This is to certify that the

dissertation entitled

AN ENERGY AND COST ANALYSIS MODEL
TO EVALUATE THE COMBUSTION
OF FOOD PROCESSING WASTES

presented by

Steven Alonzo Sargent

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Engineering Technology

James F. Steffe
Major professor

Date February 3, 1984

AN ENERGY AND COST ANALYSIS MODEL TO EVALUATE THE COMBUSTION OF FOOD PROCESSING WASTES

By

Steven Alonzo Sargent

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
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DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1984

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ABSTRACT

AN ENERGY AND COST ANALYSIS MODEL TO EVALUATE THE COMBUSTION OF FOOD PROCESSING WASTES

By

Steven Alonzo Sargent

Technical and economic factors pertinent to conversion of food processing wastes into recoverable energy were investigated. Combustion characteristics for a variety of wastes were defined, leading to the selection of components for an in-plant waste handling system for use in conjunction with each of three boiler systems representing pile burning, fluidized-bed combustion and suspension-firing technologies. Life Cycle Costing techniques were chosen to determine the total costs of the handling/combustion systems which would be incurred over a fixed payback period.

Energy and cost calculations were incorporated into an interactive computer model for analysis of individual food processing firms. The model prompts the user for input regarding the processing plant schedule, operating and loan parameters, and fossil and waste fuel characteristics. Projected annual savings in fuel and disposal costs are compared with average annual costs to determine the break-even point for cost-effective investment.

The model was validated with conservative parameters representing two sizes of Michigan apple juice processors. Apple pomace was substituted for natural gas and #2 fuel oil. Small processors were considered to be those generating 30 tons/day (27,215 kg/day) of pomace and requiring 10 million Btu/hr (10.5 GJ/hr) of processing heat. Large processors were those generating 100 tons/day (90,718 kg/day) of pomace and requiring 30 million Btu/hr (31.5 GJ/hr) of heat. Disposal costs for pomace were zero. A 14% loan interest rate with a 5-year payback period was employed, with other costs from September, 1983.

The handling/combustion systems are not currently cost-effective for either small or large apple juice processors. Combustion of packaging wastes, in addition to pomace, would reduce energy costs further and enable large processors to invest in a suspension-fired system with 1.1 tons/day (965 kg/day) of polyethylene plastic, or with 3.0 tons/day (2,735 kg/day) of corrugated paper box.

The break-even point for investment was determined to be most sensitive to processing waste flow rate, fossil fuel price and imposition of disposal cost. The break-even point was least sensitive to electrical cost and loan interest rate. Large processors could invest in a suspension-fired system with a 20% increase in fossil fuel price or in any system if disposal costs were imposed equal to 50% of the current rate. Small processors would require a 100% increase in fuel price or imposition of 100% of the disposal cost to seriously consider combustion of apple pomace.

To Suzana,

my wife

and my best friend

Come to me, all you who are weary and burdened,
and I will give you rest.

What good is it for a man to gain the whole world,
yet forfeit his soul? Or what can a man give
in exchange for his soul?

I tell you the truth, whoever hears my word
and believes him who sent me has eternal life
and will not be condemned; he has crossed over
from death to life.

Jesus Christ

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TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table | Page

LIST OF FIGURES

Figure		Page

List of Abbreviations

AAC - average annual costs
ac - acre
AP - apple pomace
Btu - British thermal unit
C - degrees Celcius
CPB - corrugated paper box
d.b. - dry basis
F - degrees Fahrenheit
FBC - fluidized-bed combustor
FKPI - Food and Kindred Products Industry
FO - #2 fuel oil
ft - foot
gal - gallon
ha - hectare
hr - hour
kg - kilogram
kJ - kiloJoule; MJ=megaJoule; GJ=gigaJoule
kW - kiloWatt
lb - pound
LCC - Life Cycle Cost analysis
lit - liter
m - meter
MC - moisture content
MSW - municipal solid waste
NG - natural gas
PB - pile burner combustor
PE - polyethylene
SF - suspension-fired combustor
UCR - Uniform Capital Recovery factor
w.b. - wet basis
WFW - wet fruit waste
yd - yard
yr - year

CHAPTER 1

Problem Definition and Analytical Approach

1.1 Introduction to the problem

Food processing plants require large quantities of energy for processing operations and in turn generate sizable amounts of solid and liquid waste materials. Rising costs for both energy and disposal have dramatically increased production costs in recent years and as a result represent a major concern to management. While the types and quantities of wastes generated by food plants vary widely, the potential exists for in-plant conversion of currently unusable or under-utilized wastes with fuel potential into recoverable energy, or more specifically, steam and hot water. Energy recovery by these means, if proven feasible, could result in significant savings for the industry in terms of lowered purchased energy costs and savings in waste disposal. Characterization and analysis of energy and disposal costs are dependent upon a basic understanding of several parameters, most importantly,

1. operating conditions representative of food processing plants;

2. biomass types, fuel potential and availability;

3. replacement equipment for handling and combustion of biomass which is readily available and reasonably priced; and

4. a cost analysis method capable of determining the feasibility potential.

1.2 Analytical approach

1.2.1 Systems analysis and models

Such a complex problem can be efficiently analyzed by a method known as systems analysis or systems research. This method, in simplest terms, is the study of "a complex set of related components within an autonomous framework" (Dent and Blackie, 1979). An understanding of the function of the related components within a sub-system permits the synthesis of the sub-systems in order to gain a better understanding of the entire system being investigated. Thus very complex problems can be analyzed by systematically studying the interactions between components within a sub-system, between sub-systems and finally between the system and the surrounding environment (Rountree, 1977; Bingham and Davies, 1978).

Development of a procedure to examine the feasibility of a new technology is essentially a means to model a defined system. A model is a replica or representation of a real object or system and can be constructed in three forms. An iconic model is a physical representation of a real system; an analog model utilizes the properties of one system to represent another; and a symbolic model employs mathematical relationships to describe a real system (Ackoff, *et al.*, 1962). A model can be static (with the system analyzed in equilibrium) or dynamic (with changes in system behavior analyzed over time). A dynamic model can be further classified as stochastic for prediction of random-occurring events, or deterministic for solutions based upon known input variables.

1.2.2 Simulation as a decision-making tool

In the literature the distinction between modelling and simulation tends to be nebulous. Modelling is the technique of developing and using a model to determine the solution to a problem, normally with the aid of a computer. Simulation increases problem-solving capability by adding to the modelling phase a second phase of experimentation (Wright, 1970). Feedback during model development and testing leads to refinement or adjustment of the model structure. Later during experimentation, the user's understanding of the system behavior is enhanced as the results are analyzed followed by variation of the input parameters. This cyclic pattern of input/output/analysis/input provides in-depth information for use in decision-making (Figure 1).

There are several advantages to the use of a computer-based model for analysis of agricultural systems (Dent and Blackie 1979).

1. Systems can be studied which would otherwise be prohibitive due to high cost or inconvenience.

2. Non-existent systems can be explored.

3. Long-term effects can be evaluated.

4. The evaluator or model-builder has a method which promotes thoroughness and objectivity in approaching the problem.

Cautions associated with model usage were also noted.

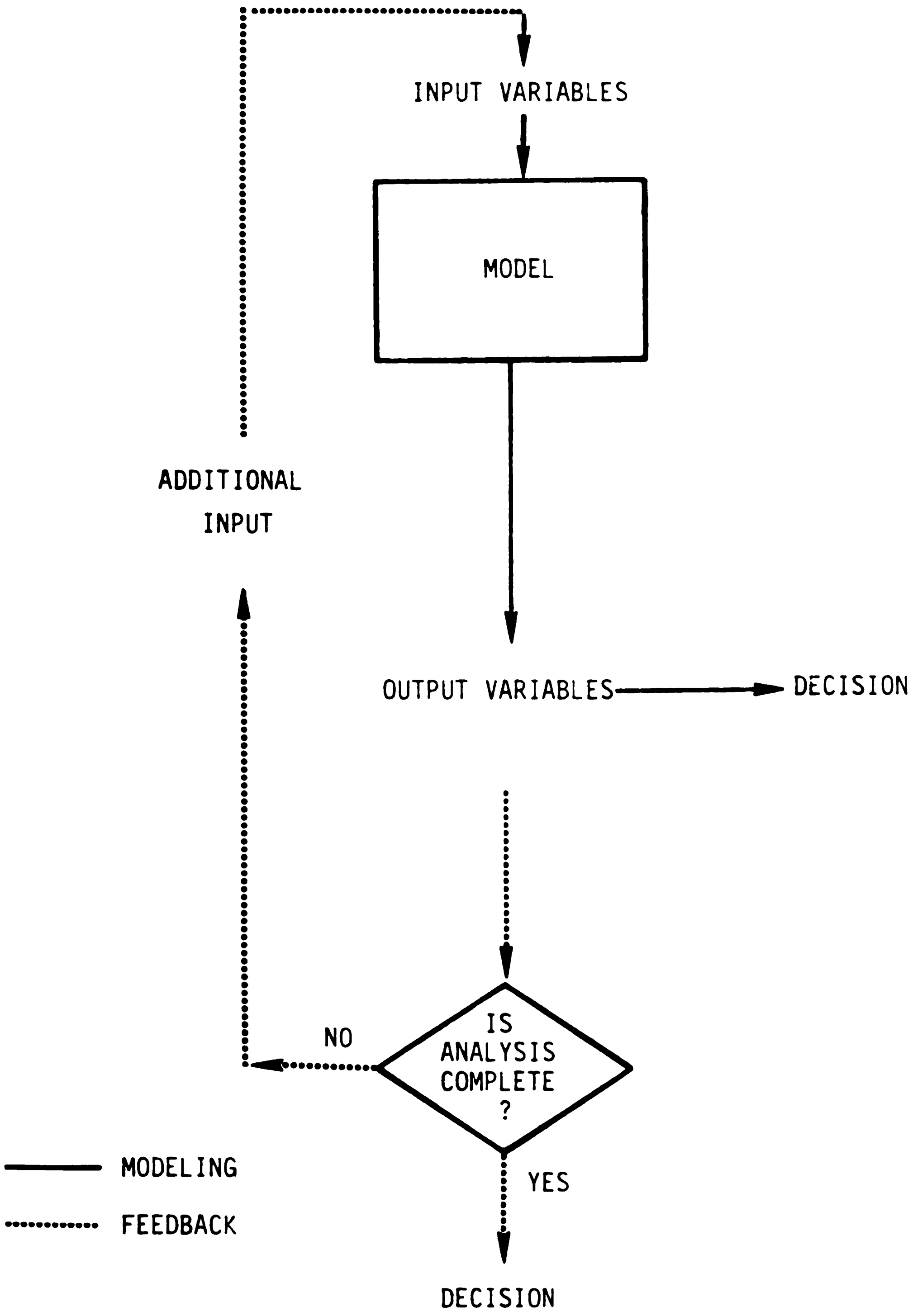

Figure 1. Flow diagram illustrating the modeling and feedback phases of simulation technique.

1. Many times estimates must be used in place of actual data, which will affect accuracy of the results.

2. The entire process of problem analysis, data collection, model construction and validation can be very time consuming and costly.

3. Model validation is problematic, because results may be distorted by programmed biases or unreliable data. This may lead to false security in the results of the simulation.

Since a model is designed to represent a real system, care must be exercised during all phases of development to maintain the integrity of the analysis. A model must not only be verified (checked to ensure that the results are mathematically correct), but also be validated (compared to the real system for degree of accuracy). The decision-maker must determine the suitability of the results in accomplishing the objectives of the study.

Wright (1970) listed nine steps to be taken in simulation.

1. Specify the problem and objectives.

2. Understand the system.

3. Formulate the initial system model.

4. Collect data.

5. Specify a detailed system model.

6. Program the computer.

7. Validate the model.

8. Experiment with the model.

9. Analyze the results.

1.3 Research objectives

Succeeding chapters illustrate the use of computer modelling to determine the technical and economic feasibility of utilizing food processing plant wastes as in-plant boiler feedstocks. The Michigan apple juice industry was selected for analysis to develop and validate the model. Research objectives relating to technical feasibility were:

1. identify and characterize combustible wastes generated by the industry;

2. identify optimal energy conversion technology;

3. determine current operating parameters of the apple processing industry in Michigan;

4. identify and size components for biomass handling and energy conversion systems.

Objectives relating to economic feasibility were:

1. select the appropriate cost analysis method;

2. collect fixed cost data for components of the handling/conversion systems, and variable cost data with respect to systems operation;

3. write and verify a computer model based upon the technical and economic approach developed, applicable for analysis of a variety of food processing operations;

4. validate the model using parameters representive of the Michigan apple juice industry and determine a) the technical and economic feasibility of recovering energy from apple pomace, b) the sensitivity of key operating parameters, and c) the effects of combusting other in-plant wastes in conjunction with apple pomace on feasibility.

CHAPTER 2

Characteristics of the Food Processing Industry

2.1 Energy consumption and cost

2.1.1 By state and Industry Group

According to the U.S. Bureau of the Census (1983a,b), the top 10 energy consuming states in 1981 accounted for 58 percent of all the energy purchased in the U.S., with Texas, Pennsylvania and Louisiana in the top 3 (Table 1). All but 2 states decreased in consumption from 1980-1981, reflecting the slowdown in the economy which occurred during this period. Michigan showed the greatest decrease in the ratio of 1981 to 1980 fuel purchased at 0.92, slightly below the 10-state average of 0.96. However energy costs increased in all states, with ratios ranging from 1.12 for Indiana to 1.27 for Louisiana. California industries paid the highest for energy ($6.47/million Btu or $6.83/GJ), over 100 percent that

Table 1. Energy trends for all Industry Groups in the top 10 consuming states.

	Consumption		Costs		
	1981 (10^{12} Btu)*	1981/1980 Relative Change	1981 ($/million Btu)	Cost Rank	1981/1980 Rel. Change
1. Texas	1,523.7	0.95	3.94	9	1.25
2. Pennsylvania	787.2	0.95	4.99	5	1.17
3. Louisiana	779.0	0.93	3.16	10	1.27
4. Ohio	760.6	0.97	4.59	7	1.14
5. California	615.5	0.95	6.47	1	1.13
6. Illinois	563.3	0.97	5.16	4	1.15
7. Michigan	506.5	0.92	4.98	6	1.15
8. Indiana	481.4	1.02	4.33	8	1.12
9. New York	430.4	1.01	5.78	2	1.18
10. Alabama	309.5	0.96	5.18	3	1.17
Total Top 10	= 6,757.1	$\bar{x}$=0.96	$\bar{x}$=4.66		$\bar{x}$=1.18
Total U.S.	= 11,562.7	$\bar{x}$=0.97	$\bar{x}$=4.78		$\bar{x}$=1.18

Adapted from U.S. Bureau of the Census, 1983a,b. *(See Appendix 2 for conversion factors) of Louisiana. Michigan firms paid an average of $4.98/million Btu ($5.25/GJ), slightly above the U.S. average.

In 1981, the Food and Kindred Products Industry (FKPI) Group ranked sixth nationally in terms of fuel and electrical energy consumption, purchasing 913.1 trillion Btu (963,000 GJ), or 7.8 percent of the total consumption of 11,562.7 trillion Btu (12,199,000 GJ) (Table 2). The average energy cost was $4.78/million Btu ($5.04/GJ) for all industry groups, ranging from $3.72-$8.28/million Btu ($3.92-$8.73/GJ) for 1981. Energy costs for the FKPI Group were $4.81/million Btu ($5.07/GJ), up 17.6 percent from 1980 costs. Regarding the value of product shipments, the FKPI Group ranked first, with a value of $272,136.6 million, or 13.5 percent of the total of $2,017,542.5 million.

Several trends in energy usage can be noted during the period of 1967 - 1981 (Table 3). U.S. energy consumption peaked in 1971 at 1,030.3 trillion Btu (1,087,000 GJ) before declining to 958.8 and 913.1 trillion Btu (1,011,000 GJ and 963,000 GJ) in 1974 and 1981, respectively. The decrease during that 10-year period partly reflects energy conservation practices which were initiated as a result of the increased fossil fuel costs beginning in the 1970's. Greatest cost increases were for petroleum fuels, with 1029, 956 and 881 percent hikes for residual oil, fuel oil and natural gas, respectively. Coke and breeze, coal and electrical energy had price increases of 493, 464 and 340

Table 2. Energy consumption and value of product shipments for major U.S. Industry Groups, 1981.

Industry	Total Purchased Fuels and Electrical Costs			Value of Product Shipments	
	10^{12} Btu	\$/million Btu	cost rank	millions \$	rank
1. Chemical, allied prod.	2,630.2	3.96	2	180,459.2	5
2. Primary metal indust.	2,240.6	4.76	5	141,942.1	6
3. Paper, allied prod.	1,262.2	4.36	4	80,223.8	9
4. Petroleum, coal prod.	1,137.4	4.14	3	224,131.4	2
5. Stone, clay, glass prod.	1,077.5	3.72	1	48,000.4	15
*6. Food, kindred prod.	913.1	4.81	6	272,139.6	1*
7. Fabricated metal ind.	351.9	6.35	10	123,661.6	8
8. Transportation equip.	329.1	6.69	11	205,221.7	3
9. Machinery, exc. electr.	324.8	7.01	13	201,539.1	4
10. Textile prod.	292.3	5.83	7	50,262.2	12
11. Elec., electronic equip.	235.0	7.73	14	140,194.4	7
12. Rubber, misc. plastic pr.	222.7	6.97	12	53,172.8	11
13. Lumber, wood prod.	184.8	6.29	8/9	46,807.1	16
14. Printing, publishing	91.1	8.28	15	77,260.6	10
15. Instruments, related pr.	78.5	6.29	8/9	48,291.4	14
Industry Total	11,562.7	$\bar{x}$= 4.78		2,017,542.5	

Adapted from U.S. Bureau of the Census, 1983a,b.

Table 3. Trends in energy costs by fuel type for major U.S. Industry Groups and the Food and Kindred Products Group, 1967-1981.

	U.S. Industries Energy Costs ($/million Btu)			Food & Kindred Products Group (% Usage)			
Fuel Purchased	1981	1967	% Change	1981	1974	1971	1967
Electrical energy	11.23	2.55	340	15.5	13.2	11.7	9.3
Distillate oil	6.55	0.62	956	2.7	8.0	7.4	6.6
Residual oil	4.74	0.42	1029	6.6	7.8	7.3	8.2
Coal	1.58	0.28	464	13.0	9.5	13.6	24.0
Coke & Breeze	4.21	0.71	493	0.2	0.2	0.2	0.2
Natural gas	3.14	0.32	881	51.6	57.1	57.9	49.8
Other fuels	--	--	-	10.4	4.2	1.9	1.9
				100.0	100.0	100.0	100.0
Total Energy Consumption Trends (trillion Btu) -				913.1	958.8	1,031.3	899.6

Adapted from U.S. Bureau of Census, 1983a,b; ME Caspar, 1977.

percent, respectively, during this period.

2.1.2 Within the Food and Kindred Products Group

Within the FKPI Group, electrical energy usage increased markedly from 9.3 to 15.5 percent of all energy purchased during 1967-1981 (Table 3). The use of "other" fuels (including liquid petroleum gases) also increased from 1.9 to 10.4 percent. Use of coal dramatically decreased from 24.0 to 13.0, while distillate and residual oil usage decreased only slightly and there was no change in the use of coke and breeze. Natural gas usage increased from 49.8 to 57.9 percent in 1971, before gradually declining to 51.6 percent in 1981.

Energy consumption for the industries within the FKPI Group ranged from 153.3 trillion Btu (161,700 GJ) for Grain Mill Products to 50.2 trillion Btu (52,964 GJ) for Bakery Products (Table 4). Preserved Fruits and Vegetables ranked third with 113.6 trillion Btu (119,855 GJ), behind Sugar and Confectionary Products with 127.8 trillion Btu (134,837 GJ). Energy costs for this Group ranged from $3.63/million Btu ($3.83/GJ) for Sugar and Confectionary Products to $6.09/million Btu ($6.43/GJ) for Miscellaneous Foods and Kindred Products. These costs for the nine industries were fairly dependent upon total energy consumption; the larger operations generally had lower overall costs/heat unit than

Table 4. Energy consumption and costs and the value of product shipments for industries within the Food and Kindred Products Group, 1981.

Industry	Energy Consumption and Costs 10^{12} Btu	Rank	$/million Btu	Value of Product Shipments millions $	Rank
1. Grain mill products	153.3	8	4.11	31,914.7	4
2. Sugar & confec. prod.	127.8	9	3.63	16,282.7	9
3. Preserved fruit & veg.	113.6	4	5.41	27,719.5	5
4. Beverages	111.9	6	4.90	36,074.9	3
5. Fats & oils	109.1	7	4.32	17,948.8	7
6. Meat products	103.4	5	5.32	65,909,0	1
7. Dairy products	87.3	2	5.65	36,941.6	2
8. Misc. foods & kindred prod.*	56.4	1	6.09	22,443.5	6
9. Bakery products	50.2	3	5.61	16,904.9	8
Food & Kindred Prod. Ind. =	913.1		$\bar{x}$=4.81	272,139.6	
All U.S. Industry Groups=	11,562.7		$\bar{x}$=4.78	2,017,542.5	

*Includes seafoods, coffee, macaroni, food preparations.

Adapted from U.S. Bureau of the Census, 1983a,b.

did the smaller ones due in part to the economy of scale of operation (larger plants normally have higher ouput per unit of total cost than do smaller plants).

In terms of the value of product shipment, Meat Products were ranked first, with a total value of $65,909 million in 1981. Second and third were Dairy Products and Beverages, with $36,942 and $36,075 million, respectively. Least valued shipments were from Sugar and Confectionary Products, with $16,283 million. Preserved Fruit and Vegetables ranked fifth in value at $27,719 million.

From this overview, energy costs are substantial for the Food and Kindred Products Industry Group. It was the sixth largest energy purchaser in 1981, utilizing almost 8 percent of the total energy, and ranked sixth most efficient in terms of cost/heat unit. This industry shipped the highest valued products of all Industry Groups.

2.2 Generation of food plant wastes

2.2.1 Biomass wastes

2.2.1.1 National level

In 1968 the Office of Solid Waste Management, U.S. Environmental Protection Agency, conducted the first national survey of solid waste disposal by food processors. The areas covered in the survey were for canned, frozen and dehydrated foods, and later the following conclusions were published (Hudson, 1978):

1. The food processing industry produces approximately 18,600 million lb (8,437 million kg) of solid residual per year.

2. Of this amount, fruit and vegetable processors generate 93 percent of the residuals, or 17,200 million lb (7,802 million kg). Specialty processors (baby foods, soup, stew, TV dinners,

spaghetti) account for 4 percent or 741 million lb (336 million kg), while seafood processors account for 3 percent or 560 million lb (254 million kg).

3. An additional 637 million lb (289 million kg) are disposed of as liquid waste by these industries, or approximately 16 percent of the total wastes generated.

The type and size of processing plant operation will greatly influence the kinds of wastes produced. For example, for each ton (1000 kg) of raw apples processed, the following wastes are generated: 5000 gal (20,861 lit) of of waste water containing 5.0 lb (2.5 kg) of suspended solids, and 600 lb (300 kg) of solid residuals. From citrus processing, however, 3000 gal (12,517 lit) of waste water are produced for each ton (1000 kg) of raw fruit, along with 5.0 lb (2.5 kg) of suspended solids and 220 lb (440 kg) of solid residuals (Woodruff and Luh, 1975).

Processing operations produce such solid residues as peelings, trimmings, cores, stems, pits, culls of undesirable fruits or vegetables, nut shells, kernal fragments and grain hulls. The physical properties of these wastes will be discussed in a later section. Liquid wastes arise from several processing operations. Waste water with low levels of suspended solids arises from hydro-handling systems and product cleaning operations, which require periodic replacement to remove accumulated field and chemical contamination. This may be disposed in sewage or irrigation systems, provided no toxic chemical levels are present. Liquids containing toxic constituents, such as salt brines from pickling cucumbers or lye from caustic peeling operations, must be detoxified prior to disposal.

Peeling operations generate the largest amount of liquid wastes in the food industry, followed by blanching operations (White, 1973). Both of these latter wastes contain high amounts of suspended solids and require some treatment before being released to the environment.

2.2.1.2 Michigan food processing industry

Solid waste quantities produced by Michigan food processors in the 1981-82 season were estimated from data published by the Michigan Agricultural Reporting Service (Table 5). Estimates for each crop were calculated by multiplying the total production amount for each crop by the corresponding waste fraction. The total amount of residues for Michigan was estimated to have been 7,827.1 million lb (3,550.3 million kg), fresh weight. The moisture content (MC) for fresh fruits and vegetables has a range of 77 to 96 percent, wet basis, while processed food wastes from pressed products may have MC as low as 52 percent for grape pomace to over 70 percent for apple pomace, depending upon the method and efficiency of the press.

The total amount of solid wastes for Michigan is disproportionally higher than the national total, since wastes from sugar beet processing accounted for 96.4 percent of the MIchigan total. Without beet wastes, 283.0 million lb (128.4 million kg) of wastes were generated, which is 1.5

Table 5. Major processed commodities and solid waste estimates for Michigan, 1981.

COMMODITY	AMOUNT PROCESSED (million kg, fresh wt)	MOISTURE CONTENT (%,wet wt)	PROCESSING WASTE FRACTION	SOLID WASTE ESTIMATE (million kg,fresh wt)
1) Sugar beet - root	2,086.5	84[3]	.64[7]	1,335.4
- top (animal feed)	2,086.5	84	1.00[7]	2,086.5
2) Potato - processed & chips	222.3	79	.05	11.1
3) Apple - juice	98.0	84	.25[6] (pomace)	24.5
- canned, frozen	92.5	84	.35	32.4
4) Tomato	107.0	94	.33	35.3
5) Pickling cucumber	91.4	96	.05[5]	4.6
6) Cherry - tart & sweet	58.5	86	.05[2] (pit)	2.9
7) Grape - juice & wine	46.6	77	.12[6] (pomace)	5.6
8) Snap bean	32.8	89	.07	2.3
9) Carrot	22.0	89	.33	7.3
10) Prune, plum	7.8	81	.05[2] (pit)	0.4
11) Asparagus	5.3	94	.30	1.6
12) Peach	2.4	89	.08[2] (pit)	0.2
13) Strawberry	1.8	86	.10	0.2
TOTALS	4,961.4			3,550.3

1) Michigan Agric. Rept. Serv., 1982; 2) Winton and Winton, 1935; 3) White and Plaskett, 1981; 4) Ben-Gera and Kramer, 1969; 5) Hudson, 1978; 6) Kranzler and Davis,1981; 7) Stewart, 1981.

percent of the national total for the fruit and vegetable processing industry.

2.2.1.3 Michigan apple juice processing industry

In 1982 Michigan ranked third nationally in terms of apple production, with a harvest of 980 million lb (444.5 million kg) (Figure 2). Of this amount, 365 million lb (165.6 million kg), or 37.2 percent, was consumed by the fresh market and the balance of 615 million lb (279.0 million kg), or 62.8 percent, was divided among the processed products (Figure 3). The bulk of processed apples went for juice and cider (37.5 percent), while the remainder decreased in percentage as canned (14.6), frozen (9.8) and other, including vinegar, jam and wine (0.9). During the past five years the apple processing industry has been shifting to produce more juice and cider and less canned and frozen products to meet a growing consumer demand for juice. This trend is expected to continue through the 1980's (Ricks, 1981).

Juice processors must not only contend with increasing energy costs, but also with a large volume of by-product in the form of apple pomace (or presscake), the solid residue which remains after the juice is pressed. Pomace is also produced from wine and vinegar operations. An efficient press will remove about 75 percent of the fresh weight of the

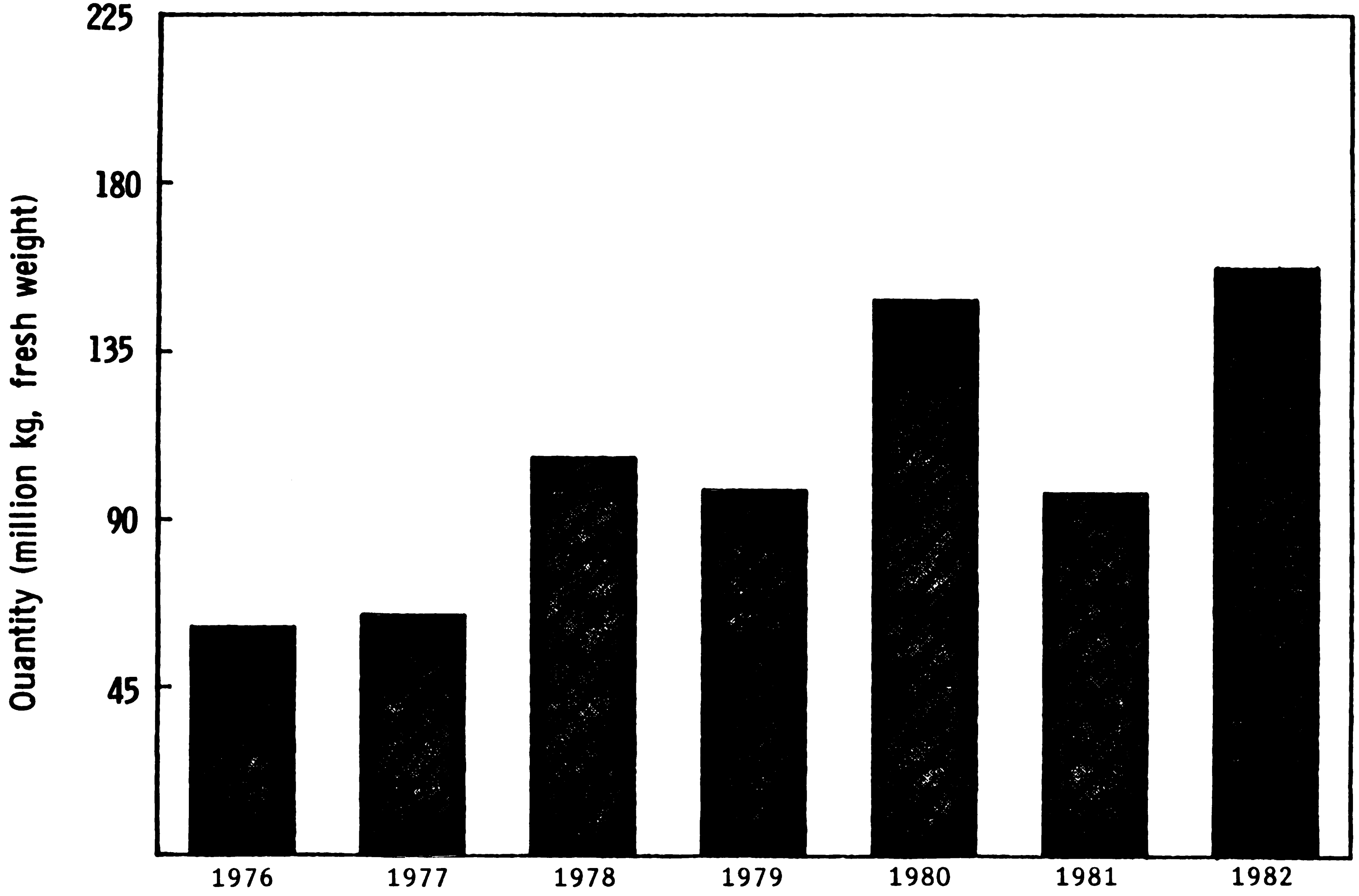

Figure 2. Process apple utilization for juice and cider in Michigan, 1976-1982 (Michigan Agricultural Reporting Service, 1983).

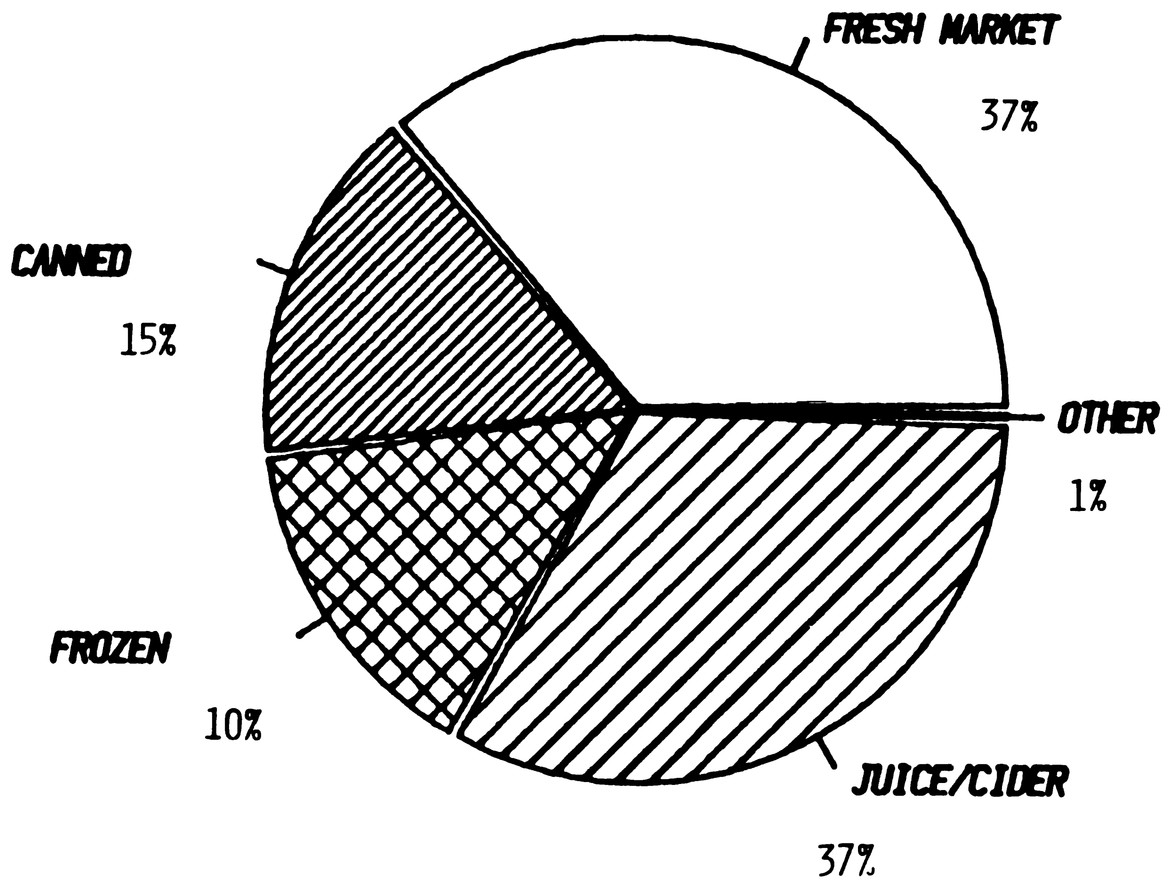

Figure 3. Michigan apple utilization for the 1982-1983 processing season (Michigan Agricultural Reporting Service, 1983).

apple, leaving the pomace at 65 percent MC (Kranzler and Davis, 1981). Therefore from the 367 million lb (166.5 million kg) of apples pressed during the 1982-83 season, about 92 million lb (41.6 million kg) of pomace required disposal in Michigan.

For large processors, up to 100 tons (90,718 kg) of pomace are produced per day of operation, posing a significant disposal concern since pomace cannot be left in the plant. The high moisture content and presence of soluble sugars in pomace permits rapid fermentation, providing an excellent media for microbial pathogens, insects and other pests, as well as objectionable odors (Smock and Neubert, 1950).

2.2.2 Other processing plant wastes

Non-food processing wastes are generated from shipping, canning, maintenance and office operations, most importantly packaging materials, but also assorted solid wastes such as office trash, floor sweepings and garbage. In some instances field residues from cleaning or nearby harvest operations must also be disposed. The food industry is the largest consumer of packages, the next being the beverage industry. For 1976, total packaging materials consumption was estimated at 128.3 billion lb (58.2 billion kg) nationally (Mantell, 1975):

	kg (billions)	percent
Paper, paperboard	33.5	57
Glass	10.8	19
Metals	7.6	13
Wood	4.0	7
Plastics	2.3	4
TOTAL	58.2	100

2.3 Waste utilization and disposal practices

Waste physical characteristics, governmental waste discharge restrictions and disposal costs primarily determine the method of disposal for the processor. Returning to the data published by Hudson (1978):

1. For the industry as a whole, 79 percent of the residuals or 14.6 billion lb (6,622 million kg) are utilized as by-products, with the remaining 21 percent disposed as waste.

2. About 97 percent 14.2 billion lb (6,441 million kg) of the residuals utilized as by-products are fed to animals.

3. Of the 4.0 billion lb (1,814 million kg) disposed as

solid waste, 50 percent is placed in landfills (both sanitary and open), 49 percent is spread on the land and 1 percent is burned on-site.

4. Liquid wastes, which carry 16 percent of the total wastes (637 million lb or 289 million kg), are disposed as follows - 50 percent released untreated into streams, lakes, rivers, or oceans, with lesser amounts disposed in public sewer systems. Very few plants utilize on-site treatment or irrigation.

These data are summarized in graphic form (Figure 4).

Public concern and governmental legislation over environmental contamination has reduced the number of wastes which are considered safe for disposal (Hills and Roberts, 1981). Buried processing and municipal wastes (refuse tips) may produce temperatures up to 300°F (150°C) as well as gases such as methane, carbon monoxide and hydrogen sulfide due to microbial decomposition under anaerobic conditions. Methane may accumulate and begin to seep from the tip, creating the danger of explosion. A pilot project to recover such gases was initiated prior to 1979 at a municipal landfill in the Los Angeles area, with estimates of recovery of 4.5 billion gal (17 billion lit) per year over a 15 year period (Burnett, 1979). Several other examples of by-product disposal practices and utilization follow.

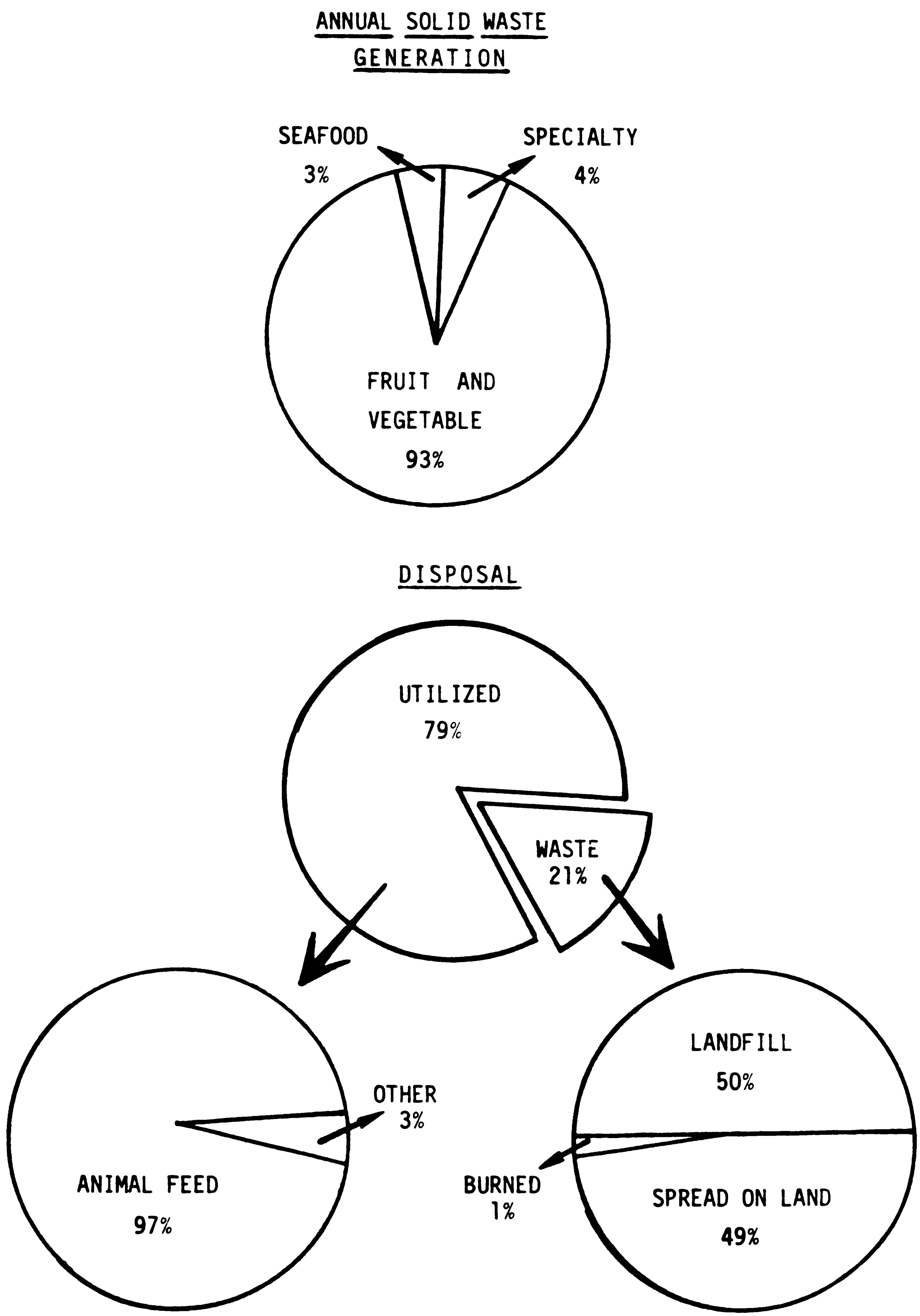

Figure 4. Waste generation and disposal in the U.S. Food Processing Industry.

Cannery wastes make a very palatable and nutritious animal feed supplement. Often the wastes are transported and fed in the same form as when they are produced. Such wastes may have high MC (above 50 percent) originating from screening, trimming, peeling and pressing operations. Potato and corn by-products are sold as cattle feed (Licht and Revel, 1981), while apple pomace is given to cattle operators for the cost of transportation. Pomace is fed to beef cattle as a fiber substitute. Feeding to pregnant cows is not recommended, since those fed pomace supplemented with non-protein nitrogen gave birth to dead or weak calves, the cause undetermined (Fotenot, *et al.*, 1977). Further studies on the nutritional aspects of apple pomace in beef cattle are currently in progress (Waller, 1983).

Prepared feeds are made from sugar beet pulp and citrus pomace, which are dried, treated with nutrient additive and packaged prior to shipment (Henderson and Kesterson, 1965). These wastes account for the greatest portion of wastes utilized as feed and have the advantage of longer storage periods and reduced loss of nutrients when compared to high MC feeds due to less microbial action (Pugsley, 1975). Recently, apple pomace became available as a flavor/fiber ingredient for the baking industry (Apple Fiber and Rice Crunch; Mid-America Food Sales, Northbrook, Illinois 60062). Other residues are by nature of low MC, and include grain pieces and rice hulls; rice hulls, while added to feed rations, are not recommended for use as a solitary feed due to possible abrasion in the digestive tract of the animal (Hsu and Luh, 1980).

Other uses of by-products with economic importance, are most notably production of pectin from citrus wastes (Henderson and Kesterson, 1965), bedding from hulls and shells and extraction of chemicals (e.g., furfural from corn cobs, Arnold, 1975). Soil incorporation of tomato and fruit cannery wastes has been demonstrated by first spreading the wastes on the topsoil at rates up to 223,050 lb/ac (250,000 kg/ha), followed by disking. No soil or groundwater contamination by heavy metals occurred at these rates (Timm, *et al.*, 1980; Noodharmcho and Flocker, 1975). Conversion of high MC wastes to humus is feasible by composting (Rose, *et al.*, 1965; Toth, 1973). Many growers dispose of apple pomace as a mulch on their orchards, but must periodically neutralize the acidity added by the pomace by incorporating lime into the soil. The fresh pomace left in the orchard has potential to act as a host for disease organisms, and adds to weed control problems due to seeds which germinate the following spring.

2.4 Conversion of processing wastes into energy

2.4.1 Energy conversion methods

Several processes exist which can transform biomass into energy. Selection of the appropriate process is dependent upon several factors: the physical state of the biomass (initial moisture content, the heat value, physical properties), the efficiency of the energy conversion process, energy demands of the plant and economic feasibility. The following methods have proven technically feasible for a wide spectrum of processing wastes: anaerobic digestion, in which microorganisms breakdown biomass materials to produce methane gas and carbon dioxide; fermentation, in which yeasts ferment simple sugars into ethanol; and thermochemical conversion, in which heat is released by thermochemical reaction (White and Plaskett, 1981).

Anaerobic digestion and fermentation are best suited for conversion of wet processing residues to fuels, such as cannery wastes (Lane, 1979). Citrus juice extractor residues (peel, pulp, seeds) and the press liquor resulting from dewatering of these residues, show potential for utilization as substrates to produce fermented products (Graumlich, 1983). Of the three, thermochemical conversion produces the highest amount of heat per unit of fresh product (Hall, 1981), and has proven cost-effective on an industrial scale for conversion of a variety of waste materials into usable energy, such as process steam or electricity (Table 6). With assistance from governmental funding, Knouse Foods, Inc. has demonstrated the possibility of converting apple pomace into process steam and cogenerating electricity by direct combustion (Schwieger, 1982).

Conversion of industrial solid wastes to useful energy is growing in acceptability. In 1977 it was estimated that approximately 15 percent of non-wood processing wastes were converted into energy, equivalent to 90.0 trillion Btu (94,900 GJ) (Tillman, 1977). In 1980 a plant in Cheboygan, Michigan began combusting plastics, cellulose fibers and factory and office trash, generating up to 28 million Btu/hr (29.5 GJ/hr) and saving over $350,000/year in fossil fuel costs and over $550,000/year in disposal costs (Reason, 1982).

Municipal solid wastes (MSW) are converted to produce approximately 41.2 trillion Btu (43,400 GJ) per year in the U.S. (Tillman, 1977). Composition of MSW was estimated to be 80 percent organic combustibles (food wastes, paper, plastics, leather, rubber, wood) and 20 percent inorganic non-combustibles (glass, metal) (Baum and Parker, 1973). Conversion of MSW requires extensive presorting to remove the inorganic residues and has proven cost-effective on a municipal scale basis.

There are three methods of thermochemical conversion of biomass. Direct combustion occurs when the biomass is oxidized with air in excess of stoichiometric requirments and

Table 6. Industrial conversion of by-products into usable energy by direct combustion.

BY-PRODUCT	RESULTANT ENERGY PRODUCED	LOCATION	REFERENCE
Walnut hulls	Steam, electricity	Stockton, CA	Anonymous, 1981
Pecan shells	Steam	Florence, SC	Howard, 1981
Apple pomace	Steam, electricity	Orrtanna, PA	Schwieger, 1982
Plastic, paper waste	Steam	Charlevoix, MI	Reason, 1982a
Solid municipal waste	Steam, electricity	Saugus, MA	Cheremisinoff, 1980
Sugar cane bagasse	Steam, electricity	Kauani, Hawaii	Reason, 1982b

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held above the ignition temperature, assuring complete combustion. The stoichiometric requirement is the theoretical amount of oxygen necessary to completely oxidize the carbon, hydrogen, sulfur and trace elements in the biomass to produce primarily carbon dioxide, water vapor and heat (Fryling, 1966). Derived fuels are obtained when the combustion air is sub-stoichiometric (gasification) or absent (pyrolysis, or carbonization). Gasification produces biogas, or producer gas, while pyrloysis produces charcoal or char liquid, both of low-to-medium heat value.

The derived fuels (methane, ethanol, biogas, charcoal and char liquid) contain more heat value per unit of final fuel weight and are therefore more economical to transport and store than the raw residue. But direct combustion results in the highest heat value per unit of raw biomass material (Hall,1981). The wood products industry has utilized direct combustion for years to produce steam and heat for drying kilns, and more recently to cogenerate electricity (Jamison, 1979).

Conversion efficiencies of direct combustion, anaerobic digestion and submerged microbial fermentation were determined for apple and grape pomace (Kranzler, *et al*., 1983). Direct combustion releases 752 Btu/lb (1,750 kJ/kg) of fresh apples, whereas anaerobic digestion and fermentation release 395.0 and 38.7 Btu/lb (920 and 90 kJ/kg), respectively. Heat values for grape pomace were 550.3, 236.5 and 12.9 Btu/lb (1,280, 550 and 30 kJ/kg) of fresh grapes for direct combustion, anaerobic digestion and fermentation, respectively. Of the three methods, it was concluded that direct combustion is the most efficient means to convert pomace and least complicated method to retrofit to existing steam generating systems. Anaerobic digestion was considered viable, although less efficient, while fermentation was a decidedly disadvantageous alternative for pomace conversion due to the low heat value and complex equipment required. Solid-state fermentation of apple pomace produced approximately 4.3 percent alcohol by weight, and increased protein in the remaining pomace by 50 percent, improving the animal feed value (Hang, *et al.*, 1981).

2.4.2 Selection of direct combustion process

Thermochemical conversion of pomace by the direct combustion process was selected as the optimal method for in-plant conversion of fruit and vegetable processing wastes to recoverable energy for the following reasons:

1. direct combustion generates the most heat per unit fresh biomass;

2. in-plant production and combustion is more energy efficient than other conversion processes;

3. efficient biomass combustion boiler systems are readily available to the industry and have less complex operation than those for other conversion process;

4. the ash by-product of combustion accounts for a small portion of the initial volume, greatly reducing disposal costs, and has potential for utilization as a fertilizer (Hsu and Luh, 1980) and as a component for ornamental plant media (Regulski, 1983).

CHAPTER 3

Technical Considerations for Processing Wastes

3.1 Physical properties

3.1.1 Apple pomace

Handling and energy conversion of processing wastes are highly dependent upon the physical characteristics of the material. A description of a typical apple juice processing plant will clarify the physical origin of pomace. Whole apples brought to the processor are held in common storage until scheduled for pressing (Figure 5). Lower grade fruits (usually those not suitable for fresh market due to physical blemishes, handling injury or small size) are inspected and washed prior to grinding by a hammermill (Smock and Neubert, 1950). In plants with simultaneous canning or freezing operations peelings and cores are also fed into the hammermill.

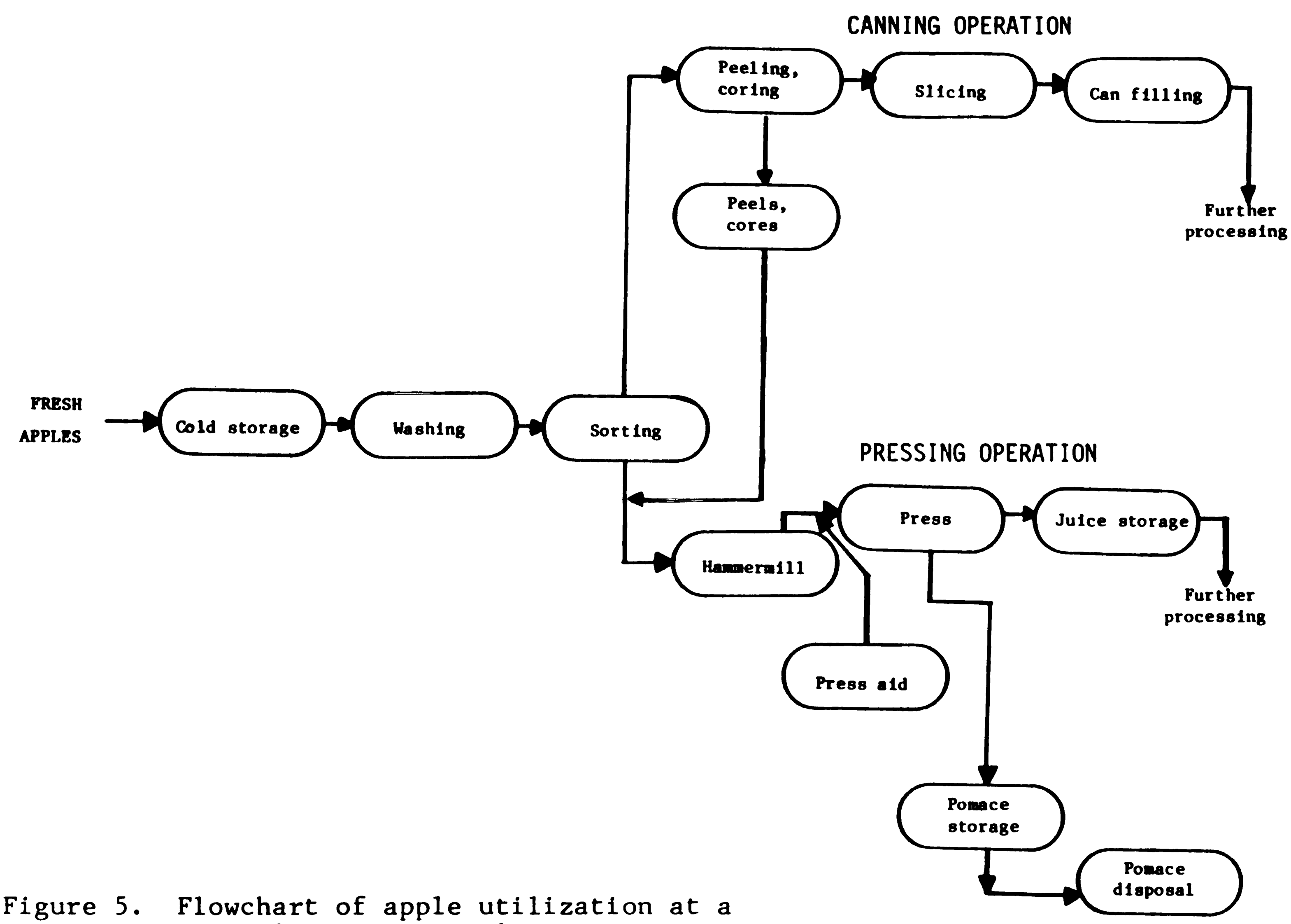

Figure 5. Flowchart of apple utilization at a typical processing plant.

Upon grinding, rice hulls or loose cellulose fibers are metered into the mixture at a rate of 2-4 percent weight/weight basis as a press aid, which improves juice extraction efficiency. Rice hulls are especially desirable since the hard texture and waxy surface layer renders the hulls almost totally impermeable to juice infiltration. Press aids are believed to create channels for the juice to flow more freely from the pulp during the pressing operation (Moyer, 1967).

After pressing, a belt conveyor or screw auger is generally used to remove pomace from the plant. Clumps of pomace may form during conveyance, most notedly in the case of the screw auger. Although particulate, pomace is very cohesive due to a high moisture content (a minimum of 65 percent, wet basis) and a high sugar content (17.5 percent, dry basis; Fotenot, *et al.*, 1975). For this reason pomace cannot be stored in the plant for extended periods of time, since fermentation begins in the pile, creating objectional odors and heat.

Little data is available regarding the mechanical properties of apple pomace which would be useful in conveyance and storage applications. Preliminary tests were performed to obtain estimates for bulk density under at compression and kinetic angle of repose. The bulk density ranged from 8.4 lb/ft^3 (135 kg/m^3) for bone dry pomace, to 24.0 lb/ft^3 (385 kg/m^3) for pomace at 68 percent MC. The angle of repose was 37° and 32° for bone dry and 68 percent MC pomace, respectively. A complete description of the procedures and data are described (Appendix 1).

3.1.2 Other processing wastes

Bulk densities for processing plant wastes must be known for accurate sizing of conveyance systems. Values for several wastes range from 1.0 lb/ft^3 (16.0 kg/m^3) for expanded polystyrene to 48.1 lb/ft^3 (770.0 kg/m^3) for oak (Table 7). Those wastes with high initial MC (such as uncompacted vegetable waste) will have significantly lower bulk densities if dried.

Packaging wastes typically have a MC below 15 percent, which is favorable for in-plant storage; however other handling problems are created. Nails, staples and wire bindings must be removed from such items as pallets, crates and paper boxes in order to avoid excessive wear on equipment. Metallic objects have been reported to ignite dry biomass from sparks generated by handling equipment, especially hammermill size reducers (Kut and Hare, 1981). Removal of metal fasteners would increase hand labor costs, while loose metal objects could be removed by an in-line metal detector/removal system prior to any shredding operations. Plastics likewise require no drying (2 percent MC), although ambient temperatures must be maintained below

Table 7. Bulk densities for selected industrial wastes.

		kg/m^3	lb/ft^3
1)	Folded newspapers, cardboard packed or baled	500	31.2
2)	Loosely crumpled paper	50	3.1
3)	Loose waste paper (in sacks)	20	1.2
4)	Uncompacted vegetable waste, separated food wastes (70-80%)	200	12.5
5)	Cotton gin trash[2]	56	3.5
6)	Oak, 14% MC	770	48.1
7)	Pine, 15% MC	570	35.6
8)	Polystyrene, expanded	16	1.0

[1]Kut and Hare, 1981; [2]Beck and Halligan, 1980

the melting point in order to prevent blockage and untimely maintenance.

3.2 Waste combustion properties

3.2.1 Solid fuel combustion theory

A review of combustion theory will provide better understanding of the fuel characteristics of the biomass wastes. In order for sustained combustion of a solid material to occur, three conditions must be satisfied - proper temperature, time and turbulance. The fuel must be confined for an adequate residence time above the ignition point, the latter being that temperature at which combustion becomes self-sustaining. Turbulance ensures that sufficient oxygen is available to combine with hydrogen, carbon, sulfur and trace elements released during the combustion reaction. With these conditions met the three-stage combustion process begins (Elliott, 1980).

During the first stage any remaining moisture is evaporated from the fuel. This represents a net energy loss, since the heat required to raise the water to the boiling point and the heat of vaporization is equal to roughly 1,118 Btu/lb (2,600 kJ/kg) of water and the fuel temperature is held near the 212^{o}F (100^{o}C). Upon vaporization the second, or flaming combustion, stage begins in which volatile gases evolve from polymeric compounds within the biomass as temperatures rise from 300-1000^{o}F (150-540^{o}C). This phase releases great amounts of heat as the ignition point is surpassed and the process becomes self-sustaining. Gases released include carbon monoxide (later oxidized to carbon dioxide), the parafin series (e.g., methane), the olefin series (e.g.,ethylene), the aromatic series (e.g. benzene), and others, including sulfur compounds and water vapor (Perry and Chilton, 1973). Finally, the remaining fixed carbon is oxidized during the glowing combustion stage, releasing carbon dioxide and leaving ash. The principal reactions concerning direct combustion are described by the following equations (Babcock and Wilcox, 1978).

For carbon:

$$C + O_2 = CO_2 + 32,797 \text{ kJ/kg}$$

For hydrogen:

$$2H_2 + O_2 = 2H_2O + 142,119 \text{ kJ/kg}$$

3.2.2 Combustion emissions considerations

Particulate emissions are the principal pollutants arising from combustion of biomass materials. The amount of fly ash carried by the stack gases varies with the method of combustion, the biomass and the combustion system being employed. Federal standards for stationary sources relevant to biomass fuel combustion are 0.043 kg/MJ for particulates in either coal/wood or gas/wood-fired boilers (Table 8). An excellent review of particulate collectors can be found in the Special Report by the editors of Power (1980). The cyclone collector is commonly used to remove larger particulates and may be adequate for efficient combustion systems. Baghouse collectors can be added if emissions are not met by the cyclone collectors, removing greater than 99.9 percent of the flyash. Wet scrubbers remove fines but require substantial post-treatment of the waste water. Electrostatic precipitators are also widely used where biomass is burned in conjunction with coal.

The most toxic gaseous pollutants to economic crops are sulfur dioxide, hydrogen flouride, ozone, nitrogen dioxide and peroxyacetal nitrate. The principal mode of action is by disruption of biochemical reactions upon pollutant uptake through open stomata (Tibbitts and Kobriger, 1983). Only sulfur dioxide and nitrogen oxides (NO_x) emissions are restricted by the federal government; however these latter pollutants pertain normally to fossil fuels since biomass fuels contain miniscule amounts of sulfur and nitrogen. Conversion of atmospheric nitrogen to NO_x occurs only when combustor temperatures exceed 3,000^{o}F (1650^{o}C) (Babcock and Wilcox, 1978).

Table 8. Federal stationary source emission performance standards.*

SOURCE	POLLUTANT	STANDARD
A. Coal; Coal/Wood	Particulate	0.043 kg/MJ
*Residue-Fired	Opacity	20%; 40% 2 min/hr
Boilers over	SO_2	0.516 kg/MJ
264 GJ/hr	NO_x	0.301 kg/MJ
B. Gas;Gas/Wood	Particulate	0.043 kg/MJ
*Residue-Fired	Opacity	20%; 40% 2 min/hr
Boilers over	NO_x	0.086 kg/MJ
264 GJ/hr		
C. Incinerators	Particulate	0.18 g/dry standard m^3,
over 45.4 Mg/day		corrected to 12% CO_2

*Olexsey, 1980.

3.2.3 Sources of heat loss

As stated previously, adequate turbulance is essential to ensure stoichiometric requirements are met. This is accomplished by introducing excess air into the combustion chamber. Excess air is measured as the percent ambient air added above the stoichiometric requirement, and varies with the fuel, MC and combustor design. Inadequate excess air causes incomplete combustion, resulting in unburned carbon and carbon monoxide leaving the stack and carbon remaining in the ash. Seventy-two percent of the heat value of carbon is lost if CO is not oxidized. Too much excess air results in fly ash being carried in the exhaust gases, severe cooling of the combustion chamber and excessive heat loss, since the air will be heated and exhausted to the atmosphere (Hughes, 1976). Thus precise monitoring of the combustion system is fundamental in establishing and maintaining optimal combustion conditions.

Combustion chamber temperatures must likewise be controlled, since ash becomes molten when heated above the respective fusion temperature. As the ash cools, it congeals into a solid, glass-like substance known as slag. Deposits of slag within a combustor or boiler create costly maintenance problems and greatly reduce heat tramsfer efficiency (Schwieger, 1980). Ash fusion temperatures have been determined for fuel candidates and should be consulted prior to fuel/air adjustments of combustion systems, since the fusion temperatures vary between ash types.

Stack temperatures range from 390 to over 700°F (200-370°C). Although any exhaust gases above the ambient temperature represent an energy loss, a minimum of 390°F (200°C) should be maintained in order to avoid inadequate updraft and condensation which causes corrosion in the heat exchanger and stack (Bender, 1964). These heated gases are the major source of heat loss for power boilers, with lesser amounts being lost to hot ash removal, radiation losses from the system and blowdown (flushing of hot water from boilers as a maintenance routine).

3.2.4 Waste heat recovery

Recovery of waste heat is possible from these sources, and methodology for energy accounting of food processing operations has been described in detail by Singh (1978). A study of food processing plants in the Pacific Northwest identified exhaust gases to discharge up to 18 percent of the total energy lost, followed by dryer exhausts and condenser cooling water (Davis, *et al.*, 1980). Significant savings in energy costs have been realized by recovering waste heat from exhaust gases from the dehydration of citrus wastes (Bryan, 1977) and from wastewater discharged to a drain (Combes and

Boykin, 1981).

As noted in Table 6, besides producing steam or hot water many plants are also cogenerating electricity. In several cases the processor changed from that of an electrical importer to that of an exporter to the local power grid. The pulp and paper industry has shown particular promise, with estimates of 750 trillion Btu (791,000 GJ) in energy savings per year (Johanson and Sarkanen, 1977).

3.2.5 Apple pomace

The primary constituent of pomace is cellulose. Volatile and fixed carbon amount to 95.99 percent of bone dry pomace with the remaining 4.0 percent as ash and 0.1 percent as sulfur and trace elements (Table 9). Ash and sulfur contents are much lower for pomace and other biomass wastes than for coal, and sulfur is also less than that for #2 fuel oil. Natural gas produces virtually no ash or sulfur. Rice hulls contain an average of 17.4 percent ash, and when present in pomace, will raise the overall ash content by less than 1 percent.

Analyses of ash (Table 10) reveal the high level of silicon in rice hulls (95.8 percent), which affects handling characteristics. The presence of rice hulls in the apple pomace is reflected by the high percentage of silicon, as compared to wood or coal ash. Silicon is very abrasive, and

Table 9. Comparison of selected analyses for apple pomace and fossil fuels.

	apple pomace [1]	rice hulls [2]	coal [3]	#2 fuel oil [4]	natural gas (96% methane) [5]
Ultimate Analysis (%)					
Carbon	44.6	39.2	75.5	87.3	74.9
Hydrogen	6.2	5.0	5.0	12.6	25.1
Oxygen	44.8	32.7	4.9	0.004	--
Nitrogen	0.4	2.0	1.2	0.006	--
Sulfur	0.05	0.1	3.1	0.22	--
Ash	4.0	17.4	10.3	--	--
H_2O	--	3.6	--	--	--
Heat Content					liquid
Btu/lb	7,780	5,760 [5]	13,000	18,670	23,885
kJ/kg	18,096	13,398	30,238	43,427	55,557

Ash Fusion Temperature

	bituminous coal [3]	apple pomace [6]	grape pomace [6]
°F	2,450	2,700	2,400
°C	1,343	1,482	1,315

Sources: 1 Kranzler and Davis, 1981; 2 Singh, et al, 1980; 3 Elliot, 1980; 4 Perry and Chilton, 1973; 5 Hsu and Luh, 1980; 6 Kranzler, et al. 1983.

Table 10. Ash analyses for selected biomass and fossil fuels.

	Percent Ash				
	Apple Pomace[1]	Rice Hulls[2]	Grape Pomace[1]	Wood[3]	Coal[3]
Silicon dioxide	83.0	95.8	19.3	33.8	37.6
Iron oxide	0.3	--	1.9	1.6	29.3
Aluminum oxide	0.0	--	23.7	2.6	20.1
Magnesium oxide	1.4	--	5.2	4.7	1.3
Potassium oxide	9.0	--	16.9	0.1	1.6
Calcium oxide	2.2	--	18.9	56.5	4.3
Sodium oxide	0.2	--	1.1	0.5	0.8
Barium oxide	0.0	--	0.2	0.0	0.0
Titanium oxide	0.0	--	0.0	0.2	0.8
Sulfur trioxide	0.7	--	4.4	0.0	0.0
Phosphorous pentoxide	2.3	--	7.7	0.0	0.0
Undetermined	0.9	4.2	0.7	0.0	4.3
Total	100.0	100.0	100.0	100.0	100.0
*Percent ash produced by combustion	4.0	17.4	2.7	0.1	10.3
*Ash fusion temperatures					
°F	2700	--	2400	2580	2450
°C	1482	--	1315	1415	1343

[1]Kranzler, et al., 1983; [2]Nelson, et al., 1950; [3]Babcock and Wilcox, 1978.

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would restrict use of pneumatic handling of dried pomace containing rice hulls. Rice hulls are alternately used as industrial abrasives for cleaning metal parts (Schwieger, 1982).

Bone dry apple pomace has a heat content of 7,780 Btu/lb (18,100 kJ/kg), similar to that for wood, and approximately 60 percent that for coal, since it contains less fixed carbon (Table 9). Rice hulls have a heat content of 5,757 Btu/lb (13,390 kJ/kg). The ash fusion temperature of apple pomace is 2700°F (1,482°C), higher than that for bituminous coal. With combustion chamber temperatures held below the fusion temperature slag deposits will be minimized. The heat content of pomace, as with other biomass fuels, is inversely related to MC. As MC increases from 0 to 20 to 65 percent, the heat content decreases from 7,780 to 5,300 to 1,698 Btu/lb (18,100 to 12,330 to 3,950 kJ/kg), respectively (Kranzler and Davis, 1981).

It would be advantageous to dry pomace prior to combustion for several reasons. With a lower initial MC, more heat would be available to produce steam; any moisture in the fuel must be evaporated prior to combustion, therefore more heat is lost with higher MC fuels. Handling dry pomace requires much less power and has fewer equipment problems than wet pomace and may be stored as a stable biological product prior to combustion. Also, several biomass boilers require a dry fuel for efficient energy conversion. Wood chips are typically stored and combusted at 35 percent MC

(Schwieger, 1980), while 20 percent MC was suggested for apple pomace as a compromise between net heat content and drying costs (Kranzler and Davis, 1981). Pelletizing pomace would produce a dense fuel with a higher heat content per unit mass, but is very energy intensive and was not considered as an option in this study (Swint, 1980).

Ash, fly ash and slag residues have been utilized in several manners. Ash from a gasifier combustion system was determined to be very acceptable with peat as a container media for the nursery industry (Regulski, 1983). Fly ash from coal combustion has proven acceptable as a component for stabilizing aggregates for use as a highway paving (Anonymous, 1976). Recently, coal cinders were evaluated for use as a container media component, and found to contribute significant amounts of micronutrients to growing plants; heavy metals were also added, the possible toxic effects on the plants to be determined later (Neal and Wagner, 1983). These residues are sterile and inexpensive by-product sources.

3.2.6 Other processing wastes

Many processing wastes have significant energy potential (Table 11). Most cellulosic residues have heat contents in the range of 6,000-10,000 Btu/lb (13,956-23,260 kJ/kg) (dry weight), which includes paper and wood packaging wastes, nut

Tab

Table 11. Combustion characteristics of selected processing wastes and residues.

		Heat Content (dry basis)		Ash
		kJ/kg	Btu/lb	%
A.	Packaging Wastes[1]			
**1)	Corrugated paper boxes	17,280	7,429	5.3
2)	Brown paper	17,924	7,706	1.1
3)	Paper food cartons	17,980	7,730	6.9
4)	Waxed milk cartons	27,289	11,732	1.2
5)	Plastic coated paper	17,917	7,703	2.8
6)	Newspaper (packing)	19,724	8,480	1.5
**7)	Polyethylene, polypropylene	44,194	19,000	0.0
8)	Polystyrene	40,123	17,250	---
9)	Polyamides (nylon)	29,657	12,750	---
10)	Polyesters	27,912	12,000	---
11)	Polyurethane	26,749	11,500	---
12)	Polystyrene foam	42,147	18,120	---
13)	Polyvinyl chloride (PVC)	19,189	8,250	2.1
14)	Vinyl	20,539	8,830	0.0
15)	Softwood (pine)	21,283	9,150	0.1
16)	Hardwood (oak)	20,194	8,682	0.1
B.	Field Residues[2]			
1)	barley straw (spring)	18,000	7,739	5.3
2)	barley straw (winter)	17,800	7,653	6.6
3)	bean straw	18,000	7,739	5.3
4)	oat straw	17,900	7,696	5.7
5)	pea straw	17,900	7,696	7.7
6)	potato foliage	17,300	7,438	13.5
7)	rape straw	18,000	7,739	4.5
8)	rye straw	18,200	7,825	3.0
9)	sugar beet tops	15,400	6,621	21.2
10)	wheat straw	17,600	7,567	7.1
11)	corn stover (35% MC, w.b.)[3]	10,730	4,613	4.0
12)	corn cob (15% MC, w.b.)[3]	18,600	7,997	1.4
13)	cotton gin trash (12.5% MC)[4]	18,775	8,072	---
C.	Nut Shells and Fruit Pits[5]			
1)	almond (soft)	19,445	8,360	3.1
2)	black walnut	18,608	8,000	0.3
3)	chestnut	18,375	7,900	n.a.*
4)	English walnut	18,608	8,000	0.8
5)	filbert	19,306	8,300	0.7
6)	peanut	20,469	8,800	8.8
7)	pecan	20,818	8,950	1.8
8)	apricot	19,817	8,520	0.7
9)	cherry	18,143	7,800	0.8
10)	peach	19,073	8,200	0.4

Table

Table 11 (continued).

D.	Assorted Solid Wastes[1]	MOISTURE CONTENT (as received, wet basis)	HEAT CONTENT (dry basis) kJ/kg	Btu/lb
1)	Paper	10.2	17,612	7,572
2)	Wood	20.0	20,033	8,613
3)	Grass	65.0	17,894	7,693
4)	Brush	40.0	18,375	7,900
5)	Greens	62.0	16,461	7,077
6)	Leaves	50.0	16,505	7,096
7)	Leather	10.0	20,585	8,850
8)	Rubber	8.2	26,353	11,330
9)	Plastics	2.0	33,420	14,368
10)	Oils, paints	0.0	31,168	13,400
11)	Linoleum	2.1	19,329	8,310
12)	Rags	10.0	17,798	7,652
13)	Dirt	3.2	8,815	3,790
**14)	Wet fruit wastes	80.0	19,734	8,484
15)	Fats	0.0	38,844	16,700

[1]Baum and Parker, 1973; [2]White and Plaskett, 1981; [3]Claar, et al, 1979; [4]Oursborn, et al, 1978; [5]Mantell, 1975; *not available; ** used in this analysis.

shells, fruit pits and field residues. Plastics, rubber, fats and oils have higher heat contents due to the higher proportion of hydrogen and carbon per unit. The greater percentage of oxygen in biomass materials as compared to plastics, reduces the heat content of these materials, since the carbon and hydrogen are already partly oxidized (White and Plaskett, 1981).

Combustion of plastics increases heat recovery substantially, but requires special attention. Sudden flare-ups in the combustion chamber can occur with flow rates in excess of 10 percent of the total fuel (Kut and Hare, 1981). Combustion of poly-vinyl chloride (PVC) plastic results in the release of chlorine, which combines with hydrogen to form hydrochloric acid (HCl). Severe corrosion occurs in the heat exchanger when HCl condenses on the surfaces. Chlorine is also released from the burning of salt in food processing wastes and paper products. As long as the temperature in the heat exchanger and stack is maintained above the condensation point of HCl (300-660^{o}F or 150-350^{o}C) corrosion problems will be minimized (Baum and Parker, 1973). The sulfur content for plastics (1-2 percent) is not significant.

Biomass wastes with the highest ash contents were sugar beet and potato foliage (21.2 and 13.5 percent, respectively). All other reported values were below that for peanut shells at 8.8 percent (Table 11). The most likely fuel candidates for Michigan processing firms are within the range for adequate emission control; values for cherry and peach pits are less than 1 percent.

Ash fusion temperatures for paperboard, textiles, paper and plastics will not be reached under normal operating conditions in a biomass boiler, and therefore will produce little or no slag (Table 12).

Table 12. Ash fusion temperatures for selected processing wastes.*

ASH	°C
Mixed waste	1,205
Paperboard, textiles	1,227
Plastics, rubber	1,261
Coal	1,330

*(Kut and Hare, 1981; Kranzler, *et al.*, 1983).

Combustion of these residues would require the same emission standards as those for waste-fueled combustors listed previously (Table 8). Limits for HCl emission have not been set at the federal level; however, the State of Michigan allows a maximum of 0.07 mg/m^3 when measured at the property line of the plant. These requirements have been easily met by all waste-fuel facilities in the State (Tilesz, 1983). Fly ash absorbs some HCl while being carried in the flue gas, and any excess HCl can be satisfactorily removed by water scrubbers (Baum and Parker, 1973). It should be repeated that HCl is produced only by combustion of PVC plastics.

3.3 Selection of Handling/Combustion System Components

3.3.1 Handling system

Criteria for selection of system components were based upon four general considerations:

1. pomace availability, including quantities produced, length of processing season and plant processing schedule;

2. types of handling equipment available to the industry;

3. characteristics of the combustion furnaces, including dependability, combustion efficiency, retrofit potential and multifuel capability;

4. equipment costs relating to purchase, installation and maintenance.

The advantages of drying wet processing wastes prior to combustion has already been delineated. Apple pomace flow rates (considered at 65 percent MC) were calculated for two production rates of 30 and 100 tons pomace/day (27,215 and 90,718 kg/day), or 1.9 and 6.3 tons/hr (1,836 and 5,508 kg/hr), representative of a range of firms in the Michigan apple juice industry. When dried to 15 percent MC, the flow rates reduce to 1,667 and 5,000 lb/hr (756 and 2,268 kg/hr). At these rates, 15 percent MC pomace would generate 10 and 30 million Btu/hr (10.5 and 31.5 GJ/hr). Calculations assumed a production schedule of 16 hr/day, 25 days/month and a 5-month processing season (i.e., from September to February).

Handling system components were evaluated and selected from pertinent references and conversations with industrial representatives, followed by sizing according to the pomace flow rate (Figure 6). A rotary drier was selected due to the capability for efficient drying of particulate, high MC materials, and the flexibility for use in batch or continuous operations. The drier was assumed to combust natural gas or fuel oil, but the potential exists to reduce drying costs by recovering waste heat from the boiler stack and introducing into the drier. Waste heat recovery was not assumed in this analysis.

The pomace should be agitated prior to drying to break up any clumps which may have formed. Clumps passing through the drier would be fed through a hammermill and reintroduced

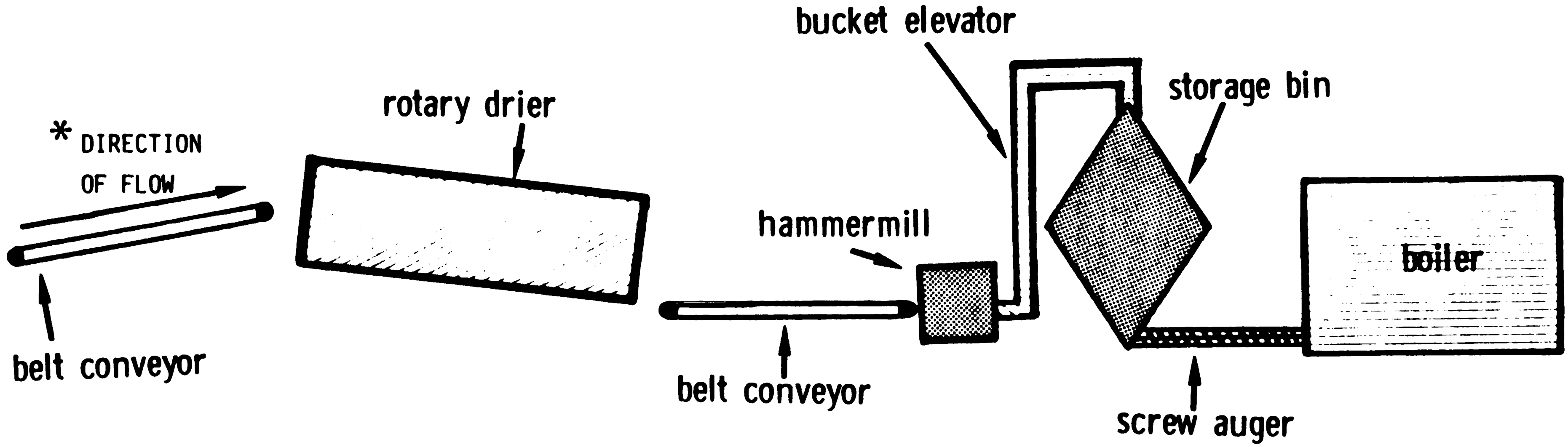

Figure 6. Proposed processing waste handling system components.

into the drier, since clumps case-harden at the surface, thereby reducing drying efficiency. The dry surface acts as an insulating barrier, hindering moisture diffusion from the inside; the clumps could also block subsequent pomace flow and disrupt the combustion process in the combustion chamber.

Upon drying, pomace would be transported by belt conveyor or bucket elevator to a bulk collector for short-term storage. Pneumatic handling would be advisable only for pomace without rice hulls, since the high silica content is very abrasive to transport piping. The hulls could be separated from dried pomace by air classification, which would then permit pneumatic handling and allow the hulls to be recycled on a daily basis as a press aid. Air classification of the rice hulls was not included in this analysis.

The bulk collector would be located outside of the building and adjacent to the boiler room. The purpose of the collector would be for protection against adverse weather with a maximum capacity of one day production. The handling/combustion system was designed for a continuous production schedule; storage would be necessary to prevent accumulation of pomace within the plant in the event of brief shutdowns of the boiler. Screw augers at the base of the collector would transport and meter the pomace to the boiler. Bridging of pomace can be avoided with an appropriate removal system.

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3.3.2 Combustion systems

Several multifuel combustors are available for direct combustion of biomass fuels, fossil fuels and combinations of these fuels. Many of these combustors can be retrofitted to existing boilers or purchased as an integral part of a package boiler. Retrofit combustors require less capital investment than the package boiler systems; however based on conversations with industry representatives, the heat recovery efficiency for retrofit applications decreases by approximately 25 percent through heat losses between the combustor and the heat recovery boiler. Package boilers (those produced at the factory with the combustor and heat exchanger boiler as a single unit) have heat recovery efficiencies of 70-90 percent, depending on the method of construction and flame adjustment.

Three package boiler systems were selected and evaluated for the two pomace production rates assumed in this study. Combustion technologies employed by these systems are known as pile burning, fluidized-bed combustion and suspension firing. The boilers are of the fire tube design and were sized for energy generation of 10 and 30 million Btu/hr (10.5 and 31.5 GJ/hr), based on the respective pomace flow rates at 15 percent MC. Pile burning and suspension firing systems have been extensively used by the wood products industry for combusting wastes ranging from hogged brush to sawdust fines (Bullpit, 1980). Fluidized-bed combustion is a relatively new technology used for burning coal and municipal wastes on a powerhouse scale, but also showing excellent promise for use on a smaller scale for combusting biomass.

In pile burning systems (Figure 7), solid fuel is introduced into the combustion chamber through the bottom grate by a screw auger, forming a pile as it is pushed outward. It may also be pneumatically fed into the chamber from above, where it partially burns in suspension before falling onto the grate. The fuel accumulates in a thick bed pile with combustion occurring at the surface of the pile. This permits fuels of 50-60 percent MC and of non-uniform size to be combusted, since the extended residence time facilitates drying in the combustion chamber. Furnace designs are the dutch oven, fuel cell, cyclone, wet cell, inclined water-cooled pinhole grate, traveling-grate spreader-stoker and vibrating grate (Perry and Chilton, 1973).

Dry, particulate fuels (15 percent MC) are required by suspension firing systems, in which the fuel is pneumatically fed into the combustion chamber (Figure 8). Nearly complete combustion occurs by proportionally metering the air with the fuel flow rate. These systems have been installed in powerhouse operations, and pulverized coal is routinely combined with biomass fuels to increase heat output. Furnace designs are the cyclonic and solid fuel burners (O'Grady,

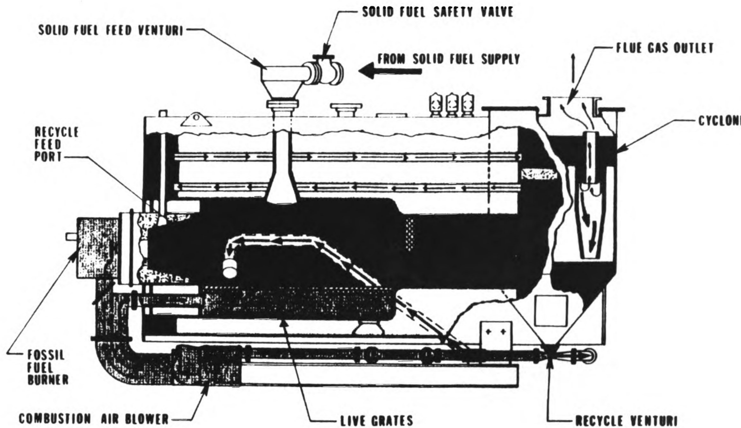

Figure 7. Biomass pile burning boiler (Ray Burner Company).

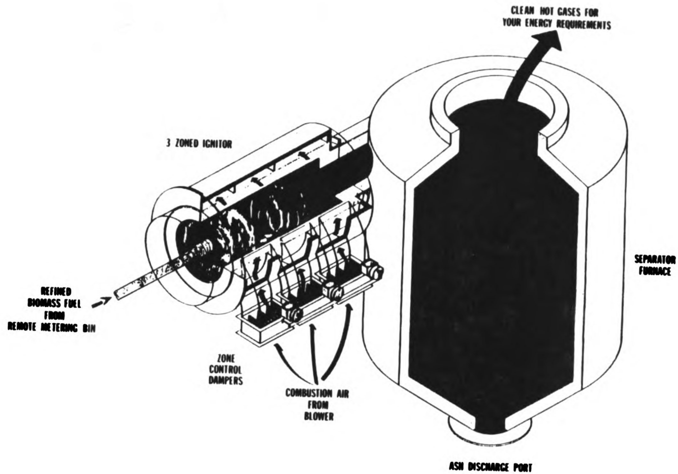

Figure 8. Biomass suspension-fired combustor system (Guaranty Performance Company).

1980).

The current interest in fluidized-bed combustion systems has developed because of the capability of burning a variety of fuels up to 55 percent initial MC at non-uniform sizes. The combustion air is forced upward through a bed of heated sand maintained at approximately 1,700°F (927°C). The air causes the sand particles to become fluidized (Figure 9), at which time the fuel is introduced into the bed, dried and combusted by the continuous agitation from the hot sand particles. Addition of lime to the sand allows combustion of high sulfur coals, the lime acting to absorb sulfur compounds before release to the exhaust gases (LePori, *et al.*, 1981).

Due to the higher amounts of ash derived from thermochemical conversion of cellulosic materials, a rigid schedule must be maintained for removal of ash from the combustion chamber to prevent slag formation. The trend has been to design combustors which have automatic ash removal systems in the grate area which permit continuous operation by elimination of frequent manual cleaning. Several of these systems also separate and reinject unburned char pieces back into the combustion zone, improving efficiency up to 7 percent (Johnston Boiler Co., 1978).

These systems were selected to provide a greater choice for the processor considering investing in biomass conversion technology. Each has advantages and disadvantages (Table 13), and selection of a particular combustor is dependent upon several technical factors, including size of operation,

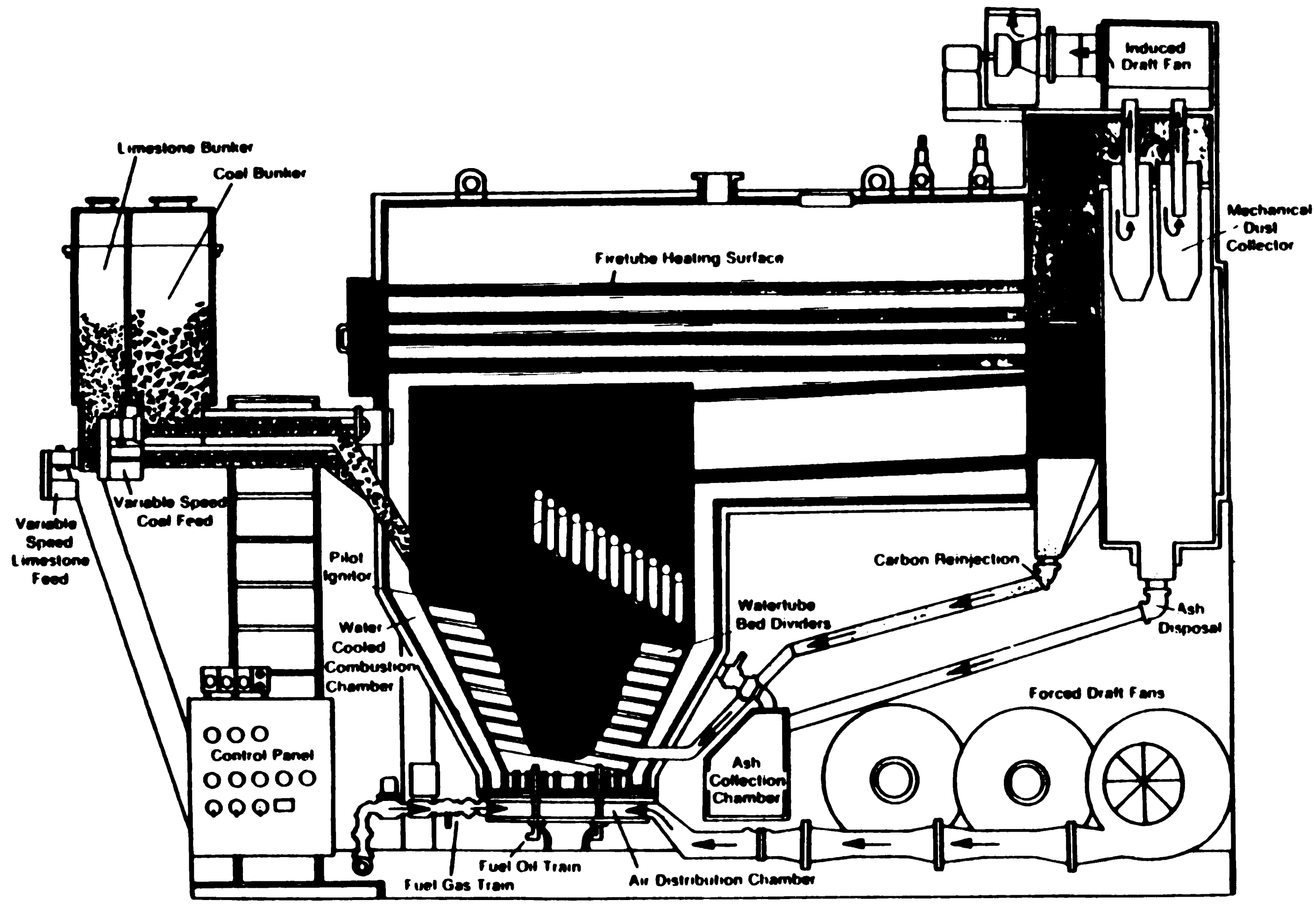

Figure 9. Biomass fluidized-bed combustion boiler (Johnston Boiler Company).

Table 13. Differences between direct combustion systems*.

	ADVANTAGES	DISADVANTAGES
PILE BURNING	1) use of high MC fuels	1) high refractory repair costs
	2) non-uniform fuel size	2) slow response to load changes
	3) simple design and operation	3) manual ash removal (some systems)
SUSPENSION FIRING	1) low particulate emission	1) low MC fuels only
	2) rapid response to load changes	2) uniform fuel particles
		3) pneumatic handling only
		4) very accurate air control required
FLUIDIZED BED COMBUSTION	1) use of high MC fuels	1) slow response to load changes
	2) non-uniform fuel size	2) preheat bed with fossil fuel
	3) package boilers available	3) clinker formation in bed

*Sources: Schwieger, 1980; Bullpit, 1980.

MC of the fuel, need for multi-fuel combustion, energy recovery form required (e.g., steam, hot water, hot air) and presence of abrasives in the biomass. Economic factors will be discussed in Chapter 4. A list of the equipment and manufacturers used in the analysis is provided (Appendix 3).

CHAPTER 4

Engineering Cost Analysis

4.1 Analytical Approach

Cost analysis is a necessary step in the process of determining the overall feasibility of an engineering project. An accurate knowledge of the anticipated costs and returns of implementing a new technology is essential before a decision can be reached regarding its adoption. In this chapter (1) the essential elements of a cost analysis will be outlined along with the basic criteria necessary in selecting a cost analysis method, (2) an analytical method will be presented for this problem and (3) techniques for interpretation of the results will be discussed.

There is a basic difference between the accounting and engineering approaches to cost analysis. The accountant reviews the financial history of a firm in order to explain its current economic status. Engineers, however, are concerned with projecting the economic impact of adopting a new technology on present and future costs. Thus an appropriate cost analysis provides a base from which a promising technology can be realistically evaluated in terms of future returns to the company (Barish and Kaplan, 1978). Projects requiring cost analysis are as diverse as energy conservation/alternative energy sources, machinery design/selection, building structures and new methods or procedures for agricultural operations.

The first step in determining an appropriate cost analysis method is to identify clear-cut, measurable objectives, based upon the constraints of the intended firm. Knowledge of investment requirements and firm constraints establishes the system boundaries of the analysis. Boundaries are necessary in order to control or limit the number of parameters being investigated, enabling an accurate, but manageable analysis. Thus the extent of the analysis would be defined by those parameters having a direct bearing on the feasibility of the investment - total costs, loan interest rates, disposal costs (such as for processing wastes), machinery power requirements, space limitations (in buildings), potential to retrofit into the existing system, etc.

The type of firm will also have bearing on the objectives. Goverment agencies or institutions and large firms are normally able to absorb capital outlays over a longer period of time than smaller firms. Non-profit organizations have different objectives than do private firms, the former having objectives more subjective and intangible than the latter which operate to maximize profits. The availability of grants, special low-interest loans or tax credits can also make some high-cost or high-risk ventures feasible where they otherwise would not be.

4.2 Determination of total costs

4.2.1 Fixed and variable costs

Project costs must be identified and quantified, being classified into two broad groups; as fixed (or investment) costs and as variable (or operating and maintenance) costs. Direct fixed costs are those associated with the purchase of the investment - feasibility studies, equipment and installation, insurance, loan interest and taxes. Indirect fixed costs are associated with administration and plant overhead expenses. Variable costs are reflected in the size and frequency of operation and maintenance upkeep of the investment - the price of energy, labor and repairs, and production materials. Further discussion of variable costs follow in a later section. Non-economic costs include social, political and psychological costs, and are difficult to estimate in terms of real dollars (Blanchard, 1978). For feasibility analyses only present and future costs are included in the calculation of total costs (Barish and

Kaplan, 1978).

4.2.2 Cost estimation

Often it is difficult to obtain exact values for such costs as new equipment, insurance, taxes and maintenance due to lack of data. Accepted methods for estimating these and other costs have been discussed at length (Ostwald, 1974; Humphreys and Katell, 1981).

4.2.2.1 Cost indexes

Cost indexes are compiled to provide a means of converting past data into current costs. Various indexes are published for cost factors such as new equipment, labor rates and materials. They are established by collecting costs for desired industries during a base year, and setting the indexes equal to 100. Current costs can be determined by:

Present Cost =

Original Cost X (Present Index Value/Original Index Value)

Well-recognized indexes include the Marshall and Swift all-industry indexes, the Engineering-News Record Construction Cost Index and the U.S. Department of Labor materials and labor indexes. Current Marshall and Swift indexes are published in each issue of Chemical Engineering. Caution must be exercised in using indexes, since they are based on cost averages. They likewise should not be used for periods exceeding 10 years (Peters and Timmerhaus, 1968).

4.2.2.2 Equipment scaling

At times cost data are needed for equipment sizes other than those for which data has been obtained. A useful formula for scaling of project size and cost is as follows:

Unknown equipment cost =

$$\text{Known equipment cost X (Unknown size/Known size)}^{n}$$

where "n" is the cost capacity exponent for the given equipment. Values for cost capacity exponents were derived for individual equipment and installation costs in 1961 (Bauman, 1964). Plots on log-log scale were constructed for equipment size vs. cost, and the slope of the line through the points yielded the specific exponent for each piece of equipment. Although the equation describes continuous functions, in reality equipment costs are step functions, since equipment are designed to perform over a fixed range. However for purposes of feasibility studies, the costs can be approximated by continuous functions. The average was 0.6

for all exponents, with a range from 0.16 to over 1.00. Normally the factor corresponding to the type of equipment being analyzed is selected; 0.6 is used only when another factor is unavailable. Scaling should be confined to a ten-fold range based on the data from which the factors are derived.

4.2.2.3 Other parameters

Estimates for annual maintenance costs were given as percent of new investment costs - simple processes: 2-6 percent; average operating conditions: 5-9 percent; and severe or complex operating conditions: 7-11 percent (Peters and Timmerhaus, 1968).

For analyses in which detailed data are available, a more accurate determination of costs can be included. The cost capacity exponent can be determined by the method outlined above to provide greater accuracy in equipment scaling. Calculation of corporate income taxes for a new investment is dependent upon divulsion of proprietary information such as taxable income. Knowledge of the tax bracket, depreciation method and energy tax credits (for some investments) would permit determination of exact taxes which would be incurred over the life of a new investment. For such a specific case depreciation of the investment would be included only as it directly affects tax costs, using an approved method for depreciation calculations. It should be noted, however, that depreciation costs are not included as a direct cost, since they have already been included in the original purchase cost of the investment.

4.3 Life cycle cost analysis

4.3.1 Cost analysis methods

New technologies are many times evaluated and selected or rejected solely on the basis of the lowest initial (or purchase) costs. Another commonly used method, known as payback period, calculates the length of time necessary to pay off an investment, by dividing investment costs by the anticipated savings. This payback period is compared to a previously set maximum. Although both of these methods are simple and involve little calculation time, very inaccurate results and disasterous conclusions can result by overlooking a group of costs which are far more expensive than initial investment costs. These are operating and maintenance costs and the time value of money.

Life Cycle Costing is a cost analysis method which considers not only investment costs, but more importantly the significant costs which would be incurred over the life of the investment, in other words the total cost of ownership.

It is becoming widely adopted in the public and private sectors for investments which are subject to substantial operating and maintenance costs. Life cycle costing (LCC) is influenced by four factors (Brown and Yanuck, 1980):

1. expectation of high energy costs during the life of the investment,

2. a long life span,

3. savings in operating and maintenance costs resulting from the new technology, and

4. high investment costs.

Life Cycle Costing has been effectively applied to evaluate the viability of implementing retort pouch technology (Williams, *et al.*, 1981), energy conservation in residential housing (Jones and Harp, 1981) and farm machinery selection (Rotz, *et al.*, 1983). Therefore the majority of engineering projects requiring cost analysis would be best served by LCC analysis.

4.3.2 Time value of money

Besides including variable costs, a second advantage of LCC is consideration of the time value of money. In order for a firm to make a major investment such as a biomass handling/combustion system, capital would be required, often obtained by a loan. The present value of a sum of money is worth more than its value would be at a later date since the real value of money decreases due to inflation. This concept is referred to as the time value of money, which is often approximated by the cost of borrowing money, and is included in the interest rate charged by lenders. An example would be helpful.

One thousand dollars would be worth only $900 after one year at 10 percent annual inflation; in other words it would take $1100 of future dollars next year to be equivalent to $1000 of present dollars at this inflation rate. Interest rates are set to cover losses due to inflation as well as to provide a margin of profit. The cost of interest (or the opportunity cost of owned capital) is thus an inherent cost of any analysis concerning the cost of capital.

There are six basic formulas for determining the present or future worth (value) of money, encompassing a variety of situations. These are: Single Compound Amount, Single Present Worth, Uniform Capital Recovery, Uniform Present

Worth, Uniform Sinking Fund and Uniform Compound Amount. An excellent description of these formulas and accompanying examples is presented in Brown and Yanuck (1980).

Present worth techniques utilize the above formulas in order to calculate the current value of future dollars. Three techniques pertinent to feasibility analysis are (1) net present value, which calculates the present value of total costs over the life of the investment, (2) uniform annual costs, in which present and future costs are divided into equal annual costs over the life of the investment, and (3) internal rate of return, which determines the discount rate at which present value costs and benefits are equal. Internal rate of return is the least recommended of the three; even though more accurate, it involves complicated iterations by computer or by trial and error. The decision to use either net present value or uniform annual costs would be dependent upon loan restrictions, and in some cases upon guidelines for feasibility studies required by the firm or organization.

4.3.3 Average Annual Cost

After consideration of the above formulas and methods, the Uniform Capital Recovery (UCR) factor was selected for use in this analysis. The UCR factor is used to determine the Average Annual Cost of a loan based on a fixed interest rate and loan repayment period:

Average Annual Cost =

Principle X UCR + Yearly Operating and Maintenance Costs

where UCR =

$$\frac{i(1+i)^n}{(1+i)^n - 1}$$

i = interest rate (decimal)

n = number of interest periods

4.4 Interpreting the analysis

4.4.1 Break-Even Analysis

It is mandatory to determine the length of time which would be necessary to pay back the total costs of a new investment. Use of the payback period method was previously mentioned, but should be limited to inexpensive, short-term investments since the time value of money and variable costs are ignored. Knowledge of the Average Annual Cost (AAC) of the proposed investment and the resultant savings (or losses) as compared to the current system permits calculation of the time necessary to recover the AAC. The point at which AAC equal savings is known as the break-even point. With the Break-Even Analysis the cost/savings history of the investment can be plotted for determination of the true payback period as well as future savings to be expected by the investment (Park, 1973). Energy-related projects are normally considered viable if the payback period is 5 years or less (Lapeau, 1983).

4.4.2 Sensitivity Analysis

Once the results of a cost analysis are available it is important to gain an understanding as to which individual cost variables influence the overall feasibility of the new investment. For example, how would the break-even point be affected by fluctuations in loan interest rates or electrical and fossil fuel costs? The influence of such parameters is determined by performing a Sensitivity Analysis, in which total costs are calculated as each of the costs is varied, one at a time. The value of this method is that even though a particular investment may not be presently feasible, projections can be made as to the economic conditions demanded for it to become feasible. Sensitivity Analysis can also be used to optimize the system by investigating interactions between the parameters and to explore areas of risk or uncertainty (Allen, 1972).

4.5 Feasibility Analysis Data

4.5.1 Fixed cost data

4.5.1.1 Equipment costs and power requirements

Costs and power requirements were obtained from manufacturer representatives for each of the handling system components in August, 1983 (Table 14). These data were based on component sizes calculated for a plant biomass output of 12,500 lb/hr (5,670 kg/hr), w.b., which would represent a large processor. Installation estimates were included with purchase costs for all components. Power requirements included all motors related to fuel handling and combustion air. The rotary drier was the costliest handling system component, accounting for 86 percent of the total handling costs (Figure 10), and 64 percent of the power requirement. The storage bin was sized to contain the biomass from a single day's production (at 15 percent MC).

Table 14. Installed purchase costs and power requirements for handling/boiler system components.

Handling System		Purchase Costs ($)	Power Consumption (kW)
Belt conveyor		14,595	0.67
Rotary drier		259,560	111.63
Hammermill		13,081	54.00
Bucket elevator		8,549	4.50
Storage bin		11,610	--
Screw auger		3,445	2.70
	Total	310,840	173.50
Boiler Systems			
Pile burning		863,720	144.00
Fluidized-bed		734,500	119.00
Suspension-fired		348,906	103.00

Manufacturers' prices for August 1983 for a large processor with biomass output of 12,500 lb/hr (5,670 kg/hr).

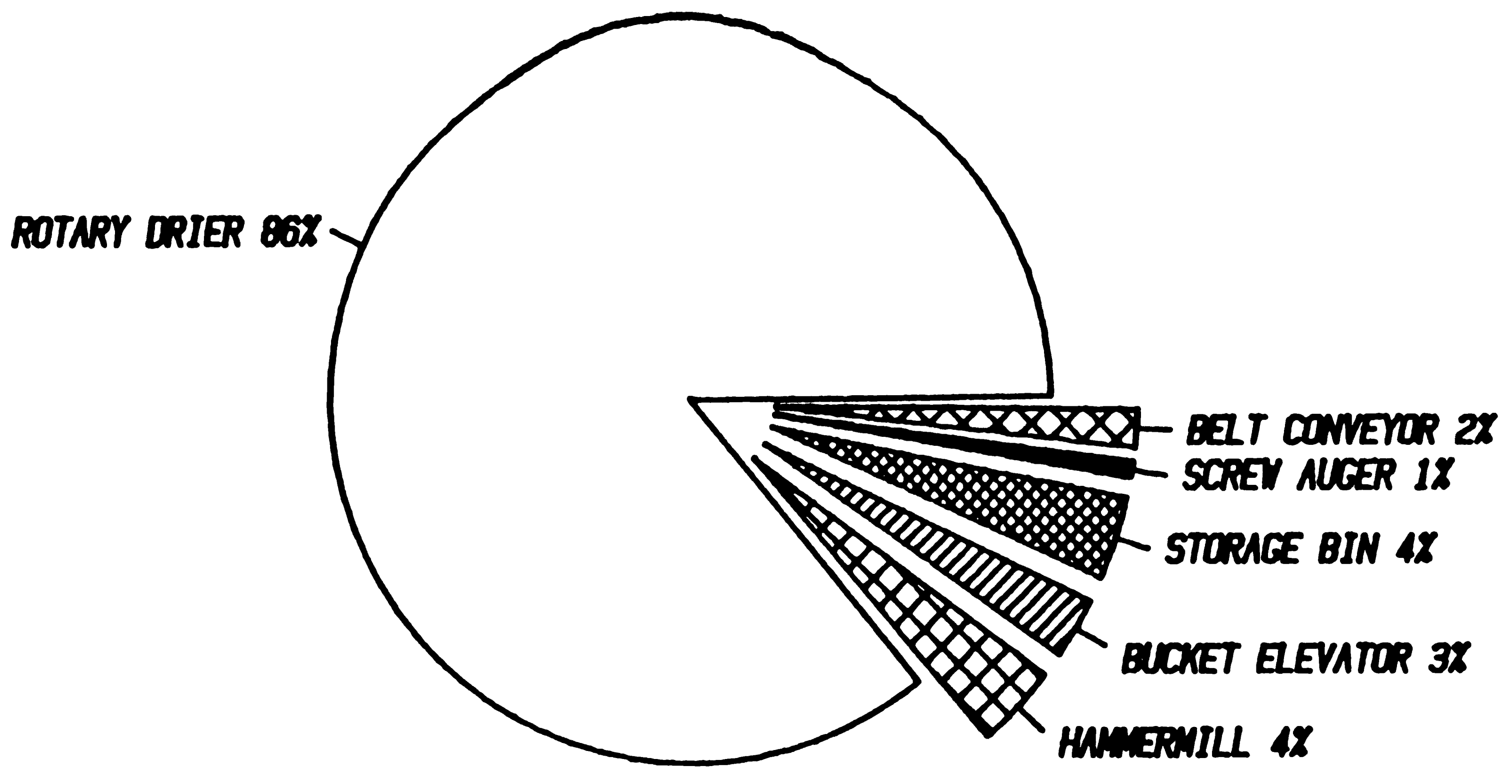

Figure 10. Representative investment costs for handling system components.

4.5.1.2 Equipment scaling

Costs for equipment sizes other than those obtained were estimated in the feasibility model by use of the scaling formula previously explained. Cost capacity exponents were derived for each of the boiler systems as outlined by Bauman (1964). Installed costs for two boiler sizes were plotted on log-log graph paper, the slope recorded as the exponent (Figure 11). The exponents were 0.36, 0.65 and 0.18 for pile burning, fluidized bed and suspension-fired boiler systems, respectively. The exponent used for the handling system was 0.53, based on a composite of values reported by Bauman (1964) for belt and screw conveyors (0.53) and by Perry and Chilton (1973) for a vertical carbon steel tank (0.52). The actual cost for the rotary drier was used in the analysis based on plant biomass output: 0-6,000 lb/hr (0-2721 kg/hr) = $129,780 and 6,000-16,000 lb/hr (2721-7257 kg/hr) = $259,560.

A power consumption exponent was derived as above for estimation of power requirements for scaled equipment. The exponent was determined from manufacturer's data for power consumption of two equipment and boiler sizes. From these data the analysis should be valid for processors requiring from 1 million Btu/hr (1.05 GJ/hr) to 100 million Btu/hr (105.5 GJ/hr).

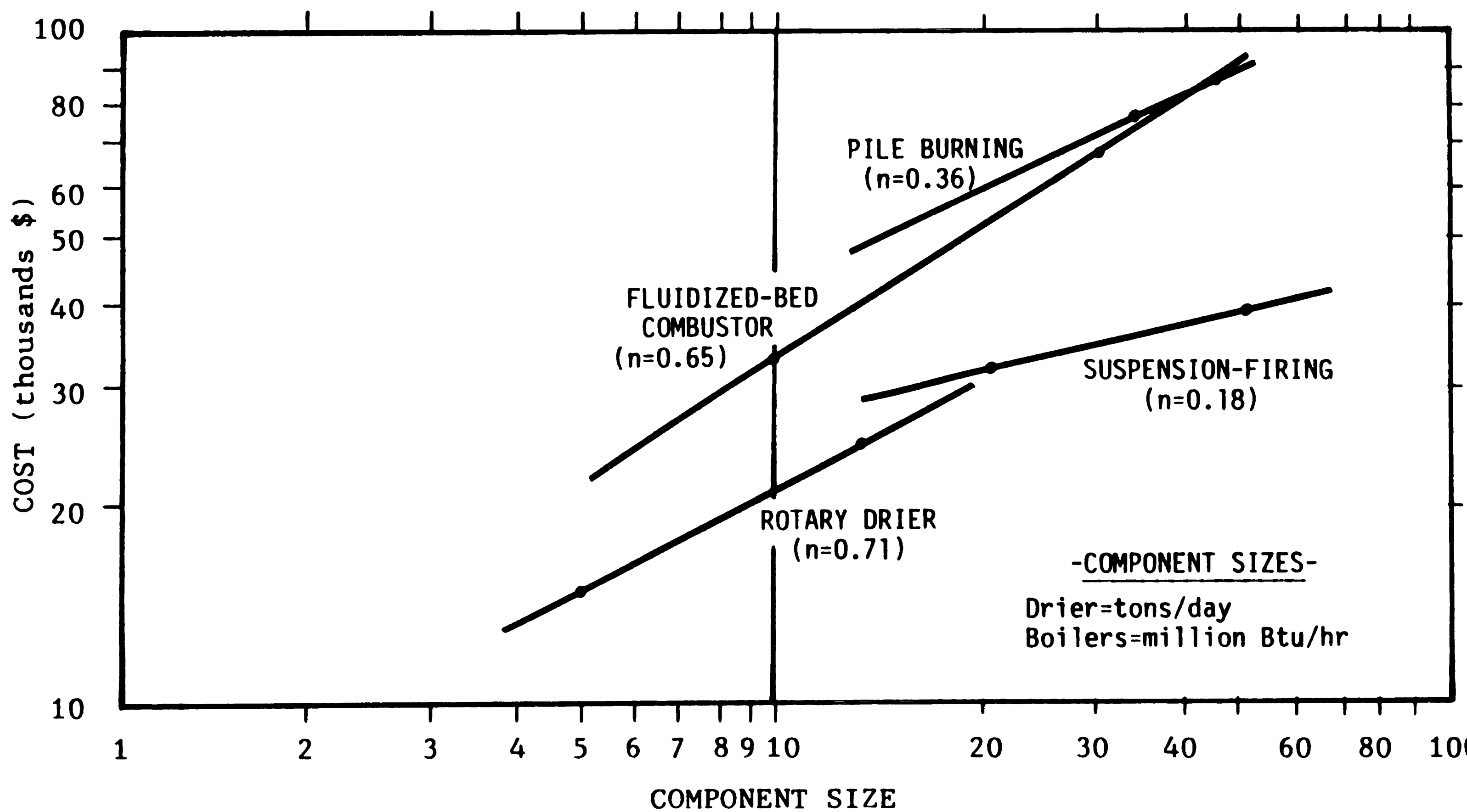

Figure 11. Cost capacity exponents for the rotary drier and combustors (1983 price base).

4.5.2 Variable cost data

Local sources were consulted for variable cost data in August, 1983. Electrical rates were obtained from the local utility company based on the sum of the demand rate ($5.90/kW), base rate ($0.0243/kW-hr),fuel-cost adjustment ($0.00672/kW-hr) and 4 percent Michigan sales tax. It was assumed that the processor owned the transformer, qualifying it for the least expensive primary rate. Natural gas cost $4.795/1000 ft^3 ($0.169/1000 lit) and #2 fuel oil cost $0.948/gallon ($0.2504/lit). The fuel oil price had significantly dropped by 17 percent since July 1982, while the natural gas price increased 4 percent during the same period. The sharp decrease in the fuel oil price reduced the difference in net costs between the two fuels to $6.771/million Btu ($7.1438/GJ) for fuel oil and $4.795/million Btu ($5.0593/GJ) for natural gas.

Disposal costs were $18.30/ton ($16.60/1000 kg), based on a large capacity trailer 40 yd^3 (31 m^3). The loan interest rate for a firm in good economic standing was 14 percent annually for a fixed rate loan with a 5-year payback period. Insurance for boiler and related machinery would be $668/yr. The extra labor rate was fixed at $10.00/hr. Several costs were determined to be irrelevent to the analysis and therefore not included: administrative costs for the new system were assumed to be equal to present costs; salvage value of the old system was assumed to equal to the removal costs; and property tax increases were estimated at one percent of investment costs. Specific tax calculations based on depreciation of the investment were not made since individual processor tax brackets vary widely.

CHAPTER 5

Energy and Cost Analysis Model

5.1 Model description

5.1.1 Initial considerations

In planning the computer model, the overriding objective was to create a tool from which industries other than the apple juice industry may be evaluated. This model would serve as a reference from which refinements may be made as deemed necessary after further experimentation and analysis. Having access to a Cyber CDC 750 computer at Michigan State University, it was decided to program the feasibility approach as described in the previous chapters as a "user-friendly" model. A user-friendly model is one in which the user can directly interact with the program from a terminal by means of a series of prompts, or questions, from the model. Fortran 5 was selected as the program language due to broad processing capability and wide usage in engineering disciplines.

Upon completion of the programming stage, the model was verified by comparison of model responses with hand calculations. Clear documentation was inserted to facilitate later use. The program can be stored in compiled form for future use as a low-cost teaching aid in energy or cost analysis.

The model is divided into two parts, a biomass energy model to calculate biomass net heat content and fossil fuel savings, linked with a cost analysis model (Figure 12). The user is given the option to perform either the biomass energy analysis or both analyses, depending upon the study being conducted. Single or multiple parameters may be varied at the completion of an analysis to aid in simulation, avoiding re-initialization of all parameters. Parameters which may be varied relate to boiler size and type, biomass and/or fossil fuel type, loan interest rate and payback period. The option to begin a new analysis or exit is also available.

The following sections describe in detail model structure and operation.

5.1.2 Input parameters

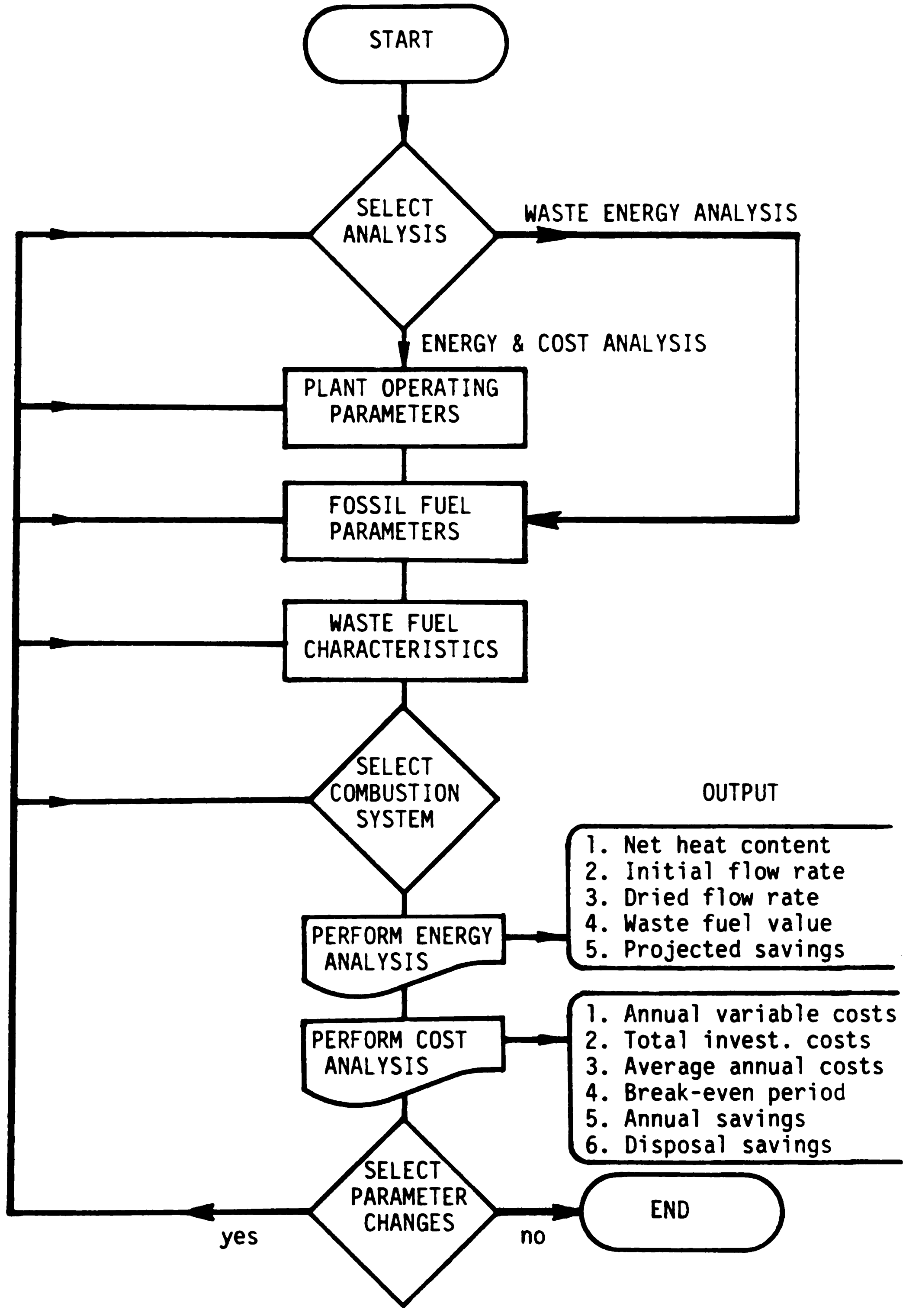

Figure 12. General flowchart for the waste energy and cost analysis model.

5.1.2.1 Plant operating and economic parameters

All variables were programmed for English units, due to almost exclusive usage within the industry for measurement of power generation and energy consumption. This description will assume selection of the complete energy/cost analysis. Plant operating conditions of significance are requested which relate to the processing schedule, waste disposal cost, utility rates and peak heat demand. Variables affecting the cost analysis of the proposed system for input are extra hours to be required, hourly salary for the worker, loan interest rate and desired loan repayment period (Figure 13).

5.1.2.2 Biomass input parameters

A maximum of 3 biomass types can be analyzed with a single run, and consider single or multiple processing seasons. Parameters required for fossil fuel inputs are current fuel type (natural gas, #2 fuel oil or other) and price. Those related to the biomass are biomass heat content (dry weight), initial MC, dried MC, daily production rate, processing season length, and opportunity cost (or the value for alternate use). Finally selection of from 1 to all 3 combustion systems is requested, followed by combustor

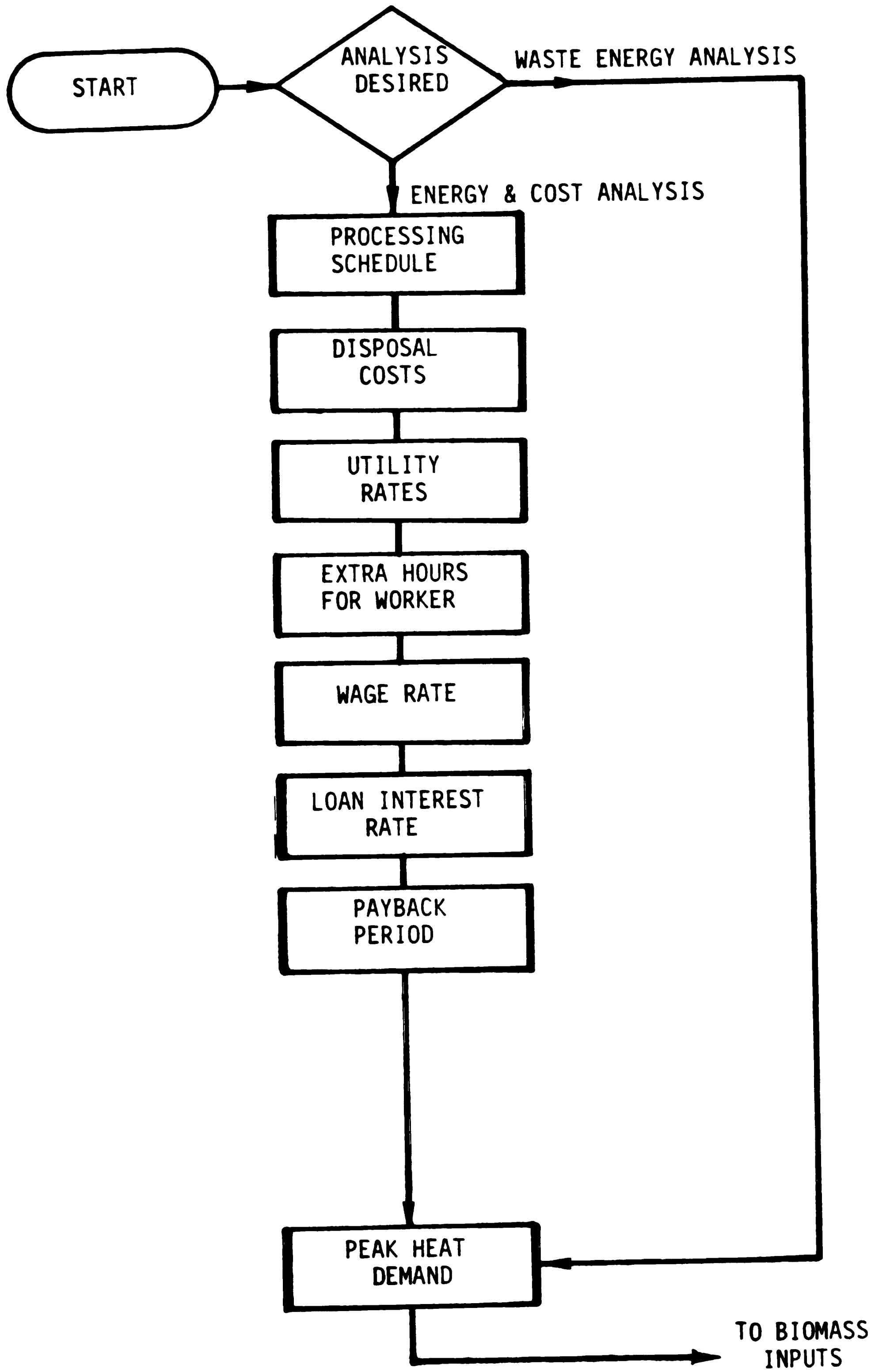

Figure 13. Initial input parameters for processing plant operating conditions.

efficiency (Figure 14).

5.1.3 Calculations for energy analysis

The net heat content of the biomass(es) is determined by first calculating the amount of heat required by the drier to reduce the MC as specified by the input conditions. A drier efficiency of approximately 50 percent was assumed by utilizing 1700 Btu/lb (3954 kJ/kg) of water, to provide drying costs using the fossil fuel. Second, the water remaining in the biomass after drying was assumed to require 1300 Btu/lb (3024 kJ/kg), to account for evaporation within the boiler prior to combustion. The difference of these heat losses from the heat content (for bone dry material) is the net heat content of the biomass used in the calculations in the energy analysis. A summary of the drying calculations is presented (Appendix 2).

5.1.3.1 Biomass energy savings

Hourly savings from costs of disposing the biomass (if any) are next added to hourly savings in fossil fuel costs (including the boiler efficiency) less drying costs, to arrive at the net hourly savings when combusting the biomass. The net hourly savings can be converted to annual savings and summed for each of the biomass fuels being analyzed yielding

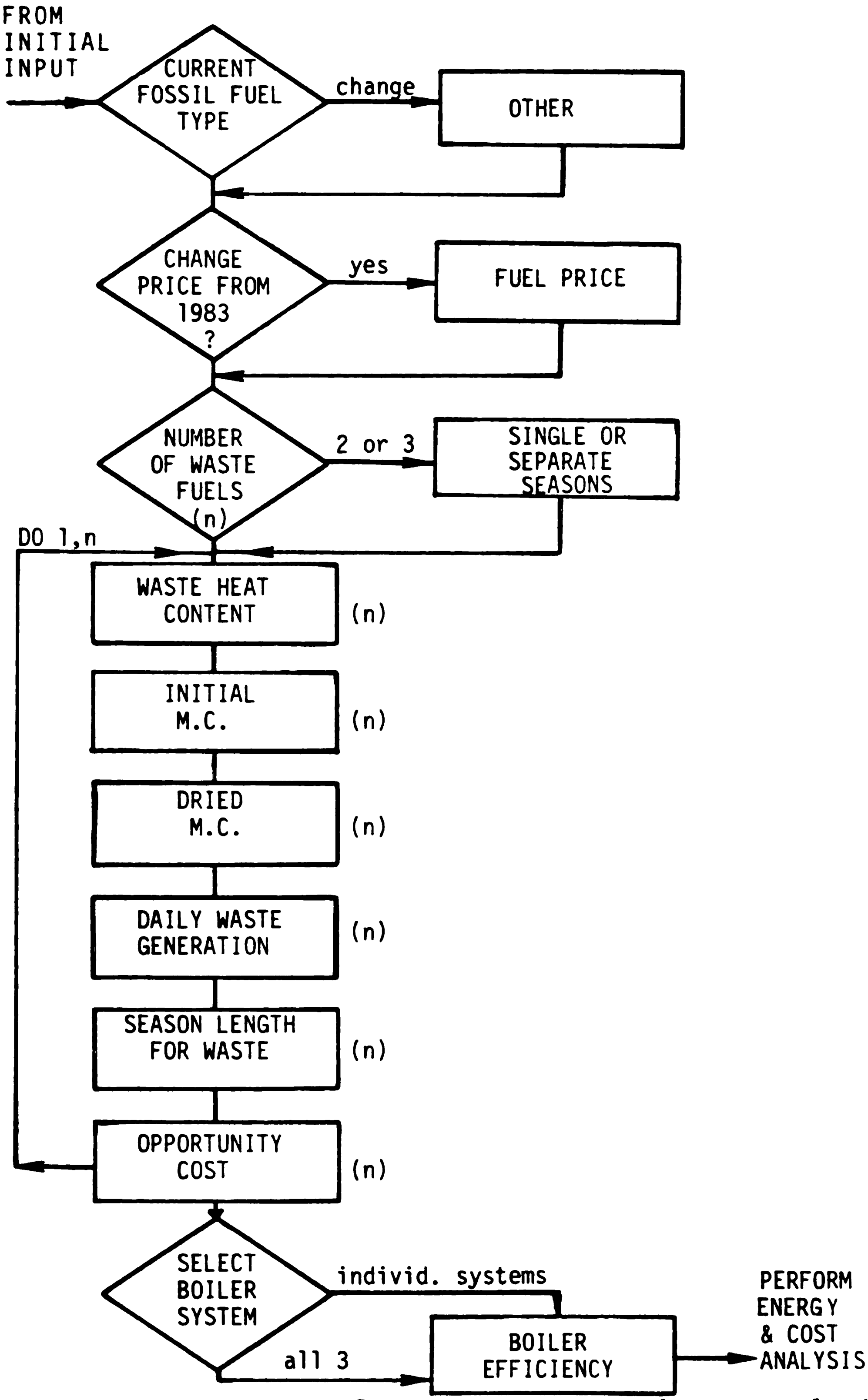

Figure 14. Input parameters for waste energy and cost analysis.

the total annual savings.

5.1.4 Calculations for the Life-Cycle Cost Analysis

5.1.4.1 Total costs

Annual electrical costs are estimated for the handling and boiler systems, based on the respective scaling exponents. Maintenance, property tax and insurance costs are summed to obtain an annual total for system operating costs. Total investment costs are calculated from the respective scaling exponents for the handling and boiler systems and for the sized drier.

5.1.4.2 Investment savings (losses)

The uniform capital recovery (UCR) factor is calculated from the loan interest rate and repayment period, from which is determined the Average Annual Cost of the investment for the duration of the loan period. Annual investment savings (or losses) are determined by subtracting the AAC from the annual total savings. The actual break-even point is also calculated in terms of the number of months of operation required on biomass in order to recover the AAC.

5.1.5 Output parameters

5.1.5.1 Biomass energy analysis

A table is printed for each biomass type, identifying the system size, waste fuel type and fossil fuel being substituted (Figure 15). Variables listed are: heat content of bone dry material, heat which would be generated and recovered from combustion, and the heat required for drying (if any). Pre- and post-drying flow rates, fuel value per unit mass, and hourly and yearly savings in fossil fuel and disposal costs are also printed. Determination of flow rates is essential for additional system design with respect to equipment throughput and storage capacity, while heat available for recovery can be used in sizing boiler systems.

5.1.5.2 Life-Cycle Cost Analysis

A heading lists the key operating and investment conditions succeeded by variable and fixed costs printed in tabular form (Figure 16,A). For wastes in addition to the principle waste being evaluated, another table is printed for the flow rates which would be required of that waste in order

LARGE PROCESSOR REPLACING #2 FUEL OIL

```
============================================================
       3000000. BTU/HR SYSTEMS
------------------------------------------------------------
FOR BIOMASS FUEL #1 REPLACING #2 FUEL OIL    (apple pomace)
WITH INITIAL MOISTURE CONTENT OF 65. PERCENT
------------------------------------------------------------
             HEAT CONTENT (BTU/LB, BONE DRY):      7780.000
          HEAT GENERATED FROM COMB. (BTU/LB):      6418.000
     HEAT REQUIRED TO DRY (BTU/LB, FRESH WT):      1000.000
------------------------------------------------------------
                 WET WASTE FLOW RATE (LB/HR):     12500.000
               DRIED WASTE FLOW RATE (LB/HR):      5147.059
                    WASTE FUEL VALUE ($/TON):      16.87846
     PROJECTED SAVINGS BURNING THIS WASTE:
                                     $/HOUR:        105.490
                                     $/YEAR:     210980.786
============================================================


FOR WASTE FUEL #2 REPLACING #2 FUEL OIL        (polyethylene)
WITH INITIAL MOISTURE CONTENT OF 2. PERCENT
------------------------------------------------------------
             HEAT CONTENT (BTU/LB, BONE DRY):     19000.000
          HEAT GENERATED FROM COMB. (BTU/LB):     18594.000
     HEAT REQUIRED TO DRY (BTU/LB, FRESH WT):         0.000
------------------------------------------------------------
                 WET WASTE FLOW RATE (LB/HR):       375.000
               DRIED WASTE FLOW RATE (LB/HR):       375.000
                    WASTE FUEL VALUE ($/TON):     214.04350
     PROJECTED SAVINGS BURNING THIS WASTE:
                                     $/HOUR:         40.133
                                     $/YEAR:      80266.314
============================================================


FOR WASTE FUEL #3 REPLACING #2 FUEL OIL       (corrug. paper
WITH INITIAL MOISTURE CONTENT OF 10. PERCENT             box)
------------------------------------------------------------
             HEAT CONTENT (BTU/LB, BONE DRY):      7429.000
          HEAT GENERATED FROM COMB. (BTU/LB):      6556.100
     HEAT REQUIRED TO DRY (BTU/LB, FRESH WT):         0.000
------------------------------------------------------------
                 WET WASTE FLOW RATE (LB/HR):       375.000
               DRIED WASTE FLOW RATE (LB/HR):       375.000
                    WASTE FUEL VALUE ($/TON):      75.47008
     PROJECTED SAVINGS BURNING THIS WASTE:
                                     $/HOUR:         14.151
                                     $/YEAR:      28301.279
============================================================
```

Figure 15. Example output of the energy analysis for apple pomace, polyethylene and corrugated paper box.

```
===============================================
            LIFE-CYCLE COST ANALYSIS
-----------------------------------------------
      FOR A PLANT PRODUCING 100. TONS/DAY
        WITH A 5.-MONTH PROCESS SEASON
-----------------------------------------------
          30000000. BTU/HR SYSTEMS
        SUBSTITUTING FOR #2 FUEL OIL
     FUEL VALUE: $  6.7714/MILLION BTU
-----------------------------------------------
      LOAN: 14.PERCENT; 5.YEAR PAYBACK
       WITH DISPOSAL COSTS OF $0. PER TON
===============================================
```

a

```
REQUIRED FLOW RATE FOR ADDITIONAL WASTE IN ORDER
FOR BREAK-EVEN OF AVERAGE ANNUAL COSTS TO OCCUR.

COMBUSTOR                    LB/HR,WET WT
-----------------------------------------------
WASTE #2  (polyethylene)
PILE BURNING                     923.9
FLUIDIZED BED                    718.8
SUSPENSION FIRED                 132.9
WASTE #3  (corr. paper box)
PILE BURNING                    2620.4
FLUIDIZED BED                   2038.7
SUSPENSION FIRED                 377.0
===============================================
```

b

HANDLING AND COMBUSTION SYSTEM COSTS
(VARIABLE AND FIXED COSTS)
($)

COMBUSTOR	UTILITY (ANNUAL) HANDLING	UTILITY (ANNUAL) COMBUSTOR	OPERATING (ANNUAL) HANDLING	OPERATING (ANNUAL) COMBUSTOR	INVESTMENT (TOTAL) HANDLING	INVESTMENT (TOTAL) COMBUSTOR
PILE BURNING	16517.5	13709.0	28822.0	39620.0	304551.1	863720.0
FLUIDIZED BED	16517.5	11329.0	28822.0	33364.0	304551.1	734500.0
SUSPENSION FIRED	16517.5	9805.8	28822.0	20272.9	304551.1	348906.0

c

COMBUSTOR	AVE ANNUAL COSTS	OPERATION REQUIRED (MONTHS)	INVESTMENT SAVINGS (ANNUAL)
PILE BURNING	408740.8	9.69	-89192.4
FLUIDIZED BED	364844.5	8.65	-45296.1
SUSPENSION FIRED	239436.3	5.67	80112.1

d

ANNUAL DISPOSAL SAVINGS: $0.

Figure 16. Example output of the economic analysis for apple pomace, polyethylene and corrugated paper box.

for the system to break-even (B). Utility costs, total operating costs and total investment costs (in dollars) are listed for each of the three handling/boiler systems (C). Average Annual Costs, the number of months of operation on biomass required for payback of AAC, and annual investment savings (losses) are also printed for each system (D).

5.2 Verification and Validation of the Model

5.2.1 The Michigan apple juice processing industry

5.2.1.1 Apple pomace input parameters

The model was verified by comparing energy and cost data determined by the model with known values derived by hand calculations. Values for input variables were selected to represent two sizes of Michigan apple juice processors. Operating conditions were set to evaluate the technical and economic feasibility for the processing situations, one for a small processor generating 30 tons/day (27,215 kg/day) of apple pomace (AP), and the other for a large processor producing 100 tons/day (90,718 kg/day). Handling and boiler systems were sized for these pomace flow rates, assuming a maximum energy requirement of 10 million Btu/hr (10.5 GJ/hr) for small processors and 30 million Btu/hr (31.5 GJ/hr) for large processors. The processing schedule was calculated for 16 hours/day, 25 days/month over a 5-month processing season (e.g., from mid-September to mid-February).

The annual loan interest rate was fixed at 14 percent, with a 5-year payback period. It was also assumed that the total investment cost was satisfied by the loan; in other words, no initial down payment was made.

5.2.1.2 Input parameters for additional in-plant wastes

In many processing plants significant energy may be available from waste streams other than pomace. From the list of waste fuel candidates (Table 11), three were selected for analysis of waste fuel and economic feasibility: polyethylene (PE), corrugated paper box (CPB) and wet fruit waste (WFW). Criteria for selection of these wastes were, 1) the likelihood of waste availability at the plant (packaging wastes and biomass from concurrent or other season processing operations), and 2) representation of a range of wastes from better candidates (PE and CPB, which require no drying) to the worst candidate (WFW with a high MC of 80 percent).

Small processors were assumed to generate 30 tons/day (27,215 kg/day) of WFW, equivalent to that of AP, and 1 ton/day (907 kg/day) of both PE and CPB packaging waste.

Large processors were likewise assumed to generate 100 tons/day (90,718 kg/day) of WFW and 3 tons/day (2,721 kg/day) of PE and CPB waste.

5.2.2 Feasibility Analysis Results

5.2.2.1 Energy value of apple processing wastes

The model was validated by performing an energy and cost analysis for apple juice processors in Michigan. The energy analysis was performed for the four processing wastes, AP, WFW, CPB and PE. Heat generated from combustion of the dried materials was estimated for AP, WFW and CPB at 6,418, 7,016 and 6,556 Btu/lb (14,928, 16,319 and 15,249 kJ/kg), respectively (Table 15). Heat loss to drying amounted to 15.6 percent for AP and 18.5 percent for WFW of the net heat content for each waste after drying. Polyethylene had the highest heat generation estimate at 18,594 Btu/lb (43,250 kJ/kg). Flow rates for AP and WFW were reduced 59 and 77 percent, respectively, after drying.

Annual savings anticipated from the decrease in fossil fuels was a function of the biomass flow rate and heat content (Table 16). A small processor could expect a net savings of $44,820/year, substituting AP for natural gas (NG), and $63,294 substituting for #2 fuel oil (FO).

Table 15. Energy analysis for selected apple processing wastes.

	MOISTURE CONTENT (%,w.b.)	HEAT CONTENT (bone dry)		HEAT GENERATED FROM COMBUST.[1]		HEAT REQUIRED TO DRY	
		Btu/lb	kJ/kg	Btu/lb	kJ/kg	Btu/lb	kJ/kg
Apple pomace	65	7,780	18,096	6,418	14,928	1,000	2,326
Wet fruit waste	80	8,484	19,734	7,016	16,319	1,300	3,024
Polyethylene	2	19,000	44,194	18,594	43,250	0	0
Corrugated paper box	10	7,429	17,280	6,556	15,249	0	0

[1] Heat available for recovery, including heat losses to combustion process and boiler efficiency, (85%).

Table 16. Hourly biomass flow rates and annual savings for small processors.

	BIOMASS FLOW RATE				ANNUAL SAVINGS ($) FROM BIOMASS Substituting for:	
	Fresh		Dried			
	lb/hr	kg/hr	lb/hr	kg/hr	Natural Gas	#2 Fuel Oil
Apple pomace	3,750	1,701	1,544	700	44,820	63,294
Wet fruit waste	3,750	1,701	882	400	3,714	5,245
Polyethylene	125	57	125	57	18,946	26,755
Corrugated paper box	125	57	125	57	6,680	9,434

*Based on a 5 month process season; maximum power demand of 10 million Btu/hr (10.5 GJ/hr); no disposal costs.

Combustion of PE would save \$18,946 and \$26,755/year in place of NG and FO, respectively, since the high heat content would offset the low flow rate of 1 ton/day (907 kg/day). Savings from combustion of CPB and WFW were minimal, due to the low flow rate of the former and the high drying costs and resultant low flow rate of the latter.

Large processors could anticipate savings of \$149,400 and \$210,981/year substituting AP for NG and FO, respectively; PE would save \$56,838 and \$80,266 in place of NG and FO, respectively (Table 17). Savings for CPB and WFW were proportionately low.

Net fuel values for the four candidates ranged from \$1.00/ton (\$0.91/1000 kg) for WFW replacing NG, to \$214.04/ton (\$194.17/1000 kg) for PE substituting for FO (Table 18). Relative fuel values as compared to pomace = \$1.00 were: PE = \$12.70; CPB = \$4.50; and WFW = \$0.10.

Savings from reduction in biomass and packaging wastes would greatly increase annual savings, as current disposal rates are \$18.30/ton (\$16.60/1000 kg). The effects of disposal costs and other variables will be discussed in the section concerning the Sensitivity Analysis.

Table 17. Hourly biomass flow rates and annual savings for large processors.

	BIOMASS FLOW RATE				ANNUAL SAVINGS ($) FROM BIOMASS Substituting for:	
	Fresh		Dried			
	lb/hr	kg/hr	lb/hr	kg/hr	Natural Gas	#2 Fuel Oil
Apple pomace	12,500	5,670	5,147	2,335	149,400	210,981
Wet fruit waste	12,500	5,670	2,941	1,334	12,381	17,483
Polyethylene	375	170	375	170	56,838	80,266
Corrugated paper box	375	170	375	170	20,041	28,301

*Based on a 5 month process season; maximum power demand of 30 million Btu/hr (31.5 GJ/hr); no disposal costs.

Table 18. Net fuel values for selected apple processing wastes.

	NET FUEL VALUES FOR BIOMASS SUBSTITUTING FOR: Natural Gas		#2 Fuel Oil		VALUE RELATIVE TO APPLE POMACE
	$/ton	$/1000kg	$/ton	$/1000kg	($)
Apple pomace	11.96	10.85	16.80	15.24	1.00
Wet fruit waste	1.00	0.91	1.40	1.27	0.10
Polyethylene	151.56	137.49	214.04	194.17	12.70
Corrugated paper box	53.44	48.48	75.48	68.47	4.50

*Based on 5 month process season; no disposal costs.
Natural gas = $4.795/million Btu ($5.059/GJ).
Fuel oil = $6.77/million Btu ($7.140/GJ).

5.2.2.2 Life-Cycle Cost Analysis Results

5.2.2.2.1 Total costs for handling/combustion systems

The analysis assumed that the investment capital was obtained entirely by a loan at an annual loan interest rate of 14 percent and a payback period of 5 years. Apple pomace was substituted for either natural gas or #2 fuel oil and assumed no costs for disposal; in other words it was disposed of as a local animal feed at no charge to the processor.

To purchase a handling/combustion system, small processors would need to borrow $735,128, $513,184 or $439,851 for the pile burning (PB), fluidized-bed (FB) or suspension-fired (SF) systems, respectively (Table 19). Annual operating costs would be $52,032 $43,263 or $39,712 for PB, FB or SF systems, respectively.

A large processor would require a loan of $1,168,271, $1,039,051 or $653,457 to purchase a PB, FB or SF system, respectively, while annual operating costs would be $68,443, $62,186 or $49,095 for these same systems. Of the total costs which would be incurred over the 5-year payback period, interest costs would account for an average of 25 percent, investment costs for 55 percent and operating costs for 20 percent.

Table 19. Total costs for small and large handling/combustion systems.

	TOTAL COSTS ($)			
	Operating	Investment	Interest	Grand Total
SMALL SYSTEMS				
Pile burning	260,160	735,128	335,527	1,330,815
Fluidized-bed	216,315	513,184	234,226	963,725
Suspension-fired	198,560	439,851	200,759	839,170
LARGE SYSTEMS				
Pile burning	342,215	1,168,271	533,219	2,043,705
Fluidized-bed	310,930	1,039,051	474,239	1,824,220
Suspension-fired	245,475	653,457	298,248	1,197,180

14% loan interest rate with 5 year payback period; no disposal costs
Small system = 10 million Btu/hr (10.5 GJ/hr).
Large system = 30 million Btu/hr (31.5 GJ/hr).

5.2.2.2.2 Average annual costs and the break-even point

5.2.2.2.2.1 Apple pomace

Average annual costs (AAC) were calculated for small and large processors with the following results (Table 20). For small processors, AAC were $167,834, $192,745 and $266,163 for SF, FB and PB systems, respectively. For large processors, AAC for these same systems were $239,436, $364,845 and $408,741.

Waste fuel savings were subtracted from estimates of the AAC to obtain the net annual savings (or losses) for each of the three handling/combustion systems evaluated for the two boiler sizes. None of the systems would be cost-effective for either small or large processors under the economic conditions assumed in this analysis, since net annual losses were projected in each case. The losses for large processors would range from a maximum of $259,341/year for a PB system substituting for natural gas (NG) to a minimum of $28,455 for a SF system replacing fuel oil (FO). Losses for small processors would be a maximum of $221,343/year for a PB system substituting for NG, and a minimum of $104,540 for a SF system substituting for FO.

Table 20. Average annual costs and net annual savings for small and large processors combusting apple pomace.

	AVERAGE ANNUAL COSTS ($)	SAVINGS (LOSSES) ($) Substituting for: Natural Gas	Fuel Oil
SMALL SYSTEMS			
Pile burning	266,163	(-221,343)	(-202,869)
Fluidized-bed	192,745	(-147,925)	(-129,451)
Suspension-fired	167,834	(-123,013)	(-104,540)
LARGE SYSTEMS			
Pile burning	408,741	(-259,341)	(-197,760)
Fluidized-bed	364,845	(-215,444)	(-153,864)
Suspension-fired	239,436	(-90,036)	(-28,455)

*14% annual loan interest rate over 5-year payback period; 5-month processing season with no disposal costs.

Small system = 10 million Btu/hr (10.5 GJ/hr); 30 tons/day (27,215 kg/day) apple pomace generated.

Large system = 30 million Btu/hr (31.5 GJ/hr); 100 tons/day (90,718 kg/day) apple pomace generated.

5.2.2.2.2.2 In-plant packaging wastes

The analysis was repeated for small and large processors including the packaging wastes polyethylene (PE) and corrugated paper box (CPB). While varying widely, small processors were assumed to generate 1 ton/day (907.2 kg/day) each of PE and CPB, and large processors 3 tons/day (2,721.5 kg/day) each of PE and CPB (Mantell, 1975). Under these conditions, large processors could invest in a SF system substituting these biomass fuels (in addition to AP) for FO, and save $80,112/year (Table 21). The next least-cost system would be a SF system substituting for NG, which would lose $13,157/year.

The flow rates of PE and CPB required for break-even of AAC were calculated. (These rates would be in addition to AP.) Small processors would require a minimum of 3.9 tons/day (3,545 kg/day) of PE only, or 11.1 tons/day (10,053 kg/day) of CPB only to break-even with a SF system (Table 22). Large processors would need a minimum of 1.1 tons/day (965 kg/day) of PE or 3.0 tons/day (2,735 kg/day) of CPB for investment in a SF system to be cost-effective (Table 23).

Table 21. Effect of packaging wastes on net annual savings for small and large processors.

	AVERAGE ANNUAL COSTS ($)	SAVINGS (LOSSES) ($) Substituting for: Natural Gas	Fuel Oil
SMALL SYSTEMS			
Pile burning	266,163	(-195,717)	(-166,680)
Fluidized-bed	192,745	(-122,299)	(-93,262)
Suspension-fired	167,834	(-97,387)	(-68,351)
LARGE SYSTEMS			
Pile burning	408,741	(-182,461)	(-89,192)
Fluidized-bed	364,845	(-138,565)	(-45,296)
Suspension-fired	239,436	(-13,157)	80,112

*14% annual loan interest rate over 5-year payback period; 5-month processing season with no disposal costs.

Small system = 10 million Btu/hr (10.5 GJ/hr); 30 tons/day (27,215 kg/day) apple pomace; 1 ton/day (970 kg/day) each of polyethylene and corrugated paper box.

Large system = 30 million Btu/hr (31.5 GJ/hr); 100 tons/day (90,718 kg/day) apple pomace; 3 tons/day (2,910 kg/day) each of polyethylene and corrugated paper box.

Table 22. Required amounts of packaging wastes for cost-effective investment for small processors (in addition to apple pomace).

	FLOW RATE REQUIRED			
	Polyethylene		Corrugated Paper Box	
Systems Substituting For:	tons/day	kg/day	tons/day	kg/day
Natural Gas				
Pile burning	11.7	10,598	33.1	30,058
Fluidized-bed	7.8	7,083	22.1	20,089
Suspension-fired	6.5	5,890	18.4	16,705
#2 Fuel Oil				
Pile burning	7.6	6,879	21.5	19,509
Fluidized-bed	4.8	4,389	13.7	12,449
Suspension-fired	3.9	3,545	11.1	10,053

Based on: 14% annual loan interest rate over 5-year payback period; 30 tons/day apple pomace generated for 5 months. Small Processor = 10 million Btu/hr (10.5 GJ/hr).

Table 23. Required amounts of packaging wastes for cost-effective investment for large processors (in addition to apple pomace).

	FLOW RATE REQUIRED			
	Polyethylene		Corrugated Paper Box	
Systems Substituting For:	tons/day	kg/day	tons/day	kg/day
Natural Gas				
Pile burning	13.7	12,417	38.8	35,218
Fluidized-bed	11.4	10,316	32.3	29,258
Suspension-fired	4.7	4,311	13.5	12,227
#2 Fuel Oil				
Pile burning	7.4	6,705	21.0	19,017
Fluidized-bed	5.7	5,217	16.3	14,796
Suspension-fired	1.1	965	3.0	2,736

Based on: 14% annual loan interest rate over 5-year payback period; 100 tons/day apple pomace generated for 5 months. Large Processor = 30 million Btu/hr (31.5 GJ/hr).

5.2.2.2.3 Sensitivity of the analysis

5.2.2.2.3.1 Effect of waste disposal cost

Additional savings would be realized from combustion of processing wastes if costs were being incurred for disposal. (Commercial carriers typically charge $18.30/ton, or $16.60/1000 kg, for local disposal.) The analysis was performed with the same operating and economic constraints and included disposal costs of 100 percent of the current rate and 50 percent ($9.15/ton, or $8.30/1000 kg). For small processors the SF system replacing NG would become cost-effective as disposal costs approached 100 percent (Figure 17). Pomace substitution for FO would allow purchase of FB and SF systems, with the latter yielding savings of $31,338/year.

Large processors could invest in all but the PB system if replacing NG and incurring 50 percent of the disposal costs (Figure 18). Savings of $11,018/year for the FB system and $136,427/year for the SF system could be anticipated. With full disposal costs replacing NG, net annual savings for all systems would range from $193,584 to $362,889. For large processors substituting for FO, all systems would be

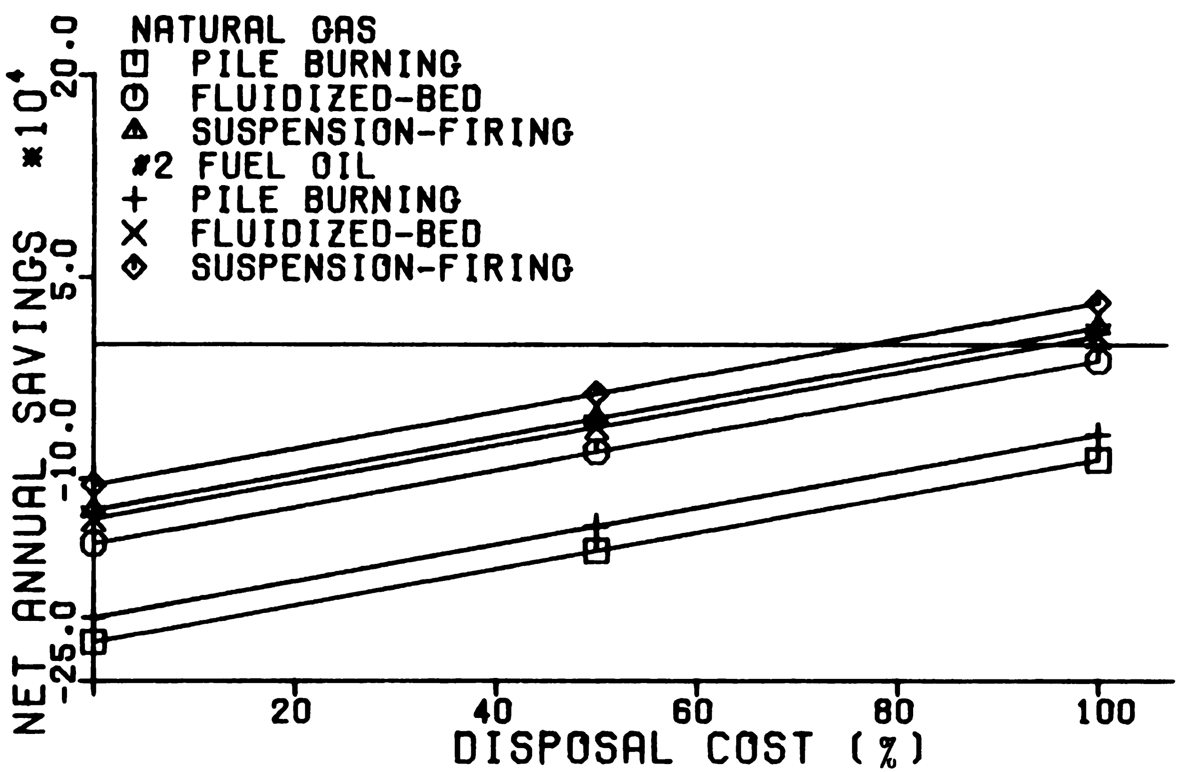

Figure 17. Effect of disposal cost on net annual savings for small processors (100% = $18.30/ton or $16.60/1000 kg).

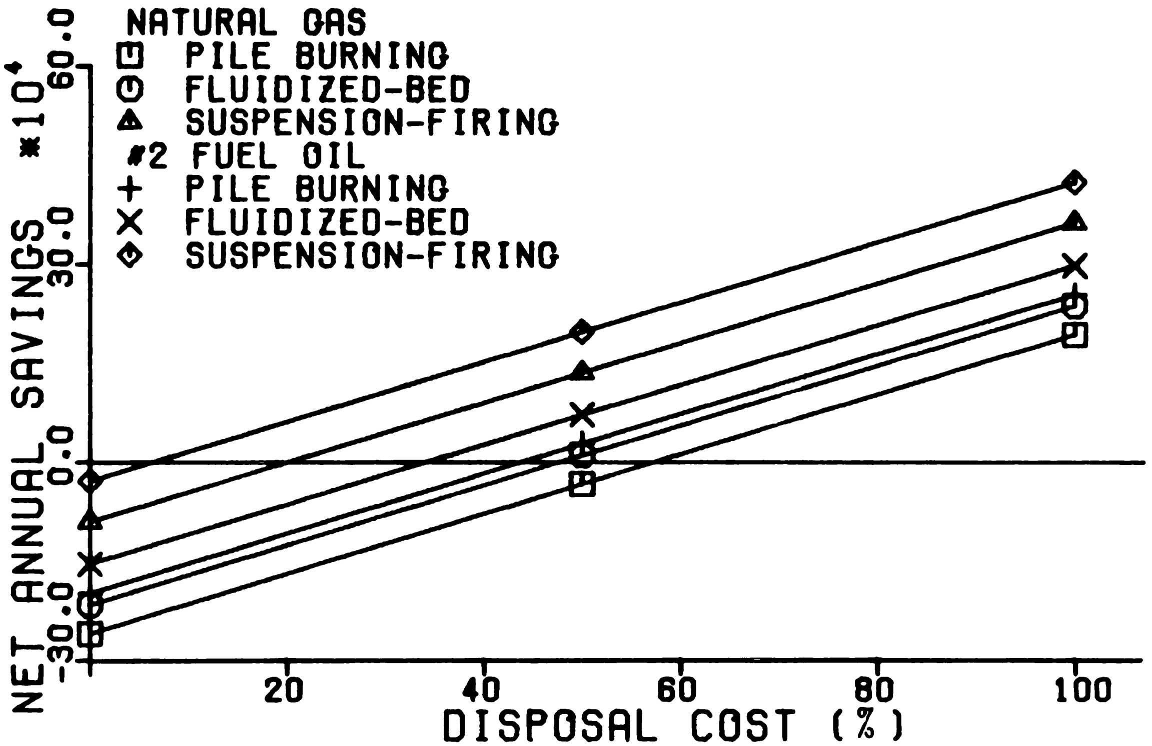

Figure 18. Effect of disposal cost on net annual savings for large processors (100% = $18.30/ton or $16.60/1000 kg).

cost-effective for disposal costs of 50 and 100 percent, with net annual savings ranging from $28,703 for the PB system, to $424,469 for the SF system. (See Appendices 4 and 5.)

5.2.2.2.3.2 Effect of fossil fuel price

Prices for NG and FO were converted to $/million Btu ($/GJ). Natural gas was priced at $4.795/million Btu ($5.059/GJ) and #2 fuel oil at $6.77/million Btu ($7.14/GJ). Using FO as a base, fuel prices were increased by 20, 50 and 100 percent, or to $8.124, $10.155 and $13.54/million Btu ($8.571, $10.714 and $14.28/GJ), respectively. Systems for small processors would become feasible only with fuel price increases in excess of 100 percent (Figure 19). Large processors could afford to invest in a SF system with a 20 percent increase to $8.124/million Btu ($8.571/GJ) (Figure 20). Investment in PB and FB systems would not be cost-effective until fuel prices rise by nearly 100 percent. (See Appendix 6.)

5.2.2.2.3.3 Effect of loan interest rate

Loan interest rates were varied from 10 to 18 percent for each of the systems. None of the small or large systems would become cost-effective even if the unlikely rate of 10 percent financing were obtained (Figure 21). For a loan

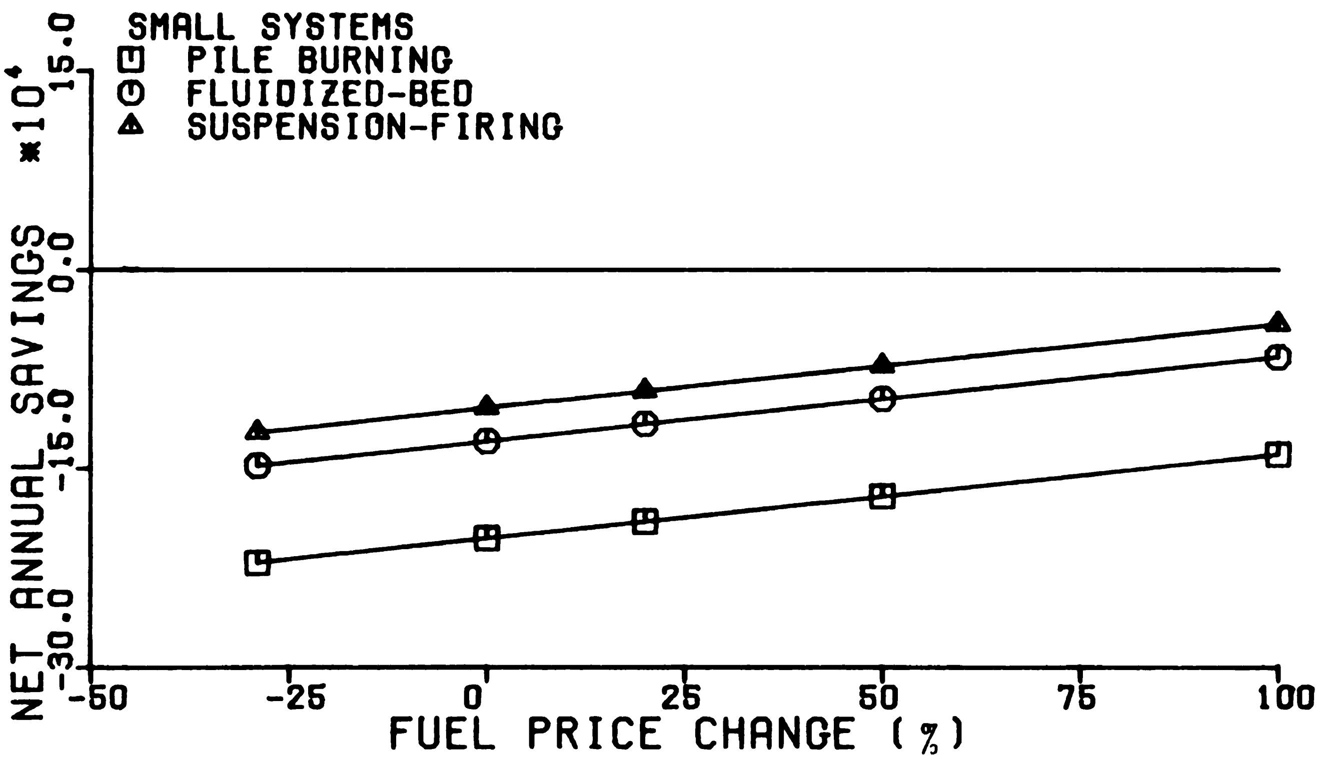

Figure 19. Effect of fossil fuel price change on net annual savings for small processors (0% = $6.77/million Btu or$7.14/GJ).

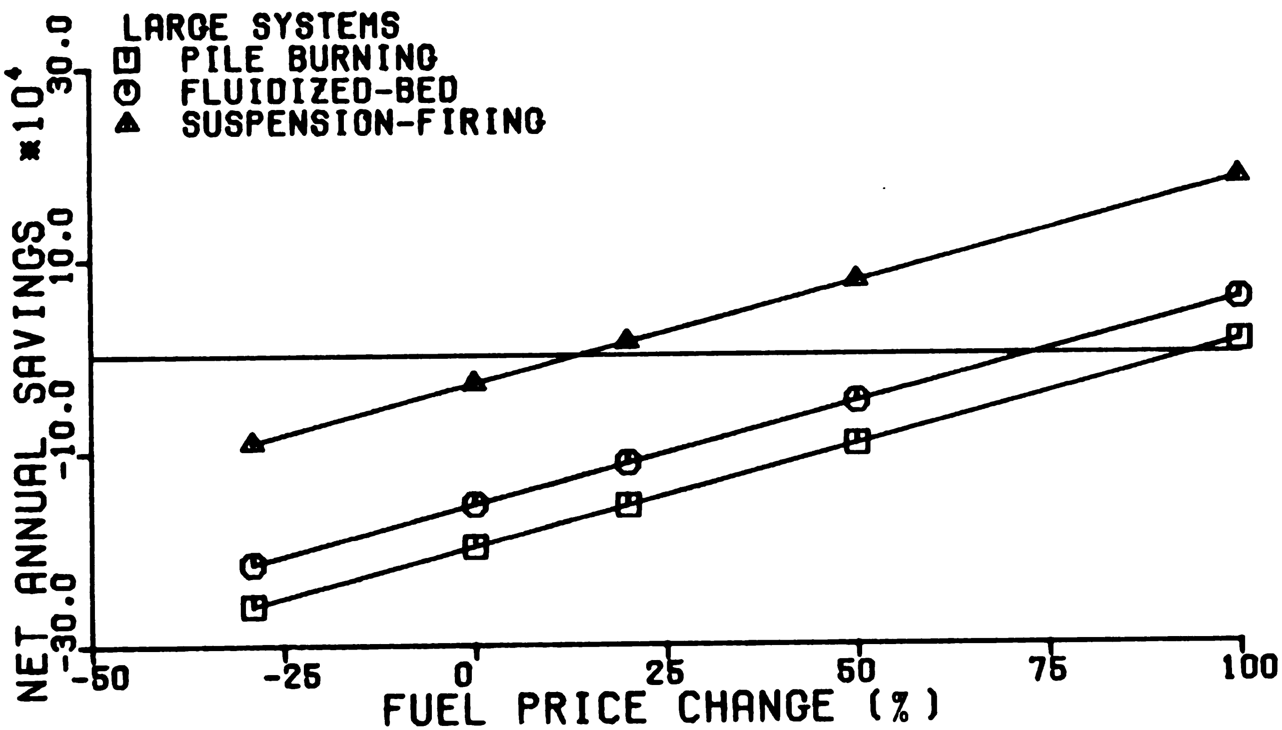

Figure 20. Effect of fossil fuel price change on net annual savings for large processors (0% = $6.77/million Btu or $7.14/GJ).

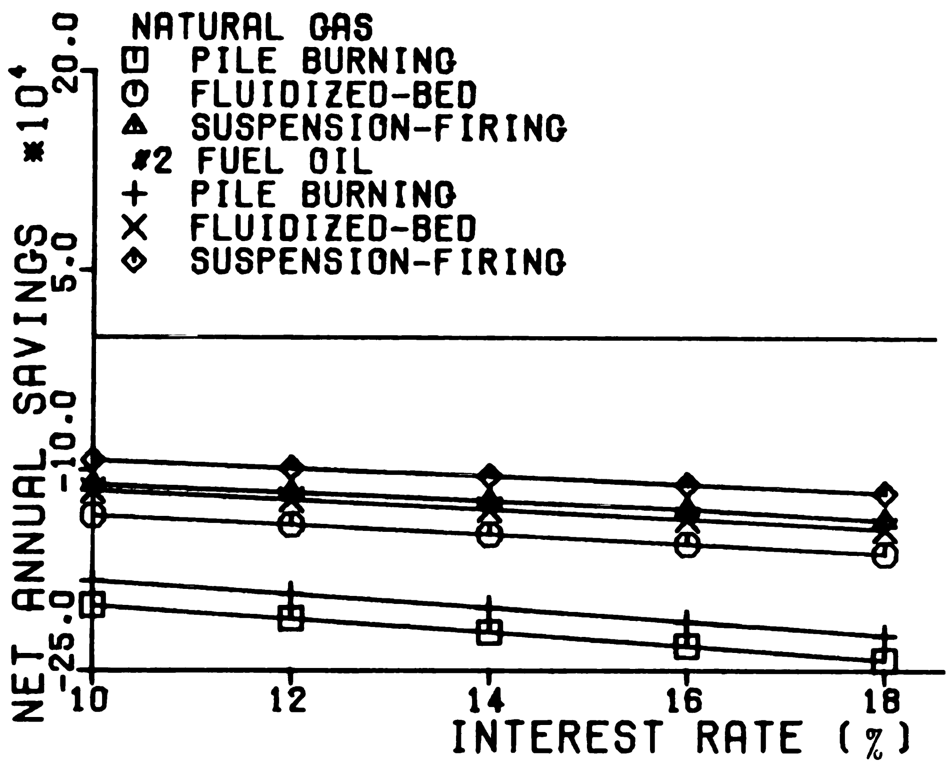

Figure 21. Effect of loan interest rate on net annual savings for small processors.

obtained at 10 percent, net annual losses for small processors were reduced by 9 percent, while for large processors losses were reduced by 12 percent for substitution of NG, and by 16 percent for substitution of FO (Figure 22). (See Appendices 7 and 8.)

5.2.3 Feasibility Analysis Discussion

5.2.3.1 Fossil fuel costs, disposal costs, loan interest rate

The cost analysis projected net annual losses for investment in the systems with economic constraints representing current processing operations. Net annual savings were projected by the Sensitivity Analysis when key parameters were varied over a range of operating conditions. As a result projections can be made as to the economic conditions which would justify such an investment. Fossil fuel costs played a major role in cost evaluation of biomass and other renewable fuels from 1973-1981, when fuel prices increased dramatically. However fuel prices have stabilized since then (at least for the foreseeable future), and break-even points have become extended due to the equivalent fuel value of the biomass in question remaining fairly static. The price for #2 fuel oil has even decreased during

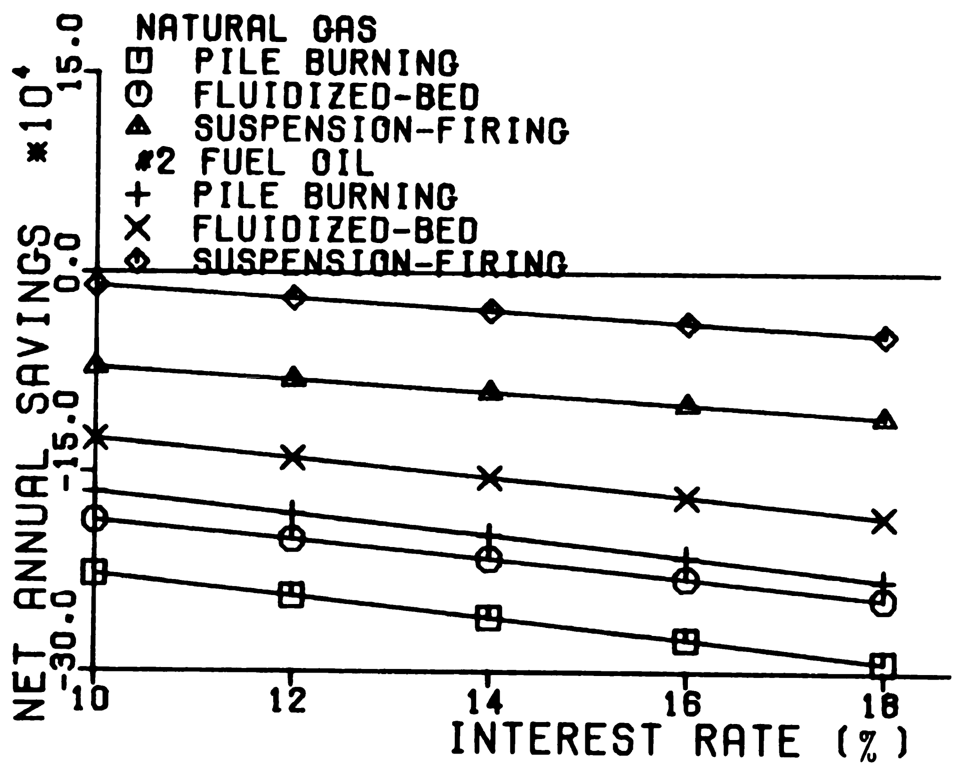

Figure 22. Effect of loan interest rate on net annual savings for large processors.

the past year. Fossil fuel prices would need to increase over 15 percent ($7.785/million Btu, or $8.214/GJ) in order for the least-expensive system (SF) to become cost-effective for a large processor.

Waste disposal costs are beginning to rival fossil fuel costs as a significant concern for many industries. Although few apple juice processors currently pay for disposal, increased regulation is reducing the number of disposal sites considered safe, along with the types and quantities of wastes which can be disposed of in the remaining sites. Large systems employing FB or SF boilers would become cost-effective if disposal costs of 50 percent ($9.15/ton or $8.30/100 kg) of the current cartage fee were imposed.

While interest rates were shown to be substantial costs, they were not a significant factor in comparison with disposal and fossil fuel costs, and therefore should not be given first priority in evaluating cost-effectiveness.

5.2.3.2 Additional wastes with fuel value

The fuel value of PE and CPB packaging wastes has been shown to contribute significantly to the payback of AAC for the combustion systems. Therefore the availability of these and/or other waste with fuel potential must be examined in the energy and cost analyses for specific processing situations. Wet fruit wastes (with MC of 80 percent) were determined to be infeasible for direct combustion, due to the excessive amount of water which must be removed. Such processing wastes as cherry and peach pits would appear to have potential for significant fuel savings during other processing seasons.

5.2.3.3 System selection considerations

Variations in capital investment and operating costs are the primary reasons for the distinct differences in the average annual costs of the three combustion systems. However, each prospective investor must carefully weigh not only the value calculated for net annual savings or losses, but also the advantages and drawbacks for each system. The SF system represents the least-cost alternative for applications permitting a dry (15 percent MC), particulate and non-abrasive solid fuel. This system would be optimal in situations with a highly uniform waste, and in some cases can be retrofitted to an existing boiler.

The PB and FB systems have higher capital investment and operating costs, but can burn fuels with as much as 60 percent MC. For applications in which pomace could be combusted immediately, storage would not be required, eliminating the need for the storage bin and accompanying handling equipment. Thus pomace would require minimal drying, reducing the size of the rotary drier which is the costliest of the handling system components. The PB and FB systems can combust non-uniform solid fuels as well, allowing greater flexibility in the types of wastes converted. These systems which require higher capital expenditure may prove to be cost-effective at current fossil prices with reductions in investment costs, depending upon individual processing situations.

Increases in electrical costs were not considered significant, because rate increases are often based on increased fuel costs at the generating utility. Since the fuel value for pomace is calculated from the current value of the fossil fuel it replaces, the savings from pomace combustion will be higher, offsetting the increased utility costs.

5.2.3.4 Potentials for improving cost-effectiveness

Other means of cost reduction at the plant may play important roles in the economic feasibility of pomace combustion. The availability of other in-plant wastes with fuel value (waste paper, shipping material, used pallets, and processing wastes such as cherry or peach pits) could allow a processor to combust for more than 16 hours/day or beyond the 5-month process season assumed in this analysis. Local sources of inexpensive solid fuel might also be available.

A processor may have a lower energy demand than that associated with the pomace production rates for these calculations. In this case average annual costs would be less, since a smaller-sized boiler could be purchased. By storing excess pomace, combustion could be extended beyond the 5-month processing season, further reducing fossil fuel costs, with a relatively small increase in investment costs for a larger storage system. The potential also exists for recovery of waste stack heat in order to offset fossil fuel costs in pomace drying, and for recycling of rice hulls by air classification from pomace containing the press aid. The latter source would reduce purchase costs of rice hulls and permit pneumatic handling of dry pomace.

CHAPTER 6

Summary and Conclusions

6.1 Model Development and Validation

Technical and economic factors were evaluated pertinent to in-plant conversion of food processing wastes into recoverable energy. A waste handling system was proposed for use in conjunction with three direct-combustion boiler systems. With proper equipment and operation, gaseous and particulate emissions from combustion of biomass and other wastes can be controlled to meet state and federal standards, while disposal volume can be reduced by a minimum of 90 percent.

Life Cycle Cost Analysis techniques were selected to evaluate cost-effectiveness, based on determination of average annual costs over the loan payback period. From the approach derived from these investigations, a computer model was developed to perform energy and cost feasibility analyses for food processors with energy requirements in the range of 1 million Btu/hr (1.05 GJ/hr) to 100 million Btu/hr (105.5 GJ/hr).

6.1.1 Apple pomace waste

The model was validated with variables representing operating conditions for two processing plant sizes for Michigan apple juice processors. Small processors were assumed to generate 30 tons/day (27,215 kg/day) of apple pomace and require 10 million Btu/hr (10.5 GJ/hr) of heat for processing. Large processors were assumed to generate 100 tons/day (90,718 kg/day) and require 30 million Btu/hr (31.5 GJ/hr) of heat. Using investment and operating costs from September 1983, the following conclusions were made:

1. The break-even point for conversion to an apple pomace handling/combustion system is most sensitive to pomace flow rate, waste disposal costs and fossil fuel costs, and least sensitive to electrical costs and loan interest rates.

2. The proposed systems are not currently cost-effective for processors incurring no disposal costs for pomace removal; however analysis of individual apple juice operations is warranted, particularly for large processors. Variations in plant production schedule and energy demand, the

availability of other in-plant wastes with fuel value or further restrictions in waste disposal methods and materials could interact to make investment in a handling/combustion system an economically viable alternative.

3. With a 20 percent increase in fossil fuel price to \$8.124/million Btu (\$8.571/GJ), large processors could purchase a suspension-fired system. Small processors could purchase this system only after fuel price increases of more than 100 percent.

4. For large processors incurring disposal costs greater than \$9.15/ton (\$8.30/1000 kg), or 50 percent of the current cartage fee, investment would be cost-effective for either fluidized-bed or suspension-fired systems replacing natural gas or #2 fuel oil.

5. Small processors could purchase a system if currently spending \$18.30/ton (\$16.60/1000 kg) in disposal costs. Those replacing natural gas could invest in a suspension-fired system, while those replacing #2 fuel oil could purchase either a fluidized-bed or suspension-fired system.

6.1.2 Packaging wastes

Other in-plant wastes with fuel value could be combusted to reduce fossil fuel and disposal costs. Packaging wastes in particular show promise due to low moisture content and relatively high heat content. Further analysis for combustion of polyethylene or corrugated paper box (in addition to apple pomace) revealed:

1. A large processor could invest in a suspension-fired system with the availability of 1.1 tons/day (965 kg/day) of polyethylene, or 3 tons/day (2,735 kg/day) or corrugated paper box.

2. A small processor would require 3.9 tons/day (3,545 kg/day) of polyethylene, or 11.1 tons/day (10,053 kg/day) of corrugated paper box for investment in the suspension-fired system.

3. Wet processing wastes, with moisture contents above 80 percent, wet basis, would not be cost-effective as a directly-combusted fuel due to excessive drying requirements for efficient combustion.

6.2 Recommendations for Further Application

The model was developed to aid in assessing the overall economic feasibility of converting food processing wastes into recoverable energy. In order to perform the analysis representative of the apple juice processing industry, conservative assumptions were made with respect to operating parameters and investment costs. Other food processing industries could be similarly analyzed and assessed, including the sugar beet, grape juice/wine, and cherry processing industries, each of which generates substantial quantities of wastes.

The need exists to charactize these industries, in terms of the types and quantities of wastes generated, method and distribution of waste disposal, and processing energy requirements. With a greater data base available, the model could be employed in the evaluation of these handling/combustion systems for individual processing plants. The model could be further refined and expanded to analyze and select an optimal system from a variety of handling or combustion system components.

APPENDICES

Appendix 1. Procedure and preliminary results for bulk density and angle of repose for apple pomace.

Procedure

Apple pomace at an initial MC of 68 percent was obtained from a local cider processor and held in a drying oven at 100°C for various periods resulting in pomace samples of 62, 42 and 0 percent MC. Bulk densities were determined by compressing a known mass of uncompressed pomace under progressive loads in a graduated chamber.

The angle of repose was calculated by filling a one liter cylinder with pomace, vertically lifting the cylinder, and allowing the pomace to seek its own level. Three replicates were performed for each MC, in which the mean radius and height of each pile were measured. The mean angle of repose was calculated by the equation:

$$\text{angle of repose} = \tan^{-1}(\text{height}/\text{radius})$$

This value is referred to as the 'kinetic' angle of repose, since it combines both kinetic and static features in the measurement presented in this discussion. A kinetic measurement would allow the pomace to fall a known distance before measuring the angle, while a static measurement would be determined by the angle at which a tilted pile begins to slide in on itself (Mohsenin, 1970).

Results and discussion

Two trends are evident from the data for bulk density (Figure A): first, pomace compresses very little over the range of 0-140 kg/m^2, and second, bulk density increased with increasing MC. Densities ranged from 135-146.5 kg/m^3 for bone dry pomace, to 385-410 kg/m^3 for fresh weight (68 percent) pomace. There were no major differences in slopes of the lines indicating the compression rate to be independent of MC. The presence of sugar solutes in the pomace causes it to clump with slight pressure at higher moisture contents.

The angle of repose (Figure B) was 36.6° for bone dry, and 41.9, 33.3, and 32.1° for 42, 62 and 68 percent MC, respectively. Lesser angles for the higher MC were not due to the pomace being more fluid, but rather being more adhesive. During measurements, clumps formed from compaction against the cylinder wall and fell under weight of gravity, causing non-uniform particulate movement. An alternative to this method might be that of pomace at rest on a horizontal surface being tilted until movement begins (which would be the static angle of repose as previously described). The tangent of the static angle would be the static coefficient of friction (Ross and Kiker, 1967).

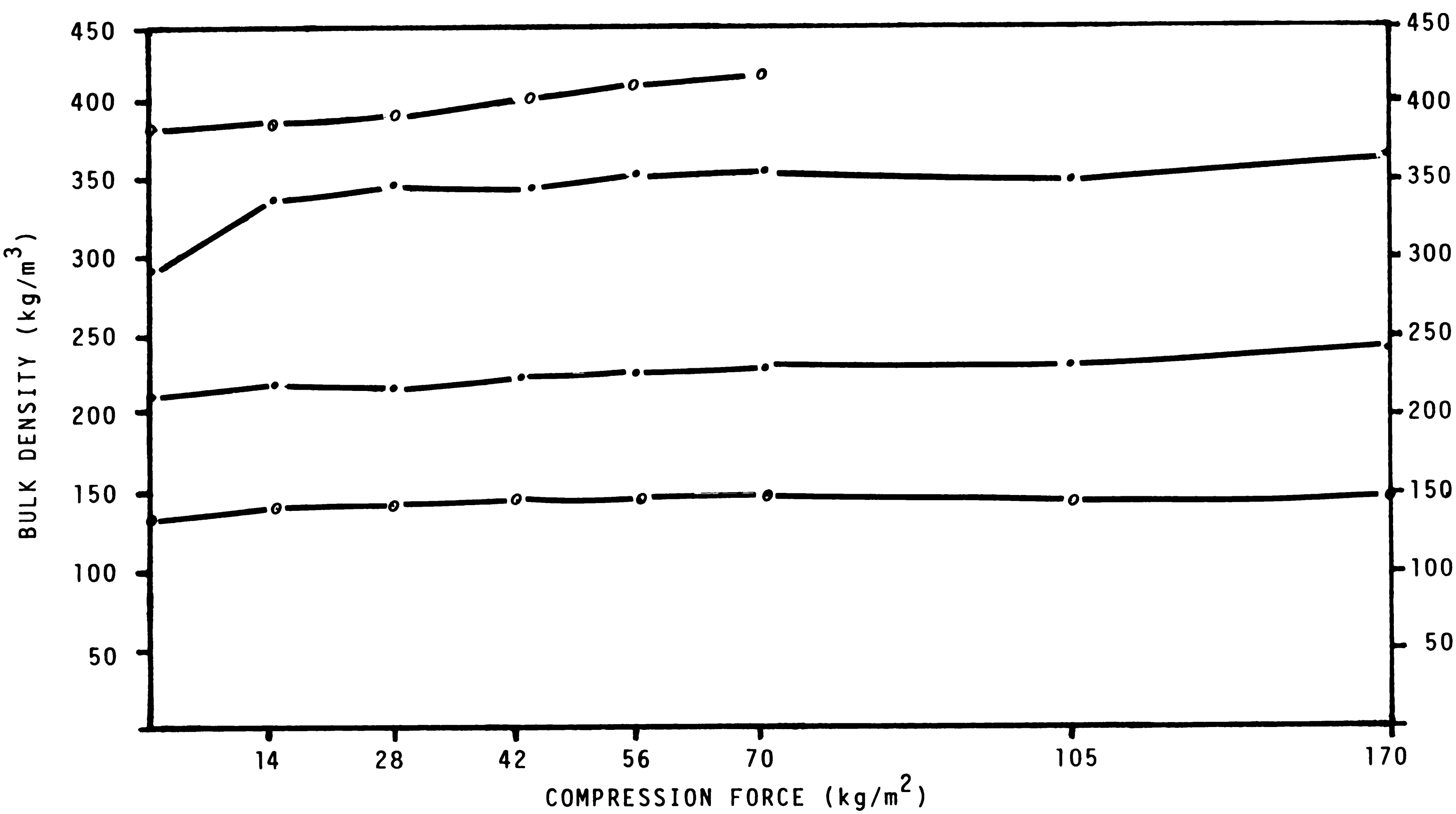

Figure A. Bulk density of apple pomace compressed at various moisture contents.

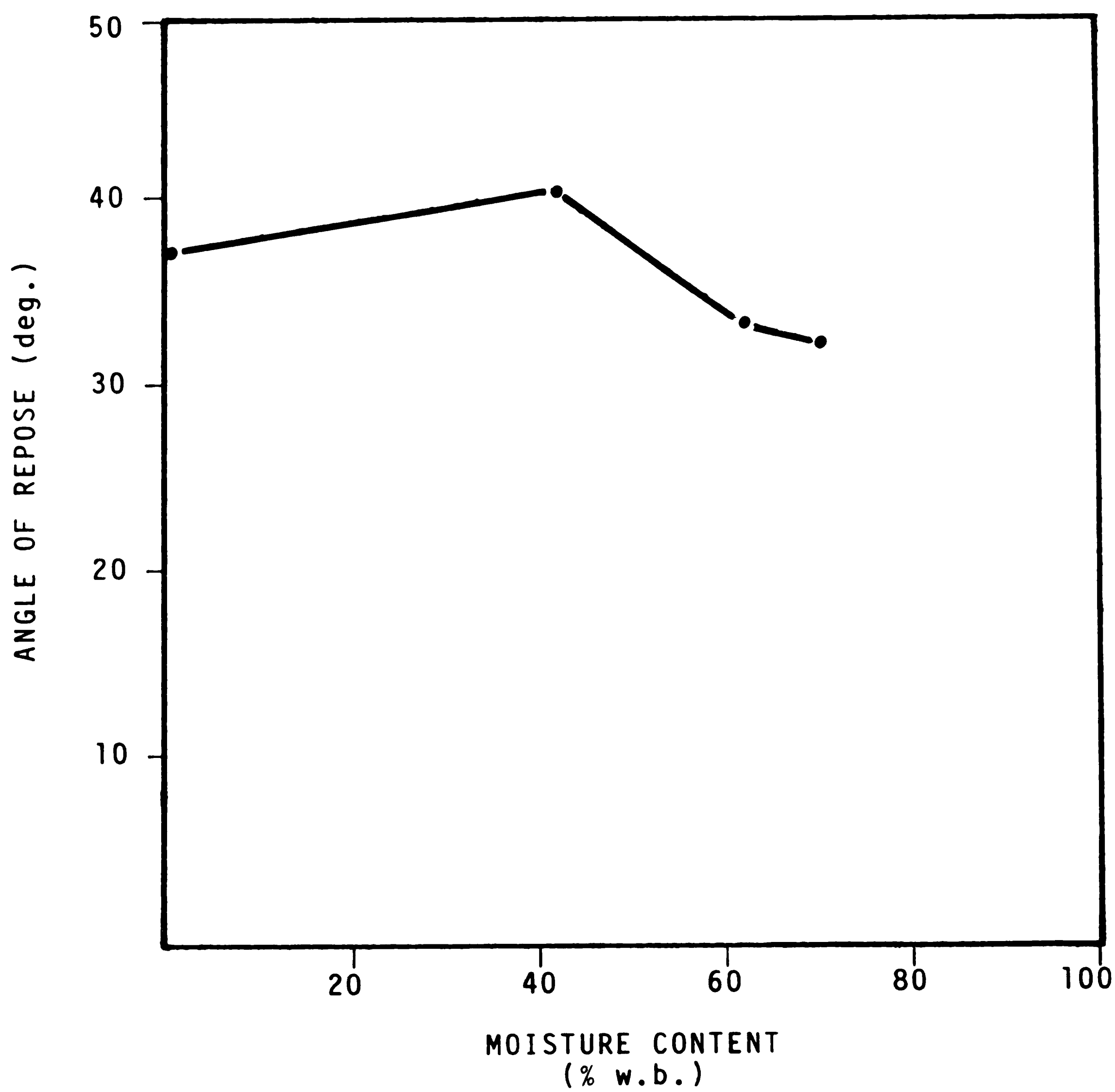

Figure B. The effect of moisture content on angle of repose of apple pomace.

Knowledge of these values at various MC would be especially useful when transferring pomace by means of bulk containers where tilting is involved. With the present method, an improvement could be made by allowing the sample to free-fall a short distance upon leaving the cylinder to reduce clumping tendencies.

Summary

These tests have estimated some mechanical properties of apple pomace, while revealing the complexity of collecting these data. Bulk density and clumping were proportional to MC and compression; both are important aspects for flow or mechanical conveyance, such as might be necessary for calculation of tilt angle or screw auger power requirements. Compression could be measured with higher forces (above 140 kg/m^2 measured in this study) and correlated to clumping tendencies and MC. Pomace behaved similar to grain (when clumping was not a factor during measurement of angle of repose), in that it was free flowing and the angle of repose decreased with decreased MC.

Problems which might be encountered during handling of fresh pomace relate mainly to moisture content. Sugar deposits could accumulate considerably on handling equipment without imposition of a rigorous cleaning program between uses. Clumping would without doubt increase power requirements, causing excess wear on parts and raising fuel or electrical costs. Storage life would be greatly reduced as well.

Appendix 2. Conversion factors and drying calculations for apple pomace.

a) Conversion factors:

1 ac = 0.4046 ha

1 Btu = 1.055 kJ

1 Btu/lb = 2.326 kJ/kg

$^{o}F = 1.8 \times {}^{o}C + 32$

1 gal (U.S.) = 3.7854 lit

1 lb = 0.45359 kg

1 lb/ft^2 = 4.8824 kg/m^2

1 lb/ft^3 = 16.0185 kg/m^3

1 ton = 907.18 kg

1 yd^3 = 0.7645 m^3

b) Drying calculations:

1. Amount of water dried: (65% to 15% MC, w.b.)

75% of fresh weight pressed as juice, 25% remains as pomace @ 65% MC (Kranzler and Davis, 1981).

*Dry weight:

1 kg - .65 kg water = .35 kg dry matter

*Weight at 15% MC:

$$\frac{x-.35}{x} = .15$$

$$x = .35/.85 = .4118 \text{ kg}$$

*Per unit pomace:

1.00 - .41 = .59 **kg** water to be dried

2. Heat required for drying: (drying efficiency=60%)

3954 kJ/kg water = x kJ/.59 kg water

x = 2333 kJ/kg pomace @ 65% MC
= (1003 Btu/lb)

Appendix 3. Equipment and manufacturers of system components used in the analysis.

Component	Manufacturer
<u>Handling System</u>	
Rotary Drier	Aeroglide Corporation Raleigh NC 27611
Belt Conveyors (high, low MC)	Dunckley Company Kalamazoo MI 49001
Hammermill	Shutte Pulverizer Co Buffalo NY 14240
Bucket Elevator Screw Auger	Laidig Silo Michiwauka IN 46544
Storage Bin	IMCS, Inc. Zeeland MI 49464
<u>Package Boilers</u>	
Suspension/Pile Burning (Ray Biomass Boiler)	Ray Burner Company San Francisco CA 94112
Fluidized-Bed Combustion (Fluid-Fire Package Boiler)	Johnston Boiler Company Ferrysburg MI 49409
Suspension Firing ROEMMC Burner System)	Guaranty Performance Company, Inc. Independence KS 67301

Appendix 4. The effect of savings in disposal costs on net annual savings for small processors.

SYSTEMS SUBSTITUTING FOR:	NET ANNUAL SAVINGS (LOSSES) ($) Percent Disposal Costs 0	50	100
Natural Gas			
Pile burning	(-221,343)	(-153,405)	(-85,466)
Fluidized-bed	(-147,925)	(-79,987)	(-12,048)
Suspension-firing	(-123,013)	(-55,075)	12,864
#2 Fuel Oil			
Pile burning	(-202,869)	(-134,931)	(-66,992)
Fluidized-bed	(-129,451)	(-61,513)	6,426
Suspenison-firing	(-104,540)	(-36,601)	31,338

14% annual loan interest rate over 5 year payback period; 30 tons/day (27,215kg/day) apple pomace generated for 5 months.

50% = $9.15/ton ($8.30/1000kg)
100% = $18.30/ton ($16.60/1000kg)
Small system = 10 million Btu/hr (10.5 GJ/hr)

Appendix 5. The effect of savings from disposal costs on net annual savings for large processors.

SYSTEMS SUBSTITUTING FOR	NET ANNUAL SAVINGS (LOSSES) ($) Percent Disposal Costs [2] 0	50	100
Natural Gas			
Pile burning	(-259,341)	(-32,878)	193,584
Fluidized-bed	(-215,444)	11,018	237,481
Suspension-firing	(-90,036)	136,427	362,889
#2 Fuel Oil			
Pile burning	(-197,760)	28,703	255,165
Fluidized-bed	(-153,864)	72,599	299,061
Suspension-firing	(-28,455)	198,007	424,469

[1] 14% annual loan interest rate over 5-year payback period; 100 tons/day (90,718kg/day) apple pomace generated for 5 months.

[2] 50% = \$9.15/ton (\$8.30/1000kg)
100% = \$18.30/ton (\$16.60/1000kg)
Large processor = 30 million Btu/hr (31.5 GJ/hr)

Appendix 6. The effect of changes in fossil fuel price on net annual savings for small and large processors.

	NET ANNUAL SAVINGS (LOSSES) ($) Percent Fossil Fuel Increase				
	-29	0	+20	+50	+100
SMALL SYSTEMS					
Pile burning	(-221,343)	(-202,869)	(-190,227)	(-171,242)	(-139,602)
Fluidized-bed	(-147,925)	(-129,451)	(-116,808)	(-97,824)	(-66,184)
Suspension-fired	(-123,014)	(-104,540)	(- 91,897)	(-72,913)	(-41,272)
LARGE SYSTEMS					
Pile burning	(-259,341)	(-197,760)	(-155,617)	(-92,336)	13,132
Fluidized-bed	(-215,444)	(-153,864)	(-111,721)	(-48,440)	57,028
Suspension-fired	(- 90,036)	(- 28,455)	13,687	76,968	182,436

14% loan interest rate over 5 year period; 5 month process season; no disposal costs.

-29% = $4.795/million Btu ($5.059/GJ) Sept. 1983 price - natural gas
0% = $6.770/million Btu ($7.140/GJ) Sept. 1983 price - #2 fuel oil
+20% = $8.124/million Btu ($8.571/GJ)
+50% = $10.155/million Btu ($10.714/GJ)
+100% = $13.540/million Btu ($14.280/GJ)

Small system = 10 million Btu/hr (10.5 GJ/hr)
Large System = 30 million Btu/hr (31.5 GJ/hr)

Appendix 7. The effect of loan interest rate on net annual savings for small processors.

	NET ANNUAL SAVINGS (LOSSES) ($) Loan Interest Rate (%)				
SYSTEMS SUBSTITUTING FOR:	10	12	14	16	18
Natural Gas					
Pile burning	(-201,138)	(-211,144)	(-221,343)	(-231,728)	(-242,290)
Fluidized-bed	(-133,820)	(-140,806)	(-147,925)	(-155,175)	(-162,548)
Suspension firing	(-110,924)	(-116,911)	(-123,014)	(-129,227)	(-137,547)
#2 Fuel Oil					
Pile burning	(-182,663)	(-192,670)	(-202,869)	(-213,253)	(-223,816)
Fluidized-bed	(-115,346)	(-112,331)	(-129,451)	(-136,700)	(-144,074)
Suspension-firing	(- 92,450)	(- 98,437)	(-104,539)	(-110,752)	(-117,073)

5 year payback period; 5 month process season with no disposal costs.
Small processor = 10 million Btu/hr (10.5 GJ/hr)

Appendix 8. The effect of loan interest rate on net annual savings for large processors.

	NET ANNUAL SAVINGS (LOSSES) ($) Loan Interest Rate (%)				
SYSTEM SUBSTITUTING FOR:	10	12	14	16	18
Natural Gas					
Pile burning	(-227,229)	(-243,132)	(-259,341)	(-275,843)	(-292,630)
Fluidized-bed	(-186,885)	(-201,029)	(-215,444)	(-230,122)	(-245,051)
Suspension-firing	(- 72,075)	(- 80,970)	(- 90,036)	(- 99,267)	(-108,656)
#2 Fuel Oil					
Pile burning	(-165,649)	(-181,552)	(-197,760)	(-214,263)	(-231,049)
Fluidized-bed	(-125,304)	(-139,448)	(-153,864)	(-168,542)	(-183,471)
Suspension-firing	(- 10,495)	(- 19,389)	(- 28,455)	(- 37,686)	(- 47,075)

5 year payback period; 5 month process season with no disposal cost.
Large processor = 30 million Btu/hr (31.5 GJ/hr)

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