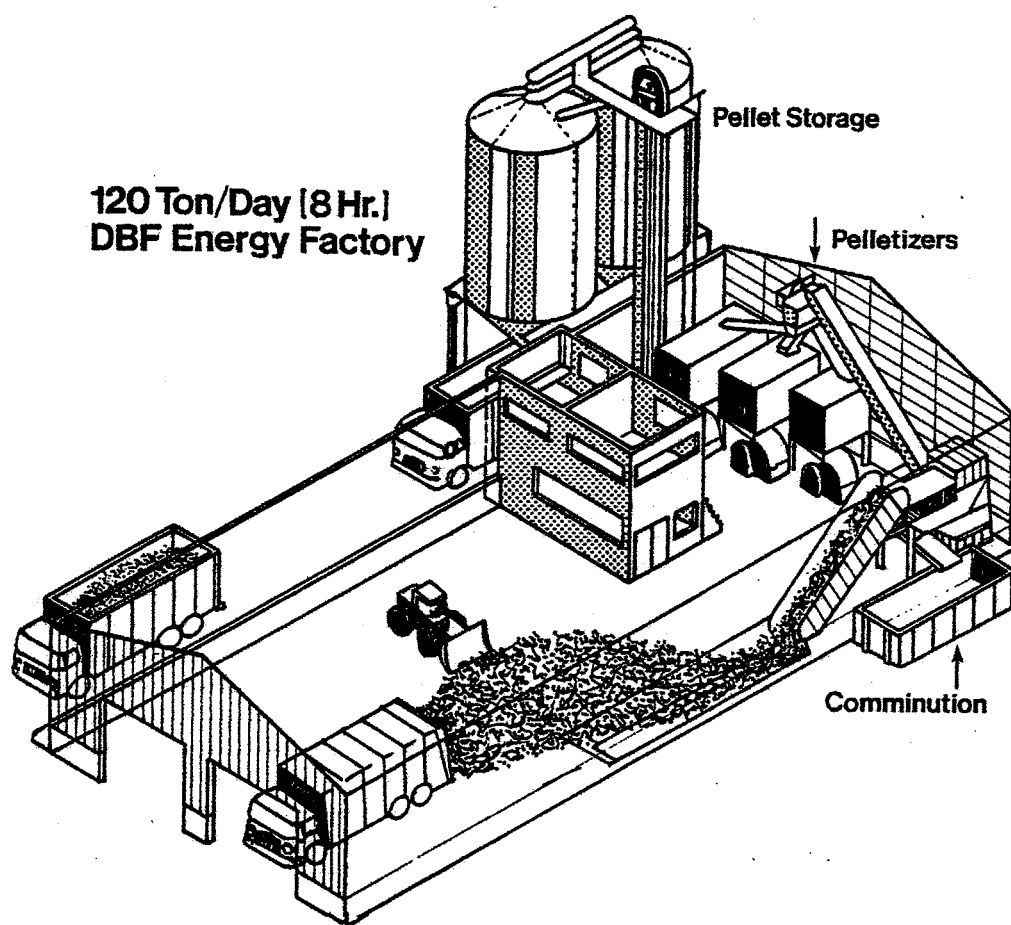


# DENSIFIED BIOMASS

## A NEW FORM OF SOLID FUEL

*With a forward for the 21st Century*



**Thomas Reed and Becky Bryant**

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DENSIFIED BIOMASS:  
A NEW FORM OF SOLID FUEL

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July 1978

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A Division of Midwest Research Institute

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# FORWARD TO 21<sup>st</sup> CENTURY DENSIFIED BIOMASS

I wrote "Densified Biomass" with Becky Bryant in the first year I spent at the Solar Energy Research Institute, 1978, after visiting the experimental facilities of Prof. Ray Currier at Oregon State University and the production facilities of Rudy Gunnerman's "Woodex" plant nearby.

At that time I was just beginning my career in biomass energy. It was my opinion then that if biomass were to play an important role in providing renewable energy, densification would be very important. I said then "Biomass is an economically and environmentally attractive fuel, but it is often difficult to collect, store, ship and use. Densifying biomass to a specific gravity of 1.0 (sinks in water) eliminates most of these problems and produces a uniform, clean, stable fuel: "Densified biomass fuel" or DBF. (Densifying includes pelletizing, briquetting and logging.)

It is instructive to read one's own words 22 years later. These are still – even more – my opinions. What has changed in that time is that now densified biomass fuels are available commercially in at least two forms: ¼ inch diameter pellets for pellet stoves (available in most hardware stores in Denver for \$2.50/ 40 lb bag); and peanut shell pellets, available for ~\$50/ton at plants that produce peanuts.

It has taken a long time to reach this stage of commercialization – a period of low cost oil in which it was difficult for any renewable energy to compete. We may be coming to the end of that period (oil is currently over \$30/bbl). In any case, success feeds on success and we can hope that many more forms of DBF will become available as the demand for renewable energy increases.

~~~~~  
On my scale of biomass fuels (1 to 10), straw is zero and densified straw is 9 (higher ash than wood pellets). In my opinion there is a great deal more research that could be done in understanding the pelletization process and thus reducing the energy and cost of converting "trash biomass" (straw, paper,....) to pellets, cubes or logs.

As a first step in that research I wrote a VERY fundamental paper on Biomass Densification with George Trezek and L. Diaz in 1979. I am enclosing this paper as an Appendix for those of you who may be interested in directions for future research.

There is now a large industry out there making pellets of various kinds. This book is an "oldy but goody". Anyone interested in knowing more on the subject today should contact the Pellet Fuels Institute in Edina MN at 612 8311 3205.

Here's to a bright future for biomass and brighter with densified biomass fuels.

Happy reading

Thomas B. Reed

President, BEF Press

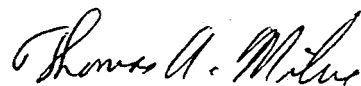
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This report was initially issued by the Solar Energy Research Institute as SERI-35 in July 1978, by the U.S. Department of Energy.

## PREFACE

The intent of this report is to present a state-of-the-art evaluation of densified biomass fuel in support of Task 3302, "Assessment of Bio/Chemical Conversion Processes." Although densified biomass fuel is already used commercially on a limited scale, this report is believed to be the first comprehensive documentation of processes, energy balance, economics, and applications. A follow-up report on international processes and applications is currently being compiled, and we plan to address in detail issues such as economics and gasification of densified biomass in a later report.

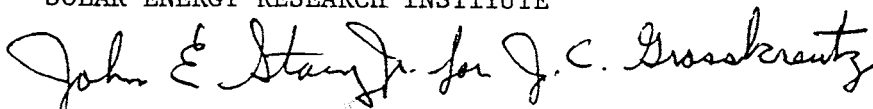
The authors would like to express their gratitude for the information supplied by process manufacturers and developers. We are particularly in debt to Richard Caputo, SERI, and Professor Ray Currier at the Forest Products Laboratory, Oregon State University.



Acting Branch Chief  
Bio/Chemical Conversion

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE



J. Charles Grosskreutz  
Assistant Director  
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## TABLE OF CONTENTS

|                                                        | <u>Page</u> |
|--------------------------------------------------------|-------------|
| I. Introduction . . . . .                              | 1           |
| II. Biomass Densification Processes . . . . .          | 4           |
| III. Properties and Performance of DBF . . . . .       | 16          |
| IV. Energy Balance for Biomass Densification . . . . . | 17          |
| V. Economics of Biomass Densification . . . . .        | 20          |
| VI. Applications of Densified Biomass Fuels . . . . .  | 26          |
| VII. Summary . . . . .                                 | 28          |
| References . . . . .                                   | 29          |
| Appendix A--Conversion Factors . . . . .               | A-1         |
| Appendix B--Energy Content of Biomass . . . . .        | B-1         |



# LIST OF TABLES

| <u>Table</u> |                                                                                              | <u>Page</u> |
|--------------|----------------------------------------------------------------------------------------------|-------------|
| 1            | Energy Content of U.S. Biomass Residues . . . . .                                            | 2           |
| 2            | Energy Densities of Various Fuels by Mass<br>and Volume . . . . .                            | 5           |
| 3            | Manufacturers of Densification Equipment for<br>Feed and Fuel . . . . .                      | 7           |
| 4            | DBF Producers and Developers: Process Status . .                                             | 8           |
| 5            | Energy Required for Pelletting (300 hp pellet<br>mill) . . . . .                             | 18          |
| 6            | Daily Energy Balance for 300 ton/day Bark<br>Pellet Plant . . . . .                          | 19          |
| 7            | Case Study Cost Analysis of Pelletting Silvicultural<br>Wastes (300 ton/day plant) . . . . . | 21          |
| 8            | Case Study Cost Analysis of Densified, Refuse-<br>Derived Fuel (300 ton/day) . . . . .       | 24          |
| B-1          | Energy Content of Biomass and Other Fuels . . . . .                                          | B-2         |





# LIST OF FIGURES

| <u>Figure</u> |                                                                                                 | <u>Page</u> |
|---------------|-------------------------------------------------------------------------------------------------|-------------|
| 1             | Pelleting Process . . . . .                                                                     | 9           |
| 2             | Typical Biomass Compaction Plant . . . . .                                                      | 12          |
| 3             | Taiga Extrusion Process . . . . .                                                               | 13          |
| 4             | Sensitivity of Break-Even Selling Price to Feed-<br>stock Cost and Capital Investment . . . . . | 22          |
| 5             | Sensitivity of Break-Even Selling Price to<br>Dumping Cost and Capacity Factor . . . . .        | 22          |
| B-1           | Sensitivity of Energy Content to Moisture<br>Content . . . . .                                  | B-5         |



## ABSTRACT

Biomass is an economically and environmentally attractive fuel, but it is often difficult to collect, store, ship, and use. Densifying biomass to a specific gravity of 1.0 eliminates most of these fundamental problems and produces a uniform, clean, stable fuel: "densified biomass fuel" or DBF.

Before conversion to DBF, raw biomass residues generally require preparation: the separation of noncombustibles from combustibles, especially for solid municipal waste; milling; and drying. About 5% of the energy content in raw biomass can be expended in preparation and 1% to 3% in densification. In its densified form, biomass can be burned in standard equipment with reduced emissions and increased heat release and thermal efficiency. Tests have shown that DBF is an acceptable substitute or diluent in existing coal-fired systems. In addition, DBF may be used in home heating, pyrolysis, gasification, and power generation.

Based on component equipment costs and the installed cost of existing plants, the estimated break-even selling price of Woodex pellets is \$1.20 to \$3.40/MBtu or \$19.20 to \$54.40/ton, depending on feedstock cost. Within that cost range, DBF appears to be economically competitive with coal in some markets, particularly when taking into account environmental advantages of low sulfur content. Even when forest and farm residues are available for fuel purposes, it may be preferable to pellet the residues, rather than combust them directly, because of transportation, storage, and capital investment savings.



## DENSIFIED BIOMASS: A NEW FORM OF SOLID FUEL

### I. INTRODUCTION

Biomass refers to all products of photosynthesis, such as wood, corn, and algae as well as to human and animal wastes. In the United States, the energy equivalent of 30 quads\* of biomass is produced each year. Nearly one-half of that total is captured in food and fiber products, 3.3% is used as energy, and the balance (13.4 quads) appears as unused biomass residues (see Table 1). Since the U.S. energy consumption in 1978 is 75 quads, the energy potential of biomass residues represents a significant national energy income. Coal, by comparison, contributes 13 quads to the energy supply stream.

In addition to its potential for making a significant contribution to U.S. energy needs, biomass has a number of other advantages. The sulfur content of biomass is less than 0.1% by weight; the sulfur content of coal is between 1% and 5%. Coal-fired power plants use expensive flue gas scrubbers to remove 90% of sulfur emissions; plants firing biomass would not require sulfur control equipment. Biomass has a 1% ash content which can be returned to the soil as a fertilizer and soil conditioner; coal's 5% to 20% ash content creates a disposal problem. Biomass is renewable; it stores energy in cellulose and other stable compounds and is widely distributed throughout the United States. Partly offsetting these advantages are the wide variety of forms in which biomass occurs, its high moisture content, and the difficulty of shipping and storing biomass. With further processing--separation, pulverization, drying, and densification--these constraints can be mitigated by converting all forms of biomass

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\*See Appendix A for conversion factors.

TABLE 1  
ENERGY CONTENT OF U.S. BIOMASS RESIDUES\*

| <u>CATEGORY</u>      | <u>Quads/Year</u> |                               | <u>Estimated Cost<br/>(\$/MBtu)</u> |
|----------------------|-------------------|-------------------------------|-------------------------------------|
|                      | <u>Produced</u>   | <u>Easily<br/>Collectible</u> |                                     |
| Dry Biomass          |                   |                               |                                     |
| Municipal Waste      | 1.5               | 1.0                           | 0-2                                 |
| Agricultural         | 5.1               | 1.5                           | 2-3                                 |
| Forest               | 3.2               | 1.6                           | 1-3                                 |
| Wet Biomass Residues |                   |                               |                                     |
| Sewage               | 0.2               | 0.1                           | 2-5                                 |
| Manures              | 3.4               | 0.4                           | 2-5                                 |
| Total                | 13.4              | 4.6                           |                                     |

Source: J. R. Benemann. Biofuels: A Survey of Potential  
and Prospects. Palo Alto: EPRI, December 1977.

into a standard commodity fuel which is convenient to ship, store, and burn. The object of this report is to evaluate the desirability and feasibility of upgrading biomass in this manner.



## II. BIOMASS DENSIFICATION PROCESSES

Plants produce cellulose as a bundle of hollow tubes which transport water and nutrients and provide high structural strength; the tubes are glued together with lignin. The molecular specific gravity of biomass is about 1.5; but due to its open structure, raw biomass has a specific gravity (oven dry) of 0.65 for hard woods, 0.45 for soft woods, and even less for agricultural and aquatic biomass.

A fuel with high mass energy density (MED) and volume energy density (VED) values is preferable to a fuel with low values because it is more efficient to store, ship, and burn. Efficiency of combustion has a positive correlation to increasing density and low moisture content because: (1) efficiency of boiler heat exchange is a function of gas quantity, (2) the thoroughness of combustion decreases with increasing water content, and (3) the energy output of a furnace depends on the energy density of the fuel. MED and VED values for raw biomass, DBF, and other fuels are indicated in Table 2. The following tabulation, based on Table 2, shows that drying and densification convert biomass to a fuel which is similar to coal in terms of fuel value per unit of weight and volume.

| <u>Biomass<br/>Characteristics</u>   | <u>Ratio of<br/>Biomass MED to<br/>Coal MED</u> | <u>Ratio of<br/>Biomass VED to<br/>Coal VED</u> |
|--------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 50.0% water content;<br>1.0 density  | 0.33                                            | 0.25                                            |
| 10.0% water content;<br>1.0 density  | 0.66                                            | 0.57                                            |
| 10.0% water content;<br>1.25 density | 0.66                                            | 0.72                                            |

TABLE 2  
ENERGY DENSITIES OF VARIOUS FUELS BY MASS AND VOLUME\*

| Fuel              | Water<br>Content<br>(%) | Density<br>g/cm <sup>3</sup><br>(lb/ft <sup>3</sup> )** | Heat of Combustion (low)           |                                                                |
|-------------------|-------------------------|---------------------------------------------------------|------------------------------------|----------------------------------------------------------------|
|                   |                         |                                                         | Mass (MED)<br>kJ/g<br>(MBtu/ton)** | Volume (VED)<br>kJ/cm <sup>3</sup><br>(Btu/ft <sup>3</sup> )** |
| Biomass           | 50                      | 1.0<br>(62.4)                                           | 9.2<br>(8.0)                       | 9.2<br>(250.0)                                                 |
|                   | 10                      | 0.6<br>(37.5)                                           | 18.6<br>(16.0)                     | 11.2<br>(300.0)                                                |
| Densified Biomass | 10                      | 1.0<br>(62.4)                                           | 18.6<br>(16.0)                     | 20.9<br>(499.0)                                                |
|                   | 10                      | 1.25<br>(78.1)                                          | 18.6<br>(16.0)                     | 26.1<br>(625.0)                                                |
| Charcoal          | -0-                     | 0.25<br>(15.6)                                          | 31.8<br>(24.0)                     | 8.0<br>(374.0)                                                 |
| Coal-Bituminous   | -                       | 1.3<br>(81.1)                                           | 28.0<br>(24.1)                     | 36.4<br>(977.0)                                                |
| Methanol          | -0-                     | 0.79<br>(49.3)                                          | 20.1<br>(17.3)                     | 15.9<br>(426.0)                                                |
| Gasoline          | -0-                     | 0.70<br>(43.7)                                          | 44.3<br>(38.1)                     | 30.9<br>(832.0)                                                |

\*Values shown are representative of a range for each fuel.

\*\*"Density," as used in this column, refers to the compactness of individual pieces of biomass. Another term frequently used is "bulk density," which is the compactness of bulk biomass. Because of a fluff factor in the case of wood chips or stacking in the case of DBF, bulk density is less than the density of individual biomass pieces. The bulk density of green wood chips, for example, is 20 lb/ft<sup>3</sup>, indicating a fluff factor of about three. DBF has a bulk density which is about 70% the density of individual pellets, cubes, or briquettes.

The first U.S. Patent for densification was issued in 1880; it describes a process where sawdust or other wood residues are heated to 150°F and then compacted to the "density of bituminous coal" with a steam hammer (Smith, 1880). Since then, the U.S. Patent Office has issued a number of patents for processes that make dense forms of biomass. At first, the processes were used to produce animal feed. Several companies are now using the biomass densification processes to produce fuel for the energy market (see Tables 3 and 4), and a number of new patents have been recently issued (Beningson, 1975; Bremer, 1975; Gunnerman, 1977; Livingston, 1977).

Five forms of biomass densification are now practiced commercially; other processes are well on the way to commercialization. Pelleting (used, for example, in feed manufacture) employs a hard steel die which is perforated with a dense array of holes 0.3 to 1.3 cm (1/4 to 1/2 in.) in diameter (see Figure 1). The die rotates against inner pressure rollers, forcing a biomass feedstock into dies with pressures of 7.0 kg/mm<sup>2</sup> (10,000 psi). As the pellet is extruded through the die, it is broken off at a specified length. Cubing is a modification of pelleting which produces larger cylinders or cubes, 2.5 to 5.0 cm (1-2 in.) across. Straw and paper feedstocks are generally used. Briquetting compacts a feedstock between rollers with cavities, producing forms like charcoal briquettes. Extrusion uses a screw to force a feedstock under high pressure into a die thereby forming large cylinders 2.5 to 10 cm (1-4 in.) in diameter. Binding agents such as pitch or paraffin are often added to increase structural strength and heat content. Extruded logs are widely available in U.S. supermarkets; they have a specific gravity of 1.0. Another process, rolling-compressing, is based on "the natural tendency of forage crops to wrap tight around rotating shafts" (Molitoris, 1974). Finished rolls are

TABLE 3

## MANUFACTURERS OF DENSIFICATION EQUIPMENT FOR FEED AND FUEL\*

| <u>Company</u>                                    | <u>Type of Equipment</u>            |
|---------------------------------------------------|-------------------------------------|
| Agnew Environmental Products, Grants Pass, Oreg.  | Extruder                            |
| Agropack, Medina, Wash.                           | Roller-compressor                   |
| Bonnet Co., Kent, Ohio                            | Wood and Wax Extruder               |
| Briquettor Systems, Inc., Reedsport, Oreg.        | Extruder                            |
| California Pellet Mill Co., San Francisco, Calif. | Extruder and Pellet Mills,<br>Cuber |
| Gear Cube Co., Moses Lake, Wash.                  | Cuber                               |
| Hawker Siddeley Canada Ltd., Vancouver, B.C.      | Extruder                            |
| John Deere, Moline, Ill.                          | Cuber                               |
| Papakube Corp., San Diego, Calif.                 | Extruder Cuber                      |
| ReydcO Machinery Co., Redding, Calif.             | Extruder                            |
| Sprout Waldron, Munev, Pa.                        | Pellet Mills                        |
| Taiga Industries, Inc., San Diego, Calif.         | Extruder                            |

\*There may be other manufacturers unknown to the authors; this list in no way constitutes an endorsement by SERI or the authors.

Sources: R. A. Currier, "Manufacturing Densified Wood and Bark Fuels." Special Report 490. Oregon State University Extension Service, July 1977. Cohen and Parrish. "Densified Refuse Derived Fuels." Bulletin 6, No. 1. Washington, D.C.: National Center for Resource Recovery, Winter 1976.

TABLE 4

## DBF PRODUCERS AND DEVELOPERS: PROCESS STATUS\*

| <u>Company</u>                                                    | <u>Process Status</u> |                          |
|-------------------------------------------------------------------|-----------------------|--------------------------|
|                                                                   | <u>Commercial</u>     | <u>Under Development</u> |
| Bio-Solar Corp., Eugene, Oreg. (Woodex)                           | X                     |                          |
| Combustion Engineering Corp.                                      | X                     |                          |
| Guaranty Performance,<br>Independence, Kans.                      | X                     |                          |
| Lehigh Forming Co., Easton, Pa.                                   | X                     |                          |
| National Center for Resource<br>Recovery (NCRR), Washington, D.C. |                       | X                        |
| Papakube Corp., San Diego, Calif.                                 | X                     |                          |
| SRI International                                                 |                       | X                        |
| Taiga Industries, San Diego, Calif.                               | X                     |                          |
| Teledyne National,<br>Cockeysville, Md.                           | X                     |                          |
| University of California<br>Richmond Field Station                |                       | X                        |
| Vista Chemical and Fiber,<br>Los Gatos, Calif.                    |                       | X                        |

\*This list does not constitute an endorsement of particular processes by SERI or the authors. Furthermore, it is not an exhaustive listing of processes.

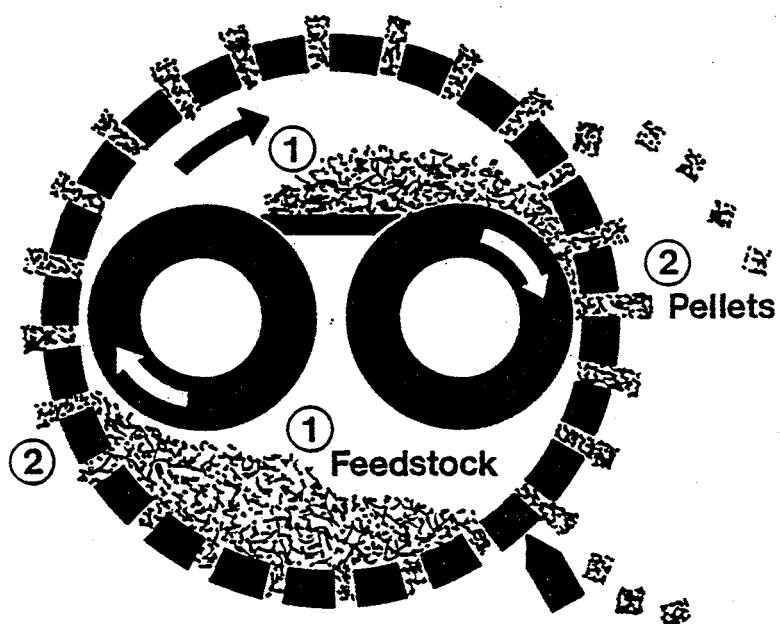


Figure 1. Pelleting Process

cylindrical with diameters ranging from 5 to 7 in., lengths between 3 and 8 in., and densities from 20 to 50 lb/ft<sup>3</sup>. Presently commercial, this process has been employed to increase the efficiency of haying operations and to produce a high-quality cattle feed.

Although these densification techniques are widely practiced, little explanation of the mechanism by which biomass attains high density or "selfbonding" is available. The following explanation is based on observation of processes and on densification patents and literature. Cellulose is stable at temperatures up to 250°C, but the lignin, a "waterproof glue" which holds the cellulose together, begins to soften at 100°C, permitting the moulding of wood shapes in steam boxes. Water plays an important role in densification; if the feedstock is either too dry or too wet, the pressures required for densification increase dramatically. For that reason, a moisture content of 10% to 25% is optimal. The feedstock is heated to 50°C to 100°C, both to soften the lignin and to obtain the desired moisture content. Mechanical densification follows with the product fuel emerging at 150°C. The dies also reach this temperature at steady-state, but temperature can be controlled by water cooling. The mechanical work of densification requires 32 to 80 J/g. With a heat capacity of about 1.7 J/g/°C, this would raise the temperature of the pellet by 20°C to 50°C, which is enough to cause both local boiling in areas that are not fully compacted and the excretion of waxes and volatiles. The resulting fluids act as a glue to hold the pellets together after cooling. The hot pellets are fragile and must be carefully handled until cooled.

Manufacturers of compaction equipment are listed in Table 3. Because their product has been used for animal feed production, many of these manufacturers have an established record of equipment reliability. Die wear, however, can be a major expense, unless precaution is taken to remove abrasive foreign materials.

A typical biomass compaction plant is shown in Figure 2. The first step is separation--stones and sand must be removed from forest or agricultural wastes and inorganics from municipal waste. The remaining biomass portion is then pulverized with hammer mills or ball mills to a size that is somewhat smaller than the minimum dimension of the pellets to be formed. This fraction is then dried in a rotary kiln or convection dryer. Finally, dried biomass is fed into the compactor which then delivers pellets for storage or use.

One of the more completely developed processes to date is R. Gunnerman's Woodex process employing a hammer mill, dryer, and pellet mill. A 120 ton-per-day plant has been operating since 1976 in Brownsville, Oregon. Gunnerman's company, Bio-Solar, recently installed a second, 300 ton-per-day plant in Brownsville; its dryer operates completely on pellets. Bio-Solar sells its products to customers in Oregon and Washington, where a major purchaser is the Western State Hospital near Tacoma. Two other Woodex plants are operating at the Sierra Power Corporation in Fresno, California, and the E. Hines Company in Burns, Oregon. Three plants are under construction, and several additional business groups have acquired Woodex licenses.

A continuous flow extrusion technique is used by Taiga Industries\* (Bremer, 1975). Pulverized biomass with a moisture content of 10.0% is compressed by a screw, then fed into a prepressure chamber where it is forced against a rotating spiral die-head with a cutting edge as shown in Figure 3. The frictional heat of the die face converts the biomass into a semi-fluid; the die-head shears off a spiral slice of compressed biomass, forcing it into

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\*Taiga publishes a Mod-Log sales brochure which describes the modified Bremer process, plant operations, costs, etc.



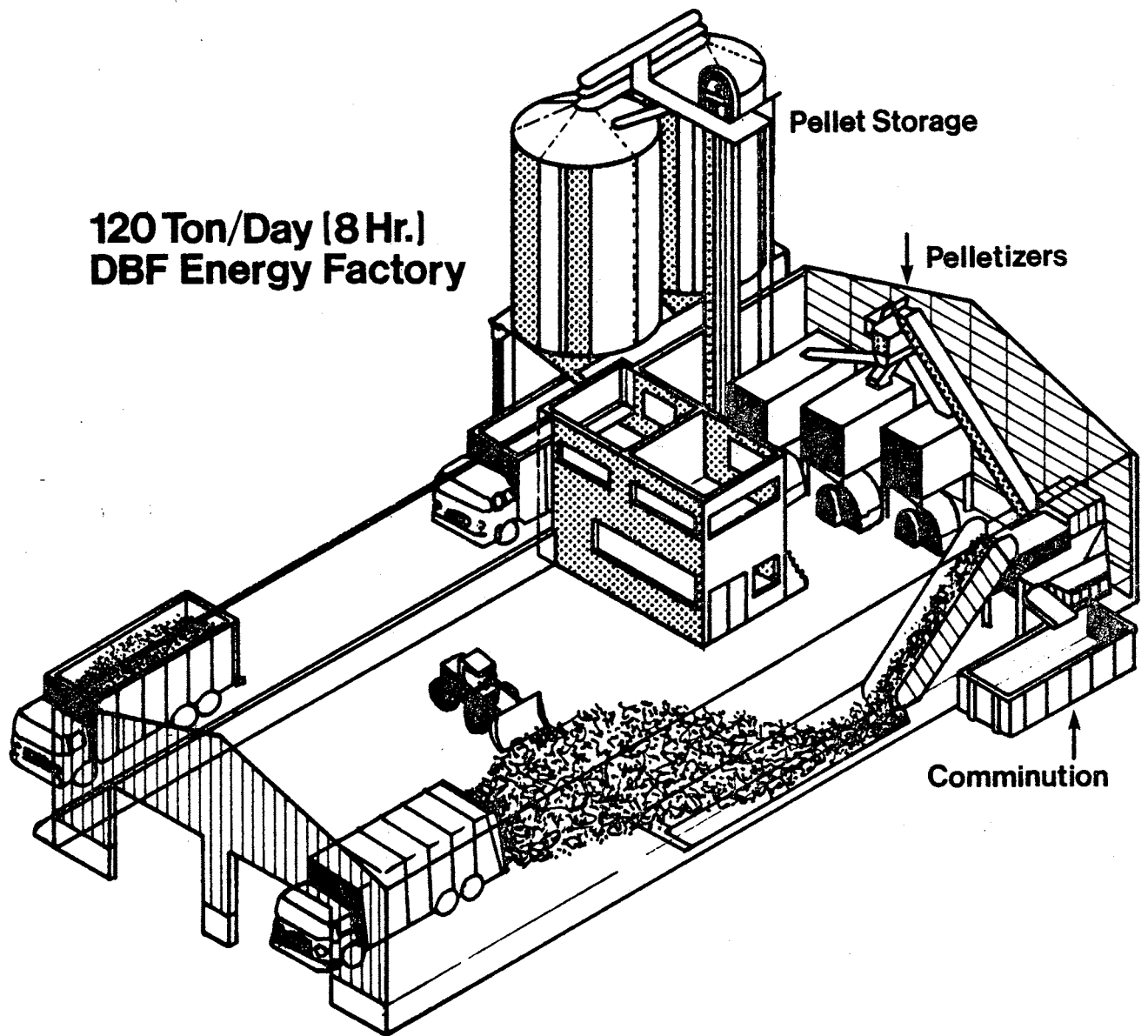


Figure 2. Typical Biomass Compaction Plant

Source: PapaKube Corp., San Diego, Calif.

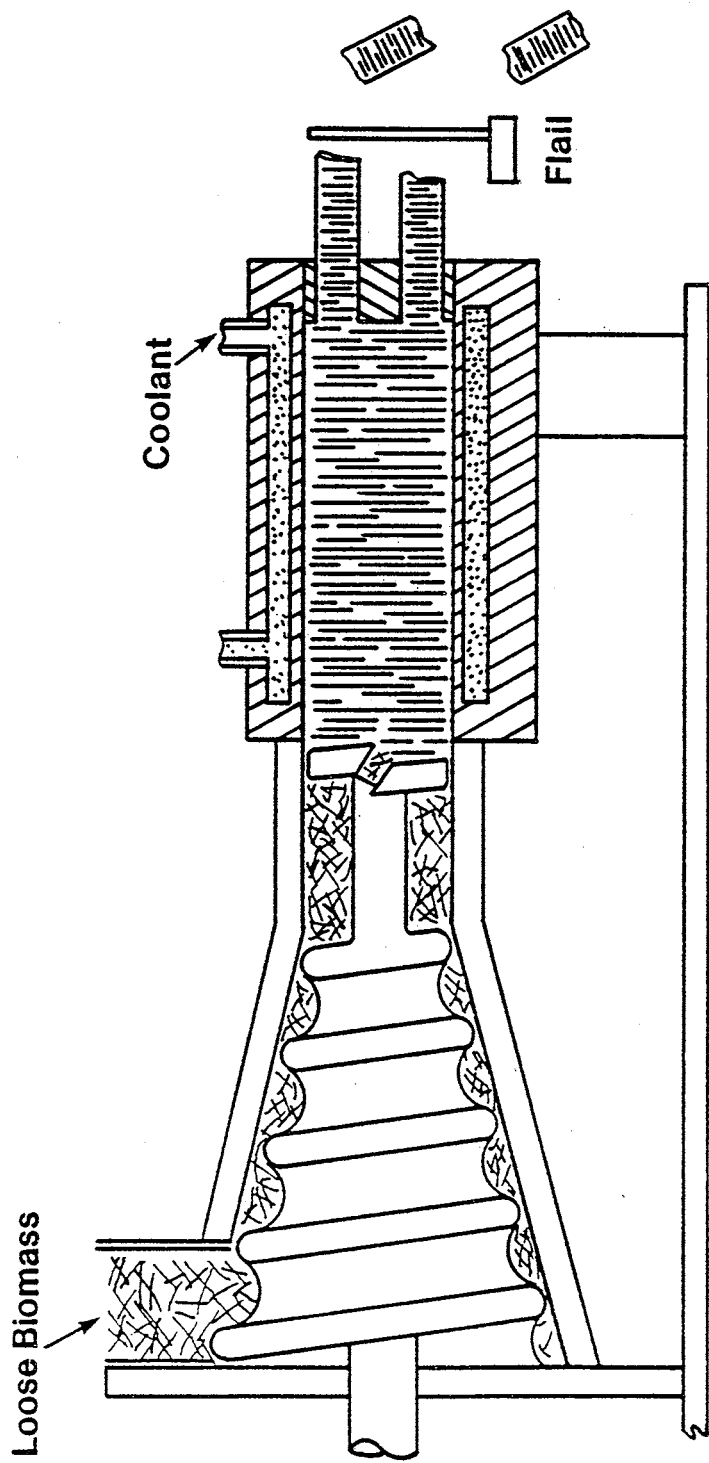


Figure 3. Taiga Extrusion Process

the die chamber. The densified product is expelled and cut to a specified length by a rotating flail. Taiga produces either a 10 cm by 30 cm log or 2.5 cm briquettes with a specific gravity of 1.2 to 1.45. The process expends 50 to 90 hp to produce 1 ton per hour of DBF (see Section IV on energy balance).

Another process, originally developed by Edward Koppelman to upgrade lignite, has been modified for biomass feedstocks and is now pending patent issuance (Koppelman, 1977). SRI International in cooperation with Koppelman has constructed a pilot plant and tested various feedstocks. Details of the process are considered proprietary information but general features are: a water slurry feed system; a pyrolysis reactor; a water recovery system; and an output stream of a carbonaceous solid, a combustible gas, and a small amount of aromatic liquid. Product yields and composition depend on the feedstock and key controllable variables (temperature, pressure, water content, and reaction time.) SRI claims a process energy efficiency of 85% to 90%. The projected cost for a 1,800 ton-per-day plant is \$10 to \$15 million.

Solid waste densification is an attractive option because it helps solve two urban problems at once: energy supply and waste disposal. Baltimore County and the Maryland Environmental Service with Teledyne National as prime contractor are operating a plant which separates combustibles from the solid waste stream, shreds that fraction, and then compacts it with a pellet mill (Herrman, 1978). Ten tons per day are sold to a paper mill in Spring Grove, Pennsylvania, where the pellets are mixed with bark, ground in a hog mill, and blown into a boiler. A full-scale burn test program is now underway. Contracts with a utility and cement company are pending confirmation of performance.

A unique, noncompacting process has been recently developed by A.D. Little and Combustion Equipment Corporation (Beningson, 1975). This process produces a dense powder called Ecofuel II from separated municipal waste. Shredded, classified waste is ball milled under a chemical embrittling agent such as hydrochloric or sulfuric acid. The resulting powder has been successfully suspension-fired in boilers; it has an average particle size of 0.25 mm, a bulk density of 0.65-0.82 g/cm<sup>3</sup>, and a specific gravity of well over 1.0. The process is aided by some hydrolysis and weakening of the cell wall, permitting collapse and release of air.

### III. PROPERTIES AND PERFORMANCE OF DBF

The pellets or other forms of DBF generally have a moisture content of 5% to 10% and a bulk density of 0.5-0.8 g/cm<sup>3</sup>. The heat of combustion of "Woodex" pellets made from Douglas Fir bark by the Bio-Solar Corp. is 18.6 kJ/g (16 MBtu/ton) (Armstrong). The density is 1.0 g/cm<sup>3</sup>. Densified biomass formed from other feedstocks should have similar characteristics except for fuel derived from municipal waste, which may have a much higher ash content. Samples of densified municipal refuse, tested at the National Center for Resource Recovery, had a moisture content of 20%, ash content of 27%, density of 1.1 g/cm<sup>3</sup>, and heating value of 14.0 kJ/g (NCRR, 1977).

Depending on the degree of compaction and the material compacted, densified biomass may have a water-repellent skin. However, exposure to water should be avoided during storage, particularly if the DBF has a high paper content. Because compacted fuels have a low moisture content, they biodegrade slowly and can be stored for long periods if kept dry.

Biomass pellets make a satisfactory fuel for fixed grate boilers, either in supplement to or replacement of coal. In June 1977, the National Center for Resource Recovery began a series of tests, co-firing a densified fuel derived from municipal refuse in two 60,000 lb/hr boilers (NCRR, 1977). Sulfur dioxide emissions dropped from 1,500 to 250 ppm, NO<sub>x</sub> emissions were not affected, and chloride emissions increased from 40 ppm to 630 ppm, when densified refuse was substituted for coal. The high chloride emissions in municipal waste are due to plastics; the chloride content of agricultural or forestry products is low.

#### IV. ENERGY BALANCE FOR BIOMASS DENSIFICATION

The energy required for densification will depend on the moisture content, size and type of the feedstock, pellet size, equipment used, etc. Approximate energy requirements and feed rates for several kinds of biomass in a 300 hp pellet mill have been supplied by California Pellet Mill (CPM) and are listed in Table 5. The energy required for densification is 1% to 3% of that contained in the feedstock, but biomass often occurs in a form that is too wet and too large for pelleting so more energy must be expended for drying and comminution. Drying is a major energy sink but one that is justified because it greatly increases the capacity of the combustion equipment, improves the efficiency of heat transfer, and reduces emissions (Arola, 1976).

A complete energy balance for a 300 tons/day Woodex densification plant is shown in Table 6. The energy content of the biomass at varying moisture contents is taken from Appendix A, and the electrical energy consumption is derived from the thermal energy necessary to generate power. Again, the densification step alone requires very little energy, but the overall process requires about 7% of the energy contained in the initial feedstock. The energy required for drying appears explicitly as a major process energy in the densification energy balance. However, the larger fraction of this loss, which is the theoretical energy required to vaporize water, does not appear in the total energy balance because the heating value of the wet feedstock must be derated by this figure (see the discussion in Appendix B). Thus, we have the apparent paradox that 16% of the pellets produced could be required for drying and yet the overall process efficiency is 93%. This paradox is resolved because about two-thirds of the energy used for drying is recaptured in the product's increased heat of combustion. (Other sources of heat for drying, such as waste combustion heat, can be used.)

TABLE 5  
ENERGY REQUIRED FOR PELLETING (300 hp Pellet Mill)

| <u>Feedstock</u>               | <u>Production Rate</u><br>metric tons/hr<br>(tons/hr) | <u>Electrical<br/>Energy Used</u><br>kWh/metric ton<br>(kWh/ton) | <u>Fraction<br/>of Product<br/>Energy<br/>Consumed</u><br>(%) |
|--------------------------------|-------------------------------------------------------|------------------------------------------------------------------|---------------------------------------------------------------|
| Sawdust                        | 6.1<br>(6.7)                                          | 36.8<br>(33.5)                                                   | 2.3                                                           |
| Aspen wood                     | 8.2<br>(9.0)                                          | 27.2<br>(24.8)                                                   | 1.7                                                           |
| Douglas Fir bark               | 4.5<br>(5.0)                                          | 49.2<br>(44.7)                                                   | 3.1                                                           |
| Municipal Solid<br>Waste (MSW) | 9.1<br>(10.0)                                         | 16.4<br>(14.9)                                                   | 1.0                                                           |

Notes:

- (1) 11.6 kJ (11,000 Btu) thermal/kWh.
- (2) The pelleting of MSW is volume limited in 300 hp mill due to low density of feedstock - uses 200 hp.
- (3) The figures in this table are only representative; values are highly dependent on feed size, moisture content, etc.

Source: Data supplied by California Pellet Mill.

TABLE 6  
DAILY ENERGY BALANCE FOR 300 TON/DAY BARK PELLET PLANT

|                                                                             | <u>GJ</u>  | <u>MBtu</u> |
|-----------------------------------------------------------------------------|------------|-------------|
| Feedstock Input Energy: 540 tons wet bark<br>(50% moisture @7.91 MBtu/ton)  | 4,502      | 4,272       |
| Process Energy Requirement                                                  | <u>GJ</u>  | <u>MBtu</u> |
| Pulverizing: 6 Hammer mills,<br>50 hp ea.                                   | 62         | 59          |
| Drying: Evaporation of 203<br>tons of water                                 | 755        | 716         |
| Dryer motors, 50 hp                                                         | 10         | 10          |
| Pelleting: (337 tons bark<br>@20% moisture)<br>2 Pellet mills,<br>600 hp    | <u>124</u> | <u>118</u>  |
| Total Process Energy Requirements                                           | <u>951</u> | <u>902</u>  |
| Total Energy Input<br>(process requirements plus feedstock<br>energy input) | 5,453      | 5,175       |
| Product Energy: 300 tons @10% moisture                                      | 5,059      | 4,800       |
| Process Energy Efficiency                                                   | 92.8%      |             |

Notes:

- (1) Values for biomass energy content derived from Table B-1.
- (2) Rotary dryer requires 3.16 J/g (3.00 MBtu/ton) to remove water. Because it is coupled to a gasifier operating at 85% efficiency, however, the total drying energy cost is 3.71 kJ/g (3.52 Btu/ton). The gasifier would probably be fired with product pellets, consuming 47 tons/day or 16% of the DBF product. All electric power assumes 11.6 kJ/kWh (11,000 Btu/kWh) thermal. Power for remaining plant operations is assumed to be insignificant.
- (3) Energy Efficiency = Product Energy/Energy Inputs (calculated with the low heating value of wet bark).

Source: Data based in part on figures quoted by Woodex Corporation and on observation of the 150 ton/day Woodex plant in Brownsville, Oregon.



## V. ECONOMICS OF BIOMASS DENSIFICATION

The economics of using biomass for fuel vary dramatically from region to region, time to time. For that reason, the results shown in Tables 7 and 8 should be used only as gross indications of the relative competitiveness of DBF with other fuels.

Using the required revenue method (ERDA, 1976), which addresses the direct costs of purchasing, installing, and operating a system, we derived the minimum energy price necessary to recover the cost of converting biomass into pellets. A major limitation with this method of analysis is that it looks at economics from the perspective of the firm, ignoring other direct costs and benefits which may accrue to state and local jurisdictions in the form of tax revenues and employment.

Cost data used in Table 7 are based on the Woodex process of the Bio-Solar Corp.; financial data are based on lumber and paper industry averages. The 300 ton-per-day Woodex plant in Brownsville, Oregon, cost about \$1.25 million, including the cost of classifying, feeding, and cooling equipment; hammer mills; dryers; pellet mills; and storage. The estimated breakeven selling price (BESP) from Table 7 is \$19.70/ton (\$1.20/MBtu). Bio-Solar sells pellets to Western State Hospital near Tacoma, Washington, for \$22/ton f.o.b. plant (May 1978). Figure 4 is a sensitivity analysis of BESP to feedstock cost and capital investment. Feedstock cost has a strong influence on BESP, but doubling the capital investment increases BESP by only 5% to 12%, depending on feedstock cost.

At the lower feedstock costs, DBF is competitive with utility coal in regions where the f.o.b. mine price is as high as \$1.65/MBtu (DOE, 1977). Industrial and commercial users, purchasing coal in smaller quantities, pay even higher prices. Pollution control

TABLE 7

CASE STUDY COST ANALYSIS OF PELLETING  
SILVICULTURAL WASTES (300 ton/day plant)

|                                          |                             |
|------------------------------------------|-----------------------------|
| Annual Feedstock Cost                    | \$ 640,000                  |
| Total Capital Investment                 | \$1,250,000                 |
| Annual Operating and<br>Maintenance Cost | <u>\$ 640,000</u>           |
| Break-Even Selling Price<br>of Pellets   | \$19.70/Ton<br>\$ 1.20/MBtu |

## Notes:

- (1) Feedstock cost of \$6.50/ton (300 ton/day), capital cost of \$1.25 million, and operating and maintenance cost of \$6.50/dry ton.
- (2) DBF heat value of 18.6 kJ/g (8,000 Btu/lb).
- (3) Capacity factor of 0.92, 30-year plant life, construction begins 1978, and the first year of operation is 1980.
- (4) Financial assumptions: 0.35 effective tax rate; ratio of debt to total capitalization, 0.32; ratio of common stock to total capitalization, 0.58; ratio of preferred stock to total capitalization, 0.10; internal rate of return 0.14.
- (5) General economic assumptions: general rate of inflation, 0.05; growth rate for capital costs, 0.05; escalation rate for operating and maintenance costs, 0.06; escalation rate for fuel costs, 0.02.

Source: Gunnerman, R. and Breithaupt, personal communications, November 1977 and February 1978.

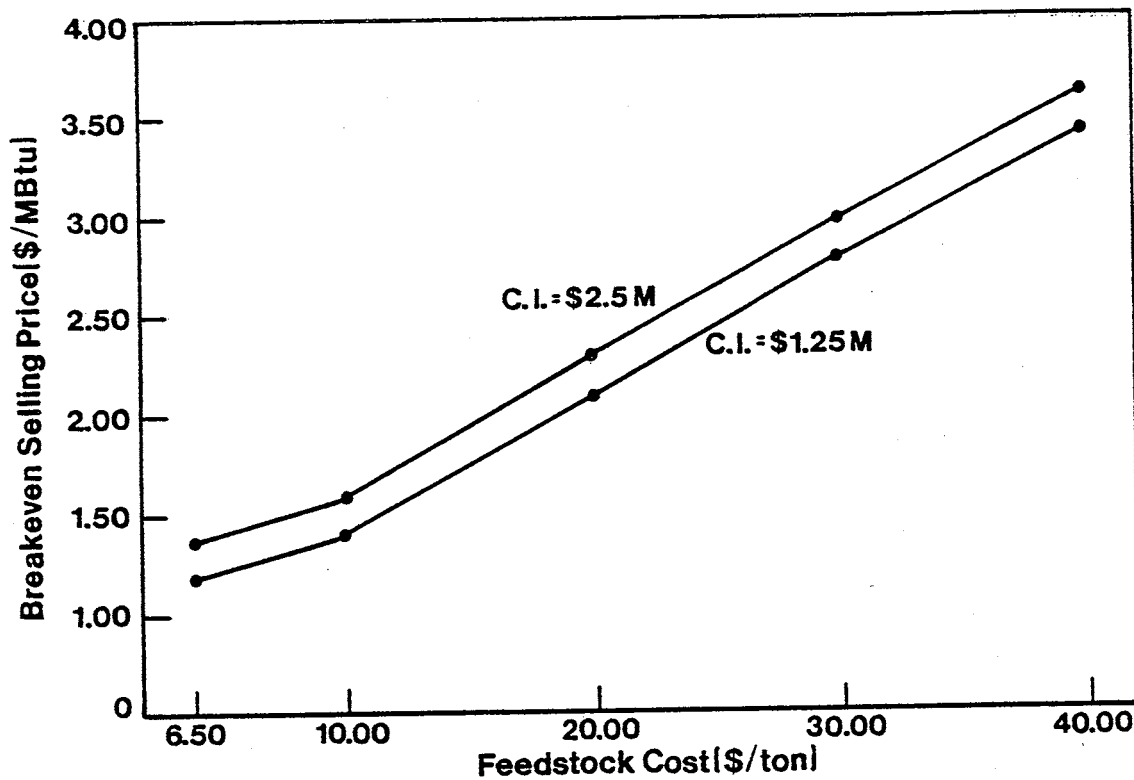


Figure 4. Sensitivity of Break-Even Selling Price to Feedstock Cost and Capital Investment

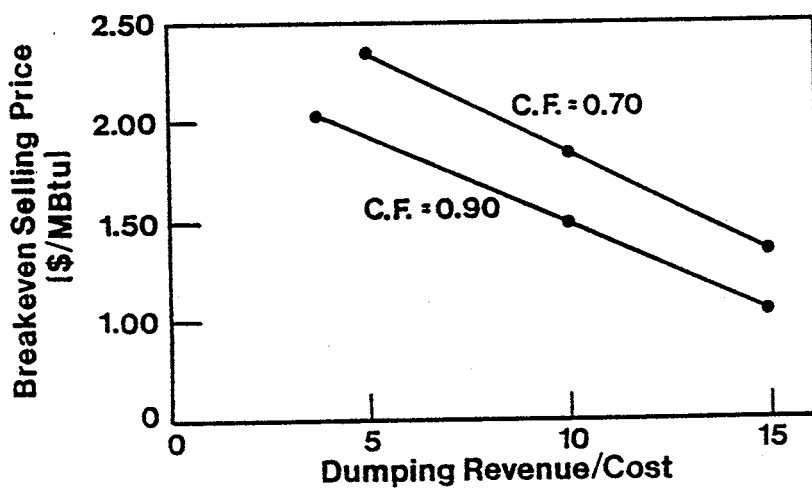


Figure 5. Sensitivity of Break-Even Selling Price to Dumping Cost and Capacity Factor

costs are another inducement for using DBF instead of coal; low sulfur DBF used in supplement to or replacement of coal reduces or eliminates the need for sulfur control equipment.

Whether or not it is practical and economic to pellet biomass when users have the option of directly composting green biomass with only milling as required preparations is a complex issue not resolved in this report. The Woodex process of milling, drying, and pelleting adds \$0.80/MBtu to the feedstock cost. Savings that result from this additional processing accrue because DBF has a higher density and lower moisture content than green biomass. Converting green biomass into pellets, cubes, briquettes, or rolls increases the number of Btus that can be transported, stored, or handled at a constant cost per unit of weight or volume. Furthermore, moisture content is a key economic factor in residue combustion systems. The lower the moisture content of the fuel, the higher the combustion efficiency of the boiler, a correlation which translates directly into fuel savings, capital investment savings because of reduced capacity requirements, and emissions control savings (USFS, 1976).

Table 8 is an analysis of the production cost of pelleted refuse-derived fuel. The front-end separation and materials recovery costs are based on the Horner and Shifrin Company's experience in St. Louis. The pelleting costs are based on California Pellet Mill equipment: \$100,000 for a 300 hp mill plus auxiliary classifying, feeding, and cooling equipment. The estimated final cost of pelletized, refuse-derived fuel, is \$21.60 per ton or \$1.80 per MBtu. According to the sensitivity analysis indicated by Figure 5, the cost of densified, refuse-deriving fuel is highly dependent on local dumping costs. Tripling the dumping revenue/cost from \$5 to \$15 decreases the breakeven selling price by nearly one-half. Furthermore, if the capacity factor is increased from 0.70 to 0.90, then price decreases from 13% to 24%, depending on dumping cost/revenue.

TABLE 8

CASE STUDY COST ANALYSIS OF DENSIFIED,  
REFUSE-DERIVED FUEL (300 ton/day)

|                                                                                   | <u>Expense</u>    | <u>Revenue</u>               |
|-----------------------------------------------------------------------------------|-------------------|------------------------------|
| Annual Dumping Revenue <sup>(2,4)</sup>                                           |                   | \$1,270,000                  |
| Capital Investment in<br>Front-end Separation and<br>Materials Recovery Equipment | \$7,446,000       |                              |
| Annual Front-End Operating<br>and Maintenance                                     | \$1,142,000       |                              |
| Annual Metal Recovery<br>Revenue                                                  |                   | \$1,450,000                  |
| Annual Dumping Costs <sup>(2,4)</sup>                                             | \$ 356,000        |                              |
| Capital Investment in<br>Pelletizing Equipment                                    | \$ 200,000        |                              |
| Annual Pelletizing Operating<br>and Maintenance Cost                              | <u>\$ 486,000</u> |                              |
| Break-Even Selling Price of Pellets                                               |                   | \$ 21.60/ton<br>\$ 1.80/MBtu |

## Notes:

- (1) Plant has a 30-year life; capacity factor is 0.70; construction begins in 1979, operation in 1982.
- (2) Dumping revenue or cost is \$10/ton.
- (3) Front-end separation and materials recovery capital cost of \$14,600/ton of capacity, operating cost of \$9/ton (from Schulz, 1975, but updated to 1978, assuming 12% annual inflation); aluminum priced at \$1,000/ton and scrap steel and iron at \$70/ton.
- (4) Twenty-eight percent of the waste stream is noncombustible; 6.3% of the waste stream is scrap iron and steel, 0.7% is scrap aluminum; 65% of the waste stream is combustible with a 20% moisture content; the densified product has a 10% moisture content and a fuel value of 12 MBtu/ton.

TABLE 8 (Continued)

- (5) Pelleting capital cost of \$200,000 for two 300 hp mills (MacDaniel, 1977) and operating and maintenance cost of \$6.50/ton (Gunnerman, 1977).
- (6) The plant accepts 510 tons of municipal refuse per day. Of that total, 330 tons of combustibles becomes feedstock for the pelleting operation, which produces 300 tons per day of densified, refuse-derived fuel.
- (7) See the financial and general economic assumptions (Notes 4 and 5) from Table 7.

Sources:

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## VI. APPLICATIONS OF DENSIFIED BIOMASS FUELS

Densified biomass fuel has several of coal's more desirable characteristics; it has a high energy content per unit of weight and volume and is convenient to transport, store, and combust. While DBF does not share two additional advantages of coal--concentrated sources of supply and an established industrial infrastructure--neither does it share many of coal's liabilities: sulfur emissions, strip-mining, ash disposal, and black lung disease. Although any economic and market analysis of DBF vs. coal is highly site and time sensitive, it appears that DBF may have an economic advantage over coal in regions with abundant biomass but no coal and that DBF may be preferable to coal for industrial or utility processes where sulfur abatement is required. Thus, DBF can be thought of as an approximate substitute for coal and may be used in most applications where coal is used and in a few applications where coal cannot be used.

The technology for burning DBF in supplement to or replacement of coal is well developed. Suspension and spreader stoker coal firing systems can burn DBF with little or no modification (Fernandes, 1978). Boilers specifically designed to burn wood--fluidized bed combustors, small firetube boilers, bark burning boilers, and vortex combustors--have multi-fuel firing capability and are commercially available today in a wide range of capacities. Direct combustion of DBF yields steam, process heat, or, if coupled to a turbine/generator, electricity. The 24 ton-per-day Taiga Industries Unit and the 300 ton-per-day California Pellet Mill are capable of fueling 3.7 MW<sub>e</sub> and 47 MW<sub>e</sub> of base load electric generating capacity, which is sufficient for the electric needs of 2,200 and 28,000 people.\*

---

\*Assuming 40% efficiency, 0.5 plant factor, 18.6 kJ/g, and an average per capital energy consumption of 7,400 kWh/yr. Calculating on the basis of average per capita residential energy consumption, the two units would support 7,200 and 92,000 residential customers.

It is neither practical nor economical to substitute coal or DBF in existing gas and oil boilers (Fernandes, 1978). DBF, however, is an attractive feedstock for low- to medium-Btu gasification; the product gas can be used to produce process heat and to fuel existing gas and oil installations with only minor engineering modifications. The Woodex process employs a gasifier to convert 15.0% of total pellet production into a fuel gas which is then fired in a kiln dryer to dry the biomass feedstock. Because gasifiers perform best on a uniform, dense, and clean feedstock, DBF may be preferable to coal or green biomass.

Other potential uses of DBF are:

- fueling residential, commercial, or industrial central heating systems;
- fueling airtight wood stoves;
- firing external combustion engines, such as the advanced Brayton and Stirling engines now under development for automotive and solar thermal-electric applications;
- fueling fireplaces and outdoor grills;
- producing pyrolysis oil and high-density charcoal.



## VII. SUMMARY

The process of densifying biomass shows promise of providing a dry, uniform, easily stored, and conveniently shipped fuel from the wide variety of residues produced in agriculture, forestry, and food processing. Compared to coal, densified biomass is clean, easy to handle, and burns with low ash and sulfur emissions. The process of densification consumes about 7% of the energy in the feedstock. The break-even cost of densifying wood is \$1.20 to \$3.40/MBtu, depending on the feedstock cost. Widespread use of densification could generate a commodity fuel market capable of supplying both small and large fuel users from the residential heating market to utility applications. Pellets are suitable for conversion to low- or medium-Btu gas for heat, power, or chemical synthesis.

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APPENDIX A  
CONVERSION FACTORS

The data in this paper are presented in SI metric units with English units in parentheses to communicate with the widest possible audience. The following tabulation provides useful conversion factors between metric and English.

| <u>From</u>        | <u>To</u>          | <u>Multiply by</u>       |
|--------------------|--------------------|--------------------------|
| g/cm <sup>3</sup>  | lb/ft <sup>3</sup> | 62.4                     |
| kJ                 | kcal               | 0.239                    |
| kJ                 | Btu                | 0.949                    |
| kJ/g               | Btu/lb             | 430.0                    |
| kJ/g               | MBtu/ton           | 0.860                    |
| kW                 | horsepower         | 1.341                    |
| lb/ft <sup>3</sup> | g/cm <sup>3</sup>  | 0.016                    |
| kcal               | kJ                 | 4.18                     |
| Btu                | kJ                 | 1.054                    |
| Quad               | kJ                 | 1.054 x 10 <sup>15</sup> |
| Btu/lb             | kJ/g               | 2.32                     |
| MBtu/ton           | kJ/g               | 1.16                     |
| Horsepower         | kW                 | 0.75                     |



APPENDIX B  
ENERGY CONTENT OF BIOMASS

Regardless of its source, the energy content of oven dry biomass is remarkably constant, ranging from 19 to 21 kJ/g (16-18 MBtu/ton) as shown in Table B-1. (Exceptions are municipal waste which has a lower heat value due to its high inorganic content and biomass with a high oil or resin content, such as soybeans or guayule, which have a higher than average heat value.) Because of these variations, we have chosen a value of 20.9 kJ/g for oven dry biomass or 18.6 kJ/g (16.0 MBtu/ton) for biomass containing 10% moisture, a more realistic basis for evaluating "normally dry" biomass.

The energy content of biomass is frequently stated as a function of wet weight or dry weight, varying moisture contents, and high heating value or low heating value. The following discussion is designed to minimize the reader's confusion when confronted with these different bases for comparing energy content.

Water Content--Wet vs. Dry Basis

Two systems are used to evaluate the water content of biomass: the "wet basis" and the "dry basis." If a quantity of biomass ( $m_d + m_w$ ) contains a weight ( $m_d$ ) of dry biomass and ( $m_w$ ) of water, the fractional water content, wet basis is:

$$X = m_w / (m_d + m_w) \quad (1)$$

and the percentage water content is 100 X on a wet basis. This same biomass is said to have a fractional water content of:

TABLE B-1  
ENERGY CONTENT OF BIOMASS AND OTHER FUELS

| <u>Biomass Fuel</u> | Oven Dry<br>Q*<br>(kJ/g) | 10% Moisture<br>Q (0.1)<br>(kJ/g) | 50% Moisture<br>Q (0.5)<br>(kJ/g) |
|---------------------|--------------------------|-----------------------------------|-----------------------------------|
| Bagasse             | 19.6                     | 17.4                              | 8.6                               |
| Coconut Shells      | 20.6                     | 18.3                              | 9.1                               |
| Beech               | 20.4                     | 18.1                              | 9.0                               |
| Birch               | 20.4                     | 18.1                              | 9.0                               |
| Pine                | 21.2                     | 18.8                              | 9.4                               |
| Oak                 | 19.6                     | 17.3                              | 8.5                               |
| Oak Bark            | 20.5                     | 18.2                              | 9.0                               |
| Pelletized Fuel**   | 20.5                     | 18.2                              | 9.0                               |
| Typical Value       | 20.9                     | 18.6                              | 9.2                               |
| Charcoal            | 31.8                     | 28.3                              | 16.1                              |
| Crude Oil           | 48.1                     | --                                | --                                |

\*Q is the low or net heating value of oven-dry biomass

\*\*See Armstrong.

Source: Data from Handbook of Chemistry and Physics, 33rd Edition,  
Chemical Rubber Publishing Company, Cleveland, Ohio,  
1951, p. 1595.

$$X' = m_w/m_d \quad (2)$$

or a percentage water content of  $100X'$ ; dry basis. These two bases for determining water content are related by the following equations:

$$X' = X/(1-X) \quad (3)$$

$$X = X'/(1 + X') \quad (4)$$

For example, when wood is first cut, it is about 50% water ( $X = 0.5$ ), wet basis but 100% water ( $X' = 1.0$ ), dry basis. When biomass is oven dry,  $X = X' = 0$ .

In calculating combustion performance, the wet basis is commonly used; and that practice was followed in this paper.

#### Energy Content--High vs. Low

The energy content of biomass (heat of combustion) is usually determined by use of a bomb calorimeter, which measures the energy change for combustion to gaseous carbon dioxide and liquid water. This gives the "high" or "gross" heating value of the biomass ( $Q'$ ), including energy recovered from the condensation of the water; but the 2.45 kJ/g (1,050 Btu/lb) required to vaporize water is not recovered in combustion processes. Therefore, in combustion calculations the "low" or "net" heating value ( $Q$ ) is used. The low heating value ( $Q$ ) can be derived from the high heating value ( $Q'$ ) by:

$$Q = Q' - 0.2122 H \quad (5)$$



where H is the percentage of hydrogen by weight and all figures are in kJ/g. Thus, the sample of Woodex pellets tested by the National Bureau of Standards has a hydrogen content of 5.8%,  $Q' = 20.62$  kJ/g and  $Q = 19.39$  kJ/g, a 6.3% difference between the high and low heating values.

#### Energy Content vs. Water Content

Most biomass contains significant quantities of moisture which greatly decrease the energy release in combustion processes for two reasons: (1) the volatile biomass is only  $(1 - X)$  and (2) the fraction  $(X)$  of water must be evaporated. The available energy in biomass, containing a fraction,  $(X)$  of water is:

$$Q(X) = (1 - X)Q - 2.45X \quad (6)$$

where  $Q$  is the low heat of combustion of the dry biomass,  $Q(X)$  is the low heat of combustion of the wet biomass, and all figures are in kJ/g. Representative values of  $Q$  for various biomass forms are shown in Table B-1 and the sensitivity of  $Q$  to  $X$  is shown in Figure B-1. It can be determined from Table B-1 and Figure B-1 that the presence of water in biomass greatly affects the energy content. Because of these practical and theoretical factors, it is becoming increasingly common to dry biomass before burning.

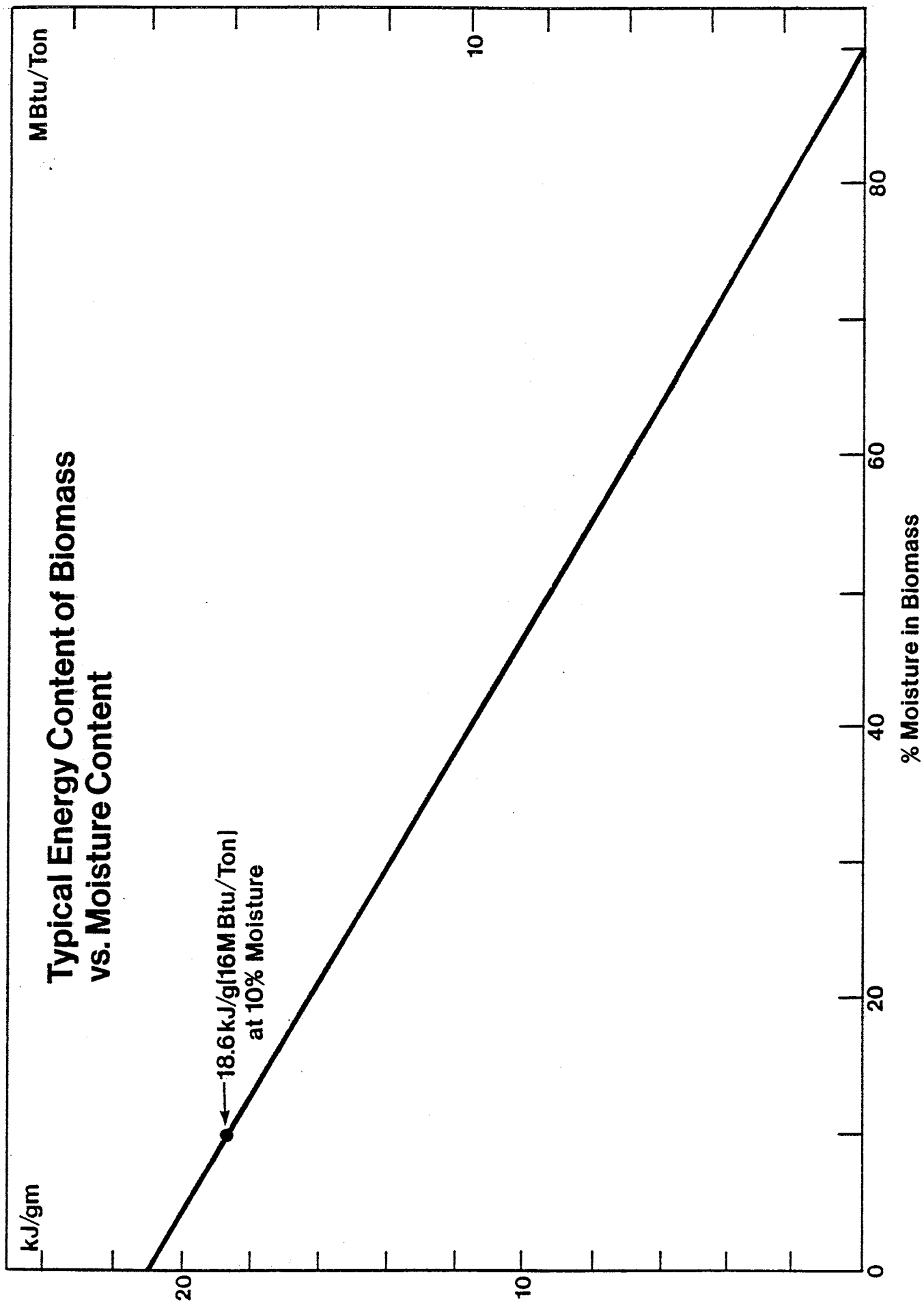


Figure B-1. Sensitivity of Energy Content to Moisture Content



BIOMASS DENSIFICATION  
ENERGY REQUIREMENTS

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## BIOMASS DENSIFICATION ENERGY REQUIREMENTS

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Biomass materials, especially residues, are in many ways an attractive renewable fuel. However, they suffer from low volume energy content and occur in a wide variety of forms unsuitable for fuel use. Densification of biomass to pellets, briquettes, logs, or dense powders yields clean, renewable fuels with energy densities comparable to coal.<sup>(1-4)</sup> Yet the cost and energy required for densification must be considered in deciding whether densification is practical in a given situation. A knowledge of the dependence of this energy on various operating parameters also will make possible design of better densification processes.

The purpose of this study was to determine the work required for densification under various laboratory conditions and to compare this to the energy consumed by practical operating equipment.

### Experimental Procedure

The apparatus used to study densification by compression is shown in Figure 1 (a). It consists of a steel die and piston 2.5 cm in diameter capable of being heated to various temperatures during pressing. The travel of the piston was measured as a function of applied pressure. Ten-gram samples of minus 10 mesh pine sawdust dried at 110 C were held at temperature for 15 min after initial cold compaction at 200 psi, and the pressure was then increased in 300-psi increments to 10,000 psi. The resulting densities are shown as a function of pressure in Figure 2 for temperatures from 100-225 C. Runs were made also at 250 and 300 C, but wood was heavily pyrolyzed in the process and the results were discarded.

Elemental and proximate analyses were run on the initial sawdust and a 225 C pellet and are shown in Table I. The energy contents of the sawdust and the resulting pellets are shown in Table II.

The experiment just described was designed to simulate the densification process by direct compression, a batch process. However, many commercial densification machines provide continuous extrusion of pellets. Sufficient pressure is built up to cause the material first to densify and then to flow through a constricting nozzle. The apparatus of Figure 1 (b) was designed to simulate this extrusion process. Twenty-gram samples

Table I. Analysis of Pine Sawdust and 225 C Pellet From Compression Experiments

| Experiments <sup>1</sup>                | Dry Sawdust <sup>2</sup> | 225 C Pellet |
|-----------------------------------------|--------------------------|--------------|
| <u>Proximate Analysis<sup>3</sup>-%</u> |                          |              |
| Ash                                     | 0.83                     | 0.99         |
| Volatile Matter                         | 83.19                    | 85.05        |
| Fixed Carbon                            | 15.98                    | 13.96        |
| Sulfur                                  | 0.06                     | 0.06         |
| <u>Ultimate Analysis-%</u>              |                          |              |
| Carbon                                  | 49.89                    | 52.09        |
| Hydrogen                                | 6.40                     | 6.28         |
| Oxygen                                  | 42.48                    | 40.36        |
| Nitrogen                                | 0.36                     | 0.22         |
| Chlorine                                | —                        | —            |
| Sulfur                                  | 0.05                     | 0.06         |
| Ash                                     | 0.86                     | 0.99         |
| Heating Value - kJ/g                    | 19.3                     | 21.4         |
| Btu/lb                                  | 8290.0                   | 9200.0       |

<sup>1</sup> Analysis and heats of combustion by Hazen Assoc., Golden, Colo.

<sup>2</sup> Average of 3 runs.

<sup>3</sup> The C, H, O correspond to an elemental formula  $\text{CH}_{1.57} \text{O}_{0.65}$  for sawdust and  $\text{CH}_{1.32} \text{O}_{0.58}$  for the 225 C pellet.

Table II. Heats of Combustion of Pine Sawdust and Pellets Made at Various Temperatures at 10,000 psi Pressure

| Form         | Temp.<br>°C | Density<br>g/cm <sup>3</sup> | Weight<br>Remaining<br>% | Energy Content |        |
|--------------|-------------|------------------------------|--------------------------|----------------|--------|
|              |             |                              |                          | kJ/g           | Btu/lb |
| Pine sawdust | —           | —                            | 100.0                    | 19.3           | 8290   |
| Pellets      | 100         | 1.278                        | 99.3                     | —              | —      |
| Pellets      | 150         | 1.340                        | 97.6                     | 19.6           | 8420   |
| Pellets      | 175         | 1.374                        | 96.5                     | 19.6           | 8440   |
| Pellets      | 200         | 1.422                        | 95.6                     | 19.6           | 8450   |
| Pellets      | 225         | 1.435                        | 91.2                     | 21.4           | 9200   |
| Pellets      | 250         | 1.316                        | 71.2                     | 23.0           | 9890   |

of screened solid municipal waste (SMW) were loaded into the container and heated to the desired temperature for 15 min. Pellets were then extruded at a rate of 5, 10, or 20 cm/min and the pressure was recorded as a function of deflection. The deflection versus pressure is shown in Figure 4 for four temperatures and in Figure 5 for three rates of extrusion at room temperature. The resulting pellets were well formed, especially those made at higher temperatures, and had a density of about 1.0 g/cm<sup>3</sup>.

The work done during densification is given for both processes by:

$$W = A \int_0^x P \, dx = A \int_0^x P \, dx \quad (1)$$

where  $P$  is the applied pressure,  $x$  is the sample thickness, and  $A$  is the cross sectional area of the die and piston. In the compression apparatus of Figure 1 (a) the density at each point was calculated from:

$$P = m/xA \quad (2)$$

where  $m$  is the sample mass. The work of compression is shown as a function of density, calculated from these equations, in Figure 3. The total work of extrusion was obtained by integrating the curves of Figures 4 and 5 and is shown in Table III.

Table III. Work of Extrusion of RDF<sup>1</sup>

|                                   | Energy    |         |
|-----------------------------------|-----------|---------|
|                                   | kWh/tonne | kWh/ton |
| <u>Temperature<sup>2</sup></u>    |           |         |
| °C                                |           |         |
| 25                                | 7.76      | 7.06    |
| 93                                | 6.09      | 5.54    |
| 149                               | 6.23      | 5.67    |
| 204                               | 4.45      | 4.05    |
| <u>Extrusion Rate<sup>3</sup></u> |           |         |
| cm/min                            |           |         |
| 5                                 | 7.76      | 7.06    |
| 10                                | 10.93     | 9.95    |
| 20                                | 10.90     | 9.92    |

<sup>1</sup>From integration of Figure 5.

<sup>2</sup>Extrusion rate 5 cm (2 in.)/min.

<sup>3</sup>At 25 C.



## Discussion of Results

Three basic types of pressure application are used in commercial densification processes: (1) Straight compression in a die; (2) Extrusion through a constriction; and (3) Shear of precompacted material to produce heat and flow under pressure. Approximate energy consumptions supplied by the manufacturers are compared to the laboratory tests reported here in Table IV but it must be stressed that these figures are only approximate, depending critically on type of material, size, temperature, etc.

**Table IV. Comparison of Reported Energy Requirements For Commercial Densification Apparatus with Laboratory Results**

|                            | Material | Density | Work      |         |
|----------------------------|----------|---------|-----------|---------|
|                            |          |         | kWh/tonne | kWh/ton |
| <u>Compression</u>         |          |         |           |         |
| In Laboratory <sup>1</sup> | Sawdust  | 1.0     | 4.0       | 3.6     |
|                            | Sawdust  | 1.2     | 6.6       | 6.0     |
| Commercial <sup>2</sup>    | Sawdust  | ~1.2    | 37.4      | 34.0    |
| <u>Extrusion</u>           |          |         |           |         |
| In Laboratory <sup>3</sup> | MSW      | 1.0     | 7.76      | 7.06    |
| Commercial <sup>4</sup>    | MSW      | 1.0     | 16.4      | 14.9    |
|                            | Sawdust  | 1.0     | 36.8      | 33.5    |

<sup>1</sup>This study, 2.5 cm pellet, Figure 1 (a) at 100 C and Figure 3.

<sup>2</sup>From specifications of 150 hp Hausmann briquetor No. FH 2/90/200 for 8 cm diameter log.

<sup>3</sup>This study, 1.2 cm pellet made at 25 C, 5 cm/min, Figure 1 (b) and Table III.

<sup>4</sup>From Ref. 1, data supplied by California Pellet Mill Corp.

The work of compression measured in this study is seen to be lower by a factor of two to ten than that consumed in operating compression machines. This is to be expected because the work measured here does not include motor and bearing losses associated with commercial equipment, and the measurements were made under idealized conditions. Given these differences, the agreement is satisfactory and the laboratory results probably represent a lower limit to the work required.

An important result of this study is the finding that the work and pressure of compression or extrusion can be reduced by a factor of about two by preheating the feedstock to 200-225 C before densification. This requires extra thermal energy for complete drying and to heat the biomass (heat capacity about 1.8 J/g-C) to the higher temperature; however, these are offset by lower electrical power costs, lower equipment costs because of the lower pressure requirements, possibly reduced die wear due to improved lubricity of the biomass at increased temperatures, and increased fuel value due to complete water removal and prepyrolysis. These factors must be tested at the commercial scale before any conclusions can be drawn on the desirability of preheating feedstock.

The analyses reported in Tables I and II show that the pellet made at 225 and 250 C had considerably higher energy contents than those made at lower temperatures. The energy content of the pellet made at 225 C is 20.2 J, essentially all of the energy in the sawdust from which it was made (91.2% of 21.4 J/g). This suggests that there is a "prepyrolysis" reaction for biomass, similar to that which occurs for lignite, in which  $\text{CO}_2$  and  $\text{H}_2\text{O}$  are driven off with little or no energy loss.

Many commercial densification machines use extrusion rather than straight compression, because extrusion can be adapted to continuous rather than batch processing. An examination of Figures 4 and 5 suggests that there is an initial stage in which the feedstock is compressed to a pressure sufficient to overcome the static friction at the throat. At this point the pressure drops slightly to a value necessary to overcome the sliding friction encountered as the biomass passes through the constriction. The data of Figure 4 and Table I clearly show the same trends observed in Figures 2 and 3—that the work of densification drops by a factor of about two as the feedstock is preheated to 200 C.

Although the data are not directly comparable because they were taken on different feedstocks, it seems clear that the work required for compression is less than the work required for extrusion. In commercial equipment, the friction involved in extrusion performs a useful function—the heating and drying of the pellets.

Although the data in Figure 5 and Table I suggest that the work of extrusion increases with increasing rates, the effect is small here. Other data taken in pilot plant and commercial operation generally show a dramatic decrease of extrusion work with flowrate.

### Conclusions

- The pressure required for densification is reduced a factor of two by heating to 225 C.
- The energy required for both compression and extrusion is decreased by a factor of about two as temperature increases from room temperature to 225 C.
- The energy content of the pellets rises with temperature of densification.

- Energies measured for densification in the laboratory are comparable to but smaller than those required in commercial equipment.

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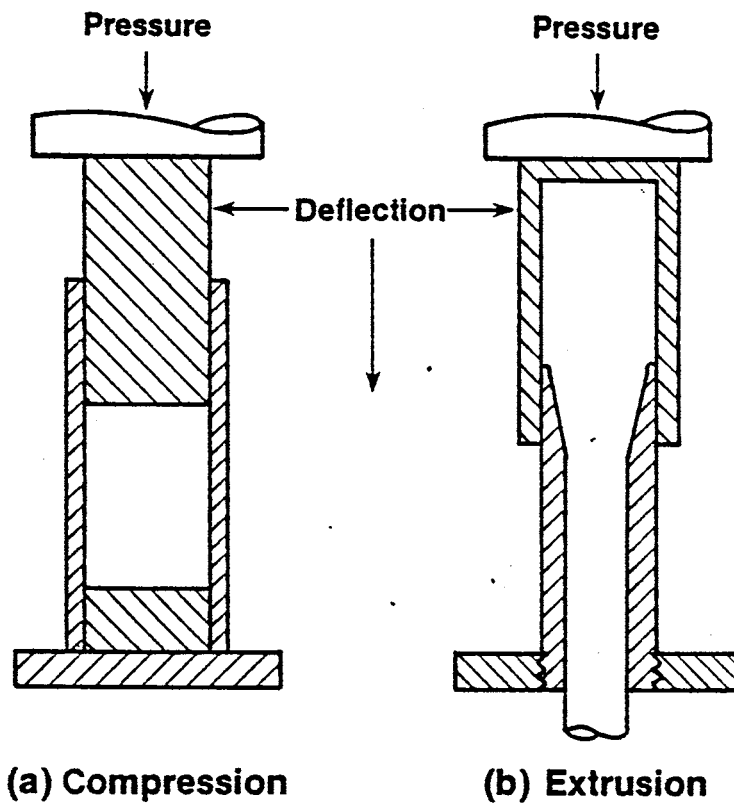


Figure 1.

## Densification Test Configurations

