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Thermal Energy Recovery from Feedlot Manure – Pilot Trials

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Abstract

Beef feedlot manure has a high energy content, similar to other organic waste materials. As such, it offers the potential for energy recovery using thermal processes such as combustion, gasification or pyrolysis. However, certain factors can reduce the energy potential of feedlot manure such as volatile solids degradation over time, high moisture content and contamination due to soil and gravel. To date, there have been no full-scale experience in Australia with energy recovery from feedlot manure and only limited data is available from overseas. This project identified via a literature review, the current status of energy recovery from feedlot manure around the world and demonstrated the techno-economic efficacy of combustion, gasification and pyrolysis as energy recovery options, via pilot trials of these technologies. In addition, a benefit-cost analysis was conducted to assess the economic advantages (if any) offered by energy recovery from feedlot manure, compared to land application of harvested manure in broad-acre agricultural operations.

Executive summary

Beef feedlot manure has a high energy content, similar to other organic waste materials. As such, it offers the potential for energy recovery using thermal processes such as combustion, gasification or pyrolysis. However, certain factors can reduce the energy potential of feedlot manure such as volatile solids degradation over time, high moisture content and contamination due to soil and gravel. To date, there have been no full-scale experience in Australia with energy recovery from feedlot manure and only limited data is available from overseas. This project identified via a literature review, the current status of energy recovery from feedlot manure around the world and demonstrated the techno-economic efficacy of combustion, gasification and pyrolysis as energy recovery options, via pilot trials of these technologies. In addition, a benefit-cost analysis was conducted to assess the economic advantages (if any) offered by energy recovery from feedlot manure, compared to land application of harvested manure in broad-acre agricultural operations.

A cattle feedlot is a facility where beef cattle are housed in open pens and fed a prepared ration until they reach a specified weight. The pen surface is typically compacted clay or gravel. Depending on site-specific conditions, feedlot pens are stocked at between 10 and 20 m^2/head. Cattle excrete fresh manure (urine plus faeces) onto the pen surface (known as the feedpad) where it immediately begins to breakdown. Ammonia and other volatile components such as VFAs are lost from the manure. After a period of time, machinery removes the manure from the pens. The removed manure is typically held in a manure stockpile area where it may be composted prior to sale off-site or spreading as an organic fertiliser on agricultural land. When only manure is removed from pens, the annual manure harvested is about 1 t DM/head/yr or less. However, if soil is removed with the manure, the annual harvested tonnage is much higher. Fresh faeces mix with the manure on the pen surface and starts to degrade. The volatile solids content declines markedly from 80% VS when excreted to less than 35% in some cases. Pen moisture content is highly variable depending on local weather conditions. Pen moisture content can vary from 10% to 90%.

Feedlots are generally located across the grain-growing regions of Australia. The climatic zones in which feedlots are located are of relevance. Thermal energy recovery methods require “dry” manure as the energy source. The amount and annual patterns of rainfall affect the moisture content of manure on the pen surface and the rate at which that manure breaks down. About 12% of feedlot cattle are located in zones where annual rainfall exceeds 750 mm and about 27% of feedlot cattle are located in zones where rainfall is winter-dominant. Both of these climatic zones are not conducive to providing “dry” manure for thermal energy recovery.

Thermal energy recovery options include combustion (burning), gasification and pyrolysis. Gasification is a thermal process where a small portion of the waste (typically 5 to 15%) is combusted under starved air combustion conditions to raise the waste material to a temperature of about 900°C. The end products of gasification are a syngas (comprising mainly carbon monoxide, hydrogen and carbon dioxide) and an ash or char product, depending on operating temperature. Pyrolysis, also called carbonisation, is a process where waste is heated indirectly, in the absence of oxygen, to a temperature of between 350 and 500°C. Under these thermal conditions, the waste decomposes and about 30 to 60% of the dry mass is volatilised to produce a crude syngas with the remaining solids converted to a char product. Pyrolysis is the thermal destructive distillation of organic materials. Traditionally, the pyrolysis syngas is condensed to generate oil, produced water and a non-condensable gas. To date, none of these technologies have been used in Australian feedlots and there are very few operational examples in the USA.

The methodology for this project was:

1. Initial manure sampling and assessment
2. Manure collection for initial combustion and gasification trials
3. Initial combustion trial
4. Initial gasification trial
5. Re-evaluation of project methodology
6. Second round of manure collection
7. Second combustion trial
8. Second gasification trial
9. Pyrolysis trial
10. Data analysis

Initially, manure samples from different locations within a feedlot were sampled to determine suitability for thermal energy recovery. It was determined that only manure taken directly from pens would be suitable. Pen manure from Feedlot A was collected for initial combustion and gasification trials. In both instances, technical problems with the equipment occurred and the trials were terminated. A re-evaluation of the project resulted in selection of a different site for the combustion trial, inclusion of a second feedlot for manure collection (Feedlot B) and the inclusion of pyrolysis in the pilot trials.

The second combustion trial was conducted at Feedlot A using their own boiler. Due to biosecurity concerns, manure from Feedlot B could not be included in the trial. The manure combustion trial clearly confirmed that feedlot manure with a TS of about 74% and a VS of only about 40% is not a suitable feedstock for energy recovery via combustion. In hindsight, the combustor used was not ideally suited for combustion of manure of this quality. The combustion air flow rate during the manure combustion trial was significantly in excess of that required for efficient combustion. Had the combustion air flow rate been that required for efficient combustion, there would have been about 1.85 GJ/h of energy available for steam generation, which could have produced up to 670 kg/h of steam. However, this is still not considered an acceptable energy/steam output and it is considered that feedlot manure combustion for energy recovery will only be technically viable provided that the manure VS is above 60% and the TS is preferably above 75%. To achieve these TS and VS requirements, feedlot operators will need to be more diligent in their pen manure harvesting procedures. In addition, a more efficient combustor, such as a Fluid Bed Combustor (FBC), is regarded as being highly desirable if manure combustion is to be contemplated. The fouling of heat transfer surfaces in the boiler, by low-melting eutectic mixtures containing potassium and phosphorus, is a major issue that needs to be addressed and assessed prior to proceeding with a commercial scale feedlot manure combustion system.

The gasification trial was conducted using air-dried manure from Feedlot A and Feedlot B. It indicated that for the process to be technically feasible, the primary and secondary air needs pre-heating to ensure that the thermal oxidiser temperature can be maintained above 750°C. This obviously applies to the manures as tested and is particularly true for the low volatile Feedlot A manure. This temperature requirement is needed to ensure that flue gas emission limits will meet regulatory requirements. The chars produced from gasification are suitable for reuse in agriculture.

The pyrolysis trial confirmed that both the Feedlot A and Feedlot B manures could be successfully pyrolysed. However, the energy recovery potential of the low VS Feedlot A manure is very low. For the low TS manure, the usable energy recovery is only 0.34 GJ/dry tonne which increases slightly to 0.92 GJ/t for the high TS manure. Thus, from an energy recovery perspective, pyrolysis of low VS manures is not at all commercially attractive. The low VS manures do however produce a significant amount of char due to the high ash content of the manure. Char from the Feedlot A manure only had a VS content of 23% and a carbon content of 15%. These values categorise this char at the lowest level that is suitable for agricultural reuse.

The economics of thermal energy recovery from feedlot manure via thermal processing was assessed based on four input scenarios, covering small and large feedlots, with two different manure TS and VS assumptions. For the pyrolysis and gasification options, the manure quality, as tested was used, and economics were developed based on two assumed manure TS values, namely 65 and 75%.

For combustion, the estimated net operating and maintenance costs for all facilities are negative, indicating revenues exceed costs. Financial analysis for these facilities is based on a Net Present Value (NPV) approach as well as developing simple payback periods. The NPVs are calculated on the assumption that the discount rate is 7% and the period is 20 years. The payback period varied from 8.9 to 86.9 years. This financial analysis shows that combustion of feedlot manure, even with reasonable VS values (about 60%) is not commercially attractive for small feedlots and marginally attractive for large feedlots.

For gasification, the financial analysis shows that gasification of manure from small feedlots, even with reasonable VS values (about 60%) is only marginally attractive, based on the 6 year payback period and a char sale value of $250/t. Gasification of manure from large feedlots, even with low VS values (about 40%) appears to be very attractive, with payback periods of less than 3 years. However, this economic assessment is very sensitive to the price that will be obtained for the char. For example, if the char revenue drops to $100/tonne the payback period for the large feedlot options decreases to about 5.5 years, making them only marginally attractive. For the small feed lots gasification is no longer a viable management option if char revenues fall to $100/tonne.

This financial analysis shows that pyrolysis of manure from small feedlots, even with reasonable VS values (about 60%) is not commercially attractive. Pyrolysis of manure from large feedlots appears to be marginally attractive, on the assumption that the char generated can be sold, at $250/tonne, for reuse in agriculture. If the revenue for char sales falls to values of $100/tonne, pyrolysis no longer becomes an economically viable management option, even for large feedlots.

The results of this study confirm the existing knowledge that manure with a higher moisture content and/or high ash content is a poor thermal fuel. If thermal energy recovery is to be viable, feedlots need to manage pen manure moisture content and ash content. For an existing site, little can be done to prevent rainfall. However, steps can be taken to reduce ash content (maximise VS content). This includes pen cleaning that retains the manure interface layer (and prevents the collection of clay and gravel) and frequent pen cleaning, which minimises the VS degradation on the pen surface.

The conclusions of this study are that thermal energy recovery systems may be viable at Australian feedlots but pen manure management practices must be undertaken to maximise volatile solids content and minimise moisture content. If the manure is to be used for combustion, the correct design of the boiler is essential. The viability of gasification and pyrolysis technologies is highly dependent on the returns obtained from selling biochar.

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List of Abbreviations and Terms

ADG	Average daily gain
BD	Bulk density
BEEFBAL	Feedlot nutrient balance model
BiG	Black is Green Pty Ltd
BOD	Biochemical oxygen demand
C	Carbon
CHNOS	Carbon, hydrogen, nitrogen, oxygen, sulphur
CH_4	Methane
COD	Chemical oxygen demand
CO_2	Carbon Dioxide
DAF	Dissolved air flotation
DM	Dry Matter
DMD	Dry Matter Digestibility
DMDAMP	Dry Matter Digestibility Approximation of Manure Production
DMI	Dry Matter Intake
DOF	Days on Feed
FBB	Fluid bed boiler
FBC	Fluid bed combustor
FCR	Feed conversion ratio
FS	Fixed Solids
GCV	Gross calorific value
GHG	Greenhouse gas
GJ	Gigajoule
HHV	Higher Heating Value
kW	Kilowatt
LWT	Liveweight
MLA	Meat & Livestock Australia
M&E	Mass and energy
MJ	Megajoule
MSW	Municipal solid waste
MW	Megawatt
MWh	Megawatt hour
N	Nitrogen
NCV	Net calorific value
NOx	Oxides of nitrogen
NPV	Net present value
O&M	Operating and maintenance
P	Phosphorus
PFD	Process flow diagram
PW	Paunch waste
REC	Renewable energy credit
SCU	Standard cattle unit (regulatory standard in Queensland)
SOx	Oxides of sulphur
TN	Total nitrogen
TP	Total phosphorus
tpd	Tonnes per day
TS	Total solids
VFA	Volatile Fatty Acids
VS	Volatile solids

1 Introduction

1.1 Background

Beef feedlot manure has a high energy content, similar to other organic waste materials such as sewage sludge and agricultural residues. As such, it offers the potential for energy recovery using thermal processes such as combustion, gasification or pyrolysis. However, certain factors can reduce the energy potential of feedlot manure such as volatile solids (VS) degradation over time, high moisture content and contamination due to soil and gravel. To date, there is no full-scale experience in Australia of energy recovery from feedlot manure and only limited data is available from overseas. This project aims to identify via a literature review, the current status of energy recovery from feedlot manure around the world and more importantly, to demonstrate the techno-economic efficacy of combustion, gasification and pyrolysis as energy recovery options, via pilot trials of these technologies. In addition, a benefit-cost analysis will be conducted to assess the economic advantages (if any) offered by energy recovery from feedlot manure, compared to land application of harvested manure in broad-acre agricultural operations.

A previous MLA desktop study, which reviewed energy recovery options from feedlot wastes (Bridle (2011a)), identified *that energy recovery from harvested manure, using thermal techniques, appeared* to offer very attractive economics, even for small feedlots (10 000 SCU). However, this report based its findings on the average characteristics for harvested manure from Australian feedlots, as detailed in the report by Davis et al. (2010). From a manure energy recovery perspective, the rapid decline of volatile solids (VS) after excretion will affect the economic feasibility of capturing this potential energy source and therefore validation of those economics by conducting pilot scale combustion and gasification trials on harvested manure is required. This forms the basis of this project.

1.2 Project methodology and reporting

By 28 February 2103, the project aimed to deliver the following major outcomes.

1. A comprehensive literature review on the use of thermal technologies for energy recovery from harvested beef feedlot manure.
2. Collection and characterisation of suitable high and low calorific value harvested manures from the Feedlot A and Feedlot B in Queensland.
3. Pilot-scale testing and demonstration of gasification as a technically viable thermal processing option for energy recovery from both high and low calorific value harvested feedlot manures.
4. Pilot-scale testing and demonstration of pyrolysis as a technically viable thermal processing option for energy recovery from both high and low calorific value harvested feedlot manures.
5. Commercial-scale testing and demonstration of combustion as a technically viable thermal processing option for energy recovery from both high and low calorific value harvested feedlot manures.
6. Assessment of the costs associated with the application of manure to land and combustion/gasification cost estimates.
7. A techno-economic assessment, inclusive of a cost-benefit analysis of thermal energy recovery options versus land-application of harvested beef feedlot manures.

This is the Final Report for this Project.

1.3 Methodology outline

According to the project contract, the project was to be conducted in a number of stages. These included:

Literature review: This was to be carried out jointly by Bridle Consulting and FSA Consulting, making use of scientific journals and internet searches in conjunction with their collective network of professional and research associates in Australia, Europe and North America who work in the animal manure industry.

Identification of manure sampling sites: FSA Consulting was to collect different manure samples at different points in the manure management cycle (fresh, pen, stockpiled and composted manure) at Feedlot A. These samples will be tested for TS and VS content.

Additional samples, which are known to contain less soil material admixture, were collected from Feedlot B. Thermal tests were to be conducted on samples from each location, except for the combustion trial. Biosecurity procedures in place at Feedlot A mean that it was not possible to take manure from another feedlot onto the site. Therefore, only one manure sample was to be tested through the combustion process.

Combustion and gasification trials: The gasification trials were to be conducted by Black is Green Pty Ltd, using their BiGchar 1000 pilot plant situated at Nambour in Queensland. These trials were to be supervised by Bridle Consulting. Two steady-state trials were to be conducted on the two manure samples. Complete mass and energy balances were to be provided for each run as well as emissions monitoring. The resulting char was to be fully characterised. Six manure and six char samples were to be taken from the gasifier. The manure was to be analysed for TS, VS, CHNOS, gross calorific value (GCV), P, K, Na, Fe, Al, Ca, Si, Cu, Zn, Cl and SO_4. The char was to be analysed for TS, VS, TN, P, K, Cl, SO_4, Fe, Al, Ca, Na, Cu and Zn.

The initial combustion trials were to be conducted by Steam Systems Pty Ltd using a 1 MW commercial boiler (supplied by Steam Systems) situated at Yarra Junction in Victoria. These trials were to be supervised by Bridle Consulting. Two steady-state trials were to be conducted on the two manure samples.

Unfortunately, problems occurred with this section of the project. The contract was amended to require that the combustion trials were conducted by the project team utilising the commercial boiler located at the Feedlot A. These trials were to be supervised by Bridle Consulting. One steady-state trial was to be conducted on the manure sample and complete mass and energy balances were to be provided for each replicate as well as emissions monitoring.

Complete mass and energy balances were to be provided for each run as well as emissions monitoring. The resulting ash was to be fully characterised. Six manure samples and six ash samples from the combustor were to be taken. The manure was to be analysed for TS,VS, CHNOS, gross calorific value (GCV), P, K, Na, Fe, Al, Ca, Si, Cu, Zn, Cl and SO_4. The ash was to be analysed for TS, VS, TN, P, K, Cl, SO_4, Fe, Al, Ca, Na, Cu and Zn.

The pyrolysis trials were to be conducted by Pacific Pyrolysis utilising their pilot plant located in Somersby, NSW. These trials were to be supervised by Bridle Consulting. Two steady-state trials were to be conducted on the two manure samples and complete mass and energy balances were to be provided for each run as well as emissions monitoring. The resulting char were to be fully characterised. Six manure samples and six char samples were to be taken from the pyrolyser. The manure will be analysed for TS, VS, CHNOS, Gross calorific value (GCV), P, K, Na, Fe, Al, Ca, Si, Cu, Zn, Cl and SO_4. The char will be analysed for TS, VS, TN, P, K, Cl, SO_4, Fe, Al, Ca, Na, Cu and Zn.

Final report: FSA Consulting and Bridle Consulting will jointly prepare the Final Report that will summarise the findings and will include a detailed cost-benefit analysis of the energy recovery options compared to broad-acre land application of manure.

2 Literature review

2.1 Measurement of manure characteristics

2.1.1 Definitions for Moisture / Solids Content and Volatile Solids

Throughout this report, various terms describing manure samples are used. This section provides some definitions.

Any sample (soil, manure, feed) consists of three sub-components – air, water and solids. Depending on the application, the solid component can be referred to as Dry Matter (DM). Dry Matter (or total solids (TS)) comprises organic and inorganic components. The relative proportions of organic and inorganic matter in a sample can be determined by combustion of the sample in an oven at 600°C. The organic component (volatile solids (VS)) is burnt off leaving the ash (fixed solids (FS)) component. Each sub-component has a mass and volume within a sample as in Table 1.

Table 1 - Sub-components of soil and manure samples

Sample Sub-components	Mass	Volume	Density (g/cm^3)
Air	$m_a = 0$	V_a	0.0
Water	m_w	V_w	1.0
Volatile Solids	m_{vs}	V_{vs}	
Fixed Solids	m_{fs}	V_{fs}	2.65 for a soil

From this basic information, numerous parameters can be defined.

Total volume of sample, $V_t = V_a + V_w + V_{vs} + V_{fs}$

Volume of solids, $V_s = V_{vs} + V_{fs}$

Total mass of sample, $m_t = m_w + m_{vs} + m_{fs}$ - for a manure / compost

Total mass of sample, $m_t = m_w + m_s$ - for a soil (assuming no organic matter)

Total Solids, TS = VS + FS (Ash) = $m_{vs} + m_{fs} = m_s$ for a soil

Moisture Content Definition

Confusion often exists on the definition of the moisture content of a sample. Typically, engineering soil laboratories implicitly use moisture content expressed on a “dry basis” while agricultural laboratories use moisture content expressed on a “wet basis” (see definitions below). Very often, the exact basis on which moisture content is calculated is not explicitly stated. When the moisture content is low, there is little difference between “dry basis” and “wet basis” but this is not true for very wet samples.

Moisture content (% db – dry basis) = m_w / m_s
Moisture content (% wb – wet basis) = m_w / m_t
To convert (%wb) to (%db) %db = %wb /(100-%wb)
Moisture content (% v/v) = V_w / V_t
Convert (%db) to (%v/v) %v/v = %db x BD /1000 (where BD = kg/m^3)
Convert (%db) to (%v/v) %v/v = %db x BD (where BD = g/cm^3)
Bulk Density (BD) (wb) = m_t / V_t
Solids Density = m_s / V_s range of 2.5 to 2.7 (say, 2.65)
Field / Dry Bulk Density, (BD) = m_s / V_t (usual definition of soil bulk density)
Dry Matter (DM) (%) = m_s / m_t
Total Solids (TS) (%) = m_s / m_t
Volatile Solids (VS) (%) = m_{vs} / m_s

2.1.2 Dry Matter (Total Solids) determination

Dry Matter (DM) or TS is that matter remaining after water is completely evaporated from the sample (Peters et al. 2003b). For soils, this is a relatively straightforward process. Most standards specify drying at 105°C for either 24 hours or until the weight of the dried sample is constant, e.g. Standards Australia (1992).

However, for samples containing a large percentage of organic or volatile material, it is likely that some of the volatile organics will be lost during the drying process. Certainly, anyone who has actually dried manure samples would know that more compounds than just water are driven from the samples. Peters et al. (2003b) reports the outcome of a program that conducted a manure sample exchange between 14 state university laboratories in the USA. They found that drying temperatures ranged from 50°C to 110°C and documented drying times ranged from 16 to 24 hours. Clearly, there is a lack of standard methodology used for manure samples. It is probably that the lower drying temperatures used by some laboratories is an attempt to minimise the loss of volatile organics during the drying process.

The whole issue of the effect of drying temperature on TS and VS determination is exemplified when Hollman et al (2008) stated that "*to our knowledge, no data exist in the scientific literature comparing DM excretion estimates to total solids estimates*". On the face of it, this statement seems nonsensical as most authors assume (as is done in this report) that DM (dry matter) is equivalent to TS. However, Hollman et al (2008) goes on to say that DM is typically determined by agricultural scientists by drying at 60°C while TS are determined by engineers by drying at 105°C and that these two methods do not necessarily produce the same result with more variability in results dried at 60°C.

2.1.3 Volatile Solids determination

The method to measure VS in the laboratory is to burn (ash) dried manure samples at high temperature. Examples are 550 ºC (APHA 1989) or 440°C or 750°C (ASTM 2008). The VS portion of the sample is burnt off and only the ash remains. The VS are determined by mass balance. However, the VS determined using this process may be an under-estimate of the total VS due to the loss of VFAs during the initial drying process. This will be discussed in the following section.

2.1.4 Organic components of manure

Manure constitutes urinary excretions as well as the fraction of the diet consumed by an animal that is not digested and excreted as faecal material. Manure is urine plus faeces. Manure is composed of dry matter, which contains macro and micro nutrients, and water. The dry matter is the TS, which is composed of organic matter (measured as either VS or chemical oxygen demand (COD)), and FS (ash).

In manure, a significant proportion of the organic matter can be in the form of volatile fatty acids (VFAs). Total VFA is usually the sum of acetic, propionic, butyric, isobutyric, isovaleric, valeric and caproic acids. As the name suggests, these acids are volatile – particularly the short chain acids such as acetic and propionic - and can disperse into the atmosphere after the faeces is excreted from the animal. The volatilisation rate of VFAs is dependent on pH, temperature, moisture content and other factors.

Hao et al. (2005) examined the effect of diet on the characteristics of feedlot manure including the VFA content. The manure was taken from the pen floor after 113 days on feed and included wood chips that accounted for about 60% of the dry matter. They found that acetic acid accounted for 75 to 82% of VFA while propionic acid accounted for 12 to 18% of VFA. Together, these two acids made up 93 to 96% of VFA in the feedlot manure samples.

McGinn et al. (2002) investigated the effect of three barley-based diets on manure composition in a feedlot. They did not measure the VFA content of the manure but did measure VFA emissions from the manure using a collection chamber. The dominating VFA compounds were acetic (30 to 34% of total VFA), propionic (19 to 30%) and butyric (29 to 30%), followed by valeric (4 to 6%), isovaleric (2 to 3%), isobutyric (2%) and caproic (<1%). The percentage of each VFA compound was consistent across all treatments. In the McGinn et al. (2002) study, the proportion of VFA made up of acetic and propionic in the emissions from manure is much smaller than in the acetic and propionic content within manure (Hao et al. 2005). This may be due to different VFA profiles within the manure or it may suggest that VFAs volatilise at a different ratio to their content in manure. This may have implications when drying manure samples.

The content of VFAs in manure samples is an important consideration when determining moisture content and VS content of the manure. As is explained in following sections, the moisture content of a sample is determined by heating the sample thus driving the moisture out of the sample. It is well known, but rarely quantified, that VFAs also leave the sample during drying.

For example, Pind et al. (2003) undertook a study of the anaerobic digestion of a cattle manure slurry. They measured the TS and VS of the manure using standard procedures (i.e. drying at 105°C) to be 76.6 g/L and 60.2 g/L respectively (VS/TS = 78.6%). They assumed that 80% of the VFAs in the sample are lost during drying but do not provide a reference for this assumption. After applying this correction, they state that the corrected TS and VS are 83.6 g/L and 67.2 g/L respectively (VS/TS = 80.4%). Reanalysing their data, it appears that VFAs constitute 13 % of all VS and that VS was underestimated by 10% using standard laboratory drying procedures.

Another example is Vedrenne et al. (2008) who noted that, during TS determination, the volatilisation of a part of the organic fraction was suspected during drying of the manure at 105°C, leading to an underestimation of the TS and VS concentrations. They undertook an analysis of the total organic carbon in wet and dried (at 105°C) manure slurries and showed a loss of organic carbon after drying at 105°C (Figure 1). Analysis of carbon on wet slurry indicated a carbon content equal to 31 g L-1 while the carbon content of the same slurry, on the same basis but after drying, fell to 23.6 g L-1. The organic fraction responsible for this loss was the VFA fraction in the manure. According to this observation and in order to avoid analytical errors, Vedrenne et al. (2008) developed a methodology to quantify exactly the TS and VS content. VFA were determined for all slurries before (on raw slurry) and after drying (after 2 h extraction of dried slurry with water). The difference between the two values was considered to correspond to the VFA lost during drying. As shown in Figure 1, the carbon mass balance confirmed their hypothesis and showed that the VFA fraction was the main loss during drying. Applying this methodology to all their samples, Figure 2 shows VFA volatilisations during drying and the respective VS underestimations for the 13 slurries studied. Contrary to Pind et al. (2003) who applied a fixed 80% correcting factor of VFA lost during drying, the proportion of VFA volatilisation was variable and represented from 0% to 88% of total VFA. Vedrenne et al. (2008) found no correlation between slurry characteristics (pH, TS, VFA contents) and VFA losses. The VS underestimations resulting from the VFA losses could reach 25%. This work clearly demonstrates that VS can be underestimated due to VFA loss during the initial drying of the manure sample but provides no guidance on an appropriate correction method.

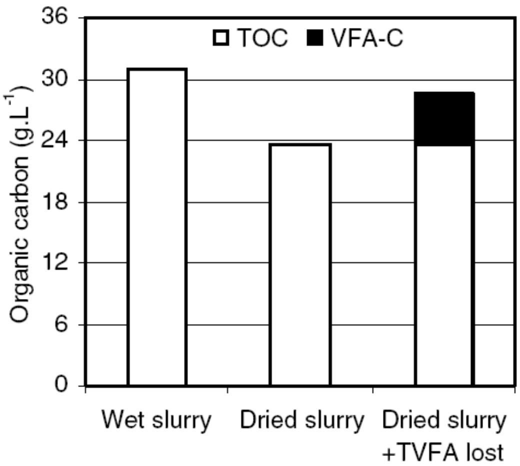


Figure 1 – Loss of VFAs during manure drying at 105°C (Vedrenne et al. 2008)

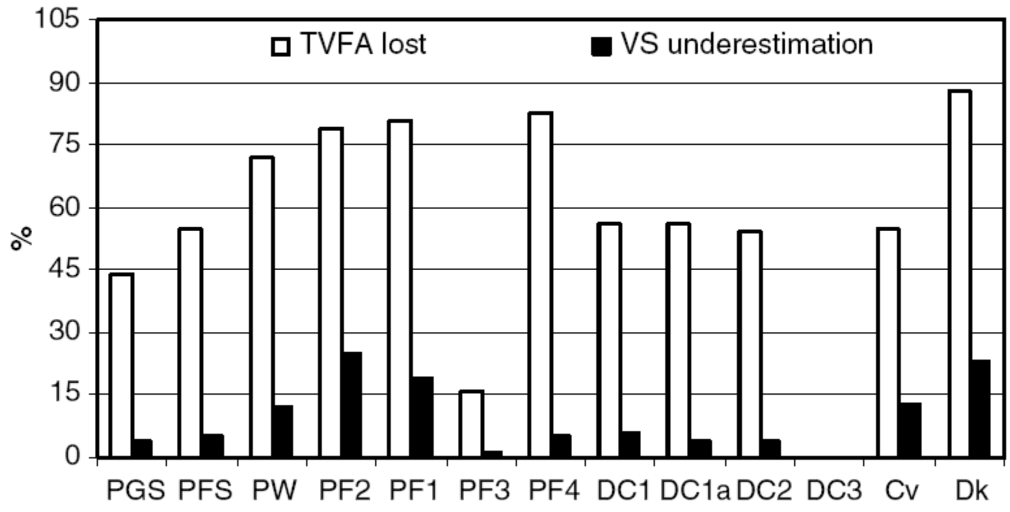


Figure 2 – VS underestimation due to drying (Vedrenne et al. 2008)

2.1.5 Relationship between Faecal VS and Manure VS

Manure consists of faeces and urine. For field work in feedlot pens, it is not possible to sample urine but it is possible to sample fresh faeces (see Photograph 12). In this project, the objective is to measure manure VS content. Hence, it is necessary to determine if a correction factor needs to be applied when only faeces is sampled.

Sinclair (1997) undertook an experiment that aimed to determine the dietary concentration of P on both the amounts and routes of excretion of P from cattle. In their experiment, ten weaner steers were fed five different diets with varying P contents. Urine and faeces was measured separately for each animal. The dry matter and ash content of the faeces and urine was measured for each treatment. Hence, it is possible to determine the VS content of urine and faeces separately.

Table 2 shows the data presented by Sinclair (1997). This shows that the VS of the faeces alone averages about 82% but, when the urine is added, the VS of the total manure is about 79%, i.e. manure VS is about 97% of faeces VS. As this correction is fairly minor, it has not been applied to any fresh faeces samples in this study.

Table 2 – Feed and manure data for five diet treatments

		TREATMENT – Diet P Content				
Parameter	Units	0.26% P	0.30% P	0.35% P	0.45% P	0.55% P
Mean LWT	kg	304.9	304.7	304.2	305.5	302.2
DMI	kg DM/day	8.0	8.3	8.5	8.3	7.9
ADG	kg/d	1.2	1.2	1.2	1.2	1.2
FCR	kg DM/kg gain	6.9	7.1	7.4	7.1	6.8
P						
Intake	g/d	24.2	25.6	28	34.1	35.4
Faecal excretion	g/d	13.9	13.8	16.8	16.8	18.3
Urine	g/d	3.3	4.1	4.5	5.6	8.0
TOTAL	g/d	17.2	17.9	21.3	22.4	26.3
N						
Intake	g/d	200.2	212	218.6	214.5	200.7
Faecal excretion	g/d	69.2	72.7	75.7	74	71.9
Urine	g/d	92.1	96.3	101.4	98.2	101.3
TOTAL	g/d	161.3	169.0	177.1	172.2	173.2
% N in urine	%	57.0	57.0	57.0	57.0	58.0
Faeces						
Total	kg/d	9.6	10.2	10.4	10.4	10.1
DM	%	27.0	27.0	28.0	27.0	27.0
DM	kg/d	2.7	2.8	2.9	2.85	2.7
Ash	% DM	18.3	18.1	18.1	17.4	18.1
VS	% DM	81.7	81.9	81.9	82.6	81.9
VS	kg/d	2.2	2.3	2.4	2.4	2.2
Urine						
Total	kg/d	9.9	10.6	11.8	11.0	11.4
DM	%	4.8	4.5	4.3	4.4	4.5
DM	kg/d	0.5	0.5	0.5	0.5	0.5
Ash	% DM	34.7	34.0	33.9	33.5	33.5
VS	% DM	65.3	66.1	66.1	66.5	66.5
VS	kg/d	0.3	0.3	0.3	0.3	0.3
Total Manure	kg/d	19.6	20.8	22.2	21.4	21.5
	% LWT	6.4	6.8	7.3	7.0	7.1
	DM/d	3.1	3.3	3.4	3.3	3.2
Faeces VS	%	81.7	81.9	81.9	82.6	81.9
Manure VS	%	79.2	79.6	79.5	80.2	79.5
Manure VS / Faeces VS		96.9	97.1	97.1	97.2	97.0

Source: Sinclair (1997)

2.2 Cattle feedlots in Australia

2.2.1 Overview

A cattle feedlot is a facility where beef cattle are housed in open pens and fed a prepared ration until they reach a specified weight. Only weaned cattle enter the feedlot and no breeding of cattle occurs at the feedlot. The pen surface is typically compacted clay or gravel. Depending on site-specific conditions, feedlot pens are stocked at between 10 and 20 m^2/head. Animal size is sometimes standardised to SCU (standard cattle units) (Skerman 2000).

In Australian feedlots, cattle are fed for different market specifications. Within a typical feedlot, there could be several different market types being fed at any one time. The parameters that specify the herd component of the feedlot system include:

- Entry weight (kg) – the liveweight of individual incoming cattle. This typically ranges from 250 kg to 450 kg depending on market type.
- Exit weight (kg) – the liveweight of individual cattle leaving the feedlot. This typically ranges from 400 kg to 700 kg depending on market type.
- Days on feed (DOF) – the number of days that cattle of each market type are fed. This typically ranges from 60 days to 300 days depending on market type
- Average daily gain (ADG) (kg/day) – the average daily liveweight gain from entry to exit
- Dry matter intake (DMI) – daily feed intake (kg DM/head/day)
- Liveweight gain (kg) – Exit weight, minus entry weight
- Mortality rate (%) – the percentage of incoming cattle that die during their time at the feedlot (typically 0.5% to 1.5%)
- Cattle-on-hand – the number of cattle in the feedlot at any one time
- Occupancy (%) – cattle-on-hand as a percentage of pen capacity.

Photograph 1 - Typical view of cattle in an Australian feedlot

2.2.2 Location of feedlots in Australia

Feedlots are generally located across the grain-growing regions of Australia. The climatic zones in which feedlots are located are of relevance to this study. The thermal energy recovery methods assessed in this study require "dry" manure as the energy source. The amount and annual patterns of rainfall affect the moisture content of manure on the pen surface and the rate at which that manure breaks down. Table 3 shows a summary of Australia's current feedlots in areas with above and below 750 mm of mean annual rainfall. Figure 3 shows the current feedlot distribution with annual rainfall. This shows that 26% of individual feedlots are in areas that have greater than 750 mm of annual rainfall. While this is a significant number of individual feedlots, it only represents 12% of Australia's current total pen capacity.

Table 3 – Location of current feedlots with respect to mean annual rainfall

	No. of Feedlots	%	Average Capacity	Pen Capacity	% Industry Capacity
Summary					
< 750 mm	628	74%	1874	1,176,767	88%
> 750 mm	223	26%	709	158,085	12%
< 600 mm	142	17%	2566	364406	27%
600-650 mm	250	29%	1867	466743	35%
650-700 mm	143	17%	1809	258752	19%
700-750 mm	93	11%	934	86866	7%
> 750 mm	223	26%	709	158085	12%
TOTAL	**851**	**100%**	**1,569**	**1,334,852**	**100%**

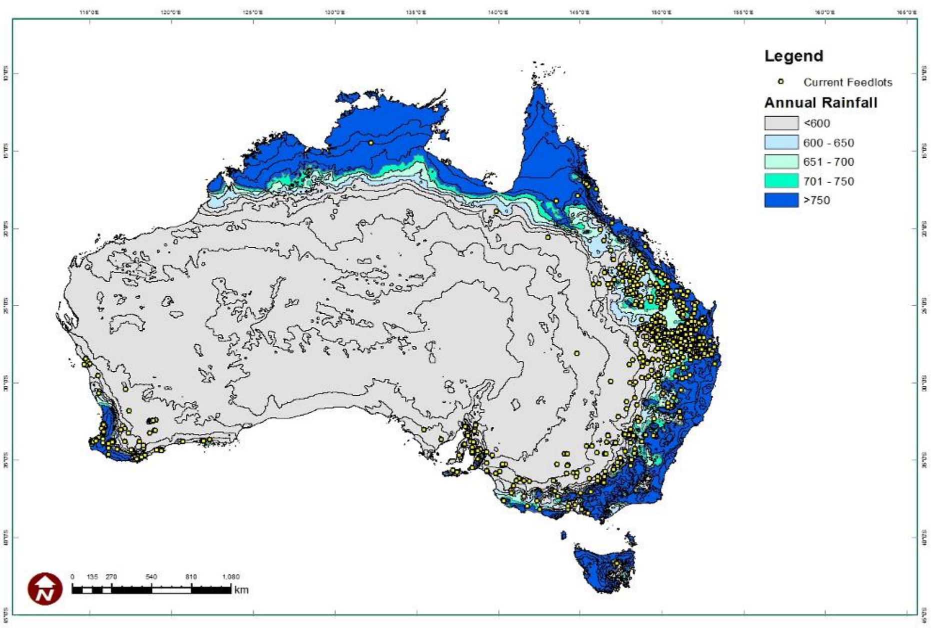


Figure 3 – Location of Australian feedlots vs. annual rainfall

The distribution of rainfall throughout the year has a significant bearing on the management of a feedlot (Tucker et al. 1991). Feedlots located in areas with high winter rainfall and low evaporation rates have problems with odour management, as a wet pad is the main cause of odour generation (Tucker et al. 1991). This clearly has a bearing on the viability of thermal energy recovery systems because wet, degraded manure is not viable.

Table 4 shows a summary of Australia's current feedlots in relation to seasonal rainfall. Figure 4 shows the current feedlot distribution with seasonal rainfall. Currently, 22.8% of individual feedlots are located in winter dominant rainfall areas. This accounts for 26.7% of current pen capacity.

Table 4 – Current distribution of feedlots in seasonal rainfall regions

Climatic Zone	No. of Feedlots	%	Average Capacity	Pen Capacity	% Industry Capacity
Winter Dominant	53	6.2%	1,214	64,354	4.8%
Winter	141	16.6%	2,075	292,521	21.9%
Total Winter	194	22.8%	1,840	356,875	26.7%
Summer Dominant	33	3.9%	1,999	65,973	4.9%
Summer	577	67.8%	1,282	739,705	55.4%
Total Summer	610	71.7%	1,321	805,678	60.4%
Arid	1	0.1%	400	400	>0.1%
Uniform	46	5.4%	3,737	171,899	12.9%
TOTAL	851	100.0%	1,569	1,334,852	100.0%

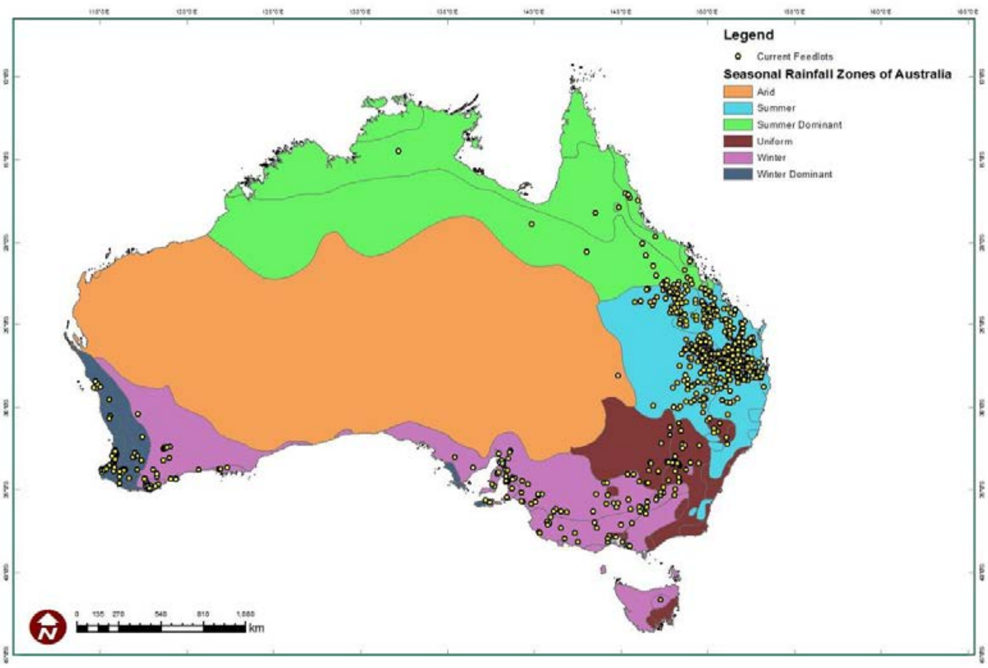


Figure 4 – Location of Australian feedlots vs. seasonal rainfall zones

2.3 Feedlot manure management systems

2.3.1 Manure management overview

Cattle excrete fresh manure (urine plus faeces) onto the pen surface (known as the feedpad) where it immediately begins to breakdown. Ammonia and other volatile components such as VFAs are lost from the manure. After a period of time, machinery removes the dry manure from the pens (Photograph 2). The removed manure is typically held in a manure stockpile area where it may be composted prior to sale off-site or spreading as an organic fertiliser on agricultural land. A small percentage of manure is removed from pens by runoff during heavy rainfall events. Dry matter (mainly carbohydrates) is lost from manure to the atmosphere as CO_2 and CH_4 in all phases of manure handling and storage.

Manure management is site-specific, since it depends on feedlot design, management, labour, climate and seasonality. In Australian feedlots, the components of manure management are:

- Pen cleaning and manure harvesting
- Manure stockpiling and/or composting
- Manure utilisation as fertiliser.

Potentially, manure is a valuable organic fertiliser but the monetary value depends on local circumstances. It is also the source of most odour emitted from a feedlot. Hence, there has been considerable research undertaken over the years into the characteristics of feedlot pen manure.

2.3.2 Pen cleaning systems

As cattle occupy feedlot pens, excreted manure accumulates on the pen surface. It is now well understood that excessive accumulation of manure has an adverse effect on animal performance, animal welfare and environmental impact. Hence, pens should be cleaned of manure at a frequency that prevents adverse effects.

Pens are typically cleaned using box scrapers, front-end loaders or excavators. In some instances, scrapped manure is immediately removed from the pens. In other instances, manure is mounded into a pile in the centre of the pen. The mound is then removed at a later date. Further breakdown of the manure occurs in the mounds so feedlots that mound generally remove a reduced tonnage of manure from the pens.

The frequency at which pens are cleaned (pen cleaning frequency) depends on a range of factors including:

- pen stocking density (head per m^2)
- occupancy (% of time that pen is occupied by cattle)
- feed processing method (better feed processing means better feed conversion means reduced manure excretion)
- animal liveweight and daily feed intake
- pen manure moisture content.

Taking all of the above factors into account, pen cleaning frequency can range from every three weeks to every six months.

A short-term issue that affects pen cleaning frequency is the moisture content of the pen surface. If the pen surface is too dry, pen cleaning causes significant dust. It is difficult to form stable manure mounds (see Photograph 2). Under wet pen conditions (such as are experienced in southern feedlots in the winter), it is difficult to remove the manure as it becomes close to a slurry (see Photograph 3). Most lot feeders agree that the optimum moisture content at which to clean pens is about 35% (which is too wet for all thermal energy options).

On top of the original pen surface, it is typical for what is called the interface layer to form. This is a layer of hard-compacted manure immediately on top of the base gravel or clay (see Photograph 4). Some lot feeders ensure that pen cleaning does not remove this interface layer. This ensures that a soft pen surface is left for the cattle and that excess clay or gravel is not removed from the pens. Photograph 5 is an example of a pen surface where about 25 mm of loose dry manure has been removed but the hard, compacted interface layer is retained. In this case, the removed manure is not contaminated with clay or gravel. Photograph 6 is an example of pen cleaning where the interface layer is completely removed leaving a compacted clay base. In this instance, it is inevitable that some clay contaminates the manure, thus reducing its quality as a fertiliser or a thermal energy source. The differences in pen manure quality resulting from different manure management practices will be documented in later sections of this report.

Photograph 2 – Pen cleaning using a box scraper under dry conditions

Photograph 3 – Pen cleaning using a box scraper under wet conditions

Photograph 4 – Example of the compacted manure interface layer

Photograph 5 – Pen cleaning while retaining a compacted manure interface layer

Photograph 6 – Pen cleaning with a front-end loader where the interface is removed exposing the clay base

2.3.3 Quantity of harvested feedlot pen manure

The economic analysis of any thermal energy recovery option needs an estimate of the quantity of manure produced at a feedlot. While there are many studies that report the characteristics (quality) of feedlot pen manure (from a fertiliser perspective), surprisingly few studies have quantified the manure removed from feedlot pens. As the following section shows, when assessing "manure" production, it is important to understand the proportion that is manure and the proportion that is soil, clay or gravel.

Recently, Kissinger et al. (2006b) and several others measured manure removal from a number of feedlot pens. Kissinger et al. (2007) reviewed available literature on the characteristics and quantity of manure removed from feedlot pens in the USA. Table 5 is a summary of his review. When using this data in Australia, care should be taken in interpreting the results as there are significant variations in:

- Feedlot pen characteristics
- Manure management methods
- Manure sampling and handling protocols
- Manure testing methods
- Climatic conditions

Sweeten et al. (1985) analysed manure harvested from several different feedlots in the USA in 1979 and 1980. Samples were analysed for ash content, moisture content, total-N, sulphur and heat of combustion. Table 6 shows Sweeten's results from one site. Average manure depth is stated to be 115 mm above the original soil layer. For the surface layer, VS is 72.5% but this decreases to only 26.5% in the interface layer. This means that the manure in the interface layer is either well degraded or it is mixed with soil. This would be common at feedlots in the USA at that time when limited feedlot pad preparation was undertaken and soil was often harvested with the manure. Photograph 7 shows a US feedlot where virtually no earthworks are undertaken and the pens are simply located on bare uncompacted soil. In this situation, it is common to harvest considerable soil volumes with manure during pen cleaning. Photograph 8 shows pen mounding, another common activity in US feedlots. Sometimes, earth mounds are constructed in the middle of feedlot pens to provide a dry refugee for cattle during wet conditions. Under these circumstances, when manure is removed, particularly under wet conditions, considerable soil can be taken with the manure.

In the second part of the Sweeten project, manure was removed from pens at Feedlot A and Feedlot B using a wheeled loader. The loader operator was instructed to leave a 25 mm thick "uncollected" layer of manure above the soil. The VS content of the removed manure at Feedlot A (65%) was much higher than at Feedlot B (36.8%). It was assumed that, in Feedlot B, previous wet conditions had led to a significant amount of soil being mixed in with the pen manure. The VS content of the "uncollected" layer was 20.7% and 35.1% for Feedlots A and B respectively.

This data highlights the need to be fully aware of the circumstances behind pen manure samples. Low VS contents can either be due to prolonged manure breakdown or due to mixing of manure with soil. For example, Miller (2001) undertook a study looking at the compounds in "feedlot soil" that might contribute to odour emissions. (In US studies, "feedlot soil" refers to the combination of soil and manure harvested from pens.) The organic matter (assumed to be VS) of their manure sample taken from the feedlot pens was 32.4% (DM basis) with a total-N of 1.82%. This low VS content clearly indicates that this sample is a combination of manure and soil. Kissinger et al. (2007) reports the results of manure harvesting data from six Nebraska feedlots. The average TS and VS removal was 5.3 and 1.5 kg/head/day respectively. This implies a VS content of the removed material to be 28%, on average, indicating a large proportion of soil in the harvested manure.

However, they did report a large range for VS/TS from 19% to 55%. They noted that different management practices resulting in different proportions of soil removed during pen cleaning.

Table 5 - Excreted and harvested manure from cattle feedlots (Kissinger et al. 2007)

Reference	Animal Characteristics	Housing / Ration	Moisture (% wet basis)	TS	VS	N	P	K
				Kg/hd/day unless otherwise indicated				
Excreted Manure								
(Gilbertson et al. 1974)	420-kg feeder, Eastern NE	High energy		1.76	1.65			
(NRCS 1992)	420-kg feeder	High forage	88	2.84	2.53	0.13	0.046	0.1
	420-kg feeder	High energy	88	2.48	2.28	0.13	0.039	0.088
	272-kg calf	Calf	87	2.05	1.74	0.082	0.027	0.054
(ASAE 2005)	446-kg feeder	High energy	92	2.4	1.9	0.16	0.022	0.11
(Lorimor et al. 2000)	499-kg feeder	High energy	92	2.8	2.6	0.24	0.042	0.12
	340-kg feeder	High energy	92	1.9	1.8	0.17	0.028	0.083
	499-kg feeder	High forage	92	3.4	3.4	0.28	0.042	0.14
	340-kg feeder	High forage	92	2.4	2.4	0.19	0.028	0.094
	204-kg calf		92	1.3	1.3	0.063	0.020	0.041
Harvested Manure								
(NRCS 1992)	454-kg feeder	Open lot	45					
		Surfaced – high forage	53					
		Surfaced – high energy	52					
(ASAE 2005)	446-kg feeder	High energy	33					
(Gilbertson et al. 1974)	420-kg feeder	Roofed – high energy	78					
	408-kg feeder	Eastern NE open lot – High energy	55					
(Gilbertson et al. 1971)	18.5 m^2/hd Eastern NE	Eastern NE open lot	54					
(Kissinger 2005)		Eastern NE open lot	[a]	[b]	[b]	[b]		
	Summer – 467 kg (132 pens)		30±15	4.7±4.4	1.1±1.0	0.06±0.06		
	Winter – 465 kg (112 pens)		39±21	8.8±8.6	2.2±1.5	0.10±0.07		
(Sweeten et al. 1985)	15.5 m^2/hd	TX open lot – Heifers – 152 day feeding period	[a] 22-40%		[c] 26-72%	[c] 2.6%		
(Sweeten et al. 1985)		Eastern CO open lots – 152 day feeding period	[a]		[c]	[c]		
	20-23 m^2/hd		48±19%		65±24%	2.6±0.5%		
	17-20 m^2/hd		38±26%		37±35%			
(Sweeten et al. 1985)		Eastern CO open lots – 152 day feeding period	[a] 52±10%		[c] 62±11%	[c] 2.7±0.4%	[c] 1.5±0.6%	

[a] Mean ± 2 standard deviations expressed as % wb.
[b] Mean ± 2 standard deviations expressed as kg/head/day.
[c] Mean ± 2 standard deviations expressed as % db.

Table 6 - Pen manure characteristics at different depths

Manure Zone	No of samples	Moisture content (%)	Ash (%)	VS (%)
Loose surface layer	4	21.5	27.5	72.5
Moist loosely-compacted layer	3	39.7	32.6	67.4
Moist interface layer	3	21.7	73.5	26.5

Source: Sweeten et al. (1985)

Kissinger et al. (2006a) summarised the data from 18 separate manure harvesting experiments in Nebraska. As they have cold, relatively dry winters and warm, wet summers, the data was summarised into summer and winter experiments. The average amount of dry matter removed in summer experiments was 4.7 kg DM/head/day but this almost doubled to 8.8 kg DM/head/day in winter. The average moisture content of removed manure was 30.4% in summer and 38.6% in winter. The amount of VS removed increased from 1.1 kg VS/head/day in summer to

2.2 kg VS/head/day in winter. The VS/TS ratio for summer manure removed was 24.1% while it was only slightly different in winter (27.5%). Assuming similar TS excretion from the summer cattle compared to the winter cattle, it must be assumed that the greater VS removal per head in winter is due to decreased VS breakdown in the pens in winter due to cold conditions. However, the results are confused by the apparently higher content of soil in winter-removed manure. If the summer and winter manure removal rates are annualised, the TS removal rates are equivalent to 1.7 and 3.2 t DM/head/yr respectively.

The VS/TS ratio in the harvested manure in the Kissinger et al. (2006a) trials ranged from 9.5% to 52.4%. Material with only 9.5% VS must be mainly soil. However, the removed material that was 52.4% VS is probably degraded manure with a small soil content. This wide range of VS content in material harvested from feedlot pens demonstrates the influence of pen design and management on the quality of manure removed from the pens.

In summary, in the last 25 years, the main good quality US studies undertaken to determine the amount of manure removed from feedlot pens have been undertaken in Nebraska. The manure removal ranges from about 4.7 kg DM/head/day to 8.8 kg DM/head/day (1.7 to 3.2 t DM/head/yr) depending on climatic and pen harvesting conditions. The VS content of the harvested manure ranges from 10% to 55% depending on the amount of VS breakdown and the soil content of the manure. None of these studies provide any data on the amount of soil or gravel that is replaced into pens to restore the level of the original pen surface.

When data is presented on the concentration of nutrients in feedlot manure (following sections), this is determined on pen manure samples that may contain an unknown percentage of soil from the pen surface. This would tend to produce nutrient and VS concentration levels that are lower than would be measured from a “pure” pen manure sample.

By contrast to US feedlots, most new Australian feedlots have a pen surface that was well compacted, often gravelled and levelled prior to cattle entry. Pen cleaning usually aims to leave a shallow interface layer of manure so as not to disrupt the compacted pen surface. Hence, in most Australian feedlots, the amount of soil removed during pen cleaning should be minimal. This should be reflected in a higher VS content in Australian harvested pen manure than in US or Canadian feedlots.

In Australia, for many years, the “standard” amount of manure removed from feedlot pens was assumed to be 1 t DM/head/yr (2.74 kg DM/head/day). In recent years, some lot feeders have indicated that their manure harvesting records indicate the real number could be half of this (0.5 t DM/head/yr or 1.37 kg DM/head/day). It is reasonable to suggest that improved diet formulation and feed processing methods have improved diet digestibility so that less manure is excreted per head.

Photograph 7 - A US feedlot with pen surface of uncompacted soil

Photograph 8 - Feedlot pen with manure mound

In order to determine whether manure harvested from Australian feedlot pens does contain less soil than US pen manure, Davis et al. (2010) undertook a study aimed at measuring the quantity and quality of manure removed from Australian feedlot pens and comparing that data with BEEFBAL predictions. BEEFBAL is a mass-balance model used to predict manure excretion at feedlots (Davis et al. 2012).

Six feedlots across Australia, which are representative of climatic zones, feeding regimes and manure management processes, were selected as study sites for this project. A methodology to measure manure accumulation rates was developed based on grid-sampling pattern to provide a feedlot 'manure budget'. The grid-sampling pattern allowed representative sub-samples to be collected from across the pen. The appropriateness of the grid pattern for obtaining representative samples was assessed using electromagnetic (EM38) induction mapping. The EM38 survey data confirmed that the grid sampling pattern would provide representative samples being taken from these pens. Manure accumulation rates and manure decomposition data from four feedlots (two feedlots dropped out of the study) were collected several times between pen cleaning events over a 12-month period. For each batch of cattle, records of cattle numbers and liveweights, ration types and feed consumption were collected. Feedlot managers were asked to completely clean pens at the start of the study and then clean them back down to exactly the same level at the end of the study so that there would be no net accumulation or reduction in manure in the feedpad.

The results showed that manure depth was quite variable across the pen due to deposition rates and moisture content at the time of measurement. Under dry conditions, on average across the pen, about 20 mm of manure had accumulated after about 25 days. Manure accumulated gradually to about 30 mm after 75 days. With continued dry conditions, the manure pack gradually increases to around 35 mm after a further 100 days (see Feedlot D in Figure 5). These data indicate that the feedpad compacts very tightly under dry conditions. Further, it is likely that some manure is removed from the pen as dust under these conditions but it was impossible to quantify this loss.

Conversely, under wet conditions, on average across the pen, a manure depth of 30 mm was measured after about 25 days. After 75 days, a manure depth of 50 mm on average was measured (see Feedlot F in Figure 5). When the compact manure pack is moistened due to rainfall, it can expand the dry compacted depth two-fold or more. The wetter the pen surface, the greater the variation across the pen. Greater depth measurements indicate areas of higher manure deposition and pugging of the manure due to cattle concentration.

Note: Feedlot A and Feedlot B referred to by Davis et al. (2010) are not the same feedlots as Feedlot A and Feedlot B in this study.

Davis et al. (2010) regularly measured the VS content of the manure on the pen surface. Pen manure samples were obtained directly after pen cleaning, prior to harvest and in between. Over time, the VS in the manure breaks down and is released to the atmosphere as CH_4 or CO_2. The loss of VS from the pen surface was calculated. The following can be concluded from the pen manure decomposition stage of the study.

- After 20 days, a reduction of between 60 and 70% in VS in the pad manure compared to fresh manure was measured. Fresh faeces typically is about 80% VS. The greatest rate of VS decomposition occurs in the first 10-20 days - see Figure 6.
- After 35 days, a reduction of 70% in VS in the pad manure compared to fresh manure was measured.
- After 80-100 days, a reduction of 75% in VS in the pad manure compared to fresh manure was measured.

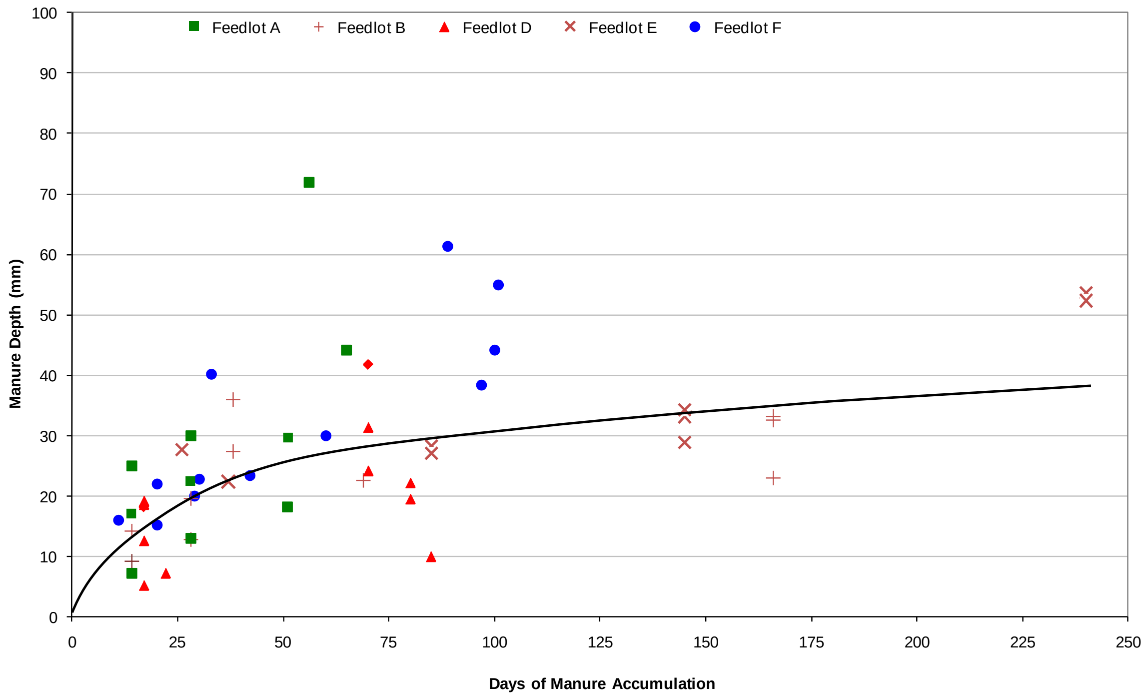


Figure 5 – Manure depth vs. days since cleaning (all pens)

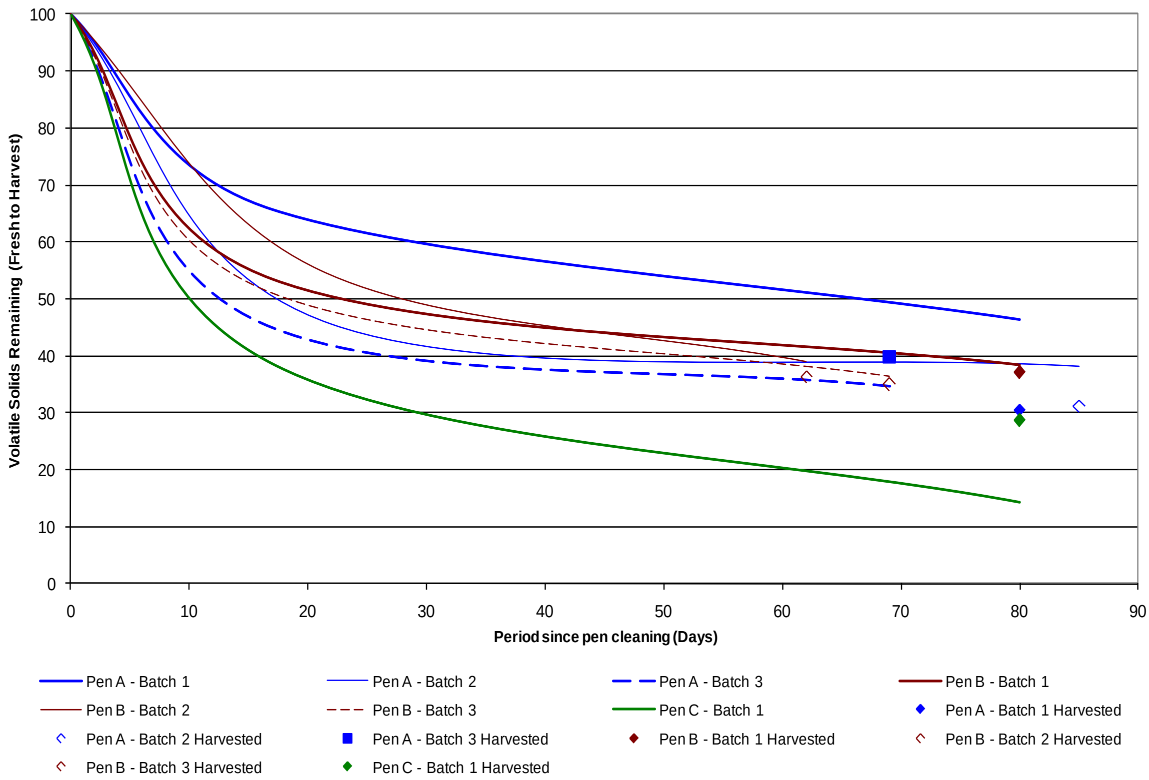


Figure 6 – Volatile solids remaining over time (Feedlot D)

Data on the mass of harvested manure was obtained from four feedlots. The wet mass of manure from pens was weighed and representative samples taken to determine moisture content. From this data, TS and VS excreted was estimated and compared with BEEFBAL predicted values (Figure 7). Estimated data was comparable to predicted data at only one feedlot. At this feedlot, manure excretion ranged between 800 and 1200 kg DM/SCU/year. Dry conditions and maintenance of a manure interface layer ensured that the material harvested was manure only, thus resulting in comparable data. At this site, the data suggests that little soil was harvested, which is consistent with an understanding of the management at that feedlot.

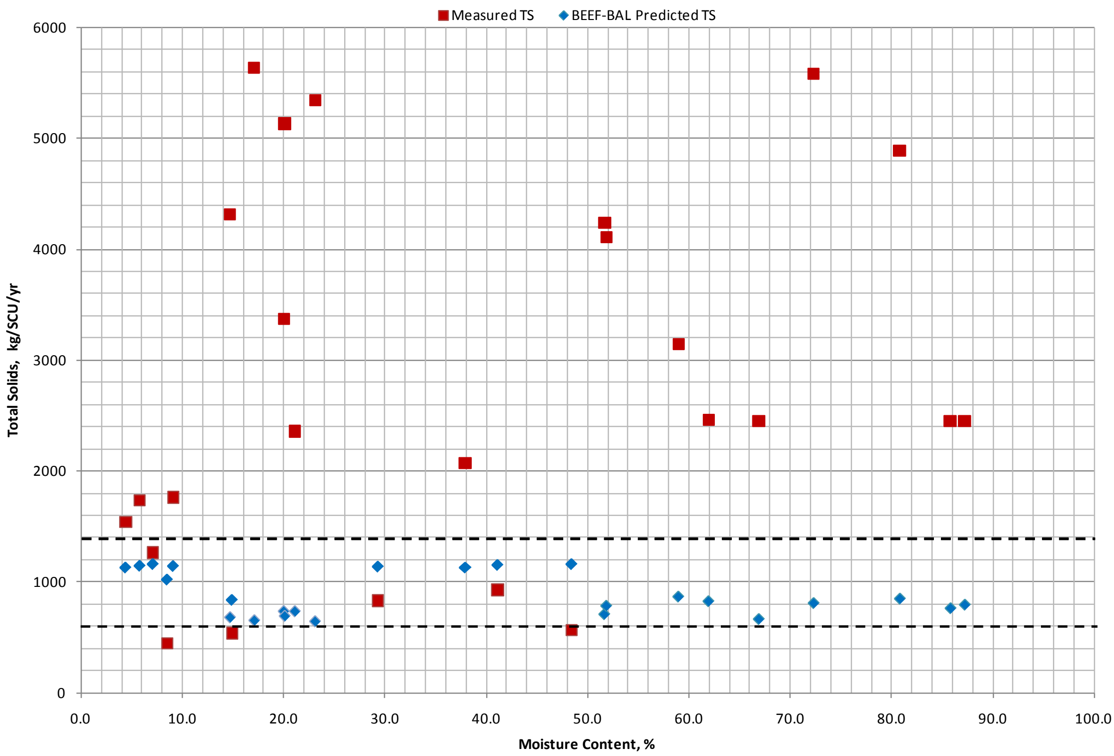


Figure 7 - Comparison of measured versus predicted manure (TS) removed from pens at different moisture contents

At feedlots which cleaned their pens back to the gravel base, the measured TS was up to five times higher than the predicted value using DMDAMP in BEEFBAL. In addition, the VS/TS ratio of the excreted manure was about half that of fresh manure. Data from these feedlots suggest that the material harvested contains material other than manure. This additional material (e.g. rocks and/or soil) influences the results by increasing quantity of material harvested and lowering the organic content. This is consistent with US feedlots where "feedlot soil" is harvested.

Summary

The data of Davis et al. (2010) suggests that, when only manure is removed from pens, the annual manure harvested is about 1 t DM/head/yr or less as previously quoted. However, as with US experience, if soil is removed with the manure, the annual harvested tonnage is much higher. Fresh faeces mixes with the manure on the pen surface and starts to degrade. After only 10 to 20 days, 60% to 70% of the VS in the fresh faeces has been lost. After 10 to 20 days, only 10 mm to 15 mm of manure would have accumulated on the pen surface. Pen moisture content is highly variable depending on local weather conditions. Pen moisture content can vary from 10% to 90%.

2.3.4 Quality (characteristics) of feedlot manure

The economic and thermal energy value of feedlot manure is largely determined by the composition (quality) of the manure. Table 7 shows typically measured concentrations of various elements in manure taken from the pen surface. Table 8 shows similar data for samples taken from feedlot manure stockpiles. This manure may be aged for a prolonged period of time. These results show a wide variation in the reported data. Thus, typical manure concentrations of nutrients and salts are usually provided with a range of values to emphasise the inherent variation. This occurs due to wide variations in design, management, diets and climatic conditions between feedlots.

Bridle (2011) used the data in Table 9 as design manure characteristics for a feasibility study into energy from feedlot wastes. Bridle (2011) assumed an average dry matter content of 73% (i.e. 27% moisture). This value is in the range of typical data but drier than the average. Bridle (2011) assumed an average VS content of 67.6%. This is typical of manure taken directly from pens but is too high for manure taken from stockpiles.

Table 7 – Typical feedlot pen manure analyses

Parameter	Av. Result	Min	Max	Number of Samples
Dry Matter (%)	65.4	19.6	95.6	152
Volatile Solids (% db)	61.1	24.6	89.0	150
Total Nitrogen (% db)	2.5	1.0	4.1	78
Total Phosphorus (% db)	0.8	0.2	1.2	27
Potassium (% db)	1.8	0.6	3.1	27
Sodium (% db)	0.3	0.1	0.5	27
Sulphur (% db)	0.5	0.3	0.7	29
$EC_{1:5}$ (dS/m)	14.3	5.9	18.8	22
Ammonia-N (mg/kg db)	2100	130	8600	49
Nitrate-N (mg/kg db)	147	0	774	44
Copper (mg/kg db)	43.8	11	68	23
Iron (mg/kg db)	11783	1900	27,000	23
Zinc (mg/kg db)	280	79	430	23

While there is not a large amount of data in the open literature on the heavy metal content of harvested feedlot manures, there is an abundance of data in the literature on the heavy metal content of beef and dairy cattle manures and slurries. Table 10 provides a summary of some of the cattle manure and slurry heavy metal data from the UK (Chambers et al. 1998, Nicholson et al. 1999).

Table 8 – Typical aged (stockpiled) feedlot manure analyses

Parameter	Av. Result	Min	Max	Number of Samples
Dry Matter (%)	61.1	37.2	89.0	19
Volatile Solids (% db)	46.5	18.3	73.3	17
Total Nitrogen (% db)	2.0	0.8	3.3	78
Total Phosphorus (% db)	0.8	0.2	1.5	62
Potassium (% db)	1.9	0.8	3.8	64
Sodium (% db)	0.4	0.1	1.7	59
Sulfur (% db)	0.5	0.2	0.8	57
Calcium (% db)	2.4	0.8	17.7	59
Magnesium (%db)	0.8	0.2	1.6	57
$EC_{1:5}$ (dS/m)	8.7	0.2	20.4	52
pH	7.2	6.3	8.7	54
Ammonia-N (mg/kg db)	1830	0.0	11,200	38
Nitrate-N (mg/kg db)	121	0.0	862	33
Boron (mg/kg db)	35.4	0.0	240	34
Cobalt (mg/kg db)	9.6	2.3	30	13
Copper (mg/kg db)	35.3	3.9	78	34
Iron (mg/kg db)	14,145	200	54,000	31
Manganese (mg/kg db)	349	53	870	34
Molybdenum (mg/kg db)	6.1	0.8	19	20
Ortho-phosphate (mg/kg db)	1200	0.0	3173	13
Zinc (mg/kg db)	221	70	490	58

Table 9 - Design harvested manure characteristics (Bridle 2011a)

Parameter	Units	Design Value
TS	%	73.0
VS	%	67.6
Ash	%	32.4
Carbon	%	41.0
TN	%	2.2
TP	%	0.8
Total Sulphur	%	0.6
Potassium (K)	%	2.3
Sodium (Na)	%	0.6
Chlorides (Cl)	%	1.4
GCV	GJ/dry tonne	16.1
NCV	GJ/dry tonne	15.1
Dry mass	kg/head/day	2.5

Table 10 – Cattle manure heavy metal data (mg/kg DM)

Parameter	Mean values from Nicholson et al (1999)				Mean values from Chambers et al			
	Beef cattle manure	Beef cattle slurry	Dairy cattle manure	Dairy cattle slurry	Beef cattle manure	Beef cattle slurry	Dairy cattle manure	Dairy cattle slurry
Arsenic	0.8	2.6	1.6	1.4	0.7	1.0	1.2	1.1
Cadmium	0.1	0.3	0.4	0.3	0.1	0.2	0.4	0.2
Chromium	1.4	4.7	5.3	5.6	1.5	2.6	2.6	5.3
Copper	16.4	33.2	37.5	62.3	15.6	30.9	31.4	51.0
Lead	2.0	7.1	3.6	5.9	1.4	5.8	2.2	4.8
Nickel	2.0	6.4	3.7	5.4	2.1	3.3	2.8	5.5
Zinc	81	133	153	209	63	132	145	176
TS (%)	21.0	12.0	18.4	7.6	21.0	13.0	16.0	7.0

The heavy metal content of beef cattle manure and slurry is consistently lower than that reported for dairy cattle manure and slurry. It is also clear that slurries have higher heavy metal contents than manures, probably due to the inclusion of soil and other foreign material in the manure samples. This data suggests that beef cattle feedlot manure is likely to have heavy metal contents similar to those reported for beef cattle manures. These heavy metal concentrations are relatively low when compared to those of sewage sludge and should not cause any environmental issues when harvested manure is treated thermally.

The limited data available for heavy metals in beef feedlot harvested manure is sourced primarily from the USA (Kissinger et al. 2007, Sweeten et al. 2006b). A summary of this data is depicted in Table 11. This data generally supports that reported by Nicholson et al. and Chambers et al. for beef cattle manure and confirms that the more toxic heavy metals such as arsenic, cadmium, lead and chromium are at low levels in beef feedlot manure. The only heavy metals present at any level of significance are barium, manganese and zinc.

Table 11 – Beef feedlot manure heavy metal data

Parameter	Units	Kissinger et al. (2007) data	Sweeten et al. (2006b) data	Sweeten et al. (2006b) data
VS	%	30.0	41.3	79.8
Silicon	%		17.7	2.4
Calcium	%	1.71-1.89	3.0	2.9
Sodium	%	0.32-0.33	0.6	0.7
Iron	%	1.02-1.09	1.2	0.2
Aluminium	%		2.4	0.2
Magnesium	%	0.59-0.62	0.8	0.9
Arsenic	mg/kg		2.4	0.8
Barium	mg/kg		393	529
Cadmium	mg/kg		<1.0	0.4
Chromium	mg/kg		<12.0	4.0
Copper	mg/kg	60-65		
Lead	mg/kg		12.0	4.0
Manganese	mg/kg	320-384		
Zinc	mg/kg	275-284		

2.3.5 Thermal energy properties of feedlot manure

Prior to this study, it appears that there is no published data on the thermal energy (calorific) properties of feedlot manure in Australia. Hence, it is necessary to rely on data published in the USA.

Over the past 20 years, several studies have been conducted into combustion or gasification of feedlot manure and/or combinations of feedlot manure and other biomass materials (e.g. coal, poultry litter, wood). Some of these are outlined in later sections of this report.

It is well understood that the thermal energy value (described as HHV – higher heating value or Gross Calorific Value (GCV)) is decreased with increasing moisture content and ash content of the manure. Eigenberg et al. (2012) cites the commonly used formula that relates HHV to moisture content and ash. It is:

$$HHV = 0.85 * VS * (100 - MC)$$

where HHV – higher heating value (BTU/lb)
VS volatile solids (%db)
MC moisture content (%wb).

Figure 8 usefully shows this relationship graphically.

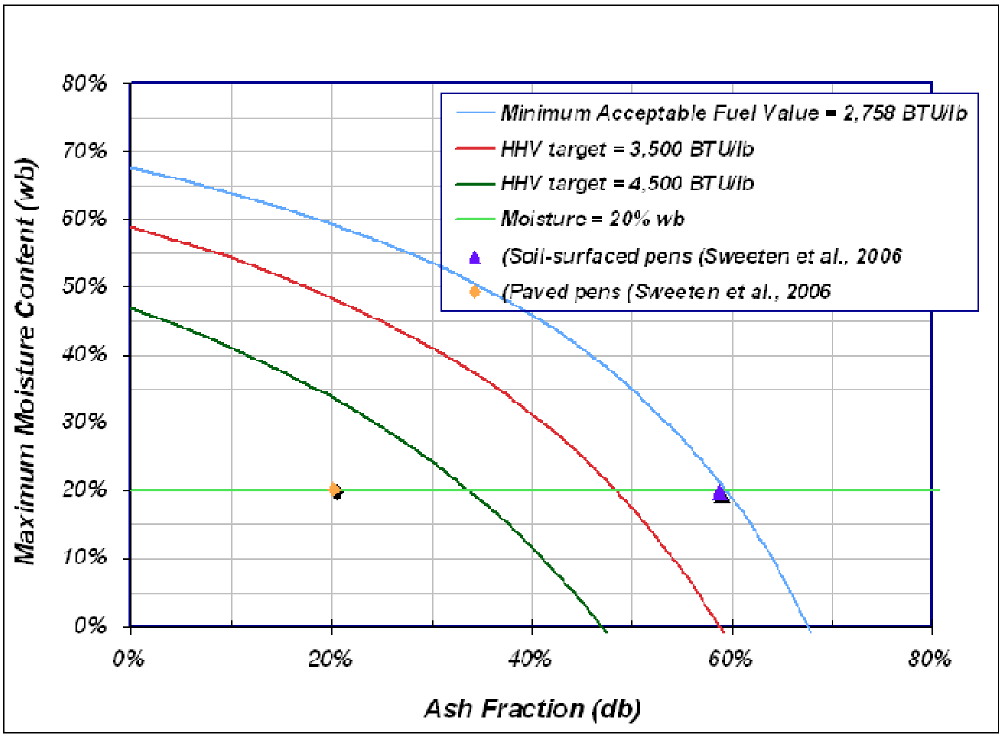


Figure 8 – Relationship between HHV, ash and moisture content for feedlot manure

2.4 Energy consumption at cattle feedlots

Davis et al. (2009) undertook a study of energy usage at Australian feedlots. Eight feedlots were selected such that the feedlots represent a cross section of geographical, climatic and feeding regime diversity within the Australian feedlot industry. The sub-system boundary was the feedlot site itself plus the transport component of bringing cattle and feed into the feedlot and delivering cattle from the feedlot. Energy sources included electricity, diesel for stationary and mobile plant, and gas for steam-flaker boilers.

Power meters were installed to allow an examination of usage by individual activities. Activities that use a significant amount of energy include water supply, feed management, waste management, administration and repairs and maintenance.

The average monthly total energy usage across all feedlots for March 2007 to February 2009 ranged from 49 MJ/head-on-feed/month to 160 MJ/head-on-feed/month. Feedlots with steam flaking feed processing systems had an average usage in the order of 120 MJ/head-on-feed/month, compared with an average of about 45 MJ/head-on-feed for feedlots that process grain by other means. For steam flaking systems, the average monthly gas energy usage measured in 2007-2008 ranged from 240 to 380 MJ/t grain processed. Slightly higher levels were measured in 2008-2009 (260-430 MJ/t grain processed). There were three types of gases used within the four feedlots with steam flaking systems. These included LPG, butane and natural gas. All of these gas sources have different calorific values (heating content) and pricing structures and therefore impact on energy consumption. Some of the variation in gas usage can be attributed to heating efficiency during winter months. However, mill management also impacts on energy consumption.

The best use of the energy generated from the thermal energy recovery from manure would be to provide the steam for feed flaking operations at the feedlots. Davis et al. (2009) has indicated that the average energy required for steam flaking is 120 MJ/head-on-feed/month. Based on this data, Bridle (2011) calculated the daily energy required for steam flaking at 10,000, 25,000 and 60,000 head feedlots (see Table 12). This table also shows the inherent energy in the steam required for flaking.

Table 12 – Steam-flaking energy requirements

Feedlot size (SCU)	Thermal energy for flaking (GJ/d)	Inherent steam energy for flaking (GJ/d)
10,000	40	28
25,000	100	70
60,000	240	168

2.5 Potential energy recovery from feedlot manure

The following sections review the three main processes of thermal energy recovery from biomasses such as feedlot manure. These sections also include a preliminary proposal for their application at cattle feedlots.

2.6 Combustion of biomass

2.6.1 Combustion fundamentals

Combustion is defined as the “rapid exothermic oxidation of the combustible elements of a fuel” (U.S. EPA 1975). That is, combustion is the thermal reaction of oxygen with the carbon, hydrogen and sulphur in a fuel or solid waste yielding heat energy and the principal products of combustion namely, carbon dioxide, water and sulphur dioxide. Provided that there is sufficient air (the stoichiometric amount), the quantity of heat released from the combustible components in a fuel or solid waste is shown in Table 13 (Water Environment Federation 1992).

Table 13 – Stoichiometric combustion reactions

Combustible	Thermal reaction	Product	Heat release (mj/kg combustible)
C +	O_2	CO_2	**32.8**
$2H_2$ +	O_2	$2H_2O$	**142.1**
S +	O_2	SO_2	**9.3**
$6NH_2$ +	$3O_2$	$3N_2 + 6H_2O$	**127.7 (as h_2)**

To ensure complete burn-out of the combustibles in a fuel or solid waste, excess air is required. For wastes such as sludges and manures, it is typical to operate the combustor with excess air in the range of 50 to 150 % over that required stoichiometrically. If excess air is not supplied, only partial combustion will occur and carbon monoxide, soot and other products of incomplete combustion will be generated, causing air pollution issues.

When combusting sludge or manure, the amount of water (moisture content) and combustible material (volatile solids) present in the feed will significantly influence the quantity of usable energy which can be generated by the combustor or in fact, the auxiliary fuel required to effect complete combustion. Figure 9 is a nomogram of combustion energy requirements for sewage sludge at various TS and VS values (U.S. EPA 1975). This data shows that a sewage sludge, with a VS of 60%, combusted in a multiple hearth furnace is autogenous (needs no auxiliary fuel) provided that the TS is 34% or greater. If the VS increases to 75%, autogenous combustion will occur if the TS is 29% or greater. Feedlot manures should behave similarly since its gross calorific value is very similar to sewage sludge.

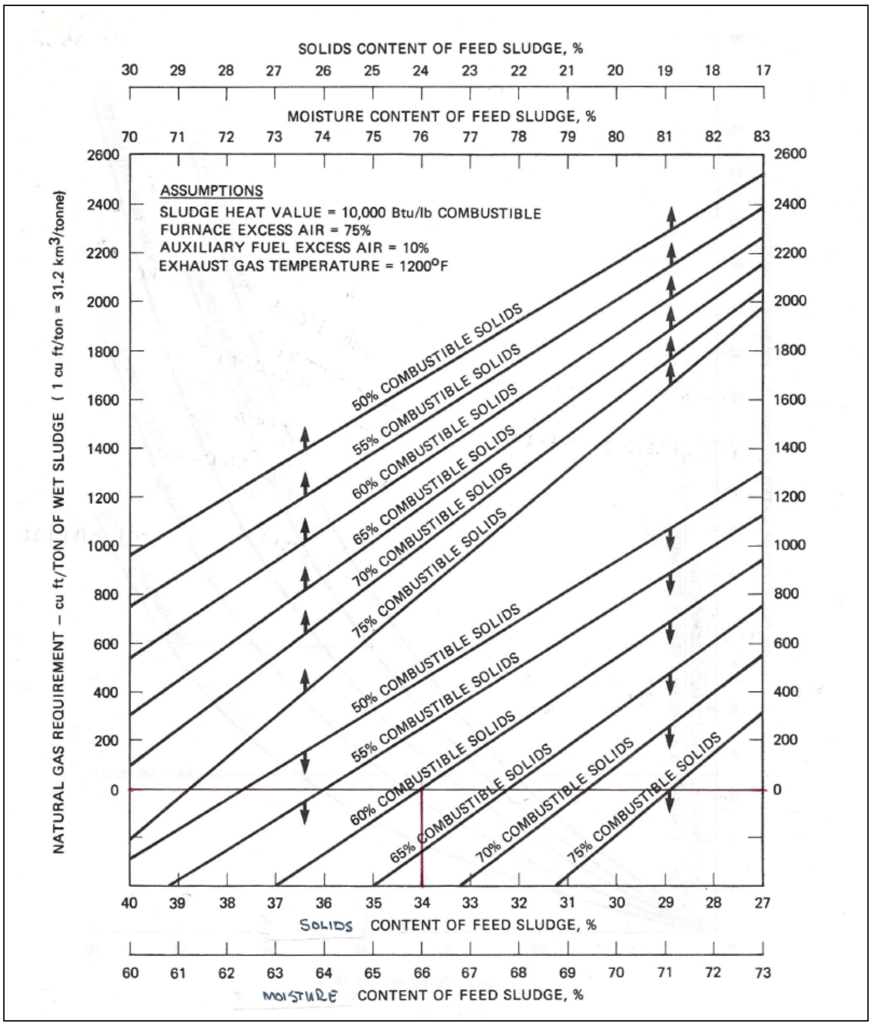


Figure 9 - Impact of feed TS and VS on combustion

2.6.2 Combustion processes

Combustion of solid fuels or wastes is usually affected using three or four types of combustion processes. The most common combustion process is the moving grate furnace, which is the principal combustor used to combust coal and produce electricity. Moving grate furnaces/boilers are also used extensively in the red meat industry to provide heat, hot water and steam to abattoirs and feedlot operations, normally burning wood waste or coal. A schematic of an inclined moving grate furnace is shown in Figure 10 and a picture of MSW burning on a horizontal moving grate furnace shown in Figure 11.

In the past, most sewage sludge was combusted in multiple hearth furnaces but this combustion process is rarely used now due to the problems associated with air emission levels. The most common combustion process now used, especially for solid wastes such as wood waste, sludges and manures, is the fluid bed combustor (FBC). FBCs provide excellent combustion (heat and mass transfer) conditions and thus generate very low levels of nitrous oxides and un-burnt carbon in the flue gas. These combustors offer the most efficient process for combustion of organic waste materials such as sludges and manures. The heart of a FBC is the bed of hot fluidised sand that acts as the combustion chamber. Mixing in the fluidised bed is near perfect and thus there are no hot or cold spots that effect combustion efficiency. Waste solids and sludges are normally fed just above or even into the bed as is shown in Figure 12. Fluidising air is fed from the wind box through the refractory arch into the sand bed. Secondary combustion air is normally fed in the freeboard of the FBC to ensure complete burn-out of combustible material. Fluid beds typically operate at a temperature of between 700 and 800°C in the bed and 800 to 900°C in the freeboard section.

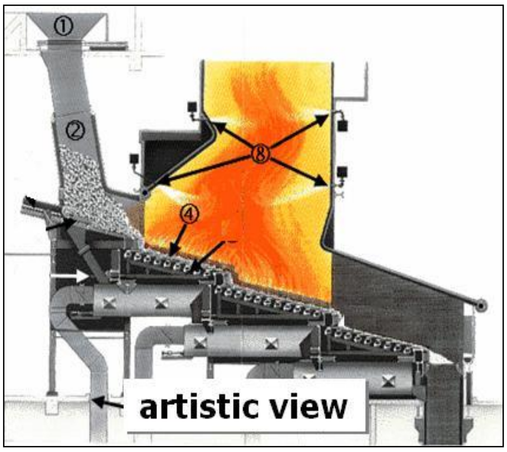


Figure 10 - Schematic of Grate Furnace

Figure 11 - MSW burning on grate

In Europe, the Waste Incineration Directive (WID) dictates that when combusting waste materials in a fluid bed that the minimum temperature in the freeboard must be 850°C and the minimum gas retention time (GRT) be 2 seconds (EU, Directive 2000/76/EC on the incineration of waste, 4 December, 2000). Many Australian environmental agencies apply the same requirement to waste combustion here in Australia.

Many FBCs are designed and operated to be Fluid Bed Boilers (FBBs) with the installation of water tubes in the freeboard area. This is shown in Figure 13. All FBCs and FBBs produce a bottom ash that is withdrawn automatically from the base of the bed as shown in Figure 13. In addition, some of the very fine ash is elutriated out of the bed and must be removed from the flue gas usually using cyclones, electrostatic precipitators or baghouse filters.

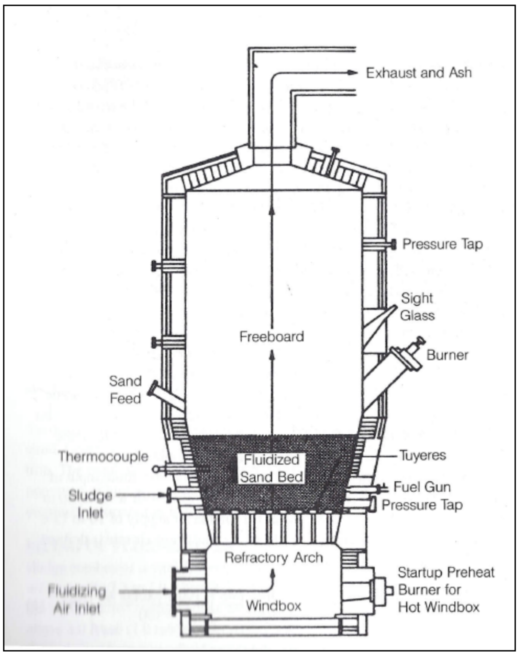


Figure 12 - Schematic of a FBC

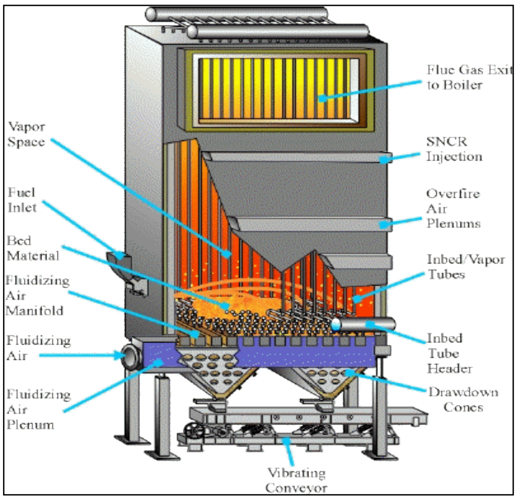


Figure 13 - Schematic of a FBB

2.6.3 Feedlot manure combustion experience

There are currently no commercial facilities combusting feedlot manure in Australia. However, much research and pilot-scale combustion trials have been conducted around the world. There are now a few commercial feedlot manure combustors operating in the USA. Whilst there appears to be no public literature on feedlot combustion test trials in Australia, it is known that Steam Systems from Melbourne have done some combustion testing of feedlot manure from a large feedlot in southern Queensland. According to the principal of Steam Systems, this test work was successful but no reports or data has been made publically available (pers. comm.. K Holland to Trevor Bridle, March 2012).

A significant amount of research on feedlot manure combustion has been conducted in the USA and reported in the open literature. Much of this has been done by researchers at the Texas Agricultural Experimental Station in Amarillo and the Texas A&M University at College Station, Texas. Sweeten et al (2006a) reported results from the combustion of feedlot manure, primarily aimed at identifying the characteristics of the ash generated. This work identified, as expected, that combustion of high VS manure produces ash with higher levels of manure constituents such as sodium, potassium, phosphorus, chlorine and sulphur. During this work, about 40 tonnes of manure was combusted in a commercial scale FBC operated by Panda Energy Corporation in Idaho. There were no problems encountered with this commercial test burn of high VS (80%) feedlot manure.

Much work has also been done to confirm that co-firing of feedlot manure with conventional fossil fuels such as coal significantly reduces the amount of NOx emissions from the combustor (Annamalai et al. 2003). It is hypothesised that the ammonia in the feedlot manure reacts with the NOx to produce nitrogen, as is accomplished in commercial NOx reduction processes.

Energy Products of Idaho (EPI) are a major international supplier of both FBCs and FB gasifiers for the processing of biomass including cattle feedlot manure and cattle processing waste, mainly paunch manure (www.energyproducts.com). EPI, which has recently been acquired by Outotec Energy Products (www.outotec.com), have a wealth of experience in the combustion of a wide variety of animal-based waste products including pig manure, abattoir wastes, chicken and turkey litter and manure as well as feedlot manure. EPI has installed three commercial FBC facilities processing feedlot manure and paunch manure in the US. Table 14 shows details of these facilities.

Table 14 - Commercial manure combustion facilities in the USA

Parameter	Panda Energy, Hereford, Texas	Cargill Meat Solutions, Alberta, Canada	Beef processing facility, Kansas
Feedstock	Beef feedlot manure and cotton gin trash	Paunch manure	Paunch manure
Energy input (GJ/h)	380		12.70
Approx. feed input (dry tph)	25		0.85
Steam output (tph)	121	26.1	3.63

The Panda Energy beef feedlot manure combustion facility was installed in 2008 and it is not known whether it is still in operation. It has been reported that Panda Energy went into receivership and was purchased by a division of Walmart (Madden 2011). Photograph 9 shows this beef feedlot manure combustion facility.

Photograph 9 - Panda Energy beef feedlot manure combustion facility

There is not a lot of data in the literature on the combustion of harvested manure (see Section 2.3.5). However, with the exception of higher potassium and chloride levels, the characteristics of feedlot manure (Table 9) are very similar to that of sewage sludge, for which there is a wealth of combustion information in the literature. Hence, it is considered that combustion is a well-proven technology for manure processing, with the exception that the high potassium and chloride levels may cause problems with ash fusion and melting in the combustor. Potassium and chlorides are well known flux agents, which depress the melting point of solids. The US data on combustion of manures Sweeten et al. (2006a) with properties similar to those shown in Table 9, indicates that ash generated from manure combustion does have moderate levels of potassium (K_2O of 12.7%). Thus, ash fusion/melting may very well be a problem. This would be best overcome by use of fluid-bed combustors (FBCs) which operate at uniform temperatures without “hot-spots” which could cause ash melting.

FBCs are used extensively to burn waste materials including manures, sludges, wood wastes and other organic residues. Figure 14 is a typical schematic of a FBC. Since combustion of the waste takes place within a bed of fluidised sand, the consistency or heterogeneity of the waste has little or no impact on combustion efficiency. This attribute makes FBCs ideal for the combustion of organic wastes such as manure. In addition, very stable bed temperatures are maintained with very high combustion efficiencies being achieved. The process design parameters for the manure FBC are shown in Table 15.

The FBC is designed to operate under the minimum operating conditions specified in the European Union Waste Incineration Directive (WID). That is, a minimum bed temperature of 800°C and a minimum Gas Retention Time of two seconds at a minimum temperature of 800°C. These conditions are required to ensure the complete thermal destruction of solid wastes, including manures. Standard industry boiler and steam turbine efficiencies are used in these combustion process designs.

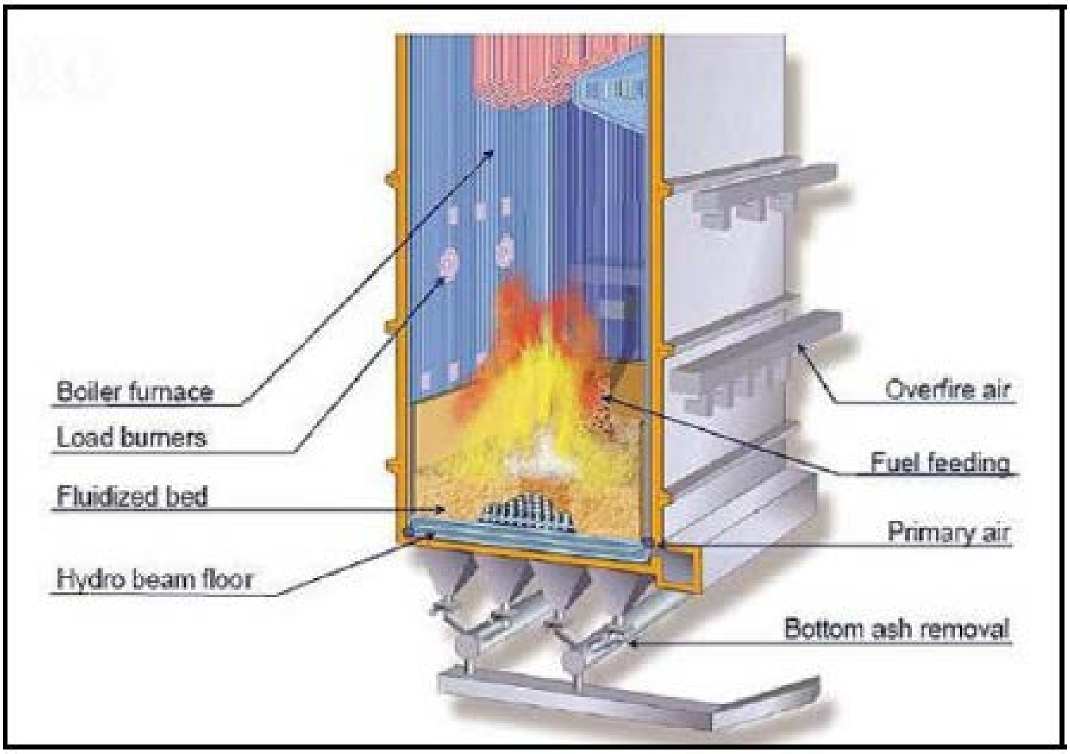


Figure 14 - Schematic of a fluid-bed combustor (FBC)

Table 15 - FBC process design parameters

Parameter	Units	Process Design Value
FBC Temperature	°C	800
Gas Retention Time	seconds	2
Boiler efficiency	%	70
Bottom ash	%	70
Fly ash	%	30
Steam Turbine efficiency	%	25

Table 12 indicates that a 10,000 SCU feedlot uses about 40 GJ/d of energy for steam flaking. Based on the process design parameters shown in Table 15 and the feed flaking energy requirements shown in Table 12, Bridle (2011a) proposed a simplified Process Flow Diagram and Mass and Energy balance for a 60,000 SCU manure combustor (Figure 15).

The fluid-bed boiler (FBB) combusts 150 dry tpd of manure and generates 1586 GJ/d in thermal energy as steam for use in the steam flakers and steam turbines for electricity production. Flue gas from the FBB is first cleaned in a cyclone to remove fly ash and then in scrubbers to remove contaminants such as SOx, NOx and possibly dioxins. This sized FBB is designed to provide all the steam required for feed flaking and also generate 4.1 MW of electricity.

Table 16 shows the process design inputs and outputs from the FBCs treating harvested manure from 10,000, 25,000 and 60,000 SCU feedlots (Bridle 2011a). There is a very significant energy recovery potential from the combustion of manure at feedlots. Even for relatively small feedlots of 25,000 head, it is possible to generate 680 kW of electricity and provide all the energy for steam flaking.

The FBCs do produce bottom and fly ash that requires disposal. The total quantity of ash generated varies from 8.1 tpd for the 10,000 SCU feedlot increasing to 48.6 tpd for the 60,000 SCU feedlot. Since the ash is benign and does contain valuable nutrients (P&K), it is assumed that it is spread on the feedlot property. Such combustion facilities will require regulatory approval and the required gaseous emission limits might be stringent.

This study aims to verify the assumptions made by Bridle (2011a) in the analysis above.

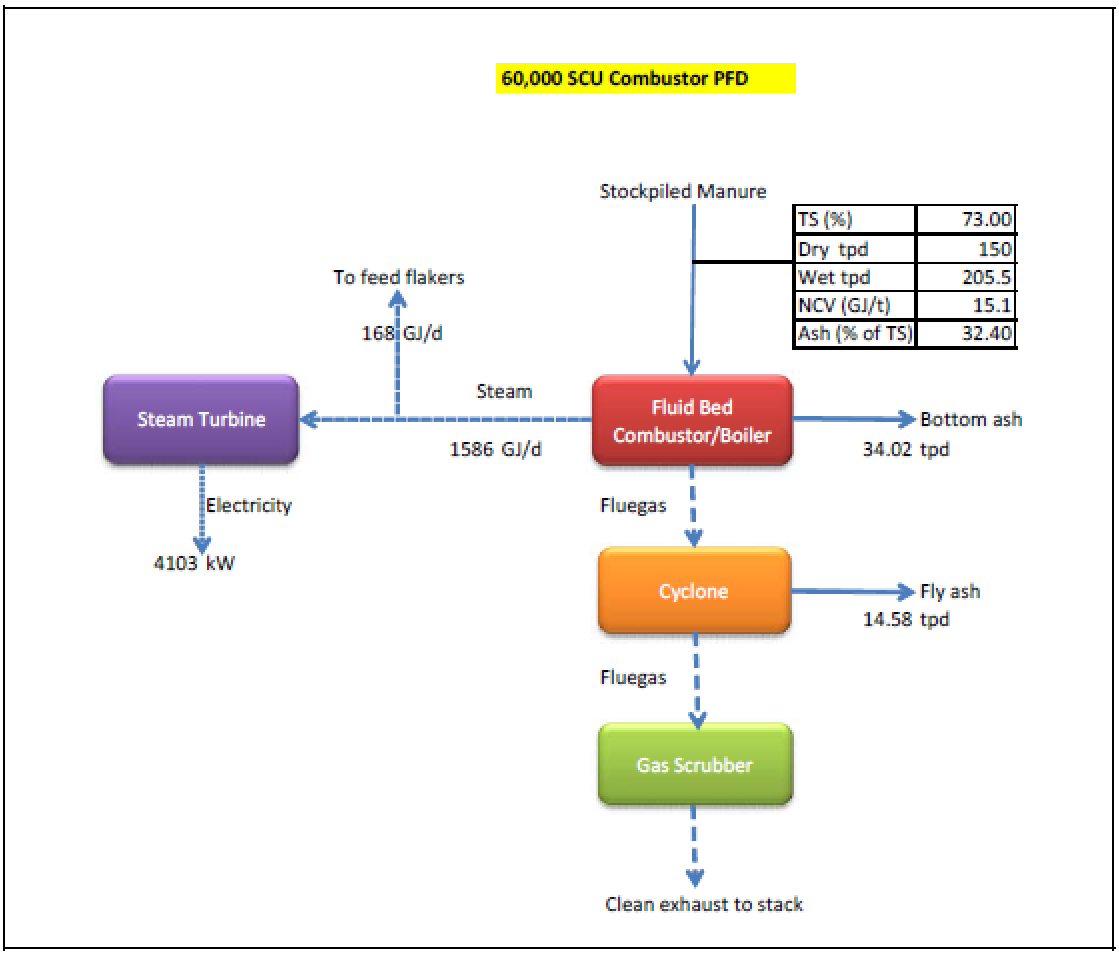


Figure 15 - M&E balance for a 60,000 SCU manure combustor

Table 16 - Process inputs and outputs from manure combustion

Combustor Input/ Output Parameter	Units	10,000 SCU Value	25,000 SCU Value	60,000 SCU Value
Dry manure processed.	tpd	25.0	62.5	150.0
Thermal input	GJ/h	15.7	39.3	94.4
Steam to feed flakers	GJ/d	28.0	70.0	168.0
Bottom ash generated	tpd	5.7	14.2	34.0
Fly ash generated	tpd	2.4	6.1	14.6
Electricity generated	MW	0.7	1.7	4.1

2.7 Gasification of biomass

2.7.1 Gasification fundamentals

Gasification is a thermal process where a small portion of the waste (typically 5 to 15%) is combusted under starved air combustion conditions to raise the waste material to a temperature of about 900°C. The end products of gasification are a syngas (comprising mainly carbon monoxide, hydrogen and carbon dioxide) and an ash or char product, depending on operating temperature. Typically, air, oxygen and/or steam are used in gasification processes. Air gasification is the most common process used but this produces a low-grade syngas with an energy content about 4 to 6 MJ/m^3. Oxygen-based gasification processes produce a much higher quality syngas with an energy content of about 10 to 18 MJ/m^3. In gasification, most of the feed energy is transferred to the syngas as chemical energy that can be reused to generate heat (via combustion), electricity (via combustion in gas engines) or used to generate chemicals such as methanol, hydrogen and ammonia (via Fischer-Tropsch conversion). This is shown schematically in Figure 16 (Juniper Consulting Services Ltd 2000).

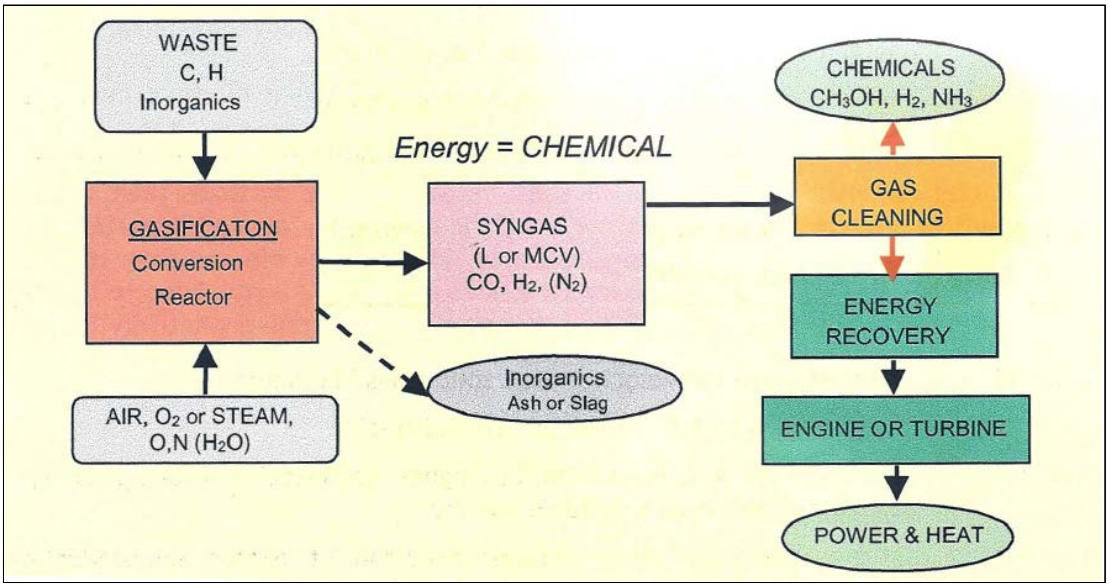


Figure 16 - Schematic of the gasification process

Gasification can be regarded as a three-step process:

- Drying of the feed by heat from combustion of a portion of the waste
- Pyrolysis to volatilise the organic constituents of the waste to produce the syngas (and tars and the solid residue)
- Gasification of the solid char and the pyrolysis tars and upgrading the syngas by partial oxidation of the higher molecular weight hydrocarbon compounds.

Gasification has been used for over 100 years to produce town-gas from coal and is now used extensively in Europe and Japan to provide central heating and electricity, predominately from the gasification of wood wastes. Gasification of solid wastes such as agricultural residues, MSW, sewage sludge and animal manures is a relatively recent application of the technology and there are only a few such commercial applications around the world.

2.7.2 Gasification processes

There are essentially three types of gasification processes, namely fixed bed, fluidised bed and moving bed systems. The earlier gasifiers were all of the fixed bed type, which can be operated in downdraft (solid moves down, gas down), updraft (solid moves down, gas up), counter-current (solids and gas move in opposite directions or cross-current (solid moves down, gas horizontal) mode. Most of the early Lurgi gasifiers used to produce town-gas and fuels from coal (e.g. the Sasol plant in South Africa) were all fixed bed gasifiers. Fluidised bed gasifiers are now much more common and are used extensively by a number of suppliers such as Lurgi, Foster Wheeler and EPI, primarily for the gasification of wood waste and agricultural residues. The most notable moving bed gasifier is that developed by Australian company Black is Green Pty Ltd (BiG). This system is classified as multiple hearth gasifier. This gasifier has 4 to 5 hearths stacked vertically which rotate on a common shaft. Waste material enters on the top hearth and moves down ward via a conveying mechanism on each hearth. Air for combustion and gasification enters from the bottom of the gasifier and flow is provided by the negative pressure in the system via the "chimney" effect. Photograph 10 shows the BiGchar Model 2200 gasifier.

Photograph 10 - BiGchar Model 2200 Gasifier

2.7.3 Feedlot Manure Gasification Experience

A review of the published literature indicates that there are currently no commercial gasifiers processing cattle feedlot manure. However, limited work has been done at pilot scale, predominately in the USA. Texas A&M University (TAMU) has conducted pilot-scale gasification trails on dairy manure (Engler et al. 2010). They constructed a 30 cm diameter by 1.5 m high fluid bed gasifier that had a capacity of 1.6 tpd of dairy manure. Photograph 11 shows this gasifier. The dairy manure processed had a VS of 70%, a TS of 87% and a GCV of 15.93 MJ/kg DM. Gasification of this at about 700°C produced a syngas with an energy content of 4.2 MJ/m^3 and a yield of 2.11 m^3/kg dry manure. The syngas contained 56% of the manure energy. The char mass was 20% of the dry feed manure, had an energy density of 19 MJ/kg DM and contained 24% of the manure energy. Twenty percent of the manures energy was used to heat the gasifier. It was noted that slagging of the gasifier was evident at a temperature of only 600°C.

In 2010, Don Madden from Smithfield Feedlot was awarded a Nuffield Australia Farming scholarship to review gasification as an energy recovery option for feedlot manure. He visited numerous organisations in the USA, Europe and Asia (Madden 2011). The most valuable information on gasification was obtained from the TAMU facility in Texas, identified above. The principal conclusions of this review were:

- The high silica and ash content of feedlot manure ensures that existing biomass gasification systems may be of limited use.
- Gasifiers specifically designed to handle feedlot manure need to be developed with turn-key commercialisation if adoption is to occur within the industry.

It thus appears very likely that conventional gasifiers may be of limited use for the processing of feedlot manure. The BiGchar gasifier, which operates at a temperature of less than 600°C, may thus prove to be an effective system for feedlot manure. This is the system to be tested via pilot plant gasification trials in this project and results are discussed in this report.

Photograph 11 - TAMU Fluid Bed Gasifier Pilot Plant

Since gasification is a much more mature technology than pyrolysis for the processing of solid waste materials, this technology is chosen as a potential option to process the harvested manure from feedlots.

MLA has recently completed a pilot-plant scale assessment of pyrolysis and gasification for the processing of dried Paunch Waste (PW) and Dissolved Air Flotation (DAF) sludge from abattoirs (Bridle 2011b). This study piloted the Black is Green Pty Ltd (BiG) gasification process. BiG is one of a number of Australian companies offering waste gasification technology and is one of the most mature companies, with commercial facilities currently under construction. Based on the very successful gasification trial on PW and DAF sludge, the BiGchar process has been selected for the gasification of the feedlot manure.

The BiGchar gasification process is a conventional air-gasification technology, where a small proportion of the waste is combusted to provide the energy to raise the waste temperature to about 600°C. The gasifier is a vertical tube with multiple hearths and rabble arms mounted on the central shaft that rotates to move the material from hearth to hearth. As the material moves downward from the top of the gasifier, its temperature increases and pyrolysis and gasification occurs. The air required for limited combustion to raise the feedstock to about 600°C is provided by a natural updraft ventilation system. The products of gasification are a syngas and a solid char material. The char discharges from the bottom of the vessel where there is essentially no oxygen. The char is sprayed with water as it exits the reactor to prevent combustion. The syngas exits from the large stack at the top of the reactor that creates the draft in the reactor. The ventilation rate is controlled by dampers on the side of the reactor. Photograph 10 shows the BiGchar system. Unlike conventional combustion, the conditions in the gasifier are reducing and, at the lower operating temperature of about 600°C, there is unlikely to be any ash fusion of melting issues.

The gasifier operating conditions and process design criteria are the best estimates of BiG, for manure of the characteristics shown in Table 9. These process design parameters are shown in Table 17.

Table 17 - Gasification process design parameters

Parameter	Units	Process Design Value
Gasifier Temperature	°C	~600
Syngas energy	% of feed	55
Char energy	% of feed	25
Char yield	% of dry feed	45
Carbon to char	%	30
Nitrogen to char	%	40
Phosphorus to char	%	100
Potassium to char	%	100
Syngas to steam effy.	%	70
Steam Turbine effy.	%	15 to 25

Based on the process design parameters shown in Table 17 and the steam-flaking energy requirements shown in Table 12, Bridle (2011a) proposed a simplified Process Flow Diagram and Mass and Energy balance for a 60,000 SCU manure gasifier (Figure 17).

Figure 17 shows that 150 dry tpd of manure is gasified and generates 67.5 tpd of char for reuse and 1246 GJ/d of thermal energy in the syngas stream. The syngas is combusted in a boiler to generate steam for use in the steam flakers and steam turbines for electricity production. The char has significant quantities of nitrogen, phosphorus and potassium and thus should make an excellent soil amendment product, with high value. However, it must be noted that the predicted carbon content of the char is 27%, which is below the 40% considered by the industry to be required to be classified as char. Thus, there is some risk regarding the predicted sale price of $250/tonne for the char. This carbon deficiency is however offset by the very high nutrient contents of the char. A significant amount of carbon is sequestered in the char, which in light of the planned carbon tax of $23/t, might prove an additional financial benefit. This sized gasifier is designed to provide all the steam required for feed flaking and also generate 2.04 MW of electricity. This is significantly lower than the combustion option due to the energy captured in the char and the small portion of feedstock combusted to raise the material temperature to 600°C. Flue gas from the combustor/boiler will require cleaning to remove particulates and other contaminants such as SOx and possibly NOx.

These gasification facilities will require regulatory approval and the required gaseous emission limits might be stringent. The process design inputs and outputs from the gasifiers treating harvested manure from 10,000, 25,000 and 60,000 SCU feedlots are shown in Table 18. There is a very significant energy recovery potential from the gasification of feedlot manure at feedlots, although not as much as for the combustion option. However, this is offset by the generation and sale of char.

This study aims to verify the assumptions made by Bridle (2011a) in the analysis above.

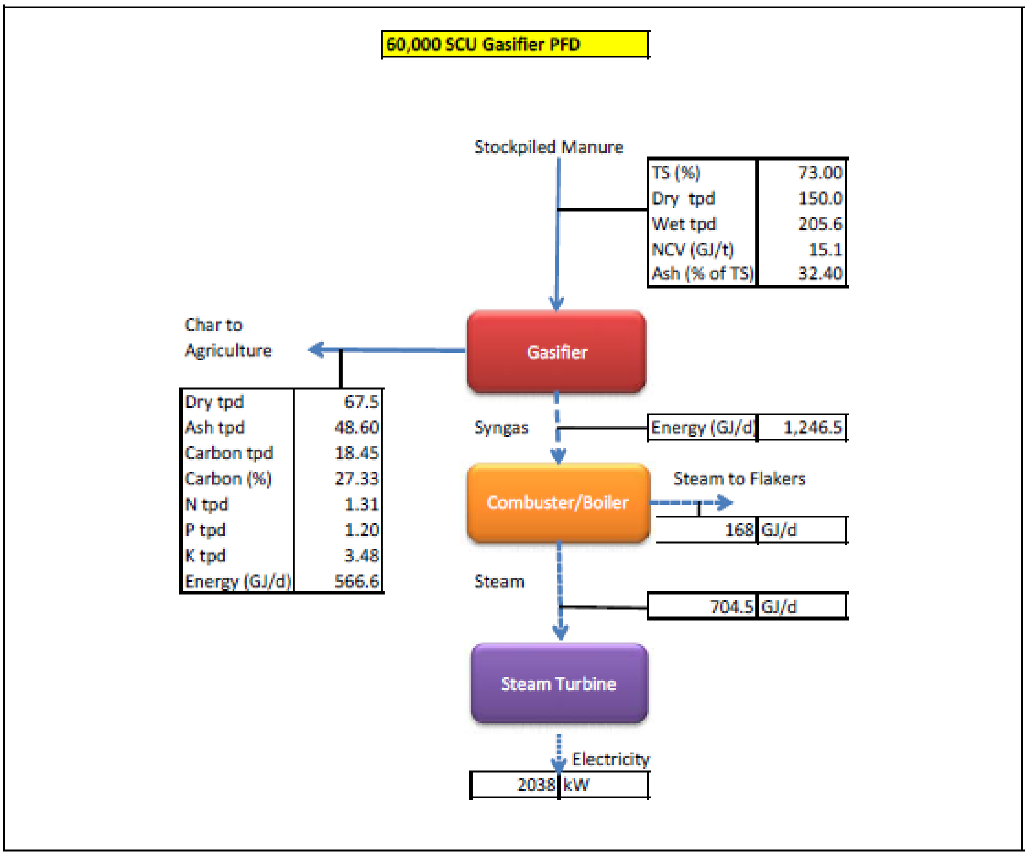


Figure 17 - M&E balance for a 60,000 SCU manure gasifier

Table 18 - Process inputs and outputs from manure gasification Bridle (2011a)

Gasifier Input/ Output Parameter	Units	10,000 SCU Value	25,000 SCU Value	60,000 SCU Value
Dry manure processed.	tpd	25.0	62.5	150.0
Thermal input	GJ/h	15.7	39.3	94.4
Steam to feed flakers	GJ/d	28.0	70.0	168.0
Char generated	tpd	11.3	28.1	67.5
Carbon in char	tpd	3.1	7.7	18.5
Nitrogen in char	tpd	0.2	0.6	1.3
Phosphorus in char	tpd	0.2	0.5	1.2
Potassium in char	tpd	0.6	1.5	3.5
Electricity generated	MW	0.2	0.9	2.0

2.8 Pyrolysis of biomass

2.8.1 Pyrolysis fundamentals

Pyrolysis, also called carbonisation, is universally regarded as a process where waste is heated indirectly, in the absence of oxygen, to a temperature of between 350 and 500°C. Under these thermal conditions, the waste decomposes and about 30 to 60% of the dry mass is volatilised to produce a crude syngas with the remaining solids converted to a char product. In essence, pyrolysis is the thermal destructive distillation of organic materials. Traditionally, the pyrolysis syngas is condensed to generate oil, produced water and a non-condensable gas (NCG).

The process is endothermic and requires about 1 to 1.5 GJ of thermal energy per tonne of dried waste processed. Unlike gasification, which involves some combustion of the feedstock, pyrolysis involves no combustion and consequently the products contain all of the chemical energy that was present in the original waste material. A process schematic of waste pyrolysis, showing the various process configurations and product end-use options is shown in Figure 18.

Pyrolysis converts complex organic molecules to simple gases, producing organic vapours, synthesis gases and a char product containing the remaining elemental carbon, non-volatilised metals and other inert material in the feedstock (ash). The products of pyrolysis always comprise gas, liquid and solid char with the relative proportions of each depending on the feedstock, method of pyrolysis and the reaction parameters, such as time, temperature and pressure. Lower temperatures produce more liquid product and high temperatures produce mostly syngas. However, subsequent processing can convert one to another as is shown in the pyrolysis schematic in Figure 18.

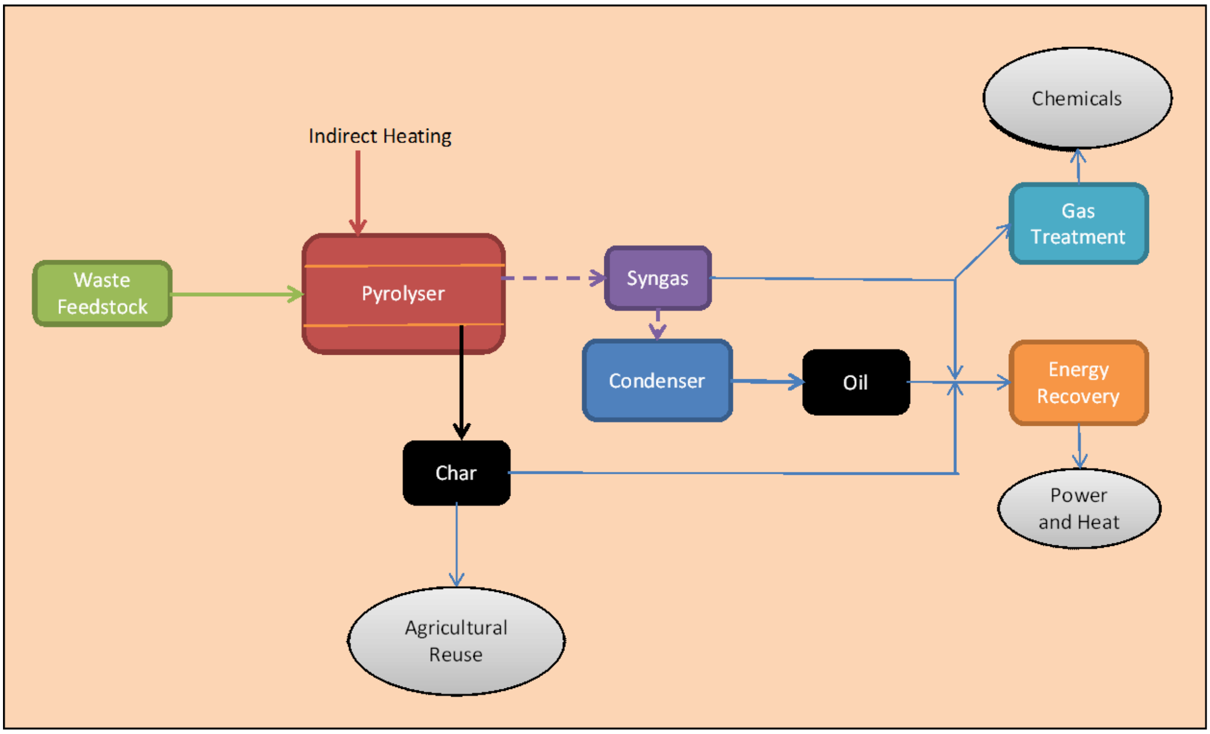


Figure 18 - Pyrolysis Process Flow Diagram

2.8.2 Pyrolysis processes

Pyrolysis can be characterised as "Fast Pyrolysis" or "Slow Pyrolysis". Fast pyrolysis occurs in a matter of a few seconds or less and decomposes organics to mostly vapours, aerosols and some charcoal. Fast pyrolysis maximises the production of syngas and liquid products. Slow pyrolysis requires a slow reaction time, typically hours or even days, at low temperatures (less than 500°C) to maximise the yield of solid char. A typical example of slow pyrolysis or carbonisation is the production of charcoal from wood and wood waste, as has been practiced by ancient civilizations for many millennia.

Fast or flash pyrolysis is used to maximise either gas or liquid products. In fast pyrolysis, the organic materials are rapidly heated to 450 - 600°C in the absence of air, for a process time of a few seconds or less (heating rates of up to 1000°C/sec). Under these conditions, pyrolysis gases, organic vapours, and a little char are produced. The gas is of a medium heating value (13-21 MJ/Nm^3). The vapours are subsequently condensed to produce liquids ("pyrolysis oil" or "bio-oil" if the substrate is biomass). These oils are very complex mixtures of hydrocarbons, which can be upgraded for conversion to chemicals, power or heat. Fast pyrolysis is probably not the preferred process for non-homogeneous wastes such as feedlot manures due to the need for finely ground and uniform quality feedstocks.

Slow pyrolysis has traditionally been used for the production of charcoal. Slow pyrolysis (or carbonisation) requires a slow reaction, longer residence times (~30 seconds for gas phase, 30-60 minutes or even longer for solids) at low temperatures (typically 450°C or lower) to maximise the yield of solid char. Its main advantages over fast pyrolysis include:

- Higher reaction times and surface areas are available for heat and mass transfer
- A simpler process (batch or semi continuous) enabling use of less sophisticated equipment and easier controls
- Potential to process less uniform or larger size feedstocks compared with fast pyrolysis
- Higher char yield.

In the past few decades, numerous companies have developed more sophisticated slow pyrolysis systems designed to process various waste streams including wood waste and agricultural residues, industrial and clinical wastes, the organic fraction of MSW, industrial sludge, plastics, sewage sludge and manures. In Australia, there are a number of companies who have developed or are developing slow pyrolysis systems and a listing of these companies is shown below:

- Environmental Solutions International Ltd (ESI). They developed and patented the Enersludge™ process for the pyrolysis of sewage sludge and a commercial 25 tonnes per day (tpd) demonstration plant was operated for about two years at the Subiaco wastewater treatment plant in Perth. ESI went into liquidation in 2004 and the technology is no longer available in Australia.
- BEST, now Pacific Pyrolysis, in NSW who have developed a range of slow pyrolysis processes aimed at conversion of wood and agricultural wastes to char.
- Black is Green Pty Ltd of Mackay who have developed the BigChar process. Technically however, this process is low temperature gasification.
- Anthroterra Pty Ltd of Sydney.
- Crucible Carbon of Newcastle who have a 100 to 400 kg/hr pilot plant available for test-work.
- Biochar-Energy System Pty Ltd.

- Chaotech Pty Ltd of Rocklea, QLD who have a 60 kg/hr pilot plant available for test-work.
- Entech Pty Ltd of Jandakot, WA who offer commercial gasification and pyrolysis systems

Typically the TS of the feed to a pyrolysis system needs to be greater than 85% (i.e. <15% moisture content). This is to minimise energy consumption in the pyrolyser (heat of vaporisation of the water and the sensible heat to raise the steam to the operating temperature) and also to ensure that the syngas has a reasonable heat value (i.e., is not too much water vapour with no energy). The particle size of the feedstock is also important. For rotary kiln and tubular reactors particle size is usually limited to 10 mm in size and for fluid bed systems to 2 to 3 mm in size.

2.8.3 Feedlot manure pyrolysis experience

There are no commercial waste pyrolysis systems operating in Australia but there are systems operating in Europe, the US and Japan. These plants process mostly MSW and a few co-process industrial and sewage sludges. There is no data available in the open literature on manure pyrolysis but it is known that companies such as PacPyro and the now-defunct ESI have internal data on manure pyrolysis. The only commercial waste pyrolysis system that has operated in Australia was the Subiaco WWTP sludge pyrolysis facility in Perth, WA. This facility was based on the ESI Enersludge technology, a slow pyrolysis process using two tubular reactors in series with screw conveyors for solids transport in the reactors. The facility was designed to process 25 dry tpd of sewage sludge and operated for about two years before being shut down by the client (Water Corporation of WA) due primarily to cost considerations. Detailed operational results from this facility have been documented previously (Bridle & Rovel 2002) but a summary of the product yields and energy values is shown in Table 19. Sewage sludge has characteristics similar to animal manures and thus one would expect similar performance results, as shown in Table 19, when processing manures. PacPyro has some experience, at laboratory scale, processing animal manures.

Table 19 - Sewage sludge pyrolysis results

Product	Yield (%)	Energy Content (MJ/kg)	Percent of Sludge Energy
Char	43	18	40
Oil	29	30	45
Non-condensed gas	14	15	11
Reaction water	13	6	4

3 Methodology

3.1 Methodology summary

The steps in the methodology for this project were:

1. Initial manure sampling and assessment
2. Manure collection for initial combustion and gasification trials
3. Initial combustion trial
4. Initial gasification trial
5. Re-evaluation of project methodology
6. Second round of manure collection
7. Second combustion trial
8. Second gasification trial
9. Pyrolysis trial
10. Data analysis

3.2 Manure sampling testing

In Section 2.1, issues around the testing of manure samples were discussed. It was noted that drying manure samples at high temperatures for prolonged periods of time removes not only water but also volatile solids. Hence, high-temperature drying can over-estimate moisture content and can under-estimate VS content. Notwithstanding this, most commercial laboratories follow standard procedures and methods.

In this study, samples were analysed at NATA-accredited, commercial laboratories. The laboratories used AWWA/APHA Standard Methods for TS and VS. TS was determined by drying at 104°C, and then heated the dried solids to 450 to 500°C for determination of VS. Standard methods were also used for all other parameters analysed in the manures. The methods used for all the analyses are referenced in the analytical laboratory reports. All analyses, except moisture content and TS, are expressed on a dry matter basis (i.e. % of TS or %db).

3.3 Initial manure sampling and assessment

3.3.1 Manure decomposition

The initial manure sampling part of the project was divided into two stages. The first stage involved the sampling of manure at different points in the manure management cycle (fresh, pen, stockpiled and composted manure). This stage involved sampling of different stages of the manure decomposition cycle. These samples were analysed for TS, VS and moisture content. The data collected from this sampling and analysis provided an indication of breakdown rates of manure under current management practices. The samples were taken at Feedlot A.

3.3.2 Sampling locations

The sampling of manure for decomposition assessments was done according to the following broad guidelines:

- The fresh manure was collected from freshly-dropped faeces piles.
- The pen (pad) manure was collected from the 2-3 separate sections of the pen to avoid samples only being collected from the most convenient locations (i.e. moist or uncompacted areas). Manure was collected from Pen A1 and Pen ST1.

- The stockpile sample collected was recently removed from the pen and was approximately 100 days old. It was sampled from a minimal depth of 10 - 20 cm at different locations around the stockpile. Care was taken to include the various laminations from the crusted manure in samples from stockpiles. Two stockpile samples were taken (S1 and S2).
- Composted manure was not collected from the feedlot as the TS and VS would have been broken down below levels suitable for combustion.

Photograph 12 – Fresh faeces prior to sampling

3.3.3 Sample collection

The manure collected from each location was a bulked composite from at least 12 separate sub-samples. Samples were collected using a small garden spade, and transferred into a plastic bag lined bucket with three to four scoops of manure taken from each of the twelve sampling locations and placed into the bag inside the bucket. This generally filled a 10 L bucket to about half-full. The sample bag was then removed from the bucket, labelled according to the location and type of sample, sealed and placed in a second bag for safety.

The manure was sealed in a plastic container (insulated cooler box) and immediately covered with an ice pack, or refrigerated at 4°C to reduce volatilisation losses. The samples reached the laboratory within one day of sampling. This falls within the recommended holding time according to the studies done by Peters et al. (2003a).

Photograph 13 –Sampling manure from pad surface – Pen A1

3.3.4 Sample analysis

Table 20 presents the preliminary manure sample results. The fresh faeces was 79% moisture content and 73% VS. This is quite typical of fresh faeces. The pen surface manure, as shown sampled in Photograph 13, was fairly dry for feedlot pens (7-12% moisture content). The VS content was 51-59%, which is typical of pen manure. The stockpile manure was 29-34% moisture content, which is typical of manure within a stockpile. The VS content was quite low at 23-43% VS indicating contamination with soil from the pens.

Table 20 –Preliminary manure samples

	Fresh	Pen Manure		Stockpile Manure	
	Faeces	PA1	PST1	S1	S2
%MC	78.6	12.4	7.4	34.4	28.9
%TS	21.4	87.6	92.6	65.6	71.1
%VS	73.4	59.3	50.8	43.3	23.0

3.4 Manure collection for initial combustion and gasification trials

The second stage of the project involved collecting large quantities of manure from Feedlot A for combustion and gasification trials. Pen manure was selected for the trials, based on results from the manure samples analysed for TS, VS and moisture content. Sampling was undertaken on 14 March 2012.

The manure was harvested at the required time of pen cleaning and during a period of dry weather to ensure that the moisture content of the manure did not exceed the recommended amount for gasification and combustion. One cubic metre 'bulka' bags were used to collect the large samples of manure. The procedure for harvesting the pen manure involved scraping manure off the pad as close as practically possible to the surface. All the sample bags were filled by the staff at the feedlot whose assistance is acknowledged.

Once filled, each 'bulka' bag was weighed on the facility's weighbridge. This allowed the total mass of manure collected from each site to be recorded. The bags were stored under cover at the feedlot until loading onto trucks when the combustion and gasification trials were ready. The manure was transported by truck from Feedlot A to the Nambour and Yarra Junction sites. The 'bulka' bags were sealed and loaded on pallets (see Photograph 14).

Photograph 14 – Bulk manure loaded into 'bulka' bags

3.5 Initial combustion trial

The initial feedlot manure combustion trial was conducted at the Reid Brothers Timber sawmill at Yarra Junction in Victoria on 3 April 2012. The sawmill operates a boiler to provide steam and hot water to the mill. The boiler was designed by Kohlbach Asia Pacific Pty Ltd and built by Fluid Systems Pty Ltd of Victoria. The boiler was supplied in 2004. The boiler is of the walking-grate stoker design with a thermal output of 1 MW. The maximum design steam pressure is 1000 kPa. The boiler is normally fired with sawdust from the mill and the design sawdust feed-rate ranges from 247 to 380 kg/h on a wet weight basis. Sawdust is fed into the boiler by a ram feeder that pushes a plug of sawdust up an inclined chute onto the grate. Flue gas from the boiler is cleaned in a wet scrubber and then discharged via the stack. The boiler, the scrubber and stack, and the sawdust fed to the boiler are shown in Photograph 15 to Photograph 18.

The first manure combustion trial was conducted using the high VS manure taken from Pen A1. On removal from the bags, it was noted that the manure had formed large dry and hard clumps as shown in Photograph 19. These had to be broken up with spades before feeding to the boiler. The manure was transferred into 20 L pails for weighing before being manually transferred to the feed system that conveyed the material to the ram feeder. Feeding of the manure commenced at 9:00 am and, by 10:15 am, steady state conditions had been achieved in the boiler, now completely fuelled by manure. About 340 kg of manure had been fed to the boiler by 10:15 am. Just as the steady-state combustion monitoring period was due to commence, the feed system jammed. The trial was aborted after an hour of unsuccessful attempts to unblock the feed chute.

It was concluded by all in attendance of the trial (Steam Systems and Bridle Consulting) that the reason for the blockage was the extremely strong plug of manure formed during the compression in the ram feeder, which had too great a frictional force that could not be overcome by the hydraulics of the ram feeder.

Photograph 15 – Boiler showing viewer port

Photograph 16 – Boiler and fans

Photograph 17 – Scrubber and stack

Photograph 18 – Sawdust fed to boiler

Photograph 19 – Manure being transferred to pails for weighing

Similar conditions have been experienced when feeding dry sewage sludge, which is very similar in nature to manure. Experience has indicated that, to effectively feed dry sewage sludge to thermal processes, no compression zones can be tolerated. It was thus recommended that, in any follow-up combustion trial, the boiler should have no compression zones in the fuel feeding system. It should be noted that, during the 90 minutes of manure feeding, combustion in the boiler was regarded as being very good with uniform temperatures and steam flow being noted.

Samples of the manure used during the combustion trial were collected at the Reid Brothers Timber sawmill at Yarra Junction. The manure samples were collected in sample bags, labelled according to the location and type of sample, sealed in a plastic container (insulated cooler box) and transported by truck to the SGS laboratory in Toowoomba for analysis. The samples were analysed for TS, VS, CHNOS, gross calorific value (GCV), P, K, Na, Fe, Al, Ca, Si, Cu, Zn, Cl and SO_4. Table 21 shows the results of two samples taken of the Pen A1 scrapped pen manure from Feedlot A. The VS content of these samples is only 41-43% VS, which is lower than the 51-59% initially measured in this pen. The reason for this lower VS content is unknown although there could have been some manure breakdown occurring during storage and transport to Victoria.

Table 21 – Manure samples – Steam Systems combustion trial

Analysis	Unit	Sample	
		PA1/01	PA1/02
Chloride	mg/kg	5802.0	5739.0
Sulphate	mg/kg	19.0	15.0
Carbon	%	22.1	18.9
Hydrogen	%	3.9	3.7
Nitrogen	%	1.7	1.7
Oxygen	%	26.3	25.5
Sulphur	%	0.4	0.4
Ash	%	54.2	56.4
Moisture	%wb	17.8	23.4
TS	%wb	82.2	76.6
VS	%	42.8	40.7
Phosphorous	%	0.8	0.8
Potassium	%	0.2	2.0
Sodium	%	0.3	0.4
Iron	mg/kg	16000.0	1700.0
Calcium	%	2.6	2.7
Copper	mg/kg	51.0	54.0
Zinc	mg/kg	340.0	380.0
Aluminium	mg/kg	12600.0	11800.0
Calorific Value	MJ/kg	9.0	7.5

3.6 Initial gasification trial

The initial feedlot manure gasification trial was conducted using the Black is Green Pty Ltd gasification pilot plant in Nambour, Queensland on 18 and 19 April 2012. Black is Green Pty Ltd is an Australian company which specialises in mobile, modular or relocatable thermal treatment systems. The BiGchar 1000 gasification unit has previously processed cypress sawdust, chipped green waste and household garbage feedstocks and is of the updraft gasifier design.

Feedlot manure taken from Feedlot A had been transported from Texas to Nambour in 1 m^3 'bulka' bags. The first trial commenced on 18 April 2012 using a woodchip feedstock to start the system. The woodchips were fed onto an inclined conveyor chute that feeds into the BiGchar 1000 gasification unit. Air was passed through the gasifier from tuyers in the downdraft direction and the combustible gases were collected at the top of the unit. An auger automatically removed the char from the bottom of the unit. The temperature of the gas leaving the gasifier was recorded at approximately 300°C. The manure feed system into the gasifier, the BiGchar 1000 gasification unit, the stack and the char from the woodchip gasification are shown in Photograph 20 to Photograph 23.

During the trial, staff from Black is Green Pty Ltd advised that, when emissions were acceptable, the char quality was poor and, when char quality was good, the emissions were very poor. The problems with the unit related to a recent modification of the oxidiser unit following the pyrolysis stage. A second gasification trial was conducted on 19 April that resulted in similar problems of poor char quality and high emissions. Staff from Black is Green Pty Ltd endeavoured to fix these problems but to no avail. The trial was halted without using the feedlot manure as a feedstock. It is thus recommended that the follow-up gasification trial be conducted once the problems with the equipment have been rectified.

Photograph 20 – Manure feed system into the gasification unit

Photograph 21 – BiGchar 1000 Gasification unit

Photograph 22 – Flue gas sampling from the stack

Photograph 23 – Char from the woodchip phase of the gasification

3.7 Re-evaluation of project methodology

The failure of both initial trials was disappointing but this reflects the issues encountered when moving from the laboratory and conducting pilot-scale trials. The situation was discussed with the project manager within MLA and it was decided to continue the project with new attempts at combustion and gasification. It had been concluded that undertaking trials on stockpiled manure (low calorific value), as per the original contract, is not beneficial as the VS content of this manure has declined below viable levels. However, it would be desirable to obtain fresh pen manure from another site such as Feedlot B near Toowoomba.

In addition, it was decided to add pyrolysis to the testing regime due to the strong interest in biochar amongst the farming community. For the continued project, it was decided to:

1. Examine the possibility of conducting the combustion component of the project at Feedlot A where there is a large, coal-fired boiler in constant use.
2. Undertake the gasification trials at Black is Green Pty Ltd after they have fixed the problems with their unit.
3. Undertake the pyrolysis trials at Pacific Pyrolysis in Somersby, NSW.

Subsequently, an inspection of the Feedlot A boiler was undertaken to determine its suitability. After some issues with the Feedlot A boiler are resolved, a revised contract was developed.

3.8 Evaluation of Feedlot A boiler

This section covers the features of the boiler at Feedlot A investigated to ensure that it was suitable for the manure combustion trials. The section also covers other aspects relevant to the proposed trial.

The boiler was installed in 1989. The technical manual that was supplied at that time has been provided. The feedlot management wanted the trial to be as representative as possible of actual operating conditions. They wanted to use manure taken directly from pens and screened immediately so that the manure was as fresh as feasible and had rocks and gravel removed. Due to biosecurity reasons, no manure from any other feedlot could be brought on-site. Hence, only Feedlot A manure could be burned in the trial.

3.8.1 Coal / manure feed system

Feedlot A has an open coal bunker which can hold about 20 t of coal (Photograph 24 and Photograph 25). The current coal usage rate is about 300 kg/hr so there is about 70 hours of combustion available in a full bunker. It was feasible to complete a steam-flaking run with coal and burn the remaining coal, then load the bunker with manure that had been weighed over the weighbridge. The coal bunker would not need to be filled with manure but a known weight could be burned.

There is no direct way in which manure / coal feed rate can be measured as m^3/hr. The manure / coal is moved with a vertical bucket elevator from the coal bunker and then dropped down a chute that feeds into the furnace. The feed rate is controlled by a wheel (Photograph 27). This would be kept constant throughout a trial. The chain speed can be measured and the thickness of the inflow on the chain bed can be estimated. Hence, an estimate of average fed rate can be calculated. This could then be compared to the overall time taken to empty the known mass from the bunker.
The major advantage of this combustor is that the feed is not compressed during conveyance and delivery/deposition onto the combustion grate, as was the case with the Yarra Junction combustor. This combustor is a 4 MW John Thompson coal-fired water-tube boiler which uses a chain grate

stoker to convey the coal along the length of the grate. The boiler fuel is conveyed to the stoker grate by a combination of screw conveyors and bucket elevators and is fed by gravity, via a chute, onto the chain grate, as is shown in Photograph 27. This feed/conveyance system was deemed as suitable for feeding manure.

3.8.2 Stack flue gases

Photograph 28 shows the exhaust stack. At about it's mid-height, there is an access platform. There are 2 x 100 mm sampling ports available at the platform (Photograph 29). Apparently, these had never been used. Hence, there seemed to be no issues with sampling flue gases.

3.8.3 Ash

Ash is conveyed to an external bunker (Photograph 30). This bunker could be cleaned out prior to a manure trial. Hence, it would be easy to collect samples and to weigh all of the ash produced during a trial. Water is used to control dust from the ash. This ash also includes ash settled out of the flue gases.

3.8.4 SCADA System

The SCADA system that controls the operation of the boiler and the whole feed mill was installed in 1989. Hence, it is quite old. Photograph 31 and Photograph 32 shows the panels that control the boiler. While it is known that PLCs control the operation of the boiler, the feedlot manager did not know how to acquire the data during an experiment nor the full range of variables that are measured. An electrician who was experienced with PLCs was needed to be engaged to sort out the correct logging of variable during any trials.

3.8.5 Boiler assessment summary

Whilst the boiler at Feedlot A is old (it was installed in 1989) and is not equipped with an extensive data monitoring and recording system (SCADA), it was deemed suitable for the combustion trial based on the following considerations:

- Manure feed rate could be determined first by calculating the volumetric feed rate onto the grate and then converting this to a mass feed rate using a measured bulk density of the manure. The width and depth of the feed on the grate is known and the speed of the chain grate can be calculated, thus giving the volumetric feed rate.
- The water feed rate to the boiler is measured as is the steam flow rate and pressure. These could be logged manually during the trial. Thus the thermal energy output of the boiler, in the produced steam, could be calculated.
- The ash could be sampled and its mass generation rate calculated by the measured VS values of both the manure and ash produced.
- The boiler stack was equipped with a suitable platform and sampling ports to allow the flue gas to be monitored, sampled and analysed by NATA-registered stack samplers.

Consequently, there was adequate monitoring and recording systems in place to allow a complete mass and energy balance to be conducted across the boiler during the combustion trial.

Photograph 24 – Coal bunker – covers in place

Photograph 25 – Coal bunker opening

Photograph 26 – Coal feed into boiler

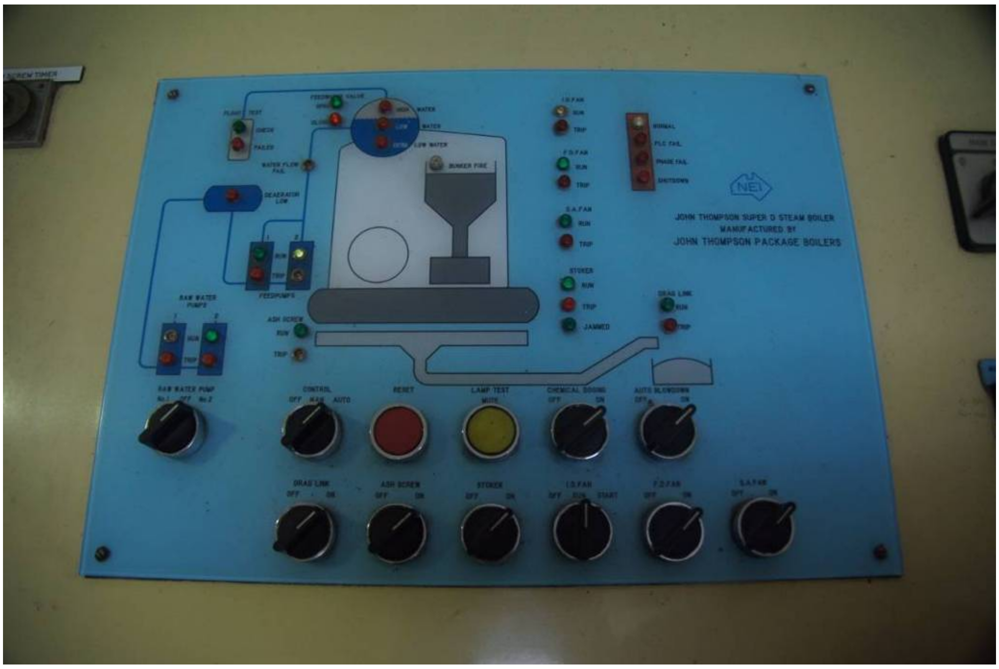
Photograph 27 – Chain bed and control gate on coal feed

Photograph 28 – Flue with platform at mid height

Photograph 29 – Sampling port on flue

Photograph 30 – Ash collection bunker

Photograph 31 – Boiler control panel



Photograph 32 – Boiler control panel

3.9 Second round of manure collection

3.9.1 Manure collection at Feedlot B

In the revised project methodology, it was decided to sample pen manure from a feedlot known to retain the interface layer when pen cleaning, thus having little clay or gravel contamination of the scrapped pen manure. Feedlot B was selected.

On 17 September 2012, pen manure samples were taken from Pen E1 at Feedlot B. The pen was very dry at the time of sampling. A box scraper scrapped about 25 mm of manure from the surface into a loose mound. The loose manure was shovelled into the 'bulka' bags (Photograph 33). Photograph 34 shows the pen surface after scrapping. Loose surface manure has been removed leaving the hard, compacted interface layer. This pen manure had little contamination from underlying material.
Table 22 gives the analysis of three replicate samples of the pen manure collected on that day. At 13%, these samples were very dry for feedlot pen manure with an average VS of about 63%.

3.9.2 Manure collection at Feedlot A

On 21 September 2012, it was proposed to undertake the pre-trial combustion run at Feedlot A. In preparation for this, staff at Feedlot A harvested and screened pen manure from Pen A1 on 17 September 2012. This screened manure was placed, under a plastic cover, adjacent to the coal bunker for the boiler (Photograph 35). On 18 September 2012, 'bulka' bags of this material were loaded (Photograph 36) and transported to the gasification site. As this manure was wetter than the Feedlot B samples, some of this manure was dried on a plastic sheet in the sun before packaging and transport to the pyrolysis site. Table 23 gives the analysis of three replicate samples of the pen manure collected on that day. These samples were typical moisture content for pen manure (about 32%) with a low VS content of about 45%.

Photograph 33 – Collection of pen manure at Feedlot B

Photograph 34 – Interface layer left after pen cleaning – Feedlot B

Table 22 – Manure sample analyses – Feedlot B - Pen E1

Analysis	Unit	Sample		
		Rep 1	Rep 2	Rep 3
Chloride	mg/kg	170.0	180.0	177.0
Sulphate	mg/kg	95.0	100.0	100.0
Carbon	%	32.9	33.3	33.0
Hydrogen	%	4.8	5.1	5.0
Nitrogen	%	2.5	2.47	2.5
Oxygen	%	35.2	35.8	35.3
Sulphur	%	0.6	0.54	0.6
Ash	%	39.2	36.4	35.4
Moisture	%wb	12.7	13.1	13.5
TS	%wb	87.3	86.9	86.5
VS	%	60.8	63.6	64.6
Phosphorous	%	0.8	0.8	0.8
Potassium	%	1.6	1.8	1.5
Sodium	%	0.5	0.5	0.4
Iron	mg/kg	10000.0	7800.0	5700.0
Calcium	%	3.4	3.3	2.9
Copper	mg/kg	52.0	53.0	46.0
Zinc	mg/kg	250.0	260.0	240.0
Aluminium	mg/kg	6400.0	5600.0	4100.0
Calorific Value	MJ/kg	12.0	12.6	11.7

Table 23 – Manure sample analyses – Feedlot A - Pen A1

Analysis	Unit	Sample		
		Rep 1	Rep 2	Rep 3
Chloride	mg/kg	6851.0	6347.0	6878.0
Sulphate	mg/kg	<1.0	<1.0	<1.0
Carbon	%	22.0	23.7	23.6
Hydrogen	%	2.8	3.1	3.1
Nitrogen	%	1.7	2.0	2.0
Oxygen	%	25.6	27.3	26.9
Sulphur	%	0.3	0.4	0.4
Ash	%db	52.1	55.5	55.4
Moisture	%	31.1	33.8	32.6
TS	%	68.9	66.2	67.4
VS	%db	47.9	44.5	44.6
Phosphorous	%	0.3	0.2	0.2
Potassium	%	0.7	0.6	0.6
Sodium	%	0.1	0.1	0.1
Iron	mg/kg	3500.0	4100.0	3300.0
Calcium	%	0.6	0.6	0.6
Copper	mg/kg	12.0	11.0	11.0
Zinc	mg/kg	110.0	98.0	95.0
Aluminium	mg/kg	2600.0	2900.0	2300.0
Calorific Value	MJ/kg	7.4	6.9	6.9

Photograph 35 – Screened pen manure at Feedlot A used in combustion trial

Photograph 36 – Loading screened pen manure for transport to gasification trial

3.10 Second combustion trial

To confirm that the boiler feed system would be suitable for the Feedlot A manure, it was decided to conduct an exploratory run to ensure no feed issues prior to conducting the actual combustion trial. This was agreed to by feedlot management. In addition, feedlot management agreed to stockpile flaked feed prior to the manure combustion trial to ensure there would be no pressure to operate the boiler at design steam outputs during the trial.

The plan for the combustion trial was thus:

- Conduct the exploratory run a week before the planned combustion trial.
- Conduct the combustion trial using only Feedlot A manure as the feed stock.

The plan was to run the boiler at the maximum fuel feed rate possible (due to the low manure GCV compared to coal) and operate the boiler under steady state conditions for one hour to obtain sufficient data to complete mass and energy balances and also provide sufficient time for the stack samplers to obtain representative samples of the flue gas for analysis. Three samples of manure and ash were to be collected during the combustion trial.

3.11 Second gasification trial

The gasification trial was conducted using the Black is Green Pty Ltd (BiG) gasification pilot plant. This decision was based on successful use of this pilot plant for previous MLA studies assessing thermal processes for energy recovery from abattoir paunch waste solids and DAF sludge (Bridle 2011b). The original gasification trial had to be aborted due to problems that were however not related to the feedstock being processed. Thus the second trial was planned using the same pilot plant. The BiG gasification pilot plant is a 1 metre diameter unit fitted with 4 hearths and is shown in Photograph 37. The facility has a nominal throughput of 200 kg/h.

Photograph 37 - BiG gasification pilot plant

The plan was to run two gasification trials using both Feedlot B and Feedlot A manures. The test programme called for operating on each feedstock at steady-state conditions for about one hour, with the recording of operational parameters and collection of three feed and char samples during this steady-state period. Off-gas from the gasifier thermal oxidiser was to be analysed by qualified stack samplers. BiG were contracted to provide a report on the results of the testing, with complete mass and energy balances and costs for commercial scale facilities. Appendix A gives full results of this trial.

3.12 Pyrolysis trial

The pyrolysis trial was conducted using the Pacific Pyrolysis (PacPyro) batch pyrolysis reactor unit, with a working volume of 20 L. This decision was based on successful use of this batch reactor for previous MLA studies assessing thermal processes for energy recovery from abattoir paunch waste solids and DAF sludge (Bridle 2011b). PacPyro indicated that since they had an extensive pyrolysis data-base on a wide range of feedstocks, including manure, that pilot plant testing was not necessary for them to be able, with confidence, use data from their batch reactor system to design a commercial scale manure pyrolysis facility. On this basis, it was agreed to conduct batch pyrolysis tests on the Feedlot B and Feedlot A manures. Photograph 38 shows the PacPyro batch pyrolysis reactor system.

Each trial involved placing about 20 L of pre-dried manure in the reactor and heating it to 550°C and holding the temperature for 30 minutes before cooling the reactor. Three samples of manure and char were analysed to allow mass and energy balances to be developed for the pyrolysis process. Appendix B presents full results for this trial.

Photograph 38 - PacPyro batch pyrolysis reactor

4 Results

4.1 Second combustion trial

As indicated in Section 3.10, the combustion trial at the Feedlot A was conducted in two stages, an exploratory combustion run to confirm the manure feed system was capable of feeding manure into the boiler and then the actual steady-state combustion trial.

4.1.1 Exploratory combustion run

The exploratory combustion run was conducted on the 21 September 2012. Fresh screened pen manure (from Pen PA-1) was collected by Feedlot A personnel during the week of 17 September, screened and stockpiled adjacent to the combustor for the exploratory and full combustion trials. Photograph 39 shows the manure being transferred to the boiler coal bunker.

Photograph 39 - Manure being transferred to coal bunker

The manure was relatively dry (analyses were only obtained after the exploratory run was completed) and had been well comminuted by the screening operation. However, many large (up to 30 mm) stones were still present in the manure. This manure was successfully fed through the conveyance and feed system to the boiler and was actually fed onto the boiler grate for about 30 minutes. During this short run, it was noted that the energy output from the manure was significantly lower than that achieved with coal as the feedstock, which was not unexpected. It was thus concluded that the full combustion trial could proceed as planned, but it was recommended that the manure be air-dried to increase TS prior to the combustion trial. TS and VS analyses of this manure were received after the exploratory run had been completed. The average TS was 67.5% and the average VS was 45.7%.

4.1.2 Combustion trial results

The detailed combustion trial was conducted at the Feedlot A on the 28 September 2012. The same manure as used in the exploratory trial was used in the combustion trial and unfortunately no additional air-drying was done on the manure, although it had been under cover for the ensuing week.

4.1.3 Boiler details

A picture of the boiler is shown in Photograph 26 and boiler specifications are outlined in Table 24. Based on the data in Table 24, it can be calculated that the feed energy required to achieve the design steam output is 18.24 GJ/hr.

Table 24 - Feedlot A boiler specifications

Parameter	Data/Value
Supplier	John Thompson
Year installed	1999
Boiler type	Water tube with chain grate stoker
Design Heat Output	4 MWth
Design Steam Output	5,500 kg/h
Design Steam Pressure	690 kPa
Design Coal Feed Rate	694 kg/h
Design Coal Energy Content	26.28 GJ/t
Design Thermal Efficiency	79%
Excess Air	30%
Grate Heat Release	1.13 $MWth/m^2$
Grate Surface Area	4.5 m^2
Grate Length	3.33 m
Grate Width	1.35 m

4.1.4 Historical manure data

Feedlot A manure from Pen A-1, had been analysed on three occasions prior to conducting the combustion trial (Table 20, Table 21 and Table 23). This data is summarised in Table 25.

Table 25 - Feedlot A Pen A-1 manure characteristics

Parameter	Units	Surface Sample	Harvested Sample 15 May			Harvested Sample 18 September			
		17 February	Rep 1	Rep 2	Mean	Rep 1	Rep 2	Rep 3	Mean
TS	%	87.6	82.2	76.6	79.4	67.4	66.2	68.9	67.5
VS	%	59.3	42.8	40.7	41.75	44.6	44.5	47.9	45.7
Carbon	%		22.1	18.9	20.5				
Hydrogen	%		3.85	3.66	3.76				
Nitrogen	%		1.66	1.65	1.66				
Oxygen	%		26.3	25.5	25.9				
Sulphur	%		0.42	0.42	0.42				
GCV	GJ/dry t		8.96	7.54	8.25				

Table 25 shows that the surface sample of manure taken in February had a VS of 59.3% compared to harvested manure VS values ranging from 40.7 to 47.9%. This indicates a significant proportion of pen base material is excavated when harvesting the manure at Feedlot A. This has significantly reduced the combustible fraction in the manure. Based on the average VS value of the harvested manure to be used in the combustion trial (VS of 45.7%), it was estimated that the GCV of this material was 9 GJ/dry tonne. On a wet basis, the GCV was estimated at 6.1 GJ/wet tonne, which is roughly 4.3 times lower than the energy in the coal normally used for combustion. Thus, at the estimated maximum manure feed rate of about 690 kg/h, the energy input into the boiler would be 4.3 times lower than that achieved with coal. It was thus decided to operate the manure combustion trial at the maximum feed rate possible; that is with a grate speed of 100% and the maximum practical bed depth possible.

4.1.5 Combustion trial data

Prior to commencing manure feed to the boiler, four sub-samples were taken and the bulk density (BD) measured on-site. The average bulk density measured was 613 kg/m^3. The methodology used to calculate the manure feed rate during the combustion trial is shown in Table 26. Table 28 shows the analysis of three replicate samples of the manure used in this trial.

Table 26 - Calculation of manure feed rate

Parameter	Units	Value
Grate speed at 100% setting	m/h	7.27
Grate width	m	1.35
Manure bed depth	m	0.11
Cross sectional area	m^2	0.15
Volumetric feed rate	m^3/h	1.08
Wet mass feed rate	kg/h	661.70

Manure feed to the boiler (i.e. manure on the grate) commenced at 1 pm and the combustion trial was concluded at 2:20 pm. The boiler monitoring data for this time period are shown in Table 27.

The analytical data generated for the manure and ash samples taken during the combustion trial are shown in Table 28. The manure VS data provided by the laboratory was not credible, so the samples were re-analysed in December and these results are reported. The average manure VS was only 39.1% compared to the original value of 45.7% measured on the 18 September. This reduction may be due to the extended storage of the samples before analysis again in December. It is thus possible that the VS of the manure fed during the trial was actually 45.7%.

The boiler monitoring data in Table 27 shows that two of the steam flakers were off-line prior to feeding manure. Unfortunately, boiler steam flow data was not available (not manually recorded) for the period prior to manure feeding but it is a fair assumption that steam output was probably less than 50% of design (5500 kg/h). According to the contract boiler attendants, the steam flow meter on the boiler is unreliable. Water flow data should be used to infer steam flows. Table 27 shows that steam flow decreased from 2400 kg/h at the start of the manure combustion trial to only 600 kg/h at the end of the trial. In addition, steam pressure steadily declined from 800 kPa at the start of the trial to 0 kPa at the end of the trial. This indicates that there was insufficient energy in the manure to sustain steam generation. This is borne out by the energy balance during the steady state combustion trial shown in Table 29.

Table 27 - Boiler monitoring data

Time	FD fan setting	ID fan setting	Stoker setting (%)	Steam (kg)	Steam flow (kg/h)	Steam pressure (kPa)	Water (kL)	Water flow (kg/h)	Comments
11:00	400	100	40			800			On coal, 2 flakers off-line
13:00	710	110	100			800			Manure on grate
13:40	350	120	100	5661		120	416.3		Start SS trial
13:50	375	110	100	5682	126	98	416.7	2400	
14:00	400	100	100	5705	138	25	416.8	600	
14:10	400	95	100	5730	150	2	416.9	600	
14:20	400	92	100	5750	120	0	417.0	600	End of trial

Table 28 – Combustion trial manure analytical data – Pen A1

		Manure results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	77.4	70.9	72.7	73.7
VS	%	37.6	39.3	40.5	39.1
GCV	GJ/dry t	6.48	7.63	8.38	7.50
C	%	21.3	22.1	21.9	21.8
H	%	3.39	3.51	3.39	3.43
N	%	1.68	1.68	1.73	1.70
O	%	23.5	22.4	23.1	23
S	%	0.45	0.41	0.41	0.42
P	%	1	0.89	1.1	1.00
K	%	2.2	2.0	2.2	2.1
Na	%	0.4	0.37	0.41	0.4
Fe	mg/kg	27,000	20,000	24,000	23,667
Al	mg/kg	12,000	10,000	13,000	11,667
Ca	%	2.7	2.3	2.7	2.6
Cu	mg/kg	66	53	60	60
Zn	mg/kg	430	370	420	407
Cl	mg/kg	333	335	356	341
SO_4	mg/kg	2,300	1,800	2,100	2,067
Si	%	1.5	1.2	1.2	1.3

Table 29 - Energy balance during manure combustion trial

Wet manure feed rate	661.70	kg/h
Dry manure feed rate	487.45	kg/h
Ash feed rate	296.69	kg/h
Energy Input	3.65	GJ/h
Energy Needs		
To vaporise water	0.38	GJ/h
To heat water to 400°C	0.11	GJ/h
To heat air to 400°C	3.38	GJ/h
Total energy needs	3.87	GJ/h

Table 30 – Combustion trial ash analytical data

Parameter	Units	Coal ash	Man. ash-1	Man. ash-2	Man. ash-3	Ave M ash
TS	%	66.9	62.7	51.6	53.9	56.07
VS	%	29.1	44.1	40	25.6	36.57
GCV	GJ/dry t	10.2	11.64	9.25	6.15	9.01
C	%	31.7	33.9	25.2	16.4	25.17
H	%	0.4	2.83	2.92	1.52	2.42
N	%	0.4	0.98	1.16	0.59	0.91
O	%	1.9	11.8	16.8	8.8	12.47
S	%	0.2	0.33	0.35	0.09	0.26
P	%	0.01	0.5	0.87	0.68	0.68
K	%	0.02	0.67	1.2	1.2	1.02
Na	%	0.03	0.15	0.26	0.24	0.22
Fe	mg/kg	5,700	11,000	16,000	31,000	19,333
Al	mg/kg	1,900	7,400	11,000	14,000	10,800
Ca	%	0.05	1.1	2.2	1.7	1.67
Cu	mg/kg	29	38	55	50	47.67
Zn	mg/kg	16	170	320	260	250
Cl	mg/kg	<45	<45	76	54	65
SO_4	mg/kg	1,800	400	1,500	810	903
Si	%	7.4	1.9	1.7	4.1	2.57
Time sampled	13:55	14:00	14:20	14:30		

The energy input from manure during the combustion trial was only 3.65 GJ/h, compared to a design maximum energy input of 18.24 GJ/h. The major energy requirements for combustion of the wet manure are that needed to vaporize the moisture in the manure and raise the water vapour temperature to boiler operating temperature plus the energy to raise the combustion air temperature to the boiler operating temperature. These calculated energy requirements are shown in Table 29. Since there is no temperature monitoring in the combustion zone of the boiler, for the energy balance calculations it has been assumed that boiler temperature was only 400°C. In addition, the combustion air mass flow rate has been calculated from the measured dry stack gas mass flow rate and corrected for the amount of volatiles generated during combustion. This has been estimated at 8.47 t/hr of air. Based on these assumptions, it is calculated that there is insufficient energy in the manure to meet the energy needs and thus there was no excess energy available for steam generation, as has been validated by the boiler monitoring data. In addition, the ash analysis showed significant unburned carbon present, thus further reducing the energy release in the combustor.

It must be emphasised that during the manure combustion trial, the combustion air flow rate was maintained at too high a level by the contracted boiler operators, despite a request to reduce air flow rate. This can be seen from the data in Table 27 which shows the Forced Draft (FD) and Induced Draft (ID) fan settings were maintained essentially the same as when burning coal. The combustion rule-of-thumb is that 0.32 tonnes of air are required per GJ of input fuel energy. Thus, for this trial, the air flow should have been only 1.17 t/hr, compared to the estimated value of 8.47 t/hr. Thus, the air flow rate was probably 7 times too high. Had the air flow rate been correct, there may well have been some energy available for steam generation. This excessive use of combustion air during the trial is also validated by the stack gas monitoring data, which shows the stack gas carbon dioxide concentration was only 0.84%, compared to the normal level of 12% when good combustion conditions are maintained. The stack gas was essentially air.

4.1.6 Ash analysis

The manure characteristics in Table 28 show that the harvesting procedure has incorporated a significant amount of pen base material in the product. This is borne out by the low VS and nutrient (NPK) values and the higher than expected “soil” components such as Al, Fe, Ca and Si. A constituent mass balance from manure to ash is shown in Table 31. In conducting this mass balance, the ash analytical data from the Rep 3 sample (Table 30) was used as it is likely that this sample best represents the true manure ash quality. This is due to the relatively long retention time of the coal ash on the feed grate. The ash mass flow rate is based on the ash content of the manure and also the VS content of the ash. This Rep 3 ash VS value of 25.6% indicates that there is 102.1 kg/hr of unburnt VS in the ash, increasing the total dry ash mass flow rate from the theoretical value of 296.7 kg/hr to 398.8 kg/hr.

The mass balance data in Table 31 shows that 61.64% of the carbon remained unburned in the ash. This again supports the premise that there were very poor combustion conditions in the boiler, most likely due to the excessively high air flow rate and thus very low combustion temperatures.

Table 31 -Manure/ash constituent balance

Parameter	Manure mass (kg/h)	Ash mass (kg/h)	% in Ash
C	106.10	65.40	61.64
H	16.72	6.06	36.25
N	8.27	2.35	28.45
O	112.11	35.09	31.30
S	2.06	0.36	17.39
P	4.86	2.71	55.82
K	10.40	4.79	46.02
Na	1.92	0.96	49.92
Fe	11.54	12.36	107.16
Al	5.69	5.58	98.17
Ca	12.51	6.78	54.19
Cu	0.03	0.02	68.56
Zn	0.20	0.10	52.30
Cl	0.17	0.02	12.94
SO_4	1.01	0.32	32.06
Si	6.34	16.35	258.02

As expected, non-volatile metals such as Fe, Al, Ca, Cu and Zn are mainly classified to the ash. The calculated Si balance is obviously wrong, probably due to the non-homogeneous nature of both the manure and ash. One or two large stones in a sample would significantly increase the concentration of Si and metals such as Fe, Al and Ca.

It is interesting to note that about 45% of the phosphorus and 54% of the potassium is vaporized during the combustion process. This could have a major impact on the fouling of heat transfer surfaces in boilers burning manure.

The coal ash sample analysed (Table 30) was collected prior to any manure ash exiting the boiler. This ash sample shows very low levels of manure components such as P, K, Na, Al, Ca and Fe.

4.1.7 Air emission data

Stack emissions during the manure combustion trial were sampled and analysed by NewEQ. A summary of these results is shown in Table 32.

Table 32 - Stack Emission Results

Parameter	Units	Value
Stack Temperature	°C	125.0
Stack Velocity	m/s	5.1
Actual Stack Flow Rate	m^3/min	174.0
Dry Std Stack Flow Rate	Nm^3/min	111.3
Dry Stack Gas Density	kg/Nm^3	1.3
Dry Stack Gas Flow Rate	kg/h	8,616.2
CO_2	%	0.8
O_2	%	19.7
N_2	%	79.2
CO	mg/Nm^3	1608.0
CO at 7% O_2	mg/Nm^3	18,888.0
Particulate Matter (PM)	mg/Nm^3	123.0
PM at 12% CO_2	mg/Nm^3	1728.0
SOx as SO_3	mg/Nm^3	31.9
NOx as NO_2	mg/Nm^3	45.0
H_2SO_4 as SO_3	mg/Nm^3	<1.5
Total Volatile Organic Compounds	mg/Nm^3	348.0

This data clearly shows that there was an excessive amount of combustion air used during the manure combustion trial. The stack gas is essentially air, with almost no major combustion products, namely CO_2. Under good combustion conditions, the stack gas should contain about 12% CO_2 on a dry basis and the oxygen should have been reduced to about 7%. Emissions of PM, CO, SOx and NOx were acceptable, but when calculated based on standard conditions (CO_2 of 12%) emission concentrations were relatively high.

4.2 Second gasification trial

The second gasification trials were conducted at Nambour, using the 1000 mm BiG pilot plant gasifier, on 1 October 2012. Both Feedlot A and Feedlot B manure were processed. Manure samples were transported to the Nambour site in 1 m^3 'bulka' bags. Pictures of the manures, in the 'bulka' bags, are shown in Photograph 40.

The Feedlot B manure was more uniform in particle size than the Feedlot A manure, more fluffy and had very few stones and other foreign matter. Stones are visible in the Feedlot A manure. The bulk densities of the manures were measured to allow mass feed rates to the gasifier to be calculated. The bulk density of Feedlot B manure was about 400 kg/m^3 and that of the Feedlot A manure was about 600 kg/m^3.

Manure from the 'bulka' bags was measured via 10 L buckets and transferred to 60 L plastic bags for feeding to the gasifier. Thus, volumetric feed rates were known, which were transferred to mass feed rates using the manure bulk density values.

Feedlot A Manure **Feedlot B Manure**

Photograph 40 – Feedlot A and Feedlot B manures for second gasification trial

The gasifier was started up using paper and wood waste to get it up to temperature and the Feedlot B trial commenced at 1:20 pm and this trial was successfully completed at 2:10 pm, with a complete stack analysis being conducted. A summary of operational and analytical data are shown in Table 33 and Table 34. It should be noted that the Hearth # 2 temperature declined from 570 to 350°C during the trial. Ideally, a minimum temperature of 420°C is required to ensure satisfactory operation of the thermal oxidiser.

The Feedlot B manure VS value is significantly higher than the Feedlot A manure value (63% versus 41.8%, see Table 34 and Table 37) indicating significantly less feedlot pen base material is extracted when the manure is harvested. The measured dry char yield for the Feedlot B manure gasification trial was 37%. A picture of the char generated from this gasification trial is shown in Photograph 41.

The Feedlot A manure gasification trial commenced at 3:05 pm and had to be aborted at 3:25 pm due to decreasing temperatures in the gasifier, indicating there was insufficient energy in the Feedlot A manure to sustain the gasification process. Table 36 shows that the Hearth #2 temperature fell to only 299°C when the run was aborted. The emission monitoring programme also had to be curtailed. A summary of operational and analytical data recorded during the Feedlot A trial are shown in Table 36.

The measured dry char yield for the Feedlot A manure gasification trial was 41.7%, significantly higher than that measured for the Feedlot B manure. This is due to the significantly higher ash content of the Feedlot A manure and probably also partly due to the poor gasification performance with the Feedlot A manure.

Table 33 - Feedlot B manure gasification operational data

Parameter	Units	Value
Run time	minutes	50.0
Wet manure fed	kg	114.0
Dry manure fed	kg	99.1
Dry manure feed rate	kg/h	118.9
Gasifier temperature range	^{0}C	570-350
Wet char recovered	kg	91.5
Dry char recovered	kg	36.7
Char Yield	%	37.0

Table 34 – Gasification trial – Feedlot B manure analysis

		Manure results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	87.3	86.9	86.5	86.9
VS	%	60.8	63.6	64.6	63.0
GCV	GJ/dry t	12.0	12.6	11.8	12.1
C	%	32.9	33.3	33.0	33.1
H	%	4.82	5.12	4.99	4.98
N	%	2.46	2.47	2.45	2.46
O	%	35.2	35.8	35.3	35.4
S	%	0.56	0.54	0.55	0.55
P	%	0.81	0.84	0.75	0.80
K	%	1.6	1.8	1.5	1.6
Na	%	0.45	0.50	0.43	0.46
Fe	mg/kg	10000	7800	5700	0.78
Al	mg/kg	6400	5600	4100	0.54
Ca	%	3.4	3.3	2.9	3.2
Cu	mg/kg	52	53	46	50
Zn	mg/kg	250	260	240	250
Cl	mg/kg	170	180	177	176
SO_4	mg/kg	95	100	100	98
Si	%	0.63	0.53	0.64	0.60

Table 35 – Gasification trial – Feedlot B char analysis

		Char results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	42.7	36.5	41.0	40.1
VS	%	30.9	35.8	30.4	32.4
GCV	GJ/dry t	8.75	9.79	8.75	9.1
C	%	26.1	29.6	28.4	28.0
H	%	1.34	1.34	1.21	1.30
N	%	1.39	1.49	1.38	1.42
O	%	10.3	10.9	10.1	10.4
S	%	0.39	0.48	0.43	0.43
P	%	1.5	1.7	1.7	1.6
K	%	2.2	2.5	2.6	2.4
Na	%	0.63	0.69	0.7	0.67
Fe	mg/kg	1.7	1.5	1.8	1.7
Al	mg/kg	1.3	1.3	1.4	1.3
Ca	%	6.2	6.7	7.0	6.6
Cu	mg/kg	96	100	110	102
Zn	mg/kg	450	500	520	490
Cl	mg/kg	119	159	144	141
SO_4	mg/kg	65	76	65	69
Si	%	3.1	3.6	3.7	3.5

Photograph 41 – Feedlot B char

Table 36 - Feedlot A manure gasification operational data

Parameter	Units	Value
Run time	minutes	20.0
Wet manure fed	kg	48.0
Dry manure fed	kg	42.8
Dry manure feed rate	kg/h	128.5
Gasifier temperature range	^{0}C	527-299
Wet char recovered	kg	33.0
Dry char recovered	kg	17.9
Char Yield	%	41.7

Table 37 – Gasification trial – Feedlot A manure analysis

		Manure results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	89.1	88.5	90.0	89.2
VS	%	41.9	40.5	42.9	41.8
GCV	GJ/dry t	7.5	7.2	8.1	7.6
C	%	21.3	20.7	21.7	21.2
H	%	3.4	3.4	3.5	3.4
N	%	1.8	1.8	1.9	1.8
O	%	21.8	22.4	23.4	22.5
S	%	0.5	0.5	0.5	0.5
P	%	0.8	0.8	0.8	0.8
K	%	1.8	1.8	1.8	1.8
Na	%	0.3	0.3	0.3	0.3
Fe	mg/kg	1.6	1.5	1.5	1.5
Al	mg/kg	0.8	0.8	0.9	0.8
Ca	%	2.1	2.3	2.2	2.2
Cu	mg/kg	43.0	46.0	46.0	45.0
Zn	mg/kg	310.0	330.0	330.0	323.0
Cl	mg/kg	126.0	113.0	122.0	120.0
SO_4	mg/kg	6.0	1.0	3.0	3.3
Si	%	1.8	2.3	1.7	1.9

Table 38 – Gasification trial – Feedlot A char analysis

		Char results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	51.2	57.6	53.6	54.1
VS	%	24.0	19.6	18.8	20.8
GCV	GJ/dry t	5.8	5.1	4.5	5.2
C	%	18.7	15.8	14.0	16.2
H	%	0.8	0.9	0.80	0.9
N	%	0.9	1.0	0.9	0.9
O	%	8.0	7.5	6.0	7.2
S	%	0.2	0.8	0.2	0.2
P	%	1.0	1.0	1.1	1.0
K	%	1.8	1.9	2.1	1.9
Na	%	0.3	0.4	0.4	0.4
Fe	mg/kg	1.7	2.2	2.2	2.0
Al	mg/kg	1.3	1.4	1.7	1.5
Ca	%	2.8	2.9	3.4	3.0
Cu	mg/kg	54.0	58.0	64.0	59.0
Zn	mg/kg	400.0	410.0	440.0	417.0
Cl	mg/kg	82.0	84.0	86.0	84.0
SO_4	mg/kg	21.0	23.0	25.0	23.0
Si	%	4.1	4.5	4.6	4.4

4.2.1 BiG Gasification Results

BiG calculated the theoretical char yields based on an ash mass balance. Since the ash is conservative, all the ash must report to the char, with the exception of that lost in the syngas. With the BiG allowance of 0.5% of the ash being transferred to the syngas stream, the ash mass balance approach gave char yields of 55% and 74% respectively for the Feedlot B and Feedlot A manures. These values are much higher than the measured values. BiG indicated this is a common phenomenon encountered with short-term gasification trials. For process modelling and costing purposes, these calculated char yields are used. It is interesting to note that the pyrolysis char yields (see Section 4.3) measured were 54.1% and 72.4% respectively for Feedlot B and Feedlot A manures. Thus, the BiG calculated char yields are consistent with the pyrolysis char yields.

The char generated by these trials is suitable for agricultural use and, based on the International Biochar Initiative (International Biochar Initiative 2012), the char is categorised as a Class 3 char, as per the data shown in Table 39.

Table 39 - Char categorisation data

Parameter	Unit	IBI Range of maximum allowable thresholds (dry basis)	Mean Result Kerwee Whyalla	Comment
Organic Carbon	%	Class 1: ≥60% Class 2: ≥30% - <60% Class 3: ≥10% - <30%	28 16	Both chars fit the criteria for a IBI class 3 char, assuming that the ultimate analysis carbon measurement is a close approximation of organic carbon content.
Copper	mg/kg	63-1500	490 134	Both chars fit within the IBI acceptance criteria, however, being above 63 may exceed the limit for certain applications.
H:C ratio		0.7 max	0.55 0.63	Both chars fit the IBI acceptance criteria for definition as biochar according to H:C ratio.
Zinc	mg/kg	200-2800	490 420	Both chars fit within the IBI acceptance criteria, however, being above 200 may exceed the limit for certain applications.

BiG developed constituent mass and energy balances for the gasification process based on the calculated char yields. These results are shown in Table 40 and Table 41. The energy balance data show that 59% of the Feedlot B manure energy is transferred to the syngas and this drops down to 50% for the Feedlot A manure. As expected, the constituent mass balances show that essentially all the metals in the manure are transferred to the char. There are obvious anomalies for some elements such as silicon, where the recovery data show almost three times the manure mass in the char. Most of the manure nutrients are recovered in the char. Essentially all of the phosphorus and potassium are recovered in the char with about 35% of the nitrogen recovered in the char.

Thermal oxidiser emission data could only be measured for the Feedlot B gasification trial and these data are reported in Table 42. The emission data are generally considered to be acceptable, with the exception of the CO emissions. These should ideally be below 50 mg/Nm^3.

Table 40 – Gasification elemental mass and energy balances

Ultimate analysis Results - SGS report TW12-08104 incl. calculated parameters

					Ultimate Analysis, wt% Dry Basis								
Sample	Moisture wt%	Volatile matter dry basis	Ash wet basis	Ash dry basis wt%	C	H	N	S	O % (Calc by BiG,by diff)	H:C	O:C	C:N	Calorific Value MJ/kg
Kerwee Manure T1	12.7	60.8	26.5	39.2	32.9	4.82	2.46	0.56	20.1	1.75	0.46	15.6	11.97
Kerwee Manure T2	13.1	63.6	23.3	36.4	33.3	5.12	2.47	0.54	22.2	1.83	0.50	15.7	12.57
Kerwee Manure T3	13.5	64.6	21.9	35.4	33.0	4.99	2.45	0.55	23.6	1.80	0.54	15.7	11.79
Mean	**13.1**	**63.0**	**23.9**	**37.0**	**33.1**	**5.0**	**2.5**	**0.6**	**21.9**	**1.8**	**0.5**	**15.7**	**12.1**
Kerwee Char T1	57.3	30.9	29.5	69.1	26.1	1.34	1.39	0.39	1.7	0.61	0.05	21.9	8.75
Kerwee Char T2	63.5	35.8	23.4	64.2	29.6	1.34	1.49	0.48	2.9	0.54	0.07	23.2	9.79
Kerwee Char T3	59.0	30.4	28.5	69.6	28.4	1.21	1.38	0.43	-1.0	0.51	-0.03	24.0	8.75
Mean	**59.9**	**32.4**	**27.2**	**67.6**	**28.0**	**1.3**	**1.4**	**0.4**	**1.2**	**0.55**	**0.0**	**23.0**	**9.1**
Calculated yield to char (dry mass basis)			**55%**		**47%**	**14%**	**32%**	**43%**	**3%**				**41%**
			kg/hr to flue gas		**16.0**	**4.9**	**10.9**	**14.9**	**1.0**			**Total**	**47.7**
Manure Processing rate			122	kg/hr wet	106	kg/hr dry		410	kW thermal rate feedstock basis				
Off-gas rate			64	kg/hr wet				241	kW thermal rate to off-gas and losses				
Assumed recovery of ash to char			99.5%										

			Prox. Analysis dry basis		Ultimate Analysis, wt% Dry Basis								
Sample	Moisture wt%	Volatile matter dry basis	Ash wet basis	Ash dry basis wt%	Carbon	H	N	S	O % (Calc by BiG,by diff)	H:C	O:C	C:N	Calorific Value MJ/kg
Whyalla Manure T1	10.9	41.9	47.2	58.1	21.3	3.39	1.81	0.47	14.9	1.90	0.53	13.7	7.51
Whyalla Manure T2	11.5	40.5	48.0	59.5	20.7	3.36	1.83	0.50	14.1	1.93	0.51	13.2	7.21
Whyalla Manure T3	10.0	42.9	47.1	57.1	21.7	3.54	1.87	0.50	15.3	1.94	0.53	13.5	8.06
Mean	**10.8**	**41.8**	**47.4**	**58.2**	**21.2**	**3.4**	**1.8**	**0.5**	**14.8**	**1.9**	**0.5**	**13.5**	**7.6**
Whyalla Char T1	48.8	24.0	27.2	76.0	18.7	0.82	0.93	0.19	3.4	0.52	0.13	23.5	5.76
Whyalla Char T2	42.4	19.6	38.0	80.4	15.8	0.93	0.97	0.17	1.7	0.70	0.08	19.0	5.14
Whyalla Char T3	46.4	18.8	34.8	81.2	14.0	0.80	0.86	0.15	3.0	0.68	0.16	19.0	4.54
Mean	**45.9**	**20.8**	**33.3**	**79.2**	**16.2**	**0.9**	**0.9**	**0.2**	**2.7**	**0.63**	**0.1**	**20.5**	**5.1**
Calculated yield to char (dry mass basis)			**74%**		**56%**	**18%**	**37%**	**26%**	**13%**				**50%**
			kg/hr to flue gas		**11.2**	**3.7**	**7.4**	**5.1**	**2.7**			**Total**	**30.0**
Manure Processing rate			129	kg/hr wet	115	kg/hr dry		272	kW thermal rate feedstock basis				
Off-gas rate			44	kg/hr wet				136	kW thermal rate to off-gas and losses				
Assumed recovery of ash to char			99.5%										

BiG indicated that for both the trials the thermal oxidiser temperature did not reach the design value of greater than 750°C. This indicates that for commercial operations the gasification system will require, at minimum, air pre-heaters for both the primary air (to the gasifier) and the secondary air to the thermal oxidiser.

Based on the mass and energy data developed by BiG (Table 40), and their view that heat losses for a commercial-scale system would be 15% of feed energy, PFDs for the four manure gasification options have been developed. It is also assumed that the manures are dried to 90% TS prior to feeding to the gasifier, with the thermal energy for drying being derived from the syngas energy. In addition, the process configuration includes a boiler (integrated into the thermal oxidiser) and a steam turbine for electricity generation. As with the combustion options, steam is used for feed flaking for all the gasification options considered. These PFDs and a process summary of the four options are discussed in Section 5.4.

Table 41 – Gasification constituent mass balances (manure to char)

Inorganics Results - SGS report TW12-08104 incl. calculated parameters **Char yield 55%**

Sample	Ash wet basis	Ash dry basis wt%	Sulphate mg/kg	Chloride mg/kg	Silicon %	Zinc mg/kg	Aluminium mg/kg	Calcium %	Copper mg/kg	Iron mg/kg	Phosphorous %	Potassium %	Sodium %
			Inorganics Dry Basis										
Kerwee Manure T1	26.5	39.2	95	170	0.63	250	6400	3.4	52	10000.0	0.81	1.6	0.45
Kerwee Manure T2	23.3	36.4	100	180	0.53	260	5600	3.3	260	7800.0	0.84	1.8	0.50
Kerwee Manure T3	21.9	35.4	100	236	0.64	240	4100	2.9	240	5700.0	0.75	1.5	0.43
Mean	**24**	**37**	**98**	**195**	**0.6**	**250**	**5367**	**3.2**	**184**	**7833**	**0.8**	**1.6**	**0.5**
Kerwee Char T1	29.5	69.1	65.0	119.0	3.1	450	13000	6.2	450	17000	1.5	2.2	0.63
Kerwee Char T2	23.4	64.2	76.0	159.0	3.6	500	13000	6.7	500	15000	1.7	2.5	0.69
Kerwee Char T3	28.5	69.6	65.0	144.0	3.7	520	14000	7.0	520	1800	1.7	2.6	0.70
Mean	**27**	**68**	**69**	**141**	**3.5**	**490**	**13333**	**6.6**	**490**	**11267**	**1.6**	**2.4**	**0.7**
Yield to char (dry mass basis)			**38%**	**40%**	**318%**	**108%**	**137%**	**114%**	**146%**	**79%**	**112%**	**82%**	**80%**

Char yield 74%

Sample	Ash wet basis	Ash dry basis wt%	Sulphate mg/kg	Chloride mg/kg	Silicon %	Zinc mg/kg	Aluminium mg/kg	Calcium %	Copper mg/kg	Iron mg/kg	Phosphorous %	Potassium %	Sodium %
			Inorganics Dry Basis										
Whyalla Manure T1	47.2	58.1	6	177	1.8	310	8000	2.1	310	16000.0	0.78	1.8	0.29
Whyalla Manure T2	48.0	59.5	1	113	2.3	330	7900	2.3	46	15000.0	0.80	1.8	0.30
Whyalla Manure T3	47.1	57.1	3	82	1.7	330	8500	2.2	46	15000.0	0.79	1.8	0.29
Mean	**47**	**58**	**3**	**124**	**1.9**	**323**	**8133**	**2.2**	**134**	**15333**	**0.8**	**1.8**	**0.3**
Whyalla Char T1	27.2	76.0	21.0	82.0	4.1	400	13000	2.8	54	17000	1.0	1.8	0.30
Whyalla Char T2	38.0	80.4	23.0	84.0	4.5	410	14000	2.9	58	22000	1.0	1.9	0.37
Whyalla Char T3	34.8	81.2	25.0	86.0	4.6	440	17000	3.4	64	22000	1.1	2.1	0.41
Mean	**33**	**79**	**23**	**84**	**4.4**	**417**	**14667**	**3.0**	**59**	**20333**	**1.0**	**1.9**	**0.4**
Yield to char (dry mass basis)			**39%**	**75%**	**379%**	**37%**	**125%**	**71%**	**99%**	**76%**	**24%**	**73%**	**72%**

Table 42 - Air emission data for Feedlot B manure gasification trial

Physical characteristics of stack gas	
Average temperature (°C)	426
Average velocity at sampling point (m/s)	32.5
Actual volumetric flow rate (m^3/s)	3.12
Normal wet volumetric flow rate (Nm^3/s)	1.22
Normal dry volumetric flow rate (Nm^3/s)	1.09
Gaseous Components	
Water (wet) (v/v %)	10.3
Oxygen (v/v %)	16.3
Carbon Monoxide (v/v %)	0.32
Carbon Dioxide (v/v %)	4.48
Oxides of Nitrogen (as NO_2) (ppmv)	72.0
Emission concentrations	
Particulate matter (mg/Nm^3)	259
Particulate matter µm 10 (PM_{10}) (mg/Nm^3)	51.2
Oxides of Nitrogen (as NO_2) (mg/Nm^3)	148
Carbon Monoxide (CO) (mg/Nm^3)	4010
TVOC (mg/Nm^3)	287
Mass emission rates	
Particulate matter (g/s)	0.28
Particulate matter µm 10 (PM_{10}) (g/s)	0.056
Oxides of Nitrogen (as NO_2) (g/s)	0.16
Carbon Monoxide (CO) (g/s)	4.4
TVOC (g/s)[1]	0.31

4.3 Pyrolysis trial

4.3.1 Summary of operational data

The pyrolysis trials were conducted at the PacPyro facility in Somersby, NSW, on 1 and 2 November, 2012. The Feedlot A manure was processed on 1 November 2012 and the Feedlot B manure on 2 November 2012. Sub-samples of the Feedlot A and Feedlot B manure used for the gasification trials were sent to PacPyro for the pyrolysis trials. The sub-sample of Feedlot A manure was air-dried before shipping it to PacPyro. The as-received manure TS values, as measured by PacPyro were 91.1% for Feedlot A and 88.6% for Feedlot B. PacPyro dried these samples at 104°C to produce a bone-dry feedstock for feeding the pyrolyser.

Trevor Bridle attended the site on 2 November 2012 to witness the removal of char from the Feedlot A run and the charging of the pyrolyser with the Feedlot B manure. Photograph 42 and Photograph 43 show the Feedlot A char in the pyrolyser prior to removal and the charged Feedlot B manure in the pyrolyser before the start of the run. The weight of the char recovered from the Feedlot A pyrolysis run was 6.95 kg and 7.7 kg of bone-dry Feedlot B manure was charged into the pyrolyser for the Feedlot B pyrolysis run.

Table 43 and Table 45 give the manure analytical results from the Feedlot A and Feedlot B pyrolysis runs and Table 44 and Table 46 give the char results.

Photograph 42 – Feedlot A char in pyrolyser

Photograph 43 – Feedlot B manure in pyrolyser

Table 43 – Pyrolysis trial - Feedlot A manure analysis

		Manure results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	89.4	89.4	89.3	89.4
VS	%	34.5	36.0	37.4	36.0
GCV	GJ/dry t	8.7	7.8	7.6	8.0
C	%	20.0	19.3	20.3	19.9
H	%	3.3	3.1	3.3	3.3
N	%	1.6	1.5	1.6	1.6
O	%	21.5	21.1	23.6	22.1
S	%	0.4	0.4	0.4	0.4
P	%	0.9	1.0	1.0	1.0
K	%	1.9	1.9	2.0	1.9
Na	%	0.3	0.3	0.4	0.3
Fe	%	1.7	1.6	1.8	1.7
Al	%	1.1	1.0	1.2	1.1
Ca	%	2.4	2.5	2.7	2.5
Cu	mg/kg	52.0	54.0	57.0	54.3
Zn	mg/kg	390	400	420	403
Cl	mg/kg	11,010	11,580	11,780	11,457
SO_4	mg/kg	<1	<1	<1	<1
Si	%	1.8	2.7	1.8	2.1

Table 44 – Pyrolysis trial - Feedlot A char analysis

		Char Results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	97.8	97.7	97.8	97.8
VS	%	22.4	24.4	22.7	23.2
GCV	GJ/dry t	7.3	7.8	7.4	7.5
C	%	16.0	14.4	15.7	15.4
H	%	0.7	0.7	0.8	0.7
N	%	1.05	0.97	1.05	1.02
O	%	6.5	6.3	5.8	6.2
S	%	0.01	0.01	0.02	0.01
P	%	1.5	1.5	1.5	1.5
K	%	3.1	3.1	3.1	3.1
Na	%	0.48	0.49	0.48	0.48
Fe	%	2.3	2.2	2.2	2.2
Al	%	2.5	2.5	2.6	2.5
Ca	%	4.1	4.2	4.2	4.2
Cu	mg/kg	80	81	81	81
Zn	mg/kg	620	630	630	627
Cl	mg/kg	14,460	14,630	16,040	15,043
SO_4	mg/kg	590	590	680	620
Si	%	4.1	3.9	4.0	4.0

Table 45 – Pyrolysis trial - Feedlot B manure analysis

		Manure results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	92.5	92.4	92.5	92.5
VS	%	60.3	59.8	61.2	60.4
GCV	GJ/dry t	13.9	14.0	13.7	13.8
C	%	34.0	33.9	32.1	33.3
H	%	5.1	5.06	4.85	5.0
N	%	2.4	2.35	2.3	2.3
O	%	35.6	36.1	33.6	35.1
S	%	0.4	0.44	0.42	0.4
P	%	1.1	1.1	1.2	1.1
K	%	2.1	2.1	2.1	2.1
Na	%	0.5	0.5	0.5	0.5
Fe	%	0.9	1.1	1.0	1.0
Al	%	0.79	0.89	0.86	0.8
Ca	%	4.1	4.4	4.2	4.2
Cu	mg/kg	63.0	66.0	68.0	65.7
Zn	mg/kg	330	350	350	343
Cl	mg/kg	15,660	17,220	16,670	16,517
SO_4	mg/kg	8,600	8,600	8,400	8,533
Si	%	1.2	1.2	1.1	1.2

Table 46 – Pyrolysis trial – Feedlot B char analysis

		Char Results			
Parameter	Units	Rep-1	Rep-2	Rep-3	Average
TS	%	96.5	96.5	96.5	96.5
VS	%	37.6	37.4	36.2	37.1
GCV	GJ/dry t	12.6	13.1	12.8	12.8
C	%	30.8	31.9	31.9	31.5
H	%	1.48	1.56	1.57	1.54
N	%	2.0	2.1	2.1	2.1
O	%	10.8	11.5	11.5	11.3
S	%	0.2	0.5	0.2	0.3
P	%	2	1.9	1.9	1.9
K	%	3.7	3.6	3.6	3.6
Na	%	0.8	0.8	0.8	0.8
Fe	%	1.7	1.7	1.7	1.7
Al	%	1.6	1.6	1.6	1.6
Ca	%	7.8	7.2	7.5	7.5
Cu	mg/kg	110	110	100	107
Zn	mg/kg	590	570	570	577
Cl	mg/kg	22,710	22,580	22,710	22,667
SO_4	mg/kg	>10,000	>10,000	>10,000	>10,000
Si	%	2.7	2.5	2.5	2.6

4.3.2 PacPyro pyrolysis results

PacPyro have provided their estimated Mass and Energy Basis of Design for plants with a throughput of 1 tph dry manure, based on their own manure and char analytical results, as analysed by Bureau Veritas. These PacPyro manure and char results are shown in Table 47.

Table 47 - PacPyro manure and char analytical results

Parameter	Units	Feedlot A		Feedlot B	
		Manure	Char	Manure	Char
C	%	15.53	13.65	33.60	33.00
H	%	2.14	0.71	4.45	1.65
N	%	1.32	0.87	2.31	2.10
S	%	0.40	0.05	0.52	0.50
O	%	10.96	1.87	26.09	3.93
GCV	GJ/dry t	8.01	7.10	13.54	12.22

These results are generally in concurrence with those analysed by SGS and reported in Table 43, Table 44, Table 45 and Table 46. The notable exceptions are the carbon, hydrogen and nitrogen values for the Feedlot A manure and char where the SGS results are significantly higher than the PacPyro results.

PacPyro indicated that the Feedlot B manure had a VS value high enough to consider including a char gasifier in the design, to maximise energy recovery from the manure. The actual char yields measured during the trials were 72.4% for the Feedlot A manure and 54.1% for the Feedlot B manure. With char gasification, PacPyro has estimated that the Feedlot B char yield will drop to 43.7%.

The process model outputs for the Feedlot A and Feedlot B pyrolysis plants, as developed by PacPyro, are shown in Table 48 and Table 49. The data is based on a pyrolysis system with a feed rate of 1 tph dry manure. The predicted energy outputs in Table 48 and Table 49 are based on the usable energy available after that used within the process for manure drying and pyrolysis. The thermal energy shown in the tables is that available in the syngas for use to generate steam or electricity. The electrical energy output data is based on all the available syngas being converted to electricity in gas engines.

Table 48 - PacPyro pyrolysis process model for Feedlot B manure

		Manure TS	
	Parameter	65%	75%
	Char (%)	43.7	43.7
	kWhe/t	363.0	400.0
Electrical	GJ/h	1.3	1.4
	MWe	0.4	0.4
	kWhth/t	987.0	1197.0
Thermal	GJ/h	3.6	4.3
	MWth	1.0	1.2

Table 49 - PacPyro pyrolysis process model for Feedlot A manure

		Manure TS	
	Parameter	65%	75%
	Char (%)	72.0	72.0
	kWhe/t	62.0	102.0
Electrical	GJ/h	0.2	0.4
	MWe	0.1	0.1
	kWhth/t	94.0	256.0
Thermal	GJ/h	0.3	0.9
	MWth	0.1	0.3

Based on the char yields reported by PacPyro, a constituent mass balance, from manure to char, for the Feedlot A and Feedlot B pyrolysis trials is shown in Table 50 and Table 51.

With the exception of CHNOS, essentially all of the other manure constituents are classified to the char. It is interesting to note that about 50% of the N and all of the P&K are classified to the char. Thus, the char will be an excellent source of slow-release nutrients for crop growth. The PacPyro char analysis also shows that the carbon in the char is fixed for at least 1000 years. Thus, should carbon sequestration be considered by future Governments, a carbon credit would apply to the carbon fixed in the char.

Table 50 - Feedlot A manure / char constituent balances

Constituent	Manure mass (kg/h)	Char mass	% in Char
C	198.67	111.25	56.0
H	32.50	5.29	16.3
N	15.83	7.41	46.8
O	220.67	44.89	20.3
S	3.80	0.10	2.5
P	9.70	10.86	112.0
K	19.33	22.44	116.1
Na	3.43	3.50	101.9
Fe	17.00	16.17	95.1
Al	11.00	18.34	166.7
Ca	25.33	30.17	119.1
Cu	0.05	0.06	107.5
Zn	0.40	0.45	112.5
Cl	11.46	10.89	95.1
Si	21.00	28.96	137.9

Table 51 - Feedlot B manure / char constituent balances

Constituent	Manure mass (kg/h)	Char mass	% in Char
C	333.33	170.60	51.2
H	50.07	8.31	16.6
N	23.37	11.14	47.7
O	351.00	60.95	17.4
S	4.20	1.53	36.5
P	11.33	10.46	92.3
K	21.00	19.66	93.6
Na	5.00	4.29	85.8
Fe	9.83	9.20	93.5
Al	8.47	8.66	102.2
Ca	42.33	40.58	95.8
Cu	0.07	0.06	84.9
Zn	0.35	0.31	89.1
Cl	16.67	12.26	73.6
Si	11.67	13.89	119.0

5 Discussion

5.1 Combustion trial

The manure combustion trial results clearly confirmed that feedlot manure with a TS of about 74% and a VS of only about 40% is not a suitable feedstock for energy recovery via combustion. In hindsight, the combustor used was not ideally suited for combustion of manure of this quality. The combustion air flow rate during the manure combustion trial was significantly in excess of that required for efficient combustion. Had the combustion air flow rate been that required for efficient combustion, there would have been about 1.85 GJ/h of energy available for steam generation, which could have produced up to 670 kg/h of steam. However, this is still not considered an acceptable energy/steam output and it is considered that feedlot manure combustion for energy recovery will only be technically viable provided that the manure VS is above 60% and the TS is preferably above 75%. To achieve these TS and VS requirements, feedlot operators will need to be more diligent in their pen manure harvesting procedures.

In addition, a more efficient combustor, such as a Fluid Bed Combustor (FBC), is regarded as being highly desirable if manure combustion is to be contemplated.

The fouling of heat transfer surfaces in the boiler, by low-melting eutectic mixtures containing potassium and phosphorus, is a major issue that needs to be addressed and assessed prior to proceeding with a commercial scale feedlot manure combustion system.

5.2 Gasification trial

The gasification trial results indicated that for the process to be technically feasible, the primary and secondary air needs pre-heating to ensure that the thermal oxidiser temperature can be maintained above 750°C. This obviously applies to the manures as tested and is particularly true for the low volatile Feedlot A manure. This temperature requirement is needed to ensure that flue gas emission limits will meet regulatory requirements. The chars produced from gasification are suitable for reuse in agriculture.

5.3 Pyrolysis Trial

The PacPyro manure trials confirmed that both the Feedlot A and Feedlot B manures could be successfully pyrolysed. However, the energy recovery potential of the low VS Feedlot A manure is very low. For the low TS manure, the usable energy recovery is only 0.34 GJ/dry tonne which increases slightly to 0.92 GJ/t for the high TS manure. Thus, from an energy recovery perspective, pyrolysis of low VS manures is not at all commercially attractive. The low VS manures do however produce a significant amount of char due to the high ash content of the manure. Char from the Feedlot A manure only had a VS content of 23% and a carbon content of 15%. These values categorise this char at the lowest level that is suitable for agricultural reuse.

5.4 Economic viability

The economics of energy recovery from feedlot manure via thermal processing was assessed based on four input scenarios, covering small and large feedlots, with two different manure TS and VS assumptions. For the pyrolysis and gasification options, the manure quality, as tested was used, and economics were developed based on two assumed manure TS values, namely 65 and 75%.

For the combustion option only one manure VS quality (61.7 %) was used for both small and large feedlots and TS values of 65 and 75% were also used in the economic assessments. This is because the combustion trial with low VS manure was not deemed technically feasible.

The dry manure quantities for the small and large feedlots were based on feedlots with SCU capacities of 9,171 and 50,000 respectively and they were assumed to operate at 75% occupancy. A dry manure generation rate of 0.8 t/SCU/a has been used in estimating manure quantities. Based on this, the four sets of input feed quality data for the economic modelling of the combustion, gasification and pyrolysis systems is shown in Table 52.

Table 52 - Manure quality data for economic modelling

Parameter	Units	Small Feedlot (9,171 SCU, 75% full)		Large Feedlot (50,000 SCU, 75% full)	
		Low TS Manure	High TS manure	Low TS Manure	High TS manure
TS	%	65	75	65	75
VS, combustion	%	61.7	61.7	61.7	61.7
VS, gasification	%	63	63	41.8	41.8
VS, pyrolysis	%	60.4	60.4	36.0	36.0
Dry mass	dry tpa	5,500	5,500	30,000	30,000
Wet mass	wet tpa	8,462	7,333	46,154	40,000
Dry mass	tpd	15	15	82	82
Wet mass	tpd	23	20	126	110

5.4.1 Combustion cost analysis

Costs for the manure combustion systems were based on process sizing and performance data developed from mass and energy balances for the four combustion options, using Fluid Bed Boilers (FBB). The standard process engineering approach to developing heat and mass balances for combustors was used. For this study, the following thermal parameters were used to develop the mass and energy balances around the FBB, assuming a bed temperature of 800°C.

Table 53 - Input thermal parameters

LHV of water	2.20	GJ/t
Ave Cp of water to 800°C	2.09	kJ/kg/C
Ave air Cp to 800°C	1.09	kJ/kg/C
Cp of ash	0.84	kJ/kg/C
Air reqd for combustion	0.32	t/GJ

Based on the manure quality data in Table 52 and the thermal parameter data in Table 53, Mass and Energy balance data for the four combustion options were developed. Summaries for the small feedlot, low TS data and large feedlot, high TS data options are shown in Table 54 and Table 55.

The M&E balance data show that the boiler efficiency for the low TS options is only 54.2% which increases to 60.5% for the high TS options. These are significantly lower than the traditional boiler efficiencies of 70% when burning high TS fossil fuels. These designs do not include air pre-heaters or economisers, which would increase thermal efficiencies.

Table 54 - M&E Balance for small feedlot, low TS option

Wet mass feed rate	23.0	tpd
Water feed rate	8.0	tpd
Net energy input	178.8	GJ/d
Ash feed rate	5.8	tpd
Air for combustion	57.6	tpd
Energy Needs		
Water vaporisation	17.9	GJ/d
Heat water to 800°C	11.9	GJ/d
Heat air to 800°C	48.3	GJ/d
Ash heat loss	3.9	GJ/d
Total energy needs	81.9	GJ/d
Energy available for steam gen	96.9	GJ/d
Calculated FBB Efficiency	54.2	%

Table 55 - M&E Balance for large feedlot, high TS option

Wet mass feed rate	20.0	tpd
Water feed rate	5.0	tpd
Net energy input	178.8	GJ/d
Ash feed rate	5.8	tpd
Air for combustion	57.6	tpd
Energy Needs		
Water vaporisation	11.1	GJ/d
Heat water to 800°C	7.4	GJ/d
Heat air to 800°C	48.3	GJ/d
Ash heat loss	3.9	GJ/d
Total energy needs	70.6	GJ/d
Energy available for steam gen	108.2	GJ/d
Calculated FBB Efficiency	60.5	%

In developing combustion costs, it has been assumed that the FBB would provide all the steam required for feed flaking (120 MJt/SCU/month) with the rest of the steam being sent to a steam turbine for power generation. On this basis, a simplified PFD for the large feedlot, high TS manure option is shown in Figure 19. The efficiency used for power output from the steam turbines is 25%. A summary of major process parameters for the four combustion options is shown in Table 56.

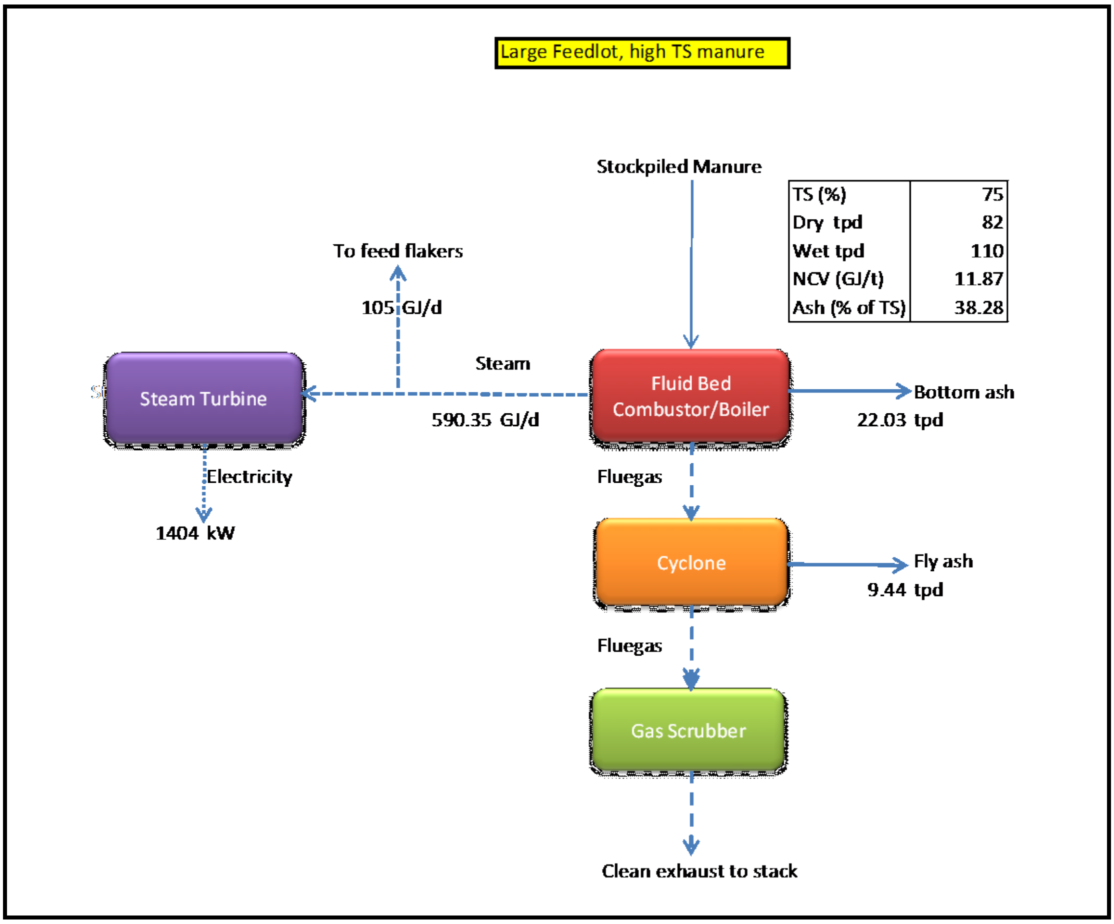


Figure 19 – Large feedlot, high TS combustion PFD

Table 56 - Combustion options process summary

Parameter	Units	Small Feedlot		Large Feedlot	
		Low TS	High TS	Low TS	High TS
Wet manure feed rate	tpd	23.0	20.0	126.0	110.0
Dry ash output	tpd	5.8	5.8	31.5	31.5
Manure feed hopper	m^3	46.0	40.0	253.0	219.0
Ash hopper	m^3	19.0	19.0	105.0	105.0
Steam for feed flaking	GJ/d	19.3	19.3	105.0	105.0
Power output	kW	224.0	257.0	1225.0	1404.0

Capital costs for the combustion facilities were estimated based on vendor costs for the FBB's and steam turbines and Bridle Consulting costs for the other major equipment items such as feed and ash hoppers and gas cleaning systems. Typical engineering cost factors were then used for the other components and this is shown in Table 57.

Table 57 - Combustion facility capital cost estimates

Cost Component	Cost Factor	Small feedlot		Large feedlot	
		Low TS	High TS	Low TS	High TS
Major equipment items					
FBB package		2,062,563	1,951,288	5,780,160	5,173,205
Manure feed hopper (2 d SRT)		205,343	187,066	640,180	581,430
Ash hopper (5 d SRT)		117,817	117,817	356,085	356,085
Gas cleaning package		515,641	487,822	1,445,040	1,293,301
Steam Turbine package		429,249	452,225	1,131,387	1,256,711
Sub-total		3,330,612	3,196,218	9,352,853	8,660,733
Piping and valves (%)	10	333,061	319,622	935,285	866,073
Electrics (%)	15	499,592	479,433	1,402,928	1,299,110
Instruments and control (%)	15	499,592	479,433	1,402,928	1,299,110
Civils (%)	10	333,061	319,622	935,285	866,073
Mech installation (%)	10	333,061	319,622	935,285	866,073
Equipment Sub-total		5,328,980	5,113,948	14,964,564	13,857,173
Engineering design (%)	8	426,318	409,116	1,197,165	1,108,574
Project management (%)	8	426,318	409,116	1,197,165	1,108,574
Sub-total		6,181,617	5,932,180	17,358,895	16,074,320
Overheads/risk (%)	7	432,713	415,253	1,215,123	1,125,202
Profit margin (%)	10	618,162	593,218	1,735,889	1,607,432
Contingency (%)	15	927,243	889,827	2,603,834	2,411,148
TOTAL		**8,159,734**	**7,830,477**	**22,913,741**	**21,218,103**

Table 57 shows the capital cost estimates for the combustion facilities vary from $7.83 million for the small feedlot high TS manure option to $22.91 million for the large feedlot low TS manure option.

Operating and maintenance (O&M) costs as well as revenues were estimated based on a number of assumptions, which are outlined in Table 58. The cost for thermal energy is the average value for use of coal, diesel, NG and LPG as the energy source. Based on these assumptions and the process data from the M&E balances, the estimated O&M costs and revenues for the four options are shown in Table 59. It has been assumed that the ash from the combustor will be spread on feedlot land at essentially little or no cost.

Electricity costs for the combustion facilities are based on power draws of 50 and 180 kW respectively, for small and large feedlots. It has also been assumed that power generation is operational for 330 days per annum. Thermal energy credits are based on amount of fossil fuel which would have been used for feed flaking at each facility.

Based on the above, the estimated net O&M costs for all facilities are negative, indicating revenues exceed costs.

Table 58 - Unit cost data

Cost factor	Units	Value
Operator Cost	$/p/a	60,000
Maintenance Cost	% of equip	4
Power Cost	$/MWh	180
Thermal Energy Cost	$/GJ	17
RECs Value	$/MWh	40

Table 59 - O&M and revenue cost estimates ($/annum)

Cost Component	No.	Unit cost	Small Feedlot		Large Feedlot	
			Low TS	High TS	Low TS	High TS
Operating staff	3	60,000	180,000	180,000	180,000	180000
Electricity		180	78,840	78,840	283,824	283,824
Maintenance	4	% of equip	213,159	204,558	598,583	554,287
Total			471,999	463,398	1,062,407	1,018,111
Electricity credit	330	d/a	319,938	366,626	1,746,692	2,001,352
REC credit	330	d/a	71,097	81,472	388,154	444,745
Thermal energy credit	365	d/a	174,845	174,845	950,245	950,245
Net O&M Cost			-93,881	-159,546	-2,022,684	-2,378,231

Financial analysis for these facilities is based on a Net Present Value (NPV) approach as well as developing simple payback periods. The NPVs are calculated on the assumption that the discount rate is 7% and the period is 20 years. A summary of this financial analysis is shown in Table 60. This financial analysis shows that combustion of feedlot manure, even with reasonable VS values (about 60%) is not commercially attractive for small feedlots and marginally attractive for large feedlots.

Table 60 - Financial analysis of the combustion options

Financial Parameter	Small Feedlot		Large Feedlot	
	Low TS	High TS	Low TS	High TS
20-yr NPV	$7,165,152	$6,140,249	$1,485,396	-$3,976,918
Payback Period (yrs)	86.9	49.1	11.3	8.9

5.4.2 Gasification Cost Analysis

Four process options were considered when developing costs for the gasification systems. The input feed data for these four options are shown in Table 52. Simple PFDs, with mass and energy balance data, for these four gasification options were developed, based on the BiG process model outputs shown in Table 40. The gasification flow sheets include steam generation and where appropriate, power generation using steam turbines. Only the large feedlot, low TS manure option does not generate sufficient energy to warrant power generation. The small feedlot, low TS option as well as the large feedlot, high TS option PFDs are shown in Figure 20 and Figure 21. A process summary of the four gasification facility options is shown in Table 61.

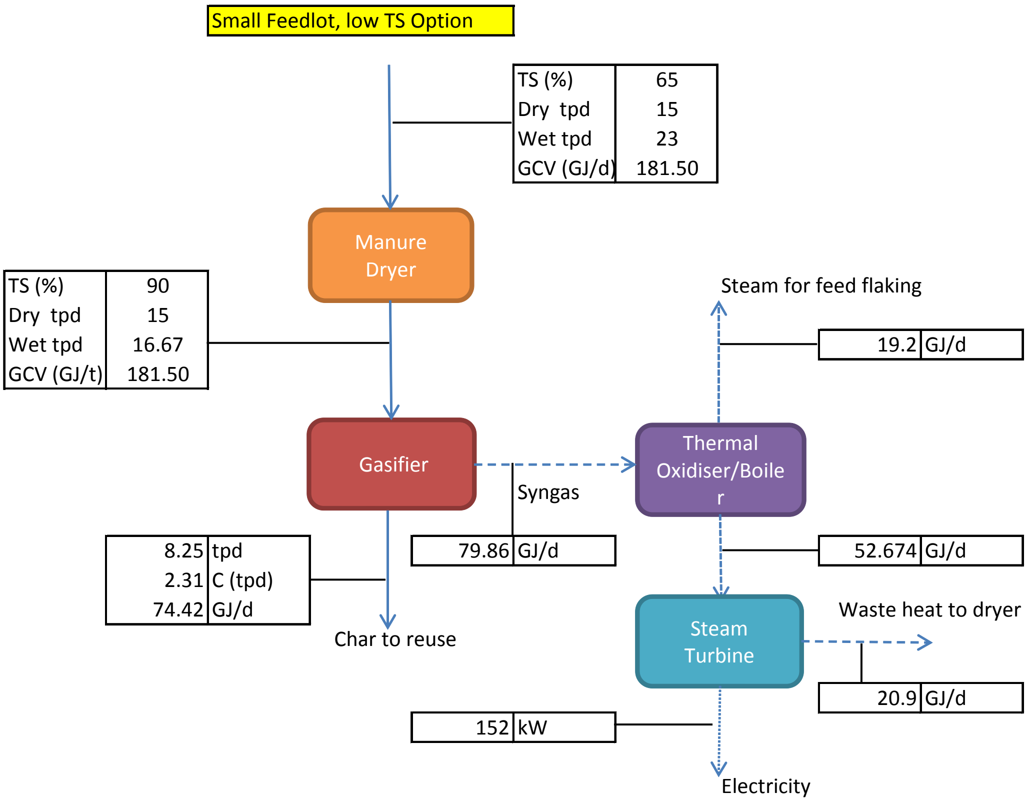


Figure 20 – Small feedlot, low TS gasification PFD

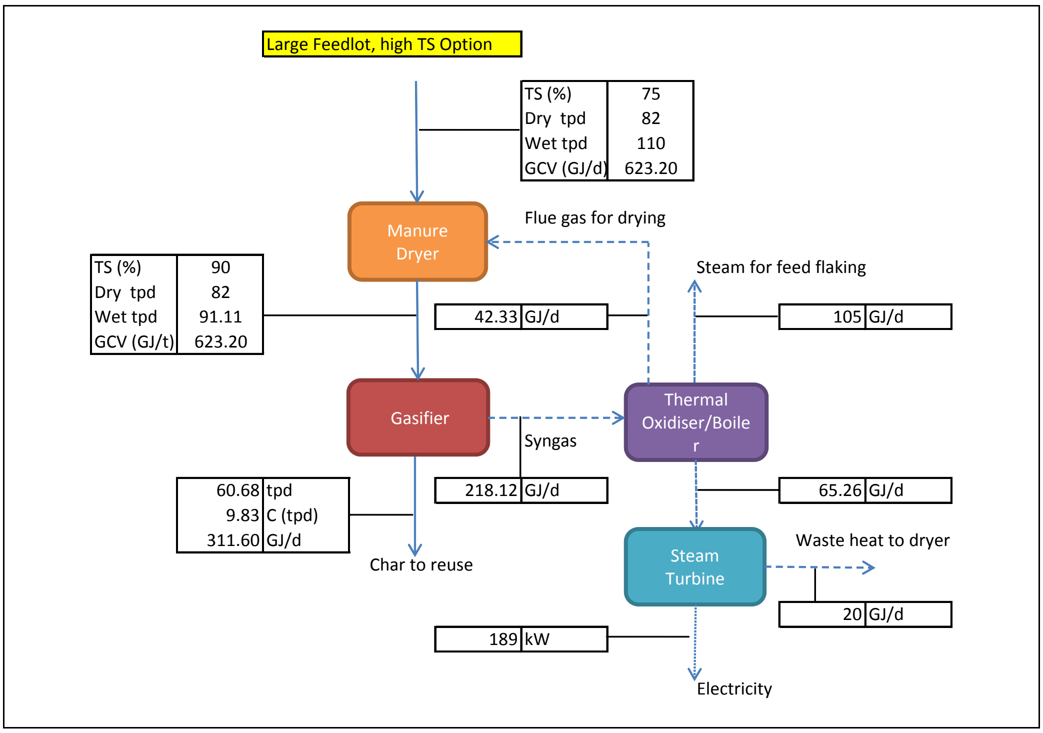


Figure 21 – Large feedlot, high TS gasification PFD

Table 61 - Gasification options process summary

Parameter	Units	Small Feedlot		Large Feedlot	
		Low TS	High TS	Low TS	High TS
Dry manure feed rate	tpd	15	15	82	82
Wet manure feed rate	tpd	23	20	126	110
Manure feed hopper	m^3	26	20	126	110
Dry manure hopper	m^3	28	28	152	152
Char hopper	m^3	21	21	152	152
Char production	tpd	8.3	8.3	60.7	60.7
Carbon sequestered	tpd	2.3	2.3	9.8	9.8
Steam for feed flaking	GJ/d	19.2	19.2	105	105
Power output	kW	152	152	0	189

The gasification options include the BiG supplied gasifiers, manure dryers, thermal oxidisers, air pre-heaters, induced draft fans, stack and associated manure and char conveying systems. In addition, the options include the supply of the wet and dry manure hoppers and the char hopper. The system also includes installation of boiler tubes in the thermal oxidisers and where appropriate, a steam turbine system. Where applicable waste, heat from the steam turbines is used as the energy required for drying the manure.

Capital costs for the manure dryers, gasifiers, thermal oxidisers, stacks, air pre-heaters, ID fans and associated conveying systems were based on costs provided by BiG for a 20 dry tpd facility. These were then pro-rated using the two-thirds plant capacity power factor, which is a common capital cost estimating tool. Bridle Consulting estimated the costs for the manure and char hoppers. Steam turbine costs were sourced from Quantum Energy. Typical engineering cost factors were then used for the other plant components and this is shown in Table 62.

Table 62 shows the capital cost estimates for the gasification facilities vary from $5.06 million for the small feedlot high TS manure option to $14.17 million for the large feedlot high TS manure option.

Operating and maintenance (O&M) costs as well as revenues were estimated based on a number of assumptions, which are outlined in Table 58. In addition to these costs, it has also been assumed that the char would be sold for $250/tonne, which is regarded as a conservative price for char, based on information from commercial operators. BiG commercial experience is that the char value will likely be in excess $250/tonne. Based on these assumptions and the process data from the M&E balances, the estimated O&M costs and revenues for the four options are shown in Table 63.

Table 62 - Gasification Facility Capital Cost Estimates

Cost Component	Cost Factor	Small feedlot		Large feedlot	
		Low TS	High TS	Low TS	High TS
Major equipment items					
Gasifier/dryer package		1,320,644	1,320,644	4,100,594	4,100,594
Manure feed hopper (1 d SRT)		140,349	117,817	402,132	367,308
Dry manure hopper (1d SRT)		146,679	146,679	455,437	455,437
Char hopper (2 d SRT)		101,524	101,524	455,133	455,133
Steam turbine package		378,691	378,691	0	405,931
Sub-total		2,087,887	2,065,355	5,413,296	5,784,403
Piping and valves (%)	10	208,789	206,535	541,330	578,440
Electrics (%)	15	313,183	309,803	811,994	867,660
Instruments and control (%)	15	313,183	309,803	811,994	867,660
Civils (%)	10	208,789	206,535	541,330	578,440
Mech installation (%)	10	208,789	206,535	541,330	578,440
Equipment Sub-total		3,340,619	3,304,568	8,661,274	9,255,045
Engineering design (%)	8	267,249	264,365	692,902	740,404
Project management (%)	8	267,249	264,365	692,902	740,404
Sub-total		3,875,118	3,833,299	10,047,077	10,735,852
Overheads/risk (%)	7	271,258	268,331	703,295	751,510
Profit margin (%)	10	387,512	383,330	1,004,708	1,073,585
Contingency (%)	15	581,268	574,995	1,507,062	1,610,378
TOTAL		**5,115,155**	**5,059,955**	**13,262,142**	**14,171,325**

Table 63 - Gasification Facility O&M cost estimates

Cost Component	No.	Unit cost	Small Feedlot		Large Feedlot	
			Low TS	High TS	Low TS	High TS
Operating staff	3	60,000	180,000	180,000	180,000	180,000
Electricity		180	78,840	78,840	268,056	268,056
Maintenance	4	% of equip	133,625	132,183	346,451	370,202
Total			392,465	391,023	794,507	818,258
Electricity credit	330	d/a	217,204	217,204	0	269,104
REC credit	330	d/a	48,268	48,268	0	59,801
Char sales credit	365	d/a	752,813	752,813	5,537,050	5,537,050
Thermal energy credit	365	d/a	174,845	174,845	950,245	950,245
Net O&M Cost			-800,665	-802,107	-5,692,788	-5,997,942

Electricity costs for the gasification facilities are based on power draws of 50 and 170 kW respectively, for small and large feedlots. It has also been assumed that power generation is

operational for 330 days per annum. Based on the above, the estimated net O&M costs for all facilities are negative, indicating revenues exceed costs. The major revenue stream, especially for the large feedlot options, is from char sales.
Financial analysis for these facilities is based on a Net Present Value (NPV) approach as well as developing simple payback periods. The NPVs are calculated on the assumption that the discount rate is 7% and the period is 20 years. A summary of this financial analysis is shown in Table 64.

Table 64 - Financial Analysis of the Gasification Options

Financial Parameter	Small Feedlot		Large Feedlot	
	Low TS	High TS	Low TS	High TS
20-yr NPV	-$3,367,092	-$3,437,570	-$47,047,338	-$49,370,963
Payback Period (yrs)	6.4	6.3	2.3	2.4

This financial analysis shows that gasification of manure from small feedlots, even with reasonable VS values (about 60%) is only marginally attractive, based on the 6 year payback period. Gasification of manure from large feedlots, even with low VS values (about 40%) appears to be very attractive, with payback periods of less than 3 years. However, this economic assessment is very sensitive to the price that will be obtained for the char. For example, if the char revenue drops to $100/tonne the payback period for the large feedlot options decreases to about 5.5 years, making them only marginally attractive. For the small feed lots gasification is no longer a viable management option if char revenues fall to $100/tonne.

At present there are only small quantities of char produced and sold in Australia. If significantly more char was available, then the high prices currently achieved for essentially niche markets are no likely to be sustainable, unless there is an approved CFI methodology that allow the user to sell accumulated Australian Carbon Credit Units. This means that char may only be sold for its fertiliser phosphorus and/or potassium value, which is estimated to be around $50/t, making the process financially unattractive for even large feedlots.

5.4.3 Pyrolysis cost analysis

Four process options were considered when developing costs for pyrolysis systems. The input feed data for these four options are shown in Table 65. Simple PFDs, with mass and energy balance data, for these four pyrolysis options, were developed, based on the PacPyro process model outputs shown in Table 48 and Table 49. The small feedlot, low TS option as well as the large feedlot, high TS option PFDs are shown in Figure 22 and Figure 23. A process summary of the four pyrolysis facility options is shown in Table 65.

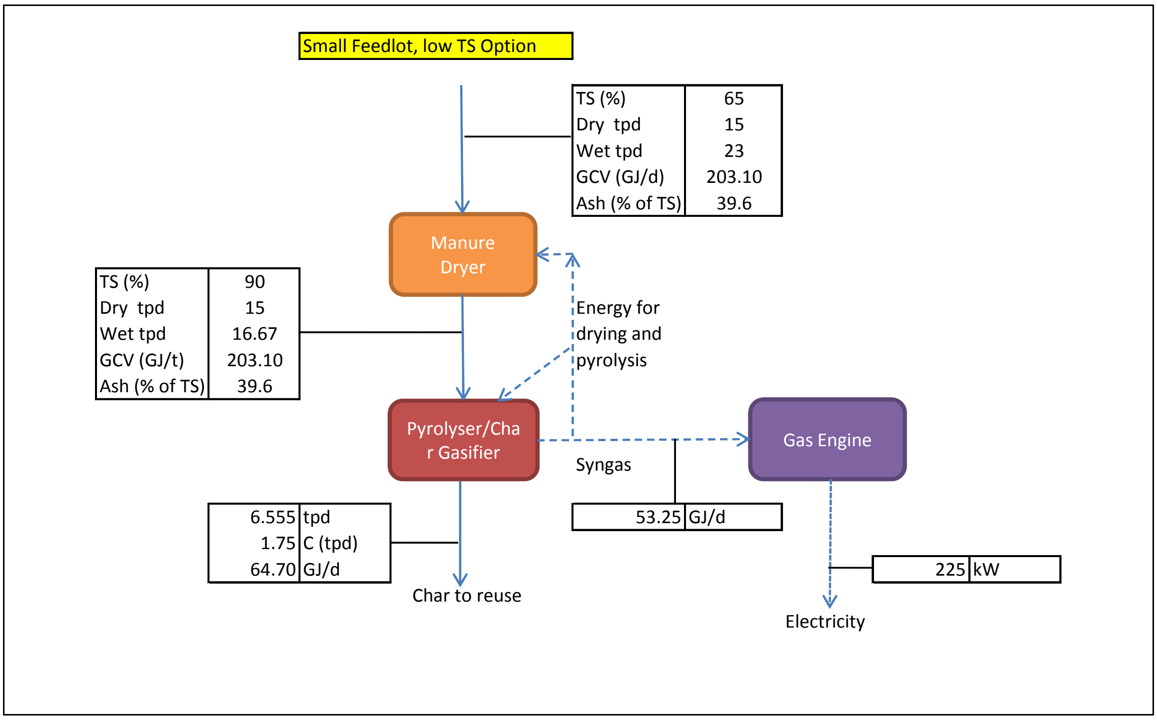


Figure 22 – Small feedlot, low TS pyrolysis PFD

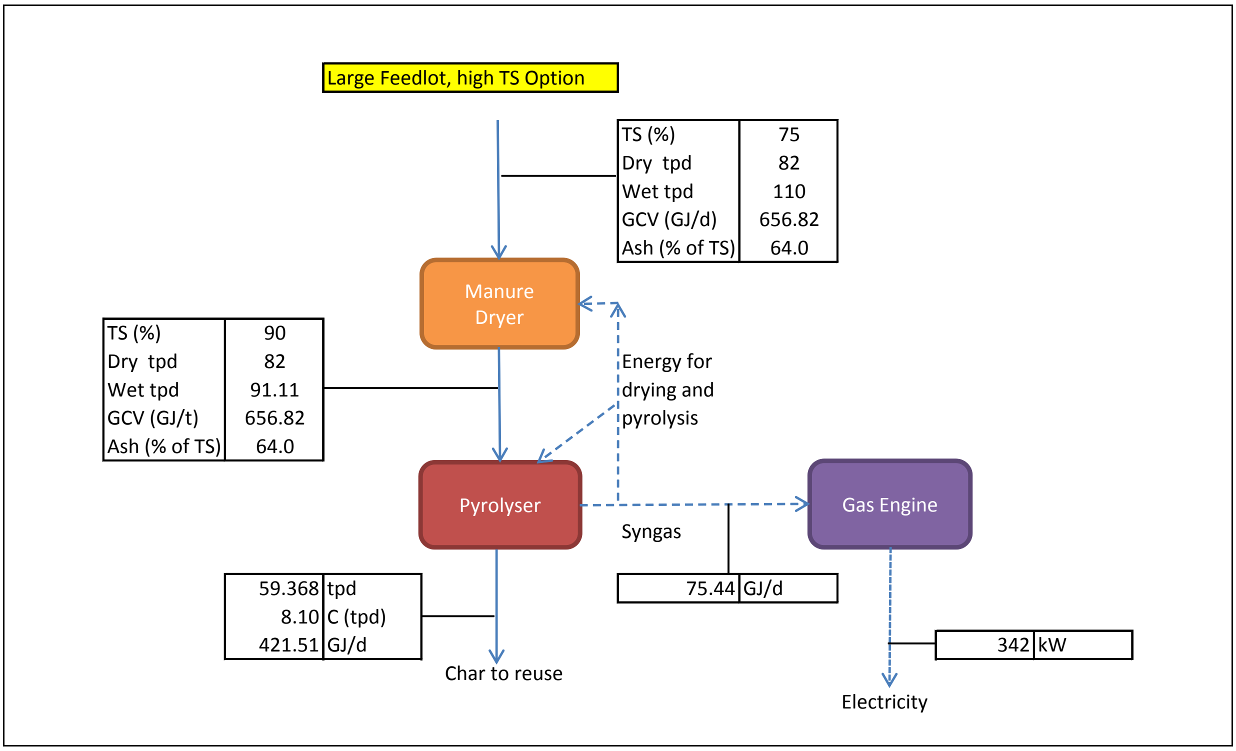


Figure 23 – Large feedlot, high TS, pyrolysis PFD

Table 65 - Pyrolysis options process summary

Parameter	Units	Small Feedlot		Large feedlot	
		Low TS	High TS	Low TS	High TS
Wet feed rate	wet tpd	23	20	126	110
Dry feed rate	dry tpd	15	15	82	82
Char production	tpd	6.56	6.56	59.37	59.37
Carbon sequestered	tpd	1.75	1.75	8.10	8.10
Excess syngas energy	GJ/d	53.25	64.65	27.88	75.44
Power generation	kW	225	250	205	342

The pyrolysis options are based entirely on the systems as identified in the PacPyro report. That is, the small feedlot options include a manure dryer followed by the pyrolyser and char gasifier. Syngas is used for drying the manure and providing the energy required for pyrolysis. Excess syngas is combusted in gas engines to produce electricity. There is no steam production to provide that required for steam flaking. The large feedlot process configuration is as for the small feedlot option with the exception that char gasification is not used.

Capital costs for the pyrolysis options were developed by Bridle Consulting, based on the existing cost data-base for hoppers, pyrolysers and dryers. Costs for syngas cleaning systems and the associated gas engines were sourced from Quantum Energy. The Quantum costs also include an allowance for connection to the electrical grid and also for a gas flare. Typical engineering cost factors were then used for the other plant components and this is shown in Table 66.

Table 66 shows the capital cost estimates for the pyrolysis facilities vary from $10.62 million for the small feedlot high TS manure option to $33.4 million for the large feedlot low TS manure option.

Table 66 - Pyrolysis facility capital cost estimates

Cost Component	Cost Factor	Small feedlot		Large feedlot	
		Low TS	High TS	Low TS	High TS
Major equipment items					
Pyrolysis/dryer package		3,877,306	3,510,593	12,054,551	10,950,819
Manure feed hopper (1 d SRT)		205,343	187,066	402,132	367,308
Dry manure hopper (1d SRT)		117,817	117,817	356,085	356,085
Char hopper (2 d SRT)		101,524	101,524	447,698	447,698
Gas engine package		392,570	418,820	371,570	515,070
Sub-total		4,694,560	4,335,820	13,632,037	12,636,981
Piping and valves (%)	10	469,456	433,582	1,363,204	1,263,698
Electrics (%)	15	704,184	650,373	2,044,806	1,895,547
Instruments and control (%)	15	704,184	650,373	2,044,806	1,895,547
Civils (%)	10	469,456	433,582	1,363,204	1,263,698
Mech installation (%)	10	469,456	433,582	1,363,204	1,263,698
Equipment Sub-total		7,511,296	6,937,312	21,811,259	20,219,169
Engineering design (%)	8	600,904	554,985	1,744,901	1,617,534
Project management (%)	8	600,904	554,985	1,744,901	1,617,534
Sub-total		8,713,104	8,047,282	25,301,060	23,454,236
Overheads/risk (%)	7	609,917	563,310	1,771,074	1,641,797
Profit margin (%)	10	871,310	804,728	2,530,106	2,345,424
Contingency (%)	15	1,306,966	1,207,092	3,795,159	3,518,135
TOTAL		**11,501,297**	**10,622,412**	**33,397,399**	**30,959,592**

Operating and maintenance (O&M) costs as well as revenues were estimated based on a number of assumptions, which are outlined in Table 58. In addition to these costs, it has also been assumed that the char would be sold for $250/tonne. Based on these assumptions and the process data from the M&E balances, the estimated O&M costs and revenues for the four options are shown in Table 67.

Table 67 - Pyrolysis facility O&M cost estimates

Cost Component	No.	Unit cost	Small Feedlot		Large Feedlot	
			Low TS	High TS	Low TS	High TS
Operating staff	3	60,000	180,000	180,000	180,000	180,000
Electricity		180	110,376	110,376	315,360	315,360
Maintenance	4	% of equip	300,452	277,492	872,450	808,767
Total			590,828	567,868	1,367,810	1,304,127
Electricity credit	330	d/a	320,760	356,400	292,248	487,080
REC credit	330	d/a	71,280	79,200	64,944	108,240
Char sales credit	365	d/a	598,144	598,144	5,417,330	5,417,330
Net O&M Cost			-399,356	-465,875	-4,406,712	-4,708,523

Electricity costs for the pyrolysis facilities are based on power draws of 70 and 200 kW respectively, for small and large feedlots. It has also been assumed that power generation is operational for 330 days per annum. Based on the above, the estimated net O&M costs for all facilities are negative, indicating revenues exceed costs. The major revenue stream, especially for the large feedlot options, is from char sales.

Financial analysis for these facilities is based on a Net Present Value (NPV) approach as well as developing simple payback periods. The NPVs are calculated on the assumption that the discount rate is 7% and the period is 20 years. A summary of this financial analysis is shown in Table 68. This financial analysis shows that pyrolysis of manure from small feedlots, even with reasonable VS values (about 60%) is not commercially attractive. Pyrolysis of manure from large feedlots appears to be marginally attractive, on the assumption that the char generated can be sold, at $250/tonne, for reuse in agriculture. As per the comments for gasification, if the revenue for char sales falls to values of $100/tonne, pyrolysis no longer becomes an economically viable management option, even for large feedlots.

Table 68 - Financial analysis of the pyrolysis options

Financial Parameter	Small Feedlot		Large Feedlot	
	Low TS	High TS	Low TS	High TS
20-yr NPV	$7,270,515	$5,686,923	-$13,287,367	-$18,922,570
Payback Period (yrs)	28.8	22.8	7.6	6.6

5.5 Implications for feedlot pen management

The results of this study confirm the existing knowledge that manure with a higher moisture content and/or high ash content is a poor thermal fuel.

It is useful to examine the typical feedlot manure characteristics provided in Section 2.3.4 in more detail, in particular the moisture and ash content data. Figure 24 is a metric version of Figure 8 on which the measured characteristics of the feedlot manure samples are plotted. This data includes samples taken in this study as well as data from Davis et al. (2012) and other sources. The manure samples have been divided into three groups.

1. Fresh faeces – these are samples of fresh faeces taken on the pen surface as shown in Photograph 12.
2. Pen manure – these are samples taken from a single point on the pen surface. As such, they do not represent an average sample across the pen and they do not represent the full depth of the manure profile on the pen surface.
3. Stockpiled / Compost manure – these are various samples taken from manure stockpile / composting areas. There is significant, un-documented variability in the age and handling method of these samples. Some samples could effectively be fresh pen manure while other samples may have been in a stockpile for months. Other samples may have been composted and regularly turned in windrows.

The fresh faeces samples are fairly closely grouped. All have a moisture content of 75% or more. Most fresh faeces samples have an ash content of 10% to 25% (VS content of 75% to 90%). These samples are too wet to be a thermal fuel but if they could be dried without any increase in ash content, they would be a suitable fuel.

The scatter in the stockpiled / composted samples is large. However, on average, the ash content of these samples is higher than pen manure samples. This is expected. Very few stockpiled / compost manure samples lie under the HHV target curve of 8.1 MJ/kg. Hence, they are unsuitable as a thermal energy fuel.

While there is a large scatter in the analyses of the pen manure samples, it is clear that a significant number of the samples lie under the HHV target curve of 8.1 MJ/kg. Figure 24 also shows the “typical” manure characteristics used in Bridle (2011) study and the low and high TS options analysed in this study (see Section 5.4). These “typical” manure characteristics fit within the middle of pen manure analyses but there is a large scatter around the “typical” analysis.

Figure 25 has been prepared to provide more information on the characteristics of pen manure. In this figure, the pen manure has been grouped by feedlot and the average data for each feedlot has been plotted. Figure 25 shows that pen manure can range from an ash content similar to fresh faeces to highly degraded manure with a high ash content.

Figure 25 shows significant differences between feedlots. For example, Feedlot 1 is consistently wetter than other sites and has some very degraded manure samples. This feedlot is located in southern Australia in a winter-dominant rainfall zone. Feedlot 2 similarly has wetter manure but significantly less degraded than Feedlot 1. Except for a few outliers, Feedlot 3 has very dry pen manure. This feedlot is located in a summer-dominant rainfall zone and it operates at a low stocking density, which results in drier pens. In summary, there are significant difference between feedlots. At each feedlot, there is a large scatter in pen manure characteristics due to management and climate. It is difficult, but not impossible, to have pen manure that consistently lies under the HHV target curve of 8.1 MJ/kg.

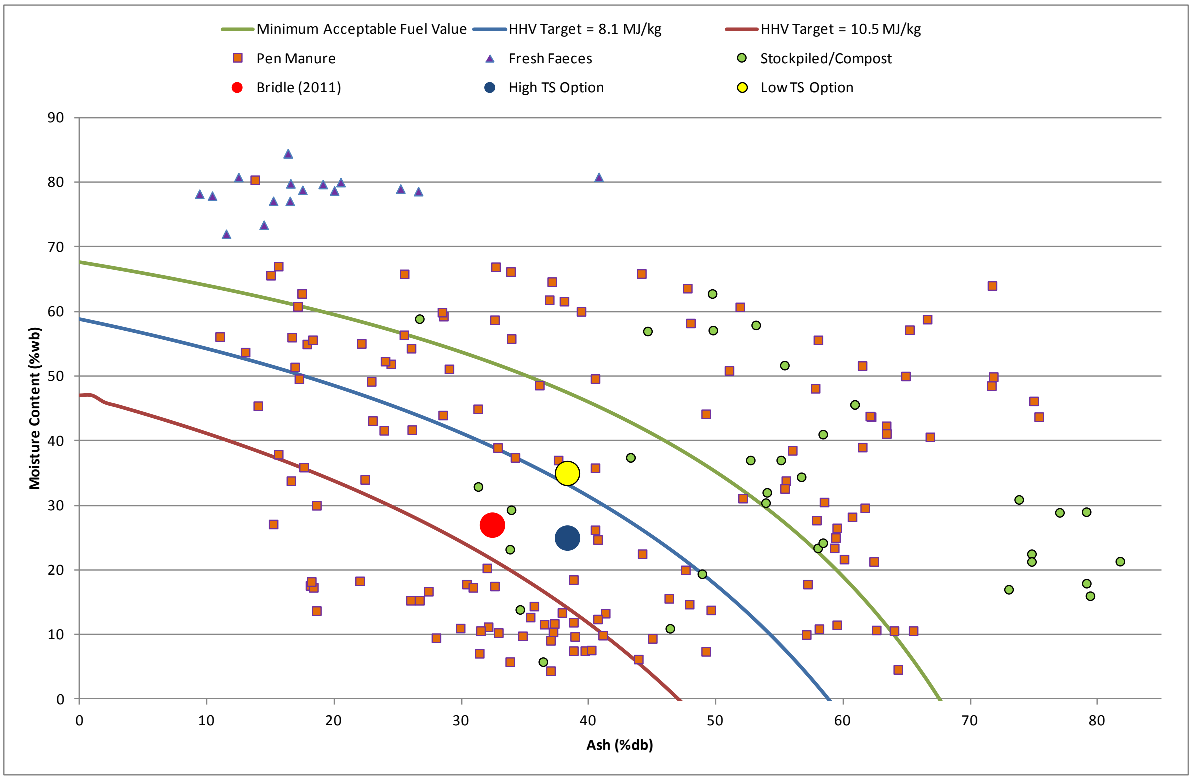


Figure 24 – Relationship between ash content and moisture content for feedlot manure samples

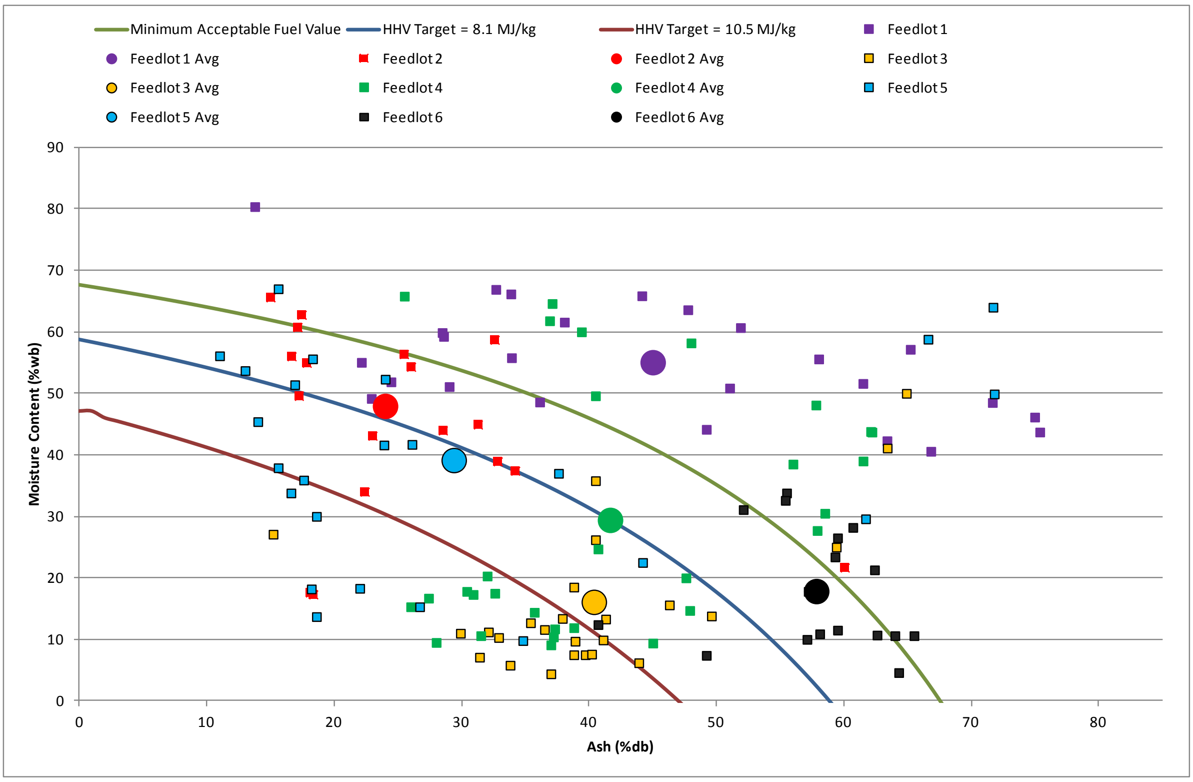


Figure 25 – Relationship between ash content and moisture content for pen manure

If thermal energy recovery is to be viable, the feedlot needs to manage moisture content and ash content. For an existing site, little can be done to prevent rainfall. However, steps can be taken to reduce ash content (maximise VS content). This includes pen cleaning that retains the manure interface layer (and prevents the collection of clay and gravel) and frequent pen cleaning, which minimises the VS degradation on the pen surface.

5.6 Fertiliser value of biochar and ash

5.6.1 Biochar fertiliser value

The simplest approach to valuing biochar is to calculate the expected nutrient value compared to synthetic fertilisers. An estimate of this is provided in Table 69 using the average nutrient content of the char produced from the Feedlot B and Feedlot A manure from the pyrolysis trials. These values correspond to users who are primarily seeking a fertiliser replacement. These users (i.e. dairy, horticulture) have the capacity to use high volumes of feedlot manure biochar but have a low capacity to pay.

Table 69 – Simple nutrient value for biochar from feedlot manure

Nutrient	Nutrient analysis (% of DM)	DM %	Total available nutrient content (kg/t)	$ Value of saleable nutrients*
N	1.49	97.2	14.9	n/a[1]
P	1.66		13.3	$ 47 [2]
K	3.27		32.7	$ 66 [3]
Ca (liming potential)	5.66		56.6	$ 29 [4]

* Nutrient values compared to commercial fertilisers are subject to fluctuation
[1] Nitrogen value not included as most research suggest biochar N is not in a plant available form.
[2] Phosphorus value based on DAP at $707/t (ex GST) delivered to farm on the Darling Downs.
[3] Potassium value based on Potash at $1007/t (ex GST) delivered to farm on the Darling Downs.
[4] Calcium value based on ag-lime at $175/t (ex GST) delivered to farm on the Darling Downs .

Values presented in Table 69 should be viewed with caution for the following reasons:

- Nutrient content in feedlot manure may vary, and nutrient content in biochar manufactured from feedlot manure will vary accordingly.
- Nutrient values are highly variable and are presented as ‘retail’ price rather than wholesale.
- Phosphorus availability can vary with pyrolysis temperature (the value has been reduced to 80% of synthetic fertiliser). A more conservative value may be required for some biochars.

With these qualifications noted, the total nutrient value of biochar based on the N, P, K and Ca content, as of 2012, is in the order of $113/t when compared with typical agricultural fertilisers. However, biochar alone is unlikely to be a balanced fertiliser and the total value of all available nutrients will not be realised in most agronomic situations. The additional benefits of biochar (related to improvements in soil health and structure) may be considerable. However, these benefits are more difficult to quantify and value for traditional users of manures.

An alternative approach to marketing biochar is to focus on the broader range of product attributes and target high-end markets such as the nursery or retail garden sector. A Queensland based firm is known to be targeting the retail market through sales of biochar in 25 L bags as a soil conditioner/fertiliser. Renewable Carbon Resources Australia (RCRA) also list several distributors within Australia whom are wholesale agents selling charcoal for use as a soil conditioner in the gardening sector. Currently the product distributed by RCRA known as deco-carbon retails for approximately $40 for a 40 kg bag ($1000/t).

From a limited market survey of current or prospective biochar manufacturers, the target sale price for their product is in the order of $700-1500/t (retail). All manufacturers are targeting high value niche markets and it is difficult to determine what is the volume of biochar that could be traded at this price. Depending on market structure and contract arrangements, the manufacturer may receive 50-100% of this retail sale value.

The potential value of biochar will be highly dependent on the target markets. Traditional high volume users of poultry litter are unlikely to pay high prices for biochar because the value is linked to fertiliser value of the product, and these users are rarely able to invest additional money in soil conditioners.

An attractive alternative would be to target garden retail or nursery markets that will have a higher capacity to pay. However, as with the compost industry, these markets may not be able to absorb large volumes of product. Further detailed analysis of product suitability and market size may be warranted in this area.

5.6.2 Ash fertiliser value

The value of ash can be determined by a simple comparison with the value of synthetic fertilisers. An estimate of this is provided in Table 69 using the average nutrient content of the ash produced in the trial with the Feedlot A manure. These values correspond to users who are primarily seeking a fertiliser replacement.

Table 70 – Simple nutrient value for ash produced from the combustion of feedlot manure

Nutrient	Nutrient analysis (% of DM)	DM %	Total available nutrient content (kg/t)	$ Value of saleable nutrients*
N	0.91	56.1	5.1	n/a[1]
P	0.54		3.1	$ 11 [2]
K	1.02		5.7	$ 11 [3]
Ca (liming potential)	1.67		9.4	$ 5 [4]

* Nutrient values compared to commercial fertilisers are subject to fluctuation
[1] Nitrogen value not included as most research suggest biochar N is not in a plant available form.
[2] Phosphorus value based on Superphosphate at $707/t (ex GST) delivered to farm on the Darling Downs.
[3] Potassium value based on Potash at $1007/t (ex GST)delivered to farm on the Darling Downs.
[4] Calcium value based on ag-lime at $175/t (ex GST) delivered to farm on the Darling Downs .

As with biochar, the values presented in Table 69 should be viewed with caution. This gives a total nutrient value of ash based on the N, P, K and Ca content (as of 2012) in the order of $27/t when compared with typical agricultural fertilisers. As with biochar, ash alone is unlikely to be a balanced fertiliser and hence the total value of all available nutrients will not be realised in most agronomic situations.

6 Summary and conclusions

The results generated from this pilot plant study has better defined the economics of using thermal technologies for energy recovery from feedlot manures, compared to that generated by the original desktop study (Bridle 2011a). The major conclusions generated by this study are outlined below.

1. Energy recovery from feedlot manure, using thermal technologies, is only economically viable if the manure TS is relatively high, preferably above 65% (i.e. moisture content below 35%) and that the VS is above about 50%. The gasification and pyrolysis processes require manure with a moisture content less than 25%. To achieve a high VS content, the harvested manure must essentially contain no pad base material and must be harvested frequently to limit degradation on the pen surface.
2. Harvested feedlot manure is highly compressible and thus feed systems to the thermal processing units must **not** provide any compression zones such as those generated by ram feeders and decreasing-pitch screw conveyors. If compressed, feedlot manure forms a very high-strength plug which is near impossible to move.

3. Combustion, gasification and pyrolysis were all shown to be technically feasible for energy recovery from feedlot manures. It is however highly desirable that FBBs be the combustors of choice for the combustion option, since this will maximise energy recovery and minimise the impacts of ash slagging in the furnace. The combustion trial showed that about 45% of the phosphorus and 54% of the potassium is vaporized during the combustion process. These elements act as flux agents and reduce the ash melting temperature could have a major impact on the fouling of heat transfer surfaces in boilers burning manure. The FBB will minimise hot-spots in the combustion zone and thus minimise the potential for ash melting.
4. Combustion was shown to be the least cost-effective technology for energy recovery from feedlot manure. It is not economically viable for small feedlot operators (10,000 SCUs) and is only marginally cost effective for large feedlot operators (50,000 SCUs). The payback period for large feedlots is in the range of 8.9 to 11.3 years.
5. Pyrolysis provided slightly improved economics compared to combustion, based on use of the Pacific Pyrolysis technology. Pyrolysis is also not economically viable for small feedlot operators and the payback period for large feedlots ranges from 6.6 to 7.6 years. The char generated by pyrolysis is suitable for use in agriculture and the economics are based on the assumption that char revenues will be $250/tonne, which is, based on industry data, a reasonable assumption. If however the char revenue falls to even $100/tonne, pyrolysis no longer becomes economically attractive, even for large feedlot operators.
6. Gasification provided the most attractive economics for energy recovery from feedlot manure, based on use of the BiG gasification technology. Gasification is marginally attractive for small feedlot operators, with payback times of about 6 years and is very attractive for large feedlot operators, with payback times of only 2.4 years. The char generated by gasification is suitable for use in agriculture and the economics are based on the assumption that char revenues will be $250/tonne, which is, based on industry data, a reasonable assumption. If however the char revenue falls to $100/tonne, gasification no longer becomes economically attractive for small feedlot operators and becomes only marginally attractive to large feedlot operators, with payback periods increasing to about 6 years.

7 Recommendations

Since gasification offers the most commercially attractive thermal processing option for energy recovery from feedlot manure, it is recommended that this technology be evaluated in more detail. One option would be to use the 2 tpd demonstration BiG facility, which includes all the unit operations that are required for a commercial plant. Two such demonstration plants are currently operating in Hawaii and Canada. Such a demonstration facility would confirm all the process operational issues of the gasification technology and more importantly, confirm the quality of the char and its likely resale value as a unique agricultural fertiliser. Project economics would also be further refined from the outcomes of such a demonstration programme Agricultural reuse trials should be conducted as part of this demonstration programme. BiG has indicated that char sales from this demonstration programme could, to a large extent, off-set the expected total project costs of $200,000.

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9 Appendix A – Gasification test results

BlackisGreen

MLA-121001

Pilot Testing Pyrolysis Systems

FEEDLOT MANURE PROCESSING IN THE BIGCHAR TECHNOLOGY

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Abstract

Meat and Livestock Australia (MLA) and FSA Consulting are conducting a research project investigating the conversion of feedlot manure to biochar and syngas, as a means to reduce carbon footprint.

One of the technologies selected for feasibility trials was the BiGchar technology offered by Black is Green Pty Ltd of Queensland.

Two manures were trialled. One was unsuitable for steady state operation of the BiGchar system, due to low volatile matter. Low VM feedstocks will require supplementing with an additional carbon source, such as sawdust.

The BiGchar process was able to produce a saleable biochar product from both samples, when assessed against the recently released International Biochar Initiative standard.

Emissions control performance was not adequate, due to low oxidiser temperatures resulting from the low calorific value of the manures. This may be compensated by the implementing preheating of the air supply to the hearth and thermal oxidiser via exchange with the oxidiser exhaust gas.

It is recommended that commercial testing be undertaken using a BiGchar 1500 system with integrated air pre-heating. This testing should include an assessment of secondary emissions control options.

Preliminary cost estimates for 5 and 20 tonne per day commercial systems were $0.8 M and $1.6 M respectively.

Executive summary

Meat and Livestock Australia (MLA) and FSA Consulting are conducting a research project investigating the conversion of feedlot manure to biochar and energy, as a means to reduce carbon footprint.

One of the technologies selected for feasibility trials was the BiGchar updraft gasification technology offered by Black is Green Pty Ltd (BiG). The system is based on a rotary hearth concept, which is highly adaptable to different feedstocks. The rotary hearth concept has proven to be very reliable in wide range of industrial duties, over the past 90 years.

The objectives and outcomes are summarised as follows:

Proposal Objective	Outcome
A. Conduct a pilot trial of pre-dried cow manure from two different locations, including monitoring and analysis of process performance and off-gases.	Two quite different manures were tested. Feedlot B: 13% moisture 63% volatile matter Feedlot A: 11% moisture 42% volatile matter The Feedlot A manure was observed to have a lower organic content than the Feedlot B, which was reflected in the volatile matter content and operating performance of the machine.
B. Determine if reliable production of a usable biochar can be achieved from the supplied feedstock	Reliable production of a usable biochar will require: (a) addition of woody biomass to the feedstock (b) Incorporation of regenerative preheating of the gasifier and thermal oxidiser air supplies
C. That the process emissions to the environment can be of an acceptable standard.	Acceptable emissions performance will require further confirmation in a system that incorporates preheating of the primary and secondary air to the system.
D. To develop a mass and energy balance associated with operation on the supplied feedstock, for use in technical and financial modelling.	The char yields for the two manures were 55 and 75% respectively. Energy yield to the off-gases was 41% (242 kW) and 50% (126 kW) respectively.
E. Provide budget proposals for the supply and commissioning of facilities for the processing of dried manure, based on the process information developed from the trials.	The estimate of installation and commissioning cost for a 5 tpd (10-15% moisture basis) facility is $800,000. The preliminary estimate for a 20 tpd manure processing facility is $1.6 M.

Manures are not an ideal feedstock for gasification, as their low calorific value and nitrogen/sulphur content present challenges for cost effective air emissions control.

BiG recommends that a 2 tonne per day demonstration of the entire integrated process be implemented at cattle operation using relocatable containerised BiGchar 1500 system. BiG has recently delivered two such systems to Hawaii and Canada for the same purpose. Total project costs are likely to be of the order of $180,000. It should be possible to offset operating costs of the trial through sale of the biochar product via the marketing arm of BiG, Black Earth Products.

9.1 Project objectives

The objectives for this project were to:

A. Conduct a pilot trial of pre-dried cow manure from two different locations. A processing time or 1 hour per manure is anticipated, including monitoring and analysis of process performance and off-gases.
B. Determine if reliable production of a usable biochar can be achieved from the supplied feedstock.
C. Determine if the process emissions to the environment can be of an acceptable standard.
D. To develop a mass and energy balance associated with operation on the supplied feedstock, for use in technical and financial modelling.
E. Provide budget proposals for the supply and commissioning of facilities for the processing of dried manure, based on the process information developed from the trials.
F. Provide a final report documenting pilot plant performance and the budget for a commercial scale system.

9.2 Materials and methods

9.2.1 Pilot plant tests

Approximately 800 kg of manure from Feedlot A and 400 kg of pre-dried manure from Feedlot B were delivered for the trial conducted on 1st of October 2012.

The manures were tested in a BiGchar 1000 pilot test unit. This unit is a 1/5th scale test/demonstration unit, with a nominal capacity of 200 kg/hr of biomass.

The witnessed trial involved the processing of 114 kg of the pre-dried Feedlot B manure in a continuous manner over sample period of 50 minutes and the processing of 48 kg of the Feedlot A manure over a sample period of 20 minutes.

Three samples of each raw feed material and char product were collected and despatched by FSA Consulting for analysis by SGS Food & Agriculture Laboratory, Toowoomba.

SGS's report no. TW12-08104 listed the in-house and international standard methods used, i.e.:

Carbon Hydrogen Nitrogen VM

- ANL001 — Anions in manure, feeds and plants using HPLC
- ANL006 — Moisture and/or Ash by Leco TGA
- AS 1038.6.3.3 — Sulphur in wood pellets
- AS1038 — Calorific Value of Biomass
- CNR001 — Volatile/Total Solids in Manure (%) (CNR001)
- MIN001 — Minerals in Solid Sample Dry Matter (MIN001)
- MIN011-2 — Silicon in Plant Tissue (MIN011-2)

- MST001 Two Stage Moisture Calculations
- PRN002 Leco Nitrogen (PRN002)

9.2.2 Yields of Char and Energy

Char yield was determined by two methods. Firstly by direct weighing of the char product from the witnessed test, with correction applied for dry weight, based on a composite of nine char moisture measurements; i.e.

$$\text{Char yield} = \frac{\text{Char mass x (1 – \% Mean Char moisture)}}{\text{Feed mass x (1 - \% Mean Feed Moisture)}}$$

The second yield calculation method was based on an ash tracer calculation. This assumed 98% recovery of the ash components in the feed to the char.

$$\text{Char yield} = \frac{\text{\% Ash in Feed (d.b.)}}{\text{\% Ash in Char (d.b.) / 99.5\%}}$$

The 99.5% represents an estimate of the char lost into the flue gases as particulate.

9.2.3 Mass and energy balance model

A spreadsheet model was utilised to perform the mass and energy balance modelling for this report. The key inputs were derived from the analytical data outlined in the results section of this report.

Flue gas energy yields were determined by the difference between the feedstock heating value (LHV) rate and the char heating value (LHV) rate. It is assumed that that 20% of the usable heat is lost from the char vessel, downstream ductwork and into the char product when using a small system. Thermal losses below 15% are expected for full scale implementations.

9.2.4 Off-gas analysis

Off gas from feed devolatilisation (gasification) process in the BIGchar unit is combusted in three stages in the test/demonstration unit. Firstly on initial release from the feed; secondly in the flue gas pipe and finally in a thermal oxidiser. The first two stages are conducted at significantly less than the stoichiometric air and in the range of 450-600^{o}C. The final stage is typically conducted at 50-100% excess air at a temperature of 750 – 950^{o}C.

The off-gas from the BiGchar unit was analysed directly on-line using a Testo 350 gas analyser with hand-held probe (Photograph 44). The analysis was performed by Joel Franklin of Threshold Environmental who also supplied the gas analyser. The analyser provided real time measurement of temperature, oxygen carbon monoxide and nitrous oxide. Carbon dioxide was calculated using an assumed carbon:hydrogen ratio in the gas.

Total NOx was estimated on the assumption the NO_2:NO ratio was 0.05 (a commonly expected ratio in combustion systems).

Further analysis undertaken by Threshold Environmental included the Volatile Organic Compounds and Total Hydrocarbons in the off-gas.

Photograph 44 - Off-gas gas analysis using the Testo 350 analyser

9.3 Results

9.3.1 Pilot plant tests - Observations

Feedstock characteristics
No problems were experienced with conveying the manure feed or transport through the BiGchar hearth.

While the Feedlot B manure was processed as delivered, the Feedlot A manure had to be air dried one week prior to the trial because the delivered moisture content was determined as 45%. BiGchar units require feedstock with moisture content of below 25% for woody biomass and lower again for high ash feedstocks.

The mean moisture content of the feed was 13.1% for the Feedlot B manure and 10.8% for the Feedlot A manure.

Apart from moisture, the Feedlot A manure had a visually lower volatile organic content, which was confirmed by the analysis.

The feedstock contained stones up to 30 mm diameter, as illustrated below.

This did not present a problem for the demonstration equipment, nor would it for the full scale BiGchar reactors. However, it is an important consideration in the set-up and sizing of any conveyor equipment used to handle manure or manure char. Stones of this size are quite likely to cause jamming and damage in screw or auger devices. Similarly this sort of contamination would not be acceptable in the char delivered to many end users. Hence, a vibrating 6 mm screen is recommended for the char post process stage.

Processing rate
The witnessed continuous run resulted in processing of 99 kg of the Feedlot B manure in 50 minutes for an average feed rate of 122 kg/hr and the processing of 43 kg of the Feedlot A manure in 20 minutes for an average feed rate of 129 kg/hr on a dry basis.

The system capacity is nominally 200 kg/hour on dry feed. The feed rate for the witnessed test was set to keep the system self-sustaining. This was not possible on either manure. As a result, the off-gas thermal oxidiser did not achieve the required temperature range of >750°C to perform adequately. In commercial systems, this aspect of design would be addressed by recuperative heating of the primary and secondary air supplies and/or supplementing the feed with a dry high organic content material.

Operating conditions
The hearth was brought up to normal operating condition on a wood chip feed.

Operating temperatures measured at the second hearth chamber from the top of the unit, commenced around 570°C, dropping to 350°C over 50 minutes with the Feedlot B manure.

For the Feedlot A manure, temperatures in the second hearth chamber commenced at 527°C and dropped to 299°C over 23 minutes.

Temperatures in the second chamber of 420°C were required for the thermal oxidiser to function. This was confirmed through the real time measurements with the Testo gas analyser where the emissions (in particular CO) increased when the hearth temperature in the upper section dropped below 420°C.

Sample analyses
Three samples of each raw feed material and char product were collected and despatched by FSA Consulting for analysis by SGS Food & Agriculture Laboratory, Toowoomba.

Table 71 summarises the results from the SGS ultimate analyses of the manure and char samples. Table 75 and Table 76 provide manure and char analyses.

9.3.2 Char Yield

Using the dry weight method previously outlined and the analytical data the char yields were estimated as:

$$\text{Char yield} = \frac{91.5\text{ kg} \times (1 - 59.9\%)}{114\text{ kg} \times (1 - 13.1\%)} = \frac{36.69}{99.07} = 37\%$$

for the Feedlot B Manure; and

$$\text{Char yield} = \frac{33\text{ kg} \times (1 - 45.9\%)}{48\text{ kg} \times (1 - 10.8\%)} = \frac{17.85}{42.82} = 42\%$$

for the Feedlot A manure.

The typical 95% confidence interval in calculated yield, based on the variance in the analytical three data sets, was estimated as +/- 8 units. Additional errors are introduced in performing the char weight measurement as an unknown amount of accumulation will occur in the hearth. This typically results in an underestimation of the char yield. For this reason BiG rarely relies on this yield estimation method for runs of less than two hours and does not normally commence the weight tally for the first 45 minutes.

Using the ash tracer method and data from the same table the char yield was estimated as:

$$\text{Char yield} = \frac{37.0\ \%}{67.6\ \% / 99.5\%} = 54\% \quad \text{(Range 51 – 57\%)}$$

for the Feedlot B Manure and;

$$\text{Char yield} = \frac{58.2\ \%}{79.2\ \% / 99.5\%} = 74\% \quad \text{(Range 71 – 77\%)}$$

for the Feedlot A Manure.

The typical 95% confidence interval in calculated yield, based on the variance in the three data sets, was estimated as +/- 7 units.

The two methods are not in close agreement. In BiG's experience this is not unusual, the direct weighing method typically under-estimates the yield in relatively short trials. This appears to have been particularly the case for the Feedlot A manure, with its substantial dense inorganic content.

Table 71 - Ultimate analysis results

		Dry Basis						
Sample	**Moisture wt%**	Ash (calc.)	Total volatiles	Carbon	H %	N %	S %	Calorific Value
Feedlot B Manure T1	12.7	39.2	60.8	32.9	4.82	2.46	0.56	11.97
Feedlot B Manure T2	13.1	36.4	63.6	33.3	5.12	2.47	0.54	12.57
Feedlot B Manure T3	13.5	35.4	64.6	33	4.99	2.45	0.55	11.79
Mean	13.1	37.00	63.00	33.07	4.98	2.46	0.55	12.11
Feedlot B Char T1	57.3	69.1	30.9	26.1	1.34	1.39	0.39	8.75
Feedlot B Char T2	63.5	64.2	35.8	29.6	1.34	1.49	0.48	9.79
Feedlot B Char T3	59	69.6	30.4	28.4	1.21	1.38	0.43	8.75
Mean	59.9	67.63	32.37	28.03	1.30	1.42	0.43	9.10

Sample	**Moisture wt%**	Ash	Total volatiles	Carbon	H	N	S	Calorific Value
Feedlot A Manure T1	10.9	58.1	41.9	21.3	3.39	1.81	0.47	7.51
Feedlot A Manure T2	11.5	59.5	40.5	20.7	3.36	1.83	0.5	7.21
Feedlot A Manure T3	10	57.1	42.9	21.7	3.54	1.87	0.5	8.06
Mean	10.8	58.23	41.77	21.23	3.43	1.84	0.49	7.59
Feedlot A Char T1	48.8	76	24	18.7	0.82	0.93	0.19	5.76
Feedlot A Char T2	42.4	80.4	19.6	15.8	0.93	0.97	0.17	5.14
Feedlot A Char T3	46.4	81.2	18.8	14	0.8	0.86	0.15	4.54
Mean	45.9	79.20	20.80	16.17	0.85	0.92	0.17	5.15

9.3.3 Char analysis for biochar characterisation

Table 71 reports the results of the biochar characterisation analysis. Table 72 contrasts the analytical data against the International Biochar Initiative (IBI) ***"Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil"*** [IBI Rev 0.8 15/05/2012]. The IBI standard provides a recognised standard definition of biochar and its characteristics related to the use of biochar as a soil amendment.

Table 72 - Comparison of char results vs IBI standard

Parameter	Unit	**IBI Range of maximum allowable thresholds** (dry basis)	**Mean Result** Feedlot B Feedlot A	**Comment**
Organic Carbon	%	Class 1: ≥60% Class 2: ≥30% - <60% Class 3: ≥10% - <30%	28 16	Both chars fit the criteria for a IBI class 3 char, assuming that the ultimate analysis carbon measurement is a close approximation of organic carbon content.
Copper	mg/kg	63-1500	490 134	Both chars fit within the IBI acceptance criteria, however, being above 63 may exceed the limit for certain applications.
H:C ratio		0.7 max	0.55 0.63	Both chars fit the IBI acceptance criteria for definition as biochar according to H:C ratio.
Zinc	mg/kg	200-2800	490 420	Both chars fit within the IBI acceptance criteria, however, being above 200 may exceed the limit for certain applications.

The samples did not undergo the full suite of tests required for complete (Category C) characterisation under the IBI Standard. However, the data is sufficient to indicate that the Category A requirements would be met.

9.3.4 Flue gas emissions

Table 73 reports the minimum, maximum and mean value of the off gas analysis measured with the Testo Gas analyser. Table 74 reports the stack test results.

The thermal oxidiser was not functioning during the Feedlot A manure tests and has thus not been reported.

9.3.5 VOC and PM10 analysis

Volatile organic compounds and particulate emissions were measured for the Feedlot B manure trial only, as the thermal oxidiser was not able to function with the Feedlot A manure.

The thermal oxidiser was operating below the minimum target temperature of 750°C. Hence, the results are not indicative of typical operation for a commercial plant. Further testing or demonstration using preheated secondary air to the oxidiser will be necessary to conclusively demonstrate the expected emissions control performance.

Table 73 - Emissions Test Results

Feedlot B Manure – Sampling period 1

	O2 [%]	CO [ppm]	NO [ppm]	NOx [ppm]	CO2 [%]	T Flue [C]
Max	16.70	190	67	70	4.64	469
Min	16.26	58	55	58	4.21	436
Mean	16.59	124	61	64	4.31	447

Feedlot B Manure – Sampling period 2

	O2 [%]	CO [ppm]	NO [ppm]	NOx [ppm]	CO2 [%]	T Flue [C]
Max	19.05	13102	145	152	7.23	585
Min	13.63	13	11	12	1.53	149
Mean	16.24	3206	69	72	4.48	407

Table 74 - Stack test results

Physical characteristics of stack gas	
Average temperature (°C)	426
Average velocity at sampling point (m/s)	32.5
Actual volumetric flow rate (m^3/s)	3.12
Normal wet volumetric flow rate (Nm^3/s)	1.22
Normal dry volumetric flow rate (Nm^3/s)	1.09
Gaseous Components	
Water (wet) (v/v %)	10.3
Oxygen (v/v %)	16.3
Carbon Monoxide (v/v %)	0.32
Carbon Dioxide (v/v %)	4.48
Oxides of Nitrogen (as NO_2) (ppmv)	72.0
Emission concentrations	
Particulate matter (mg/Nm^3)	259
Particulate matter µm 10 (PM_{10}) (mg/Nm^3)	51.2
Oxides of Nitrogen (as NO_2) (mg/Nm^3)	148
Carbon Monoxide (CO) (mg/Nm^3)	4010
TVOC (mg/Nm^3)	287
Mass emission rates	
Particulate matter (g/s)	0.28
Particulate matter µm 10 (PM_{10}) (g/s)	0.056
Oxides of Nitrogen (as NO_2) (g/s)	0.16
Carbon Monoxide (CO) (g/s)	4.4
TVOC (g/s)[1]	0.31

9.3.6 Mass and energy balance model

The calculated mass and energy balance data for the trials are presented in Table 75.

9.3.7 Calculations for 5 tpd and 20 tpd scenarios

Assuming both scenarios utilise one or more BiGchar 2200's, a single unit operating 11 hours/day, 5 days a week in the first instance and two units 24 hours/day in the second, the key values, per unit are:

Feedstock characteristic: 15% moisture, 40% ash, 8.5 MJ/kg
Operating feed rate: 668 kg/hr
Expected char yield: 45.5% (305 kg/hr)
Gross energy release: 1180 kW

Expected energy surplus after air heating and losses: 750 kW per hearth unit

Note thermal drying of the feedstock from 45% of the 15% moisture would require the removal of 301 kg/hr of water, i.e. 680 MJ/hr (190 kW) evaporation load. Assuming a relative low dryer thermal efficiency of 35%, the energy requirement for thermal drying would be 540 kW. This heat is available from the system, even when accounting for a 275 kW air preheating duty.

9.4 Discussion

9.4.1 Observations

The BiGchar hearth was not able to achieve steady state with either of the manure samples tested, as their calorific value was below the 13 MJ/kg preferred for acceptable operation and in the case of the Feedlot A manure below the 10 MJ/kg minimum for operation of the heath. These limits can be extended by blending the feed with a better quality biomass and/or preheating of the primary and secondary air sources to a minimum of 250^{o}C, using heat in the oxidiser flue gas through a shell and tube heat exchanger. The calculated thermal load to achieve the necessary preheating is 275 kW for a BiGchar 2200 system.

9.4.2 Analytical results

The analytical results for the manures and chars were used to perform mass balances for the organic and inorganic species in the samples. These are reported in Table 75 and Table 76. Yields above 100% are indicative of the scale of impact of errors in the raw data on the calculated balance. These indicate mass balance errors of up to 40% may exist for some species.

9.4.3 Mass balance

The majority of inorganic species are expected to be retained in the char. The exceptions are those elements that are volatilised at the relatively low primary gasification temperatures (450 to 600^{o}C). The short residence time in the hearth (~90 seconds) reduces the release of volatile inorganics in comparison to conventional combustion systems.

The results indicate that the majority of the nitrogen, sulphur and chlorides in the feedstock are lost to the flue gas, whereas the majority of the metal species are retained (even traditionally volatile species such as potassium and sodium).

Table 75 – Manure and char ultimate analyses

Ultimate analysis Results - SGS report TW12-08104 incl. calculated parameters

					Ultimate Analysis, wt% Dry Basis								
Sample	**Moisture wt%**	**Volatile matter dry basis**	**Ash wet basis**	**Ash dry basis wt%**	**C**	**H**	**N**	**S**	**O %** (Calc by BiG,by diff)	**H:C**	**O:C**	**C:N**	**Calorific Value MJ/kg**
Kerwee Manure T1	12.7	60.8	26.5	39.2	32.9	4.82	2.46	0.56	20.1	1.75	0.46	15.6	11.97
Kerwee Manure T2	13.1	63.6	23.3	36.4	33.3	5.12	2.47	0.54	22.2	1.83	0.50	15.7	12.57
Kerwee Manure T3	13.5	64.6	21.9	35.4	33.0	4.99	2.45	0.55	23.6	1.80	0.54	15.7	11.79
Mean	**13.1**	**63.0**	**23.9**	**37.0**	**33.1**	**5.0**	**2.5**	**0.6**	**21.9**	**1.8**	**0.5**	**15.7**	**12.1**
Kerwee Char T1	57.3	30.9	29.5	69.1	26.1	1.34	1.39	0.39	1.7	0.61	0.05	21.9	8.75
Kerwee Char T2	63.5	35.8	23.4	64.2	29.6	1.34	1.49	0.48	2.9	0.54	0.07	23.2	9.79
Kerwee Char T3	59.0	30.4	28.5	69.6	28.4	1.21	1.38	0.43	-1.0	0.51	-0.03	24.0	8.75
Mean	**59.9**	**32.4**	**27.2**	**67.6**	**28.0**	**1.3**	**1.4**	**0.4**	**1.2**	**0.55**	**0.0**	**23.0**	**9.1**
Calculated yield to char (dry mass basis)			**55%**		**47%**	**14%**	**32%**	**43%**	**3%**				**41%**
				kg/hr to flue gas	**16.0**	**4.9**	**10.9**	**14.9**	**1.0**			**Total**	**47.7**
Manure Processing rate			122	kg/hr wet	106	kg/hr dry		410	kW thermal rate feedstock basis				
Off-gas rate			64	kg/hr wet				241	kW thermal rate to off-gas and losses				
Assumed recovery of ash to char			99.5%										

			Prox. Analysis dry basis		**Ultimate Analysis, wt% Dry Basis**								
Sample	**Moisture wt%**	**Volatile matter dry basis**	**Ash wet basis**	**Ash dry basis wt%**	**Carbon**	**H**	**N**	**S**	**O %** (Calc by BiG,by diff)	**H:C**	**O:C**	**C:N**	**Calorific Value MJ/kg**
Whyalla Manure T1	10.9	41.9	47.2	58.1	21.3	3.39	1.81	0.47	14.9	1.90	0.53	13.7	7.51
Whyalla Manure T2	11.5	40.5	48.0	59.5	20.7	3.36	1.83	0.50	14.1	1.93	0.51	13.2	7.21
Whyalla Manure T3	10.0	42.9	47.1	57.1	21.7	3.54	1.87	0.50	15.3	1.94	0.53	13.5	8.06
Mean	**10.8**	**41.8**	**47.4**	**58.2**	**21.2**	**3.4**	**1.8**	**0.5**	**14.8**	**1.9**	**0.5**	**13.5**	**7.6**
Whyalla Char T1	48.8	24.0	27.2	76.0	18.7	0.82	0.93	0.19	3.4	0.52	0.13	23.5	5.76
Whyalla Char T2	42.4	19.6	38.0	80.4	15.8	0.93	0.97	0.17	1.7	0.70	0.08	19.0	5.14
Whyalla Char T3	46.4	18.8	34.8	81.2	14.0	0.80	0.86	0.15	3.0	0.68	0.16	19.0	4.54
Mean	**45.9**	**20.8**	**33.3**	**79.2**	**16.2**	**0.9**	**0.9**	**0.2**	**2.7**	**0.63**	**0.1**	**20.5**	**5.1**
Calculated yield to char (dry mass basis)			**74%**		**56%**	**18%**	**37%**	**26%**	**13%**				**50%**
				kg/hr to flue gas	**11.2**	**3.7**	**7.4**	**5.1**	**2.7**			**Total**	**30.0**
Manure Processing rate			129	kg/hr wet	115	kg/hr dry		272	kW thermal rate feedstock basis				
Off-gas rate			44	kg/hr wet				136	kW thermal rate to off-gas and losses				
Assumed recovery of ash to char			99.5%										

Note: Whyalla Manure was visually a lower grade material in terms of organic content

Table 76 – Manure and char analyses

Inorganics Results - SGS report TW12-08104 incl. calculated parameters **Char yield 55%**

			Inorganics Dry Basis										
Sample	Ash wet basis	Ash dry basis wt%	Sulphate mg/kg	Chloride mg/kg	Silicon %	Zinc mg/kg	Alumin-ium mg/kg	Calcium %	Copper mg/kg	Iron mg/kg	Phosph-orous %	Potassium %	Sodium %
Kerwee Manure T1	26.5	39.2	95	170	0.63	250	6400	3.4	52	10000.0	0.81	1.6	0.45
Kerwee Manure T2	23.3	36.4	100	180	0.53	260	5600	3.3	260	7800.0	0.84	1.8	0.50
Kerwee Manure T3	21.9	35.4	100	236	0.64	240	4100	2.9	240	5700.0	0.75	1.5	0.43
Mean	**24**	**37**	**98**	**195**	**0.6**	**250**	**5367**	**3.2**	**184**	**7833**	**0.8**	**1.6**	**0.5**
Kerwee Char T1	29.5	69.1	65.0	119.0	3.1	450	13000	6.2	450	17000	1.5	2.2	0.63
Kerwee Char T2	23.4	64.2	76.0	159.0	3.6	500	13000	6.7	500	15000	1.7	2.5	0.69
Kerwee Char T3	28.5	69.6	65.0	144.0	3.7	520	14000	7.0	520	1800	1.7	2.6	0.70
Mean	**27**	**68**	**69**	**141**	**3.5**	**490**	**13333**	**6.6**	**490**	**11267**	**1.6**	**2.4**	**0.7**
Yield to char (dry mass basis)			**38%**	**40%**	**318%**	**108%**	**137%**	**114%**	**146%**	**79%**	**112%**	**82%**	**80%**

Char yield 74%

			Inorganics Dry Basis										
Sample	Ash wet basis	Ash dry basis wt%	Sulphate mg/kg	Chloride mg/kg	Silicon %	Zinc mg/kg	Alumin-ium mg/kg	Calcium %	Copper mg/kg	Iron mg/kg	Phosph-orous %	Potassium %	Sodium %
Whyalla Manure T1	47.2	58.1	6	177	1.8	310	8000	2.1	310	16000.0	0.78	1.8	0.29
Whyalla Manure T2	48.0	59.5	1	113	2.3	330	7900	2.3	46	15000.0	0.80	1.8	0.30
Whyalla Manure T3	47.1	57.1	3	82	1.7	330	8500	2.2	46	15000.0	0.79	1.8	0.29
Mean	**47**	**58**	**3**	**124**	**1.9**	**323**	**8133**	**2.2**	**134**	**15333**	**0.8**	**1.8**	**0.3**
Whyalla Char T1	27.2	76.0	21.0	82.0	4.1	400	13000	2.8	54	17000	1.0	1.8	0.30
Whyalla Char T2	38.0	80.4	23.0	84.0	4.5	410	14000	2.9	58	22000	1.0	1.9	0.37
Whyalla Char T3	34.8	81.2	25.0	86.0	4.6	440	17000	3.4	64	22000	1.1	2.1	0.41
Mean	**33**	**79**	**23**	**84**	**4.4**	**417**	**14667**	**3.0**	**59**	**20333**	**1.0**	**1.9**	**0.4**
Yield to char (dry mass basis)			**39%**	**75%**	**379%**	**37%**	**125%**	**71%**	**99%**	**76%**	**24%**	**73%**	**72%**

9.4.4 Energy balance

Energy yield to the off-gases was 41% (242 kW) and 50% (126 kW) respectively to the two manures. In essence, the gasification process yielded half as much heat energy as a combustion process would. However, the trade-off is that a saleable biochar product is generated rather than an ash waste.

9.4.5 Emissions

CO, NOx, SOx
The target CO value for the emissions from an oxidiser on a BiGChar system is 200 ppmv. The actual value from the stack test reporting period was 0.32% (3200 ppmv or 4010 mg/Nm^3), which indicates incomplete oxidation. This is to be expected given the low operating temperature of the oxidiser, which was 426^{o}C, versus a target operating range of 750 to 950^{o}C.

The measured NOx values during the stack test period were 72 ppmv or 148 mg/Nm^3.

SOx emissions were not directly measured, however the mass balance indicates that a similar amount of sulphur was released to the flue gas as feedstock nitrogen (57% and 68% respectively). Temperatures were too low for significant thermal NOx formation, so the SOx reading would have been comparable to the NOx reading.

The values for SOx and NOx are not expected to change significantly with thermal oxidiser operating temperature, so any attempt to reduce these values, to a typical target of under 50 mg/Nm^3, would require additional gas treatment.

VOCs
Measured VOC emissions were 287 mg/Nm^3. Typical air emissions licencing limits are 50 mg/Nm^3. VOC emissions are a direct result of thermal oxidiser performance, which BiG evaluates by the CO reading. During the trials the CO values were too high, so it is no surprise that the VOC levels were unacceptably high. Preheating of the secondary air supply to the oxidiser is expected to resolve this in commercial implementations of the technology.

The primary VOC's were identified as Benzene, Acetone, Acetonitrile and Toluene. All are indicators of incomplete oxidation of volatile organics released from the manure organics. All these are serious toxics with strong odours which must be reduced to much lower levels to be acceptable.

Particulates
Total particulate release rate was 259 mg/Nm^3 or 0.28 g/s (1 kg/hr or 0.8% of feed). Typical air emissions licence limits are 50-100 mg/Nm^3 for total particulates and 25-50 mg/Nm^3 for PM10 particulates, depending on sensitivity of the receiving environment and scale of the process.

The measured value equates to a total particulate emission rate of 8 g per kg of biomass feed, which compares unfavourably to the primary particulate release rate from biomass combustor technologies, which are typically of the order of 4 g/kg. The total particulates emission rate is expected to improve with proper operation of the thermal oxidiser.

The majority of the particulates emissions were measured to be in the range of 10 – 50 micron. Less than 20 vol% of the particles were below 10 micron (ie. PM10 was 51 mg/Nm^3). Cyclone wet scrubbing of the flue gas is relatively ineffective for removal of PM10, so if this is required an electrostatic precipitator, bag house or biofilter would be required.

Minimising emissions
Where the most stringent emissions standards apply BiG recommends that the flue gases are cooled by counter-current exchange with incoming air, spray saturated to 38°C and passed through a pH controlled trickling bed biofilter, with a design loading of 1.5 m^3 per m^3/minute. Typical systems are described in ***"Biofilter Technology for NOx Control"***[California Air Resources Board – Research Division Feb 1999) Contract 96-304].

9.4.6 Concluding remarks

Manures can be gasified and converted to a saleable biochar product; however manures are not an ideal feedstock for gasification, as their low calorific value and nitrogen/sulphur content present challenges for cost effective air emissions control.

9.5 Budget Estimates for 5 and 20 tpd systems

Budget estimates for facilities capable of processing 5 tpd and 20 tpd (dried manure basis) were requested. These are presented in Table 77.

Both scenarios are based on a manure with a minimum volatile dry matter content of 60% and a maximum moisture of 15%, e.g. similar to the Feedlot B manure. Feedlot A manure would not be a suitable feedstock unless blended with a dry high volatile biomass such as sawdust.

Both systems are assumed to include primary and secondary air preheaters installed in the flue gas path to enable operation at the low calorific value feedstock.

Black is Green Pty. Ltd. offers two approaches to the commercial implementation of BiGchar systems:

Host site financed
This is BiG's preferred mode of delivery. Under this arrangement the host site is responsible for financing the installation; either party may operate and maintain the installation. Separate agreements may be struck with BiG to take some or all of the resulting product to market.

Fee for service
In this mode BiG delivers or constructs the entire plant and operates it on the host site on a fee for service basis. Apart from minor site preparation costs and regulatory approvals this is the zero capital spend option for host site. BiG's service fee takes into account the necessary return on capital, operating and maintenance costs, offset by the revenue streams derived from the products of the process (eg. char and heat). After capital recovery has been achieved the fee may be replaced with a transfer pricing agreement.

BiG's financial models indicate that a $60/tonne per m^3 of manure processed may be the necessary fee for service, assuming a biochar value of $400/tonne.

There is growing evidence on the benefit of co-composting high nutrient wastes with biochar. MLA may wish to consider options whereby a portion of the manure is charred and co-composted with the remaining quantity. This may result in a more capital effective approach than processing all of the manure from a given site.

Table 77 - Equipment specifications and budget

Scenario	Details	Budget cost for complete installed plant
5 tpd	1 x BiGchar 2200 operating 13 hours/day 7 days/week or 18 hours/day 5 days/week	\$0.8M
20 tpd	1 x BiGchar 3000 operating 24 hours/day 7 days/week Or 2 x BiGchar 2200 operating 24 hour/day 6 days/week	\$1.6M
Included in scope of equipment	Vibrating 25mm rock screen over a metering hopper Feed conveyor(s) Integrated metering bin and paddle style dryer (1 per unit) Gasification hearth (char unit) Thermal oxidiser Primary and secondary air preheater(s) (shell and tube 275 kW_{th} on each unit Induced draft fans (400^{o}C rated) 6 metre flue Char discharge to an effluent water or manure quench blending trough that discharges to a battery limit. Commissioning and operator training 12 months spares and service support	
Excluded	Environmental and council approvals. Secondary emissions control equipment (eg. biofilter) Char product storage, blending and despatch facility	

9.5.1 Recommendations for a commercial trial

Black Earth Products, the marketing arm of Black is Green currently creates a low odour compost blend with animal manures. This approach reduces the wet manure drying demand and improves the appeal of the product by conditioning the biochar with nutrient and microbial populations.

BiG recommends that a 2 tonne per day demonstration of the entire integrated process be implemented at cattle operation using relocatable containerised BiGchar 1500 system to produce a blended biochar/manure product. Such an exercise may be implemented in a six month timeframe, with testing to run for a further 6 months. BiG has recently delivered two such systems to Hawaii and Canada for the same purpose.

One of the key objectives of the testing would be to optimise the emissions performance and trial different secondary control methods with flue gas side streams.

Total project costs are likely to be of the order of $200,000, depending on the site specific installation requirements, project overheads and emissions control testing regime. It should be possible significantly offset the operating costs of the trial through sale of the biochar product via Black Earth Products.

9.6 Appendices

Extracts from Threshold Environmental report

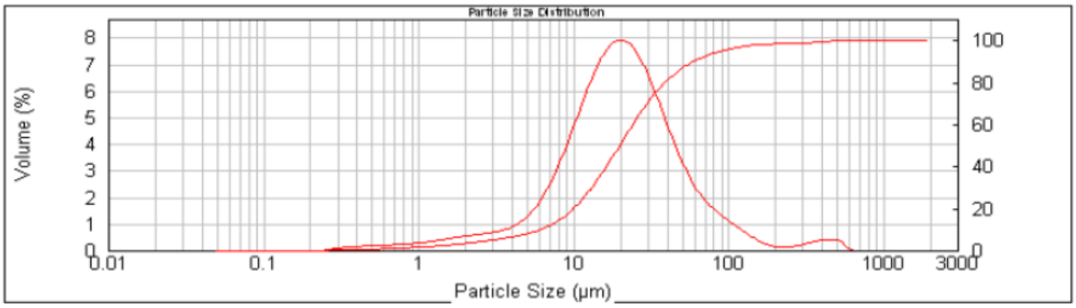
Figure 26 Particle emissions size analysis

Report Number: OL691954F1

Laboratory Number: OL691954/01

Sample Identification: NOV11010/01

d(0.1): 6.206 um d(0.5): 20.020 um d(0.9): 59.861 um



Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %	Size (μm)	Vol Under %
0.100	0.00	0.479	0.46	2.291	3.79	10.965	22.73	52.481	87.61	251.189	98.35
0.110	0.00	0.525	0.56	2.512	4.15	12.023	26.08	57.544	89.34	275.423	98.43
0.120	0.00	0.575	0.67	2.754	4.52	13.183	29.79	63.096	90.82	301.995	98.55
0.132	0.00	0.631	0.79	3.020	4.92	14.454	33.85	69.183	92.08	331.131	98.70
0.145	0.00	0.692	0.91	3.311	5.34	15.849	38.18	75.858	93.18	363.078	98.88
0.158	0.00	0.759	1.04	3.631	5.80	17.378	42.74	83.176	94.13	398.107	99.10
0.174	0.00	0.832	1.18	3.981	6.29	19.055	47.45	91.201	94.96	436.516	99.33
0.191	0.00	0.912	1.33	4.365	6.85	20.893	52.21	100.000	95.69	478.630	99.56
0.209	0.00	1.000	1.49	4.786	7.48	22.909	56.94	109.648	96.31	524.807	99.79
0.229	0.00	1.096	1.66	5.248	8.24	25.119	61.56	120.226	96.84	575.440	99.97
0.251	0.00	1.202	1.85	5.754	9.13	27.542	65.97	131.826	97.26	630.957	100.00
0.275	0.01	1.318	2.06	6.310	10.21	30.200	70.13	144.544	97.59	691.831	100.00
0.302	0.06	1.445	2.29	6.918	11.51	33.113	73.95	158.489	97.83	758.578	100.00
0.331	0.12	1.585	2.55	7.586	13.08	36.308	77.42	173.780	98.01	831.764	100.00
0.363	0.19	1.738	2.82	8.318	14.96	39.811	80.52	190.546	98.12	912.011	100.00
0.398	0.27	1.905	3.12	9.120	17.18	43.652	83.23	208.930	98.21	1000.000	100.00
0.437	0.36	2.089	3.44	10.000	19.76	47.863	85.59	229.087	98.27		

REFERENCE
Simtars Laboratory Procedure LP0060 – "Operation of Mastersizer 2000 Particle Sizer".

Table 2: Volatile Organic Compound Results for Kewee Fuel Source Trial Run

No	Compound	Concentration (mg/Nm³)	No	Compound	Concentration (mg/Nm³)
	Aliphatic hydrocarbons			**Aromatic hydrocarbons**	
1	2-Methylbutane	0.76	39	Benzene	38
2	n-Pentane	0.92	40	Ethylbenzene	1.5
3	2-Methylpentane	<0.3	41	Isopropylbenzene	0.054
4	3-Methylpentane	<0.3	42	1,2,3-Trimethylbenzene	<0.05
5	Cyclopentane	<0.3	43	1,2,4-Trimethylbenzene	0.054
6	Methylcyclopentane	<0.3	44	1,3,5-Trimethylbenzene	<0.05
7	2,3-Dimethylpentane	<0.3	45	Styrene	2.4
8	n-Hexane	0.49	46	Toluene	15
9	3-Methylhexane	<0.3	47	p&m -Xylene	1.0
10	Cyclohexane	<0.3	48	o-Xylene	0.49
11	Methylcyclohexane	<0.3		**Ketones**	
12	2,2,4-Trimethylpentane	<0.3	49	Acetone	26
13	n-Heptane	<0.3	50	Acetoin	<2
14	n-Octane	<0.3	51	Diacetone alcohol	<2
15	n-Nonane	<0.3	52	Cyclohexanone	<2
16	n-Decane	<0.3	53	Isophorone	<2
17	n-Undecane	<0.3	54	Methyl ethyl ketone	6.8
18	n-Docane	<0.3	55	Methyl isobutyl ketone	<0.3
19	n-Tridecane	<0.3		**Alcohols**	
20	n-Tetradecane	<0.3	56	Ethyl alcohol	<2
21	α-Pinene	<0.3	57	n-Butyl alcohol	<2
22	β-Pinene	<0.3	58	Isobutyl alcohol	<2
23	D-Limonene	<0.3	59	Isopropyl alcohol	<2
	Chlorinated hydrocarbons		60	2-Ethyl hexanol	<2
24	Dichloromethane	<0.3	61	Cyclohexanol	<2
25	1,1-Dichloroethane	<0.3		**Acetates**	
26	1,2-Dichloroethane	<0.3	62	Ethyl acetate	<2
27	Chloroform	<0.3	63	n-Propyl acetate	<2
28	1,1,1-Trichloroethane	<0.3	64	n-Butyl acetate	<2
29	1,1,2-Trichloroethane	<0.3	65	Isobutyl acetate	<2
30	Trichloroethylene	<0.3		**Ethers**	
31	Carbon tetrachloride	<0.3	66	Ethyl ether	<2
32	Perchloroethylene	<0.3	67	*tert*-Butyl methyl ether	<2
33	1,1,2,2-Tetrachloroethane	<0.3	68	Tetrahydrofuran	<2
34	Chlorobenzene	<0.3		**Glycols**	
35	1,2-Dichlorobenzene	<0.3	69	PGME	<2
36	1,4-Dichlorobenzene	<0.3	70	Ethylene glycol diethyl ether	<2
	Miscellaneous		71	PGMEA	<2
37	Acetonitrile	50	72	Cellosolve acetate	<2
38	n-Vinyl-2-pyrrolidinone	<2	73	DGMEA	<2
Total VOCs		**287**			

10 Appendix B – Pyrolysis Results

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PacPyro Slow Pyrolysis Technology

Slow-Pyrolysis Batch trials - Feedlot Manures

Prepared for

Meat and Livestock Australia

via Bridle Consulting via FSA Consulting

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EXECUTIVE SUMMARY

Two manure feedstocks from different feedlots, supplied by FSA Consulting, have been investigated by Pacific Pyrolysis (PacPyro) for their potential for application to a PacPyro pyrolysis project. Feedstocks originated from Feedlot A and Feedlot B and biochars produced were provided to Bridle Consulting.

Analysis of feedstocks and biochars produced by PacPyro showed slow-pyrolysis processing of each feedstock achieved successful formation of biochar and syngas as demonstrated by change in the materials O/C and H/C ratios, which suggests aromatisation of the carbon present and generation of syngas.

Feedstock received from Feedlot A was high in ash (inorganic material) (69 m/m%) and was observed to contain a large proportion of rocks/gravel. High ash contents negatively affects the pyrolysis outcomes. It was found that the Feedlot B feedstock (33m/m% ash) gave a higher output of electrical energy per tonne of feedstock processed compared to Feedlot A. A comparison is shown in Table 1.

Table 1: Estimates for PacPyro process outputs at 25% moisture (ar)

	FEEDLOT A FEEDSTOCK	FEEDLOT B FEEDSTOCK
Electrical Energy [kWhe/t feedstock (db)]	102	287
Biochar output [t biochar/t feedstock (db)]	0.72	0.54

Less than half the amount of electrical energy generated for a Feedlot B feedstock is observed for Feedlot A, although a higher biochar yield is observed as a result of the inorganic rock material contained in the Feedlot A feedstock ending up in the biochar stream.

Using sensitivity process modelling, moisture variation (up to approximately 40%m/m) was not found to have as significant an impact on process outcomes compared to ash content. Therefore modifying the collection methods of the manure in terms of minimising contamination with rocks may be key for allowing a higher energy yield and maximising carbon content of the biochar produced.

CONTENTS

1. Introduction

Objectives of this trial, as laid out in quote provided to Meat and Livestock Consulting (MLA) (doc. Ref Q1035b MLA Biochar Small Batch Trials), include:

- To determine the fundamental suitability of the client supplied feedstock for the PacPyro proprietary slow pyrolysis technology.
- Complete modelling of a mass and energy balance of a commercial scale Pacific Pyrolysis plant using an analysis of the feedstock and biochar produced by the batch trials. This information provides the process outputs required to enable an initial economic feasibility assessment of a pyrolysis project.

Deliverables also outlined in this document include:

- Pyrolysis of a single sample in 20 L batch reactor (two samples were pyrolysed, addressing Schedule 1 and Schedule 2 of Q1035b)
- Testing of feedstock and biochar for important properties by a third party laboratory.
- Electronic report

Additionally, PacPyro have provided several samples of biochar produced in batch trials to Bridle Consulting for analysis by the client. This biochar was provided under the PacPyro biochar evaluation agreement.

This report will address the trial objectives including an analysis of batch pyrolysis results and use of key feedstock and biochar properties in the PacPyro mass and enthalpy balance to give a preliminary assessment of feedstock suitability.

PacPyro can only make assumptions from information provided by the client as well as reasonable numbers determined by PacPyro. Outcomes are also specific to feedstocks provided and are not applicable to other feedstocks or applications of the technology. Modelling inputs and sensitivities are outlined in this report for transparency of conclusions.

2. Batch Trials with Feedlot Manure Feedstocks

The PacPyro batch pyrolysis reactor, referred to as 'Daisy', allows for control of heating rate, highest heating temperature, residence time, and steam injection/activation so that feed materials can be processed under a range of process conditions. The range of variation possible for feedstocks processed in Daisy and actual values used in these MLA trials are shown in Table 2.

Table 2. Controlled variables for batch pyrolysis kiln.

Control variable	Range	Used in MLA trials
Heating rate	5 - 20°C/min	7 °C/min
Highest heating temperature (HHT)	200 - 550°C	550 °C
Residence time at HHT	0 - 120 min	40 min
Steam activation of char	Yes/No	No

2.1 Batch Pyrolysis Operation

An automatic gas-controller is used to operate the burners, ensuring a constant heating rate and stable final heating temperature. The gases from the pyrolysis process are released through a flue stack into a simple flare and combusted. Once the set residence time has passed, the kiln burners are shut-off and the kiln is purged with nitrogen (to maintain an inert environment) until the reactor temperature drops below at least 200°C. This inert environment prevents oxidation of the biochar. Once cooled, the resulting biochar is collected by removing the front refractory lined flange. A photograph of the batch pyrolysis rig with key units outlined is shown in Figure 1.

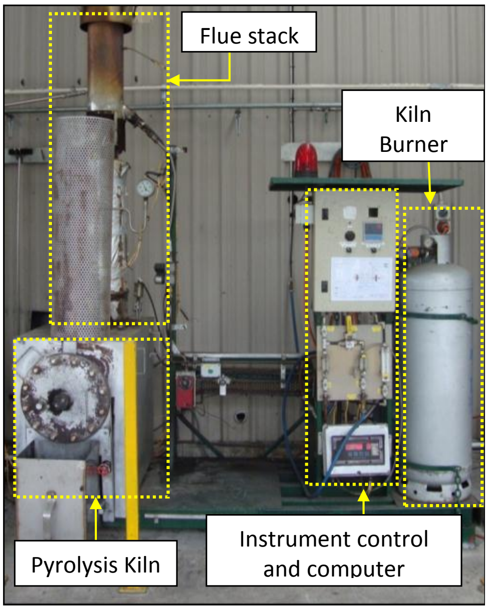

Figure 1: PacPyro batch pyrolysis rig

2.2 FEEDSTOCKS PROVIDED

Bridle Consulting provided PacPyro with two separate feedstock samples collected from two separate sites. These were specified as 'Feedlot A' and 'Feedlot B' with reference to their collection site of origin. Images of the feedstocks after drying are shown in Figure 2.

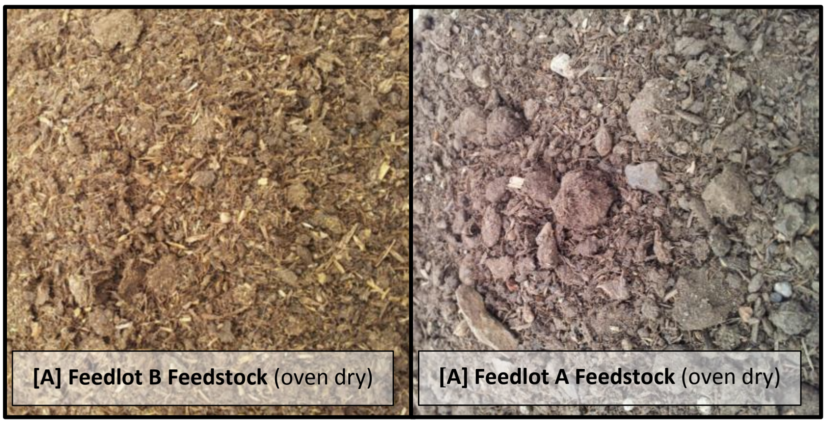

Figure 2: [A] Feedlot B and [B] Feedlot A feedstock received and dried by PacPyro

The Feedlot A feedstock was found to be highly contaminated by rocks (which can be seen in Figure 2 [B]), assumed to be as a result of the collection method used. These rocks have been separated and weighed from both the Feedlot A feedstock and biochar before being sent for analysis with Bureau Veritas (results in Appendix A). The rock matter has been included by weight as ash in both materials in analysis carried out by PacPyro. The amount of rocks separated from the Feedlot A feedstock and char are shown in Table 3.

Table 3: Summary of amount of rock matter removed from Feedlot A feedstock and biochar

		FEEDSTOCK	BIOCHAR
Full sample mass	g	740	854.5
Rock separated	g	208	268.5
Mass sent for analysis	g	532	586
Rock proportion	**m/m% (db)**	**28.11%**	**31.42%**

Assuming the rock matter would not be transferred to the syngas, the rock portion makes up only a slightly larger portion in the biochar compared to the feedstock.

2.3 BATCH TRIAL RESULTS

2.3.1 *MOISTURE CONTENT AND BIOCHAR YIELD*

Moisture content and biochar yield were determined by PacPyro using the following methods:

- *MOISTURE CONTENT*: The moisture content of the feedstock material was determined by oven drying at 95°C until the mass of the sample stabilised.

- *BIOCHAR YIELD*: The biochar yield was calculated by measuring the dry weight of the biochar divided by the dry weight of the feedstock.

The moisture content of the feedstock are outlined in Table 4. It is noted that the feedstocks were pre-dried by the client before shipment therefore these results were not used for process modelling.

Table 4: Moisture content for feedstock as supplied

Material	Moisture content [% m/m] (ar)
Feedlot A Manure Feedstock	14.05 %
Feedlot B Manure Feedstock	17.84 %

Biochar yields (char/feedstock on a dry basis) are shown in Table 5.

Table 5: Biochar yields following batch slow pyrolysis at 550°C

Feedstock	Biochar Yield [m/m% (db)]
Feedlot A Feedstock	72.4%
Feedlot B Feedstock	54.1%

2.3.2 *Feedstock and Biochar Properties*

Samples of both the dry feedstock and each of the biochars produced were sent for analysis at a NATA accredited laboratory for proximate, ultimate, energy content. Raw data from the feedstock and biochar laboratory analysis can be found in Appendix A, including an overview of the test methods used.

Proximate Analysis

General relations between the proximate analysis of feedstock and resulting biochar, which are known from extensive analysis of widely varied feedstocks at PacPyro, include:

- Feedstocks with a higher volatile fraction produce more syngas during pyrolysis and have a correspondingly lower yield of biochar.
- Feedstocks with higher ash content and/or lower volatile content tend to produce less syngas and have a higher biochar yield.
- Ash is conserved during pyrolysis; it is not converted to syngas.
- Fixed carbon can be formed during pyrolysis due to thermochemical conversion reactions.

Proximate analysis of the feedstock and char analysed in this report is shown in Appendix A.

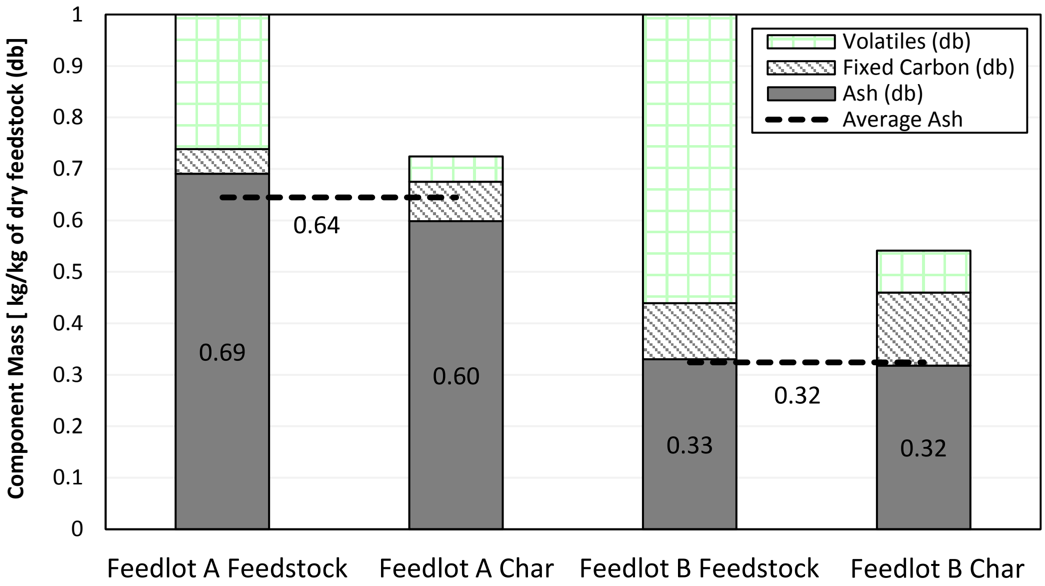

Figure 3: Proximate properties of the feedstock compared to the biochar as a result of slow-pyrolysis processing.

Since ash is conserved between the feedstock and biochar (i.e. remains in the biochar mass) the ash content of the biochar and the ash content of the feedstock should be the approximately equal as seen in Figure 3 for the Feedlot B feedstock processed. Differences are a result of precision of measurement and the effects of error accumulation in the normalisation calculation used. In the case of the Feedlot A feedstock, it is also likely a result of the errors introduced in the rock removal process.

It can be seen in Figure 3 that almost all the volatile fraction is removed from both feedstocks tested during pyrolysis via syngas formation. A small amount of increase in the fixed carbon is also observed in both feedstocks. Both observations are consistent with general relations observed by PacPyro in application of slow-pyrolysis process conditions.

Ultimate Analysis

Ultimate analysis of the feedstock and biochar gives an indication of both the elemental content and the chemical nature of the organic compounds constituting the material. The results of the ultimate analysis are shown in Table 6 and changes to the relatiove proportions of CHO between feedstock and biochar is compared in Figure 4.

Table 6: Ultimate analysis results for waste feedstock and biochar presented as m/m% (db).

Element	Feedlot A Feedstock*	Feedlot A Biochar*	Feedlot B Feedstock	Feedlot B Biochar
Carbon [C]	15.53	13.65	33.6	33.0
Hydrogen [H]	2.14	0.71	4.45	1.65
Nitrogen [N]	1.32	0.87	2.31	2.10
Sulfur [S]	0.40	0.05	0.52	0.50
Oxygen [O] (by diff)	10.96	1.87	26.09	3.93
**corrected to include rocks removed as ash*				

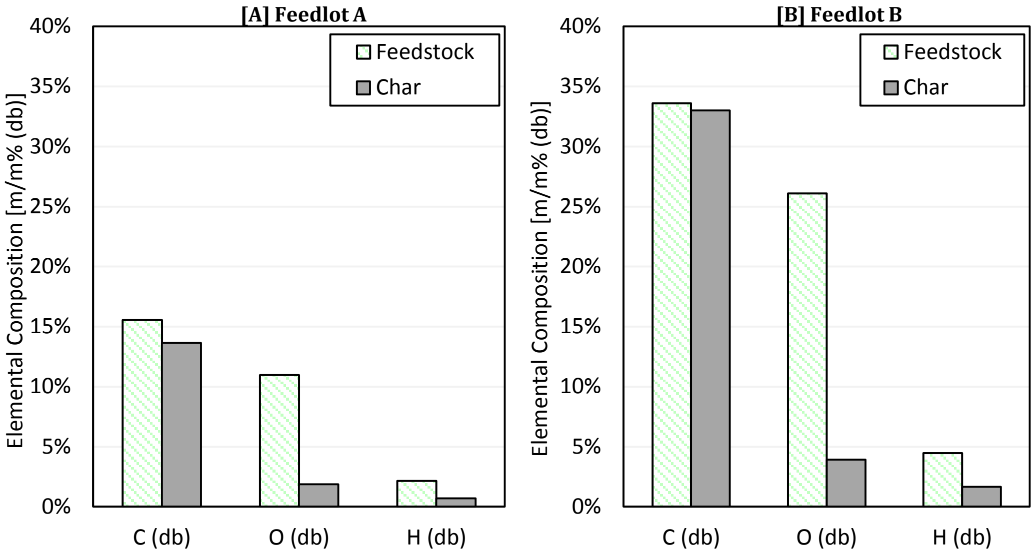

Figure 4: Comparison of elemental composition of feedstocks and chars

It can be seen in Figure 4 that carbon composition in the biochar is not very different to the feedstock. This does not mean no carbon was removed during pyrolysis, since the overall quantity of material has in fact decreased. Big differences however are observed between oxygen and hydrogen showing a large decrease in the amount of each. Since the remainder of the biochar is mainly ash, stable carbon composition with reduced oxygen and hydrogen is indicative of the stabilisation of the remaining carbon in aromatic rings. This can also be confirmed by calculation of H:C and O:C ratios. These ratios are calculated on a molar basis as follows:

$$O:C = \frac{[O]/MW_O}{[C]/MW_C}$$

$$H:C = \frac{[H]/MW_H}{[C]/MW_C}$$

Where MW_n is the molecular weight of element '*n*'.

Ratios for the feedstocks and chars examined here have been calculated using results in Table 6 and are presented in Figure 5 in what is known as a 'Van Krevelen' Diagram.

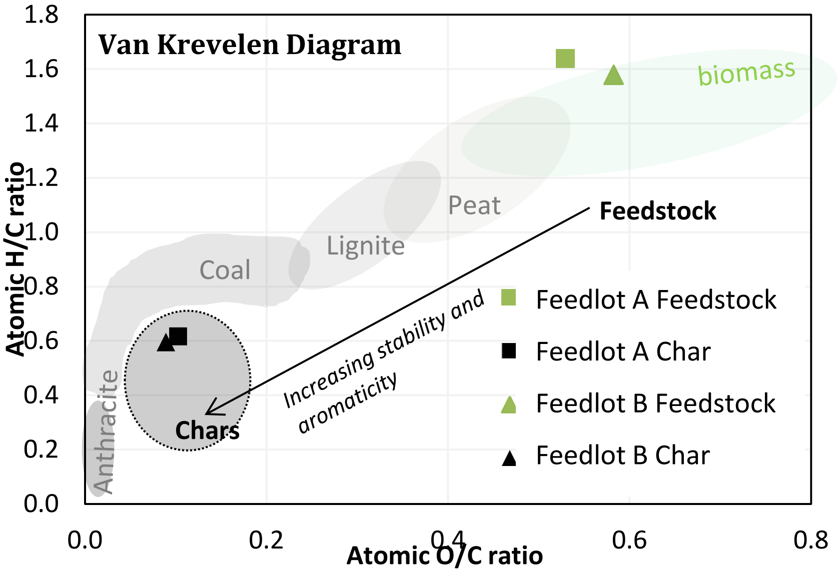

Figure 5: Van Krevelan diagram of feedstock and resulting biochar. O/C ratio<0.2 indicates biochar stable for >1000 years

These ratios indicate the changing aromaticity of the biomass as biochar forms, indicated in Figure 5. Increasing aromaticity indicates formation of a higher energy density material. A significant change in aromaticity is observed in Figure 5 for both manures investigated as they are converted to biochar. The O:C and H:C ratios indicate remaining carbon in the biochar is stabilised against decomposition and will not readily be released as CO_2 in the environment.

Energy Content Analysis

The energy content, measured as gross calorific value for each feedstock and biochar, is shown in Figure 6.

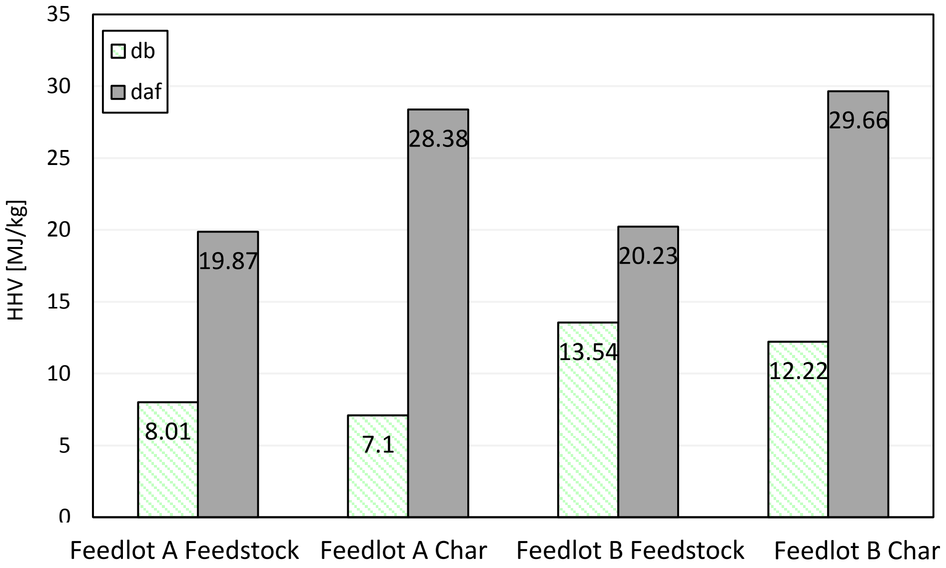

Figure 6: Comparison of energy density (mass) on a dry and dry ash free basis

Removal of the volatile fraction in the feedstock during pyrolysis increases the overall concentration of ash and fixed carbon remaining in the biochar since their mass is not reduced during pyrolysis. The effect of increasing the fixed carbon concentration increases the energy density of the non-ash portion (daf – dry ash free) of the biochar compared to the feedstock since the fixed carbon fraction has a greater calorific value than the volatile fraction. This results in a higher calorific value for the biochar compared to the feedstock in both cases.

3. Biochar Samples Provided

Sub-samples of all biochars produced were evaluated as shown above while a representative portion of the biochar was collected by Trevor Bridle for analysis. Information for biochars provided to the client are listed in Table 7.

Table 7: Summary of biochar samples provided to Bridle Consulting

PacPyro Reference	MLA/FSA Reference	Description
D-021112-KER	7777MS1747KER01	Feedlot B manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-021112-KER	7777MS1747KER02	Feedlot B manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-021112-KER	7777MS1747KER03	Feedlot B manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-021112-KER-550-N	7777CHAR1747KER01	Feedlot B manure biochar sample pyrolysed by PacPyro in Daisy at 550°C
D-021112-KER-550-N	7777CHAR1747KER02	Feedlot B manure biochar sample pyrolysed by PacPyro in Daisy at 550°C
D-021112-KER-550-N	7777CHAR1747KER03	Feedlot B manure biochar sample pyrolysed by PacPyro in Daisy at 550°C
D-011112-WHY	7777MS1747WH01	Feedlot A manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-011112-WHY	7777MS1747WH02	Feedlot A manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-011112-WHY	7777MS1747WH03	Feedlot A manure sample dispatched to PacPyro. Dried by PacPyro at 95°C
D-011112-WHY-550-N	7777CHAR1747WH01	Feedlot A manure biochar sample pyrolysed by PacPyro in Daisy at 550°C
D-011112-WHY-550-N	7777CHAR1747WH02	Feedlot A manure biochar sample pyrolysed by PacPyro in Daisy at 550°C
D-011112-WHY-550-N	7777CHAR1747WH03	Feedlot A manure biochar sample pyrolysed by PacPyro in Daisy at 550°C

4. Preliminary Process Model Outputs

PacPyro have developed a mass and enthalpy balance model for full integration of all unit operations of their slow-pyrolysis technnology in order to predict process outputs in terms of the amount of biochar produced and the electrical and thermal energy delivered from the process.

In summary, feedstock enters the rotary drier where the majority of its moisture is removed. The drier exhaust is vented to the atmosphere while the dry feedstock continues to the pyrolysis kiln. The PacPyro slow pyrolysis process results in the thermal degradation of the organic feedstock producing three main components; biochar, bio-oil and syngas. Bio-oil production is minimised through optimised operating conditions. The raw syngas produced in the kiln contains bio-oils which are cracked to yield more syngas through a proprietary gas clean-up system. Char produced in the kiln also contains bio-oils which are transformed to syngas in the char conditioner/gasifier. The char can also be optionally gasified in this process to yield more syngas. As a conditioner however its main function is to develop the materials properties to ensure production of a quality biochar with well-developed surface area.

Clean syngas resulting from both the pyrolysis process (majority) and any syngas produced in the char conditioner/gasifier are used to supply heat internally to the process. As first priority syngas produced is fed to the pyrolysis kiln burner. Exhaust gases from the burner provide heat to the kiln by passing them through a kiln heating shell. Since only a portion of the heat contained in the exhaust is transferred to the kiln, exhaust from the pyrolysis kiln heating shell is fed directly to the rotary drier for moisture removal of the feedstock. Syngas can also be fed to the drier burner if required for feedstock moisture removal.

Syngas produced is preferentially used for internal processing requirements, such as to heat the pyrolysis kiln and the drier (if required). Syngas produced in excess of that required by the internal process is able to be used outside the process. A gas engine and generator are used to produce an electrical output from the syngas. Exhaust gases from the engine can also be directed to the rotary drier for moisture removal from feedstocks.

The process modeling has been done, as per standard practice, for steady-state operation. It should be noted however that the process design includes management for start-up, shut-down and stand-by operating conditions. For example the process includes a flare that can be operated at a capacity to take excess gas from the process under steady state operation, but also to fully combust the total potential syngas stream if required.

A degree of flexibility has been built into the process design to accommodate different project circumstances. This may include the requirement to add and subtract various unit operations as needed to meet the commercial, regulatory and design objectives of the project.

4.1 Main Process Model Inputs

Bridle consulting have provided in email correspondence specified moisture contents of 25 and 35% of the feedstocks should be used by PacPyro for modelling purposes. Other important mass and enthalpy inputs include analysis results from batch pyrolysis trials including composition of feedstock and biochar (proximate and ultimate) and calculated pyrolysis yield detailed in Section 2.3. To allow comparison of feedstock used, a design basis feed rate of 1 tph (db) has been used in process modelling. However, it should be noted that current PacPyro process designs are based on modular 2 and 4 tph process plants. Key inputs used in process modelling for each feedstock are shown in Table 8.

Table 8: Input values used in process modelling

		Feedlot A		Feedlot B	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2
Moisture Content	m/m% (ar)	25%	35%	25%	35%
Biochar Yield	m/m% (db)	72.4		54.1	
Feed rate	tph	1		1	

4.2 Process Model Outcomes for Feedlot B Feedstock (1 tph basis)

Using feedstock design parameters specified in Table 8, process modelling has been used to estimate both the electrical and thermal energy outputs for the Feedlot B feedstock provided to PacPyro. These results are shown in Table 9.

Table 9: Feedlot B Process Model Outcomes

		25 % moisture (ar)		35 % moisture (ar)	
		BIOCHAR OPTIMISED	*ENERGY OPTIMISED*	*BIOCHAR OPTIMISED*	*ENERGY OPTIMISED*
Char Yield	m/m % (db)	54%	43.70%	54%	43.70%
Electrical Energy Generated	kWh_e/t feed (db)	287	400	256	363
	GJ	1.03	1.44	0.92	1.31
	MW_e	0.29	0.40	0.26	0.36
Thermal Energy (Syngas produced)	kWh_{th}/t feed (db)	882	1197	683	987
	GJ	3.17	4.31	2.46	3.55
	MW_{th}	0.88	1.20	0.68	0.99

Electrical energy refers to the amount of electrical energy able to be supplied to the grid after conversion of syngas to electricity in an engine generator set. Thermal energy is the raw thermal potential of the syngas produced prior to electrical conversion. It should be noted that either electrical or thermal energy is produced not both.

Table 9 also shows outputs for a “biochar” and “energy” optimised scenario. These scenarios refer to the treatment of the biochar after leaving the pyrolysis kiln. It is possible to further gasify the biochar produced in the kiln to create more syngas and thus allow more electricity to be generated. This leaves the biochar with a higher ash content and less biochar remains after processing. The ash content of the feedstock limits the energy achievable from gasification. It has been assumed that the materials is gasified to an 80% ash content, due to further gasification likely to be energetically unfavourable. The biochar and energy optimised scenarios therefore represent the expected range of electrical generation capacity of the plant for a specified feedstock.

Since the inputs provided may be somewhat variable, a sensitivity analysis of the expected electrical energy output of the process as a function of both moisture and ash content has been carried out in order to determine the amount of variation possible with changes in these important feedstock specifications. This has been done for both a “biochar” and “energy” optimised scenario. Results for this modelling are shown in Figure 7.

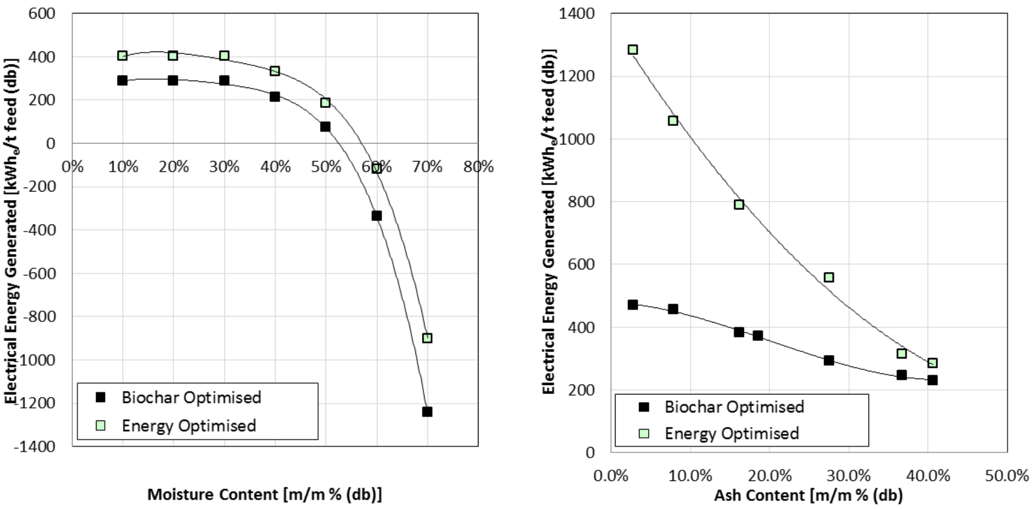

Figure 7: Sensitivity of electrical energy output to [a] moisture (fixed ash 33%) and [b] ash (fixed moisture 25%) of input feedstock.

It can be seen in Figure 7 [a] that the electrical energy is not significantly sensitive to the moisture content until the moisture exceeds ~40%. This is a result of a tipping point being reached passed this moisture content where internal process energy available is no longer sufficient to dry the feedstock and external energy is required (i.e. negative energy values).

Figure 7 [b] demonstrates the sensitivity of the electrical energy output to the ash content of the feedstock at fixed moisture. It can be seen that the electrical output is most sensitive under an “energy” optimised scenario. This is a result of the extra calorific value available for gasification in the case of low ash feedstocks. It can also be seen that the sensitivity model only extends to an ash content of 40 m/m% (db) and beyond this point significantly diminished returns are expected.

4.3 Process Model Outcomes for Feedlot A Feedstock

Process outputs have been calculated for the Feedlot A feedstock supplied as shown in Table 10.

Table 10: Feedlot A Process Model Outcomes

		25% Moisture	35% Moisture
		BIOCHAR OPTIMISED	
Char Yield	m/m % (db)	72%	72%
Electrical Energy Generated	kWhe/t feed (db)	102	62
	GJ	0.37	0.22
	MWe	0.10	0.06
Thermal Energy (Syngas produced)	kWhth/t feed (db)	256	94
	GJ	0.92	0.34
	MWth	0.26	0.09

The Feedlot A feedstock was only assessed for a 'biochar' optimised process. This is because of the relatively high ash content of the feedstock of 69% meaning an insignificant difference in scenarios would be observed (assuming gasification can only be done favourably to an ash content of 80m/m%). The high ash content also puts the feedstock beyond the PacPyro sensitivity modelling carried out for Feedlot B feedstock of up to 40%m/m ash (db). However sensitivity to moisture has been investigated as shown in Figure 8.

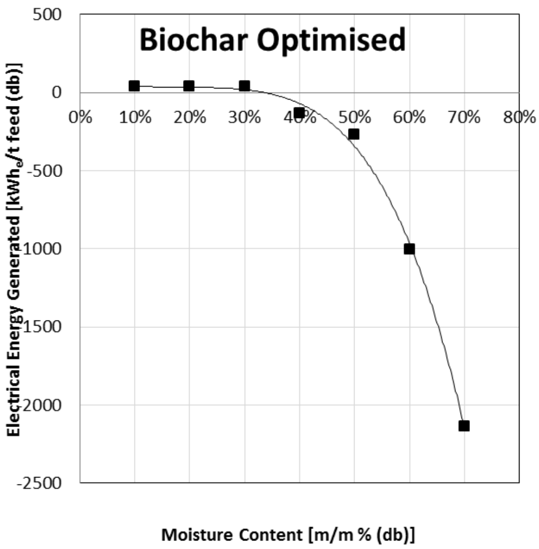

Figure 8: Sensitivity of electrical output to moisture (fixed ash 69%).

Similarly to the Feedlot B feedstock analysed, the electrical output decreases significantly beyond a 50% moisture content with little to no electrical energy produced for the Feedlot A feedstock even in the case of low feedstock moisture. This is a result of the high ash found in the case of Feedlot A.

It is thought a contributing factor of this high ash content may be a result of the collection method used for the feedstock since a large portion of the feedstock was determined to be rocks. It is recommended that a review of methods to limit this contamination is undertaken.

CONDITIONS AND LIMITATIONS

Pacific Pyrolysis Pty Ltd (PacPyro) has prepared this document (the "Report") for the exclusive use of "*Meat and Livestock Australia*" (the "Client") for the purposes of developing a pyrolysis project.

The report must be read in light of:

i. the limited readership and purposes for which it was intended;
ii. its reliance upon information provided to PacPyro by the Client and others which has
iii. not been verified by PacPyro and over which it has no control;
iv. the limitations and assumptions referred to throughout the Report;
v. the cost and other constraints imposed on the Report, and
vi. other relevant issues which are not within the scope of the Report.

Subject to the limitations referred to above, PacPyro has exercised all due care in the preparation of the Report and believes that the information, conclusions, interpretations and recommendations of the report are both reasonable and reliable.

Subject to any contrary agreement between PacPyro and the Client:

i. PacPyro makes no warranty or representation to the Client or third parties (expressed or implied) in respect of the Report particularly with regard to any commercial investment decision made on the basis of the Report;
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The report does not constitute a legal opinion. The principles, procedures and standards applied in conducting any investigation are neither regulated nor universally applied.
PacPyro has conducted the investigation in accordance with the methodology outlined in its proposal. It is acknowledged that the methods of evaluation employed, while aimed at minimising the risk of unidentified problems cannot guarantee their absence. While the information provided by the Client and others was reviewed, PacPyro was required to rely upon this information without independently verifying its accuracy.

The disclosure of any information contained in this report is the sole responsibility of the Client.

This disclaimer must accompany every copy of the Report, which is an integral document and must be read in its entirety.

APPENDIX A

BUREAU VERITAS – INTERNATIONAL TRADE
4 ENTERPRISE CRESCENT
MAISON DIEU ESTATE SINGLETON NSW 2330
TEL(02) 65711033 FAX(02) 65711099

REFERENCE NUMBER	:	**HV 85013483**
REPORT TITLE	:	**Project 1035** **Supplied Samples**
CLIENT NAME AND ADDRESS	:	**Ms Jessica O'Brien** **Pacific Pyrolysis Pty Ltd** **56 Gindurra Road** **Somersby NSW 2250**
DATE SAMPLED	:	**Unknown**
SAMPLED BY	:	**Unknown**
DATE SAMPLES RECEIVED	:	**09-Nov-12**
DATE SAMPLES ANALYSED	:	**9-Nov-12 to 15-Nov-12**
REPORTED BY	:	**Elise Baker** **Reporting Officer**
DATE REPORTED	:	**16-Nov-12**
REPORT STATUS	:	**Provisional**
ISSUED BY	:	**Doug Hamment** **Manager and Senior Coal Consultant**
SIGNATURE	:	

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MAISON DIEU ESTATE SINGLETON NSW 2330
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ORIGIN:	**Pacific Pyrolysis Pty Ltd**		
DESCRIPTION:	**Project 1035**	REF.No:	**HV 85013483**
REPORTED TO:	**Ms Jessica O'Brien**	DATE REC'D:	**09/11/12**

Supplied Sample

Project No:		**1035**		
Sample ID:		**D-011112-WHY**		
Sample type / Matrix		**Whyalla Feedstock**		
BVITA Sample ID:		**1467266**		
Mass Received:	(g)	**532.0**		
Analysis Basis		**(ad)**	**(db)**	**(daf)**
Proximate Analysis				
Moisture	(%)	**4.6**		
Ash	(%)	**55.1**	**57.8**	
Volatile Matter	(%)	**34.1**	**35.7**	**84.6**
Fixed Carbon	(%)	**6.2**	**6.5**	**15.4**
Gross Calorific Value	(MJ/kg)	**8.01**	**8.40**	**19.87**
	(kcals/kg)	**1913**	**2005**	**4747**
Ultimate Analysis				
Carbon	(%)	**20.6**	**21.6**	**51.1**
Hydrogen	(%)	**2.83**	**2.97**	**7.02**
Nitrogen	(%)	**1.75**	**1.83**	**4.34**
Total Sulfur	(%)	**0.53**	**0.56**	**1.32**
Oxygen (by difference)	(%)	**14.59**	**15.29**	**36.20**

CHN performed at BVITA Newcastle to Australian Test Methods
Calorific Values have been Total Sulfur corrected.

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DESCRIPTION:	**Project 1035**	REF.No:	**HV 85013483**
REPORTED TO:	**Ms Jessica O'Brien**	DATE REC'D:	**09/11/12**

Supplied Sample

Project No:		**1035**		
Sample ID:		**D-011112-WHY-550-N**		
Sample type / Matrix		**Whyalla Char**		
BVITA Sample ID:		**1467267**		
Mass Received:	(g)	**585.8**		
Analysis Basis		**(ad)**	**(db)**	**(daf)**
Proximate Analysis				
Moisture	(%)	**2.1**		
Ash	(%)	**73.4**	**75.0**	
Volatile Matter	(%)	**9.5**	**9.7**	**38.8**
Fixed Carbon	(%)	**15.0**	**15.3**	**61.2**
Gross Calorific Value	(MJ/kg)	**6.95**	**7.10**	**28.38**
	(kcals/kg)	**1661**	**1696**	**6778**
Ultimate Analysis				
Carbon	(%)	**19.5**	**19.9**	**79.6**
Hydrogen	(%)	**1.01**	**1.03**	**4.12**
Nitrogen	(%)	**1.24**	**1.27**	**5.06**
Total Sulfur	(%)	**0.08**	**0.08**	**0.33**
Oxygen (by difference)	(%)	**2.67**	**2.73**	**10.90**

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DESCRIPTION:	**Project 1035**	REF.No:	**HV 85013483**
REPORTED TO:	**Ms Jessica O'Brien**	DATE REC'D:	**09/11/12**

Supplied Sample

Project No:		**1035**		
Sample ID:		**D-021112-KER**		
Sample type / Matrix		**Kerwee Feedstock**		
BVITA Sample ID:		**1467268**		
Mass Received:	(g)	**270.8**		
Analysis Basis		**(ad)**	**(db)**	**(daf)**
Proximate Analysis				
Moisture	(%)	**6.2**		
Ash	(%)	**31.0**	**33.0**	
Volatile Matter	(%)	**52.6**	**56.1**	**83.8**
Fixed Carbon	(%)	**10.2**	**10.9**	**16.2**
Gross Calorific Value	(MJ/kg)	**12.70**	**13.54**	**20.23**
	(kcals/kg)	**3034**	**3235**	**4831**
Ultimate Analysis				
Carbon	(%)	**31.5**	**33.6**	**50.2**
Hydrogen	(%)	**4.17**	**4.45**	**6.64**
Nitrogen	(%)	**2.17**	**2.31**	**3.46**
Total Sulfur	(%)	**0.49**	**0.52**	**0.78**
Oxygen (by difference)	(%)	**24.47**	**26.09**	**38.96**

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REPORTED TO:	**Ms Jessica O'Brien**	DATE REC'D:	**09/11/12**

Supplied Sample

Project No:		**1035**		
Sample ID:		**D-021112-KER-550-N**		
Sample type / Matrix		**Kerwee Char**		
BVITA Sample ID:		**1467269**		
Mass Received:	(g)	**586.0**		
Analysis Basis		**(ad)**	**(db)**	**(daf)**
Proximate Analysis				
Moisture	(%)	**3.4**		
Ash	(%)	**56.8**	**58.8**	
Volatile Matter	(%)	**14.5**	**15.0**	**36.4**
Fixed Carbon	(%)	**25.3**	**26.2**	**63.6**
Gross Calorific Value	(MJ/kg)	**11.80**	**12.22**	**29.66**
	(kcals/kg)	**2819**	**2919**	**7084**
Ultimate Analysis				
Carbon	(%)	**31.9**	**33.0**	**80.2**
Hydrogen	(%)	**1.59**	**1.65**	**3.99**
Nitrogen	(%)	**2.03**	**2.10**	**5.10**
Total Sulfur	(%)	**0.48**	**0.50**	**1.21**
Oxygen (by difference)	(%)	**3.80**	**3.93**	**9.55**

CHN performed at BVITA Newcastle to Australian Test Methods
Calorific Values have been Total Sulfur corrected.

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ORIGIN: **Pacific Pyrolysis Pty Ltd**
DESCRIPTION: **Project 1035** REF No : **HV 85013483**
REPORTED TO: **Ms Jessica O'Brien** DATE REC'D: **09/11/12**

The highlighted Standards will have been used for this report

Reference Number	Reference Description
AS 1038.1	Higher rank coal - **Total Moisture**
AS 1038.3	**Proximate** analysis of higher rank coal
AS 1038.5	Gross **Calorific Value** of coal and coke - Automatic isothermal-type Calorimeters
AS 1038.6.1	Ultimate analysis of higher rank coal - Determination of **Carbon and Hydrogen**
AS 1038.6.2	Ultimate analysis of higher rank coal - Determination of **Nitrogen**
AS 1038.6.3.3	Ultimate analysis of higher rank coal - Determination of **Total Sulphur** (Infrared method)
AS 1038.9.3	Coal and Coke - **Phosphorus** - Ash Digestion Method
AS 1038.11	Coal - **Forms of sulphur**
AS 1038.12.1	Higher rank coal - Caking and coking properties **- Crucible swelling number**
AS 1038.15	Higher rank coal ash and coke ash - **Ash fusibility**
AS 1038.20	Higher rank coal - **Hardgrove grindability index**
AS 1038.21.1.1	Higher rank coal and coke - **Relative density** - Analysis sample / density bottle method
AS 1038.23	Higher rank coal - **Carbonate carbon**
AS 3881	**Size analysis** - higher rank coal
AS 4156.1	Higher rank coal - **Float and sink testing**
AS4264.1	Higher rank coal - **Sampling procedures**
AS1038.12.4.1	Higher Rank Coal - **Gieseler Fluidity**