GASIFICATION OF FOOD PROCESSING BYPRODUCTS - AN ECONOMIC WASTE HANDLING ALTERNATIVE

By

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GASIFICATION OF FOOD PROCESSING

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ALTERNATIVE

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NOMENCLATURE

AC_d	-	Ash content – dry basis
ASTM	-	American Society for Testing and Materials
APWA	-	American Public Works Associations
BGMP	-	Biomass gasifier monitoring program
BTG	-	Biomass Technology Group
C_2H_4	-	Ethylene
cal	-	Calories
CDC	-	Communicable Disease Center
CH_4	-	Methane
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
CYTMSW	-	Composting Yard Trimmings and Municipal Solid Waste
DEQ	-	Department of Environmental Quality
EIA	-	Energy Information Administration
EPA	-	Environmental Protection Agency
EPA-TRS	-	EPA- Terminology Reference System
FPB	-	Food Processing Byproducts
H_2	-	Hydrogen
IWSA	-	Integrated waste services association

LHV	-	Lower Heating Value
MB	-	Mass Burn
Mcf	-	Thousand Cubic feet (of gas)
MC_w	-	Moisture Content – wet basis
MSW	-	Municipal Solid Waste
N	-	Nitrogen
NO_x	-	Nitrogen Oxides
O_2	-	Oxygen
P_g	-	Percentage gasified
PTE	-	Polyethylene Terephthalate
RDF	-	Refuse Derived Fuel
SO_x	-	Sulfur Oxides
TDS	-	Techline data services
USDA	-	United States Department of Agriculture
USPHS	-	United States Public Health Service
VTT	-	Technical Research Centre of Finland, Espoo, Finland
WTE	-	Waste To Energy
$\%wt_{db}$	-	Percentage weight – dry basis
η_{cg}	-	Cold Gas Efficiency

CHAPTER I

INTRODUCTION

Waste disposal has become a major concern for both developed and developing countries. The state of economy has a strong impact on consumption and waste generation. Municipal Solid Waste (MSW) consists of everyday items such as product packaging, grass clippings, furniture, clothing bottles, food scraps, newspapers, appliances and batteries (EPA, 2003). This waste comes from both residential and industrial sources. More than one quarter of America's food or about 44 million kgs of food a year, goes to waste in commercial kitchens, manufacturing plants, markets, schools and restaurants. The annual estimated cost to dispose of this waste is about $1 billion (Browner and Glickman, 1998).

Tons of waste in the form of meat trimmings, inedible meat, meat breading, sludge and other products is generated unceasingly by food processing companies (Rao et al., 2004). The disposal of this waste poses a major issue to companies in the food industry. According to Greene (2001), even after a 25% source reduction, the total amount of food waste is 11.8 million kgs. Food Processing Byproducts (FPBs) fall under the category of MSW and must be disposed of as solid waste. Only solid waste is accepted by landfills (DEQ, 2004). Other wastes, such as sludge and inedible meat, must be disposed using other means such as drying or land application.

Oklahoma State University has an ongoing research to produce "Grassohol", or ethanol, derived from prairie grasses. The gasification research on this project influenced the conception of this work. This project was developed, with the idea of using the gasification experience gained in the grassohol project, to implement gasification technologies for different byproducts from the food industry.

Gasification technologies offer an alternative process for the conversion of low-value materials to a more valuable product - producer gas (Orr and Maxwell, 2000). Producer gas is a combustible mixture of gas, usually consisting of carbon monoxide, hydrogen, carbon dioxide, methane and traces of other gases. The producer gas has high heating value and thus can be used for energy generation applications (GTC, 2004). This producer gas can be used for co-firing applications in existing boilers or to directly fire a boiler. The value-added process of gasification is the conversion of carbonaceous food byproducts by the application of heat to generate a producer gas that is combustible. Gasification has many potential benefits when compared to conventional options such as incineration or disposal by combustion (Orr and Maxwell, 2000). Gasification for different biomass materials like wood; coal; straw from grains; husks from rice, coconuts or coffee; and bagasse from sugar cane has been tested in the past (Quaak et al., 1999). Commercial gasifier systems like updraft gasifiers, downdraft gasifiers, cross current gasifiers and fluidized bed gasifiers have been used for various biomasses and have been proven for their performance

(Abraham, 1985; Li, 2002; Meister, 2002; Orr and Maxwell, 2000; Quaak et al., 1999; Turare, 2004).

A laboratory scale updraft gasifier was built and used to check the feasibility of gasifying some of the byproducts generated by a major food processor in Oklahoma. Initial tests conducted successfully demonstrated the capability of producing a producer gas. This thesis discusses a more thorough study conducted on FPBs. Different FPBs generated by the food processor were identified and mixtures were gasified to test the feasibility of gasification. Samples of FPBs generated by this company were collected, preprocessed and gasified to generate producer gas.

A survey was conducted to evaluate the generation statistics and the disposal costs involved in disposing these wastes. The data collected in this survey was used to project potential savings in waste disposal costs.

The foci of this thesis were to identify and quantify the waste streams generated by a food processor and gasify the byproducts and its combinations, thus testing the feasibility of gasification and evaluating potential savings.

Objectives

The specific objectives of this research were:

1. Identify and define the FPBs generated by a meat food processing plant in Oklahoma.
2. Evaluate characteristics such as moisture content and energy content of FPBs identified.

3. Conduct a survey to quantify the FPBs identified in objective 1 and evaluate the cost of their disposal.
4. Gasify the FPBs and combinations to evaluate the heating value of the producer gas and calculate cold gas efficiencies.
5. Evaluate cost savings potential for replacing natural gas with producer gas at the value-added meat processing plant in Oklahoma.

This study will form a basis for further research and implementation of waste disposal by gasification.

CHAPTER II

REVIEW OF LITERATURE

A report on the brief history of solid waste management in the U.S. during the last 50 years stated that the environmental movement began in the 1800s when the United States Public Health Service (USPHS) was charged with eradicating from the U.S. a number of communicable diseases (Hickman, 1999). The report also identifies the most notable pioneering organizations during the formative years of solid waste management (beginning in the late 1930s through 1970); the American Public Works Associations (APWA) and the USPHS's Division of Sanitation and Communicable Disease Center (CDC). Refuse Collection Practice (APWA, 1941), a manual published by the APWA represented the first serious effort in the U.S. to consider both the basic collection requirements and the economic considerations in establishing a foundation of best practices in the refuse field. Disposal options in the 1950s included incineration, composting, recycling and salvaging, and the sanitary landfill. Economics, flexibility, and broad geographical applicability made the sanitary disposal of refuse on land, the disposal option of choice (Hickman, 1999). A report published in 1974 discusses America in transition between two fundamentally different approaches to materials' use – the era of consumption and pollution and the future era of conservation and environmental control (Darnay, 1974). According to Environmental Business International Inc., a market research firm based in San Diego, CA, annual environmental industry revenues in the U.S. had reached nearly $140 billion at the end of 1994 (TDS, 1995).

National data on solid waste management in the United States is produced by two agencies. One is BioCycle's "State of Garbage in America" survey while the other is an annual survey conducted by Franklin Associates for the U.S. Environmental Protection Agency, "Municipal Solid Waste in The U.S.: Facts and Figures" (BioCycle, 2004). According to these agencies, generation of solid waste has increased from 269 million tons in 1989 to about 483 million tons in 2002; an increase of about 55% in 13 years.

Some of the traditional disposal options are landfills, incineration and microbial decomposition (Abraham, 1985). These methods may prove to be expensive, cumbersome and sometimes unavailable. Stringent waste disposal regulations from the local and federal governments have spurred the research for alternative methods. Agencies like Department of Environmental Quality (DEQ), EPA, Illinois Waste Management and Research Center (IWMRC), Urban Waste Management and Research Center (UWMRC), and waste management programs at various universities in the U.S. are some examples that are examining disposal alternatives. Other waste disposal options are converting to animal feed; recycling for the production of pet foods, soil amendments or fuel for energy production (Lohr, 1991).

General waste disposal techniques

Figure II-1 shows management of municipal solid waste in the U.S.

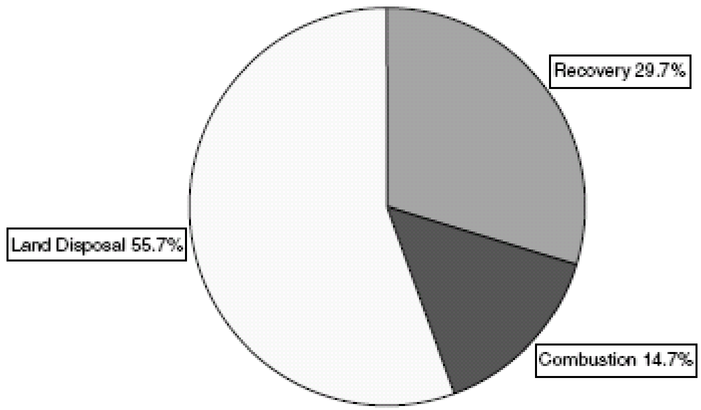


Figure II-1 Management of MSW in U.S. – 2001, Source: EPA, 2003

It is very evident from the figure that a large proportion of the waste in the U.S. is disposed by land filling. The following highlights the most common waste disposal techniques.

Landfills

The idea of landfills was conceived early in the 20th century. Literature dating back to 1929 includes an article on garbage disposal by "sanitary fill" (Engineering News Record, 1929). An example of a landfill studied in 1949 was described as follows: "Refuse was dropped and spread out over a large area to allow scavengers easy access. At the end of the day pigs were allowed on the spread-out refuse for overnight feeding. The next day the pigs were herded off and the refuse was pushed to the edge of the fill for burning" (SERP, 1952). A report by the APWA (1961) states that by the end of 1945, almost 100 cities in U.S. were using sanitary landfills, and by the end of 1960, some 1400 cities were using sanitary landfills. Ever increasing environmental concerns called for standard operating procedures (USPHS, 1961). Technology improved and the USEPA published criteria for solid waste management facilities (USEPA 1991).

EPA defines landfills as a facility in which solid waste from municipal and/or industrial sources is disposed (EPA-TRS, 2004). Generally, a landfill is described as a cavity dug up in the ground where waste is disposed and compacted. Since the contents of the waste may be toxic or hazardous, the aim is to avoid any hydraulic [water-related] connection between the wastes and the surrounding environment, particularly groundwater (Zerowasteamerica, 2004). To avoid contamination and pollution, liners are placed at the bottom and sides of the landfills.

For new landfills to be built by local governments, an environmental impact study must be done on the proposed site to determine area required for the site, composition of underlying soil, flow of surface water over site, impact of landfill on environment and wildlife (Freudenrich, 2004). Issues concerning pollution caused by landfills have contributed to the reduction in new landfill sites. Figure II-2 shows that the number of landfills has reduced from 7,924 in the year 1988 to 1,858 in 2001.

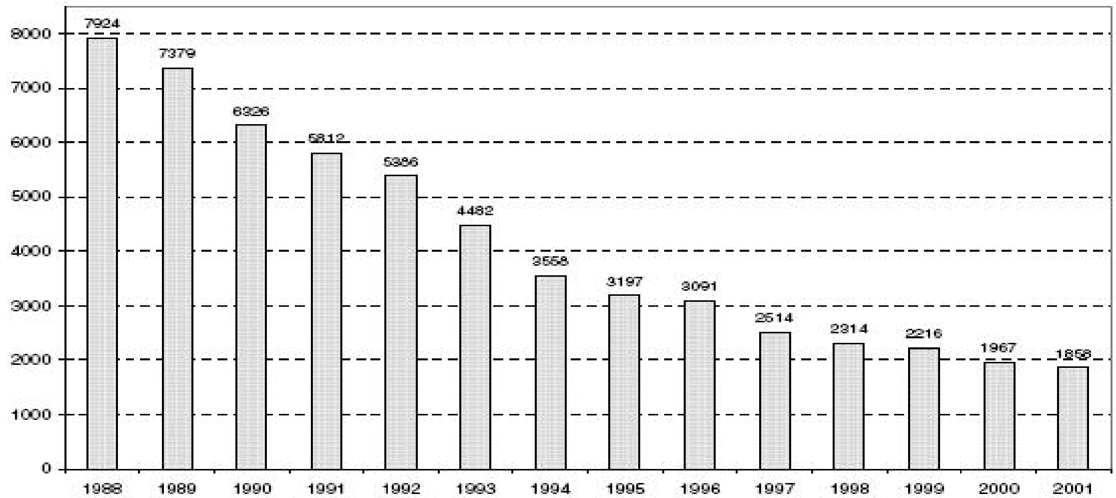


Figure II - 2 Landfills in the U.S., Source: EPA, 2003

Customers, both industrial and residential, have to remit waste disposal costs or tipping fees, freight charges and rentals. With the number of landfills reducing each year, the cost of waste disposal continues to increase. This is one of the several reasons for industries to evaluate alternate waste disposal options.

Composting

The American Public Works Association (APWA) reports that the first significant development in composting as an engineering process took place in India in 1925 (APWA, 1961). Also known as Indore Process, it was a simple process consisting of alternating layers of garbage, animal manure, night soil, sewage sludge, and straw, either buried or done in piles. The Netherlands built the first full-scale composting plant in Europe in 1932 using the van Mannen process, a variation of the Indore process (Hickman, 1999).

Compost is a decomposed organic material that is produced when bacteria in soil break down garbage and biodegradable trash, making organic fertilizer (EPA, 2004). Composting can occur under aerobic (requires free oxygen) and anaerobic (without free oxygen) conditions. Aerobic composting is 10 to 20 times faster than anaerobic composting (EPA, 1994). Usually, the compost can be used as a fertilizer. The EPA has cited different uses of compost such as bioremediation and pollution prevention, disease control for plants and animals, erosion control and landscaping, reforestation, wetlands restoration and habitat revitalization (Composting, 2004).

Waste Combustion

Apparently, the U.S. Army built the first solid waste incinerator in the U.S. on Governor's Island in New York Harbor in 1885. In the same year, the City of Allegheny, PA, built the first local government-owned incinerator (Hickman, 1999). The use of incineration in the U.S. grew during the early decades of the 20^{th} century until, by the end of the 1930s; there were more than 700 units. MSW incineration technologies in the U.S. (beginning in 1965) concentrated on the use of solid waste as an energy source (Hickman, 1999). Due to environmental concerns like hazardous air emissions and toxic ash, the number of incinerators in operation has fallen considerably (IWSA, 2004).

The combustion process can take place both under controlled and uncontrolled burning. Consequently, depending on the process, energy may be recovered or wasted into the atmosphere. Incineration is a treatment technology involving destruction of waste by controlled burning at high temperatures (EPA-TRS, 2004). Incineration of waste reduces the bulk of solid waste by burning of plastic, paper and other components. Burning MSW can generate energy while reducing the amount of waste by up to 90 percent in volume and 75 percent in weight (EPA-MSW, 2004). Waste combustion facilities, also known as, Waste-To-Energy (WTE) facilities are categorized into two process types (EIA, 1996; Hickman 1999): Mass Burn**-** The combustion of solid waste as a fuel in its as-discarded form; RDF (Refuse Derived Fuel) - The processing of solid waste into coarse or finer particles with or without separation of noncombustible materials present in the solid waste.

The Integrated Waste Services Association (IWSA) conducts a survey every year and provides updated information about the U.S. Waste-To-Energy industry. The latest survey conducted in April 2004 shows that there are 89 incineration facilities in the U.S. and these facilities manage about 13% of the total waste and generate about 2,689 megawatts (IWSA, 2004). The number of incinerators in the U.S. was 97 in the year 2001. One major reason for this decline is the large amount of toxins produced in the combustion smoke. According to the World Health Organization, municipal waste incinerators are the greatest source of dioxin in the world today and dioxins are known human carcinogens. A variety of pollution control technologies have to be implemented to abide by the EPA regulations.

Gasification

Gasification can be defined as a process technology designed and operated for the purpose of producing synthesis or fuel gas through the thermo-chemical conversion of biomass. Gasification usually involves the partial oxidation of the feedstock in a reducing atmosphere in the presence of air and/or steam (Li, 2002). Gasification when compared to WTE facilities has an advantage of lower emission levels and higher energy content in the producer gas. In the case of gasification, the chemical reactions take place in an oxygen-lean reducing atmosphere, in contrast to combustion where reactions take place in an oxygen-rich, excess-air environment (Orr and Maxwell, 2000). The excess air oxidizes the sulphur and nitrogen in the feedstock to SO_x and NO_x, which are not prevalent in the case of gasification and is a major disadvantage to incineration.

Several different biomass fuels have been used in the past for energy generation purposes. Biomass energy sources include wood, wood wastes (e.g. sawdust and bark), short rotation energy woods and crops (e.g. willow and switchgrass), agricultural crops and their residues (e.g., sugar cane bagasse, husks from rice, and stalks from maize), some municipal solid wastes, animal manure, wastes from food processing, waste sludge from pulp and paper industry (black liquor), and aquatic plants and algae (Li, 2002). The most important properties relating to the thermal conversion of biomass are: moisture content, ash content, volatile matter content, heating value and bulk density (Quaak et al., 1999).

Table II-1 shows the characteristics of different biomass fuel types used (BTG, 1999).

Type	***LHVw (KJ/kg)***	***MCw (%)***	***ACd (%)***
Bagasse	7,700-8,000	40-60	1.7-3.8
Cocoa husks	13,000-16,000	7-9	7-14
Coconut Shells	18,000	8	4
Coffee husks	16,000	10	0.6
Cotton Stalks	16,000	10-20	0.1
Cotton Gin Trash	14,000	9	12
Maize Cobs	13,000-15,000	10-20	2
Maize Stalks			3-7
Palm-oil residues			
Fruit stems	5,000	63	5
Fibers	11,000	40	
Shells	15,000	15	
Debris	15,000	15	
Peat	9,000-15,000	13-15	1-20
Rice husks	14,000	9	19
Straw	12,000	10	4.4
Wood	8,400-17,000	10-60	0.25-1.7
Charcoal	25,000-32,000	1-10	0.5-6

Table II - 1 Characteristics of Different Biomass Fuel Types

Note: LHV – Lower heating value; MC_w – Moisture content on a wet basis; AC_d – Ash content on a dry basis.

A waste processing company in Finland identifies the lower heating values as 16-20 MJ/kg for commercial waste, 14-15 MJ/kg for construction waste and 13-16 MJ/kg for household waste (VTT, 2004).

Gasification Technologies

Gasification of biomass has been tested and proven for many years. Various methods of gasification have been proven and are commercially available. The design of a gasification system depends heavily on the specific biomass material; its morphology, moisture content and mix of contaminants (Quaak et al., 1999). Depending on the hydrodynamic properties of the reactors, gasifiers can be fixed or moving beds, bubbling or circulating fluidized beds, spouted beds or rotary kilns, or some combination of these types (Li, 2002). Most common types of gasifiers in the industry are highlighted in the following.

1. Updraft gasifiers

Updraft gasifiers are one of the oldest and simplest gasification technologies. In updraft gasifiers, gas is drawn out of the gasifier from the top of the fuel bed while the gasification reactions take place near the bottom. The fuel is fed from the top, successively passing through a drying zone, pyrolysis zone, reduction zone and hearth zone, and the ash is removed from the bottom of the gasifier, from where the sub-stoichiometric air is supplied (Li, 2002). The major advantages of this type of gasifier are its simplicity, high charcoal burnout, ability to handle a variety of feedstocks, and internal heat exchange that leads to low gas-exit temperatures and high conversion efficiencies (Quaak et al., 1999).

2. Downdraft gasifiers

In a downdraft reactor, biomass is fed at the top and the air intake is at the top or the sides. The gas leaves at the bottom of the reactor and moves in the same direction (Quaak et al., 1999). Although, this design claims to enable tar-free gas production, it suffers from weak fuel flexibility and flow problems (Li, 2002). One of the major disadvantages of updraft gasifiers is the high percentage of tar in the producer gas. This problem is minimized in a downdraft gasifier (Turare, 2004).

3. Fluidized bed gasifiers

Due to inherent advantages of low process temperatures, isothermal operating conditions and fuel flexibility, fluidized bed technology has been found to be one suitable approach to converting a wide range of biomass fuels into energy (Meister, 2002). Fuel is fed into a suspended (bubbling) or circulating fluidized, hot sand bed. Fuel particles mix quickly with the bed material, resulting in rapid pyrolysis and a relatively large amount of pyrolysis gases (Quaak et al., 1999). High carbon conversion efficiency cannot be achieved because of the non-uniformity of particle residence time in the bed and solids entrainment (Li, 2002). A report by Biomass Technology Group lists typical characteristics of fixed-bed and fluid-bed gasifiers as shown in Table II-2 (BTG, 1999).

Characteristics	***Fixed-bed downdraft***	***Fluidized-bed***
Fuel: size (mm)	10-100	0-20
Ash content (%wt of feed)	<6	<25
Operating temperature(°C)	800-1400	750-950
Control	Simple	Average
Capacity (MW_{th})	<2.5	1-50
Startup time	Minutes	Hours
Tar content (g/Nm^3)	<3	<5
LHV (MJ/Nm^3)	4.5	5.1
Construction Material	Mild + refractory	Heat-resistant steel

Table II- 2 Typical Characteristics of Fixed bed and Fluidized bed gasifiers.

Increasing demand of alternate fuels has renewed the interest in biomass gasification. This has resulted in many new technologies being developed, both for gas production and gas cleaning.

The table II-3 shows the typical gas composition for different reactor types as discussed in a report for the World Bank, Biomass Gasifier Monitoring Program (BGMP) (Stassen, 1995).

Gas Composition	Updraft	Downdraft
Hydrogen (%)	8-14	12-20
Carbon Monoxide (%)	20-30	15-22
Methane (%)	2-3	1-3
Carbon dioxide (%)	5-10	8-15
Nitrogen (%)	45-55	45-55
Oxygen (%)	1-3	1-3
Moisture in gas (Nm^3 H_2O/Nm^3 dry gas)	0.20-0.30	0.06-0.12
Tar in gas (g/Nm^3 dry gas)	2-10	0.1-3
Lower heating value (MJ/Nm^3)	5.3-6.0	4.5-5.5

Table II-3 Typical Gas composition for different reactor types
(Moisture in feed = 10-20% wet basis)

The World bank report also discusses the various new technologies being developed all over the world in the field of biomass gasification.

Food Processing Waste Situation

Waste generated by food processors or prepared meat facilities falls under the category of industrial waste. A study conducted in 1998 states that 27% of all food that is produced (grown, raised, harvested and marketed) is thrown away which is about 44 million tons of food wasted in the U.S. every year (USDA-EPA, 1998). Food processing companies generate a large amount of waste in the form of meat trimmings, inedible meat, meat breading, sludge and other products (Rao et al., 2004).

For the state of Oklahoma, waste from industrial sources is categorized under MSW (DEQ, 2004). The 14th annual survey by BioCycle reports that for the state of Oklahoma, only 1% of the total MSW was recycled whereas 99% was landfilled. The decrease in the number of landfills and increase in transportation costs have contributed in the tremendous rise in waste disposal expenditure. America spends around one billion dollars each year to dispose of this waste

(Greene, 2001). The most common method of waste disposal adopted by food processors is landfills.

Summary

Waste disposal in the food processing industries is a major concern that includes both environmental and capital issues. A review of literature showed that most of the waste is disposed into landfills and only a very small percentage of this waste is recovered. The present methods of waste disposal may be expensive, cumbersome and sometimes unavailable. Gasification of FPBs may provide an alternative to this situation. Various methods of gasification have been studied and their implications understood. The product of gasification is a producer gas that may provide energy in the form of steam when co-fired with existing steam generation units.

CHAPTER III

CATEGORIZATION AND INDENTIFICATION OF WASTES

A survey was conducted at three facilities of a major food processor in Oklahoma to support the study of waste gasification. The first part of the case study was to categorize and identify the types of waste generated at these three facilities.

Multiple visits were made to the facilities and the processes were studied. After studying the different processes at the three facilities as a whole, they were broken down into different blocks or potential locations where waste was generated. This was done by consulting the plant operators and process personnel. Fig III-1 shows a hot dog making process broken down into steps and the wastes generated.

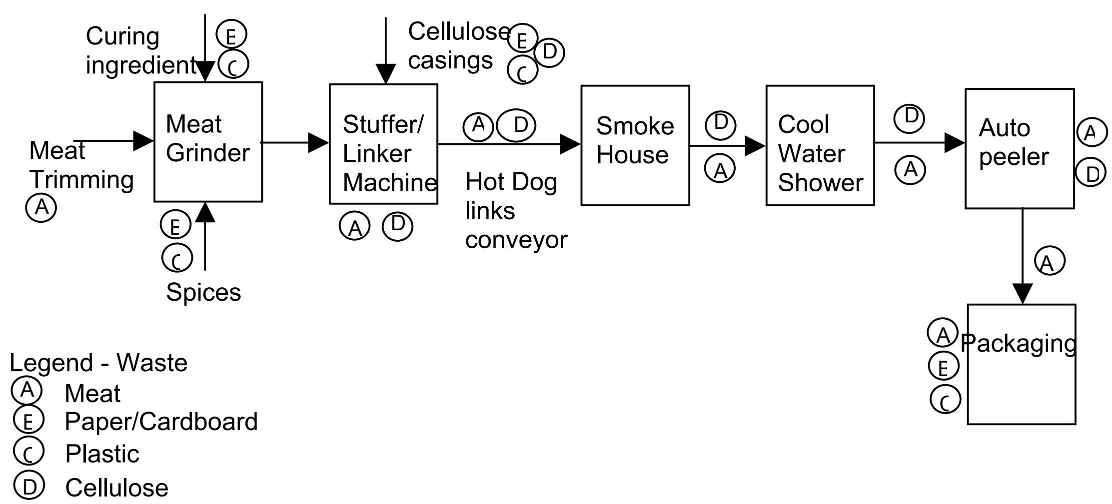
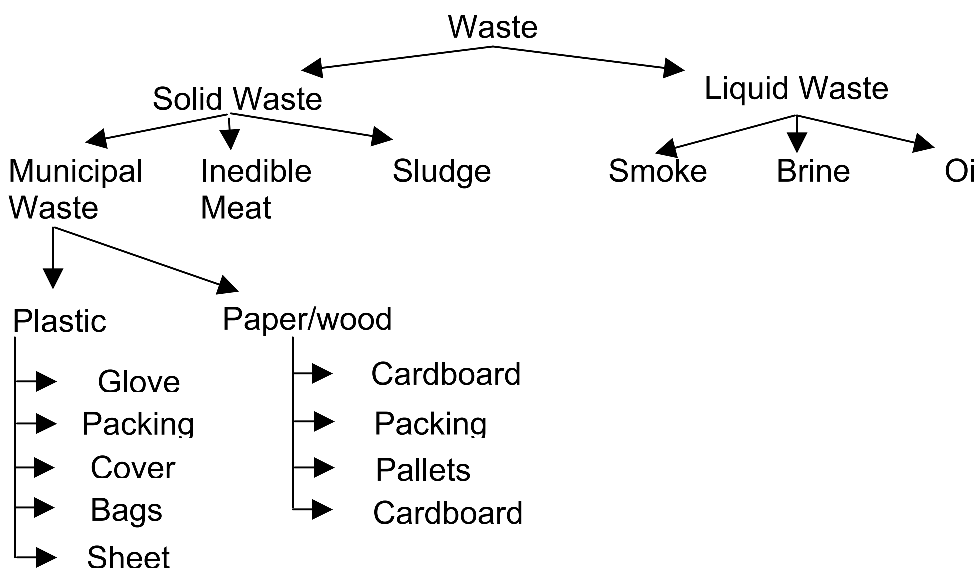


Figure III - 1 Hot dog making process block diagram identifying the different wastes generated.

The waste streams were monitored on an hourly basis to determine waste generation. Sources for the wastes were identified and an approximate composition for the mixed waste was evaluated. Waste hauling stations were also monitoring to categorize the different types of wastes according to disposal methods.

Types of waste

Figure III-2 shows the different categories and types of waste.



Out of the different types of waste shown in figure III-2, the solid wastes were considered for this project. The byproducts tested were: Inedible meat, sludge, meat breading, cardboard, and wood and combinations of these.

The following paragraphs give a brief description of the different wastes identified in the study.

Inedible meat

Any meat or meat product not suitable for consumption is known as inedible meat. Figure III-3 shows a sample of dried meat used for gasification. The average sizes of the pieces were about 1 cm X 1cm.

Figure III - 3 Dried inedible meat

This category includes the meat products that have touched the process floor or left the process line. Meat that fails any quality inspection is also included in this category.

Sludge

Figure III-4 shows a sludge sample from the air flotation units at the food processing plant. Sludge has a high moisture content and fat content.

Figure III - 4 Dewatered sludge

Each facility had its own water treatment plant specifically designed for treating waste that enters the process floor drains. These treatment plants are different from the sewage treatment plant for treating “sanitary” sewage. After preprocessing through the settling clarifiers, air flotation units and the centrifuge, the sludge is collected in a semi-liquid form to be hauled off for disposal.

Meat Breading

The coating applied to food products like meat, poultry, sea food or vegetables before cooking is known as breading. Figure III-5 shows a sample of breading obtained from the process floor at one of the facilities.

Figure III - 5 Meat breading

The breading is powdery in nature and is typically a mixture of bread batter and bread crumbs. The process of breading the meat involves the continuous pouring of breading over a conveyor carrying the meat pieces being coated. The excess coating falls off at the end of the conveyor and is collected in waste bins. The mixture collected may contain small pieces of meat that fall from the production line.

Hot dog casings

The process of making hot dogs involves stuffing the meat mixture into casings such as collagen, cellulose or plastic. Figure III-6 shows a stack of cellulose casings obtained from one of the facilities surveyed.

Figure III - 6 Hot dog cellulose casings

The meat mixture is stuffed into cellulose casings to make hot dog links. The hot dog links are then seasoned and cooked in different chambers. Once the cooking process is complete, the casing is stripped off the hot dogs and the hot dogs are sent for packaging. The used casings are collected as waste for disposal. The amount of cellulose casings generated as waste is directly proportional to the production and hence is a major waste disposal concern.

Cardboard

About 30% of the MSW generated by food processors consist of cardboard. Different types of cardboard wastes identified were: boxes, sheets, combos and cores. Figure III-7 shows 1cm X 1cm pieces of cardboard cut from boxes.

Figure III - 7 Cardboard pieces (1cm X 1cm)

Cardboard waste is generated at several locations in the production line. One of the major sources of cardboard is boxes from inventory when packed meat and meat products are unpacked. The other sources result from incorrect operation of the cardboard die cutting, labeling machine and defective cardboard boxes in production line. All the facilities surveyed have a recycle program where the cardboard containers are stored, baled and sent to recycling once there is sufficient quantity to fill a semi truck. Due to restrictions from the recycler, blood stained and wax coated cardboards are not included in the recycle program. This type of cardboard is collected daily and sent for disposal as MSW.

Plastics

Different forms of waste fall under this category, including plastic films, gloves, films, sheets, covers and bags. Figure III-8 shows an example of different kinds of plastics used in the food processing industry.

Figure III - 8 Plastic wastes in food processing industry (Source: U.S. Plastic Corp.)

Like cardboard, the sources can be from inventory resulting from unpacking. Other sources can be faulty packaging assembly and label films. Plastics amount to about 70% of the total MSW mass generated by the food processing company. Some of the plastics like sheets and covers are recycled, but this accounts for a very small percentage.

Characteristics of waste

Physical properties are an important consideration for gasification of food processing byproducts. As discussed in the Review of Literature, some of the important properties to be considered for gasification are: moisture content, ash content, volatile matter, heating value and particle size. These properties also contribute towards the design of the gasifier. Food processing byproducts may require preprocessing based on their actual properties. Of the above mentioned properties, moisture content and heating value are the most critical for gasification considerations.

Table III-1 lists the different properties of several food processing byproducts collected from a value-added meat processor in Oklahoma.

Biomass	Moisture Content (%wt_{db})	Ash Content (%wt_{db})	Volatile Matter (%wt_{db})	Heating Value (MJ/kg)
Inedible Meat	73	5.5	93.2	23.02
Sludge	72	4.2	94.4	23.03
Meat Breading	5.64	22.8	51	16.00
Mixed Cardboard	10.2*	5.4*	75.9*	16.38**
Mixed Plastic	0.2*	2.0*	95.8*	22.57

Table III - 1 Food Processing Byproduct properties

Source: * - Tchobanoglous et al., 1993.
** - EPA MSW Disposal, 2004.

Experiments were conducted to evaluate characteristics of inedible meat, sludge and meat breading. The ASTM standards 1755-01, D 3174-97, D 3175-89a were used for measurement of moisture content, ash content and volatile matter respectively (ASTM standards, 1989; 1997; 2001). Table III-1 shows mean values obtained from experiments conducted on 3 samples of each biomass type, i.e. inedible meat, sludge and meat breading. The variance in the values were less than +/-5%. The heating values were obtained from bomb calorimeter tests (Parr Instrument Company, Model – Parr 1261E Isoperibol Bomb Calorimeter, Moline, Illinois).

Some of the byproducts required size reduction for ease of handling. For the purpose of this study, inedible meat and cardboard were reduced to 1cm X 1cm pieces. Byproducts, such as meat breading, did not need size reduction since they were in a powder form.

Pre-processing Byproducts

The first phase of gasification or combustion involves evaporation of contained water (Quaak et al., 1999). A certain amount of energy is consumed to remove the water by evaporation. More energy will be required if the moisture content is high, thus reducing the overall efficiency of the gasification process. Food processing byproducts like meat and sludge have high moisture content in the range of 65-75% by weight. High moisture content byproducts, when blended with low moisture content byproducts, may provide better material handling characteristics. Other preprocessing options include drying and size reduction. The byproducts were dried using tray driers. Simple methods like straining were used to reduce moisture content from sludge. The following table III-2 shows properties of some biomass material after drying.

Material	**Actual M.C. (%wt_{db})**	**M.C. after drying (%wt_{db})**
Dried Sludge *	72.57	6.23
Inedible meat	73.06	6.18
Dewatered sludge*	76.98	31.47

Table III-2 Food Processing Byproduct properties after drying

* - The primary difference between dried sludge and dewatered sludge is the process of drying adopted. Dried sludge is produced by completely removing the moisture from the sludge using tray dryers at high temperature; whereas, dewatered sludge is produced by removal of excess water by straining and drying it at atmospheric temperature.

The heating value of cardboard lies in the range of 15-20 MJ/kg and the heating value of wood lies in the range of 18-20 MJ/kg. Cardboard has a very low bulk density compared to wood pellets. The gasifier design used for this project had a low volumetric capacity. Due to this limitation, wood pellets were used as a base material or carrier to evaluate byproduct conversions. Wood pellets were also considered as a substitute for ground wooden pallets. Blending the byproducts with wood pellets also provided ease of handling. Table III-3 shows heating values of different food byproducts when mixed with wood pellets. The proportions were randomly selected to show effects of blending. The moisture content was analyzed using the same method described earlier and the heating values were calculated using a bomb calorimeter.

Mixture	**MJ/kg**	**Effective Moisture Content (%wt_{db})**
Wood + dewatered sludge (50/50)	16.0	19
Wood(35) +meat(35) +dewatered sludge(15) + breading(15)	21.1	12

Table III-3 Food byproduct properties after blending with wood pellets

CHAPTER IV

WASTE GENERATION AND DISPOSAL

Data was collected from three different facilities of a major food processor in Oklahoma. The data included the amount of waste generated in different forms and expenses for handling and waste disposal. The scope of the survey included all waste byproducts generated in the manufacturing process.

Approach for waste economic survey

The following approach was adopted for the waste economic survey:

- Multiple visits were made to the three facilities to identify different waste streams.
- The procedure for waste categorization, described in Chapter III, was adopted. Compositions of the MSW were determined and the proportions of different components evaluated.
- Specific data for amount of waste generated and waste disposal expense was required for this study. Data was available from plant comptrollers and process personnel in the form of invoices received from the waste management agencies. In some case, waste generation and disposal cost data was obtained directly from the waste management agencies.
- Specific details of data included fat yield rate/ton, hauling charges, weekend pickup charges, monthly rental, processing fees and tipping fees.

As discussed in Chapter III, different wastes were identified and categorized according to the waste disposal methods used. Depending on the disposal methods, three predominant categories of solid waste were identified. The predominant wastes were identified as MSW, inedible meat and sludge.

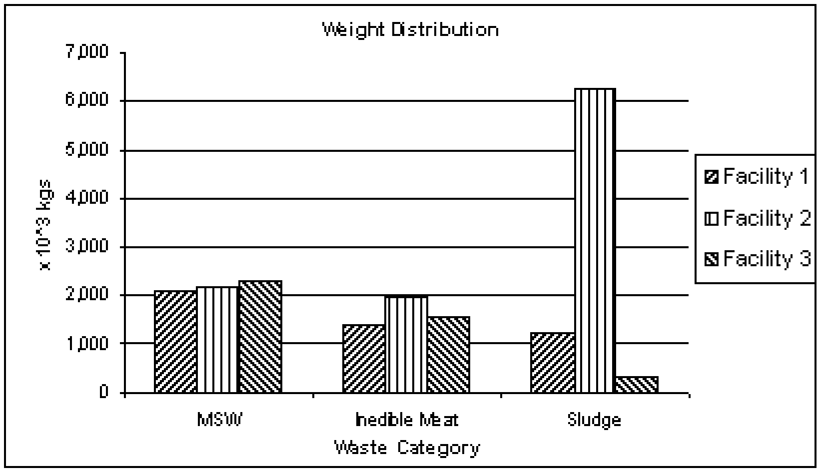
Waste Generation Statistics

The data presented in this section includes generation in kgs for three major waste streams – MSW, Inedible meat, Sludge. The following tables show a summary of the waste generation of the three facilities. See appendix A for detailed data.

Biomass	Facility 1 X 10^3 kgs/yr	Facility 2 X 10^3 kgs/yr	Facility 3 X 10^3 kgs/yr	Total X 10^3 kgs/yr
MSW	2,112	2,169	2,304	6,585
Sludge	1,222	6,260	296	7,778
Inedible Meat	1,402	1,958	1,543	4,903
Total	4,736	10,387	4,143	19,266

Table IV- 1 Waste Generation by weight for three facilities

The following figure IV-1 shows the distribution (by weight) of MSW, inedible meat and sludge for the three facilities.



FigureIV-1 Waste distribution for three facilities by weight

As discussed in the previous chapter, municipal solid waste is composed of several different wastes. A part of the survey was to visually inspect and estimate the percentage of the predominant wastes generated in the facilities. Compositions of MSW and the proportions of their components were determined by monitoring the processes and the waste hauling stations. See Chapter III for complete approach adopted to categorize and identify different wastes.

Composition of municipal solid waste at Facility 1 was estimated as:

- 70% plastics –gloves, packaging film, slipsheets, pallet wrap, and bags
- 15% casings
- 15% paper –cardboard, paper, wood pallet pieces

Composition of municipal solid waste at Facilities 2 & 3 was estimated as:

- 70% plastics –gloves, packaging film, slipsheets, pallet wrap, and bags
- 30% cellulose –cardboard, cardboard tubes, paper, wood pallet pieces

Waste Disposal methods and Economics

Disposal of waste generated by food processors is usually contracted to different waste disposal agencies, depending on the type of waste. The MSW in all three facilities was disposed by the local municipality or private waste management agencies (or a combination of both). For the other two byproducts, inedible meat and sludge, a disposal contract was given to private waste management agencies. The charges by these agencies are in the form of operating costs or disposal fees ($/kg), freight charges ($/km) and hauling charges ($/haul). In case of inedible meat, the waste management company charges operating cost and freight charges. The waste management company assumes a 40% fat yield (kg) from the total weight and multiplies this value by the present fat selling rate ($/kg). This amount is credited back to the company every month. While the 40% rate is constant, the price/kg for fat varies every week. The price/kg of fat was in the range of $0.25-$0.35. This sometimes resulted in a huge credit for disposing inedible meat. See Appendix B for waste disposal calculations.

Table IV-2 shows the waste disposal costs for the three facilities:

Facility	Operating cost, $			Freight, $			Total
	Sludge	Inedible Meat	MSW	Sludge	Inedible meat	MSW	
1	97,784	-48,974	57,600	38,740	44,390	60,720	250,261
2	249,190	-108,353	67,261	n/a*	62,426	16,028	286,552
3	23,670	-54,596	66,240	9,374	56,384	36,000	137,073
Totals	370,645	-211,922	191,101	48,115	163,200	112,748	673,886

Table IV - 2 Waste disposal costs for three facilities in 2003.

* - The waste management company for hauling sludge at facility 2 did not categorize its charges into freight costs. All charges were made under a single category of operating costs.

Waste disposal expenses on a monthly basis can be found in the Appendix A. From table IV-2 we can see that the total waste generated in the year 2003 was 19,266,000 kgs and the total expenditure for disposal of this waste was $673,886, of which $324,063 was spent on freight charges, or about 48% of the total.

CHAPTER V

EXPERIMENTAL SETUP

For calculating the efficiency of gasification, three different experimental setups were used. The heating value of the FPBs was evaluated using a bomb calorimeter. The FPBs were then gasified, using an updraft gasifier, and producer gas analysis was done using a gas chromatograph.

Heating value

The heating value is the amount of energy (kJ/kg) stored in the feedstock. To evaluate the feasibility of gasification of food processing byproducts, the heating value of the feedstock was calculated and then compared to the results of gasification. The heating values of food byproducts were measured using a bomb calorimeter (Parr Instrument Company, Model – Parr 1261E Isoperibol Bomb Calorimeter, Moline, Illinois). The PARR 1261 standard operation procedure was used for this purpose.

Gasification

Since the objective of this study was to test the feasibility of gasification of FPB's, an updraft, batch gasifier configuration was selected for its simplicity, low-cost and versatility. The basic components of the gasifier were: reactor, support frame, scraper and scraper drive (Bowser et al., 2004). K type thermocouples and a flow meter were used to measure temperature at various locations in the gasifier and air flow to the gasifier respectively. The entire unit was constructed in the Biosystems and Agricultural Engineering fabrication shop at the Oklahoma State University.

Figure V-1 shows a schematic of the laboratory scale updraft batch gasifier.

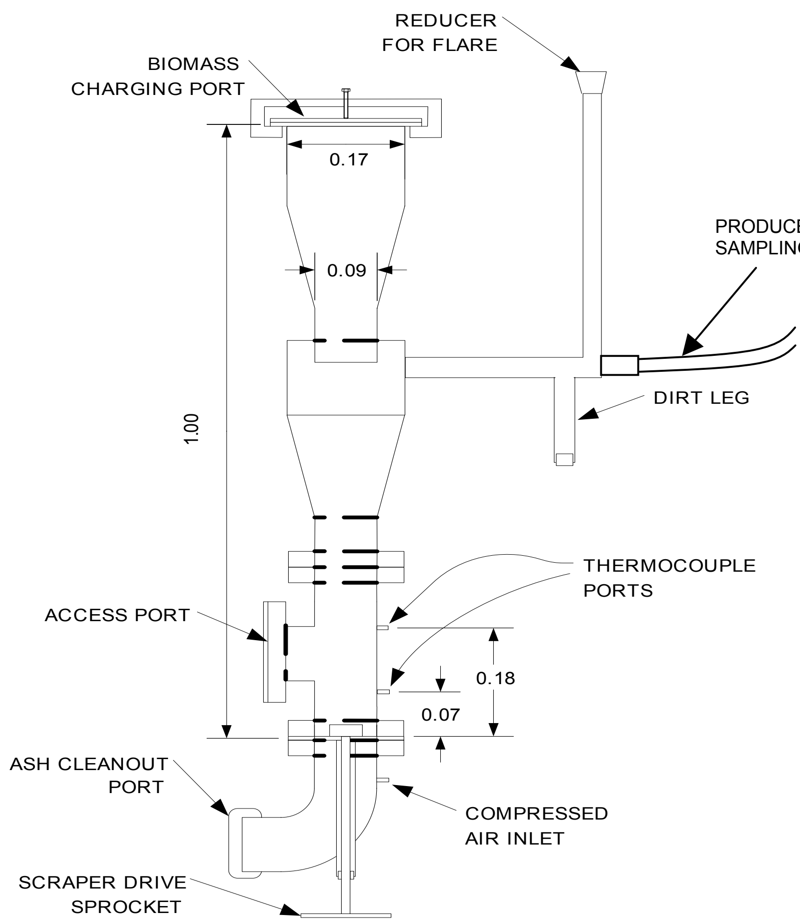


Figure V - 1 Schematic diagram of laboratory scale updraft batch gasifier (Source: Bowser et al., 2004)

The gasifier was fully insulated using Cerawool (Thermal Ceramics, Augusta, GA) to prevent heat losses. Figure V-2 is a photograph of the gasifier during a run with the flare ignited.

Figure V-2 Photograph of the gasifier and the flare

Test Procedure

The following procedure was adopted for the experiments:

1. Six charcoal briquettes (The Kingsford Products Company, Oakland, California) weighing approximately 210 gms and 50mm x 50mm in size were broken down to 25mm x 25mm pieces. These pieces were soaked with about 50 ml of charcoal lighter fluid (The Kingsford Products Company, Oakland, California). The soaked pieces were then placed onto the grate through the lower access port, and ignited with a flame. The biomass charging port remained open.
2. Compressed air (at about 34.5 kPa) was supplied to the gasifier at a rate of 2.5 m^3/hr initially to facilitate burning of the charcoal.

3. The charcoal was allowed to burn for about 20 minutes until the briquettes were completely covered with white ash and glowed cherry-red in the center.

4. The Omega, OM 5100 data logger was initialized to continuously record temperatures during gasifier operation.

5. The access port was completely sealed and one (1.0) kg of preprocessed FPB was manually added to the gasifier from the top opening; then the opening was covered and sealed.

6. For each run, 3 gas samples were taken during the first 15 minutes at the 5^{th}, 10^{th} and 15^{th} minutes. Care was also taken to stabilize the bed temperature at 700-750°C by regulating the air flow. Gas sampling was done through the sampling port shown in figure V-1.

7. The scraper blade was operated for a few seconds every five to ten minutes during the experiment after the FPB was added.

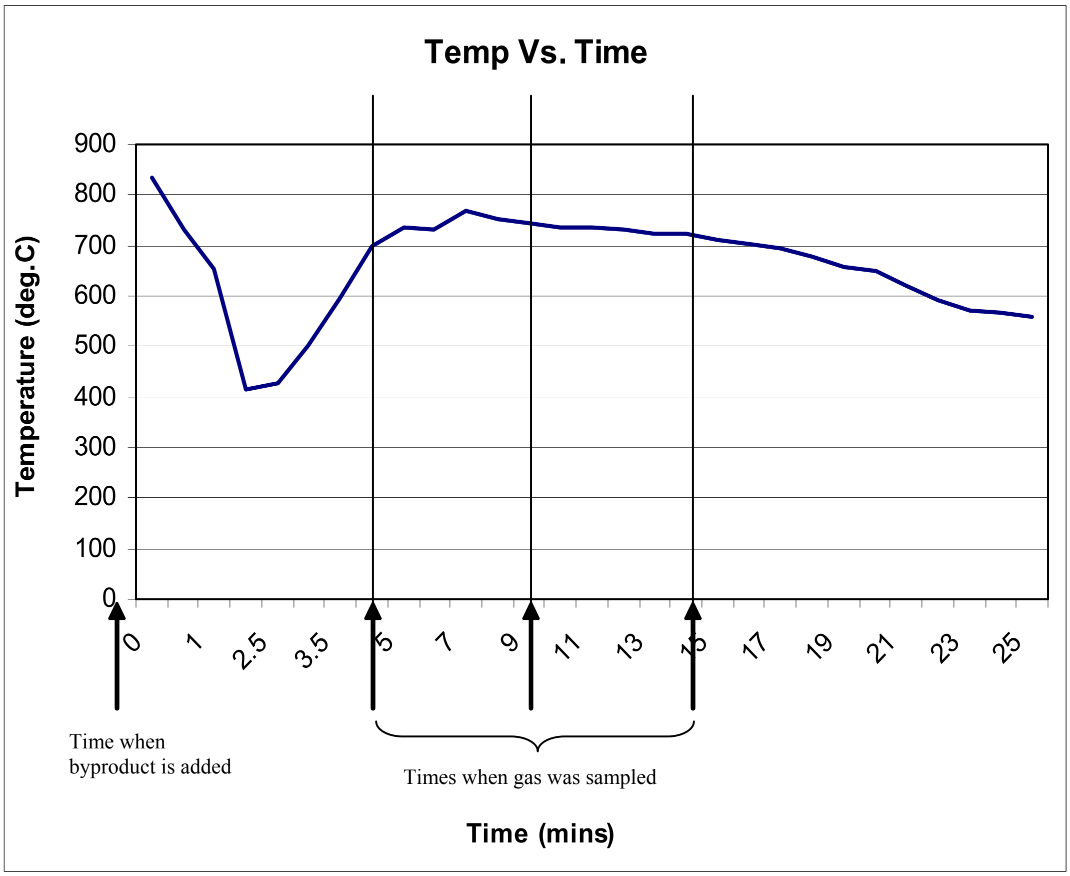
8. The flare was ignited after the gas sampling was completed. A multipurpose butane lighter (Zippo manufacturing company, Bradford, PA) was used to ignite the flare.

9. The gasifier was allowed to cool after all of the FPB was gasified. The ashes were collected from the ash cleanout port and weighed. The ash collected was a mixture of ash from the FPBs and charcoal. Due to inadequate facilities, this mixture of ash was not segregated to estimate individual ash content from FPBs and charcoal. For the purpose of this study, the total weight of ash collected was considered as ash from the

FPBs. Tar was also collected from the dirt leg of the gasifier after each run. The tar collected was weighed and observations were noted.

Gas Chromatography

As explained in the procedure, gas was sampled at different times during the runs. Figure V-3 shows a typical temperature vs. time plot for a gasifier run. It also shows the different times at which the gas was sampled.



The producer gas was collected in a sampling bottle (Article 653100-022, Kimble Kontes, Vineland, NJ). The producer gas was allowed to flush through the sampling bottle before the valves were closed. The bottle was stored in a refrigerator to allow the tars and moisture to condense onto the walls of the bottle. A gas tight syringe (Valco Instruments Co. Inc – VICI, Houston, TX) was used to draw 5 ml, of gas from the bottle through a septum. This 5ml. sample was then injected into a gas chromatograph for analysis. A Varian Chrompak gas chromatograph (Model # CP-3800, Palo Alto, CA) was used for gas analysis.

The heating value of the FPBs, heating value of the producer gas and air flow were then used to calculate gasification efficiencies. The approach used to determine cold gas efficiency is listed below:

- The byproducts and byproduct mixtures were gasified to generate a producer gas.
- The producer gas samples of each mixture were analyzed to determine the composition of the producer gas.
- The heating value of the producer gas was determined from the gas composition.

The cold gas efficiency or the burner efficiency is calculated as follows

$$\eta_{cg} = \frac{\sum \text{Heating value of gas (MJ/m}^3\text{) x Air flow (m}^3\text{/min) x X min x } P_g}{\text{Actual heating value of byproduct (MJ)}} \qquad (5.1)$$

where:

— Heating Value of Gas = Heat of combustion of the producer gas, calculated using Heat of Combustion values, MJ/m^3. (Shnidman, 1948).

— Air Flow = the amount of air supplied for gasification (m^3/min)

— X min = Number of minutes per run for 1kg of biomass (mins).

- Actual heating Value of Biomass = Energy content measured by Bomb Calorimeter (MJ), (Parr Instrument Company, Model – Parr 1261E Isoperibol Bomb Calorimeter, Moline, Illinois).

- Percentage gasified, P_g = [1 – (Ash+Tar)/kg]

Sample cold gas efficiency calculations can be found in Appendix B.

CHAPTER VI

RESULTS AND DISCUSSION

Gasification Analysis

The FPBs gasified were: dried sludge, meat breading, dewatered sludge and inedible meat. It was observed that most of the food byproducts did not perform very well when they were gasified individually. Due to the high fat content in some of the byproducts, they had a tendency to agglomerate, reducing the efficiency of gasification. Due to agglomeration, the air passed through tunnels in the agglomerated mass and did not take part in combustion. As a result of this a high amount of oxygen was detected in the producer gas. This also resulted in lower amounts of CO and H_2, which in turn reduced the efficiency of gasification. Table VI-1 shows results of gas chromatograph analysis of FPBs tested individually.

Material	**H_2**	**N**	**O_2**	**CO**	**CH_4**	**CO_2**	**C_2H_4**
Dewatered sludge	1.4	64.6	6.2	4.1	0.6	11.1	0.6
Meat	1.1	69.7	7.7	3.7	0.4	10.6	0.5
Meat Breading	1.8	66.9	5.3	7.8	0.4	13.7	0.3

Table VI - 1 Gas Chromatograph results for FPBs tested individually.

During each run, producer gas was sampled and an analysis was conducted using a gas chromatograph. Gas sampling was done using the procedure explained in chapter IV. Three tests were run for each byproduct or byproduct mixture. The average results for three samples per run and three runs per byproduct are listed in table VI-2. The numbers presented in table VI-2 are expressed as percentages of 1ml of sample injected into the gas chromatograph for analysis.

Material	% of 1 ml. sample						
	H_2	N	O_2	CO	CH_4	CO_2	C_2H_4
Wood	2.1	50.7	1.9	11.9	0.7	7.2	5.3
Dry Sludge	3.4	59.3	0.8	13.3	1.0	11.8	--*
Wood (50%) + dry sludge (50%)	2.5	54.2	--*	16.8	4.2	6.5	0.3
Wood (50%) + meat (50%)	4.5	54.1	0.7	17.5	1.1	8.0	0.3
Wood (50%) + dewatered sludge(50%)	1.2	50.6	2.2	11.8	0.7	9.6	0.2
Wood (50%) +meat (20%)+dewatered sludge (20%)+ breading (10%)	1.9	64.0	2.2	13.1	0.9	8.1	0.4
Cardboard	3.0	57.3	1.6	14.1	1.6	15.6	0.4
Cardboard (50%) + dewatered sludge (50%)	2.3	64.0	1.8	9.8	1.2	14.5	0.2

Table VI - 2 Gas Chromatograph results for various FPB mixtures (1 kg)

* - Gas was not detected in any sample of any run for the respective byproduct or byproduct mixture.

After successful runs with various FPB's, it was found that the amount of ash generated in each run was between 6-16 % of the biomass feed and tar generation was between 14%-30% as seen in table VI-3. Ash and tar were collected as explained in the procedure in Chapter V.

Material	Ash (gms)	Tar (gms)	Air (m^3/hr)	P_g %
Wood	60	300	3.9	64
Dry Sludge	160	200	4.7	64
Wood (50%) + dry sludge (50%)	70	140	3.1	80
Wood (50%) + meat (50%)	80	210	2.9	71
Wood (50%) + dewatered sludge(50%)	80	220	3.6	70
Wood (50%) +meat (20%)+dewatered sludge (20%)+ breading (10%)	100	180	3.7	72
Cardboard	60	240	4.1	70
Cardboard (50%) + dewatered sludge (50%)	70	230	3.4	70
Average (%)	8.5	21.5		70

Table VI - 3 Ash and tar values for various FPB mixtures.

The data obtained from gasification in table VI-2 were used to calculate the cold gas efficiency of the gasifier. The runs, on an average, lasted 30 minutes (20 minutes for cardboard) and consumed 1 kg of biomass. Table VI-4 shows the cold gas efficiency values calculated using equation 5.1.

Material	**Actual HV (MJ/kg)**	**Producer gas HV (MJ/kg)**	**Cold Gas efficiency (η_{cg} %)**
Wood	18.8	10.8	58
Dry Sludge	23.0	10.9	47
Wood (50%) + dry sludge (50%)	20.1	12.0	60
Wood (50%) + meat (50%)	19.5	13.8	71
Wood (50%) + dewatered	16.0	9.8	61
Wood (50%) +meat (20%)+dewatered sludge (20%)+ breading (10%)	21.1	12.8	61
Cardboard	16.4	11.0	67
Cardboard (50%) + dewatered sludge (50%)	19.7	9.7	49

Table VI - 4 Heating values and cold gas efficiency for various FPBs

The cold gas efficiency gives us an approximate conversion percentage that can be multiplied by the actual heat content of the waste to determine the usable energy released in gasification. The result can be compared to the present value of natural gas prices to compute the potential savings of FPB gasification.

One of the major factors to be considered before calculating potential savings was the energy required to preprocess or dry the byproducts. The moisture content of the FPBs were high and this would require a considerable amount of energy to dry the FPBs. As a result of this, the potential savings from gasification will be reduced. The cost analysis for this area of the project was not within the scope and hence was considered as potential further study.

Potential Savings

Gasification of FPBs may allow generation of revenue in addition to potential savings due to reduction in disposal costs. This income can be calculated on the basis of average natural gas prices, paid by the food processor. The average Natural Gas price, paid by the processor for the three facilities, in the year 2003 was $4.85/Mcf, which was equivalent to $0.0045/MJ.

This value ($/MJ) was multiplied by the available heat content (MJ) of the producer gas after gasification.

The following two assumptions were made to calculate the available heating value for gasification:

1. Though the composition of MSW was approximated to be 70%-plastic and 30%-cardboard, there could be variations in the proportions. For evaluating the potential savings, it was assumed that the proportion of cardboard was a constant 30%.
2. As discussed earlier, energy would be required to preprocess the byproducts. The design and selection of the drying equipment required for the preprocessing was not in the scope of this project. Considering these facts, it was assumed that the drying equipment selected would reduce the weight of the byproducts by 50%. This factor was applied to the byproducts of inedible meat and sludge to evaluate available mass for gasification.

Table VI - 5 shows the generation/year, actual heating value, actual available weight for gasification of the FPBs and the available energy.

Material	Actual HV (MJ/kg)	Generation $X10^3$ kgs/yr	Weight after drying $X\ 10^3$ kgs/yr	Available Energy ($x\ 10^7$ MJ)
Cardboard (30%MSW)	16.38	1,976*	1,976**	3.2
Sludge	23.03	7,778	3,889	8.9
Inedible Meat	23.02	4,903	2,451	5.6
Total			8,316	17.7

Table VI - 5 Heating Values, Available weight after drying and Available energy

* - Value presented here is 30% of total MSW, i.e. 30% of 6,585,000 kgs/year. See table IV-1, Chapter IV.

** - It was assumed that cardboard will not be dried and hence will have the same weight.

Using the cold gas efficiency values of 67%, 71% and 47% for cardboard, inedible meat and dried sludge, respectively, the potential income from gasification can be calculated as:

$$\text{Potential Income} = \text{Available energy (MJ)} \times 0.0045\ (\$/\text{MJ}) \times \eta_{cg}. \qquad 6.1$$

The average ash and tar generation was recorded at 8.5% and 21.5%, resulting in an average gasification percentage of 70 % (see table VI-3). In actual application, all the FPBs will be blended and gasified as a mixture. This was the reason for considering average ash and tar values instead of individual results. Based on these considerations, a 70% reduction in waste disposal, by weight, was assumed. This 70% will contribute to the potential savings by gasification of FPBs.

For the results shown in table VI-6, the waste disposal costs for ash and tar were not considered. The results presented are only potential savings from gasification and waste disposal cost reduction. The following table VI-6 shows potential income from gasification, potential savings from waste reduction and the total potential savings per year for the three facilities.

Material	**Available Energy ($x10^7$MJ)**	**Potential Income ($)**	**Potential Savings ($)**	**Total Potential savings ($)**
	A	B= A*0.0045*η_{cg}	C = Costs*0.70	D = B+C
Cardboard (30%MSW)	3.2	96,480	63,808*	160,288
Inedible	8.9	284,355	-34,104	250,251
Sludge	5.6	118,440	293,130	411,570
Totals	17.7	499,275	322,834	822,109

Table VI - 6 Potential savings, potential income by gasification of three categories of waste

* - The total costs for MSW, a sum of $191,101 in operating costs and $112,748 in freight costs, is $303,849. Since cardboard is 30% of the total MSW weight, the expenses for cardboard were reduced to 30% of the total, i.e. $ 91,155. The value presented here is $91,155*0.70 = $63,808. See table IV-2, chapter IV.

CHAPTER VII

CONCLUSIONS

Summary

Different food processing byproducts were identified and gasified. Analysis was conducted to determine the characteristics of the byproducts. The results of gasification were used to evaluate potential savings from waste disposal by gasification. Listed below are the specific conclusions of this study:

1. Three facilities of a major food processor in Oklahoma were surveyed. The survey was conducted to identify and categorize different types of waste. Different wastes identified were: Plastics, cardboard, cellulose casings, inedible meat, sludge and breading. Plastics, cardboard and cellulose casings were disposed as Municipal Solid Waste (MSW). Plastics amounted for 70%, and cardboard and casings amounted to 30% of the total weight of MSW generated by the three facilities.
2. It was found that the Food Processing Byproducts (FPBs) had high moisture content. The moisture content for inedible meat and sludge was found to be 73% and 72% respectively. The other characteristics such as ash content and volatile matter ranged between 2 to 22.8% (dry mass basis) and 51 to 95.8% (dry mass basis). One of the most important characteristics of the FPBs was the heating value which ranged from 16 to 23 MJ/kg.

3. The three facilities were surveyed to identify and quantify the different types of waste. The wastes were categorized into three major categories: inedible meat, sludge and MSW. The amount of waste produced by the three facilities was 6,584,000; 4,903,000; 7,778,000 kgs/yr for MSW, inedible meat and sludge. The total waste generated by the food processor was 19,265,000 kgs/yr.
4. Disposal costs for the waste categories identified were categorized into operating costs and freight costs. The operating costs for the three facilities for all the waste categories combined were $349,824 while the freight costs for the three facilities were $324,063. The freight costs amounted to about 48% of the total disposal expense of $673,886.
5. Due to a limitation of low volumetric capacity in the gasifier, wood pellets were used as a base material in several mixtures. The byproducts and byproduct mixtures were gasified and the heating values of the producer gas were evaluated. The heating values of the producer gas obtained were then compared to the actual heating value of the byproduct or byproduct mixture to evaluate the cold gas efficiency of the gasifier. The heating value of the producer gas ranged from 9.7 to 13.8 MJ/kg. The cold gas efficiency was found to be in the range of 47 to 71%.
6. The cold gas efficiency and the actual heating values of the byproducts were used to evaluate the available energy for gasification. Present natural gas prices were calculated in terms of $/MJ and were used to calculate potential savings. Potential income from gasification of

cardboard (30%of MSW), inedible meat, and sludge for all three facilities was calculated as $96,480; $284,355; and, $118,440, respectively, for a total potential income of $499,275**.** A 70% reduction in the waste disposal costs was assumed on the basis of ash and tar generation and the potential savings from waste reduction was projected as $160,288, $250,251, $411,570 for cardboard, inedible meat and sludge respectively. The total potential savings, for three facilities surveyed, was projected as $822,109/year.

Suggestions for future research

Additional information is required to compute the complete economic feasibility of using gasification as a waste disposal alternative. A large scale gasifier will behave differently and may have a higher efficiency depending upon the design. Listed below are some potential topics for further research for gasification of food processing byproducts.

1. Design of a large-scale, continuous feed gasifier with complete temperature control and continuous gas monitoring.
2. Design of a drying and blending process for preprocessing the byproducts.
3. Study of energy requirements for preprocessing the byproducts.
4. Analysis of ash and tar for finding alternate means of disposal.
5. Complete feasibility study involving capital investment for new large- scale gasifier and preprocessing equipment.

6. Cost analysis using efficiency of the new setup and expenditures for preprocessing to evaluate a pay-back period.
7. Study properties and proportions of contaminants in the producer gas and ways to reduce the same.

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APPENDIX A

WASTE GENERATION AND DISPOSAL CASE STUDY

Facility 1 – Sludge Generation and disposal costs (Jan 2003 – April 2004)

Month	Weight (kgs)	Operating Cost ($)	Freight ($)	Total ($)
Jan '03	181,002	$15,962	$6,814	$22,775
Feb '03	101,682	$8,967	$3,719	$12,685
Mar '03	108,908	$9,604	$4,025	$13,629
Apr '03	104,834	$9,245	$3,639	$12,884
May '03	68,520	$6,042	$2,392	$8,435
Jun '03	70,171	$6,188	$2,650	$8,838
Jul '03	77,510	$6,835	$2,661	$9,496
Aug '03	82,046	$7,235	$2,807	$10,043
Sep '03	32,468	$2,863	$1,166	$4,029
Oct '03	74,825	$6,598	$2,645	$9,243
Nov '03	65,118	$5,742	$1,695	$7,438
Dec '03	141,775	$12,502	$4,528	$17,030
Jan '04	104,952	$9,255	$3,063	$12,318
Feb '04	134,327	$11,846	$2,976	$14,821
Mar '04	160,690	$14,170	$3,777	$17,948

Table A - 1 Sludge generation and disposal costs at Facility 1

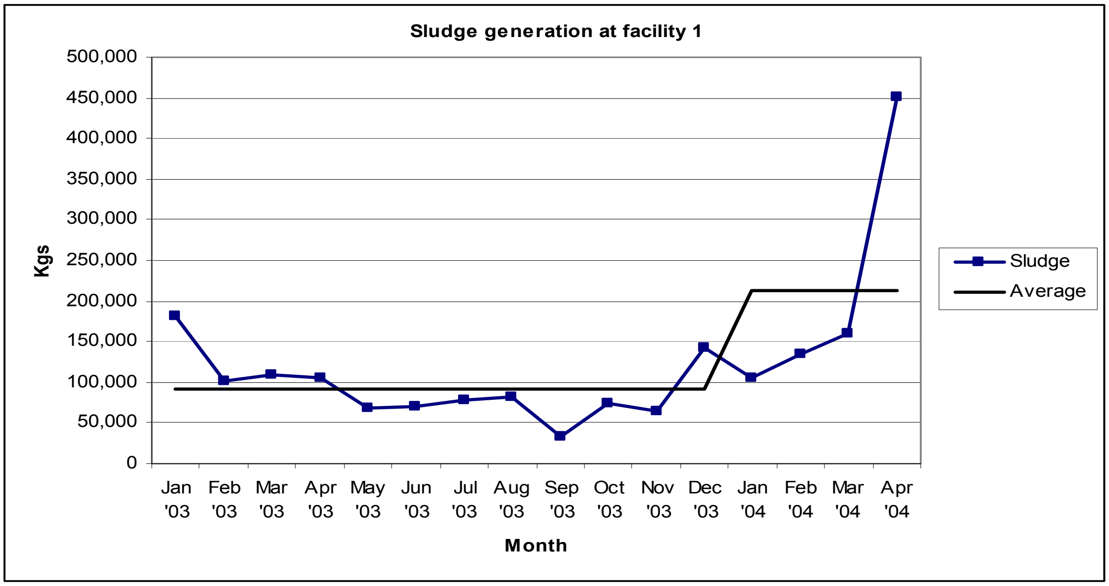

Figure A - 1 Sludge generation (kgs) from Jan'03 to Apr '04

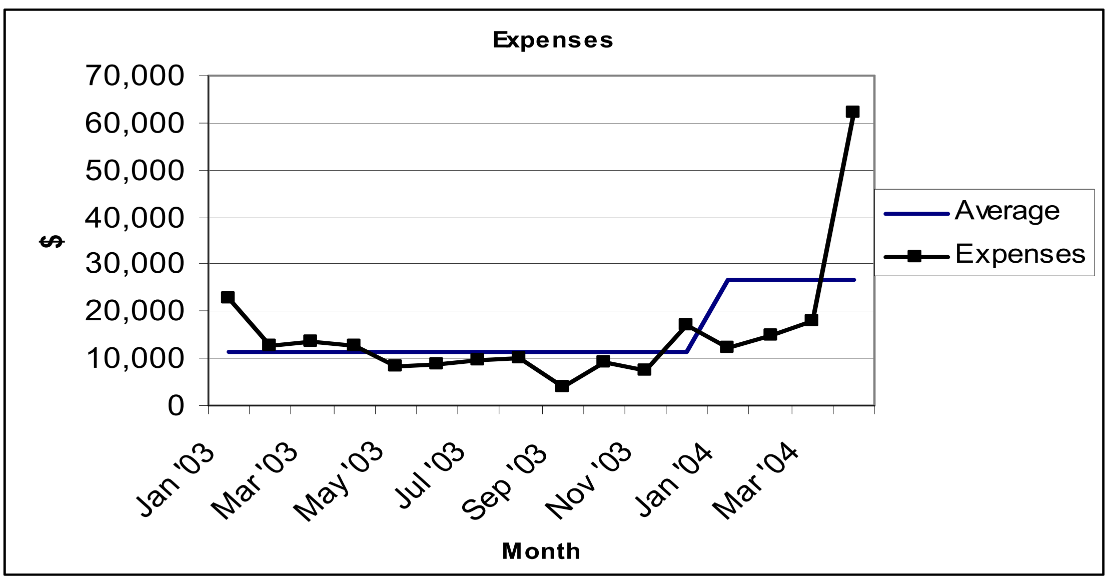

Figure A - 2 Disposal expenses for sludge at facility 1

Facility 1 –Inedible Meat Generation and disposal costs (Jan 2003 – Apr 2004)

Month	Weight (kgs)	Fat Yield ($)	Operating Cost ($)	Freight ($)	Total Cost ($)
Jan '03	125,399	-$14,259	$11,058	$4,758	$1,558
Feb '03	80,923	-$9,673	$7,136	$2,961	$424
Mar '03	84,016	-$10,311	$7,409	$3,111	$208
Apr '03	99,737	-$12,348	$8,795	$3,542	-$11
May '03	85,760	-$10,652	$7,563	$3,047	-$42
Jun '03	99,328	-$12,887	$8,759	$3,715	-$413
Jul '03	120,427	-$15,808	$10,620	$4,148	-$1,040
Aug '03	120,728	-$15,045	$10,646	$4,134	-$265
Sep '03	133,855	-$15,640	$11,804	$4,954	$1,118
Oct '03	85,375	-$10,342	$7,529	$3,000	$187
Nov '03	124,427	-$17,191	$10,973	$3,525	-$2,693
Dec '03	112,314	-$17,015	$9,904	$3,495	-$3,616
Jan '04	201,048	-$31,024	$17,729	$5,909	-$7,386
Feb '04	170,546	-$26,388	$15,040	$3,978	-$7,370
Mar '04	137,247	-$17,197	$12,103	$3,298	-$1,796

Table A - 2 Inedible meat generation and disposal costs at Facility 1

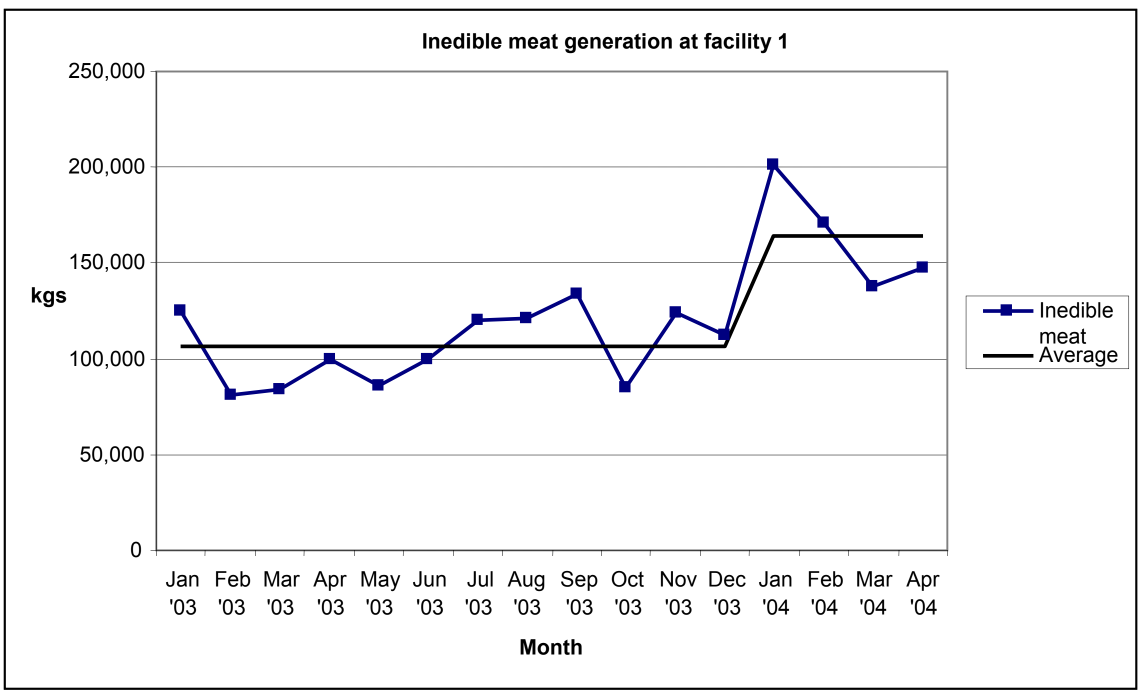

Figure A -3 Inedible meat generation (kgs) from Jan'03 to Apr '04

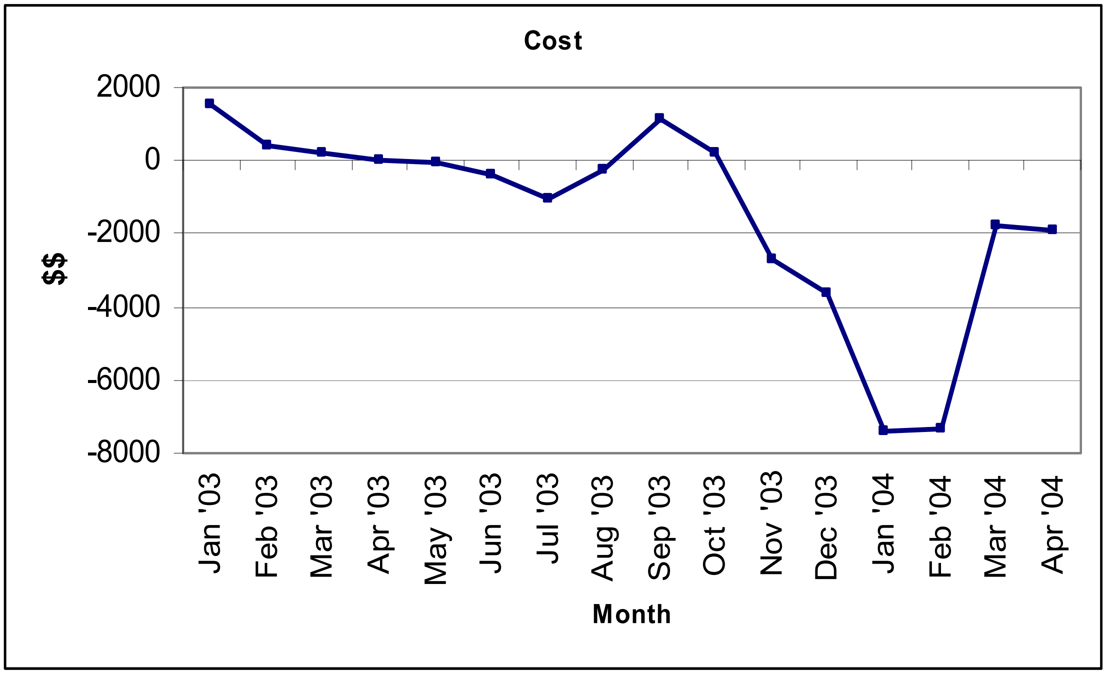

Figure A - 4 Disposal expenses for inedible meat at facility 1

Facility 1 – Municipal Waste Generation and disposal costs

Municipal waste composition: (by weight)

70% - Plastic (Gloves, Packing films, plastic covers, sheets, bags)

15% - Hot Dog casings

15% - Paper (cardboard boxes, cores, packing boxes, paper, wood pallet pieces)

Municipal waste disposal data was not available from the company. The waste management company that manages Municipal waste for the company was contacted and they provided a rough data from their records.

Load:

Loads/week = 9-10

Daily Average tonnage = 4.4. Tons

Weekly Average tonnage = 44 Tons

Charges:

Rate/Haul = $125

Rate/Ton = $28.75

Cost:

Loads/week * Rate/Haul + Weekly Average Tonnage * Rate/Ton

~ $2450 / Week

~ $10,000 /Month

~ $ 120,000 / Year

Facility 1 waste summary

Waste Category	kgs generated /year	Disposal Cost/year
Municipal waste	2,287,873	$120,000
Inedible Meat	1,272,290	-$ 4,583
Sludge	1,108,856	$136,524

Table A – 3 Waste generation and disposal expenditure summary at facility 1

Total waste disposal cost for Facility 1 for the year '03 = $ 251,941 /year.

Facility 2 –Sludge Generation and disposal costs

(Jan 2003 – June 2004)

Waste disposal cost calculation:

Charge = $790/haul+ $160/month (Monthly rental charges).

Haul weight = 18,143 kgs/haul.

Month	Total kgs	# of loads	Gross Amount
Jan '03	598,742	33	$26,230
Feb '03	707,604	39	$30,970
Mar '03	598,742	33	$26,230
Apr '03	562,455	31	$24,650
May '03	508,023	28	$22,280
Jun '03	399,161	22	$17,540
Jul '03	381,018	21	$16,750
Aug '03	344,730	19	$15,170
Sep '03	399,161	22	$17,540
Oct '03	435,449	24	$19,120
Nov '03	399,161	22	$17,540
Dec '03	344,730	19	$15,170
Jan '04	362,874	20	$15,960
Feb '04	417,305	23	$18,330
Mar '04	344,730	19	$15,170
Apr '04	235,868	13	$10,430
May '04	199,581	11	$8,850
Jun '04	333,936	18	$14,540

Table A - 4 Sludge generation and disposal costs at Facility 2

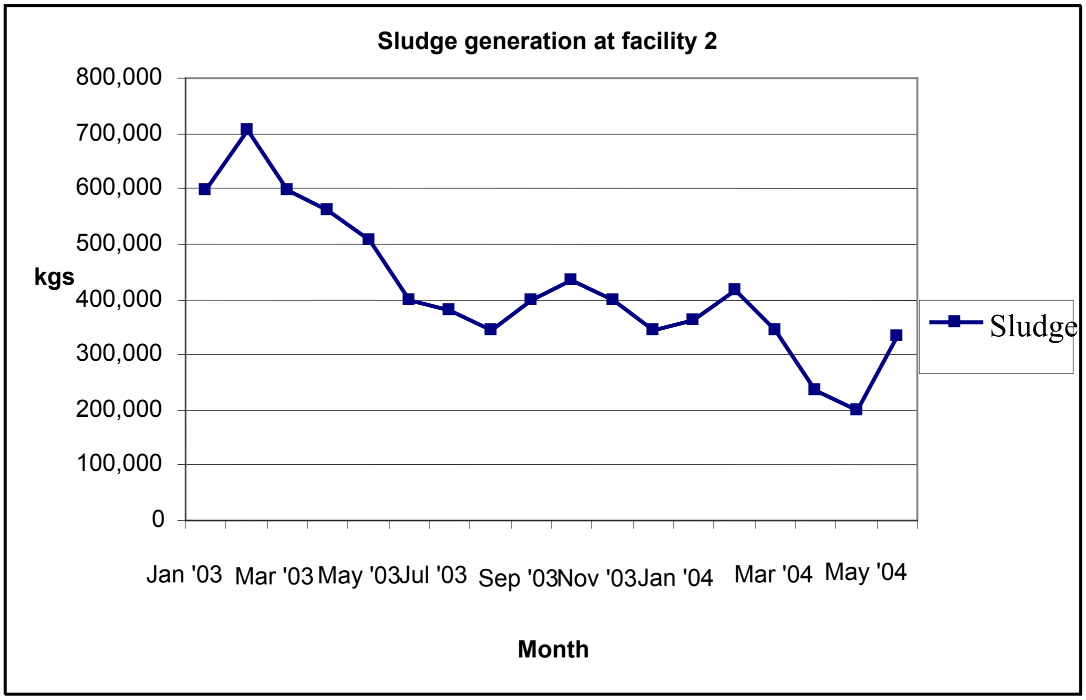

Figure A – 5 Sludge generation (kgs) from Jan'03 to May '04

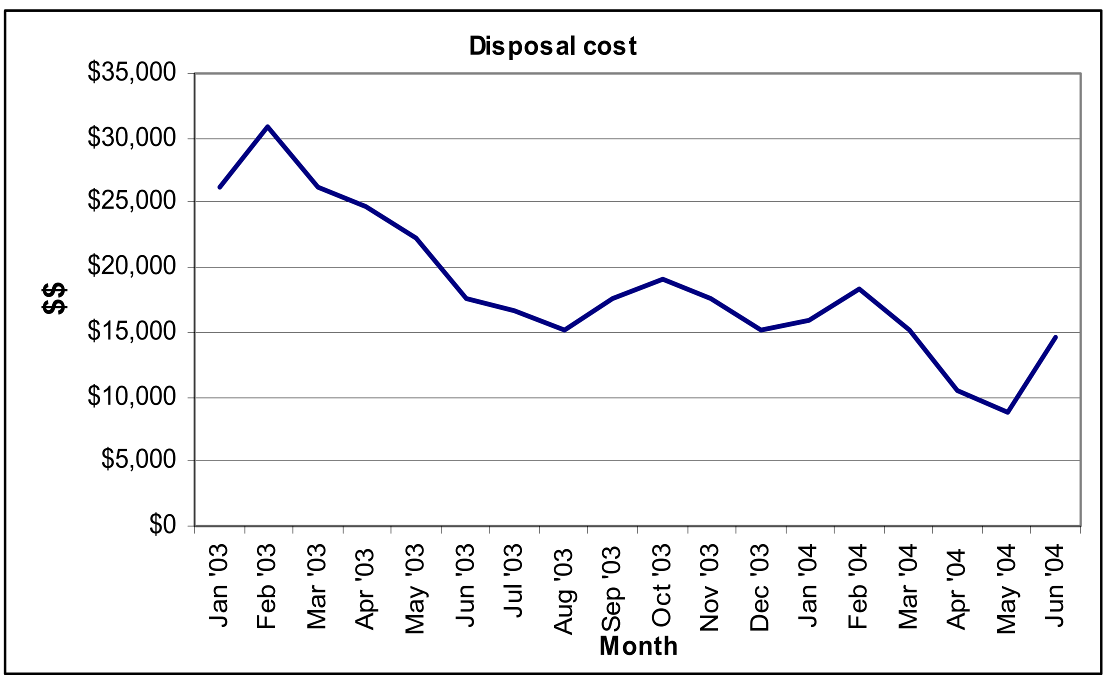

Figure A - 6 Disposal costs for sludge at facility 2

Facility 2 – Inedible Meat Generation and disposal costs

(Jan 2003 – May 2004)

Month	Weight (kgs)	Fat Yield ($)	Operating Cost ($)	Freight ($)	Total Cost ($)
Jan '03	82,829	-$9,321	$5,478	$3,207	-$636
Feb '03	139,303	-$16,527	$9,213	$5,127	-$2,186
Mar '03	186,012	-$22,761	$12,303	$6,879	-$3,580
Apr '03	86,328	-$10,682	$5,710	$3,035	-$1,937
May '03	145,675	-$18,084	$9,635	$5,233	-$3,217
Jun '03	207,384	-$27,019	$13,716	$8,047	-$5,256
Jul '03	157,427	-$20,702	$10,412	$5,518	-$4,772
Aug '03	210,010	-$26,482	$13,890	$7,094	-$5,499
Sep '03	130,940	-$15,371	$8,660	$4,794	-$1,917
Oct '03	128,045	-$15,438	$8,469	$4,480	-$2,489
Nov '03	157,950	-$21,616	$10,447	$4,385	-$6,784
Dec '03	144,090	-$21,812	$9,530	$4,628	-$7,654
Jan '04	180,839	-$27,789	$11,960	$5,235	-$10,593
Feb '04	151,340	-$23,433	$10,009	$4,437	-$8,986
Mar '04	219,246	-$28,479	$14,501	$6,336	-$7,642
Apr '04	158,347	-$20,522	$10,473	$4,550	-$5,499

Table A - 5 Inedible meat generation and disposal costs at facility 2

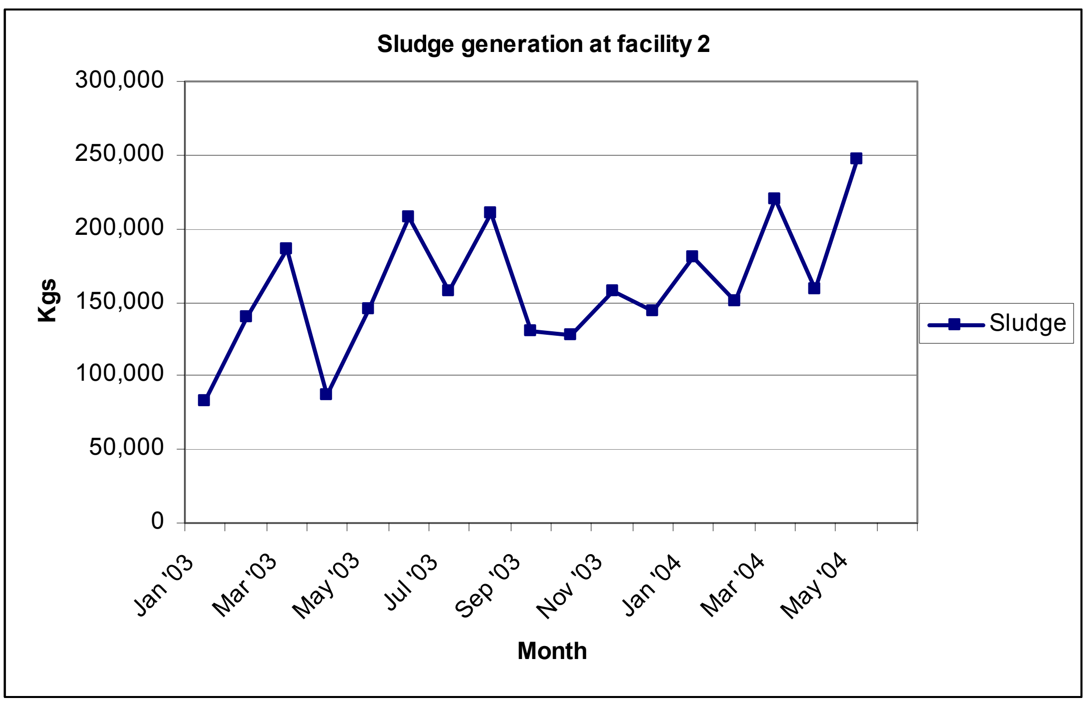

Figure A-7 Inedible meat generation (kgs) from Jan'03 to May '04

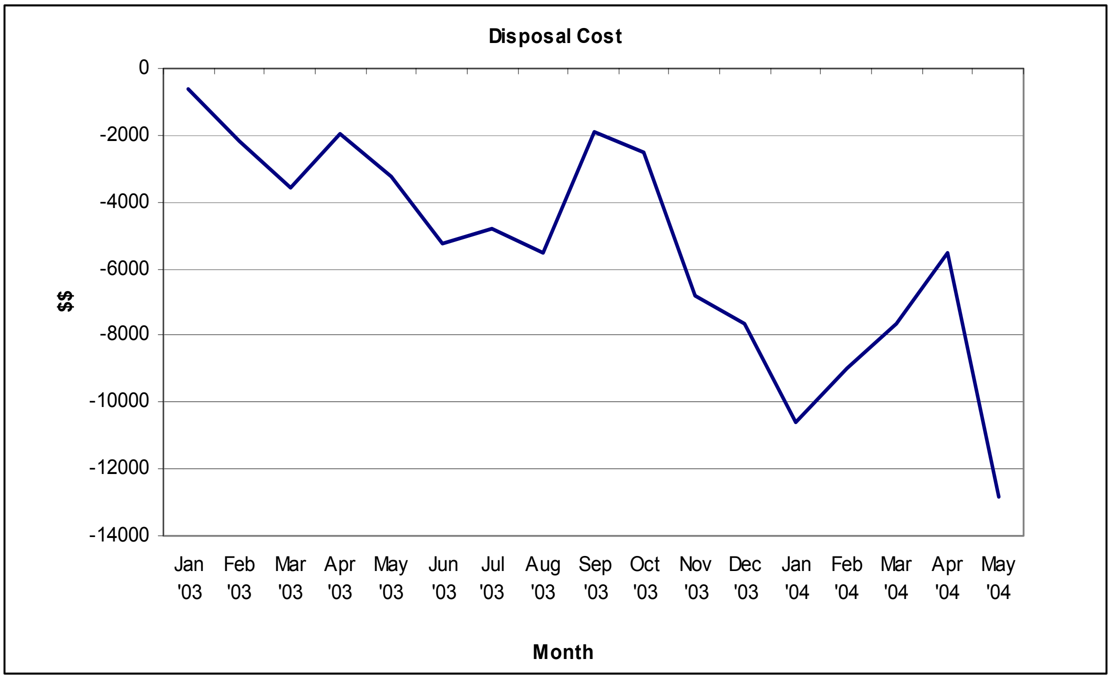

Figure A - 8 Disposal cost for inedible meat at facility 2

Facility 2 – Municipal Waste Generation and disposal costs

(Jan 2003 –May 2004)

Waste disposal calculation :

Hauling charges = $ 80/haul. Disposal fee = $ 30.64/ton.

Weekend hauling charges = $70/haul. Roll off rental = $300.

Month	Trips	Weight (kgs)	Cost ($)
Jan '03	15	151,781	$6,326
Feb '03	14	144,360	$5,996
Mar '03	17	159,220	$6,738
Apr '03	31	162,096	$8,045
May '03	14	168,138	$6,799
Jun '03	15	177,663	$7,201
Jul '03	17	167,575	$7,118
Aug '03	14	165,824	$6,882
Sep '03	14	140,142	$5,989
Oct '03	19	207,301	$8,723
Nov '03	13	168,401	$6,891
Dec '03	15	154,920	$6,583
Jan '04	14	193,711	$7,850
Feb '04	14	176,112	$7,239
Mar '04	56	309,187	$15,593
Apr '04	56	267,565	$13,837
May '04	45	231,024	$11,627

Table A - 6 MSW generation and disposal costs at facility 2

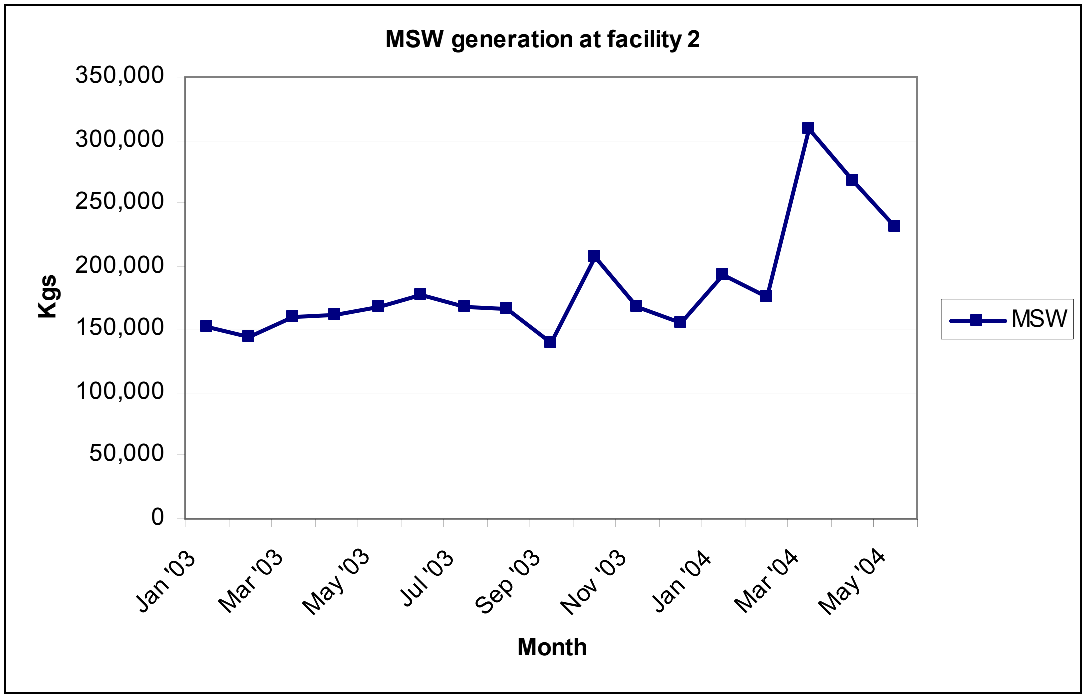

Figure A – 9 MSW generation (kgs) from Jan'03 to May '04

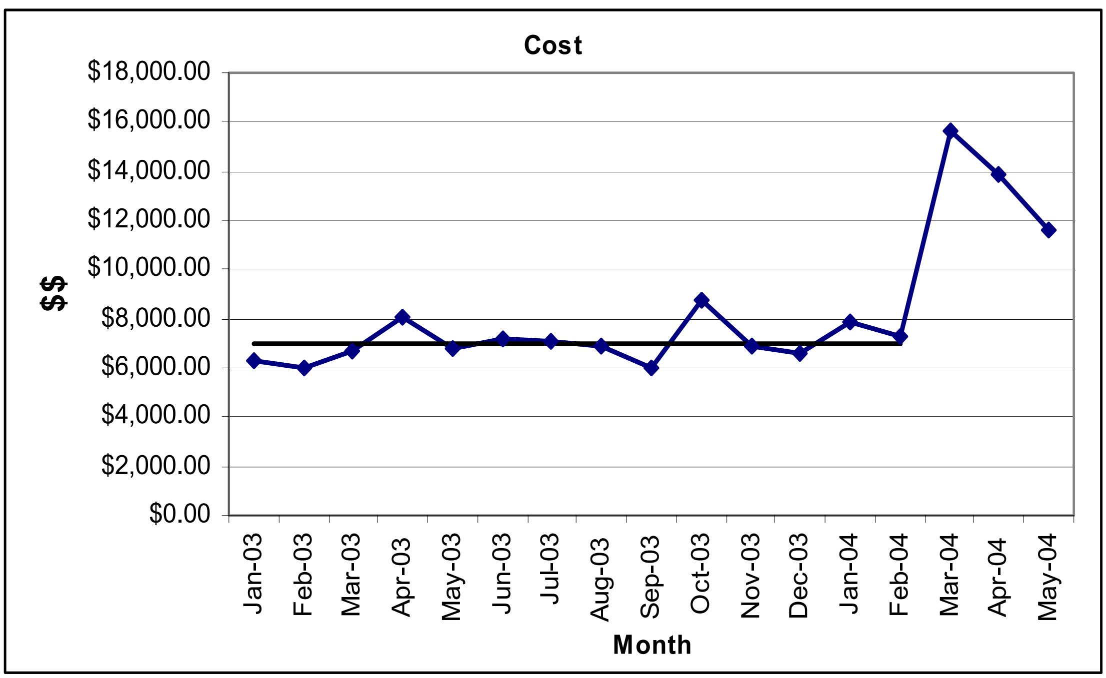

Figure A - 10 Disposal cost for MSW at facility 2

Facility 2 waste summary

Waste Category	kgs generated /year	Disposal Cost/year
Municipal waste	2,287,873	$83,289
Inedible Meat	1,775,992	-$45,926
Sludge	5,678,976	$249,190

Table A - 7 Waste generation and disposal cost summary for facility 2

Total waste disposal cost for Facility 2 for the year 2003 = $ 286,553 /year.

Facility 3 –Sludge Generation and disposal costs

(Jan 2003 – May 2004)

Month	Weight (kgs)	Operating Cost ($)	Freight ($)	Total ($)
Jan '03	0	$0	$0	$0
Feb '03	20,666	$1,822	$586	$2,408
Mar '03	32,278	$2,846	$1,172	$4,018
Apr '03	37,730	$3,327	$1,172	$4,499
May '03	20,956	$1,848	$1,172	$3,020
Jun '03	16,112	$1,421	$586	$2,007
Jul '03	36,115	$3,185	$1,172	$4,357
Aug '03	15,595	$1,375	$586	$1,961
Sep '03	36,451	$3,214	$1,172	$4,386
Oct '03	13,073	$1,153	$586	$1,739
Nov '03	18,679	$1,647	$586	$2,233
Dec '03	20,765	$1,831	$586	$2,417
Jan '04	18,216	$1,606	$538	$2,145
Feb '04	38,882	$3,429	$1,072	$4,501
Mar '04	33,212	$2,929	$1,081	$4,010
Apr '04	19,042	$1,679	$556	$2,235
May ‘04	33,393	$2,945	$1,107	$4,052

Table A - 8 Sludge generation and disposal costs at facility 3

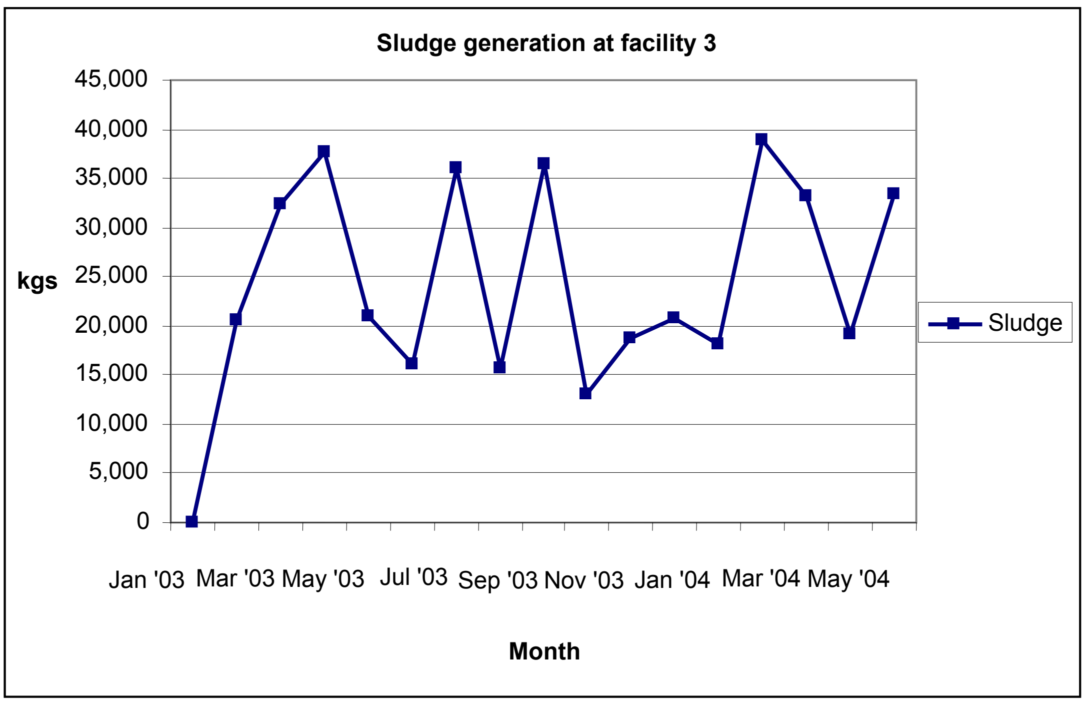

Figure A - 11 Sludge generation (kgs) at facility 3

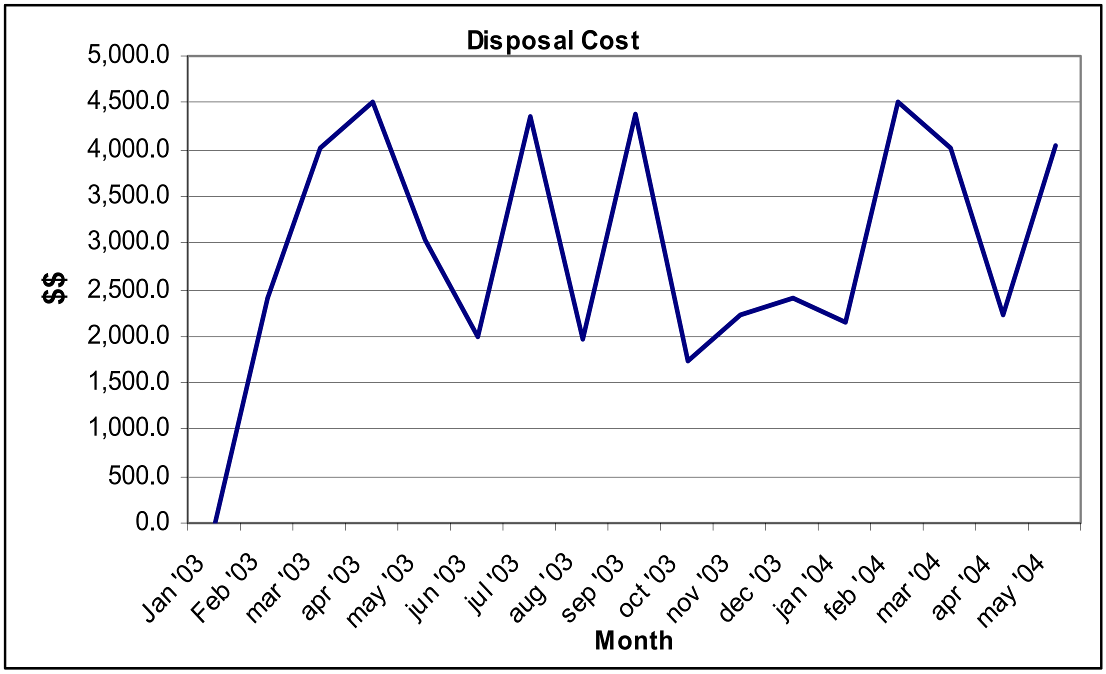

Figure A - 12 Disposal cost for sludge at facility 2

Facility 3 –Inedible Meat Generation and disposal costs

(Jan 2003 – April 2004)

Month	Weight (kgs)	Fat Yield ($)	Operating Cost ($)	Total ($)
Jan '03	98,507	-$11,310	$8,687	$1,082
Feb '03	112,692	-$13,490	$9,938	$772
Mar '03	134,016	-$16,487	$11,818	$309
Apr '03	141,675	-$17,536	$12,494	$252
May '03	132,579	-$16,469	$11,691	-$478
Jun '03	138,773	-$18,113	$12,238	-$527
Jul '03	173,165	-$22,724	$15,271	-$1,326
Aug '03	118,232	-$14,737	$10,426	-$314
Sep '03	79,151	-$9,335	$6,980	$709
Oct '03	63,238	-$7,689	$5,577	-$21
Nov '03	92,924	-$12,747	$8,194	-$1,942
Dec '03	114,948	-$17,409	$10,137	-$3,494
Jan '04	92,947	-$14,287	$6,147	-$5,320
Feb '04	95,638	-$14,807	$6,325	-$5,642
Mar '04	98,476	-$12,516	$6,513	-$3,200
Apr '04	97,532	-$12,808	$6,451	-$3,583
May ‘04	104,456	-$11,310	$8,687	$1,082

Table A - 9 Inedible meat generation and disposal costs at facility 3

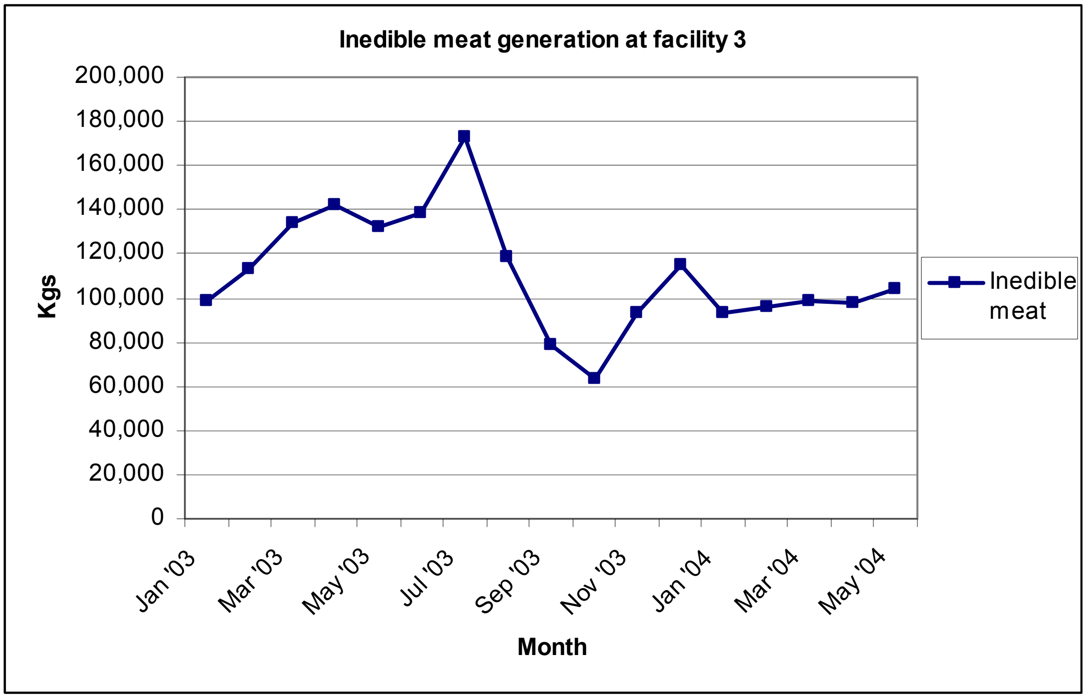

Figure A - 13 Inedible meat generation (kgs) at facility 3

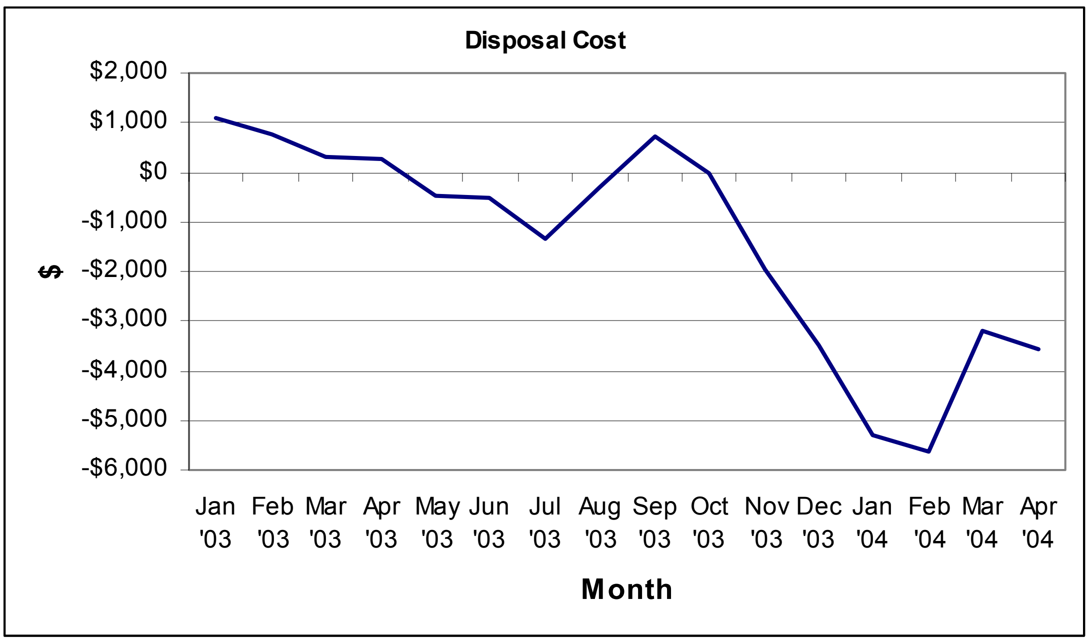

Figure A - 14 Disposal cost for inedible meat at facility 3

Facility 3 –Municipal waste generation and disposal costs

(Jan 2003 – May 2004)

Municipal waste composition: (by weight)

70% - Plastic (Gloves, Packing films, plastic covers, sheets, bags)

25% - Paper (cardboard boxes, cores, packing boxes, paper, wood pallet pieces)

5% - Other wastes.

Municipal waste disposal data was not available from the company. The waste management company that manages Municipal waste for the company was contacted and they provided a rough data from their records.

Waste disposal cost calculation:

Average tons/haul = 8

Average hauls/ month = 24

Cost:

Charge/ton = $28.75

Charge/haul = $125

Cost/month = $8,520

Cost/year = $ 102,240

Facility 3 waste summary

Waste Category	Pounds generated /year	Disposal Cost/year
Municipal waste	2,090,154	$102,240
Inedible Meat	1,399,897	-$ 4,978
Sludge	268,417	$33,045

Table A - 10 Waste generation and disposal cost summary for facility 3

Total waste disposal cost for Facility 3 for the year 2003 = $ 130,307/year.

APPENDIX B

WASTE DISPOSAL COST CALCULATION

Facility 1

Calculations:-

Inedible Meat:

Weight (kgs)* operating cost ($0.080/kg) + freight ($) – fat yield (kgs*(fat) $/kg)

Sludge:

Weight (kgs)* operating cost ($0.080/kg) + freight ($)

MSW:

(Hauls/week * $125/haul) + (weekly tonnage * $0.02875/kg)

Facility 2

Calculations:-

Inedible Meat:

Weight (kgs)* operating cost ($0.080/kgs) + freight ($) – fat yield (kgs*(fat) $/kg)

Sludge: (18,143 kgs/haul)

$790/haul + $160/month

MSW:

(Hauls/week * $0.080/haul) + (weekly tonnage * $0.03064/kg)

Weekend hauling charges = $70/haul, Roll off rental = $300

Facility 3

Calculations:-

Inedible Meat:

Weight (kgs)* operating cost ($80/kg) + freight ($) – fat yield (kgs*(fat) $/kg)

Sludge:

Weight (kgs)* operating cost ($0.080/kg) + freight ($)

MSW:

(Hauls/week * $125/haul) + (weekly tonnage * $0.02875/kg)

APPENDIX C

SAMPLE CALCULATIONS OF COLD GAS EFFICIENCIES

Table C-1 shows the gas chromatograph results of various mixtures. Nitrogen is used as a reference peak by the gas chromatograph for calculating the other percentages.

Material	H_2	CO	CH_4	C_2H_4
Dry Sludge	3.4	13.3	1.0	--
Wood (50%) +meat (20%) +dewatered sludge (20%) + breading (10%)	1.9	13.1	0.9	0.4

Table C-1 Gas Chromatograph results for various FPB mixtures (1 kg)

The cold gas efficiency is calculated by the equation 5.1 given in chapter V.

A biomass sample of 1 kg runs for approximately 30 minutes (X=30). The air flow was different for different samples.

Material	Air (ft^3/min)
Dry Sludge	2.8
Wood +meat +dewatered sludge + breading	2.2

Table A - 2 Air supply for gasifier runs on byproduct mixtures

Sample Cold gas efficiency calculations:

Heating value of common gases:

H_2 = 0.3428, CO = 0.3395, CH_4 = 1.0689, C_2H_4 = 1.7026

Dry Sludge:

Heating value of producer gas:

H_2 = (3.4/100)*0.3428*2.8*30*0.64

CO = 13.3/100*0.3395*2.8*30*0.64

CH_4 = 1.0/100*1.0689*2.8*30*0.64

C_2H_4 = 0/100*1.7026*2.8*30*0.64

∴ Total Heating value = 10.88 (MJ/kg)

Actual heating value of Dry Sludge = 23.02MJ/kg

∴ Cold Gas Efficiency = 10.88/23.02 = 47.27%

Wood (50%) + meat (20%) + dewatered sludge (20%) + breading (10%):

Heating value of producer gas:

H_2 = 1.9/100*0.3428*2.2*30*0.72

CO = 13.1/100*0.3395*2.2*30*0.72

CH_4 = 0.9/100*1.0689*2.2*30*0.72

C_2H_4 = 0.4/100*1.7026*2.2*30*0.72

∴ Total Heating value = 12.8 (MJ/kg)

Actual heating value of Mixture = 21.1 MJ/kg

∴ Cold Gas Efficiency = 12.8/21.1 = 60.55%

VITA

Bhaskar R. Rao

Candidate for the Degree of

Master of Science

Dissertation: GASIFICATION OF FOOD PROCESSING BYPRODUCTS – AN ECONOMIC WASTE HANDLING ALTERNATIVE

Major Field: Biosystems Engineering

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Personal Data: Born in Bombay (now Mumbai), India on 1st March 1980, the son of S. Ramachandran and R. Nalini.

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Experience: In-plant Instrumentation trainee for Rashtriya Chemicals and Fertilizers Ltd; at Bombay, India (2000-2001). Worked for Godrej (Chemical and Soap) Industries Ltd; Bombay, India as an Instrumentation Engineering Intern (2001-2002). Worked as Summer Intern for Bar-S Foods Co; Clinton, Oklahoma, USA (Summer 2004). Graduate research assistant at Biosystems Engineering department, Oklahoma State University, Stillwater, OK (Aug 2003-Dec 2004).

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Name: Bhaskar R. Rao Date of Degree: December, 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: GASIFICATION OF FOOD PROCESSING BYPRODUCTS – AN ECONOMIC WASTE HANDLING ALTERNATIVE

Pages in Study: 77 Candidate for Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study: The objective of this study was to evaluate the feasibility of gasification of Food Processing Byproducts (FPBs). Data was collected from three facilities of a major food processor in Oklahoma and potential savings were calculated for gasifying byproducts. A small-scale updraft gasifier was used to test the feasibility of gasifying byproducts from food processors. Also, gasification tests were conducted on combinations of different byproducts of food processing. The producer gas was analyzed for energy content and cold gas efficiencies. The results used to determine potential savings by gasification as a waste handling alternative.

Findings and Conclusions: Most of the food processing byproducts had high moisture content, in excess of 70% by weight (dry basis). The byproducts were preprocessed for ease of handling. Preprocessing involved blending and/or drying. The heating value of the producer gas ranged from 9.7 to 13.8 MJ/Kg. The cold gas efficiency was found to be in the range of 47 to 71%. The cold gas efficiency was then used to identify the potential savings by gasifying the FPBs. Waste disposal costs for three facilities in the year 2003 was $673,886. Potential income from gasification of available waste was calculated to be $499,275. Assuming a 70% reduction in waste disposal expenditure, potential savings of $322,834 was added to the potential income. The projected total potential savings was $822,109 per year.

Advisor's Approval: __________Dr. Paul R. Weckler________________________