Direct combustion of biomass : technical and economic feasibility
by Bruce Randal Kinzey

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

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Direct combustion biomass systems often do not return the economic rewards expected because of faulty cost estimations and/or mismatches between the system and the fuels used. "Hidden" costs of fuel collection and system operation may be substantial. Characteristics of specific fuels may negate their use with certain system designs.

Correct evaluation of both technical and economic aspects of biomass combustion systems and fuels is essential for achieving optimal installation results.

These topics are addressed, and a BASIC computer program developed to produce approximate annual cost comparisons between conventional and biomass fuels is included.

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PREFACE

The material contained in this thesis was compiled from research studies of the author and an extensive literature review. Its purpose was to produce an overall picture of the feasibility of biomass-fueled furnace systems for Montana.

The research project was funded primarily by a research grant from the Montana Department of Natural Resources and Conservation. The purpose of the grant was to determine possible optimization techniques for the performance of a commercially-available biomass grain dryer located at the Southern Agricultural Research Center (SARC) in Huntley. Montana. Previous research with this grain dryer (Little, 1984) had shown that it was not economically feasible to operate when the total biomass system and operating costs were compared to those of a propane system. The current research was a follow-up on Little's study and was aimed at improving the biomass system's performance.

Results of the current research were largely similar to those of the previous study. It has been determined, however, that these results apply primarily to the existing grain dryer at the SARC and the conditions and costs of fuel at that site. Rather than duplicating the negative results of the previous report, this thesis attempts to explain and clarify the operating conditions that are required to accomplish efficient use of a biomass furnace system. An introductory literature review was omitted also in efforts to avoid duplication.

The author would like to acknowledge the help of the workers at the SARC, whose inputs greatly aided the research effort, and Al Lien, whose exemplary machinist skills made the system fit together and operate.

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Abstract

Direct combustion biomass systems often do not return the economic rewards expected because of faulty cost estimations and/or mismatches between the system and the fuels used. "Hidden" costs of fuel collection and system operation may be substantial. Characteristics of specific fuels may negate their use with certain system designs. Correct evaluation of both technical and economic aspects of biomass combustion systems and fuels is essential for achieving optimal installation results.

These topics are addressed, and a BASIC computer program developed to produce approximate annual cost comparisons between conventional and biomass fuels is included.

CHAPTER 1

Introduction

The direct combustion of biomass for energy purposes represents an area of large economic potential for small energy-intensive industries like farms. Biomass is a renewable source of energy that is generally in abundant supply on agricultural lands, so it is understandable that attempts are made by farm operators to utilize this energy source. Effective returns, however, are often less than desired because extra costs are encountered that were not at first evident or were ignored in initial analyses. A greater labor input than originally perceived is often necessary, causing further dissatisfaction with installation results.

The decision to purchase a biomass system by an individual is usually influenced by manufacturer's claims of substantial annual energy savings. Estimates of fuel costs for the biomass materials used can differ greatly. Many different assumptions are possible and the resulting total cost is highly dependent on these assumptions. Annual fuel savings often do not include the extra labor and management required for fuel delivery and system operation. Actual costs for a direct combustion biomass system are dependent on the characteristics of the specific fuel to be used, the characteristics of the specific combustion system design, and the conditions of the conventional fuel (price, availability, etc.) at the site of use.

The individual attempting to make a decision on whether or not purchase of a biomass system would be a good investment should be aware of the increased costs and efforts required with using biomass as fuel. Basic knowledge about the combustion properties of biomass fuels and the mechanics of handling and burning biomass will help the individual to understand the reasons why biomass combustion requires extra labor and extra owning and operating costs. Results of research efforts at Montana State University and other locations that have been aimed at reducing or eliminating some of the costs and problems associated with biomass fuels can be useful in helping an individual evaluate the technical feasibilities of different systems.

This research project was limited to a study of direct combustion biomass systems. Other biomass utilization systems (i.e., methane digesters, ethanol plants, etc.) were outside the scope of the research and are not included in this report.

CHAPTER 2

Technical Aspects of Biomass Fuels

The technical aspects of biomass fuels are those qualities or properties of a specific material which affect its use as a fuel. These factors all help to determine the technical feasibility of using the material for fuel purposes. The availability of the material, its energy content, and its combustion and handling characteristics are examples of properties associated with all biomass materials which need to be given careful consideration in order to properly assess a specific material's suitability as fuel. These and other properties that are unique to each material are outlined and discussed in this chapter. Observations are made as to the optimal conditions needed to utilize these materials. The cost of fuels is not covered directly here, although the effects of the technical properties on fuel costs are mentioned. Estimated fuel costs are covered in Chapter 3.

Availability

A particular type of biomass must first be available in a plentiful supply to be considered as a primary fuel source. A fuel that is available only in relatively limited quantities may be useful as a supplementary source, but its usefulness is generally restricted. Limited supplies may result in competition between users and resulting shortages or increased costs at peak periods of use. Under atypical circumstances, a relatively small fuel supply can be used by a single or a few users if adequate control of the supply and subsequent use is maintained. A pertinent example is a system that utilizes grape and apple pomace from processing plants (Mason et al. 1985); such a fuel would probably be used most practically inside the plant in which it was produced. This process would also double as an inexpensive method of waste disposal, and thus could be highly cost effective.

Optimum performance for a particular fuel is usually only obtained with systems that have specialized components designed specifically for that fuel. Characteristics that vary among different materials such as friction coefficients, particle size, and combustion properties require special design considerations. It is usually not practical to design an individual system for a fuel that is in short supply because of design and equipment costs that are specific to that fuel.

It is sometimes possible to use different types of biomass materials in one system by processing them into similar form. Fuels that have dissimilar feeding properties can be made to feed similarly, for instance, by chopping, grinding, or cubing them. This may not be optimal usage, however, because of the additional energy inputs and processing costs required.

The long-term availability of a particular biomass material is likely to be more important than its present availability. Current supply conditions and costs could change rapidly if the demand for a type of biomass increased or if alternative uses for it developed. Conversely, the supply of a particular type of biomass could increase in the future as a result of different cropping practices or new technologies.

Multiple potential sources for a particular type of biomass could be an important consideration in assessing its availability for the future. Reliance on a single source makes the user or users dependent on that source, creating competition between users or a lack of competition between suppliers. Even a user who plans to produce his own fuel should have a secondary source available in the advent of unfavorable circumstances.

The cost of the fuel is directly affected by its availability. A fuel that can be obtained only in limited quantities will likely increase in price with expanded use. In addition, the specialized system components which must be designed for a fuel limited in quantity are more expensive than their more common counterparts. A shortage of a particular fuel may quickly raise its cost to users above the cost of alternatives.

Energy Content

The biomass fuels considered in this study are all composed of cellulitic materials. The potential energy or heat content (Btu/lb) can vary widely between individual fuels, however. The energy that is available from a biomass material is dependent on its density, moisture content, and specific chemical composition. Table 1 lists several biomass materials and the available energy contents for each. These energy levels are listed for oven dry material and for two moisture content (mc) levels of 10 and 20% (wet basis or wb).

It can be seen from the values in Table 1 that moisture content has a significant effect on the net heat available from each material. The combustion of biomass materials actually occurs in three stages:

1) evaporation of moisture; 2) volatilization and burning of volatile matter; and 3) combustion of fixed carbon (Stout, 1984). The first stage, evaporation of moisture, must take place before the second stage occurs. This results in an absorption of some of the available energy in the material by the water as it is evaporated. Obviously, higher moisture content materials must surrender a higher percentage of their energy to this process than those containing lower moisture levels.

Table 1. Average Net Heat Contents (Btu/lb) for Various Biomass Fuels

%mc (wb) Fuel	0	10	20
Corn Cobs	8477[a]	7514[b]	6552[b]
Corn Husk	7917[a]	7010[b]	6104[b]
Corn Stalks	9552[a]	8482[b]	7412[b]
Soybean Residue	7487[a]	6623[b]	5760[b]
Cotton Stalks	7788[a]	6894[b]	6000[b]
Wood & Wood By-products	9000[c]	7890[c]	6960[c]
Straw	7811[d]	6915[b]	6019[b]

[a] Sumner et al.(1983)
[b] Estimated, using 1150 Btu/lb for evaporation requirement of water.
[c] Johnson et al.(1951)
[d] MSU bomb calorimeter determination.

Moisture in the fuel results in other reductions in the available energy from the material that are in addition to those caused by the evaporation of water. A dry matter loss over time often occurs due to microbial activity within the fuel. Microbial activity within the fuel is encouraged by the presence of moisture. Spontaneous heating within the fuel can also occur, further enhancing biological degradation (Suggs, et al. 1985). Drying of the biomass and maintaining it in a dry condition is essential for achieving the highest available energy output at the time of use.

Corn harvest residues and other materials stored in loose form appear to be very susceptible to dry matter loss. Richey (1982) found that corn stover stored at 13.9% mc lost 10% of its dry matter after six months, while stover that had been stored at 33.4% mc lost 22.6% of its dry matter over the same time period. Smith et al. (1983) conducted a study on ventilated vs. unventilated storage piles for corn cobs and found that the net available energy of an unventilated pile was approximately 10% lower than the net available energy of a ventilated pile after 9 months of storage. Ventilation was achieved by using a fan ducted to the center of the pile. The conclusion was that the difference in energy content between the two piles was mainly due to the increased dry matter loss and moisture level in the unventilated pile.

Studies with round bales have shown that they also suffer dry matter losses when stored. Anderson et al. (1981) found that storage dry matter losses averaged 14% for alfalfa stored outside over one winter. Verma et al. (1983) found that ryegrass bales stored outside in Louisiana for 7 months averaged about 29% dry matter losses, which increased to an average of about 33% after 12 months. The high relative humidity of the surrounding air was probably a major factor in the relatively severe losses found in the latter study.

The dry matter losses for wood chips are probably less than those for straw and stover, because of their more compact and rigid structure which better resists mechanical deterioration. Losses are further reduced because wood chips only require two or three months of storage to dry 20% mc chips to an easily combustible 12.5% mc (Kinzey, 1985). Storage losses can reasonably be assumed negligible for these circumstances.

The net available heat energy from a particular type of fuel may vary for reasons other than moisture content. For example, the heat content listed in Table 1 for oven dry corn stalks (9552 Btu/lb) was for hand-harvested material. Machine-harvested corn stover in the same study was found to contain approximately 20% less total energy (7616 Btu/lb). It was surmised that the probable cause of the difference in these values was that the machine-harvested stover contained sand and soil particles, while the hand-harvested stalks were cut at ground level and were therefore cleaner. Other reasons for differences in specific biomass heat contents include age of the biomass, growing conditions, and variety within species.

Methods of Moisture Removal

It is often desirable to reduce the moisture content of a biomass fuel prior to its combustion in order to increase the net heat output during use. Several methods of moisture removal exist; more than one may be used on a single batch of fuel in some situations.

Solar- or air-drying is the most common method for removing moisture from biomass fuels. All biomass materials have an equilibrium moisture content that is related to the temperature and relative humidity of the surrounding air. Loose fuels like corn cobs or wood chips are typically pile-stored outside for a period of months before their use. Air circulating through the pile will bring the material to its equilibrium moisture content if the storage period is long enough. Straw is generally field-dried prior to harvest, and baled in its dried or equilibrium condition. The equilibrium moisture content may change as surrounding conditions change. Warming ambient temperatures may cause even further drying of the material, or an increase in relative humidity of the ambient air may cause moisture to be regained by the material.

The process of air drying uses direct solar energy to remove the water in the biomass, and can be a very effective method. Table 2 gives the results from an air-drying study on four different fuels stored at the SARC over a period of 6 months.

Table 2. The Moisture Contents (%wb) of Biomass Fuels Stored Outdoors at Huntley, Montana.

	Sample	Date of Moisture Sample		
Fuel	Location	3/28/85	7/5/85	10/5/85
Sawdust-Covered	surface	28.03	25.07	24.44
Sawdust-Uncovered	surface	58.02	51.41	-----
Sawdust-Uncovered	center	40.82	58.95	42.66
Stover-Uncovered	surface	46.56	6.51	22.5
Stover-Uncovered	center	12.71	7.82	-----
Straw-Large Round Bales	surface	17.23	2.99	5.83
" " " "	center	16.01	1.28	-----
Wood Chips-Uncovered	center	-----	20.10	12.37

A storage problem was noted with the corn cob/stover storage pile in this study (listed as "Stover-Uncovered"). Water absorbed from rainfall was drawn to the base of the pile, where it collected, causing a rotting of the cobs and stover. A moisture content determination was not performed on the base of this pile, but the material contained enough moisture that an appreciable amount could be squeezed out by hand. This resulted in a loss of energy from the storage pile, as rotting is a result of microbial activity, which consumes energy.

Surface moisture for all the fuels in the table fluctuated rapidly with ambient temperature and moisture conditions. Rainfall was quickly absorbed into the piles and either drawn to the center or subsequently evaporated. Snow required a longer period to be removed than did rain, because the snow required melting prior to evaporation. In one spring melting period, when it was desired to operate the furnace, straw remaining in the feedwagon had to be disposed of because its high moisture content made it unusable.

The sawdust used in this study also became unusable for fuel purposes because it absorbed and held moisture in a sponge-like fashion. Due to the small particle size of the sawdust, air did not circulate well through the piles, which resulted in extremely high moisture retention. This problem was most evident in the uncovered storage pile. Because of the moisture problem, and because of a tendency for wind to blow away portions of the pile, it was determined that the use of sawdust as fuel will require covered storage (preferably building storage).

There are various methods for non-solar moisture removal. These methods are usually used only when the biomass fuel is needed immediately. Air-drying the fuel requires a relatively long period of time, and generally will not be appropriate if the fuel is required soon after harvest.

One method for drying biomass is direct heating using either conventional fuels or a portion of the biomass itself. Other methods may use recovered waste heat from grain drying or other heat-intensive processes. Morey et al. (1982) noted that using biomass to dry corn cobs often caused fires when sparks in the exhaust air set fire to the drying cobs. This problem would require the use of a heat exchanger or other system modification.

Morey (1983) found that supplemental heat from a propane torch was required in order to obtain a satisfactory heat output when using corn cobs at their harvest moisture content of 33%. The supplemental heat required from the propane was approximately 10 to 15% of that amount required to dry the corn with propane alone. Little (1984) found a similar propane requirement in his study with the SARC system while using a high moisture corn cob/stover mixture.

Methods of Collection

Biomass fuels usually require some method of collection by the user, as opposed to conventional fuels which are generally delivered on-site. The methods used to collect the biomass from the field or elsewhere will vary with the type of biomass, intended use of the biomass, and the preferences of the biomass producer. Collection may be as simple as hauling and storage of a truckload of wood chips, or it may entail a great deal more effort, as in the processes of harvesting, drying, grinding, and storing of a crop residue.

Collection of crop residues for fuel purposes may or may not occur simultaneously with the crop harvest. If the biomass is to be gathered in loose form (such as corn cobs), it is usually most practical to accumulate the biomass at the same time the crop is harvested. In normal harvest procedures, the residues are typically gathered by the harvesting machine, the desired crop material is then removed, and the residual biomass material is discarded onto the field. The harvest efficiency for the crop and residue is usually reduced if the field must be harvested a second time to gather the discarded residue. Biomass harvest processes which are combined with the crop harvest typically employ an auxiliary storage vehicle, such as a trailing wagon behind the harvesting machine, to save the residual crop material as it is discarded. This storage vehicle is then emptied or exchanged as needed.

It may be desirable in some cases to leave the crop residue in the field for a period of time after harvest. Allowing straw to air-dry in the field before baling is one such example. Two or three passes over the field in addition to the crop harvest may be required for this procedure. Normally, the straw and chaff drop directly from the combine to form windrows in the field. A swather may be used to cut additional material and to form larger windrows, although this process is not common in Montana. The straw is then baled after the windrow has dried. The final pass through the field collects and removes the bales. A separate biomass harvest operation is sometimes desirable to give maximum capacity for the crop harvest operation.

Cotton and cotton plants are another example where the crop and residue are harvested separately. It is usually desirable to remove the cotton stalks and roots from the field, rather than to incorporate them into the soil. The plants deteriorate slowly in the soil and have the potential of encouraging soil borne diseases in the subsequent crop (Sumner et al. 1983). The cotton plant is not collected simultaneously with the cotton because it requires about 3 weeks to dry under good conditions after being uprooted from the soil. Typically there are at least three machine operations in addition to the cotton harvest that are required for the cotton residue's removal: 1) uprooting the plants, 2) baling the residue, and 3) collecting the bales.

Biomass harvests that require multiple operations are usually more expensive than those that can be done as part of the crop harvesting process. Baled materials, however, are easier to manage, transport, and store than loose materials, so the extra collection costs associated with baling can offset other costs incurred at a later date.

Materials Handling Characteristics of Biomass Fuels

Most biomass fuels are supplied to or metered into the furnace through a mechanical feeding system. Problems will be encountered with certain fuels when the metering properties are not matched to the specific mechanical apparatus used in the feeding system. Information about the individual fuels' feeding properties is required to assess the feasibility of a fuel with a particular system design.

A property common to all biomass fuels is their surface roughness. Lignins and other structural components of plant material give it considerable rigidity, especially when dried. Exposed edges can be very sharp and abrasive to machine parts that come in contact with the material. The coefficients of friction for several biomass materials are given in the ASAE Standards 1985. These coefficients of friction are proportional to the conveying and sliding forces of biomass encountered in a moving system.

Binding and clogging of the fuel in the feeding system is common, especially where the biomass comes in contact with flow obstructions and rotating parts. Fuels that have relatively low density, like straw, are particularly subject to wrapping and plugging. Individual straws or clumps of fuel may stop moving when they come in contact with a stationary surface, or they may intertwine and "bridge" over the top of moving surfaces. The clump of fuel that has come to rest can in turn become a stationary surface to further impede flow. Long, flexible materials, again using straw as an example, exhibit a tendency to wrap around rotating parts. The presence of surface moisture on the biomass or the machine increases adhesive forces, compounding these problems.

Higher density fuels like wood chips may also produce feeding problems. These fuels neither compress nor separate easily. A hard chunk of fuel of this type can quickly become wedged between moving components and stall the system.

Biomass fuels are bulky, which makes them difficult to meter accurately. The apparatus which separates portions of the fuel from the feedwagon prior to feeding them into the furnace must cover a large area to assure good contact with the fuel. The actual amount of fuel in contact with this apparatus at any particular time can vary and thus the amount of fuel subsequently separated can also vary. High amounts of fuel introduced into the feeding system at one instant are what typically cause the clogging and bridging problems.

Emissions

The combustion of biomass materials produces gaseous and solid compounds which are then released as exhaust. It is important to know the products of combustion in the exhaust so that its pollution effects can be understood.

The combustion process is the rapid chemical combination of oxygen with the combustible elements of a fuel. In agricultural crop residues, the combustible elements are primarily carbon, hydrogen, and metallic elements such as potassium and sodium. The chemical products produced from combustion are usually carbon dioxide, water, and metallic oxides. Complete combustion of hydrogen and carbon follow the reactions:

$$2H_2+O_2 \rightarrow 2H_2O + 6.11\text{x}10^3 \text{ Btu/lbH}_2$$

$$C+O_2 \rightarrow CO_2 + 14.1\text{x}10^3 \text{ Btu/lbC}$$

The actual metallic oxides produced in a combustion process depend on the particular fuel burned. The ultimate chemical analyses for corn stover, Douglas Fir bark, straw, and pine sawdust are shown in Table 3. The analyses for the ash from corn stover and Douglas Fir bark are shown in Table 4.

The emissions from a particular fuel during combustion can warrant limitations on its use. Standards imposed by governmental agencies or individuals can restrict a fuel's use until it is no longer economically feasible.

A common application for biomass combustion systems is in the process of drying perishable grains for sale or storage. A typical direct fired grain dryer incorporates the combustion furnace exhaust with ambient air, forcing the resulting mixture through a storage bin containing the wet grain. The grain is thus directly exposed to the chemical compounds produced by the combustion of the biomass. Some of these exhaust products may have properties that are harmful or undesirable in connection with the subsequent use of the dried grain.

Table 3. Ultimate Chemical Analyses for Various Biomass Fuels (%)

Biomass Type Component	Douglas Fir[2] bark	Corn Stover[1]	Pine Sawdust[2]	Straw[2]
Carbon	56.2	42.48	51.8	36.0
Hydrogen	5.9	5.04	6.3	5.0
Oxygen	36.6	42.65	41.3	38.0
Nitrogen	0.1	0.75	0.1	0.5
Sulfur	----	0.18	----	NS
Moisture	----	4.94	----	NS
Ash	1.2	3.96	0.5	4.75

[1] Stout (1984)

[2] Johnson et al.(1951)

NS- Not Specified

Anderson et al. (1983) conducted a study of the effects of furnace emissions on dried corn, and found that two groups of compounds are of concern. The first group, nitrous or nitric oxides, can produce compounds on the grain surface which have toxic effects on animals and man in high concentrations.

Table 4. Analyses of Ash for Corn Stover and Douglas Fir Bark (%)

Material	Douglas Fir[1] bark	Corn Stover[2]
Compound		
Silica	13.9	72.15
Iron as Fe_2O_3	4.4	4.69
Titanium Oxide	0.4	0.22
Alumina	8.7	4.3
Manganese	0.3	----
Calcium Oxide	51.4	5.15
Magnesium Oxide	3.2	3.92
Sodium Oxide	5.3	1.29
Sulphate	2.9	0.15
Chloride	0.4	----
Carbonate	7.3	----
Potassium Oxide	----	4.41
Phosphate	----	1.05
Unaccounted for	1.8	2.67

[1] Johnson et al.(1951)
[2] Stout (1984)

The second group, polynuclear aromatic hydrocarbons (PAHs), are of even greater concern. These chemical carcinogens are possibly the major cause of human cancers. Benzo(a)-pyrene (BaP) results from the incomplete pyrolysis of organic materials and appears to be one of the most active carcinogenic agents to which man is exposed. BaP levels on some of the grain samples tested in Anderson's study reached 2 ppb during drying. Anderson stated that these samples exceeded various European standards for the maximum BaP levels for smoked foods of 1 ppb.

In addition to possible carcinogenic-compound deposition, biomass exhaust sometimes leaves a noticeable odor on the dried grain. If a person grading a sample of grain notices what he considers to be a commercially objectionable odor, he may judge the grain to be "sample" grade, which could substantially reduce its value. "Sample" grade grain is not saleable in the commercial market, so any value for it would have to be found elsewhere. It was determined in Anderson's study mentioned above that drying the corn with high moisture content fuel at a low furnace output is what generally produced sample grade corn.

Problems associated with using the energy from biomass combustion because of particulates and gaseous compounds in the combustion exhaust must be controlled through furnace modifications. Methods for modifying furnace construction and the combustion process to control emissions is discussed in Chapter 4.

The environmental impact of widespread use of biomass for fuel is also a factor to consider as a result of its emissions. Combustible solid fuels like coal and wood have often caused air pollution problems where they have been used extensively. Densely populated areas or those areas which have a geographically-enclosed air supply (i.e., surrounded by mountains) could experience similar pollution problems if the direct combustion of other biomass for energy purposes became common.

Pollution standards could be a limiting factor for the use of biomass in some communities.

CHAPTER 3

Biomass Fuel Costs

The allure of biomass as a fuel source is partly due to the widespread belief that it is a cheap or even "free" source of energy, and that the costs associated with using biomass for fuel are present whether it is utilized or not. To a certain extent, this may be true. However, there are extra costs incurred as a result of the decision to use the biomass as fuel; these extra costs must be recognized to determine the true energy cost associated with the use of biomass fuels.

The amount of agriculturally-related biomass produced annually in the U.S. is estimated to be 400 million tons (USDOE, 1983). Much of this residue is considered a waste product, requiring some means of disposal. Residue disposal entails cost, and it is intuitive that the most favorable condition is obtaining an economic value for this waste product to help recover some of the disposal cost.

The cost of conventional energy sources has increased dramatically since 1971. Biomass products contain a fair amount of energy, therefore it is natural to assume that biomass utilization as fuel can help to offset both the cost of energy and the cost of residue disposal. However, the utilization of biomass as fuel introduces extra costs not entirely apparent at first glance. The purpose of this chapter is to describe most of these costs, and provide comparisons between various biomass fuels and comparable amounts of conventional fuels. Only fuel costs will be covered in this section, as system costs are covered in

Chapter 5.

Collection Costs

One of the first costs associated with the utilization of biomass is the cost of collecting the fuel. "Collection" refers to the processes of removing the biomass from its growing environment, packaging it into usable or transportable form (where applicable), and storing it for future use or transport. Many different processes can be used as separate or combined operations, depending on the biomass type and the methods used for collection.

The biomass fuels produced at the SARC consisted of two types: winter wheat straw and a corn cob/corn stover mixture. Corn cobs are a widely used source of biomass energy, and a considerable amount of research has been conducted on their use as fuel. The cob/stover mixture at the SARC was collected simultaneously with the corn harvest, using a combine attachment and a trailing wagon to catch the biomass material as it was discharged from the combine's sieves and straw walker. An extra tractor and operator were required to transport and unload the collection wagons. The harvest time was increased approximately 13% when harvesting the additional biomass, due to the heavier load of the additional biomass and the extra time required to exchange the trailing wagons. The biomass yield was calculated to be approximately 2400 lb/acre, or 2400 lb/hr at a total harvest rate of about 1 acre/hr (Little, 1984). The collection cost for the cob/stover mixture at the SARC has been estimated at $44/ton. This assumes a combine operating cost of $89/hr, a tractor operating cost of $23.55/hr, and a wage rate of $10.00/hr. The cob/stover fuel is clearly not "free". For a uniform net harvest heat content of 4745 Btu/lb (harvested at 33% mc), the collection cost translates to $4.60/million Btu. Storage costs are not included in these figures, because the cob/stover mixture was pile-stored outside, and no value was attached to the space occupied by the pile. Storage costs would have been added if there had been other uses competing with the storage pile for this space, or if some type of housing structure had been used.

Winter wheat straw, the other fuel produced at the SARC, has an economic advantage over many other biomass fuels. The costs shown above for the cob/stover mixture are extra costs required to salvage the biomass for fuel. Straw, on the other hand, is typically harvested and removed from the field for other reasons. For many straw-producing crops, the straw must be removed for disease and pest control or to facilitate crop rotations. The cost for collection of the straw is often therefore a necessary expense associated with the crop production. The cost of collection under these conditions would not be associated with the straw's use as fuel. Under these circumstances, the total cost of the wheat straw as an energy source is relatively low. The collection cost for a 660 lb round bale, such as those baled at the SARC, is estimated to be $3.37 per bale. This is equivalent to $0.74/million Btu for an assumed uniform net heat content of 6900 Btu/lb. The straw's collection costs are much less than those of the cob/stover mixture's primarily because the collection operation does not affect the harvest operation. The cob/stover mixture's collection slows down the harvest and the cost therefore includes combine operating costs. The straw's collection cost is omitted in fuel cost calculations if the straw harvest was considered necessary for production of the crop. The straw's estimate includes operating costs for the appropriate machinery and labor, but again no storage costs. Rectangular bales would have a necessary storage cost because they require the use of tarps or other cover during storage. Uncovered bales in this form quickly absorb moisture from rain or snow melt and rapidly deteriorate (Jenkins et al. 1985).

Processing the biomass into other usable forms is common. Cubing, chopping, and grinding are three examples of biomass processing operations to aid in its transport and use. Processing the biomass represents an energy input, and therefore adds another cost to the fuel. The processing cost may offset other expenditures, however, specifically those related to transportation and handling of the biomass. Jenkins (1983b), presents a method for assessing the optimum cost combination of processing, transporting, and handling the biomass for any situation using network analysis and dynamic programming.

Dobie et al. (1984) found that collection costs for rice straw in California averaged about $22/ton, or $2.00/million Btu. Rice straw must be removed after each season for disease and pest control. The cheapest means for accomplishing this was found to be simply burning the field, with a cost of about $1.50/ton. Incorporating the straw back into the soil cost about $15/ton. They concluded that, "If the straw is of sufficient value for some utilization method to cover the cost of collection and handling, such method of disposal may eventually be economically viable. ...Currently there is no such market." If open-field burning is not an environmentally acceptable alternative, however, then at least a portion of the collection cost can be included as a crop production cost, improving the economics of the biomass harvest.

Other forms of biomass also may have this economic advantage if a portion of the collection cost can be attributed to processes other than use of the material as fuel. The slash and trimmings left over from forestry processes like vegetative control, pruning, tree removal, and right-of-way clearing are examples. Present processes typically leave the material in the woods, burn the material in the woods, or chip and remove it. In the last instance, where the material is removed, the collection cost could be entirely omitted in a fuel cost estimation. Substituting collection for the other processes would add extra collection costs to these materials, but the final cost would be offset by the costs of the original processes that were eliminated. Fridley et al. (1984) has operated a slightly modified large round-baler to collect and package forestry by-products with good success. Collection costs for this system are not yet available and probably will be greater than those found in an agricultural setting. A bale of this type, however, could be expected to possess a higher heat content than other baled materials and thus may prove to be a desirable economic alternative.

Transportation Costs

Transportation and handling produce another set of costs that are encountered with use of the biomass for fuel. Transportation costs are incurred with the movement of the material from the source to the storage site and from the storage site to the location of use. Handling costs include loading and unloading of transport vehicles, loading or stoking the furnace, and any moving of the material at the storage site during the storage period.

Transportation costs can be quite large even if the utilization site is only a short distance from the collection site. The bulk density of biomass fuels is generally low, and it is difficult to utilize the full weight-carrying capacity of transport vehicles without exceeding their storage capacity. Jenkins et al. (1985) found that only 30-35% of a flatbed truck's legal weight limit could be transported per load with 1.6m wide round bales. As the transport distance increases, the transportation cost becomes a greater percentage of the total cost of the fuel. A load of wood chips used for experimental purposes at the SARC was acquired from its source 60 miles away for $21. The vehicle used for transporting the chips required 24 gallons of gasoline for the round trip, resulting in gasoline costs alone of twice the wood chips' cost. The ideal situation is production of the biomass at the same location where it is to be used, thus minimizing transportation costs.

Jenkins et al. (1983a) has presented a computer model to determine the optimum location for a centralized biomass utilization site and the accompanying total delivered fuel costs to that site. Inputs to the model are factors such as collection costs and relative locations of biomass producers in the area of study. The model finds the utilization site which produces the least total delivered cost (collection + transportation) for all of the producers in the area of concern. This model assumes that all of the biomass producers would subscribe to a central power facility.

Handling costs can also be substantial. Machines are generally required to handle biomass, adding machine operating costs to labor. The popularity of large package machines such as big-roll balers is in part due to the fact that these forms are easily and quickly handled by a single worker with non-specialized handling devices. The big round bales at the SARC were loaded into the feed wagon using a tractor and front-end loader. Handling required about 10 minutes of labor and machine operation time per bale loaded. Handling biomass in unpackaged forms, like piles of wood chips or corn cobs, is more time consuming and is less efficient, as loose materials can not be moved as quickly and some of the pile is invariably left each time the pile is moved. At the SARC, loading an amount of wood chips into the feed wagon approximately equal (in heat content) to one big bale required about twice the time as that for the bales, or 20 minutes. The actual time required for any particular situation is dependent on the distance between the storage site and the furnace site.

Jenkins et al. (1985) determined a theoretical loading rate for loading road-sided large rectangular bales of 24 dry ton/hour onto flatbed semitrailers, and an unloading rate of 84 dry ton/hour. The corresponding costs would depend on the wage rate, machine operating costs, and number of workers required.

Operating Costs

Different biomass fuels possess different combustion characteristics, and thus the amount of labor required for the actual combustion process varies with the individual fuel used.

Straw contains a relatively high ash content. The use of straw in a direct combustion furnace results in an accumulation of ash, or slag, in the base of the furnace which must be periodically removed. Problems with operation of the system will occur if this slag is allowed to build up over time. "Slagging and fouling can be a severe limitation in using direct combustion conversion equipment" (Hiler et al. 1985).

Slag was removed from the furnace at the SARC prior to each firing while using straw. It was necessary to enter the furnace to break up the hardened slag, which was then raked out through a small opening in the furnace wall. The number of combustion cycles in which the slag could have accumulated before actually causing any noticeable effects on furnace operation was not determined. Approximately twenty minutes were required for each removal period; any greater length of time required as a result of postponing the cleanings would make this chore very unpleasant. Other fuels, such as wood chips, contain lesser amounts of ash and could be operated for several combustion cycles without cleaning.

The density of biomass fuels also affects their operation costs. Less dense or more bulky fuels, like straw, do not contain as many Btu/ft^3 as higher density fuels, like wood chips. Consequently, the furnace feed wagon will have to be reloaded more often with less dense fuels than with higher density fuels. Lambert et al. (1982) noted that the availability of labor is often critical around harvest time, and the need for continual stoking of a furnace could restrict its use. The time required to reload the feed wagon could be very significant if someone had to leave his position in the field to perform this operation. It was determined in Lambert's study that widespread use of biomass conversion devices can depend on the development of cost effective automatic biomass feeding equipment.

Opportunity Costs

Although biomass is commonly considered a waste product, most biomass materials actually have alternative values. Alternative values for the biomass must also be determined to obtain the true cost for using it for fuel.

The value of agricultural residues that are reincorporated into the soil is a very real value for maintaining soil nutrients and conserving soils. Crop residues reincorporated into the soil are a very effective means of soil conservation. Crop residues increase soil organic matter, improve soil tilth, and also greatly reduce soil erosion by wind and water. The dollar value of the biomass used in this manner is difficult to determine. There is a cost savings in fertilizer applications, soil is preserved, and water retention capabilities of the soil are increased. Assigning a value to these factors is essential, and it must be performed by the individual considering the use of his crop residues as fuel.

A second major alternative use for agricultural residues is as livestock feed. Straw can be used as a portion of cattle rations. Corn and soybean fields can be grazed after harvest as pasture for foraging animals. Little (1984) determined that the corn fields at the SARC had a value of $35/acre as forage pasture. Harvesting the biomass for fuel from these crop residues greatly reduces the value that can be obtained by renting the fields out for this purpose, because the material best suited for animal feed is also the most desirable material for use as fuel.

Assuming these two uses are of paramount importance, the amount of crop residues produced annually in the U.S. still exceeds that amount required for soil incorporation and feed requirements. USDOE (1983) estimates that about 20%, or 80 million dry tons per year could be used for energy production "without adversely affecting soil quality or livestock feed supplies."

There are other alternative uses for agricultural residues that compete with its utilization as fuel. Straw is purchased by dairies and other animal-based industries for bedding and similar purposes. Wood chips and sawdust often have more value as raw materials for paper mills and pressboard manufacturers than as for fuel. Forfeiting these possible alternative values for the biomass material increases the cost of using it for fuel.

The optimum condition for a biomass material for fuel use is that it contain little or no alternative value. Straw cannot always be sold, and it is a common sight to see unused bales deteriorating in the field. Bales of this type can be used for fuel purposes with no opportunity costs entailed. Other materials, like plants uprooted from the soil for vegetative pruning or crop rotations, likely have disposal costs associated with them that can be partly recovered by obtaining an energy value for them. Plant residues such as these can often be obtained for the cost of only hauling them away.

Example values of the costs outlined in this chapter are shown in Chapter 5. The assumptions used to derive these values are contained in Appendix A.

CHAPTER 4

Combustion Systems

The system used to combust biomass fuels must be designed for the chemical and materials handling characteristics of the specific fuel in order to obtain optimum performance. The total biomass system typically includes a combustion furnace, a furnace-feeding apparatus with capacity for fuel storage, and additional equipment as needed for the particular use of the derived heat (ducting, air fans, drying bin, etc.). The word "system" can apply to individual components of the total drying system defined above (feeding system, ducting system, etc.). "Total system" as used here refers to the combination of components as a whole.

The analysis in this chapter is concerned with both the economic and technical aspects of biomass combustion systems, in a manner similar to that used for the fuels analyses.

Technical Aspects of Biomass Systems

The technical aspects of biomass systems must be considered carefully before a system is installed. Topics such as system capacity, space requirements, and materials handling techniques must be integrated to obtain a good system. Factors influencing system costs are considered in the analysis, but specific costs are reserved for Chapter 5.

Heat Output Required

The correct sizing of the total system is dependent on the amount of energy that must be produced. Most combustion systems can be operated over a range of heat outputs; however, the actual amount of heat required from the system should be estimated to aid in system optimization.

It has been shown that biomass furnace systems generally perform best at higher system operating levels (Anderson et al. 1983; Barrett et al. 1983). Systems in these studies that were operated at low outputs had lower overall efficiencies and greater exhaust contamination levels than when they were operated at higher levels. The SARC system has exhibited similar behavior. It can be concluded from this information that the system chosen to provide the required heat should be sized so that it is operating at the high end of its output range. Higher efficiency will result, and excess costs associated with an oversized system will be avoided.

The calculations for the heat required from a system are based on thermodynamic equations that use data such as the mass of water that must be removed from a grain harvest, the temperature and amount of air required to heat a building, etc. Many assumptions are required, such as average ambient conditions, efficiencies, crop conditions, etc. to produce reasonable estimations of the required output. An example system-sizing calculation and the assumptions used are included in Appendix B, and are similar to those used to generate the computer outputs contained in Chapter 5.

Space and Installation Requirements

Biomass systems have special requirements that are different from those using conventional fuels. These requirements must be considered before the biomass system alternative can be decided upon.

There is a very real fire danger associated with the combustion of biomass. There is often a direct line of fuel from the furnace to the fuel-batch storage area; a fire danger is inherently present with this design. The biomass system at the SARC has exhibited a fire problem on numerous occasions. Help from the fire department has twice been required due to the severity of the fire. These fires typically occurred when the fuel delivery system had stopped, allowing the furnace flame to burn back along the fuel line to the fuel batch. Other fires can occur from sparks in the furnace exhaust, which may be either vented into the bin or released to the atmosphere.

Safety precautions make it imperative that the system be installed at a distance from buildings or other combustible materials so that a fire can be quickly controlled. This may be a significant disadvantage on sites where available space in the area of installation is limited.

Space requirements for a biomass system are greater than those for a conventional fuels system even if no fire precautions are needed. The low bulk density of biomass fuels necessitates a relatively large storage space for the fuel batch. An area for the feeding system and furnace must be provided, in addition to the fans and other equipment that are common to all fuels. Access space to permit mechanical handling of the biomass fuel is also necessary.

A typical biomass grain drying system is installed at the SARC, and is shown in Figure 1. The feedwagon, on the right of the photograph, measures approximately 8ft x 16ft. The feed auger on the front of the feedwagon, not completely visible in the photograph, measures 2.5ft x 10.5ft. The furnace is 5ft in diameter, and an additional 40in of space

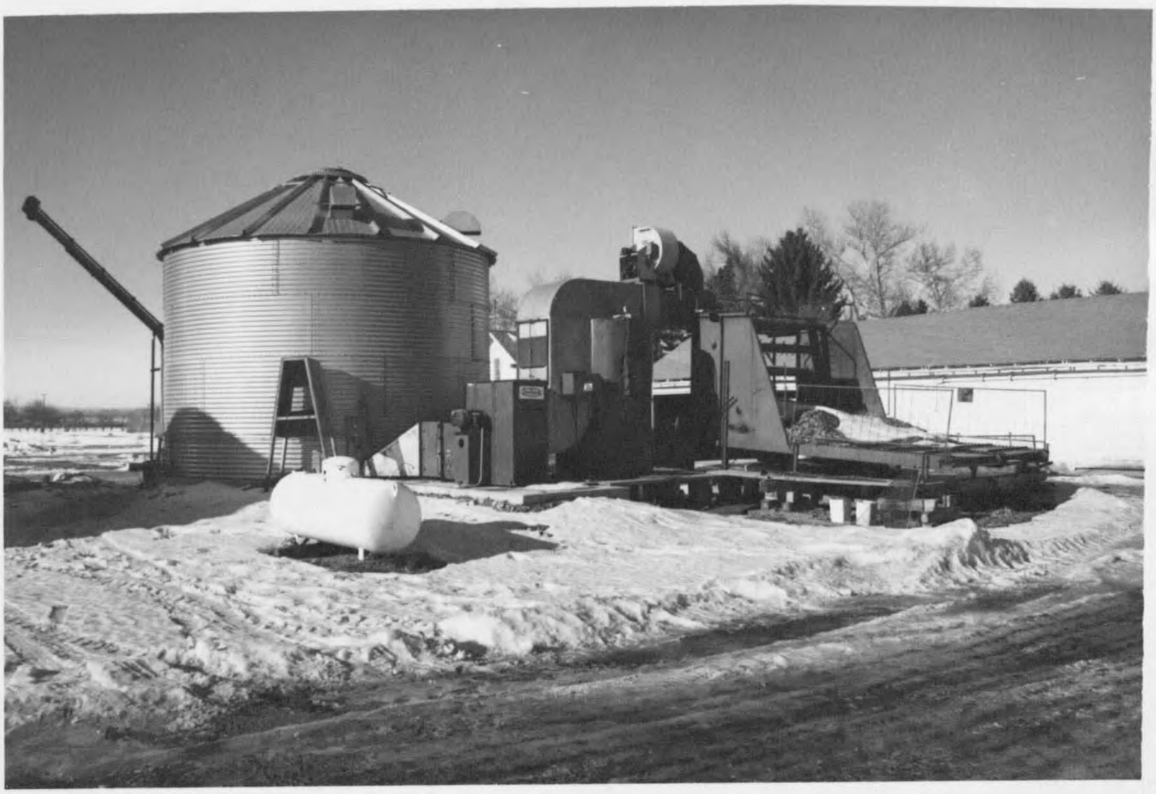

Figure 1. Biomass furnace installation at Huntley, Montana.

is required for the ducting to the fan (labeled SUKUP). The total space required so far is approximately 190 ft^2. Additional access and fire precaution space still needs to be included. Assuming a 15 ft border around the entire 190 ft^2 is sufficient for both of these requirements, the total area needed for the biomass system equals about 1000 ft^2. This is the area greater than the area required for a conventional-fueled system. The area for the grain bin and fan are not included in this figure, as they are required for all types of fuel used. The 1000 ft^2 is an **additional** space requirement needed for the use of biomass. Other fuels commonly require some method of storage such as a storage tank, but the tank can be located almost anywhere and can be filled from a distance. The extra space required for conventional fuels is thus considered negligible in most cases.

All of the equipment in the total system should be located on a concrete foundation. Only the grain bin and fan in Figure 1 have concrete foundations; the furnace and feedwagon have settled into the soil since their installation and are no longer level or aligned with each other. Recent modifications to the system at the SARC had to be adjusted to accommodate the misalignment of these components.

Biomass Systems- Problems and Solutions

Many special problems may be encountered when using biomass as fuel. Several have been mentioned: carcinogenic-compound deposition on dried grains, fire hazards, and clogging of the fuel line are examples. Many of these problems can be reduced or eliminated through design modifications to various parts of the total system.

A substantial portion of the research conducted at the SARC was aimed at reducing or eliminating problems that had surfaced when different fuels were used in the drying system. Winter wheat straw was determined to be the most desirable fuel out of all the biomass fuels studied, because straw is the most abundant and easily obtained crop residue in Montana. The system installed at the SARC, however, was a commercially-available unit from a midwestern firm that was designed to utilize corn stover. The very different characteristics of these two fuels produced feeding problems when straw was introduced as a feedstock. Much of the research effort at the SARC was expended in attempts to modify the system for satisfactory utilization of straw.

The manufacturer's feeding system consists of a feedwagon with a horizontal auger attachment that leads from the wagon to the furnace. Six spiked rotating cylinders or "beaters" separate the biomass material from the fuel batch in the feedwagon. This material then drops into the horizontal feed auger. The beaters and feed auger are electronically controlled by a thermostat circuit located in a control box on the furnace. When the temperature in the furnace decreases past the thermostat setting, control relays start the beaters and feed auger. The temperature rises as fuel is fed into the furnace, and eventually the thermostat setting is exceeded. At this time, the control relays open the circuit, stopping the beaters. The feed auger is controlled through time-delay relays, which allow it to continue operation for approximately 30 seconds after the beaters stop. The intent of the delay is to permit the feed auger to clear itself of fuel before it ceases rotation, for reasons of fire safety.

Straw did not feed well through the auger. Bridging across the auger often occurred, and 30 seconds was not sufficient time to clear all of the material from the fuel line. This problem was compounded when a malfunction in the time-delay relay circuitry resulted in no delay. The fuel line required constant monitoring to detect any fire that might escape the furnace when the auger rotation ceased.

It was decided that better performance of the feed system could be obtained by rewiring the auger so it would run continuously. The beaters were then controlled by the thermostat circuit and ran intermittently as needed. This modification made a second modification necessary because one end of the auger rested on the floor of the fuel hopper. In the original design it was intended that the mass of the fuel would act as a cushion between the auger and the hopper during the majority of auger operation. There was noticeable wear on the auger blade, drive chain, and drive sprockets after only two seasons of operation, however, which indicated that a considerable amount of contact often existed between the hopper and the auger blade. It was determined that continual operation of the auger would result in premature failure of these system components if the end of the auger was left unsupported.

A support bearing was installed on the auger to eliminate contact between the auger and the hopper. In the initial installation, the bearing was hung from the entrance to the transition tube leading into the furnace. Problems were encountered with this design, as the bearing's support shaft became an obstruction to fuel flow. Straw caught on the shaft and often did not feed past this point. Several modifications were made in attempts to correct the problem, but binding around the shaft proved to be a enduring flaw with the design. Large amounts of straw were occasionally separated from the batch by the beaters and dropped into the auger; stalling of the auger at these times was common.

A final design modification moved the bearing out of the transition tube to the approximate center of the fuel hopper. Support for the bearing was supplied from underneath the auger. This modification is shown in Figure 2. This design has decreased the chances of the auger stalling by reducing the percentage of the fuel that must flow past the bearing, but the binding problem is still present. Figure 3 shows the start of a typical binding problem as straw feeds past the bearing.

Experiences with binding and plugging of the straw in the feed auger have indicated that this problem will probably always exist as long as an auger-type fuel feeding mechanism is used. The length, low weight, and flexibility of straw make it subject to problems with rotating system components. Cubing, grinding, or other processing to make the straw usable with an auger feeding system is possible, but such processing requires equipment and energy inputs that increase the fuel's cost. Use of unprocessed straw will probably either require a different feeding mechanism, such as a conveyor belt, or a different furnace design that does not use a feeding system. The ideal furnace design would be usable for other biomass fuels (corn cobs, wood chips, etc.) as well as straw without any required system adjustments, and would not require the presence of an operator to assure satisfactory operation.

A second modification to the SUKUP system at the SARC was tested to control the particulate deposition on the dried corn. An air-to-air

Figure 2. Auger bearing installation.

Figure 3. Binding problem around bearing.

crossflow plate heat exchanger was designed, constructed, and installed on the system to eliminate the introduction of furnace exhaust into the drying bin. A 3hp fan was used on the heat exchanger to draw exhaust gases from the furnace through the exchanger before venting them to the atmosphere. The existing 20hp fan was used to draw ambient air through the heat exchanger and force it into the drying bin. The ambient air travels through the exchanger in a direction opposite that of the furnace exhaust to obtain the crossflow design. The output air from the exchanger contains no exhaust gases and could be used for either grain drying or structural heating with no further modifications to the system.

The addition of a heat exchanger resulted in a reduction of the overall thermal efficiency of the system. The overall thermal efficiency of the SARC system has been decreased from 76% prior to the exchanger's addition (Little, 1984) to approximately 64%. This results in higher operating costs for the biomass system because more fuel is required to produce the same heat output as was attained without the heat exchanger. The higher operating costs for the heat exchanger would be absolutely necessary if the system was to be used for heating a structure where animals or humans might be directly exposed to the heated air from the furnace. Justification for the additional costs for grain drying would have to be determined by evaluating the economic consequences for possibly receiving a judgment of "sample" grade for the grain. It was determined in the above study that, at least in Montana, the additional operating costs of the heat exchanger were not justified as compared to the relatively small economic risk of producing "sample" grade corn.

In order to remedy feeding problems encountered with wood chips, Suggs (1984) cut teeth into the auger blade of a wood-chip feeding system at points of clogging so that most wedged pieces of wood would not stall the system. An electronic reversing circuit was also incorporated into the feeding system. It reversed the auger momentarily when the required torque exceeded a preset level. The modified feeding system operated satisfactorily throughout the experiment.

Feeding problems during the burning phase are altogether eliminated with "whole bale burner" furnace designs that have the capacity to hold the entire fuel batch of large round bales or other fuels within the combustion chamber. Prior to firing of the system, the entire fuel batch is placed in the combustion chamber, which is then sealed and ready for use. Many different fuels can be utilized in these systems, without the feeding problems that are associated with alternating between different fuels. Fire danger is also greatly reduced, as all of the flame is contained within the combustion vessel. This large-bale design is available from several commercial manufacturers.

Two-stage biomass furnaces, or gasifiers, are very effective in eliminating unburned particulate and gaseous matter from the combustion exhaust. This design burns the material initially in a low-oxygen atmosphere, causing the release of volatile gases from the biomass. These gases are then burned at high temperature in the second stage. This high temperature combustion simultaneously burns most of the particulates that might otherwise show up as exhaust pollutants. Gasifiers typically have high operating efficiencies; 80% is a common figure claimed by commercial manufacturers. The absence of smoke in the exhaust of these systems indicates that particulate levels are well controlled.

CHAPTER 5

Economic Parameters and Computer Program

Methods for calculating equivalent biomass fuel costs vary greatly, and the resulting values therefore also vary. Different assumptions for different applications can make a significant change in cost estimates. Making the assumption that crop residue removal from a field is necessary for cropping practices, for instance, eliminates its collection costs from fuel-cost calculations, thereby directly reducing its total cost estimate.

The values shown in this chapter rely heavily on the assumptions used and these assumptions are stated in Appendix A. The costs shown are "ballpark" or typical estimates that must be modified for specific locations. Varying the estimates for either the fuel or the system may alter the results considerably.

Biomass Fuel Cost Parameters

Tables 5-10 show the cost estimates used to obtain the costs for a biomass grain dryer. Many of the assumptions used in this analysis are typical of the costs of operation for the grain dryer at the SARC. Cost equations and data were obtained from a machinery management text by Hunt (1979).

The annual fixed costs for agricultural equipment used for harvesting biomass fuels are shown in Table 5. The values shown are estimated percentages of the original purchase price (P) of the machine.

Variable costs for the equipment are shown in Table 6. The last column contains the total estimated cost/hour for using a particular machine.

Table 5. Fixed Costs of Equipment as Percent of New Cost, %P/yr

Fixed Cost Machine	Dep.	Invest. Interest	Taxes	Insur.	Shelter	Total	P ($)
Tractor	9.0	4.4	1.5	.25	1.0	16.15	15000
Combine	9.0	4.4	1.5	.25	1.0	16.15	50000
Round Baler, PTO	9.0	4.4	1.5	.25	1.0	16.15	8000
Forage Wagon	9.0	4.4	1.5	.25	1.0	16.15	4500
Hauling Wagon	4.5	4.4	1.5	.25	---	10.65	1200

Table 7 uses the total hourly equipment costs shown in Table 6 to determine the total harvest cost for two biomass materials: a corn cob/stover mixture and straw in round bales. The hours required for the combine in Table 7 are additional operating hours encountered as a result of harvesting the cob/stover mixture and do not include the portion of the combine cost used to harvest the grain. The calculations for determining the values contained in the tables are shown in Appendix A.

Table 6. Variable Costs of Equipment

Variable Cost Machine	R&M per 100hr	Labor $/hr	Fuel $/hr	Oil $/hr	Annual Use hr	Total Cost[1] per hr ($)
Tractor	.012P	10.00	6.86	.042	500	23.55
Combine	.027P	10.00	11.57	.10	150	89.00
Baler	.031P	-----	-----	----	100	15.40
F. Wagon	.018P	-----	-----	----	150	5.66
H. Wagon	.018P	-----	-----	----	100	1.87

[1] {Fixed Cost/yr + (Annual Use)(Variable Cost)}/Annual Use

Table 7. Total Collection Costs for Straw and Cob/Stover Fuels

Fuel	Straw		Cob/Stover	
Machine	hrs req'd*	cost ($)	hrs req'd*	cost ($)
Tractor	22.00	518.10	57.15	1345.88
Combine	----	------	12.15	1081.35
Baler	12.00	184.20	-----	-------
Forage Wagon	-----	------	57.15	323.47
Hauling Wagon	10.0	18.70	-----	------
Total		721.60		2750.70

*Hours required from the machine to harvest the fuel portion of the biomass.

Table 8 lists the estimated values for the extra use costs for the straw and cob/stover that were explained in Chapter 3. Table 9 provides the estimated delivered costs for wood chip material as a function of the distance between the user and the source.

Table 8. Additional Costs/Ton of Using Biomass

Cost Biomass Type	Opportunity	Operation	Trans. & Hand.	Total
Straw	20.00	7.50	7.07	34.57
Cob/Stover	12.50	6.25	15.70	34.45

Table 9. Wood Chip Fuel Costs Per Ton

One-way Miles to Source	Trans. Cost (round trip) per load	Labor	Total + \$21.00*	Cost/ Ton	+ Additional Costs/Ton**	\$/ MBtu
0	0	10.00	31.00	13.41	34.94	2.41
5	4.00	12.00	37.00	16.00	37.53	2.59
10	8.00	14.00	43.00	18.60	40.13	2.77
15	12.00	16.00	51.00	22.05	43.58	3.01
20	16.00	18.00	55.00	23.78	45.31	3.13
25	20.00	20.00	61.00	26.38	47.91	3.31
30	24.00	22.00	67.00	28.97	50.50	3.49
60	48.00	34.00	103.00	44.54	66.07	4.56

*Purchase Price/Load

**Operation and Handling

Table 10 shows the total cost estimates for the biomass fuels and a comparable cost for propane and electricity.

Table 10. Total Costs of Various Fuels

Fuel		Cost/Ton ($)	Cost/Million Btu ($)
Corn Cob/Stover Mixture		81.95	6.50
Straw		48.23	3.50
Propane[1]		-----	6.99
Electricity[2]		-----	11.72
Wood Chips	Distance From Source (mi)		
	0	34.94	2.41
	10	40.13	2.77
	20	45.31	3.13
	30	50.50	3.49
	60	66.01	4.56

[1] $0.65/gal, 93000 Btu/gal
[2] $0.04/kwh

System Costs

First costs for a drying system include its purchase, installation, and initial testing costs. Estimating first costs of biomass furnace systems requires the subdivision of combustion systems into two general categories, those designed for grain drying and those designed for structural heating. Different categories are necessary because of the relative size of the system needed for each of these purposes. The minimum output from a system designed for grain drying would typically be at least ten times the amount required for heating a residence or other building of similar size. Storage of the excess heat produced by the oversized furnace in some relatively large storage medium would be required for later use by the structure. It is therefore not normally feasible to employ a furnace system designed for grain drying as a structural heater because of the lower system efficiencies caused by low system output levels and storage medium heat losses.

Estimating system costs next requires the choice of an arbitrary method of calculation. Curtis et al.(1982) states that a reasonable estimate of the total installation costs for a wood burning system under 500 boiler horsepower is about $30/bhp. It is believed that this amount should be increased to $36/bhp for 1986 estimations. Curtis also states that a conventional energy system can be assumed to be 2/3 the cost of a wood-burning system. The first cost of other biomass furnace systems can be estimated by transforming their Btu/hr ratings into the equivalent boiler horsepower and multiplying the result by $36. This method appears to produce reasonably accurate cost estimates for other biomass materials as well as for wood. Curtis' estimate was aimed at industrial-sized systems, however, and for systems with outputs under 100,000 Btu/hr, which are typical of most residential heating units, it is believed that the installation cost equation becomes nonlinear and the cost approaches a minimum value. The total installation cost of a minimum-sized system can be reasonably approximated as $1500, when the total equipment, shipping, and installation costs are taken into consideration. A more precise estimate would require specific information about the particular installation.

Table 11 shows the resulting cost estimates for four sizes of biomass combustion systems using this method.

Table 11. Biomass System Installation Cost Estimations as a Function of Output

System Designed for:	System Output (Btu/hr)	Total Installation Cost ($)
Structural Heating	60000	1500
Structural Heating	150000	2122
Grain Drying	1000000	14144
Grain Drying	2500000	35361

The cost figures derived from the specified method are very useful as "ballpark" estimates. A good preliminary cost analysis could be performed on an accurately sized system using this method to estimate the total first cost. It is the basis for the system cost estimations used in the computer program discussed in the next section.

Computer-Generated Cost Estimations

A BASIC computer program was developed for the Montana Department of Natural Resources and Conservation for use in a preliminary feasibility analysis for biomass furnace systems. This program will be used by farmers or others interested in determining whether or not a biomass-fueled heating system would be a cost-effective investment for their operation. The program is not intended to be a precise predictor of costs and returns for a particular individual, but rather supplies enough information to that individual to enable him to decide whether or not further investigation of a biomass furnace is justified. A complete listing of the program is contained in Appendix D.

The program asks for inputs from the user that pertain to his particular situation. It then calculates relevant data and produces approximate cost comparisons with conventional fuel systems. User input includes tax status and investment information so as to produce rate of return on investment and benefit-to-cost ratio estimations. The equations used in the program follow closely those outlined in the Appendices.

Curtis also presents simple equations for estimating the additional annual operating costs of a biomass system. These are also used in the program. The additional maintenance required is estimated as 1.33% of the fixed installation cost for the biomass system. Additional electricity used by the biomass system is estimated at 0.33% of the fixed installation cost, and additional labor is given by a labor factor (defined by system size) multiplied by the operating hours, wage rate, and a 0.5 factor (labor for a biomass system is assumed to be 50% more than that of a conventional system).

Four sample outputs are included in Appendix D, two for a grain drying system and two for a structural heater. It can be seen from two of these outputs, specifically those with relatively low biomass costs and generally low labor rates, that biomass-fueled systems can in fact warrant further investigation under the right conditions.

CHAPTER 6

Summary and Conclusions

The overall feasibility of using biomass materials for fuel includes both fuel aspects and system aspects. Many extra costs and problems can be encountered with the decision to use biomass as fuel. "Hidden" costs such as alternative biomass values, extra machinery and handling costs, and unforeseen labor charges can increase fuel costs significantly. Problems can occur with mechanical furnace-feeding apparatuses, especially when substituting different materials into the fuel wagon. Greater fire dangers exist than with conventional fuels. Pollution effects of furnace exhaust may cause further problems. Extra jobs required such as periodic cleaning of the furnace can be unpleasant and time consuming.

Optimum conditions for choice of a fuel are that it be plentiful in supply, that it be typically harvested or collected for reasons other than its use as fuel, that it be sufficiently dry for good combustion, that its source be located near the site where it is to be used, and that it have little or no alternative value.

Optimum conditions for a system design are that it be usable for various fuels without alteration, that the heated air be free of particulates and smoke, that it be sized for an installation by its upper output range, and that it be matched to its desired use.

The "whole bale burner" design mentioned in Chapter 4 appears to be the system design which best meets the criteria above. With no mechanical feeding system, there is no chance of fuel-delivery failure and the resulting fire dangers, and fewer components to purchase and maintain. The gasifier design of this type is reported to be very effective in removing smoke and particulates from the exhaust, with a very high combustion efficiency resulting. Such a design is probably cheaper to operate than others because of the absence of the electrically-powered feeding components and little or no supervision requirements.

Waste straw or wood products (located nearby) appear to be the most cost-effective biomass fuel materials. These are both abundantly available, can be cheap to obtain, and are typically ready for use (sufficiently dry) either immediately after their collection or within a short period of time thereafter.

Presently, the use of biomass as fuel is cost effective for only a limited number of situations. Increasing conventional fuel costs in the future will no doubt serve to relax the conditions required for biomass' economic feasibility, and will create situations much more favorable for its use as fuel.

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Appendices

Appendix A. Biomass Fuel Cost Calculations

The calculations used in this appendix are similar to those used in the cost estimations in Chapters 3 and 5.

Collection Costs

All of the following cost and power equations are from Hunt (1977). Price data was obtained from various market-value estimation manuals.

Annual Cost =

(Fixed Cost%)P/100 + (Annual Use hrs){(Repair & Maint.%)P/hr of Equipment + Labor/hr + Oil Use/hr + Fuel Use/hr}

Where P= Purchase Price of Equipment

Example: Tractor Use Cost (60hp diesel, operating at average 40% of rated hp, P= $15000, annual use = 500hr)

Fixed Costs:

Depreciation= (P-S)/L = (P-0.1P)/10 = 0.09P/yr

Interest on Investment = (P+S)i/2 = (P+0.1P)(0.08)/2 = 0.044P/yr

Taxes = 0.015P/yr

Insurance= 0.0025P/yr

Shelter= 0.01P/yr

Where S= Salvage Value of Equipment
L= Depreciation Life of Equipment
i= Interest Rate

Total Fixed Costs= (.09 + .044 + .015 + .0025 + .01)P/yr = 0.1615P/yr

Variable Costs:

Repair & Maint.= 0.012P/100hr

Labor= $10.00/hr

Fuel= (60hp)(1 gal/8.74 hphr)($1.00/gal)= $6.86/hr

Oil= (.012 gal/hr)($3.50/gal)= $0.042/hr

Total Annual Costs:

AC= (.1615/yr)($15000) + (500hr/yr){(.012)($15000)/100hr + $10/hr + $0.042/hr + $6.86/hr} = $11773.50

Total Hourly Cost= ($11773.50/yr)(1 yr/500hr)= $23.55/hr

Similar calculations are performed on all harvest equipment. The results are shown in Table 7, page 43, and Table 8, page 44.

Appendix B. Annual Biomass Fuel Requirement and System Sizing Examples

The assumptions used for the calculations are listed in the order in which they are used to provide maximum clarity for the reader.

Assume the grain dryer is to dry corn from 30%mc to 15%mc (wb). Assume 300 acres of crop, with a yield of 120 bu/ac.

Annual Energy Use = (300 ac)(120 bu/ac)(67.5 lb corn/bu) x

(.151b water/lb corn)(2000 Btu/lb water)

= 729 million Btu (MBtu)

Using 2000 Btu/lb water allows for 1150 Btu/lb to evaporate the moisture from the corn, the heat absorbed by the corn (approximately 0.5878 Btu/lbm F) for an approximate 70 degree F temperature rise in the corn, and approximately a 75% overall thermal efficiency for the system.

Assume that 30 days are allowed to dry the harvest, with a batch drying cycle of 15 hr/day.

Size of System= 729 MBtu/[(30day)(15hr)]= 1.62 MBtu/hr

Grain Batch Size= (300ac)(120 bu/ac)/30 day= 1200 bu

Required cob/stover amount @ 4745 Btu/lb harvested (33%mc)= 153,635 lb. @ 2400lb/ac= 64 acres, assume 90 acres harvested to account for losses during storage, handling, etc.

Required straw @ 6900 Btu/lb harvested= 105,650 lb @ 660 lb/bale= 160 bales, assume 180 bales collected, with minimal losses during storage.

Little (1984) determined that harvesting the extra cob/stover biomass with the corn added approximately 0.135 hr/ac to the harvest time. The harvest rate was determined to be approximately 1 ac/hr, but this rate is unusually slow; higher harvest rates could probably be obtained through experience with harvesting the additional biomass. Assuming a normal harvest time of 2 ac/hr, the time required to harvest the cob/stover biomass is:

(90 acres)(.135hr/ac) + (90 acres)/(2 ac/hr)= 12.15 + 45 hr= 57.15 hr

Assuming the round baler operates at 5 ton/hr, 180 bales would take approximately 12 hrs to bale. It is further assumed that the hauling wagon could remove these bales from the field to their storage area in approximately 10 hrs.

The estimated costs for the cob/stover and straw's collection are shown in Table 8, page 44.

Additional Costs Associated With Using Biomass

There are other costs present when using biomass for fuel that must be included in its annual use costs. These results are summarized in Table 9 on page 44.

Operation Costs

Labor is required for periodically cleaning the furnace, firing up and extinguishing the furnace, cleaning the surrounding area, etc. It is assumed that the following values hold:

Straw- 90 min/ton @ $5/hr= $7.50/ton

Cob/Stover- 75 min/ton= $6.25/ton

Opportunity Costs

These costs are money that is foregone because the biomass is used for fuel instead of sold for some other use. Straw can occasionally be sold for $35/ton baled, it is assumed that the actual normal profit that can be made is only $20/ton. A harvested corn field can be rented for $35/acre as forage pasture, it is assumed that it retains a value of $20/acre after the 2400 lb/acre of biomass has been removed (probably optimistic). Then,

OC Straw= $20/ton

OC Cob/Stover= ($35-20/acre)(1 acre/2400 lb)(2000 lb/ton)= $12.50/ton

Transportation and Handling Costs

It is assumed that the biomass is produced on the site where it is to be used, so that no unusual transportation charges are introduced. Nevertheless, it must be transported from the storage area to the feedwagon and be loaded there, adding another cost to the total annual use costs. Loose fuels, like the cob/stover mixture, generally require more trips to load the feedwagon than a similar amount of packaged fuels, like round bales. Assuming it takes an average of 6 minutes per trip to the storage area and back with the tractor (including procuring the tractor and returning it), the costs are:

Straw @ one bale/trip= (1 trip/bale)(3 bale/ton)(.1hr/trip)($23.55/hr)

= $7.07/ton

Cob/Stover @ 300 lb/trip= (1 trip/300 lb)(2000 lb/ton)(.1hr/trip)($23.55/hr)

= $15.70/ton

Totals of Additional Costs/Ton:

Cob/Stover = $6.25 + 12.50 + 15.70 = $34.45/Ton

Straw = $7.50 + 20.00 + 7.07 = $34.57

Total Fuel Costs/MBtu

Cob/Stover

Collection= $2750.10/729 MBtu= $3.77/MBtu

Additional= ($34.45/ton)(ton/2000lb)(lb/6300 Btu)(1M)= $2.73/MBtu

Total= $3.77 + 2.73= $6.50/MBtu

Cost/ton= ($6.50/MBtu)(2000 lb/ton)(6300Btu/lb)= $81.95/ton

Straw

Collection= $721.60/729 MBtu= $0.99/MBtu

Additional= ($34.57/ton)(ton/2000lb)(lb/6900 Btu)(1M)= $2.51/MBtu

Total= $2.51 + 0.99= $3.50/MBtu

Cost/ton= ($3.50/MBtu)(2000lb/ton)(6900Btu/lb)= $48.23

Note: These costs assume that the biomass system is capable of running unattended. Assuming the system was operating @ 1.6MBtu/hr, a $5.00/hr extra labor charge for full-time system supervision would add $5/1.6= $3.13/MBtu to the above values.

Cost of Wood Chips

The total cost of wood chips is highly dependent on the transport distance from the source. Wood chips used in the SARC study were acquired from the mill source in Roundup, Montana for $21.00/truckload. It is assumed that this is an average price. Other assumptions are- 2.5 tons/truckload, 20%mc at collection, 12.5%mc at time of use, $0.20/mi fuel cost of truck, $0.20/mi fixed costs of truck, $10/hr labor for driver, 1 hour of labor required (loading, unloading, etc) + the driving time (50mph) for each load.

Additional Costs are similar to the cob/stover mixture's, minus the opportunity cost. The tabulated values are shown in Table 10, page 45.

Appendix C. Equivalent Uniform Annual Cost (EUAC) Comparisons

Equivalent uniform annual cost (EUAC) comparisons provide a means of comparing different cash flows by transforming the original cash flows into equivalent annual payments. The best alternative is then found to be the one with the least equivalent uniform annual cost. All real and potential cash flows are taken into account.

It is assumed for this example that the additional biomass equipment needed for the biomass' combustion (ie, furnace, feedwagon, etc) total $15000. The costs of the drying bin, centrifugal and aeration fans, and other equipment common to all systems are ignored in these calculations. The purpose of this analysis is to provide **comparison** between the different types of systems under consideration. This analysis was included to give the reader an idea of how biomass systems basis compare with conventional systems on an average basis. The results are shown only here, and are not included in the text of the thesis.

A different overall thermal efficiency is assumed for propane and electrical systems, because they lack the heat loss from the furnace, ducting, and combustion inefficiencies of the biomass fuels.

Conventional Energy Required=

(1200 bu/batch)(67.5lb/bu)(.5878 Btu/lbmF)(70F)= 3.333 MBtu/batch to heat corn

(1200 bu/batch)(67.5lb/bu)(.15lb water/lb corn)(1150 Btu/lb water)=

13.97 MBtu/batch to evaporate water

Assuming an 85% thermal efficiency of system, the total required=

(13.97 + 3.333)/.85 = 20.4 MBtu/batch

Total Conventional Energy Required= (20.4 MBtu/batch)(30 batch/yr)=

= 611 MBtu/yr

Propane Costs

(611 MBtu/yr)(1 gal/93000 Btu)= 6567 gal/yr required

(6567 gal)($0.65/gal)= $4268/yr

Electricity Costs

(611 MBtu/year)(kwh/3413 Btu)= 179,000 kwh

(179,000 kwh/yr)($0.04/kwh)= $7160/yr
In comparing the conventional energy systems with the biomass systems, it is necessary to assume that the additional money needed for the biomass systems could be invested if a conventional system was purchased. A 10 year life of all systems is assumed, and an interest rate of 8%.

Interest Income= P(A/P,8,10)= ($15000)(0.149)= $2235

10% Tax Credit (1st year only) = (0.1)($15000)= $1500

Adjusted system 1st cost= $15000- 1500= $13500

Interest Income from investment credit= $1500(.149)= $223.50

EUAC Propane= $4268- 2235= $2033

EUAC Electricity= $7160- 2235= $4925

The SARC biomass system has both a 1.5 hp (1.12 kW) motor and a 0.75 hp (.56 kW) motor on its feeding system. It is assumed that this is an average situation for biomass feeding systems.

Extra electricity cost for feedwagon= (1.12 + .56kW)(450hr)($0.04/kWh)

= $30.24/yr

EUAC Straw= $2235 + ($3.50/MBtu)(729 MBtu) + $30.24- $223.50= $4593.24

EUAC Cob/Stover= $2235 + ($6.50/MBtu)(729 MBtu) + $30.24- $223.50

= $6783.13

EUAC Wood Chips (0 miles)= ($2.41/MBtu)(729 MBtu) + $2235 + $30.24- $223.50

= $3798.63

Similarly, for greater distances,

EUAC 10 miles= (2.77)(729) + 2041.74= $4061.07,

EUAC 20 miles= (3.13)(729) + 2041.74= $4323.51, etc.

To illustrate the effect of varying assumptions on the EUAC values above, assume that the collection cost of the straw can be omitted as a crop necessity, and that the straw will not be sold if it is not used (possesses no alternative value). Then,

Cost of Straw= $1.06/MBtu

EUAC Straw= (729 MBtu)($1.06/MBtu) + $2235 + $30.24- $233.50= $2801.42

Or, a difference of $4593.24- $2801.42= $1791.82 due to the different assumptions made.

It can be seen from comparing the EUAC's that, with the assumptions used in these calculations, propane continues to possess the least annual cost and is therefore the best alternative.

Appendix D. BASIC Computer Program Outputs

Table 12. Output # 1.

```
PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED
        DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

              Program development sponsored by
  Montana Department of Natural Resources and Conservation

                  Program developed by
             Agricultural Engineering Department
                  Montana State University


     Enterprise name:  RUN 1               3/21/86
=======================================================
     PRODUCTION SYSTEM INPUTS
=======================================================
Grain crop grown.......................... Corn
Acres harvested........................... 450
Production, bu/ac......................... 120
Grain moisture content at harvest (%wb)... 34
Grain moisture content for storage (%wb).. 14.5
Days available to harvest and dry crop.... 30
Furnace labor requirement, hours/day...... 13
=======================================================
     FUEL USE PARAMETERS
=======================================================
Biomass fuel:    kind used................ straw or hay
                 moisture content (%wb)... 10
                 delivered cost per ton, $ 25
Comparison fuel: kind used................ electricity
                 measurement units........ kwh
                 cost per unit used, $.... .04
=======================================================
     ECONOMIC PARAMETERS USED FOR EVALUATION
=======================================================
Marginal income tax rate, % .............. 25
Interest rate for loans, %................ 10
Investment tax credit, % of first cost.... 10
Labor wage rate, $/hour................... 5
Expected system life, years............... 10
```

Table 12--Continued

```
=====================================================
     ESTIMATED EQUIPMENT NEEDS
     Consult qualified engineer for system design.
=====================================================
Required furnace capacity, BTU/hour....... 3600000
Required daily grain batch size, bu....... 1800
Grain depth in 20' dia. bin, ft........... 7.165605
Approximate fan horsepower required....... 28.34974
Avg. biomass feed rate, lb/hour........... 472.1312

=====================================================
     ECONOMIC EVALUATION SUMMARY
=====================================================
Expected total system installation cost, $.... 50919.85

Estimated additional costs associated with a biomass-
fired system compared to conventional furnace systems.
Maintenance    Electricity   Labor          Total, $/year
 678.9312       169.7328      300            1148.664

Annual cost summary, adjusted for taxes:
Fuel Savings - Add. Costs + Depr. =   Annual Return
 12507.62      1148.664     5091.985  9792.213

RETURN ON INVESTMENT ANALYSIS
===================================================

External rate of return on $ invested:       10.90962
Rate of return on same $ in money market:   6

PAYBACK PERIOD AND CASH FLOW ANALYSIS
===================================================

Year  Prin. + Int. - Tax Cr. - ITC - Returns  =  Balance
 1    50919   5091   1272      5091  9792          39854
 2    39854   3985   996             9792          33051
 3    33051   3305   826             9792          25738
 4    25738   2573   643             9792          17876
 5    17876   1787   446             9792          9424
 6    9424    942    235             9792          339
 7    339     33     8               9792         -9428

BENEFITS TO COSTS ANALYSIS
=========================
The benefit/cost ratio is present value of annual returns
divided by real fixed costs.  Based on current comparison
fuel prices, the B/C ratio is  1.572657 / 1.00
```

Table 13. Output # 2.

```
PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED
        DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

              Program development sponsored by
  Montana Department of Natural Resources and Conservation

                   Program developed by
          Agricultural Engineering Department
                Montana State University


    Enterprise name:  RUN 2                  3/21/86
=======================================================
    PRODUCTION SYSTEM INPUTS
=======================================================
Grain crop grown......................... Corn
Acres harvested.......................... 300
Production, bu/ac........................ 120
Grain moisture content at harvest (%wb)... 30
Grain moisture content for storage (%wb).. 15
Days available to harvest and dry crop.... 30
Furnace labor requirement, hours/day...... 13
=======================================================
    FUEL USE PARAMETERS
=======================================================
Biomass fuel:     kind used............... straw or hay
                  moisture content (%wb)... 10
                  delivered cost per ton, $ 15
Comparison fuel:  kind used............... propane
                  measurement units........ gal
                  cost per unit used, $.... .65
=======================================================
    ECONOMIC PARAMETERS USED FOR EVALUATION
=======================================================
Marginal income tax rate, % ............. 25
Interest rate for loans, %............... 10
Investment tax credit, % of first cost.... 10
Labor wage rate, $/hour.................. 5
Expected system life, years.............. 10
```

Table 13--Continued

```
========================================================
     ESTIMATED EQUIPMENT NEEDS
     Consult qualified engineer for system design.
========================================================
Required furnace capacity, BTU/hour....... 1857014
Required daily grain batch size, bu....... 1200
Grain depth in 20' dia. bin, ft........... 4.77707
Approximate fan horsepower required....... 18.89983
Avg. biomass feed rate, lb/hour........... 243.5428

========================================================
     ECONOMIC EVALUATION SUMMARY
========================================================
Expected total system installation cost, $.... 26266.34

Estimated additional costs associated with a biomass-
fired system compared to conventional furnace systems.
Maintenance   Electricity   Labor        Total, $/year
 350.2179      87.55448      300          737.7723

Annual cost summary, adjusted for taxes:
Fuel Savings - Add. Costs + Depr. =  Annual Return
 3271.321      737.7723     2626.634 2556.82

RETURN ON INVESTMENT ANALYSIS
=======================================================

External rate of return on $ invested:      3.609574
Rate of return on same $ in money market:  6

PAYBACK PERIOD AND CASH FLOW ANALYSIS
=======================================================

Year  Prin. + Int. - Tax Cr. - ITC - Returns  =  Balance
 1    26266   2626   656      2626  2556          23052
 2    23052   2305   576            2556          22225
 3    22225   2222   555            2556          21335
 4    21335   2133   533            2556          20378
 5    20378   2037   509            2556          19349
 6    19349   1934   483            2556          18244
 7    18244   1824   456            2556          17055
 8    17055   1705   426            2556          15778
 9    15778   1577   394            2556          14404
 10   14404   1440   360            2556          12928

BENEFITS TO COSTS ANALYSIS
=========================
The benefit/cost ratio is present value of annual returns
divided by real fixed costs.  Based on current comparison
fuel prices, the B/C ratio is  .7960506 / 1.00

The required comparison fuel cost would have to be
 .8 $/unit for breakeven conditions (B/C > 1) to exist.
```

Table 14. Output # 3.

```
PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED
       DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

              Program development sponsored by
  Montana Department of Natural Resources and Conservation

                  Program developed by
           Agricultural Engineering Department
                  Montana State University

    Enterprise name:  RUN 3                    3/21/86
=======================================================
    STRUCTURAL HEATING DATA
=======================================================
Building area............................ 1500
Extent of insulation..................... Well
Average indoor/outdoor temp. difference... 60
Furnace labor requirement, hours/day...... .25
=======================================================
    FUEL USE PARAMETERS
=======================================================
Biomass fuel:    kind used................ straw or hay
                 moisture content (%wb)... 10
                 delivered cost per ton, $ 25
                 annual amount used, tons  9.858098
                 annual cost, $........... 246.4525
Comparison fuel: kind used................ Natural gas
                 measurement units........ MCF
                 cost per unit used, $.... 3.4
                 annual amount used....... 193.2339
                 annual cost, $........... 656.9954
=======================================================
    ECONOMIC PARAMETERS USED FOR EVALUATION
=======================================================
Marginal income tax rate, % ............. 0
Interest rate for loans, %............... 6
Investment tax credit, % of first cost.... 0
Labor wage rate, $/hour.................. 5
Expected system life, years.............. 10
```

Table 14--Continued

```
=========================================================
     ESTIMATED EQUIPMENT NEEDS
     Consult qualified engineer for system design.
=========================================================
Required furnace capacity, BTU/hour....... 45000
Average daily heat requirement, BTU....... 1080000
Estimated peak requirement, BTU/hour...... 72000
Avg. daily biomass fuel use, lb........... 283.2787

=========================================================
     ECONOMIC EVALUATION SUMMARY
=========================================================
Expected total system installation cost, $.... 2000

Estimated additional costs associated with a biomass-
fired system compared to conventional furnace systems.
Maintenance   Electricity   Labor          Total, $/year
 26.66667      6.666667      168.75         202.0833

Annual cost summary, adjusted for taxes:
Fuel Savings - Add. Costs + Depr. =   Annual Return
 410.5429      202.0833     0         208.4596

RETURN ON INVESTMENT ANALYSIS
========================================================

External rate of return on $ invested......... 3.226996
Rate of return on same $ invested elsewhere... 6

PAYBACK PERIOD AND CASH FLOW ANALYSIS
========================================================

Year  Prin. + Int. - Tax Cr. - ITC - Returns  =  Balance
 1    2000    120    0         0     208          1911
 2    1911    114    0               208          1817
 3    1817    109    0               208          1718
 4    1718    103    0               208          1613
 5    1613    96     0               208          1501
 6    1501    90     0               208          1382
 7    1382    82     0               208          1257
 8    1257    75     0               208          1124
 9    1124    67     0               208          983
 10   983     59     0               208          834

BENEFITS TO COSTS ANALYSIS
==========================
The benefit/cost ratio is present value of annual returns
divided by real fixed costs.  Based on current comparison
fuel prices, the B/C ratio is  .7671398 / 1.00

The required comparison fuel cost would have to be
 3.75 $/unit for breakeven conditions (B/C > 1) to exist.
```

Table 15. Output # 4.

```
PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED
        DIRECT-FIRED INCINERATOR FURNACE SYSTEMS

             Program development sponsored by
  Montana Department of Natural Resources and Conservation

                  Program developed by
           Agricultural Engineering Department
                 Montana State University

     Enterprise name:  RUN 4                    3/21/86
=====================================================
     STRUCTURAL HEATING DATA
=====================================================
Building area.............................. 1500
Extent of insulation....................... Well
Average indoor/outdoor temp. difference... 60
Furnace labor requirement, hours/day...... .5
=====================================================
     FUEL USE PARAMETERS
=====================================================
Biomass fuel:     kind used............... straw or hay
                  moisture content (%wb)... 10
                  delivered cost per ton, $ 20
                  annual amount used, tons  9.858098
                  annual cost, $.......... 197.162
Comparison fuel: kind used............... Natural gas
                  measurement units........ MCF
                  cost per unit used, $.... 3.4
                  annual amount used....... 193.2339
                  annual cost, $.......... 656.9954
=====================================================
     ECONOMIC PARAMETERS USED FOR EVALUATION
=====================================================
Marginal income tax rate, % ............. 0
Interest rate for loans, %............... 6
Investment tax credit, % of first cost.... 0
Labor wage rate, $/hour.................. 0
Expected system life, years.............. 15
```

Table 15--Continued

```
=======================================================
     ESTIMATED EQUIPMENT NEEDS
     Consult qualified engineer for system design.
=======================================================
Required furnace capacity, BTU/hour....... 45000
Average daily heat requirement, BTU....... 1080000
Estimated peak requirement, BTU/hour...... 72000
Avg. daily biomass fuel use, lb........... 283.2787

=======================================================
     ECONOMIC EVALUATION SUMMARY
=======================================================
Expected total system installation cost, $.... 1500

Estimated additional costs associated with a biomass-
fired system compared to conventional furnace systems.
Maintenance   Electricity   Labor        Total, $/year
 20            5             0            25

Annual cost summary, adjusted for taxes:
Fuel Savings - Add. Costs + Depr. =   Annual Return
 459.8334      25            0        434.8334

RETURN ON INVESTMENT ANALYSIS
======================================================

External rate of return on $ invested......... 13.57322
Rate of return on same $ invested elsewhere... 6

PAYBACK PERIOD AND CASH FLOW ANALYSIS
======================================================

Year   Prin. + Int. - Tax Cr. - ITC - Returns  =  Balance
 1     1500    90     0         0     434            1155
 2     1155    69     0               434            789
 3     789     47     0               434            402
 4     402     24     0               434           -9

BENEFITS TO COSTS ANALYSIS
=========================
The benefit/cost ratio is present value of annual returns
divided by real fixed costs.  Based on current comparison
fuel prices, the B/C ratio is  2.815472 / 1.00
```

Appendix E. BASIC Program Flow Chart

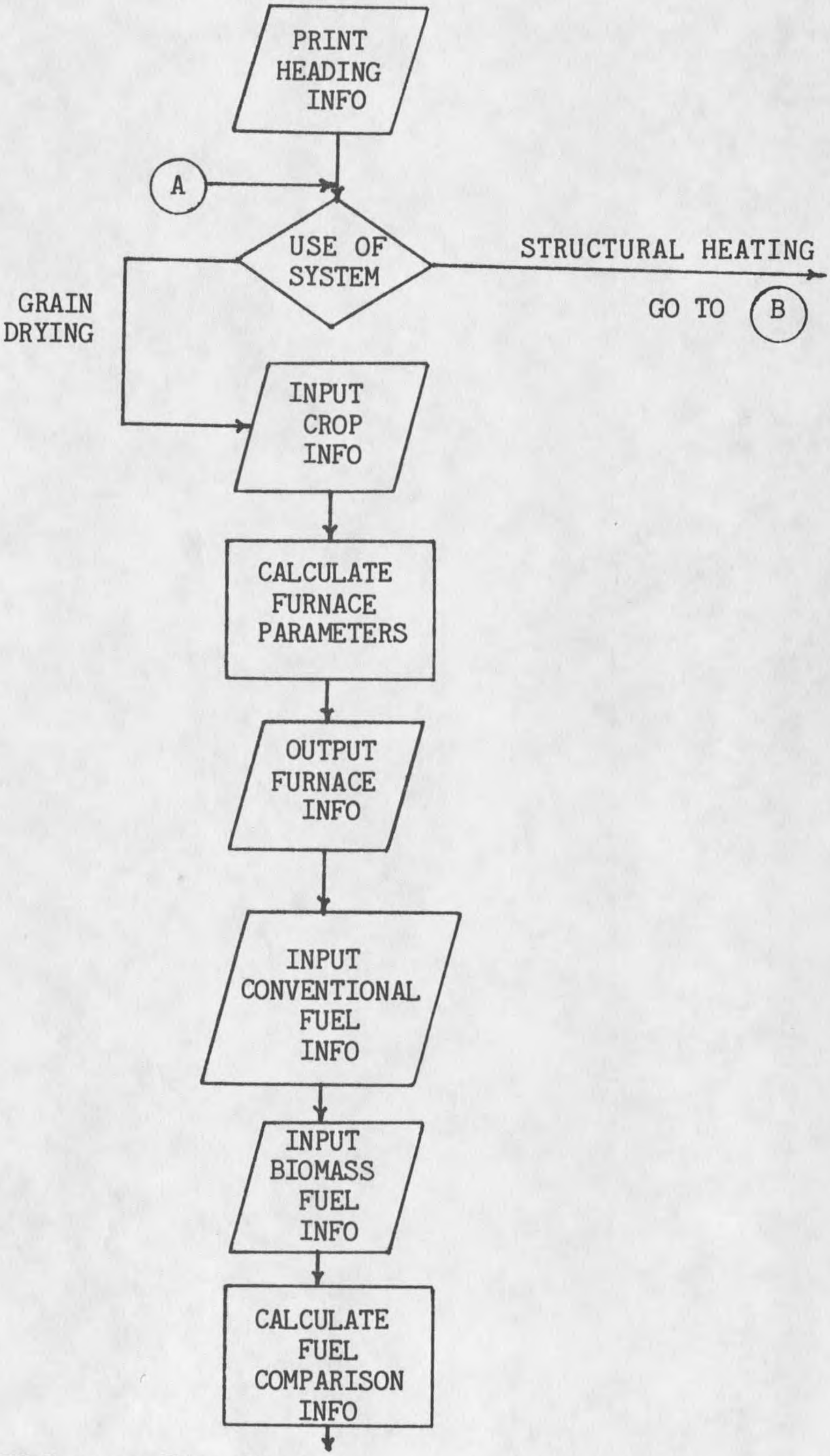
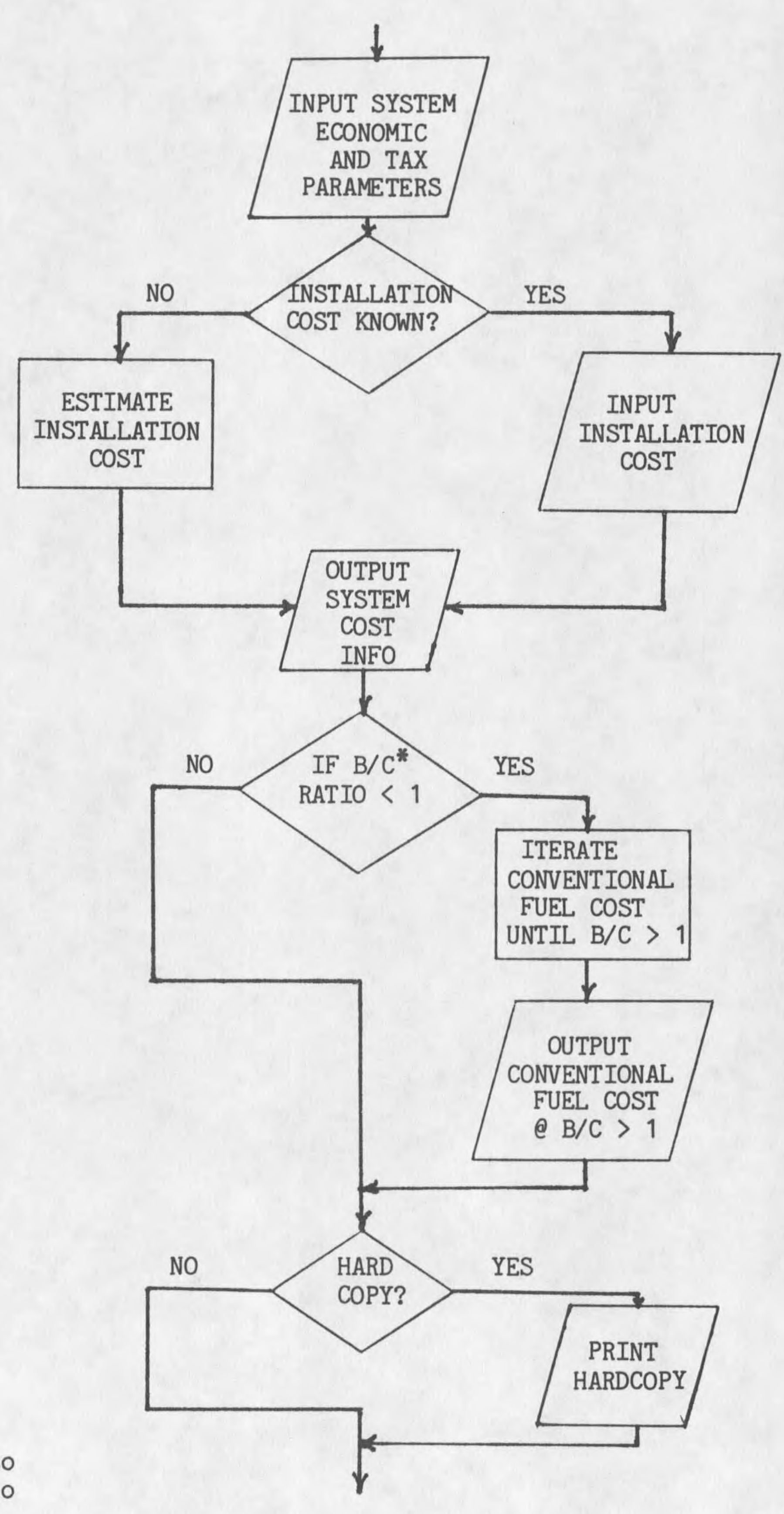
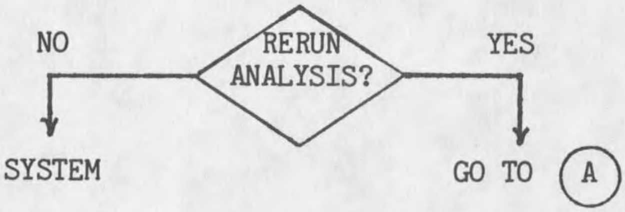
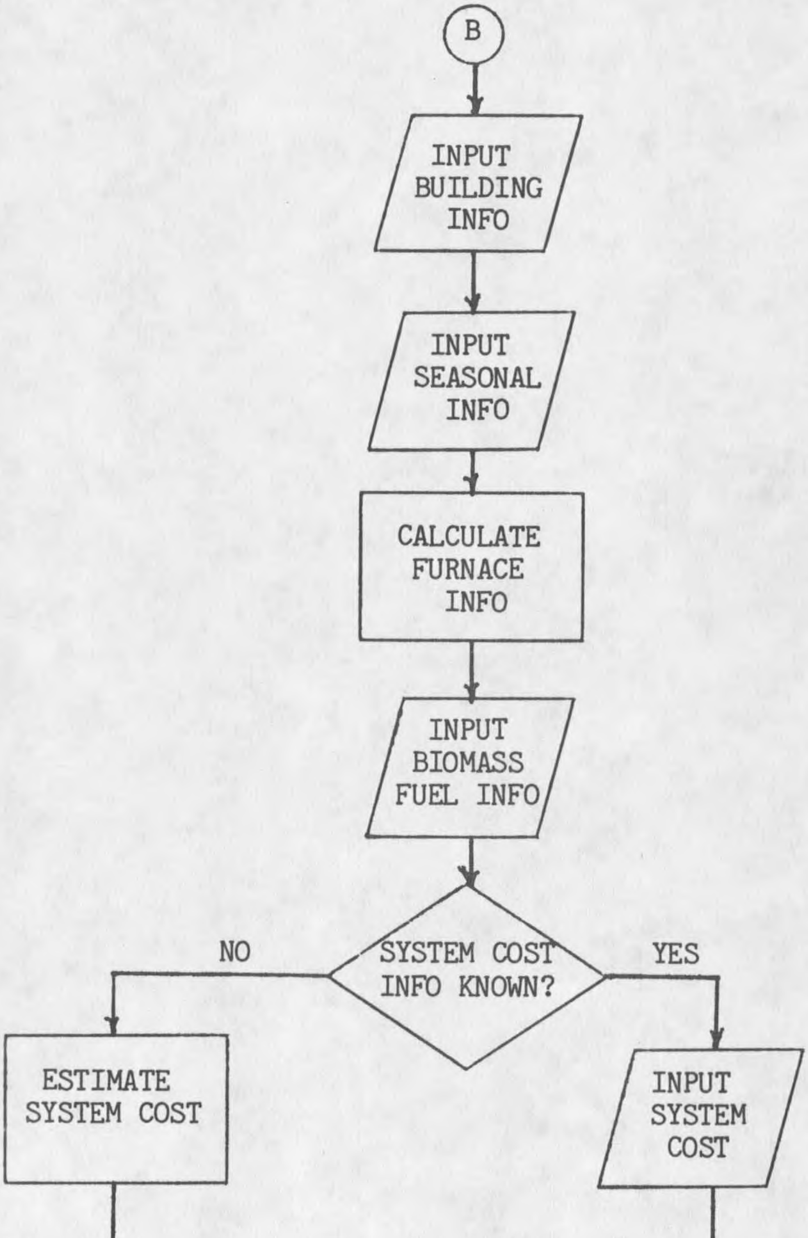


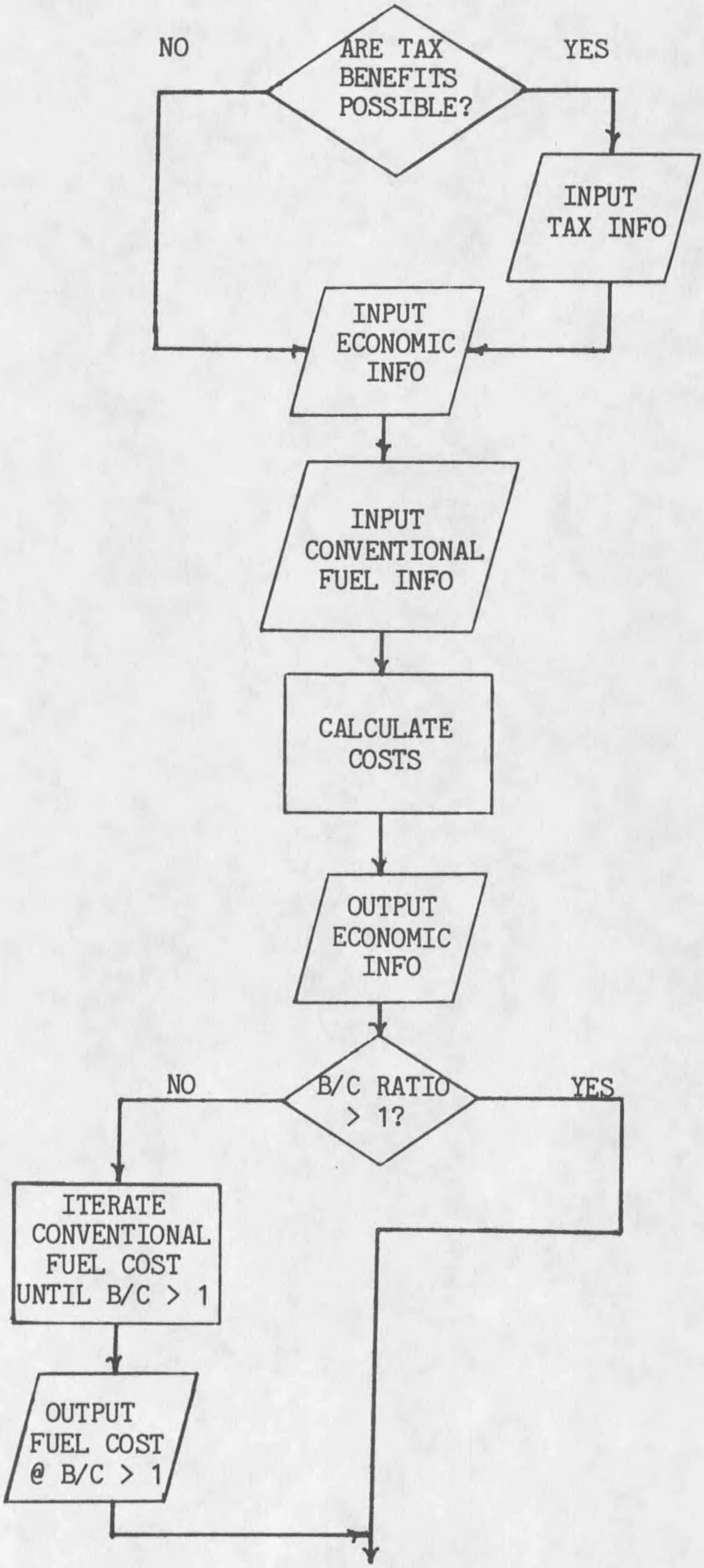
Figure 4. BASIC Program Flow Chart

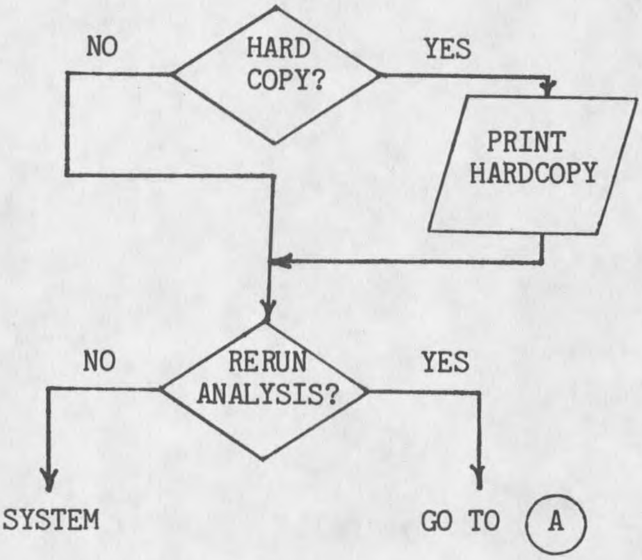


*Benefit to Cost Ratio


NO
RERUN ANALYSIS?
YES
SYSTEM
GO TO
A


B
INPUT BUILDING INFO
INPUT SEASONAL INFO
CALCULATE FURNACE INFO
INPUT BIOMASS FUEL INFO
NO
SYSTEM COST INFO KNOWN?
YES
ESTIMATE SYSTEM COST
INPUT SYSTEM COST


NO
ARE TAX BENEFITS POSSIBLE?
YES
INPUT TAX INFO
INPUT ECONOMIC INFO
INPUT CONVENTIONAL FUEL INFO
CALCULATE COSTS
OUTPUT ECONOMIC INFO
NO
B/C RATIO > 1?
YES
ITERATE CONVENTIONAL FUEL COST UNTIL B/C > 1
OUTPUT FUEL COST @ B/C > 1


NO
HARD COPY?
YES
PRINT HARDCOPY
NO
RERUN ANALYSIS?
YES
SYSTEM
GO TO
A

Appendix F. Computer Program Listing

```
100   REM    +++++++++++++++++++++++++++++++++++++++++
110   REM    ++                                     ++
120   REM    ++  ECONOMIC FEASIBILITY OF BIOMASS    ++
130   REM    ++          FURNACE SYSTEM             ++
140   REM    ++                                     ++
150   REM    ++  PROGRAMMERS: LEE ERICKSON          ++
155   REM    ++               BRUCE KINZEY          ++
160   REM    ++  AGRICULTURAL ENGINEERING DEPT.     ++
170   REM    ++  MONTANA STATE UNIVERSITY           ++
180   REM    ++  BOZEMAN MT 59715                   ++
190   REM    ++  406/994-2275      FEBRUARY, 1986   ++
200   REM    +++++++++++++++++++++++++++++++++++++++++
210   PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" "
220   A$="PRELIMINARY ECONOMIC FEASIBILITY ANALYSIS FOR BIOMASS-FUELED"
230   B$="        DIRECT-FIRED INCINERATOR FURNACE SYSTEMS "
240   C$=" "
250   D$="              Program development sponsored by "
260   E$="  Montana Department of Natural Resources and Conservation"
270   F$="                    Program developed by"
280   G$="             Agricultural Engineering Department"
290   H$="                    Montana State University"
300   I$="                         February, 1986"
310   PRINT A$
320   PRINT B$
330   PRINT C$
340   PRINT D$
350   PRINT E$
360   PRINT C$
370   PRINT F$
380   PRINT G$
390   PRINT H$
400   PRINT I$
410   PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT" ":PRINT"
":PRINT" "
420   PRINT"Enter name of enterprise:"
430   INPUT J$: PRINT" ":PRINT" "
440   PRINT"Enter today's date: e.g. 6/17/1985"
450   INPUT JJ$: PRINT" ":PRINT" "
460   OC=0:NBC=0:AW=0:FW=0:TW=0:AS=0:DC=0:  REM  CLEARS VALUES FOR RERUN
470   PRINT"Is the biomass furnace to be used for: 1=grain drying,
2=structural"
480   PRINT"heating.  Enter appropriate number."
490   INPUT UANS:PRINT" "
500   IF UANS=2 GOTO 4000
510   PRINT"Enter code number of crop grown."
520   PRINT"1 = wheat     4 = oats"
530   PRINT"2 = barley    5 = other "
```

Figure 5. Computer Program Listing

```
540   PRINT"3 = corn"
550   INPUT GRAIN:PRINT" "
560   IF GRAIN=1 THEN WT=60: K$=" Wheat "
570   IF GRAIN=2 THEN WT=48: K$=" Barley"
580   IF GRAIN=3 THEN WT=57: K$=" Corn  "
590   IF GRAIN=4 THEN WT=37: K$=" Oats  "
600   IF GRAIN=5 THEN WT=50: K$=" Other "
610   PRINT"Answer the following questions to select an appropriate
furnace size."
620   PRINT" "
630   PRINT"Enter estimated grain moisture content at harvest:"
640   PRINT"Use percent wet basis."
650   INPUT GMC1:GMC1=GMC1/100:PRINT" "
660   PRINT"Enter desired grain moisture content for storage:"
670   PRINT"Use percent wet basis."
680   INPUT GMC2:GMC2=GMC2/100:PRINT" "
690   PRINT"Enter acres of grain harvested per season:"
700   INPUT ACRES:PRINT" "
710   PRINT"Enter average production, bushels per acre:"
720   INPUT BUAC:PRINT" "
730   PRINT"Enter allowable harvest and drying period, days:"
740   INPUT DAYS:PRINT" "
750   PRINT"Enter time available to operate furnace, hours/day:"
760   PRINT"Note- You will also need time to load/unload bin in
addition"
770   PRINT"to this amount."
780   INPUT HRS: HRS=HRS-2:   REM  ASSUMED 2HRS REQD TO START/STOP
SYSTEM
790   TOTWT=ACRES*BUAC*WT:     REM  TOTAL WET GRAIN HARVEST WT, LB
800   WW1=GMC1*TOTWT:          REM  WATER CONTENT WET GRAIN, LB
810   DW=(1-GMC1)*TOTWT:       REM  DRY MATTER CONTENT WET GRAIN, LB
820   WW2=GMC2*DW/(1-GMC2):    REM  WATER CONTENT DRIED GRAIN, LB
830   WTR=WW1-WW2:             REM  AMOUNT OF WATER TO BE REMOVED, LB
840   WTRHR=WTR/(HRS*DAYS):    REM  WATER TO BE REMOVED PER HOUR, LB
850   BT=WTRHR*2000:           REM  ASSUMES 2000 BTU REQD PER LB H20
REMOVED
860   DBS=ACRES*BUAC/DAYS:     REM  DAILY DRYER BATCH SIZE REQUIRED, BU
870   DEPTH=DBS*1.25/314:      REM  GRAIN DEPTH IN 20' DIA BATCH DRYING
BIN
880    HP=.068*12000*DEPTH*1*80*1.5/(33000!*.75)
890   REM  FAN HP=LB/FT3 AIR x CFM x Depth x "H20/ft grain x 80'
air/'h20 x
900   REM           2.5 system factor/hp constant x fan eff.
910   PRINT" ":PRINT"Approximate drying system characteristics
required:"
920   PRINT;"Consult qualified engineer for detailed design
requirements."
930    PRINT;"Furnace rating, BTU/hour.................";BT
940    PRINT;"Daily dryer batch size,  bu...............";DBS
950   PRINT;"Grain depth in 20' dia. drying bin, ft....";DEPTH
960   PRINT;"Approximate fan horsepower requirement, HP";HP
970   REM  LP IS LABOR FACTOR BASED ON FURNACE SIZE  from Curtis, et.
```

```
al.
980   IF BT <= 1E+06 THEN LP = .125
990   IF BT >  1E+06 THEN LP = .25
1000   IF BT >  5E+06 THEN LP = .5
1010   IF BT > 10000000# THEN LP =  1
1020   IF BT > 20000000# THEN LP =  2
1030   IF BT > 40000000# THEN LP =  3
1040   PRINT
1045   PRINT"Answer the following questions to compare biomass and
traditional"
1050   PRINT"fuels as potential grain dryer energy sources.":PRINT" "
1060   PRINT"Enter code number fuel used for comparison:":PRINT" "
1070   PRINT"1= natural gas (MCF)  4= electricity (kwh)   7= propane
(gal)"
1080   PRINT"2= #2 fuel oil (gal)  5= bitum. coal (ton)"
1090   PRINT"3= #6 fuel oil (gal)  6= lignite coal(ton)"
1100   INPUT FU1:REM BE= BURNER EFFICIENCY AND EV= ENERGY VALUE,
BTU/UNIT
1110   IF FU1=1 THEN BE=.778: EV= 1E+06: M$=" Natural gas": N$=" MCF"
1120   IF FU1=2 THEN BE=.825: EV= 140000!: M$=" #2 fuel oil": N$=" gal"
1130   IF FU1=3 THEN BE=.825: EV= 150000!: M$=" #6 fuel oil": N$=" gal"
1140   IF FU1=4 THEN BE=.9: EV=    3413: M$=" electricity": N$=" kwh"
1150   IF FU1=5 THEN BE=.85: EV= 2.7E+07: M$=" bitum. coal": N$=" ton"
1160   IF FU1=6 THEN BE=.8: EV= 1.7E+07: M$=" lig. coal  ": N$=" ton"
1170   IF FU1=7 THEN BE=.787: EV= 93000!: M$=" propane    ": N$=" gal"
1180   PRINT" ":PRINT"Enter fuel cost, $/unit. Use appropriate units."
1190   PRINT"($/MCF, $/gal, $/kwh, $/ton)"
1200   INPUT OC:PRINT" "
1210   IF UANS=2 GOTO 4550
1220   PRINT"Enter code number of biomass fuel to be used:"
1230   PRINT"1 = grain straw or hay"
1240   PRINT"2 = wood chips or slash "
1250   PRINT"3 = corn stover "
1260   INPUT FU2:PRINT" "
1270   IF FU2=1 THEN HV=8600: O$=" straw or hay "
1280   IF FU2=2 THEN HV=8600: O$=" wood products"
1290   IF FU2=3 THEN HV=8600: O$=" corn stover  "
1300   PRINT"Enter delivered cost per ton of biomass fuel, $:"
1310   PRINT"Include collection, transportation, and storage costs."
1320   INPUT CO:PRINT" "
1330   PRINT"Enter biomass fuel estimated moisture content, percent wet
basis:"
1340   INPUT MCF:MCF=MCF/100:PRINT" "
1350   IF UANS=2 GOTO 4210:   REM RETURN TO STRUCTURAL HEATING SECTION
1360   REM CALCULATE DRY WEIGHT AND WET WEIGHT OF FUEL
1370   DW=1/(1+MCF)  :                                REM  BIOFUEL DRY
WEIGHT %
1380   WW=1-DW              :                           REM  BIOFUEL WET
WEIGHT %
1390  BW=HV*(1-MCF)-(MCF*1150):                        REM  HEAT AVAILABLE
1400  AEN=BT*HRS*DAYS      :        REM THEOR. ANNUAL ENERGY REQD., BTU
1410  AFU2=AEN/(BW*2000)  :        REM ANNUAL BIOMASS NEEDED, TONS
```