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COMPACTING SOLID WASTE MATERIALS GENERATED IN MISSOURI TO FORM NEW PRODUCTS

Final Technical Report

By

Yadong Li and Yuyi Lin

Capsule Pipeline Research Center
College of Engineering
University of Missouri-Columbia
Columbia, Missouri 65211-2200

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ABSTRACT

The unique high-pressure compaction technology developed at Capsule Pipeline Research Center (CPRC) of University of Missouri-Columbia was used to study the compaction of combustible components of municipal solid waste and flyash generated from coal-fired power plants. By compaction, the combustible wastes can be turned into uniform, densified solids for use as fuel; the flyash can be turned into high-valued building elements such as bricks and blocks.

Many important aspects of the commercial production of the compacted products (densified fuel logs or building bricks) were studied, including the size reduction of the raw materials, the effects of compaction pressure, moisture content, particle size and shape of the materials, the storage and curing of the products, and crushing of the large fuel logs. The properties of the compacted fuel logs were evaluated in terms of physical, mechanical, and combustion characteristics. The logs were test-burned in a power plant boiler and a hot-water furnace. The compacted bricks from flyash were tested for compressive strength, modulus of rupture, freezing and thawing, and water absorption, for potential use as commercial bricks.

Economic analyses for using this compaction technology to produce fuel logs and bricks for anticipated future commercial operations were performed.

It was found that under optimized compaction conditions, all the combustible waste materials can be compacted into good-quality fuel logs with a dry density of 0.8 to 1.2 g/cm^3. The large logs (5.4-inch diameter) can be burned effectively in a stoker boiler when co-fired with coal. These logs are also an ideal fuel for some small-scale furnaces.

The bricks compacted from power plant flyash have higher compressive strength than ordinary commercial bricks, but lower resistance to freezing and thawing. They can be used in certain applications.

The production cost of fuel logs from solid waste, including a 15% above-inflation return on investment, was found to be between $5.5 and $8 per ton for plants having capacities between 675,000 and 135,000 tons per year. This compaction process appears to be more economical than other conventional densification processes, and it produces a denser and stronger fuel that is easier to transport, handle and store. Analysis of the production cost for flyash bricks showed that the cost would be less than 2 cents per brick if the capital cost for a plant with a capacity of 100,000 tons per year does not exceed 1 million dollars.

TABLE OF CONTENTS

PAGE

ABSTRACT iii

TABLE OF CONTENTS iv

CHAPTER 1: INTRODUCTION 1

CHAPTER 2: METHODOLOGY AND MATERIAL 2

2.1 Equipment 2

2.2 Materials 3

2.3 Methodology 5

2.3.1 Optimization of compaction conditions 5

2.3.2 Tests of log properties 5

2.3.3 Economic analysis 7

CHAPTER 3: RESULTS AND DISCUSSION 11

3.1 Compaction of MRS Low-grade Waste Paper 11

3.1.1 Effect of compaction pressure 11

3.1.2 Effect of moisture content 11

3.1.3 Effect of particle size 12

3.1.4 Long-term performance of the logs 12

3.2 Compaction of MU Campus Waste 12

3.2.1 Effect of compaction pressure 12

3.2.2 Effect of moisture content 13

3.2.3 Long-term performance of the logs 13

3.3 Compaction of City of Columbia Waste 13

3.3.1 Effect of pressure 14

3.3.2 Effect of moisture content 14

3.3.3 Long-term performance of the logs 14

3.4 Grinding of Waste Materials 14

3.5 Mass Production of Waste Paper Logs 15

3.6 Crushing of Large Logs 15

3.7 Test Burn of the Fuel Logs 16
3.7.1 Test burn in power plant boiler 16
3.7.2 Test burn in hot water furnace 17
3.8 Compaction of Flyash 17
3.8.1 Effect of flyash-to-water ratio 18
3.8.2 Effect of compaction pressure 18
3.8.3 Effect of curing conditions 19
3.8.4 Water permeability 21
3.8.5 Summary 22
3.9 Compaction of Flyash Bricks 22
3.9.1 Strength of the bricks 23
3.9.2 Water absorption of the bricks 24
3.9.3 Resistance to freezing and thawing 24
3.9.4 Compaction pressure effect 24
3.9.5 Mass production of flyash bricks for test use 25
3.10 Economics Analysis of Fuel Log Production 25
3.11 Economics Analysis of Production of Flyash Bricks 27
CHAPTER 4: CONCLUSIONS 29
REFERENCES 31
APPENDIX A: TABLES 32
APPENDIX B: FIGURES 47
APPENDIX C: PHOTOS 60
APPENDIX D: LETTERS OF IN-KIND CONTRIBUTIONS 80

CHAPTER 1. INTRODUCTION

The Capsule Pipeline Research Center (CPRC) at the University of Missouri-Columbia has developed a high-pressure, piston-in-mold (punch-in-die) compaction process during the past decade for coal log compaction. The same process and machine are capable of producing biomass logs as demonstrated in a research project funded by the U.S. Department of Energy [1]. The process is unique in that by using suitable moisture and a pressure higher than that used in pelletization and extrusion, by using a back-pressure during ejection of compacts from molds, and by using special mold exit shape, high-quality biomass logs can be produced without binder and without heat. Also, the product (logs) is much larger in size than pellets or briquettes and hence costs less to mass-produce.

The main objective of this project is to study both technical and economic feasibilities of compacting certain types of wastes in Missouri by the CPRC compaction technology to form upgraded fuel or building products. The targeted waste materials include low-grade waste paper, non-recycled plastics and textiles found in municipal solid waste (MSW) stream, and flyash from coal-fired power plants. Although some paper products (e.g., newsprint, office paper, magazines, and cardboard) and plastic products (e.g., PET (#1) bottles and HDPE (#2) jugs) have recycling market, there are still many types of paper and plastic products that have no market value and are being discarded. Photo 1-1 (refer to Appendix C) shows some examples of the paper and plastic products found in MSW. Except for the milk jug on the lower-right corner, all the rest have no market value and are being discarded. Through compaction, the paper, plastics and textiles can be turned into a densified fuel; the fly ash can be compacted into strong building block materials such as bricks or gardening ornamental blocks. The specific objectives of the project were: (1) to identify appropriate size-reduction method for shredding the waste materials including waste paper, plastics and textiles, (2) to find the optimum compaction conditions for the waste materials to be compacted; (3) to determine key properties of the compacted products, (4) to identify method for crushing the compacted logs into appropriately-sized particles for co-firing with coal in power plant, (5) to test-burn the fuel in power plant boiler and other types of furnaces, (6) to study the economics of producing fuel from combustible waste materials and producing building products from flyash; and (7) to investigate the potential market for the compacted products.

CHAPTER 2. METHODOLOGY AND MATERIALS

This chapter presents the equipment, materials, methodologies and procedures used in the study. The results are reported in CHAPTER 3. RESULTS AND DISCUSSION.

2.1 Equipment

Two compaction machines—a small one and a large one—were used in this study for compacting the waste materials. The small compaction machine consists of a hydraulic press (Baldwin Locomotive Works, Inc.), a cylindrical mold (die) with 1.91-inch (48.5-mm) inner diameter and 12-inch (300-mm) length, and an upper piston (punch) and a lower piston having a diameter slightly smaller than the inner diameter of the mold. Driven by the hydraulic press, both pistons move up and down in the mold to compress the biomass material fed into the mold. The maximum load of the hydraulic press is 30 tons (60,000 lbs). Therefore, the maximum compaction pressure that can be generated in the 1.91-mm-diameter mold is 20,940 psi (145 MPa). During operation, the material is fed from the top of the mold with the lower piston already in the mold. Then the upper piston is advanced into the mold and the compaction force is applied. The machine is also equipped with a computerized data acquisition system so that the pressure and displacement of the pistons can be monitored during compaction and ejection of the biomass log. This compaction machine is shown in Photo 2-1.

The large machine was designed by CPRC personnel (Dr. Yuyi Lin and his students) and manufactured in 1998 by Gundlach Machine Company in Illinois for coal log compaction. The machine is housed in the CPRC Field Station on the Holstein Farm of the University. This machine, as shown in Photo 2-2, uses a single mold with an upper and a lower piston, and a hydraulic press that can generate a maximum of 250 tons of force. The inner diameter of the mold is 5.4 inches (137 mm). Therefore, the maximum pressure that can be reached in the mold is 21,800 psi (150 MPa). This machine is highly automated by using a PLC (Programmable Logic Controller). The machine can perform either single-ended or double-ended compaction. The compaction speed is fast: the highest pressure can be reached in 3 seconds. This machine is also featured with a back-pressure control, which means during ejection of logs a controlled pressure can be maintained on the withdrawing piston, preventing tension to develop in the logs during ejection, and hence preventing cracks and capping.

For producing flyash bricks, a set of rectangular mold and piston was fabricated as shown in Photo 2-3. The mold has an inner cross-section area of 4 by 8 inches. This set of mold and piston can be used in place of the cylindrical mold for the above mentioned compaction machines to produce real-size bricks from flyash.

Two hammermills—a small one and a large one—were used for grinding the waste materials into feedstocks for compaction. The large hammermill as shown in Photo 2-4 is located in CPRC Field Station along with the large compaction machine. A screen with 2-inch holes is used for grinding the combustible solid waste in this study. The small hammermill as shown in Photo 2-5 has a screen of 8-mm holes. It was used to produce small-size feedstocks for the study of particle size effect.

Besides the equipment that CPRC owns, crushers and shredders of American Pulverizer Company and Gundlach Machine Company were used to perform grinding tests of the waste materials and crushing tests of the compacted fuel logs.

2.2 Materials

The waste materials tested in this study were categorized into the following five types:

(1) Low-grade waste paper. The mixed paper sorted out of the recyclable paper from MRS Recycling Service, Inc. in Jefferson City—the largest waste paper recycler in Missouri—was studied. It consists of envelops, packaging paper, brochures, copy paper, and folders, etc. According to the Manager of MRS Recycling Service, this type of paper has a very small market and a low sale price that can barely offset the baling cost.

(2) MU campus waste. University of Missouri-Columbia (MU) campus generates about 6,500 tons of solid waste a year. About 1,200 tons of the waste is being recycled by a joint effort of the university and a private recycling company (Civic Recycling of Columbia). The recycled materials from MU are mainly paper products including cardboard, newsprint, regular office paper, phone books, and magazines. The remainder (5,300 tons) of the waste is disposed of in the City of Columbia's landfill. This remainder still consists of 47% paper of which some non-recyclable paper products account for a large percentage. It includes junk mails, packaging, computer

paper, envelopes, tissue, towel, plates, and cups. The others products and fractions are: plastics 14%, metal 3.8%, glass 2.8%, and other miscellaneous 32%. Taking the combustible components —waste paper and plastics—in the discard waste as a whole, the waste paper accounts for 77% and the plastics account for 23%. This composition was used to prepare the feedstock for the compaction study. In the paper portion are office paper, newsprint, magazine, cardboard and those non-recyclable paper products mentioned above. Among the plastics, 28% are filmed products such as bags and 72% are hard products such as containers.

(3) City of Columbia waste. The City of Columbia currently dumps 68,900 tons of municipal solid waste (MSW) per year (including the 5,300 tons from MU). The main combustibles in the waste streams are paper (41%), plastics (18%), and textiles (4%) [2]. Taking these three components as a whole, paper accounts for 65%, plastics 28%, and textiles 7%. This composition was used for the compaction study of this type of waste.

(4) High-grade flyash. This flyash was obtained from Associated Electric Cooperative's Thomas Hill Power Plant in Missouri. This plant burns Powder River Basin (Wyoming) coal, which is a sub-bituminous coal containing little sulfur. The flyash generated is Class C flyash according to ASTM standard C-618. The high-grade flyash was collected from a pulverized-coal combustor. It has a very low LOI (loss on ignition) value of 0.03%, which represents the unburned coal content. The particles are fine and uniform–the fineness was measured to be 14.7% (the amount retained on a No. 325 (45-μm) sieve). The average density of the particles was measured to be 2.67 g/cm^3. It had a light brownish-gray color.

(5) Low-grade flyash. The low-grade flyash was also from Thomas Hill Power Plant, except that it was generated from a cyclone combustor. As compared to the high-grade one, the low-grade flyash had a higher unburned coal content (LOI=9.1%), coarser particles (fineness = 26.2%), and darker color (dark gray). The density of the particles was 2.60 g/cm^3.

2.3 Methodology

2.3.1 Optimization of compaction conditions

The compaction conditions of all the biomass materials were optimized through the examination of the effects of various factors as follows:

(1) Effect of compaction pressure. The compaction pressure means the ultimate peak pressure applied during the compaction process. For the compaction of the first three types of materials as mentioned in Section 2.2, four different pressures—5,000, 10,000, 15,000 and 20,000 psi—were used to examine the pressure effect. For the compaction of flyash, more pressures from 500 to 15,000 psi were used.

(2) Effect of moisture content. The effect of moisture content on the compaction of biomass logs was studied for all the different materials tested and the appropriate moisture range and the optimum moisture were determined for the compaction of each material.

(3) Effect of particle size. The effects of particle size on the properties of the compacted logs were studied mainly for waste paper. The different particle sizes were achieved by using different hammermills.

2.3.2 Tests of log properties

The quality of the biomass logs compacted was evaluated based on the following properties tested:

(1) Density. For the logs made of combustible waste materials, their changes of density with time and humidity of the environment were studied. The dry density was used to express this property of the logs. For compacted flyash logs or bricks, wet density was used.

(2) Impact resistance. The impact resistance of the logs was tested by adapting the ASTM Standard Method D 440 for drop test for coal. The logs were dropped twice from 2 ft height onto a concrete floor. Logs made of paper rarely broke during the drop tests. Therefore, percent weight loss after two drops was used to express or compare their impact resistance. However, logs made of other materials often break, and an impact resistance index (IRI) introduced by Richards [3] was used to evaluate

the impact resistance of such logs. The IRI is calculated from $IRI=(100\times N)/n$, where N is the number of drops, and n is the total number of pieces after N drops. Because two drops were used as standard, the number of drops N in the above equation is always 2, and maximum value of IRI is 200. Thus, the IRI for paper logs would be always 200 because the paper logs rarely broke in the drop test. It should be mentioned that some logs upon hitting the concrete floor broke into pieces of various sizes ranging from large pieces to fine particles. When the number of pieces was counted in a test, the small pieces that weigh less than 5% of the initial weight of the log was not included in the calculation of the IRI. After the first drop, all the pieces that weigh less than 5% of the original weight of the log were not collected and not used for the second drop.

(3) Abrasion resistance. The abrasion resistance of the logs was tested by using a procedure adapted from the ASTM Standard Method D 441 for tumbler test for coal. In this test, three logs with a diameter of 1.92 inch and length of approximately 1.5 inch were placed in a porcelain jar. The jar was rotated at 60 rpm for 40 minutes. The total number of revolutions during a test is approximately 2400. The weight of each log before and after tumbling was measured and the weight loss was calculated as an indicator of the abrasion resistance.

(4) Long-term performance. The long-term performance of logs compacted from combustible waste materials was observed by monitoring the changes of dimensions, density, moisture, impact resistance and abrasion resistance of the logs placed in open air in the laboratory.

(5) Compressive strength. The compressive strength of the flyash logs was tested according to ASTM Standard Method C 39.

(6) Permeability. The permeability of the compacted flyash products was tested by a pressurized permeameter, and the saturated hydraulic conductivity was determined according to Darcy's Law.

(7) Properties of flyash bricks. Certain key properties of the bricks compacted from flyash were tested according to ASTM Standard Method C 67 which is designed for testing bricks and structure clay tiles. The properties tested included compressive

strength, modulus of rupture, water absorption, and endurance to freeing and thawing.

2.3.3. Economic analysis

The cost analysis involves analyzing the biomass log fuel (BLF) production cost and flyash brick production cost. A cost model using a life-cycle analysis and a net-cash-flow approach was constructed for the calculation of the unit production cost. A brief description of the cost model is provided here. Results for different scenarios can be found in Section 3.10 and 3.11 of Chapter 3.

The life-cycle cost is performed over the estimated economic life of the system, N years. The net-cash-flow approach is used which considers all the revenues (incomes) of a project as positive cash flow, and all costs (expenditures) as negative cash flow. During the life cycle (economic life) of the system, each cash flow is treated as a discrete payment (outlay of cash). Costs paid at the beginning of the project are the initial costs, and those paid subsequently are treated as annual costs (outlays). For simplicity, it is assumed that all the capital costs are encumbered at the beginning of the project. So, the capital cost and initial cost are treated as the same thing. All annual costs are assumed to be paid at the end of each year—the end-of-year convention.

The unit price, U (i.e., the price charged to customers for manufacturing, or transporting, or power-plant handling each ton of biomass in **$/T**) is calculated based on the need to generate a certain above-inflation rate of return. To achieve this return rate, the after-tax cash flow equations for each year are first developed, treating the unit price as a variable with respect to time (years). These equations include the following:

The after-tax cash flow ($ATCF$) for any year n ($n = 1, 2, 3 \ldots N$) is:

$$ATCF_n = BTCF_n - T_n \tag{1}$$

where $BTCF_n$ is the before-tax cash flow for year n, and T_n is the corporate income tax that must be paid during year n.

The quantity $BTCF_n$ is determined from:

$$BTCF_n = R_n - C_n \tag{2}$$

where R_n is the revenue for year n, and C_n is the cost for year n.

The corporate income tax of year n, T_n, in Eq. 1 is calculated from

$$T_n = (BTCF_n - d_n)t \tag{3}$$

where d_n is the depreciation of year n which must be determined from the tax code, and t is the rate of corporate income tax, assumed to be 37% in this analysis. For simplicity, a "straight-line" or uniform depreciation over 20 years is used. Therefore,

$$d_n = d = \frac{C_c}{N_d} = \frac{C_c}{20} \tag{4}$$

where C_c is the capital cost, and N_d is the years of depreciation. The value of N_d must conform to government tax code. Note that when N_d (say, 20 years) is less than N (say, 30 years), Eq. 4 is valid only for the first N_d years. Thereafter, there will be no more depreciation and $d_n=0$ for the remaining years of the project's economic life.

Combining Eqs. 1, 2, and 3 yields

$$ATCF_n = (1-t)\,(R_n - C_n) + td_n \tag{5}$$

The present value of $ATCF_n$ is denoted as $ATCF_{np}$. It can be calculated from

$$ATCF_{np} = \frac{ATCF_n}{(1+\delta)^n} = \frac{(1-t)\,(R_n - C_n) + td_n}{(1+\delta)^n} \tag{6}$$

The quantity δ in Eq. 6 is the inflation-adjusted discount rate which should be calculated from

$$\delta = r + I + rI \tag{7}$$

in which r is the above-inflation return rate, and I is the inflation rate.

The revenue R_n in Eq. 6 is to be determined for each year in such a manner that the sum of the present value of $ATCF_n$ over the N years is equal to the initial capital cost, namely,

$$\sum_{n=1}^{N} ATCF_{np} = C_c \tag{8}$$

where $n = 1, 2, 3, \ldots N$. Equation 8 can be rewritten as

$$\left[\sum_{n=1}^{N} \frac{(1-t)(R_n - C_n) + td_n}{(1+\delta)^n}\right] = C_c \tag{9}$$

The revenue is assumed to be R_n for year n, and it escalates at the rate of e_r. Therefore,

$$R_n = (1 + e_r)^n R_o \tag{10}$$

where R_o is the present value of the revenue.

Assuming that the throughput of the system is Q (T/yr), the revenue generated each year becomes

$$R_n = QU_n \tag{11}$$

where U_n is the price charged to the customer for manufacturing or transporting or handling unit weight of the biomass logs, hereafter referred to simply as the "unit price." If the present value of the unit price is U_o, then $R_o = QU_o$. Substituting this equation into Eq. 10 yields:

$$R_n = (1 + e_r)^n U_o Q \tag{12}$$

Equation 12 can now be substituted into Eq. 9 to yield

$$\sum_{n=1}^{N} \frac{(1-t)\left[(1+e)^n U_o Q - C_n\right] + td_n}{(1+\delta)^n} = C_c \tag{13}$$

Realizing that U_o in Eq. 13 is a constant and does not vary with n, it can be factored out of the equation. If Q is assumed to be the same for each year starting year 1, then

$$U_o = \frac{\sum_{n=1}^{N} \frac{(1-t)C_n - td_n}{(1+\delta)^n} + C_c}{Q\sum_{n=1}^{N} \frac{(1-t)(1+e_r)^n}{(1+\delta)^n}} \tag{14}$$

This equation can be used to determine the present value of unit price, and the unit price for any year n can be obtained from

$$U_n = (1 + e_r)^n U_o \tag{15}$$

The annual cost C_n in Eq. 14 is to be determined from

$$C_n = (1 + e_c)^n C_o \tag{16}$$

where C_o is the present value of annual cost for any year n, and e_c is cost escalation rate which is assumed to be the same as the general inflation rate I.

The present value of the annual cost, C_o, is determined from the present annual cost of various items including material, energy, fuel, salaries and wages, property tax, insurance, and other operations/maintenance costs, namely,

$$C_o = C_m + C_e + C_f + C_s + C_p + C_i + C_{o/m} \tag{17}$$

where C_m is the energy cost, C_e is the energy cost, C_f is the fuel cost, C_s is the cost of salary and wages, C_p is the property tax cost, C_i is insurance cost, and $C_{o/m}$ is other operation/maintenance costs—all first-year costs based on current values. Note that corporate income tax is not included here since it has already been included before by using t in previous equations.

The property tax, C_p, and the insurance cost, C_i, for the present year are calculated from

$$C_p = e_p C_c \tag{18}$$

$$\text{and} \quad C_i = e_i C_c \tag{19}$$

where e_p and e_i are respectively the property tax rate and the insurance rate.

More results are presented in Sections 3.10 and 3.11 of Chapter 3.

CHAPTER 3. RESULTS AND DISCUSSION

3.1 Compaction of MRS Low-grade Waste Paper

The low-grade waste paper from MRS Recycling Service, Inc. in Jefferson City was tested with different compaction pressures, different moistures, and different particle sizes.

3.1.1 Effect of compaction pressure

The effect of compaction pressure on the quality of the logs made from the MRS waste paper with different moisture contents was tested by using four different pressures: 5,000, 10,000, 15,000 and 20,000 psi. The paper was ground into pieces of about 2" x 2" by the large hammermill. Photo 3-1 shows the logs made at the four different pressures with moisture contents from room-dried (5.8%) to 20%. The pressure effect on the log density is shown in Figure 3-1. The results including impact resistance and abrasion resistance are summarized in Table 3-1. The results show that the pressure effect is significant for low-moisture waste paper; with the increase of moisture, the pressure effect decreases. It was concluded a minimum compaction pressure of 10,000 psi is necessary to produce good-quality logs from this type of waste paper.

3.1.2 Effect of moisture content

The low-grade waste paper with moistures from 5.8% (room-dried) to 30% was compacted at different pressures. It was found that the effect of moisture content is substantial. When the moisture was higher than 20%, no good logs could be produced even when 20,000 psi pressure was employed. The moisture also affects the effectiveness of pressure—pressure effect is less significant at higher moisture content (see Photo 3-1). Considering the results of density, integrity, and impact and abrasion resistances of the logs, it can be concluded that the optimum moisture content for compaction of the mixed paper is in the neighborhood of 10%. The appropriate moisture range for producing logs with reasonable quality is from air-dried (5-6%) to 20%. The quantitative effect of the moisture content can be found in Figure 3-1 and Table 3-1 (found in Appendix B and A, respectively).

3.1.3 Effect of particle size

The same waste paper was ground into particles with top size of about 8 mm with the CPRC small hammermill, and same tests as those for the larger-size (2-inch) feedstock as described in above two sections were performed. The results showed very little difference in density, impact resistance, and abrasion resistance from those made of the larger-size particles, except the appearances look a little differently. Photo 3-2 shows the logs made of the smaller particles (8-mm top size) at 10% moisture and at four different pressures.

3.1.4 Long-term performance of the logs

It is important to know the change of log properties with time during storage and transportation. The logs made of the low-grade waste paper with different initial moisture contents and compacted at different pressures were observed for their changes of dimensions, moisture, and density in the open air in the laboratory. The longitudinal expansion (elongation) was used to describe the change of dimensions of the logs. The results are shown in Fig. 3-2. It can be seen that the higher the compaction pressure was, the less the logs expanded. The logs with higher initial moisture (higher than 10%) shrank much after they had reached their expansion peaks. The shrinking was apparently caused by the evaporation of moisture. The logs with 15% initial moisture had the least expansion. All the logs reached a steady state after 7 days where the expansion stopped. They maintained their quality for a long time (several months).

3.2 Compaction of MU Campus Waste

The MU Campus waste used in this study consisted of 77% waste paper and 23% plastics on dry weight basis as described in Section 2.2. The materials were ground into particles by the CPRC small hammermill which has a screen opening size of 8 mm. The effects of compaction pressure and moisture content on the properties of the logs compacted from this type of material were tested. The long-term performance of the logs was also observed.

3.2.1 Effect of compaction pressure

Four different compaction pressures, 5,000, 10,000, 15,000 and 20,000 psi, were used to produce logs at different moisture contents. Photo 3-3 shows the logs made at the four different

pressures with moisture contents from room-dried (4%) to 20%. The pressure effect on the log density is shown in Figure 3-3. The results including impact resistance and abrasion resistance are summarized in Table 3-2. The results are similar to those for the MRS waste paper, i.e., the pressure effect is more significant for low-moisture feedstocks. When the moisture is higher than 15%, the pressure effect because minor. At the same pressure and moisture, the logs made of MU Campus waste have poorer quality—lower density and impact and abrasion resistance. Plastics in the material are detrimental to the adherence among the particles while paper helps bind the material together. In general, a minimum pressure of 10,000 psi is necessary to produce reasonably good logs from this waste material.

3.2.2 Effect of moisture content

The effect of moisture content was found to be significant on this type of waste material. To produce good logs, moisture content must be lower than 15%. A moisture content less than 10% is desired for the compaction of this type of material. The quantitative effect of the moisture content can be seen in Figure 3-3 and Table 3-2.

3.2.3 Long-term performance of the logs

The logs compacted under different pressures with different initial moisture contents were observed for their property change with time in the open air in the laboratory. Figure 3-4 shows the longitudinal expansion of the logs with time. It can be seen that the logs made at higher pressure had smaller expansion. Initial moisture also affected the expansion. The logs with 10% and 15% initial moistures expanded smaller than those made at low moisture (room-dried) and high moisture (20% or higher). All the logs reached a steady state after 7 days where the expansion stopped. The logs with less 15% initial moisture could maintain their quality for a long time.

3.3 Compaction of City of Columbia Waste

The City of Columbia waste used in this study consisted of 65% waste paper, 28% plastics, and 7% textiles on dry weight basis as described in Section 2.2. The materials were ground into particles by the CPRC small hammermill into particles with a top size of 8 mm. The

same tests as for the MU Campus waste were conducted for the City of Columbia waste. Following are the results.

3.3.1 Effect of pressure

Photo 3-4 shows the logs made at four different pressures with moisture contents from room-dried (3.5%) to 20%. The pressure effect on the log density is shown in Figure 3-5. The results including impact resistance and abrasion resistance are summarized in Table 3-3. The results are similar to those for the MU Campus waste except that the logs made of the City of Columbia waste is slightly poorer in quality—lower density and impact and abrasion resistance. The poorer quality is due to that this material has lower paper content—65% as opposed to 77% for MU Campus waste). In general, a minimum pressure of 10,000 psi is necessary to produce reasonably good logs from this waste material.

3.3.2 Effect of moisture content

The effect of moisture was found to be significant on this type of waste material. To produce good logs, moisture content must be lower than 15%. A moisture content less than 10% is desired for the compaction of this type of material. The quantitative effect of the moisture content can be seen in Figure 3-5 and Table 3-3.

3.3.3 Long-term performance of the logs

Figure 3-6 shows the observed longitudinal expansion with time of the logs made of City of Columbia waste at different pressures and moistures. All the logs reached a steady state after 7 days. The logs with 10% initial moisture had the least expansion after the steady state was reached. It should be noted that when the moisture is higher than 15%, logs made at higher pressure expanded more than those made lower pressure. This is something different from the MRS waste paper and MU Campus waste.

3.4 Grinding of Waste Materials

Size reduction of the waste materials is essential for the punch-and-die compaction process. Various kinds of commercially-available grinding machines from American Pulverizer Company and Gundlach Machine Company were used to test-grind the waste materials used in

this study, including waste paper, plastics, and textiles. It was found that the most effective machine is hammermill. However, hammermill did not work well for plastic film if the film was ground alone. Some film wrapped around the hammers and could not pass the screen of the hammermill (see Photo 3-5). If the film is ground by the hammermill in mixture with waste paper, it can be ground smoothly with a film content of up to 10% by weight. Photo 3-6 shows the ground mixture of paper and plastic film.

3.5 Mass Production of Waste Paper Logs

Two tons of low-grade waste paper was acquired from MRS Recycling Service for the mass production of fuel logs for crushing and power plant burning test. The large compaction machine and the hammermill in CPRC Field Station were used for the mass production of 5.4-inch-diameter large logs (see Photos 2-2 and 2-4). A screen of 2-inch openings was used with the hammermill so that the top particle size of the ground waste paper was about 2 inches. A compaction pressure of 10,000 psi was used with a back pressure of 500 psi applied during ejection. Each log weighed about 2.5 to 2.9 lbs and had a density of 1.1 to 1.2 g/cm^3 and a length of 2.5 to 2.8 inches. The products were rather short—their length is shorter than diameter. Photo 3-7 shows the large logs produced for crushing and burning tests.

3.6 Crushing of Large Logs

The large waste paper logs were meant to be crushed into particles of a fairly uniform size of 1.5 inches in order to be mixed with coal and co-fired in a stoker boiler of MU Power Plant. American Pulverizer Company and Gundlach Machine Company offered the test-crushing service to the project. These two companies manufacture almost all kinds of crushers being used commercially. It was found the most of the impact-type crushers such as hammermill and lump breaker did not work because they all broke the logs into loose particles. The roll-type crusher made the logs into very non-uniform particles with large chunks and small pieces (see Photo 3-8). The low-speed, high-torque shear-type shredder worked the best for this purpose. Photo 3-9 shows the crushed logs by the shear-type shredder and Photo 3-10 shows the shredder. However, this product was still too loose and had too much fine to meet the particle requirement for the stoker boiler (see the explanation letter from MU Power Plant Superintendent Gregg Coffin in

Appendix D). It was concluded there are still no commercially-available crushers which can effectively crush the compacted logs into the particles satisfactory for mixing with coal and co-firing in stoker boilers. However, large logs can be burnt effectively without grinding into smaller size (please refer to next section).

3.7 Test Burn of the Fuel Logs

The large logs compacted from MRS low-grade waste paper were test-burned in two different devices: a stoker boiler in MU Power Plant and an outdoor hot water furnace for heating.

3.7.1 Test burn in power plant boiler

It was originally planned that the large fuel logs compacted from the waste paper would be co-fired with coal in a stoker boiler at MU Power Plant. The logs would be crushed into particles with a top size of 1.5 inches and fed with coal at a blend of 10% crushed logs. The boiler burns crushed and washed coal with top particles of 1.5 inches and a maximum fine (smaller than ¼ inch) 10%. Due to the unavailability of an effective commercial crusher (see Section 3-6), the logs were tested for burnability in whole logs in a spreader stoker boiler at MU Power Plant. The boiler was manufactured by Riley Company in 1974. It generates 200,000 lbs of steam per hour. The steam temperature and pressure are 700 ^{o}F and 400 psi respectively. The temperature in the hearth of the boiler is about 2240 ^{o}F, which is slightly below the slagging temperature of the coal ash (2400 ^{o}F with full air supply).

The large logs were hand-fed into the boiler through an observation door which is located at the beginning of the traveling grate (See Photo 3-11(a)). The boiler was burning coal in normal condition when the logs were fed in. The grate traveled slowly toward the other end where the ash (slag) dropped into an ash pit. The time for the grate to travel from the front to the end was about 60 minutes. The logs were fed every 5 minutes, one at a time. Observation was made at the other end to find how the logs burned (See Photo 3-11(b)). The result was that there was no trace of the logs observed in the ash dropping into the ash pit; ash from paper logs had mixed with regular coal ash well and was not distinguishable. This means that the logs were totally burned up in the boiler.

This test revealed an important fact that the large logs (5.4-inch diameter) compacted from waste paper do not even need to be crushed for co-fired with coal in stoker boilers. As long as a feeding channel is facilitated, the whole logs can be fed without causing burning problem.

3.7.2 Test burn in hot water furnace

MU Agronomy Research Center uses an Outdoor Hot Water Furnace to heat its building. This furnace was manufactured by Taylor Manufacturing, Inc. It was designed to fire scrap wood, and now is modified to fire both gas (propane) and wood by attaching a Gas Burner on one side. The furnace has a firebox of 32 inches high, 42 inches wide and 48 inches deep. It burns gas alone when no wood or insufficient wood is used. It can burn wood and gas at the same time—when the temperature in the water heater reaches 140 ^{o}F, it automatically cuts off the gas. Photos 3-12 and 3-13 show the outside look and the firebox configuration of the furnace.

The compacted large waste paper logs were tested in this furnace as a substitute for the wood fuel. It was tested on December 12, 2001, when the outdoor temperature was 44.6 °F approximately. About 30 paper logs (about 70 pounds) were placed in the firebox, as shown in Photo 3-13. The gas was ignited first and the flame blew onto the paper logs. The paper logs started to fire in a few seconds (See Photo 3-14). The temperature in the water heater reached 140 ^{o}F in a few minutes and the gas was automatically cut off. The paper logs could sustain the fire steadily for 2 hours. Photo 3-15 shows the burning paper logs without gas being burned. After those two hours, the gas was turned on and off from time to time by the furnace controller. The logs burnt completely at last. The Superintendent of this facility indicated that the logs would be an ideal fuel for this type of furnace. Compared to wood, the paper logs burn more steadily, last longer and generate smaller amount of smoke and virtually no sparks.

3.8 Compaction of Flyash

Both the high-grade and the low-grade flyashes from Thomas Hill Power Plant were tested for the optimum compaction conditions with the CPRC small compaction machine. The flyashes were compacted into 1.91-inch-diameter logs for testing. The conditions that were tested included flyash-to-water ratio, compaction pressure, and curing conditions of the compacted

products (logs). The quality of the products was evaluated by their density, compressive strength, and water permeability. The following paragraphs summarize the results.

3.8.1 Effect of flyash-to-water ratio

The raw flyashes were in a dry form (moisture content less that 0.5%). Water must be added to facilitate the pozzolanic reactions and bonding between the particles. The flyash-to-water ratios of 9.5:0.5, 9.25:0.75, 9:1, 8.75:1.25 and 8.5:1.5 were tested for both types of the flyashes. A fixed compaction pressure of 5,000 psi was employed for the tests.

Photos 3-16 and 3-17 show the logs made of high-grade flyash and low-grade flyash at different flyash-to-water ratios. For the high-grade flyash, it was found that the 9:1 ratio (or 10% added water) is the optimum. If the ratio was too low, water was not sufficient for the pozzolanic reactions and the feedstock was dry and many cracks were generated on the logs upon ejection; if it was too high, the feedstock became too soft and sticky to mold and form good logs. For the low-grade flyash, the optimum ratio was found to be 8.5:1.5 (15% added water).

3.8.2 Effect of compaction pressure

The effect of compaction pressure on the flyash logs was studied by using four different pressures (1,000, 5,000, 10,000, and 15,000 psi) at the optimum flyash-to-water ratios for both the high-grade and the low-grade flyashes. The logs were moist-cured for 7 days and 28 days and the properties (density and compressive strength) were measured to evaluate their quality. Photos 3-18 and 3-19 show the logs compacted at different pressures for the high-grade and low-grade flyashes. Figures 3-7 and 3-8 show the effects of pressure on the density and the compressive strength of the logs made of high-grade flyash, and Figures 3-9 and 3-10 show the same thing for logs of the low-grade flyash.

It can be seen from Figures 3-7 through 3-10 that for both high-grade and low-grade flyashes, the density of the logs increased with the increase of pressure. Compressive strength of the high-grade-flyash logs also increased with pressure, but the effect became insignificant when the pressure was higher than 5,000 psi and when the curing time was longer than 28 days. For the low-grade-flyash logs, the compressive strength actually decreased when the compaction pressure was higher than 5,000 psi. It was observed that the low-grade-flyash logs expanded

more significantly upon ejection when compacted at higher pressure. The expansion caused many minor cracks on the logs. Although such minor cracks did not change the density of the logs remarkably, they reduced the strength of the logs significantly.

Based on the results above, the optimum compaction pressure was determined to be 5,000 psi for both the low- and the high-grade flyashes.

3.8.3 Effect of curing conditions

Since the pozzolanic reactions involved in the materials (flyash and water) are slow, the compacted logs must be cured for certain times in order to gain necessary strength. Four different curing conditions were studied. They are:

(1) Moist curing: logs were cured in a moist room built according to ASTM standard C-511. The room has a temperature of 23.0 ± 2.0 ^{o}C and a relative humidity of not less than 95%.

(2) Water curing: logs were first moist-cured for one day and then immersed in water for further curing. The logs needed the one-day moist curing for setting; otherwise they would fall apart if immersed in water immediately after ejection.

(3) Moist-dry curing: logs were first moist-cured for 7 days, then stored in open air at room temperature for the dry curing.

(4) Water-dry curing: logs were first water-cured for 7 days (excluding for the first day of moist curing, see water curing above), then stored in open air at room temperature for the dry curing.

The effect of curing conditions on the quality of the logs was studied for both the high-grade and low-grade flyashes with the optimum water-to-flyash ratios (9:1 for the high-grade and 8.5:1.5 for the low-grade), using 5,000 psi compaction pressure. The logs were observed for dimension, appearance, and weight changes, and tested for compressive strength with time. The measurements and tests were taken at 1, 3, 7, 14, 28, and 60 days. Three specimens were tested at each test age. The flyash log properties versus time are listed in Tables 3-4 and 3-5. The compressive strength versus curing time of the logs is plotted in Figures 3-11 and 3-12.

Discussions of these test results are given separately for high-grade and low-grade flyash logs in the following sub-sections.

A. High-grade-flyash logs

Figure 3-11 shows the compressive strength development with curing time for the high-grade-flyash logs under the four different curing conditions. It can be seen that the logs gained strength rapidly during the initial 14 days. This indicates that the main hydration reactions happened during this first period of time and reactions mainly relied on the water initially added in the feedstock. After 14 days, the moist-cured and water-cured the logs continued to gain strength slowly, but dry-cured ones started to lose strength slowly. This indicates that the hydration reactions continued to takes place as the water permeates into the bricks from outside. The reactions take longer than 60 days to complete at room temperature. The water-cured logs gained strength faster than the moist-cured ones in the later stage because the water permeated into the logs more readily under the water-curing condition. In opposite, the dry-cured logs lost water due to evaporation, causing the hydration reactions to halt or even causing the logs to shrink and form micro cracks so that the strength decreased gradually.

The density changes and weight gains of the high-grade-flyash logs with time under different curing conditions can be found in Table 3-4.

B. Low-grade-flyash logs

Figure 3-12 shows the test results for the compressive strength of low-grade flyash logs. The continuously moist-cured and water-cured logs developed increasing compressive strength as the curing time increased, but had lower strength than those made of the high-grade flyash. The densities of the low-grade-flyash logs were also lower than those of the high-grade ones made and cured under the same conditions (see Table 3-4 and Table 3-5). Therefore, the low-grade flyash is more difficult to compact and the logs made of it develop lower strength than those made of the high-grade flyash. This may indicate a lower degree of hydration for the low-grade flyash.

Figure 3-12 also shows that there was a sharp increase of strength in the beginning of the dry curing for the moist-dry- and water-dry-cured logs followed by a long period of gradual

decrease. This indicates that the composition and mechanism of strength development of the low-grade flyash are different from those of the high-grade flyash. It is assumed that the degree of hydration is low for the low-grade flyash and the crystallization of the dissolved substances in the flyash logs contributes to the increase of strength once the logs were being dried. Note that chemicals (solids) were observed to coat the low-grade logs' surface, which may be an indication of the crystallizing process.

3.8.4 Water permeability

The water permeability of the compact products of flyash was tested for both the low-grade and high-grade flyashes. The specimens were in the form of discs with a diameter of 31.5 mm and a thickness of 6.7 mm. They were made at the optimum flyash-to-water ratios (9:1 for high-grade flyash and 8.5:1.5 for the low-grade flyash) and at five different compaction pressures (1,000, 2,000, 5,000, 10,000, and 15,000 psi). The specimens were moist-cured for 7 days and then tested for permeability. The test was performed by recording the accumulated water volume and the corresponding time—the two variables to determine the flow rate (discharge) and velocity through the samples. The water pressure was set at 30 psi for the permeability experiments. The resultant water flow rate and hydraulic conductivity were calculated from the Darcy's law.

For the high-grade flyash discs, the effect of compaction pressure on the water permeability (hydraulic conductivity) is shown in Figure 3-13. The permeability decreased as the compaction pressure increased, reaching approximately 10^{-8} cm/s when compaction pressure reached 15,000 psi. This is due to the loss of pore space between flyash particles in the compacted disks. The lowest permeability of the tested specimens (5.5×10^{-9} cm/s) is close to the required permeability for water-tight structural concrete, which is recommended by the ACI Standard 301-72 to be 1.5×10^{-9} cm/s.

For the low-grade flyash discs, the effect of compaction pressure on the permeability of the discs is shown in Figure 3-14. The permeability reached a minimum of 10^{-8} cm/s at 5,000 psi compaction pressure, then began to increase at higher compaction pressures. This is due to the high expansion of the flyash discs compacted at higher pressure. The cracks caused by the

expansion resulted in higher permeability and weaker discs. Two of the three flyash discs made at 15,000 psi pressure could not be tested for permeability due to severe cracking.

3.8.5 Summary

The flyash-to-water ratio, compaction pressure, curing condition and curing time are all important for the quality of the compacted flyash logs. For the two particular types of flyashes that were studied in this project, the optimum flyash-to-water ratios are 9:1 and 8.5:1.5 for the high-grade and the low-grade ones respectively. For the high-grade flyash, the higher the compaction pressure is, the better quality of the logs can be achieved. However, when the pressure is higher than 5,000 psi, the effect of pressure on the long-term quality of the logs becomes insignificant. For the low-grade flyash, a pressure higher than 5,000 psi is detrimental to the log quality.

The compacted logs must be cured in a moist environment in order to gain strength. The longer the logs are cured, the higher strength they can gain. The strength-gaining process can last longer than 60 days. A minimum curing period of 14 days is necessary for the logs to gain high strength. After 14 days of curing, the high-grade flyash logs can reach a compressive strength of more that 6,000 psi which meets the requirements for many building products; the low-grade flyash logs can gain a compressive strength of about 2,500 psi.

It should be mentioned that under any of the curing conditions, the logs can keep their shape and dimensions. Once the logs are made, they do not change the dimension with time.

3.9 Compaction of Flyash Bricks

Based on the study on the compaction of flyash logs, real-size bricks were produced from flyash using a special set of mold and piston (see Photo 2-3). The bricks had a length of 8 inches, width of 4 inches and thickness of 2.2 inches. The optimum flyash-to-water ratios as found for making flyash logs (Subsection 3.4.1) were used for compacting bricks. Some 200 flyash bricks were produced in this project, and most of the bricks were compacted at 1,800 psi pressure which is the maximum pressure that the CPRC small compaction machine can achieve for a 8 inch by 4 inch compaction area. Some logs were compacted at different pressures from 600 psi to 10,000 psi to study the pressure effect on the quality of the bricks. The CPRC large compaction machine

was used to achieve pressure higher than 2,000 psi. The bricks were cured in a moist room after being made. The bricks were tested for compressive strength, modulus of rupture, water absorption, and freezing-thawing resistance according to ASTM Standard Method C 67 for testing brick and structural clay tile. Following subsections present the results.

3.9.1 Strength of the bricks

The compressive strength and modulus of rupture were tested for bricks made of high-grade flyash at 1,800 psi pressure and moist-cured for 7 days, 28 days, 60 days, and 90 days. Due to the limitation of time, only 28-day-cured low-grade-flyash bricks were tested. For comparison, some regular commercial bricks were also tested. The results are listed in Table 3-6. A visual comparison among the high-grade-flyash brick, the regular kilned-clay brick and concrete brick is shown in Photo 3-20.

In terms of compressive strength, the high-grade-flyash brick could develop a strength of 4,600 psi after 7 days of moist curing, which exceeds the requirement for concrete building bricks (ASTM standard specifications C 55, requires highest compressive strength to be 3,500 psi) and for clay or shale bricks (ASTM standard specifications C 62 requires highest compressive strength to be 3,000 psi). The strength of the bricks increased gradually with curing time. The compressive strength of the bricks increased to 7,850, 8600, and 9,300 psi at the 28th, 60th and 90th days of curing. For the low-grade-flyash bricks made under the same conditions and cured for 28 days, the compressive strength was 3,210 psi, which still meets the specifications for Grades S-I and S-II of concrete bricks and for all grades of clay and shale bricks. The regular red kilned bricks were also tested for comparison. The compressive strength was found to be 6,500 psi. This means that the compacted flyash bricks have a higher compressive strength than the ordinary commercial bricks when the flyash bricks are curing for longer than 28 days.

Table 3-6 shows that the modulus of rupture of the flyash bricks is much lower than the ordinary commercial bricks. However, this property is not required for most of the brick applications including the use as building bricks. Only a few applications such as heavy vehicular paving (ASTM Standard C 1272) and industrial floor (ASTM Standard C 410) require this property.

3.9.2 Water absorption of the bricks

The water absorption of the high-grade flyash bricks is about 10%, which meets the specifications for building bricks (ASTM standard C 55 and C 62) although the regular commercial bricks have a much lower water absorption (less than 1%). The low-grade-flyash bricks had a water absorption of about 21%, which does not meet the standard for concrete building bricks (ASTM Standard C 55), but meet the standard for the clay- or shale-made building bricks of grades MW and NW (ASTM Standard C-62).

3.9.3 Resistance to freezing and thawing

The freezing and thawing resistance of both the high-grade-flyash bricks and low-grade-flyash bricks which were moist-cured for 28 days were tested. For comparison, the regular commercial bricks were also tested. The tests were conducted according to ASTM standard C 67, in which a cycle consists of a 20-hr freezing at a temperature of –9 ^{o}C or lower and a 4-hr thawing at 24±5.5 ^{o}C.

The results showed that both the high-grade-flyash and the low-grade-flyash bricks started deteriorating after 7 cycles and failed at 9 cycles see Photo 3-21. The ASTM standard C 67 specifies that the bricks should endure for 50 freezing and thawing cycles to meet the requirement. In many areas in the United States, there is almost no day during a year that the temperature drops below the freezing point. The resistance to freezing and thawing in these areas is not an important property.

3.9.4 Compaction pressure effect

Bricks of high-grade flyash were made at different pressures ranging from 600 to 10,000 psi to examine the effect of compaction pressure on the property of the bricks. The density of the bricks was measured for the evaluation. Figure 3-15 shows the density of the bricks as a function of the compaction pressure. It can be seen that with the increase of compaction pressure, the density also increased, but the increase is not linear—at the lower pressure range (less than 2,000 psi), the density increase was more drastic. It was found by visual examination that the bricks made at pressures lower that 1,500 psi had loose bottom edges. By bottom edges it is meant the edges of the flat face where the moving compaction piston does not directly contact. Therefore,

a minimum pressure higher than 1,500 psi is necessary to produce high-quality bricks from flyash.

3.9.5 Mass production of flyash bricks for test use

Some 200 high-grade-flyash bricks were produced at the optimum flyash-to-water ratio and at the compaction pressure of 1,800 psi for test use in University of Missouri-Columbia (MU) Campus for gardening. The bricks are being cured in the moist room (see Photo 3-22) until January 2002. Then they will be test-used by MU Campus Facilities. They will be monitored for property change with time for about a year. The results will be separately reported when available.

3.10 Economics Analysis of Fuel Log Production

The same cost model used for the analysis of biomass log fuel production cost in a U.S. Department of Energy funded project was employed in this study. The life-cycle cost analysis model and net-cash-flow approached as indicated in Section 2.3.3 was used for the calculations of the production cost. The log fuel production plants with different capacities were analyzed and brief descriptions of the methods and assumptions are presented here. Details of the analysis can be found in a report submitted to DOE, entitled "Economic Analysis of Compacting and Transporting Biomass Logs for Co-firing with Coal in Power Plants" [4].

Different plant capacities ranging from 135,000 tons per year to 675,000 tons per year were used to examine the effect of the plant size. Large rotary presses, each having a production rate of 386 tons/day, were to be used. The itemized and total capital cost and annual cost are summarized in Table 3-7. In the calculation of the unit production price, the following assumptions were used:

(1) The general inflation rate, I, is 3%.
(2) The return rate, r, is 15%.
(3) The economic life of the project, N, is 20 years.
(4) Depreciation of capital is flat (constant) over 20 years ($N_d = 20$).
(5) The corporate income tax rate, t, is 37%
(6) The discount rate, δ, calculated from Eq. 7 in Section 2.3.3, is 0.1845.

(7) Present costs are based on Year 2001 values.

(8) All the cost items are inflated according to the same general inflation rate, I, of 3%.

(9) The revenue escalation rate, e_r, is the same as the general inflation rate.

(10) The property tax rate is equal to 2% of the total capital cost.

(11) The annual insurance cost is 0.5% of the total capital.

(12) The equity is 1.0. This means that all the money invested on the project (the capital cost) comes from the owner; no money is borrowed. Otherwise, interest rate would also enter the calculation.

(13) The specific gravity of the biomass logs is 1.0, which means that the logs have the same density as water. This refers to the density of the logs with moisture included (i.e., wet density).

(14) Biomass fuel needs protection from rain.

(15) Waste materials at the source are combustible and already separated from the non-combustible solid waste materials. No cost is included for separation of solid wastes into combustible and non-combustible parts.

(16) The cost to collect biomass and to transport it to the BLF production plant is not included.

Based on the cost items in Table 3-7 and the above assumptions, using the cost model as established in Section 2.3.3, the unit production cost or price for the different throughputs were calculated, and results are shown in Figure 3-16. It can been seen that the unit cost increases as the plant capacity decreases. For the large plant that produces 675,000 tons of logs per year, the unit production cost is only $5.47, whereas for the small plant that produces 135,000 tons per year, the unit cost is $8.16. It should be noted that these costs are based on a company return rate of 15% above inflation. The points on both sides of the curves in Figure 3-16 mark the results of a sensitivity analysis with 25% variation of capital or annual cost. It can be seen from Fig. 3-16(a) that an increase or decrease of the capital cost by 25% causes the unit cost to increase or decrease by 10% approximately. And, an increase or decrease of the annual cost (operation and maintenance cost) by 25% causes the unit cost to increase or decrease by 15% approximately as shown in Fig. 3-16(b).

3.11 Economics Analysis of Production of Flyash Bricks

Although the same cost model as described above can be used for the economic analysis of the production of flyash bricks, there are many differences in capital and annual costs and more uncertainties with the analysis of flyash brick production. The differences and uncertainties are as follows:

(1) Flyash does not need size reduction and drying equipment, but it needs equipment for mixing flyash with added water.

(2) The fuel logs can be piled and stacked for storage or transportation immediately after they are compacted. In contrast, the flyash bricks must be stored into a curing room (moist room) for at least 14 days before gaining sufficient strength. The cost of a curing room with all the handling devices is uncertain at this stage of the research.

(3) There is not even a conceptual design of a compaction machine for producing flyash bricks. Therefore, the machine cost is an educated guess.

Due to these uncertainties, a sensitivity analysis of the production cost of flyash bricks was conducted by using the case of Thomas Hill Power Plant as an example. The objective is to find the relationship between the capital cost/annual cost and the unit production cost of the bricks. The result will be useful for investors to decide the maximum investment for a plant in order to make profit.

Thomas Hill Power Plant has one pulverized coal unit which burns 8,000 tons of Powder River Basin (PRB) coal per day and two cyclone units which burn a total of 6,000 tons of PRB coal per day. The former generates about 90,000 tons of high-grade Class C flyash and latter generate about 50,000 tons of low-grade flyash per year. As shown in Section 3.9, both the high-grade and the low-grade flyashes can be compacted into bricks with usable quality as shown in Section 3.9. In this analysis, a flyash brick production plant which uses 90,000 tons of the flyash per year and produces 100,000 tons of bricks per year was used. The same assumptions as used for waste paper log production (Section 3.10) were used except for the assumptions No. 13 and No. 14. In addition, it is assumed that one compacted brick right after ejection weighs 5.2 pounds.

In reference to the costs of the fuel log production discussed in Section 3.10, a 100,000-ton plant may need a capital cost of one million to two million dollars, and the annual operation and maintenance cost of about one third of the capital cost. The analysis was done for three different capital costs: 1 million, 2 million, and 3 million dollars. And for each capital cost, five annual costs of 0.1, 0.2, 0.3, 0.4, and 0.5 times of the capital cost were used for sensitivity analysis. Table 3-8 summarizes the unit costs in terms of both dollars per ton and dollars per brick for each of the scenarios. It should be noted that the unit costs in the results include 15% after-tax return.

The results in Table 3-8 indicate that even for the most costly scenario—3 million dollar capital cost and 1.5 million dollar annual cost—the benefit-included unit cost is only 5.7 cents per brick. If the capital cost of the plant can be kept within 1 million dollars, the cost per brick will be less than 2 cents. If the bricks can be sold for 10 cents per piece, the benefit for the investors will be enormous.

CHAPTER 4. CONCLUSIONS

Through this study, it was found that the three typical biomass waste streams—low-grade waste paper, MU Campus waste and City of Columbia waste—can be compacted into dense and strong fuel logs by using the high-pressure compaction technology developed by the Capsule Pipeline Research Center, University of Missouri-Columbia. With appropriate compaction pressure, moisture, and particle size, all the biomass materials studied can be compacted into high quality logs without using any binder or heat. The logs can be used as a convenient fuel for power plants and small-scale furnaces. The flyash generated from coal-fired power plants can be compacted into building bricks and blocks, which meet most of the important property requirements for ordinary commercial bricks.

This technology was also found to be attractive economically. Important conclusions are summarized as follows:

(1) Low-grade waste paper can be compacted into high-quality fuel logs under a minimum compaction pressure of 10,000 psi and a moisture content ranging from room-dried (about 5%) to 20%. The logs are physically strong and have a dry density of 1.0±0.1 g/cm^3.

(2) The MU Campus waste, consisting of 77% waste paper and 23% plastics, can also be successfully compacted into logs. Although such logs are not as strong as those made of waste paper alone, they have higher heating value brought about by the inclusion of plastics.

(3) The City of Columbia waste, consisting of 65% waste paper, 28% plastics and 7% textiles were also successfully compacted into logs. Since it contains more plastics and textiles than the MU Campus waste, the logs produced are weaker but have higher heating value than those compacted of MU waste.

(4) There are still no commercially-available crushers which can effectively crushed the large fuel logs compacted by CPRC technology into the particles satisfactory for mixing with coal and co-firing in stoker boilers. However, the whole logs can be effectively burned in both stoker boilers and some small-scale furnaces. For use in

stoker boilers, if a separate feeding line can be economically set up, it will be more attractive to feed the whole logs separately than to feed the crushed logs blended with coal.

(5) Flyash can be compacted into bricks. Such bricks have higher compressive strength than ordinary bricks but lower resistance to freezing and thawing.

(6) The economics of producing fuel logs in large-scale plants was found to be very attractive. The unit production cost is as low as $5.5 to $8.0 per ton for plants producing 675,000 to 135,000 tons of logs. This cost includes a 15% above-inflation return for the investor. The CPRC compaction process appears to be more economical than other conventional densification processes including pelletizing, extrusion and briquetting, and produces a denser and stronger (more wear-resistant) fuel.

(7) The unit production cost for producing flyash bricks was found to be lower than 6 cents per brick for a 100,000-ton plant with 3 million dollar capital cost and 1.5 million dollar annual cost.

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