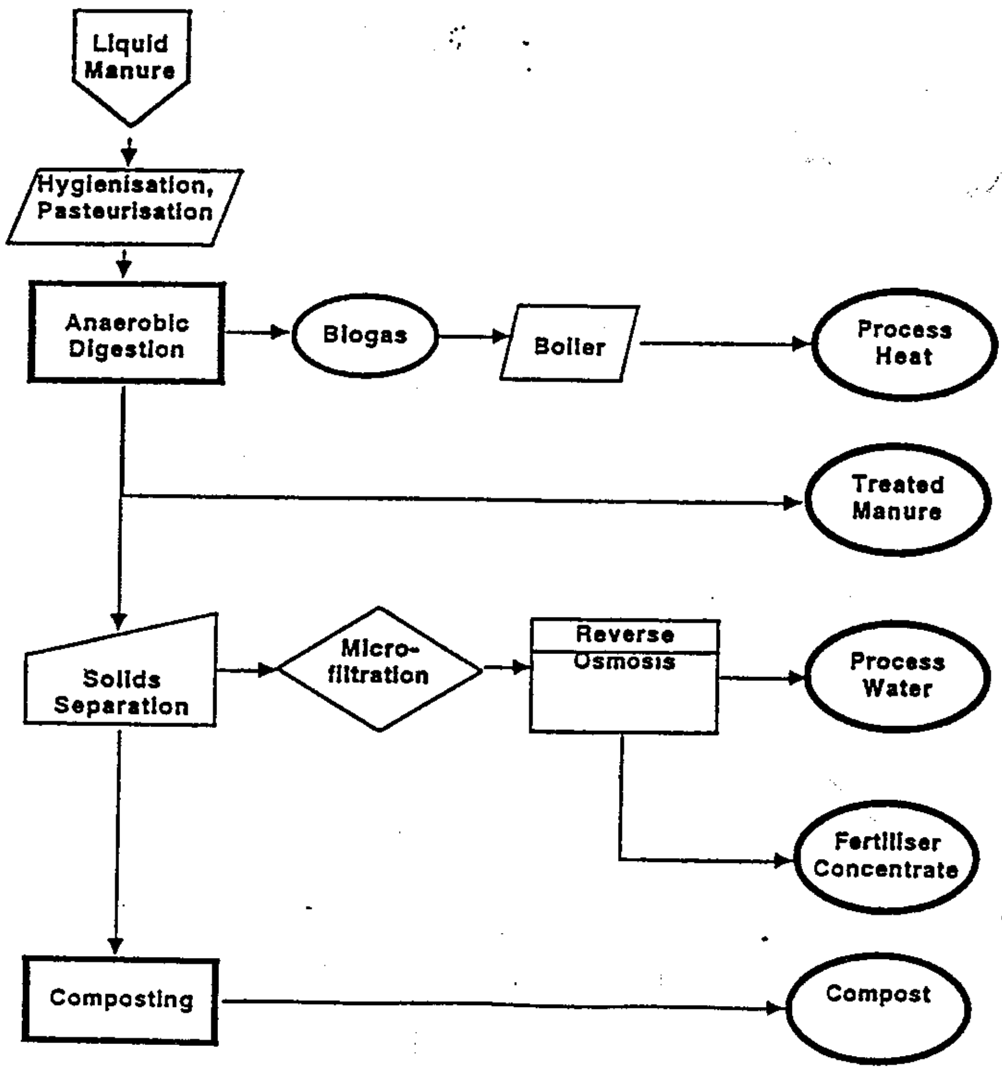
2. SUMMARY OF RESULTS OF M.737

2.1 Survey of State-of-the-art European Technology

To determine the state-of-the-art in practiced solid waste digestion technology, leading respective European experts from academic and industrial research organisation in the field were interviewed and possible applications of existing processes to the digestion of solid NMP waste were explored. Therefore this is the place to thank Professor Peter Weiland, Professor Willy Verstraete, Ass Professor Birgitte Ahring, Dr Ireni Angelidaki and Ing(s) Harry Wiljan and Gerd Mulert for their assistance and the information which they contributed to this project. During the interviews it became apparent that solid NMP waste disposal problems from large scale meat processing industries in Australia and New Zealand were unfamiliar to the European experts. The pertinent legislation in the visited countries (Germany, Belgium, Denmark) prohibits the treatment of pure solid abattoir wastes by anaerobic digestion. However, given the underlying common microbiological principles of anaerobic digestion of all organic matter it might be possible to adapt existing anaerobic digestion technologies for solid MSW to the digestion of solid NMP waste with high lipid and high protein (ammonia-N) contents.

The AD of solid organic wastes with low to medium lipid and ammonia-N contents has reached a high standard and is practised in demonstration plants and several very large full scale AD plants in many European countries. Mainly three different process concepts - single phase, two phase and solid phase AD under mesophilic and/or thermophilic conditions - are tested and implemented in full scale applications [1]. Different suppliers of comparable systems compete for a rapidly growing market for solid waste digestion. More practical experience is required before a final evaluation of the most appropriate and successful process concept can be obtained. None of the implemented solid waste AD systems offered applications for the treatment of high protein and high lipid solid wastes.

Figure 1: Process scheme for a full scale demonstration plant in Surwold (Germany) for liquid manure digestion (5- 6% TS) to fertiliser concentrate, compost, process water and biogas (used for process heat).



The anaerobic digestion (AD) in Germany advanced in the past ten years from simple farm digesters to high rate digestion processes for problematic waste to generate high effluent quality, value added products and measurable environmental benefits at reasonable costs. A conceptual diagram of one example for such advanced manure digestion schemes is given in Figure 1. This development has been favoured by respective stringent legislation and government subsidies with emphasis on recycling and value addition to wastes. The progress in such a short time was aided by fundamental and applied AD research in Germany and worldwide over the past 20 years which provided detailed knowledge of the requirements of the microorganisms and the respective appropriate processing technology. Full scale experience with NMP waste does not exist in Germany. Data from existing laboratory scale work requires still substantial development and corroboration before a pilot or full scale application to NMP waste could be expected. A description of these developments is given in the 1st progress report of this study [1].

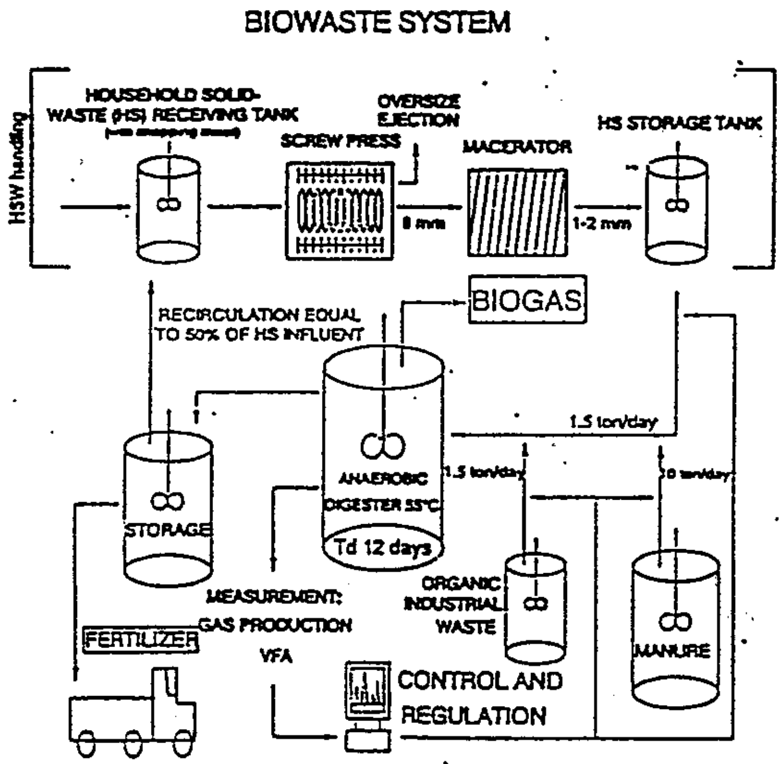
Scientific progress in fundamental understanding of the microbiology of AD as well as biotechnological advances in bioprocess monitoring and control have allowed to introduce a generic Danish biogas technology with successful thermophilic treatment on large scale. This could have impact on the treatment of solid NMP wastes as the sanitation of the effluent is a "free" by-product of thermophilic technology. The Danish program on large scale AD of solid waste has been very successful with respect to reliability, public acceptance, hygiene, renewable energy production and introduction of material cycles and use of digestion residues as organic fertilisers. The main focus in the Danish efforts is the co-digestion of solid industrial organic waste including flotation fats and slaughterhouse waste with liquid manure using simple digesters. A Danish digestion technology development is the thermophilic co-digestion at 50 - 60 °C. An example for a respective codigestion process flow scheme of industrial waste materials and manure is given in Figure 2A. Stringent legislation and government subsidies in Denmark have been crucial in promoting the development of this technology. More than 18 full scale plants with reactor volumes of up to 7000 m^3 have been installed since 1988. The resulting environmental benefits are difficult to quantify in monetary terms but certainly are sufficient reason for the continuation of the subsidised program. It is clear that increased fossil fuel prices and/or a carbon tax will further benefit the economics of these centralised biogas plants. A detailed description is given in the 1st progress report of this study [1].

Figure 2: Flow diagrams of important European solids digestion systems

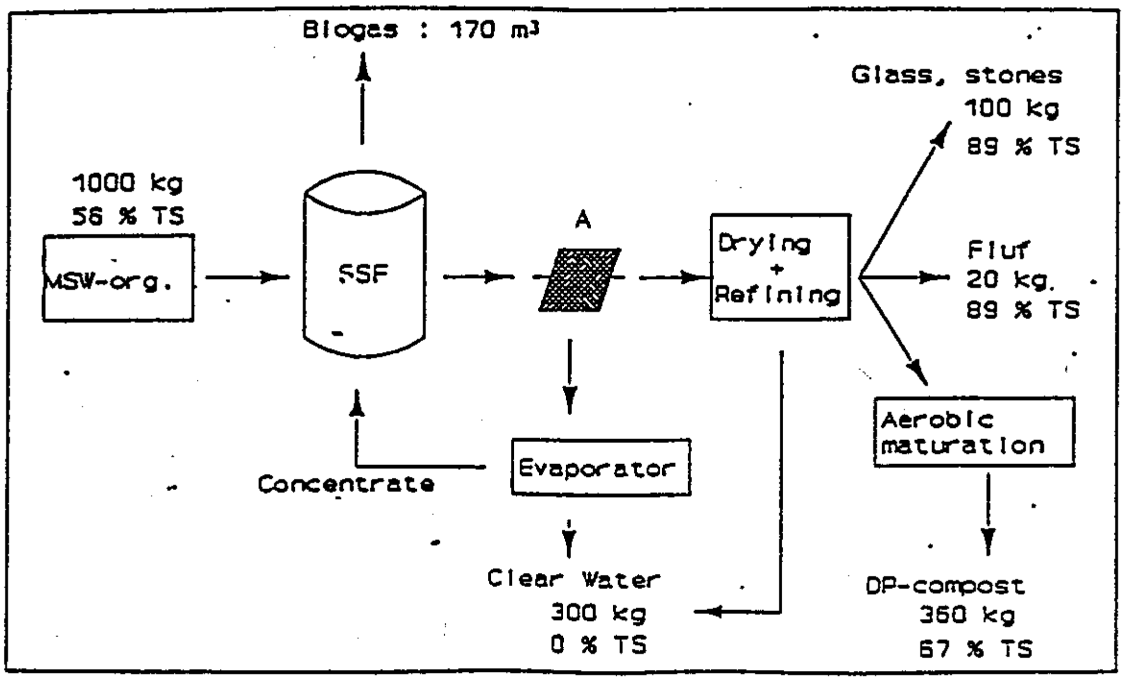
A: Schematic diagram of the large biogas plant at Vegger, Denmark [8]

B: Schematic diagram of the DRANCO process for solid wastes [9] SSF: Solid State Fermentor; A: Solid/liquid separator

A



B



Europe has been in general the "cradle" of solid waste digestion technology facilitated by population pressure, large volumes of MSW, high costs of landfilling and a growing environmental awareness. More than 30 manufacturers offer proprietary technology for the AD of "Biowaste", the organic fraction of MSW [1]. In order to identify patents that might be potentially applicable but are not yet practised for anaerobic digestion of solid NMP waste, a respective patent search was conducted at the European Patent Office. None of the patents retrieved showed direct applicability to the AD of solid NMP waste.

In conclusion, high lipid/high protein solid wastes with high total solids contents such as NMP waste seem not to be a problem in the European context. Anaerobic co-digestion of solid abattoir waste has been developed to a high standard in Denmark using as co-substrates liquid manure and/or source sorted organic household waste with high cellulose, low fat, low protein contents. Development of full scale AD technology for wastes with high total solids, high fat and high protein (ammonia-N) contents falls therefore into a gap of current European R&D efforts.

2.2 State-of-the-art Microbiology Relevant to AD of NMP Waste

In the absence of dissolved oxygen, anaerobic microorganisms will tend to ferment biodegradable matter to carbon dioxide and methane which can be collected and used as a fuel. This process is called "anaerobic digestion". It tends to occur naturally wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen, most commonly in the bottom sediments of lakes and ponds, in swamps, landfill sites and in anaerobic digesters.

The overall process of anaerobic digestion occurs through the simultaneous and combined action of three different groups of anaerobic microorganisms. **Hydrolytic, fermentative bacteria** breakdown complex organic waste such as meat protein, skins, fibre, fats, plant matter, sugars etc. into their component subunits and ferment them to short chain fatty acids (VFA), long chain fatty acids (LCFA), alcohols, hydrogen gas, formic acid and carbon dioxide. **Syntrophic acetogenic bacteria** convert the fatty acids and alcohols to acetic acid, formic acid and hydrogen gas as main substrates for the methane bacteria. **Methane bacteria** produce large quantities of methane and carbon dioxide from the acetic acid (70% of the produced methane) and also combine all available hydrogen gas and formic acid with the carbon dioxide to produce additional methane (30% of the produced methane). Hydrogen sulfide is released as toxic and corrosive by-product most of which reacts with iron and heavy metals to form insoluble sulphides.

The ultimate yield of methane depends on the composition of the organic waste feed stock but its rate of production will depend on the size and type of bacterial populations present, their growth conditions, the solubility of the waste material and the temperature of the fermentation. Microbial growth and natural biogas production are slow at ambient temperatures and are increased in the mesophilic (35-

40 °C) or thermophilic (50-70 °C) temperature range. In general, a temperature increase by 10 °C will increase digestion rates approx. 2-fold. Anaerobic digesters are in principle bioreactors with the purpose to provide optimised process conditions for these bacteria and to maximise methane yield, growth rate and process stability.

Although the biochemical constituents of solid organic wastes and wastewaters are in principle similar, the physical properties of solid wastes differ drastically from wastewaters because of their lower water content, high viscosity and poor pump ability of slurries. This causes poor mixing, poor gas and heat transfer, ineffective pH control and uneven inoculation with seed bacteria (sludge) which are necessary for the biological hydrolysis and liquefaction of the solid waste. Solid waste bioreactors (solid state fermentation) require thus dedicated digestion concepts to solve these problems arising from the physical nature of the waste in order to accommodate the biological requirements of the bacteria. The stable, economic and effective anaerobic treatment of wastewater, on the contrary, is highly developed. The state-of-the-art of high rate AD of soluble organic wastes is described in many reviews [4-7] and will not be further discussed here. It is evident that retention and concentration of active bacteria in anaerobic digesters as films or sludge particles in combination with high levels of dissolved bicarbonate (alkalinity) are main factors that ensure stable, economic and effective anaerobic treatment of wastewater.

In addition to their special physical properties, high solid content organic wastes produce higher concentrations of inhibitory digestion end products such as NH_3/NH_4^+ (ammonia) or inhibitory digestion intermediates such as LCFA (long chain fatty acids). Therefore, the AD of high lipid/high protein content solid wastes is further complicated on a microbiological level by the severe process inhibitions experienced through action of digestion intermediates and end-products.

Therefore the state-of-the-art in microbiological science with special emphasis on the AD of NMP waste was reviewed in the 2nd progress report [2] with focus on

- properties and toxicity sensitivity of the responsible bacterial groups
- properties and relative toxicity of the inhibitory substances formed
- biodegradability under anaerobic digestion conditions of:
  - triglycerides (neutral fat, tallow, oils)
  - long chain fatty acids
  - phospholipids
  - bile acids and steroid lipids
  - wax esters
  - muscle protein
  - connective tissue
  - feathers and hooves
  - cartilage
  - bones
- potential of thermophilic bacteria for the AD of solid NMP waste.

The outcomes of this analysis (Table 1) were that most NMP waste constituents (except bones) appear readily biodegradable and are hydrolysed and fermented by anaerobic bacteria to organic acids, long chain fatty acids and ammonia-N as products. But further conversion of these products to biogas (CH_4 and CO_2) by syntrophic and methanogenic bacteria under mesophilic conditions (30 - 40 °C) is expected to be a major rate limiting step for NMP waste digestion (based on the bacterial properties). Methanogenesis is the main digestion step that removes COD (= Chemical Oxygen Demand) from the waste. Inhibition of these key bacterial groups will thus result in process failures and produce a malodorous and unhygienic pasteous digestion product with high contents of volatile fatty acids, ammonia-N (NH_4^+/NH_3) and residual organic solids. Thermophilic digester operation (50 - 60 °C) is more sensitive to inhibition by LCFA and ammonia-N. However, thermophilic bacteria have their place for rapid NMP waste hydrolysis and sanitation prior to mesophilic digestion of the hydrolysis products [3].

Table 1: Biodegradability of major biochemical constituents of NMP waste and respective bacteriotoxic end-products formed.

NMP Constituent	Biodegradability under Anaerobic Conditions	Bacteriotoxic Products Formed
FAT, OIL	YES (rapid)	YES (LCFA)
LONG CHAIN FATTY ACIDS	YES (slow)	NO
PHOSPHOLIPIDS	YES (rapid)	YES (LCFA)
BILE ACIDS, STEROIDS	YES	YES
WAX ESTERS	YES	YES (LCFA)
MUSCLE PROTEIN	YES (rapid)	YES (NH_3)
CONNECTIVE TISSUE	YES (rapid)	YES (NH_3)
FEATHERS, HOOVES	YES	YES (NH_3)
BONES	PARTLY	?

Especially the formation of ammonia-N from protein degradation and of LCFA from fat hydrolysis is of major concern for NMP digester operation. Low levels (1,000 - 2,000 mg/L) of both compounds inhibit methanogenic bacteria. Solid NMP waste digestion at manageable total solids (TS) contents (10 - 15%) can produce 4,000 - 5,000 mg/L ammonia-N and 7,000 - 24,000 mg/L LCFA [3]. Based on the analysis of the bacterial properties one option is therefore to dilute the NMP-waste with wastewater prior to digestion or to codigest NMP waste with cosubstrates with low fat and low total nitrogen contents in order to avoid digestion process failures.

Alternatively, additional processing steps in the anaerobic digestion treatment such as NH_3 stripping or precipitation of ammonia-N and LCFA as insoluble products might be necessary for toxicity control. This complicates NMP digestion schemes. Several possibilities for LCFA toxicity control are described in the literature. These include precipitation of LCFA as Calcium (Ca)-salts and anaerobic digestion of the Ca-LCFA salts and/or binding of LCFA and ammonia-N to bentonite. As Ca precipitation does not remove toxic ammonia-N and a bentonite precipitation of toxic products would be extremely costly both methods appear to be impractical for full scale NMP waste treatment processes.

A third option for toxicity control is the codigestion with fibrous plant matter waste which has been shown to control LCFA toxicity in rumen contents by adsorption and LCFA immobilisation. This option is very attractive, practical and needs to be further explored as it allows for binding (adsorption) of toxic LCFA and dilution of ammonia -N by the codigested plant matter at the same time. But it depends on the availability of suitable cosubstrates.

An important objective of the project M.737 was the identification of areas where further microbiological/biotechnological research and development (R&D) efforts would be required to be able to fully develop and access the potential of anaerobic treatment for pure NMP waste. The self-inhibition of the bacteria by accumulation of toxic digestion end products is the main bottleneck for high digestion rates and lower waste treatment costs. R&D efforts for NMP AD should address (Table 2):

Table 2: Microbiological areas in need of further research and development.

(i)	protein hydrolysis in the presence of active methanogenic bacteria
(ii)	hydrolysis of fats with concurrent toxic product (LCFA) removal
(iii)	management of ammonia toxicity and high NH_3 concentrations
(iv)	management of LCFA toxicity for gram positive bacteria
(v)	stability/composition of thermophilic fermentative populations

Especially areas (iii), (iv) and (v) are important for acceptability of AD to the industry. Nothing could be more damaging than a failed digester filled with a mixture of volatile fatty acids, organic amines, ammonia and hydrogen sulfide. Thus, despite the great potential of AD for NMP wastes, it is the process control and automation, solids hydrolysis and toxicity management that will probably be the main focus for stable NMP digester operation. Therefore, research themes and underpinning fundamental research in this area should include these items.

Table 3: Biochemical composition of some constituents expected in solid NMP waste

Raw Material	**Mass** (kg/head)	Minerals (Fibre)	**Analysis** Raw Protein	**(% w/w)** Raw Fat	Water
Prime Cattle:					
Heads	10	26	17	11	46
Hooves	8.7	33	18	11	38
Guts/Trimmings (ed. fats removed)	29.0	n/a	38	12	50
Crown fat	10.4	n/a	11	59	30
Kidney fat	9.5	n/a	1	96	3
Caul fat	5.4	n/a	5	80	15
Bones	60-80	11	29	24	36
Paunch (references [12]and [17])	40-80 15 - 25	0.4 - 0.5 (4 - 6)	3 - 5	0.3 - 0.4	84
	Rendering				
Stick liquor	n/a	1	5.6	n/a	91
Fat flotates	4 - 24	0.2	2.9 - 8.0	2.6 - 6.4	85-95
Fat trap	5	(9-20)	8-18	12-30	30 - 65
Lambs:					
Heads	1.1	20	22	10	48
Feet	0.9	40	15	6	39
Guts/Trimmings (incl. crown fats)	4.1	n/a	22	19	59
Bones	approx. 4	11	29	24	36
Sheep:					
Heads	1.5	20	22	10	48
Feet	0.8	40	15	6	39
Guts/Trimmings (incl. crown fats)	6,4	n/a	22	19	59
Bones	approx. 6	11	29	24	36
Paunch (depends on feed composition)	approx. 3	0.4 - 0.5 (4 - 6)	3 - 5	0.3 - 0.4	84
Minced reject carcasses	n/a	5.3	17.2	21.3	51.3
	Rendering				
Stick liquor	n/a	1	5.6	n/a	91
Fat flotates	0.4 - 2.4	0.2	2.9 - 8.0	2.6 - 6.4	85-95
Fat trap	0.5	(9-20)	8-18	12-30	30 - 65

n/a; no data available

2.3 Survey of Abattoir and Solid NMP Waste Digestion Technology

The anaerobic hydrolysis of solid wastes with high lipid contents is technically possible. TS contents between 5% and 8.5% (w/v) can prevent the formation of floating lipid layers. Periodic mixing achieves suspension and rapid hydrolysis of lipid particles if the anaerobic sludge contains fibrous plant particles. This is a second important reason for codigestion of high lipid wastes with cellulosic substrates.

Table 3 gives the main constituents of various components expected in solid NMP waste. It appears that raw protein and raw fat are main constituents in byproducts from beef and sheep/lamb processing. Different simulated mixtures of NMP solid waste from both sources gave a 53 - 56% contribution of fat to the overall chemical oxygen demand (COD) content in NMP solid waste. A "NMP waste" composition of 60% total solids (TS), 40% water and 84% of the TS as volatile solids (VS) was assumed for this project. This was in good agreement with the biochemical analyses of respective composite samples taken during NMP waste digestion trials at Waste Solutions Ltd [10].

Figure 3: Scheme for the anaerobic solids digestion of domestic sewage [11]

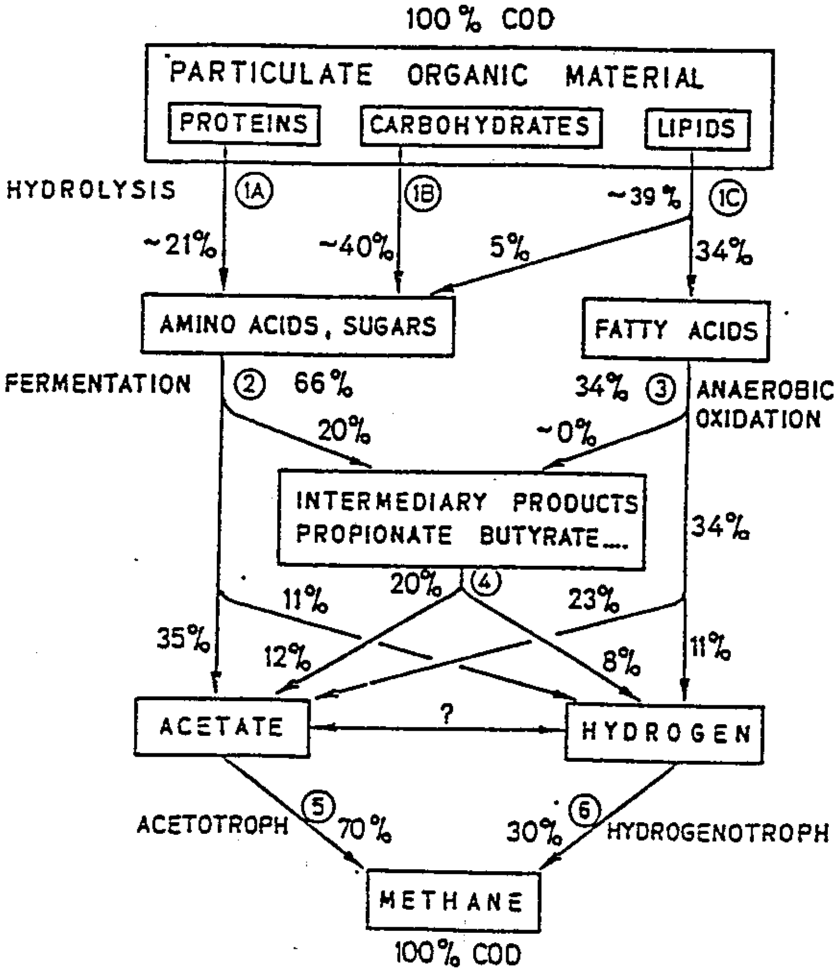
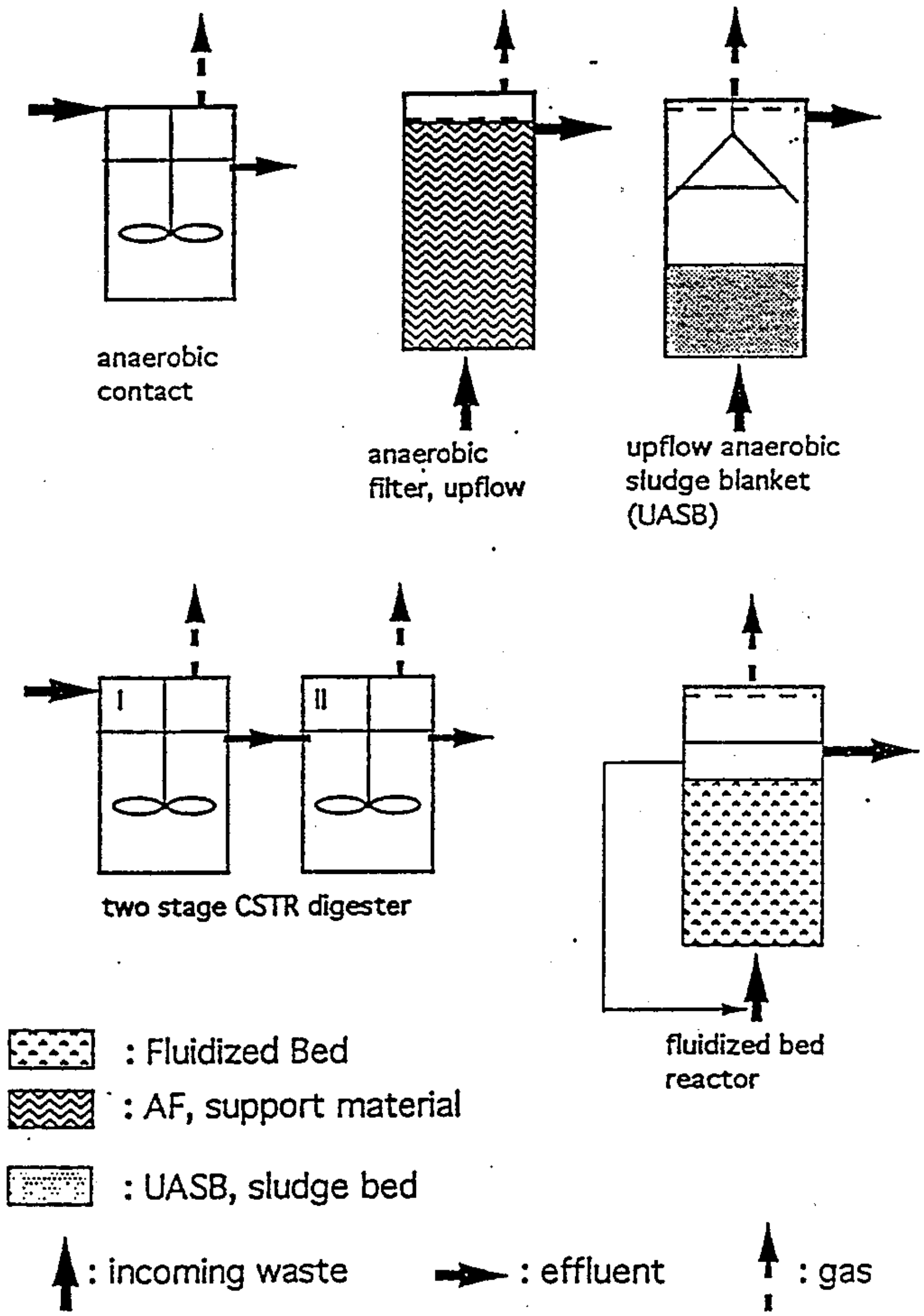


Figure 4: Working principles of different anaerobic digester configurations frequently used for treatment of abattoir wastewater [12].



The composition of NMP waste differs from sewage solids mainly by the lack of significant amounts of carbohydrates and plant fibres. As the anaerobic digestion of sewage solids is well studied [11] a sewage solids digestion scheme (Figure 3) was used as a reference case for a reaction kinetic analysis of stable and well functioning anaerobic digestion of organic solids. Under these conditions hydrolysis and fermentation were digestion rate limiting steps [11] controlling the COD removal rate from the waste and thus the waste treatment costs (see also Figure 6A). Ammonium-N toxicity for methanogenic bacteria was minimal. LCFA potentially accumulating during lipid hydrolysis were bound back onto undegraded plant fibres, paper etc. in the solid waste. Approx. 40% of the waste solids remained unhydrolysed in the digestion residue and functioned as adsorbents for LCFA toxicity control.

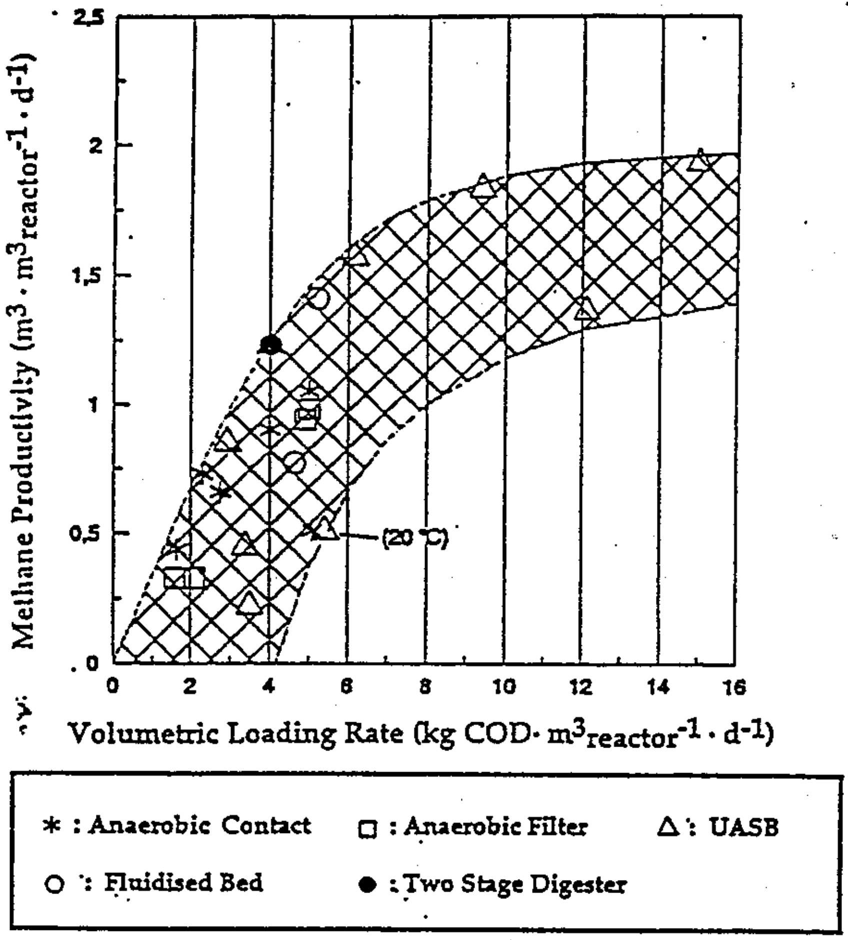
Figure 4 presents AD systems commonly used for AD of abattoir wastewater. Anaerobic contact processes and UASB reactors have been shown to be more robust and effective. Abattoir wastewater was readily treatable with various different anaerobic digester systems [3].

Figure 5 shows the methane productivities as function of the organic loading rate for the combined treatment of abattoir wastewater and paunch at low (2.5 - 3 kg TS m^{-3}; Figure 5 A) and high (70 -120 kg TS m^{-3}; Figure 5 B) total solids contents [12]. This showed that the codigestion of abattoir waste with paunch was not inhibited at high loading rates despite a considerable lipid and protein content (Figure 6B). It demonstrated also that increased TS contents from paunch additions (Figure 5 B) allowed for high organic loading rates and good methane productivities.

An analysis of the COD flow scheme during digestion of sewage solids (Figure 6A) and of abattoir wastewater (Figure 6B) showed that the COD flow in both digestion processes was virtually identical. LCFA toxicity was controlled by LCFA adsorption onto undigested plant fibres from paper in sewage and from paunch in the abattoir waste. This limited the toxicity to methanogenic and syntrophic acetogenic bacteria in abattoir wastewater and allowed for stable AD by effective LCFA, VFA and acetate breakdown to biogas (Figure 6B).

Figure 5: Methane productivity as a function of the organic loading rate for digester systems for treatment of abattoir wastes [12].

A: Abattoir wastewater with low total solids content (2.5 - 3 kg TS m^{-3}), 3- 10 days hydraulic residence times. 35-37°C



Digester operation temperature unless otherwise stated: 35-37°C

Figure 5B: Methane productivity as a function of the organic loading rate for digester systems for treatment of abattoir wastes [12].

Abattoir waste with high total solids content (70 -120 kg TS m^{-3}). 10- 50 days hydraulic residence times. 35-37 °C

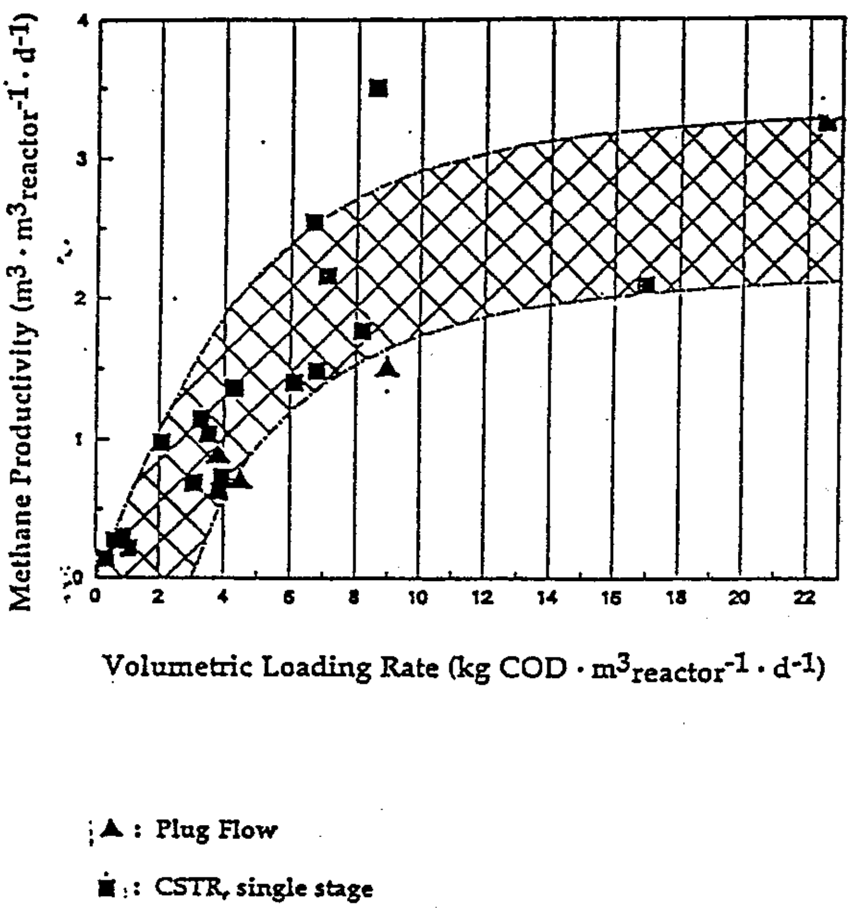


Figure 6: COD flow analysis of anaerobic digestion of sewage or abattoir waste. Rate limiting steps are : **DIGESTION STEP**

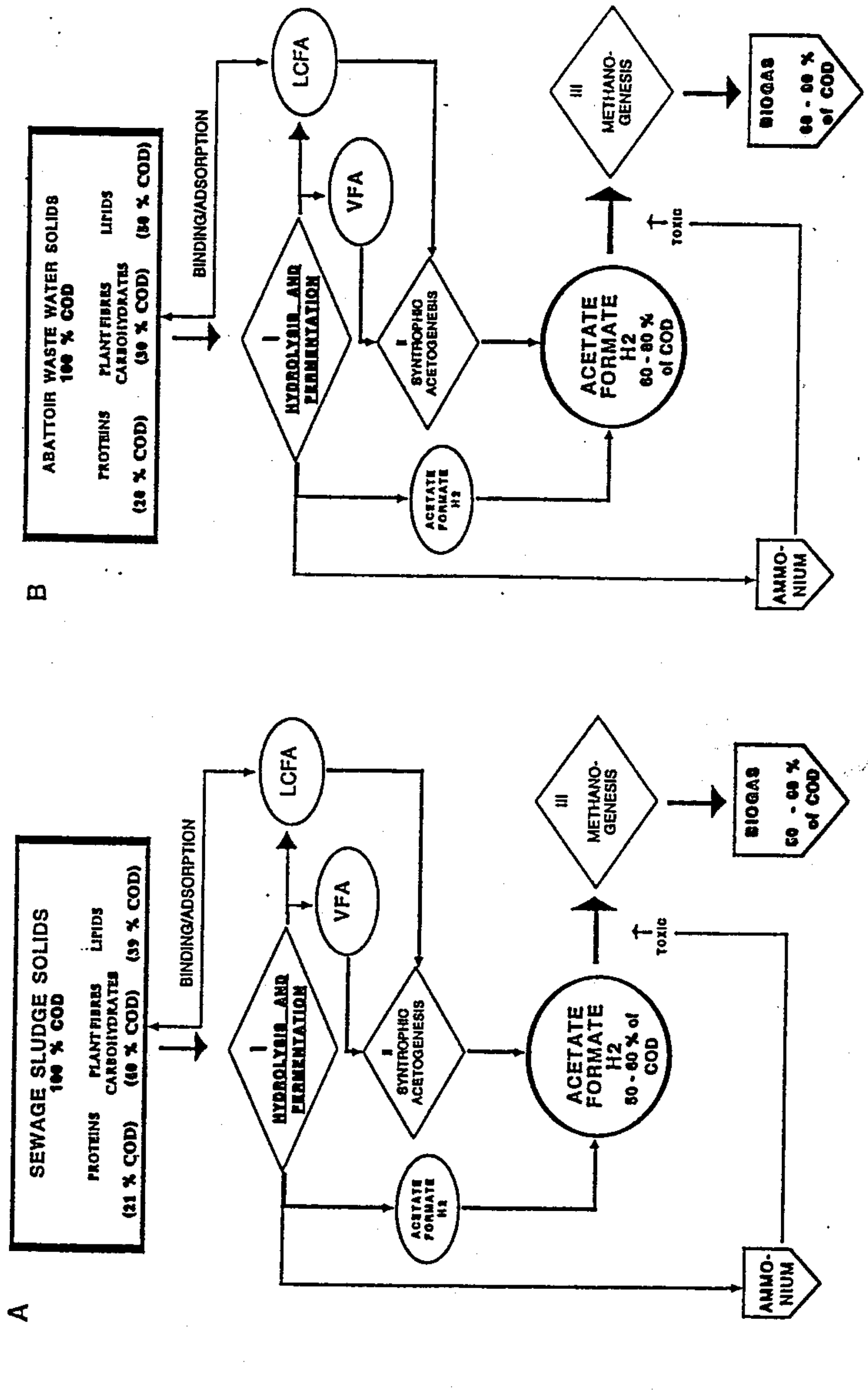
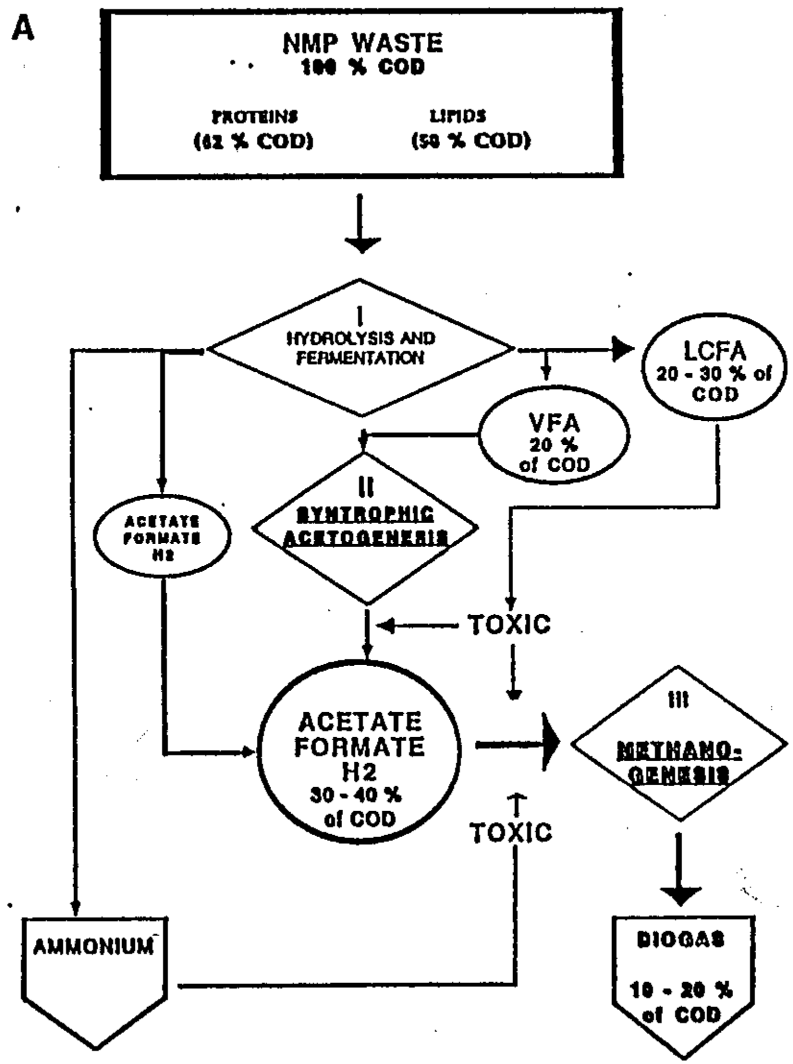
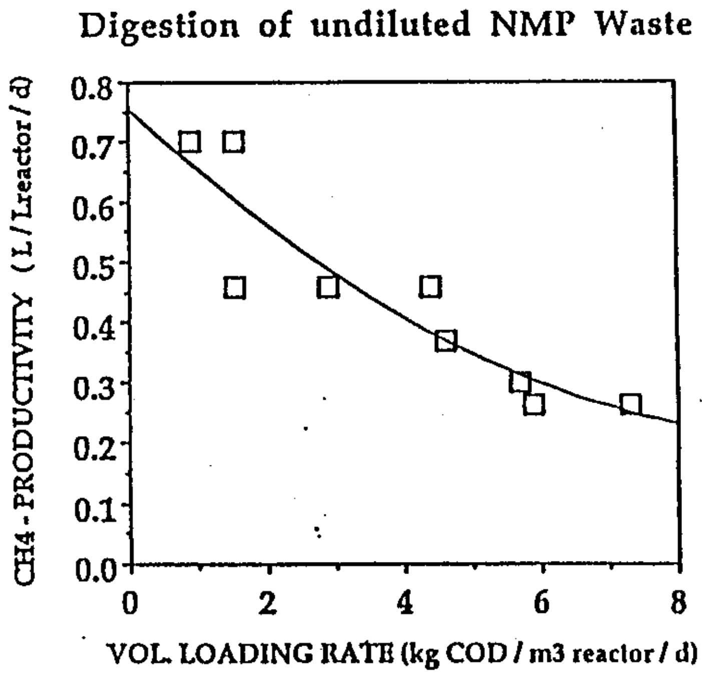


Figure 7: COD flow analysis and methane productivities for "pure" NMP waste at high TS content (10-15 %).
A: COD flow diagram. Note the strong inhibition by LCFA caued by lack of plant material and high protein concentration.
The rate limiting steps are indicated as: DIGESTION STEP

B: Methane productivity as a function of the COD loading rate. Note the low methane productivity indicating the strong process inhibition and increased inhibition with increased organic loading rates. Hydraulic residence times are 25 - 100 days. 35-37°C.

A





The anaerobic digestion of NMP waste in the absence of paunch (Figure 7) appeared strongly inhibited by the ***high concentration*** of proteins and lipids in the waste resulting in LCFA and ammonia-N production. Plant materials (by definition) are absent from the NMP waste (= no paunch, no manure). LCFA toxicity control by adsorption to hydrolysed digestion residues is thus insignificant and LCFA bind to the bacterial sludge inhibiting the bacteria. Fermentation and hydrolysis of the high protein content in concentrated NMP waste (10 - 15% TS) produced final ammonia-N concentrations of 4-5 g/L which were far too high to allow for fast growth and metabolism of methanogenic bacteria [2, 3]. Syntrophic acetogenic (Step II) and methanogenic bacteria (step III) were most sensitive to LCFA and ammonia-N toxification [2] and therefore digestion steps II and III become digestion rate limiting (Figure 7A). This was in contrast to the AD of abattoir wastewater and sewage sludge where the hydrolysis of the solids (step I) was digestion rate limiting (Figure 6). Therefore, without toxicity control NMP waste digestion results in poor methane productivity, poor COD removal efficiency and the accumulation of VFA and LCFA in the effluent due to process toxification. This was also demonstrated by respective pilot scale trials at the laboratories of Waste Solutions Ltd [10] as increased doses of the solid NMP-waste inhibited the methane production and COD removal and led ultimately to washout of the methanogenic bacterial flora and to process failure (Figure 7B).

The results of a reaction kinetic analysis of a range of different experiments are summarised in Table 4. It is clear that VFA and LCFA removal and methanogenic reactions are the slowest reaction steps in the cases of NMP waste digestion showing the longest degradation time constants. Table 5 gives the range of the critical process parameters found in practical digestion of NMP solids digestion trials. Relatively consistent pH ranges, residual total solids (TS) levels at steady state and volumetric loading rates with the respective NMP waste material were obtained. Only the thermophilic digestion of bentonite bound oil allowed for high COD loading rates and short solids residence times.

Table 4: Comparison of degradation time constants for breakdown of important biochemical NMP constituents under mesophilic conditions determined in different continuously operated CSTR digesters[11, 12, 18-21] at "steady state". Literature references are given in parentheses. This analysis is based on the growth rate constant (μ) of the respective bacterial population and the assumption that the respective materials are provided below the apparent substrate constant (K_s) of the respective bacterial group to give first order reaction kinetics[11] (= Monod kinetics; steady state criterion for continuous CSTR digester operation). The time constant is the inverse of the apparent 1st order degradation (growth) rate constant. For 95 % degradation of each material the equivalent of three degradation time constants is required.
n/a: not available.
[NH_3-N]: Concentration of NH_3/NH_4^+-N.
Low: < 1000 mg/L; High: > 4000 mg/L.

Material	Degradation Time Constant (d)			
	Laboratory cultures (Pure Materials)	Sewage sludge Digesters	NMP Waste Codigestion with plant fibres (low [NH3-N])	NMP Waste (adapted to high [NH3 - N])
Fat	6 - 7 (19)	1.7 - 2.5 (11) 5.3 - 8 (11)	approx. 1 (18)	< 8 (27)
LCFA	2 - 10 (11)	approx. 3	4.5 - 7.6 (12) 5 - 6 (64)	> 18 (20)
Protein (collagen/ gelatin)	0.36 (22)	n/a (11)	> 0.42 (26)	approx. 8 (20)
Protein (amino acids)	0.5 - 8 (23, 24) 2.1 (25)	n/a	n/a	n/a
VFA (C3 - C6)	approx.3 (11)	approx. 3 (11)	n/a	> 20 (20)
Acetate, (depends on [NH3-N])	3 - 9 (11)	3 - 7 (11)	n/a	appr. 6 - 18 (28)

Table 5: Process parameters for continuously operated single stage anaerobic digestion of solid NMP waste constituents. The data given are based on results by Tritt[12], Gujer and Zehnder[11] and Waste Sol. Ltd[18-21]. SRT: Solids residence time.
n/a: not available.
*: quasi steady state during fat/ LCFA degradation
a: addition of bentonite to control NH_3-N and LCFA toxicity[29]

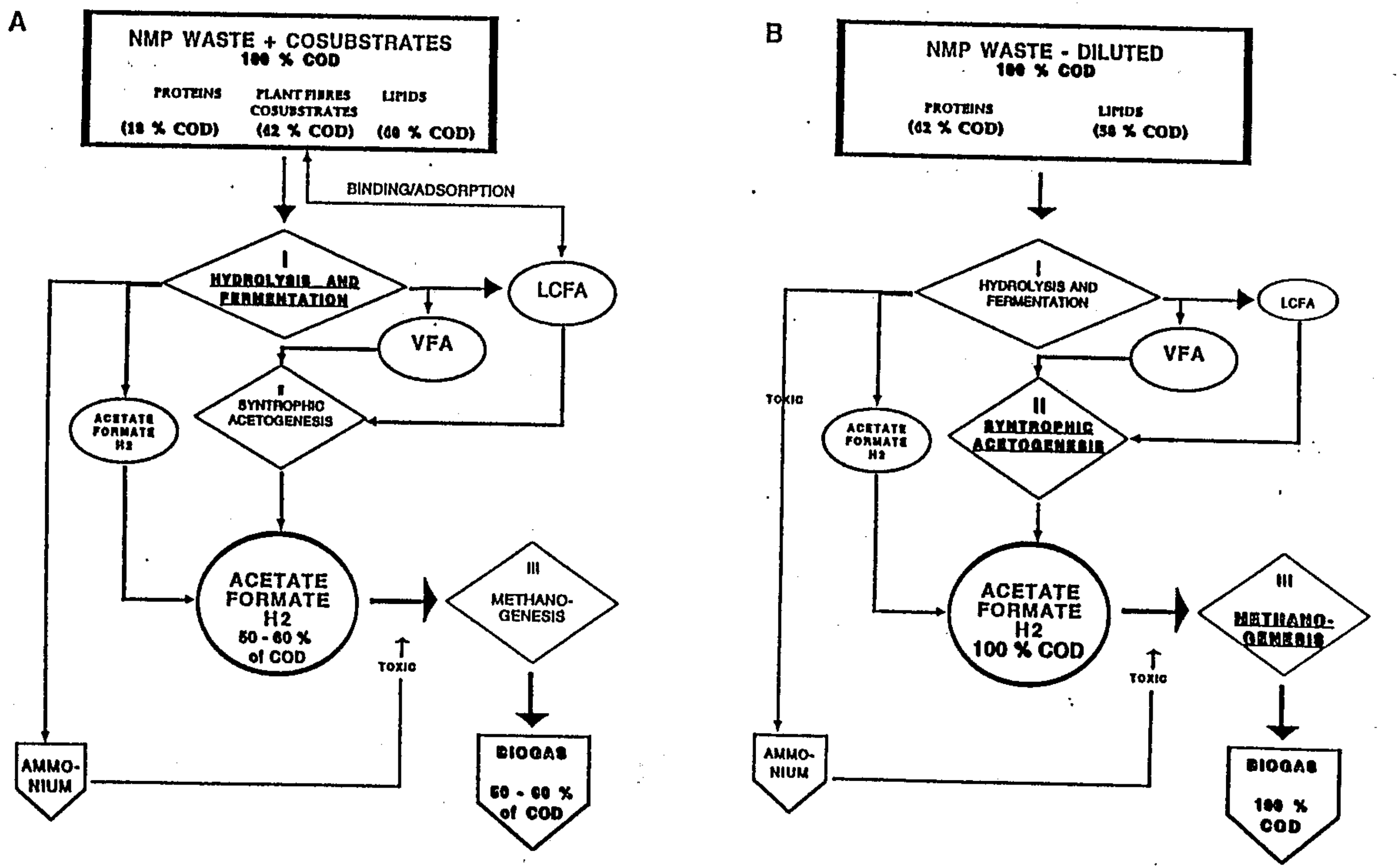
Process Parameters for AD of solid NMP Materials

NMP-Waste Material	T (°C)	NH_3-N (g/L)	pH	$TS_{react.}$ at steady state (kg/m³)	SRT (d)	Spec. NMP COD Load (kg/kg COD sludge)	Volum. NMP Loading Rate (kgwaste COD/ $m^3_{react.}$/d)	Comments
Animal fat + protein (+ LCFA, no bentonite added)	35-37	< 1.0	6.5 -8	30 - 80	> 75 75	0.27	1.8 (12)	Codigested with paunch[12,20] or manure[29] (30 - 50%)
	35-37	> 4.0	7.5 -8	30 - 80	> 79/ 79	0.78	**2.6** (20)	
(Bentonite^a bound oil)	55-56	< 3.0	7.8	60 - 75	> 15/ 15	0.44-0.78	6-10 (29)	
Animal fat + protein (no bentonite)	35	2.0	7.3	28 - 35	15-20	0.45	**2.0**(21)	
Sheep Tallow (batch)	35-37	< 1.4	7.3	24*	> 70	up to 0.54	**0.4 - 1.2**	No codigestion: Fed batch reactor[18]
Connective tissue (no added bentonite)	35	2.0	7.3	28 - 35	15-20	0.65	**1 - 2** (18)	codigestion with paunch and manure
	35	4 - 5	7.5 -8	30 -80	79/ 79	0.53	**0.7** (20)	

In recognition of the underlying microbiological principles for the digestion process inhibition two different practical approaches (variants) can be proposed for LCFA and ammonium-N toxicity management during NMP waste digestion with state-of-the-art AD technology (Figure 8).

The first approach is solid NMP waste supplementation with respective low fat and protein and high plant fibre content cosubstrate wastes . These cosubstrates could be a source sorted organic fraction of MSW (see also Figure 9) or industrial byproducts such as wastes from fruit, grain and pulp and paper processing. NMP waste could be supplemented to final crude biochemical compositions that resemble sewage sludge solids or abattoir wastewater. Good COD removal rates (Figures 8A and 9A) and good process economics are expected in analogy to the Danish codigestion programme of industrial wastes with manure. This could allow to implement AD for NMP waste disposal in the red meat industry. The NMP waste/cosubstrate mixture requires dilution with abattoir wastewater in order to reduce ammonia-N and LCFA below 2000 mg/L. Approx. 26 m^3 abattoir wastewater will be required for dilution of 1 tonne NMP waste (assuming a 60% TS in the NMP waste).

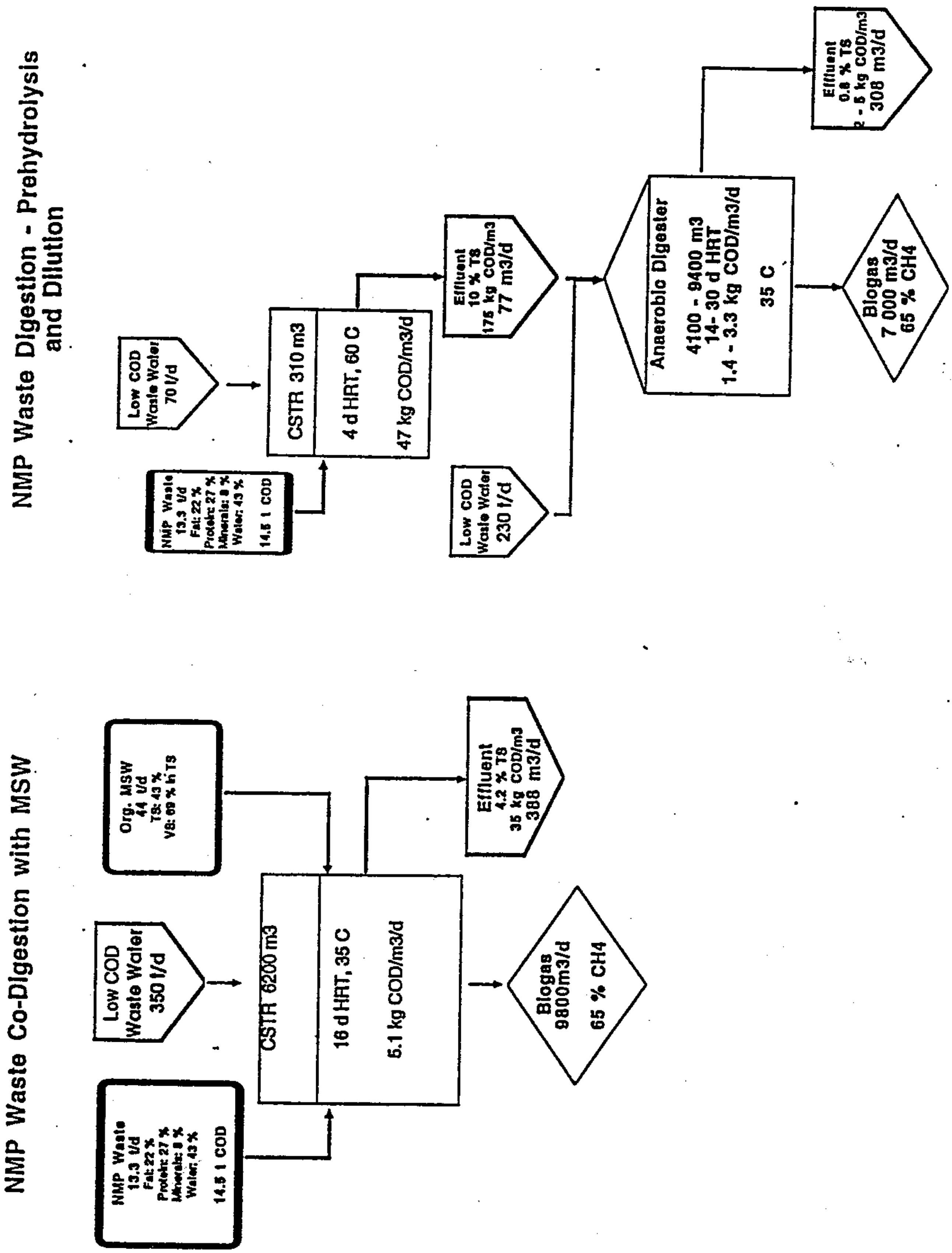
Figure 8: COD flow analysis of NMP waste digestion with various toxicity control measures in place.
The rate limiting step is indicated as: <u>DIGESTION STEP</u>



This variant depends therefore on the local availability of sufficient abattoir wastewater and suitable organic cosubstrates. Cosubstrate availability would depend on respective municipal/communal waste recycling programmes. Technical feasibility of this proposed variant must first be validated in a pilot or demonstration trial before implementation in the red meat industry can be recommended. Digestion residue sanitation prior to use as a soil builder (fertiliser) needs to be addressed. Sanitation could either be achieved by anaerobic thermophilic codigestion of the NMP waste (as in Denmark [13]) or by initial mesophilic codigestion with subsequent Autothermic Thermophilic Aerobic Digestion of digestion residues (ATAD process; [14]) with trapping of volatilized NH_3 and organics. Local marketability of the sanitised residues for re-use as organic fertiliser or compost needs to be addressed should this variant be chosen.

Alternatively, NMP waste dilution with abattoir wastewater (Figures 8B and 9B) to a final COD content of approx. 40-50 kg COD m^{-3} would reduce the LCFA and ammonium concentrations in the hydrolysed and fermented waste to below 2,000 mg/L and thus reduce the inhibition of syntrophic and methanogenic bacteria. Slow anaerobic digestion (80 - 90% COD removal efficiency) at low COD loading rates of approx. 1.5 - 3.5 kg COD $m_{reactor}^{-3}$ day^{-1} is expected. These predictions are at the lower end of the range observed for anaerobic treatment of abattoir wastewater (Figure 5) but might allow for reasonable digestion costs if loading rates of 3.5 kg COD $m_{reactor}^{-3}$ day^{-1} could be sustained on a routine basis. This needs to be validated in a pilot study before implementation of this variant in the red meat industry could be recommended (see below). Approx. 23 m^3 abattoir wastewater will be required for adequate dilution of 1 tonne NMP waste (assuming a 60% TS content of the NMP waste). Sanitation of the digestion residue with low solids but high nutrient contents is unnecessary as the initial thermophilic hydrolysis step (Figure 9B) is expected to destroy pathogenic organisms from the NMP waste. Alternatively, sanitation could also be achieved by anaerobic thermophilic digestion of the diluted NMP waste similar to the digestion of manure in Denmark [13]. However, due to the increased LCFA and ammonium-N sensitivity of syntrophic and methanogenic bacteria under thermophilic conditions we recommend to apply some caution with respect to thermophilic digestion of the diluted NMP waste. Also, the energy efficiency at the thermophilic process would be reduced due to the increased water content of the waste. Due to the dilute nature of the effluent with 0.8% residual TS (Figure 9B) sanitation of the digestion residue by subsequent Autothermic Thermophilic Aerobic Digestion with the ATAD process [14] appears impractical.

Figure 9: Process schemes for anaerobic digestion of NMP waste with various toxicity control measures [3].



A major problem with the "dilution variant" is nutrient (N, P) removal from the effluent because the high nutrient (N, P) content of the NMP waste is conserved during anaerobic digestion. Aerobic polishing with subsequent biological chemical nutrient (N, P) removal will be necessary before environmentally safe effluent discharge to land could be practiced. Aerobic effluent polishing is technically possible as the treated effluent is expected to contain between 2,000 and 3,000 mg/L COD. Alternatively, solid Magnesium-Ammonium-Phosphate (MAP) fertiliser salt with high Nitrogen and Phosphorous contents might be produced from NMP digestion effluents [3]. MAP formation was quantitative when belt press clarified digester effluent was used but required excess MgO. It is an alternative to biological N and P removal . High costs for the precipitation chemicals require further optimisation of this process before implementation for nutrient removal from NMP effluent could be recommended.

The digester technology used for the two NMP digestion variants given in Figure 9 uses simple stirred tank reactors (CSTR) as low cost options. These are very reliable for solids digestion in the specified range of TS contents (Figure 9) and have been tested by Waste Solutions in its solid waste digester at the PPCS meat processing plant in Mosgiel, NZ. The use of CSTR digesters is also consistent with the predominant experience gained with abattoir wastewater digestion [12]. An order of magnitude economic cost/benefit assessment of both NMP waste digestion variants (Figure 9) using CSTR digesters and actual digester construction costs [3] showed that only credits for the anaerobic treatment of cosubstrate wastes (Figure 9A) and/or for avoided electricity costs for alternative aerobic treatment of the NMP waste give the anaerobic digestion of NMP waste in CSTR digesters economic viability. Credits for the produced biogas alone would not be sufficient to make NMP digestion economically attractive. Tax credits (carbon tax) or environmental incentives for nutrient recycling through biological fertiliser production and introduction of material cycles (as in Germany) would be necessary to encourage this renewable energy production from NMP waste treatment. In addition to "tipping fees" for the digestion of organic constituents of MSW this would produce extra income as a subsidy for NMP digester operation.

Such tax incentives are hypothetical. It appears that new developments for the AD of solid NMP waste are necessary to be able to apply cost effective, compact, high rate anerobic digester technology (see below) for NMP waste digestion.

The MRC Environmental Issues Project M.445 [15] presented the wastewater composition and flow from five selected Australian abattoirs. The volume of abattoir wastewater produced per tonne HSCW (HSCW = Hot Standard Carcase Weight) could be classed into two groups whereas the actual wastewater composition from both groups was comparably similar.

Wastewater production in Australian Abattoirs [15]:

Group I:	**High** wastewater flows (11.8 +/- 0.95 m^3/tonne HSCW) and **high** amounts of total N and oil and grease per tonne HSCW.
Group II:	**Lower** wastewater flows (4.35 +/- 0.7 m^3/tonne HSCW) and **lower** amounts of total N and oil and grease per tonne HSCW.

With these data as boundaries and the two proposed NMP digestion variants (Figure 9) as design criteria simulation calculations were carried out to determine the minimum requirements for cosubstrates, dilution water and capital costs for anaerobic CSTR digesters at various levels of NMP waste production. Construction costs for the PPCS solids digester (Mosgiel, NZ ; Waste Solutions Ltd, internal data) were used as a basis . The results (Table 6 and 7) showed that even in abattoirs with very efficient water usage or process water re-use (group II: 4.35 +/- 0.7 m^3/tonne HSCW) the available wastewater would be sufficient for dilution of up to approx. 200 kg NMP waste/tonne HSCW produced. The amount of cosubstrate (source sorted organic fraction of MSW) required for the codigestion variant would equal the organic refuse production of approx. 270,000 population equivalent if applied to abattoirs with a peak production of 100 tonnes HSCW/day. Cosubstrate availability might therefore limit this NMP codigestion scheme in most locations. Size and costs for the digester and the transport of source sorted organic MSW and digested sludge (47,000 tonnes/year at 12% solids) would probably be more suitable for operation by municipalities than by the red meat industry.

Table 6: Minimum requirements for organic cosubstrates (eg. source sorted organic fraction of MSW), abattoir wastewater and resulting digester capital costs for anaerobic digestion of NMP waste using the codigestion variant (Figure 9A).

HSCW: Hot Standard Carcase Weight

	Minimum Requirements for AD			
			Digester Data	
Level of NMP Production (tonnes NMP/ tonne HSCW)	**Cosub-strate Requir-ment** (tonnes/ tonne HSCW)	**Wastewater Require-ment for NMP Dilution** (tonnes/ tonne HSCW)	**Size** for 100 tonnes HSCW/day (m^3)	**Capital Costs** for 100 tonnes HSCW/day **(000$A)**
0.1	**0.33**	**2.6**	**4,500**	**2,300**
0.2	**0.66**	**5.2**	**9,000**	**4,800**
0.3	**1.0**	**7.8**	**13,500**	**7,100**

Similar considerations apply for a hypothetical NMP waste dilution and digestion scheme (Table 7). Industry initiatives for implementation of AD for NMP digestion - although technically feasible - are thus not recommended until these logistic constraints are resolved. Digester construction and operation, waste handling, effluent sanitation and sludge disposal technologies are available on the market. Thus mainly the digestion inhibition on the microbiological level of the process and the large CSTR digesters required prohibit the implementation of AD for NMP waste and result in the costly waste dilution or cosubstrate transport with the consequential increased capital and operation costs. Practical measures to control or avoid the formation of bacteriotoxic NMP digestion products and the inhibition of syntrophic and methanogenic bacteria are therefore essential in order to eliminate NMP waste dilution requirements.

Table 7: Minimum requirements of abattoir wastewater for dilution and resulting digester capital costs for different levels of NMP waste production using the dilution variant (Figure 9B).

HSCW: Hot Standard Carcase Weight

Minimum Requirements for AD			
Level of NMP Production (tonnes NMP/ tonne HSCW)	**Wastewater Requirement for NMP Dilution** (tonnes/ tonne HSCW)	**Digester Data**	
		Size for 100 tonnes HSCW/day **(m^3)**	**Capital Costs** for 100 tonnes HSCW/day **(000$A)**
0.1	**2.3**	**3,200**	**2,100**
0.2	**4.5**	**6,400**	**3,800**
0.3	**6.8**	**9,600**	**5,100**

This shows that for implementation of NMP digestion in the Red Meat Industry more developmental work will be needed before the anaerobic digestion of NMP waste could become standard. An at least two-fold increase of COD removal and growth rates at 2 - 4 g/L ammonium-N must be achieved to reduce requirements for substantial cosubstrate addition or waste dilution. Based on the observed strong inhibition of thermophilic AD of pure NMP waste in standard CSTR reactors it appears questionable whether a thermophilic digestion without toxicity control measures could provide these two fold enhanced COD removal rates.

In conclusion, state-of-the-art solid waste digestion technology allows for effective NMP waste hydrolysis. Effective NMP waste degradation or waste stabilisation can only be expected in combination with other NMP-byproduct processing steps or as codisposal (codigestion) with other solid organic wastes. Stand-alone and seasonally operated anaerobic NMP digesters in small rural abattoirs would face unattractive process economics due to process inhibition, long residence times and low COD removal rates and efficiencies.

3. KEY ISSUES, SCOPE AND LIMITATION OF AD

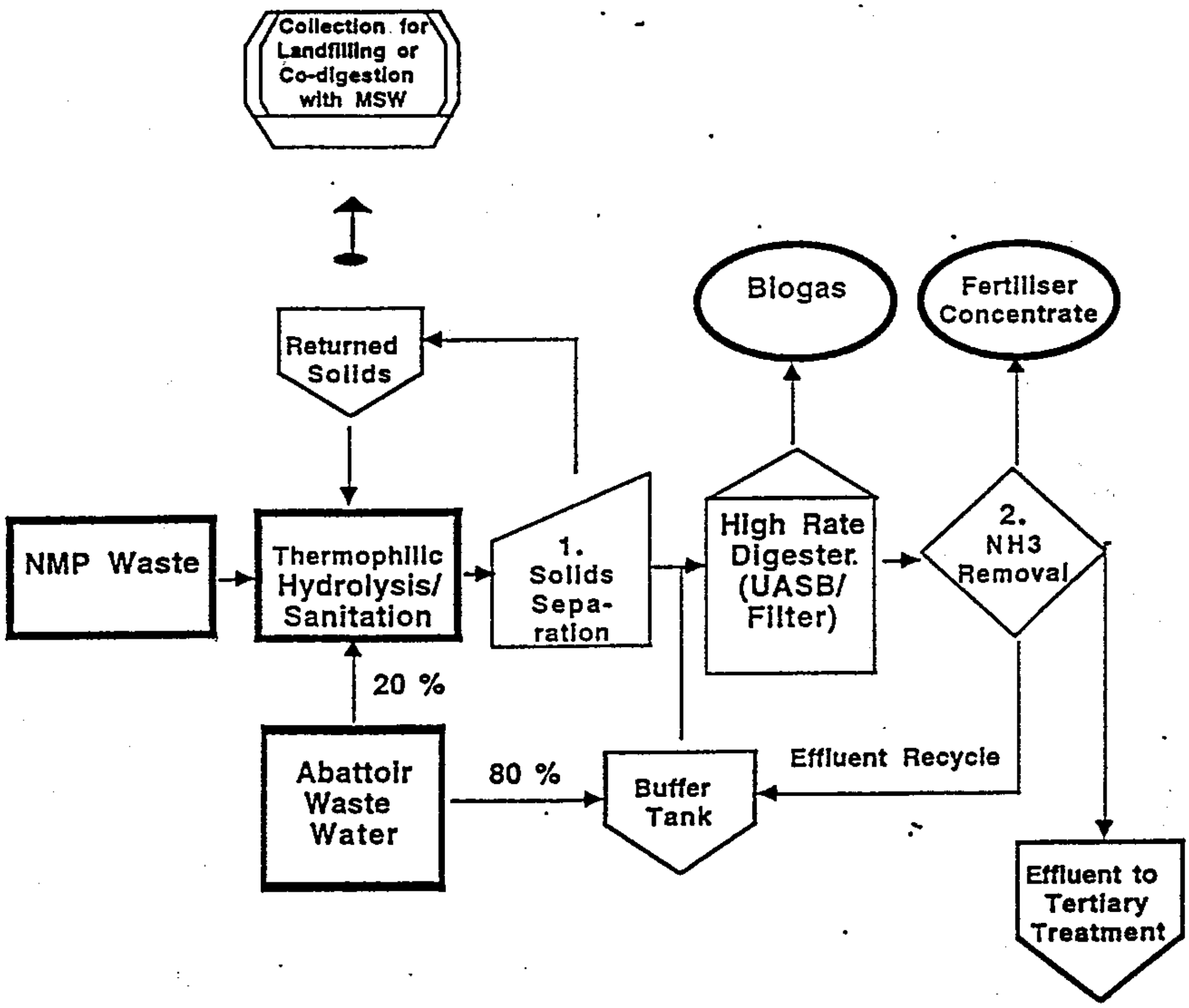
The brief of MRC project M.737 included the identification of key issues, scope and limitation of AD for solid NMP waste from the Red Meat Industry. The respective results from European solid waste digestion demonstration projects, the process microbiology and the process biotechnology were analysed in the various progress reports [1,2,3] of M.737 and in the previous sections of this final report. The analysis showed that waste properties and bacteriotoxicity limit a cost effective and environmentally friendly application of state-of-the-art AD waste stabilisation in simple CSTR digesters. Dilution with wastewater or mixing with other industrial wastes is required to adjust the waste composition to a managable residual toxicity and to improve anaerobic degradability. This approach is not suitable to achieve attractive digestion economics, guaranteed high process stability and methane productivity in CSTR digesters.

Therefore, a development of novel generic digester systems, specialised for NMP waste digestion should be attempted in order to provide the red meat industry with acceptable NMP digestion economics, process stability and methane productivity at high organic loading rates. Figure 10 outlines one possibility for development of such an advanced NMP digestion process. Most components for this scheme are available on the market. It should be noted that other high rate digestion schemes for solid NMP waste are also conceivable.

3.1 Technology Gaps

The unique properties of solid NMP waste with high TS, high lipid and high protein contents suggest that a development of dedicated NMP digestion process concepts might be necessary to bypass the inherent biological barriers for solid NMP waste digestion. Dedicated, cost effective and high rate AD reactor designs have the aim to reduce capital costs and to improve digestion performance. The European experience with AD of solid and liquid manure and of MSW [1] has shown (Figures 1 and 2) that such developments are possible by adapting and combining existing waste treatment modules on a bioprocess level downstream and upstream of modern high rate anaerobic digesters. This allows to either eliminate or bypass solid waste specific digestion barriers and bottlenecks.

Figure 10: High rate digestion scheme for NMP waste. See text for explanations. Dimensions of the thermophilic hydrolysis reactor are as in Figure 9B. The high rate anaerobic digester (UASB/Filter; 1,500 - 3,000 m^3) would have approx. ▯ of the size of a low rate CSTR digester (4,100 - 9,400 m^3; Figure 9B).



Hydrolysis, liquefaction and sanitation of NMP waste under anaerobic, thermophilic conditions appear readily achievable [3]. Abattoir wastewater with lower ammonia-N contents is also readily treatable in high rate digesters (Figure 6, p.18) with good COD removal rates (Figure 5, pp 16 - 17). Ammonia-N cannot be degraded under anaerobic conditions whereas LCFA are degraded if the LCFA and ammonia-N levels are below the respective toxicity threshold (Table 1; see also [2]). The main reason for digestion process inhibitions in CSTR digesters and for the requirement of waste dilution is the ammonia-N accumulation from protein degradation (Figure 7) leading to washout of slowly growing respectively inhibited bacteria. Thus processing of digester effluent for ammonia-N removal (Figure 10, step 2) and recycling of the treated low NH_3-N effluent for dilution of NMP hydrolysate would allow to lower concentrations of both bacteriotoxic constituents in the anaerobic digester (Figure 10) as LCFA are degraded in the high rate reactor.

Two techniques for NH_3 removal from NMP digestion effluents have been tested at Waste Solutions laboratories, MAP (Magnesium/Ammonium-Phosphate) precipitation and steam (air) stripping of NH_3. Both produced acceptable NH_3 removal with well digested effluents (low solids contents) but the respective treatment costs were not specified. High solids contents compromised efficiency and reliability of the techniques. Therefore, an efficient and cost effective solids separation technology applicable to NMP hydrolysate sludges and slurries (Figure 10; step 1) is a key component for future NMP digestion improvements. It is interesting to note that present AD efforts in Germany (Figure 1) targeted development of solids separation technology for slurries at 6 - 10% TS [1].

Separation of suspended solids from the liquified NMP-hydrolysate (Figure 10; step 1) and the dilution of the resulting low solids liquid NMP hydrolysate with digester effluent allows to lower residual suspended solids levels to less than 0.2 - 0.3%. This pretreatment results in several important benefits for AD performance and economics. The processed diluted NMP hydrolysate is high in VFA and LCFA and low in NH_3 and suspended solids. Therefore it meets the criteria for treatment with advanced high rate anaerobic digester systems (UASB, anaerobic filter; Figure 2) allowing for good methane productivities and good COD removal rates (Figure 5) and therefore cost effective anaerobic digestion. High rate digesters immobilise active and adapted bacteria as biofilms or granular sludge, provide for long residence times of adapted bacteria (up to 100 days) and avoid washout of partly inhibited slowly growing bacteria. This is a significant advantage over CSTR digesters. Also, the slow diffusive transport of LCFA into biofilms and granules further lessens their toxic effects on the digestion rate [2]. Substitution of state-of-the-art CSTR digesters with advanced high rate digesters (Figure 10) constitutes thus a qualitative improvement of stability and performance as the toxicity tolerance and volumetric activity of the retained sludges are improved.

Improved digestion stability and COD removal rates through the reconfiguration of the NMP digestion process result in lower digester sizes (Figure 10) compared to respective CSTR digesters (Figure 9B, Table 7) and lower capital costs. A reliable prediction of the resulting cost savings would depend on the outcomes of respective pilot scale digestion trials using filtered/centrifuged NMP hydrolysate and high rate digesters. But the effect of a solids separation step as pretreatment prior to the digestion in combination with cost effective NH_3-N removal as post-treatment **after** the digestion and the dilution of the NMP hydrolysate with this processed effluent could open the way for improved and cost effective high rate NMP solid waste digestion technology. Logistic problems as for the NMP solid waste codigestion with other organic wastes would be avoided. A relatively small volume with high solids content (Figure 9b) of the NMP hydrolysate feed is used for the solids separation step (Figure 10). This will reduce size and costs for the solids separation step. It is expected that these costs are outweighed by the capital cost savings for substitution of the CSTR digester with a high rate digestion technology. Added costs for the NH_3 removal should be balanced against the fertiliser value of the recovered fertiliser concentrate and resulting reduced operation costs of the digester.

Firm cost predictions for the high rate NMP digestion scheme will depend on the outcomes of respective pilot scale demonstration trials.

This NMP solid waste digestion scheme requires the adaptation of existing solids separation technology such as hydrocyclones, centrifuges, drum presses, microfiltration, chemical methods to solids removal from concentrated NMP hydrolysate in analogy to respective technology adapted in Europe to the processing of liquid manure with 6 - 10% TS [1]. It is a good example of how bioprocess technology could be used to bypass biological barriers and bottlenecks for implementation of biological waste treatment technology. The implementation of a combined anaerobic treatment of NMP abattoir wastewater and NMP solid waste hydrolysate (after solids separation) depends thus mainly on the adaptation, demonstration of technical feasibility and the pilot scale testing of existing component technologies and determination of the process parameters for four different components:

- effective thermophilic hydrolysis and sanitation of NMP wastes
- effective solids separation technologies for NMP hydrolysates
- stable high rate AD of NMP hydrolysate with low suspended solids and high VFA and LCFA contents
- efficacy and cost effectiveness of NH_3 removal from digested NMP hydrolysate.

This R&D strategy appears cost effective when compared to the microbiological and bioprocess research efforts that would otherwise be required for development of generic toxicity tolerant bacterial cultures or for control and management of LCFA and ammonia toxicity (Table 2) in simple CSTR digesters (Figure 9B). New fundamental developments are not needed for this high rate digestion scheme. Therefore, the implementation of a well integrated high rate NMP solids digestion scheme (Figure 10) into current abattoir operations in the Red Meat Industry by a combination of dedicated waste pretreatment and post treatment steps appears preferable over "microbiological engineering"of simple CSTR digester technology to treatment of "bacteriotoxic" wastes.

3.2 Bottlenecks for Implementation of AD for Solid NMP Waste

The high rate NMP solid waste digestion scheme (Figure 10) is compatible with the anaerobic treatment of abattoir wastewater for COD and ammonia-N removal. The MRC report M.445 recommended to separate the treatment of liquid "NMP" waste (= abattoir wastewater, rendering wastewater and bin drainings) from paunch and manure treatment [15]. Treatment of this "refined" abattoir wastewater could be easily combined with the high rate digestion of liquid NMP hydrolysate and a subsequent NH_3 removal as shown in Figure 10. Only a small proportion of the NMP wastewater (20-25%) would be required to predilute the solid NMP waste for the thermophilic liquefaction and hydrolysis (Figure 10). The daily mass of nitrogen from the NMP wastewater (approx 1 kg N/ tonne HSCW; [15]) is small compared to the daily mass of nitrogen from solid NMP waste hydrolysis and digestion (8 - 9 kg N/tonne HSCW). Also, the COD load from treatment of the "refined" NMP abattoir wastewater (12 - 60 kg COD/tonne HSCW; [15]) is small when compared with the COD load from NMP solid waste hydrolysis and digestion (100 - 220 kg COD/tonne HSCW assuming digestion of 100 - 200 kg NMP waste/tonne HSCW). Thus cost savings are expected for the COD and nutrient removal from the wastewater in this combined treatment as larger and more cost effective systems (economy of scale) can be used for COD and nitrogen removal from the wastewater. A combination of both treatments creates therefore synergy and cost savings.

It is expected that NMP solid waste loads will fluctuate due to fluctuations in slaughtering, processing of carcasses or from use of NMP byproducts for manufacture of biochemicals, flavour enhancers and other value added products (Figure 11). While these fluctuations would be of concern for the performance of anaerobic CSTR digesters which rely on stable loading rates they would be less problematic for combined high rate NMP solid waste digestion schemes (Figure 10). Thermophilic hydrolysis reactors (Figure 9B, 310 m^3) are small when compared to the anaerobic digester and are dimensioned for NMP solid waste peak loads without significant added costs. Good hydrolysis and sanitation performance during average or low NMP solid waste loads follows from a sequenced batch operation mode of this reactor [3]. The high rate anaerobic digester (UASB or anaerobic filter) can tolerate variable flows and volumetric shock loads with wastewater due to the immobilisation of the active bacterial flora and is dimensioned for the expected maximum COD load from NMP hydrolysate the abattoir wastewater. Good performance at lower loading rates is expected (Figure 5). Shock loads in abattoir wastewater flows can be compensated by respective automatic adjustment of the digester effluent recycle into the buffer tank (Figure 10) as the abattoir wastewater has comparably low ammonia-N contents. This ensures constant COD loading rates, hydraulic residence times and stable high rate digester performance. Thus the performance of the combined wastewater/solid NMP waste treatment scheme is very robust with respect to fluctuating waste loads.

The modular nature of the process components (thermophilic hydrolysis reactor, high rate digester, solids separation step) provides also the opportunity for the gradual integration of the NMP solids digestion schemes into operating high rate anaerobic treatment systems for abattoir wastewater. Solids separation, hydrolysis and ammonia-N removal steps are non-critical for high rate anaerobic treatment of the abattoir wastewater. High rate anaerobic treatment of abattoir wastewater could thus be first implemented as cost effective pretreatment for a subsequent aerobic effluent polishing [16] and as necessary pretreatment for biological nutrient removal from abattoir wastewater [15].

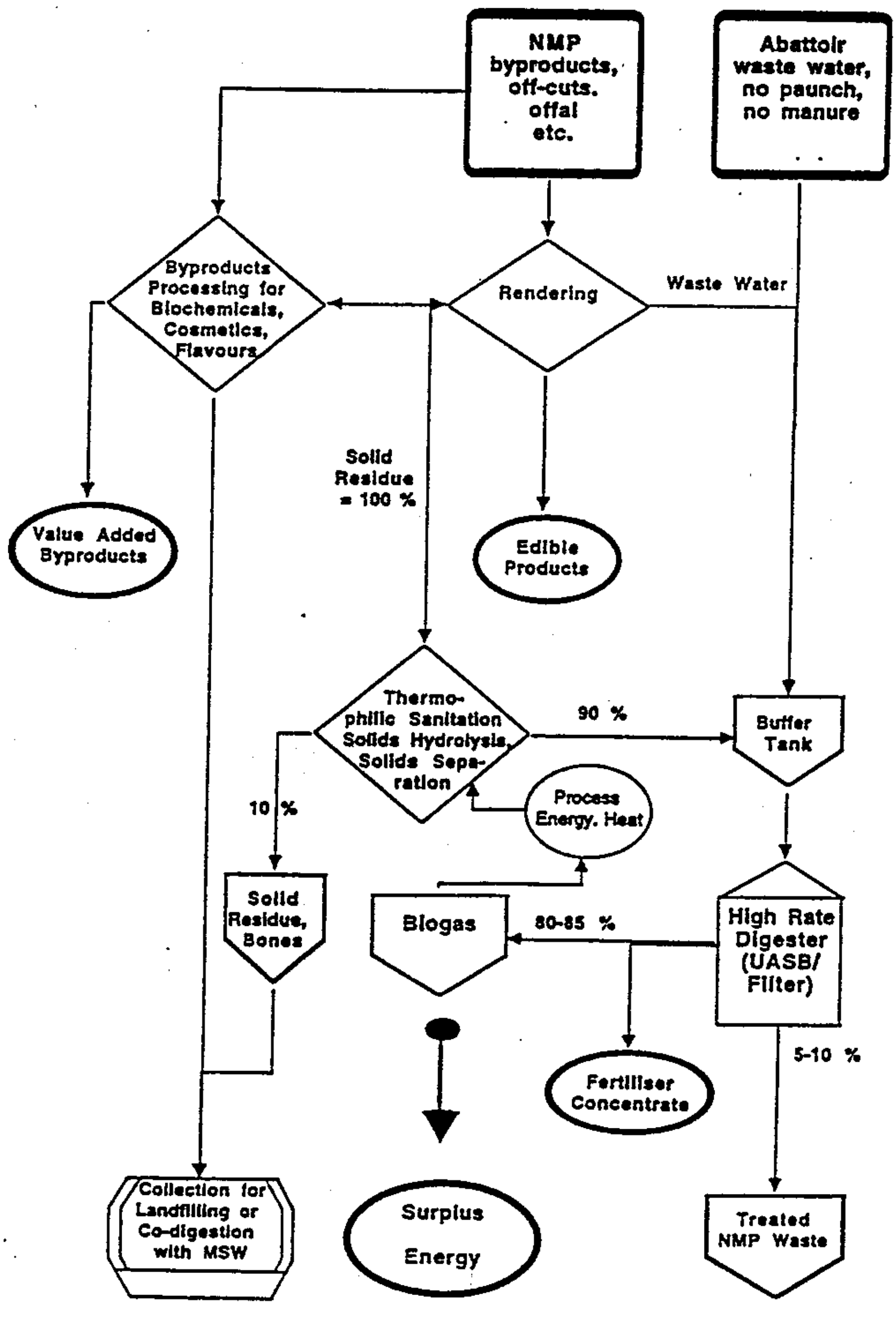
Implementation of anaerobic treatment of abattoir wastewater would be completely independent from decisions about a preferred solid NMP waste management policy. Decisions in favour of a NMP solid waste digestion could be easily implemented at a later stage by upgrading the abattoir wastewater treatment system through addition of respective thermophilic hydrolysis, solids separation, high rate digestion and ammonia-N removal steps. This can be flexibly combined with other concurrent NMP byproduct processing options such as rendering or extraction of biochemicals, cosmetics or flavour compounds (Figure 11).

An assessment of the preferred arrangement of the different NMP byproduct processing options

- extraction of biochemicals, cosmetics, flavour compounds,
- rendering to edible products,
- total conversion to biogas by anaerobic digestion,

clearly established that the anaerobic digestion option is most advantageous when implemented downstream of the other byproduct processing streams (Figure 11). The high protein-N load in NMP byproducts causes the ammonia-N toxicity problems in anaerobic digestion and contributes to most of the nitrogen load in the effluent with substantial consequential added costs for the solid NMP waste processing and nutrient removal. Thus cost effective protein extraction steps upstream of the hydrolysis, liquefaction and digestion will not only produce value added products but will also reduce waste treatment costs for the residue (Figure 11). For this strategy to become effective it is imperative that manure and paunch from the animal processing are kept separate from the NMP byproduct stream to maximise benefits from the protein/ biochemicals extraction. Combined thermophilic sanitation/ hydrolysis of the solid residues (= 100% of COD; Figure 11) is then a key component for public acceptance of this integrated scheme as it conditions and sanitises the residue for either codigestion in municipal digesters similar to the Danish model [1] or for solids separation, ammonia removal and high rate digestion similar to the German model for manure [1].

Figure 11: Possible scheme for a combined anaerobic treatment of abattoir wastewater and solid NMP waste materials integrated with other NMP byproducts processing options. The specific costs ($A/ tonne NMP residue digested) for the additional anaerobic digestion of solid residue from other byproduct processing steps (= 100 % of COD) are similar for different amounts of solid residue processed allowing a flexible integration of NMP solids digestion schemes into the anaerobic treatment of abattoir wastewater.



Effective nutrient removal from the digested effluent by tertiary treatment with biological/ chemical treatment steps has been shown in Germany for liquid manure [1]. The treatment reduced the total nitrogen content from 6100 mg/L to less than 500 mg/L and the total phosphorous content from 940 mg/L to less than 150 mg/L. Although these levels are too high for direct effluent discharge they appear acceptable for managed effluent discharge to land.

The implementation of a combined high rate anaerobic treatment for wastewater and solid waste into operating abattoirs appears thus easier than implementation of a municipal NMP solid waste codigestion scheme off-site together with industrial or municipal organic wastes (Figure 9A) or the on-site NMP solid waste dilution scheme and subsequent anaerobic digestion at low rates (Figure 9B). The expected disposal problems for the effluent with high nutrient (N, P) contents and the logistic constraints make both options less attractive than the combined on site treatment of the wastewater and the solid NMP waste as shown in Figures 10 and 11.

Thus in conclusion, important bottlenecks and constraints for implementation of the anaerobic treatment of abattoir wastewater in the Red Meat Industry do not exist. The recommended high rate treatment systems could be upgraded at a later stage for the combined digestion of wastewater and liquefied NMP waste after successful adaptation and performance demonstration of solids separation and ammonia-N removal modules in pilot projects.

3.3 Issues and Environmental Considerations

Important features of the integrated high rate NMP AD scheme (Figure 11) are:

- waste sanitation and containment of pathogenic microorganisms and odour through extensive thermophilic hydrolysis at 60 °C in closed reactor vessels,
- use of compact tower technology with limited space requirements for high rate anaerobic digesters,
- recovery of biogas as fuel,
- effective COD removal (80 - 90 % expected),
- reduced production of sludges (80 - 90% of waste COD to biogas),
- recovery of nitrogenous nutrients for re-use as organic fertiliser,
- conditioning of combined abattoir wastewater and NMP solids for N and P removal by subsequent tertiary effluent polishing,
- aeration cost savings for subsequent aerobic polishing and tertiary treatments.

These features are improvements over existing alternative waste treatment options for abattoir wastewater or solid abattoir waste and provide the abattoir on site with a flexible and hygienic disposal infrastructure for variable loads of surplus solid high lipid and high protein NMP wastes. Therefore, new issues and environmental considerations from implementation of such an advanced high rate AD scheme for solid NMP wastes are not expected. Existing environmental concerns for treatment of abattoir wastewater from the red meat industry [15] are addressed as far as possible as N and P nutrient removal from the NMP waste is maximised by protein extraction and biological NH_3 removal as fertiliser concentrate through physical chemical nutrient removal prior to tertiary treatment. The integrated solid NMP waste digestion scheme resembles in parts already implemented and tested AD schemes for "biowaste" developed and manufactured by the BTA GmbH in Germany (hydrolysis + sanitation followed by high rate AD of the hydrolysate; [1]). Examples for operating full scale BTA solid waste digestion plants can be seen in Baden-Baden, Germany and Helsingør, Denmark [1].

Alternative mesophilic NMP solid waste codigestion (Figure 2A) with muncipal waste "biowaste" in simple CSTR digesters similar to the Danish Centralised Biogas plants would raise hygienic issues for use of the partly digested solid residue as fertiliser in agriculture as well as logistic, odour and hygienic issues with respect to refuse transport, storage and guaranteed cosubstrate availability. Thermophilic anaerobic co-digestion for sanitation of the NMP waste when mixed with "biowaste" is still unproven and needs to be tested on a pilot scale level should this option be chosen. Nutrient contents in liquid digestion residues must be managed with subsequent tertiary treatment to achieve similar standards as the high rate digestion option. Therefore a NMP waste codigestion on the abattoir site is not recommended as the leachable nutrient content from the "biowaste" and the resulting responsibilities for nutrient removal are transferred onto the abattoir site with consequential added responsibilities for tertiary treatment. This would not be in the interest of the red meat industry according to the findings of a respective MRC technical report [15]. Required digester sizes and volumes (Table 6) are considerable and would probably restrict the applicability of the codigestion scheme to a few sites in Australia. Any benefits from a combined treatment of NMP waste, "biowaste" and abattoir wastewater are not expected. A thermophilic high rate solid state codigestion of NMP waste and "biowaste" in plug flow reactors similar to the DRANCO process (Figure 2B) is still unproven. However, the high ammonia -N content of solid NMP waste when treated in the high solids digester (20 - 25% TS) is expected to inhibit mesophilic or thermophilic solid state digestion.

Therefore, the lack of experience with solid NMP waste digestion in state-of-the-art solid waste digesters suggests that adaptation of high rate digestion technology for combined treatment of solid NMP waste and abattoir wastewater (as suggested in Figure 11) should be initiated. Sufficient experience with the required components (Figure 10) and handling of the waste [3] is available to evaluate a respective combined process with a pilot scale demonstration project.

3.4 Economic Dimension of Anaerobic Digestion Implementation

An analysis of the annual production of beef, veal, mutton and lamb carcasses in Australia over the years 1990 - 1995 indicates a stable meat processing industry with slight trends of increasing beef and decreasing lamb meat production [30]. Thus these statistical data (Table 8) were used as basis to determine rough order of magnitude costs for implementation of AD of solid NMP residues in the Australian red meat industry. Based on a total expected NMP byproduct residue production (after recovery of valuable components [Fig 11]) in the order of 10 - 20 % (w/w) of the 1990-1995 average annual meat production (in tonnes HSCW) and based on the measured abattoir wastewater production per tonne HSCW [17,20] an estimate of the overall order or magnitude costs for implementation of anaerobic digester technology in the industry was attempted. The costing used actual costs for construction of "turn key " state-of-the-art CSTR digester technology (approx. \$A600 - 700/m^3 $_{digester}$) [3] and excluded additional cost savings that could be achieved through adoption of high rate AD technology for abattoir wastewater and NMP solid waste.

This approach appeared reasonable to estimate the maximum investment costs that could be expected for a combined NMP solid waste and abattoir wastewater digestion if adopted by the red meat industry. Eventual cost savings through use of high rate digesters or technology innovation (through research and development) should thus result in lower operating costs. Local factors such as abattoir size, wastewater volumes and innovative byproduct processing technology will also influence the actual digester operating costs for abattoirs. The large digester volumes (Table 7) have the effect that the specific costs for digester construction and the infrastructure (DAF tank prefermentation, gas storage etc [3]) would be large independent of the actual abattoir size.

Table 8: Assessment of the annual wastewater and NMP residue production in the Australian red meat industry (1990 - 1995).

Parameter	**Meat Production** ('000 tonnes HSCW/ year)	**Wastewater**[a] ('000 tonnes COD/ year)	**NMP Residues** ('000 tonnes COD/year) at 0.1 tonnes NMP/tonne HSCW)	('000 tonnes COD/year) at 0.2 tonnes NMP/tonne HSCW)
Beef	1795 +/- 27	n/a	192	383
Veal	38 +/- 1	n/a	4	8
Mutton	370 +/- 23	n/a	40	81
Lamb	272 +/- 10	n/a	30	60
Pigs	334 +/- 15	n/a	36	73
Total Meat	2774 +/- 38	39 - 161	303	605

a: Wastewater production determined in five Australian abattoirs [20].

n/a: no data available

A total installed digester volume of 40,000 - 160,000 m^3 is required with investments in the order of \$A25 - 100 M for full implementation of AD for treatment of the abattoir wastewater (Table 8). The costs will also depend on water conservation programmes in abattoirs [20]. The estimate is based on a slaughtering season of 180 days (at full capacity) and digester loading rates of max. 5 kg COD $m_{reactor}^{-3}.d^{-1}$ for the anaerobic removal of COD from abattoir wastewater (5 - 10 days residence time). Wastewater treatment cost savings of 7 - 30 M \$A/year [3] result from an avoided electricity consumption through anaerobic biogas production (at COD removal efficiencies of 70 - 80%; see Figure 5) instead of COD conversion to bacterial cells under aerobic conditions (approx. 50 - 60% COD removal efficiency). These cost savings are balanced against the initial capital costs for the digesters. Pay back periods of 3 - 5 years are expected for high rate digestion of abattoir wastewater. AD of abattoir wastewater is therefore expected to be economically viable. Effluent treatment costs by further aerobic nutrient removal to high environmental standards are additional cost to both, aerobic and anaerobic treatment of abattoir wastewater and therefore needs to be separately considered. Other economic benefits from use of the effluent as fertiliser, or from odour control etc. were not included in this crude cost assessment.

Codigestion of the wastewater and NMP waste in integrated high rate digesters (Figure 11) would require 350,000 m^3 - 480,000 m^3 installed digester volume for treatment of 0.1 tonne NMP/ tonne HSCW if operated at loading rates of max. 5 kg COD $m_{reactor}^{-3}$ d^{-1} (10- 15 days residence time). Total investment cost for the Australian red meat industry would range from \$A220 - 300 M to install 70 - 100 large high rate anaerobic digesters for combined treatment of the wastewater + NMP residues (approx. 5000 m^3 digester size). For comparison, the Danish programme for manure and solid industrial/ household waste codigestion is based on approx. 30 CSTR digesters of approximate similar size (1,500 - 7,000 m^3) [1].

Solid NMP residues have very high oxygen demands. Any aerobic solid NMP residue stabilisation technology (composting, aerobic sludge stabilisation etc.) will thus experience significant added electricity costs for the aeration. For example, aerobic activated sludge treatment requires 1.3 kwh_{el}/kg COD. The annual electricity savings for the industry through the anaerobic codigestion of the solid NMP residues (0.1 tonne NMP/tonne HSCW) and wastewater instead of an aerobic treatment are thus expected to range from \$A50 - 125 M. Thus given the size of the red meat industry with an annual meat production worth approx. \$A6,200 M [30] the development and gradual implementation of an anaerobic treatment technology for surplus solid NMP residue together with abattoir wastewater appears economically feasible and is recommended.

4. RECOMMENDATIONS

The results from the Project M.737 provide a scientific foundation to establish alternatives for solid NMP material management in the red meat industry. Anaerobic digestion (AD) for removal of biological/chemical oxygen demand (BOD, COD) and a subsequent digester effluent polishing by tertiary treatment is - although technically feasible - a challenging task that requires development of dedicated solid NMP waste digestion processes as combinations of available waste water treatment techniques. State-of-the-art anaerobic digestion technology for solid or liquid wastes is not directly applicable to the AD of solid NMP wastes. The task is complicated by the bacteriotoxic nature of the concentrated NMP materials and by the high ammonia-N load from the digested waste. Dilution of the materials to nontoxic levels prior to anaerobic treatment would magnify the pollution problem and is not an acceptable solution. However modern treatment technology allows to achieve the same "dilution effect" through efficient reuse of treated effluent and separation/recovery of value added marketable products without generation of additional waste. The order of magnitude of solid NMP waste materials produced in the red meat industry in Australia (500,000 - 1,000,000 tonnes COD/ year) and the expected operating cost savings from anaerobic waste pretreatment prior to aerobic post-treatments (270 A$/tonne COD removed) would be an important incentive for industry efforts to initiate development of anaerobic NMP solid waste management processes prior to aerobic effluent polishing and nutrient removal.

Application of good NMP material management practices throughout the treatment process is essential. This will be facilitated by maximising the implementation of "The three Rs principles":

- Reduce
- Reuse
- Recycle.

The degradability, value, properties and amounts of three main "waste-material" streams from animal processing - i.e. (i) waste water, (ii) manure and paunch and (iii) NMP byproducts - differ significantly. Therefore we recommend as the first step to separate these material streams in order to allow for effective volume reduction, reuse and treatment of each material stream.

The anaerobic treatment of abattoir waste water on-site is economically attractive if modern, cost effective high rate anaerobic digesters (Upflow Anaerobic Sludge Blanket, Anaerobic Filter) are used. This could significantly reduce the BOD/COD content (70 - 85 %) of the abattoir effluent and reduce aeration costs for subsequent biological effluent polishing steps for further COD or nutrient (N.P) removal. It is recommended to begin implementation of high rate AD for treatment of abattoir wastewater in the red meat industry.

Combination of solid manure and paunch contents with the abattoir waste water would significantly increase the solids and nutrient (N, P) content of the waste and therefore compromise the applicability of cost effective, modern high rate anaerobic digestion technology. It would also reduce COD/BOD removal efficiencies and compromise subsequent biological effluent polishing technology. Therefore this should be avoided if possible.

A combination of solid manure and paunch materials with any residues from byproduct recovery or rendering of NMP materials (edible materials, extraction of biochemicals, cosmetics, flavour compounds etc.) could improve an anaerobic treatment through codigestion with municipal wastes in municipal digesters **off-site.** Insufficient amounts of manure and paunch are available for complete NMP residue codigestion **on-site.** Therefore it is recommended to explore possibilities to transport NMP byproduct residues from abattoirs together with solid manure and paunch to centralised municipal digesters for efficient large scale anaerobic codigestion together with sewage sludge, source sorted organic household waste and/or other industrial wastes.

Significant benefits for hygiene and COD removal could be expected from high rate thermophilic bacterial pre-fermentation processes to liquefy, condition and sanitise **on-site** high lipid, high protein content solid residues from NMP byproduct processing or rendering. This conditions the waste for disposal by either codigestion **off-site** (similar to the Danish system for centralised manure treatment) or high rate anaerobic digestion together with abattoir waste water **on-site.** Therefore it is recommended to initiate pilot scale trials to demonstrate the stability and sanitation performance of such thermophilic liquefaction processes for conditioning and sanitation of solid and liquid NMP residues.

The combined anaerobic treatment of liquefied NMP residues and abattoir wastewater **on-site** is economically attractive as it allows use of modern, cost effective high rate anaerobic digesters for efficient BOD removal (Upflow Anaerobic Sludge Blanket, Anaerobic Filter). Through cost savings from installation of larger units this would reduce the specific treatment costs for both, the wastewater and of the liquefied NMP residues. Prior to implementation of this option a pilot project should be conducted to demonstrate the cost effectiveness and performance of respective commercially available solids separation modules required for removal of potentially interfering residual solids in the liquefied NMP residue (rotating screens, hydrocyclones, centrifuges, membrane filtration).

Ammonia-N has been identified as a major non degradable and toxic inhibitory product from solid NMP waste digestion. Ammonia-N levels in the digester effluent are approx. nine-fold increased when treatment of liquefied NMP solids and abattoir waste water is combined for cost effective anaerobic digestion. This causes significant additional pollution in the effluent (nitrogen nutrients) and added costs for nutrient removal by tertiary treatment. It is a main bottleneck for implementation of the AD of solid NMP waste. We recommend therefore to demonstrate the efficacy and cost effectiveness of thermal/physical NH_3 removal from digested effluents by NH_3 stripping (steam, air) prior to tertiary treatment. This technology could provide the basis for waste water conservation through recycling of digester effluent and reduction of the ammonia-N pollution load with the discharged effluent This approach is currently evaluated for treatment of concentrated manure in demonstration projects in Germany. It is very probable that this treatment could effectively clean the NMP digester effluent and produce as byproduct a marketable liquid nitrogen fertiliser concentrate for reuse in agriculture.

Alternatively, the potential of solid mineral fertiliser production (struvite, Magnesium Ammonia Phosphate) from digested NMP residues should be fully explored using inexpensive substitutes for Mg and phosphate. This would allow to add further value to the nutrient content of NMP residues and to fully integrate abattoir operations and animal production in the farming sector.

It is not recommended to predilute pure NMP solid materials with waste water for subsequent anaerobic treatment in continuously stirred (CSTR) low rate sewage sludge digesters, plug flow solid waste digesters or other digester systems without retention of active bacterial biomass. Inhibition and slow bacterial growth require long residence times resulting in low organic loading rates, in poor COD removal efficiencies and rates and in unattractive digestion economics.

The European experience with development of generic AD technology for solid MSW, manure and codigestion schemes with industrial waste has shown that accompanying microbiological research and process monitioring can benefit digester stability, methane productivity, COD removal efficiency and effluent quality and digester operation cost savings. This requires dedicated anaerobic digestion laboratory facilities in one centre that can service a region or even one country (with remote control technology). The positive experience in Denmark with this process oriented research approach (Nordic Centre for Bioenergy and Environmental Research, Technical University of Denmark, Copenhagen) and the current practice at Waste Solutions Ltd in New Zealand suggest that returns on this investment could be significant. As the commercial potential for AD of NMP residues is substantial it is therefore recommended to establish a research centre dedicated to NMP residue digestion and related process issues. It is expected that a 3 - 5 year timeframe is sufficient to bring NMP residue digestion technology to maturity.

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