volume within a 55-gallon barrel. A spill density was determined by pouring the RDF into a 1 cubic-foot volume aluminum box typically used for measuring coal bulk density. The calculated values for bulk density (lb/ft^3) were:

As-received (compacted):	13.4
Loose (expanded):	7.8
Spill:	5.6 to 5.9

The RDF from the second determination of spill density was subjected to manual sorting to determine the primary constituents. The results of manually sorting the 5.9-lb RDF sample are shown in Table 27. Almost 95 wt% of the RDF is combustible, with approximately 87 wt% of the RDF fraction comprising paper, paperboard, cardboard, and plastic film. Although no additional separation of this fraction was performed, visual analysis showed that the plastic film constituted a significant portion of the RDF by volume. Minor combustible fractions included wood and various forms/densities of plastic fragments (pop jugs and caps, toys, utensils). The principal noncombustible components were glass (2.0 wt%) and grit (1.8 wt%). Pictures of the RDF fractions are also shown in Appendix E.

Table 27. −4-inch RDF Sorting Results

Fraction	wt%
Paper, Paperboard, Cardboard, Plastic Film*	87.03
Wood	2.95
Glass	2.08
Plastic Pop Jug	2.01
Grit <10 mesh	1.76
Dense Plastic	1.65
Light Plastic	1.05
Aluminum	0.94
Ferrous	0.54

* Grocery and garbage bag-type plastic.

Cleaning RDF with Commercial Air Classifer

A sample of the −4-inch RDF was brought to Forsberg, Inc. (Thief River Falls, Minnesota), to evaluate possible systems for removing glass, aluminum, and other heavies. After visual inspection of the RDF, Forsberg personnel determined that an air classifier, typically used to clean agricultural products such as corn, sunflowers, beans, and wheat, may be suited for this application. The air classifier is essentially a vertical box that relies on density differences between processed materials to allow lighter, buoyant particles to be separated from the heavies. The air classifier measures 152 mm × 457 mm (6 inch × 18 inch) in cross section with a vertical disengaging zone of about 1.75 m (5.75 ft). Injection of the material into the air classifier and control of material feed rate is accomplished using a variable-speed star feeder. The star feeder is the same width as the air classifier to allow uniform distribution across the column. Entrained material is knocked out of the flow stream using a large, square disengager; recovered material is gravity-discharged through an angled chute. Heavy material falls from the bottom of the column through a damper. Control of the volume rate of air through the classifier is accomplished using a baffle on the "squirrel cage" fan.

The air classifier was tested at a nominal 9.1-m/sec (30-ft/sec) air velocity. The yield of product was measured at about 87 wt%, with 78 wt% of the noncombustibles (glass, ferrous, aluminum, etc.) and only 7.6 wt% of the combustible fraction passing with the rejects based on manual sorting of the product and reject fractions. After sorting, the combustible fraction was sorted and subjected to determination of moisture and ash. From these data, the ash reduction was estimated to be approximately 35 wt%.

Although marginally effective with aluminum (25 wt% removal) the air classifier removed 80 wt% of metal and over 99 wt% of the glass as determined by hand-sorting. Further, the air classifier appeared to significantly reduce the quantity of loosely adhered grit (sand, fine glass). Digital photos of the air classifier system and product and reject fractions from the testing are presented in Appendix E. The air classifier appeared to be suited for RDF "polishing" to enhance RDF's suitability for utilization in high-pressure feed systems.

Feedstock Analysis

Select samples of biomass were subjected to the following analysis: proximate, ultimate, heating value, XRF, and total chloride; representative data for corn stover, switchgrass, and wood waste were obtained from literature (86). Results of the analysis are presented in Table 28.

Select biomass feedstocks were subjected to size reduction using a hammermill recently installed at the EERC. The hammermill has a 30-kW (40-hp) motor and a nominal capacity of 455 kg/hr (1000 lb/hr), depending on screen size and material. The hammermill is equipped with round opening screens of 3.2, 6.4, 12.7, and 25.4 mm (0.125, 0.25, 0.50, and 1.0 inch, respectively). Biomass feedstocks subjected to size reduction were labeled according to the screen size used for processing. Pictures of the as-received and size-reduced fractions of select biomass feedstocks are presented in Appendix F.

Table 29 presents bulk density data for select biomass feedstocks. The purpose for determining bulk density for these materials was to provide data that could assist in the sizing of equipment for potential feed system designs.

An attempt was made to determine the potential entrainability of the biomass materials in advanced gasifiers such as the entrained-flow gasifier operated by Global Energy at Wabash River or developmental systems such as the transport reactor being developed at the EERC and the PSDF. The entrainability was simulated by using the Forsberg air classifier that was previously described. For these tests, a weighed amount of biomass was introduced to the air classifier with the heavies and lights, then recovered and weighed. The percentage of material entrained was determined from the mass recovery of heavies relative to the mass of material fed. The presence of fines in some samples made 100% recovery of the lights impossible. Therefore, a 0 wt% recovery of heavies indicated a 100% entrainment of the material at the selected air flow rate.

Table 28. Analysis Results for Biomass Fuels (as-received)

	Soybean Hulls	RDF	Corn Stover	Switchgrass	Wood Waste	Wheat Straw
Proximate, wt%						
Moisture	11.21	4.1	6.06	8.16	10.22	9.74
Volatile Matter	70.73	69.03	75.96	72.73	67.31	71.05
Fixed Carbon	13.79	8.27	13.23	14.89	16.26	13.96
Ash	4.27	18.60	4.75	4.22	6.21	5.25
Ultimate, wt%						
Hydrogen	6.41	6.73		5.37		
Carbon	39.23	44.06		43.04		
Nitrogen	1.58	0.77		0.53		
Sulfur	0.19	0.44	0.1	0.1	0.07	0.1
Oxygen	48.32	29.40		38.58		
Ash	4.27	18.60		4.22		
Heating Value, Btu/lb	6767	7418	7780	8010	8160	7990
Chloride, µg/g	94	4440	2500	4600	1100	2300
Ash XRF, wt% as oxide						
Silicon	9.2	51.7				
Aluminum	1.6	10.2				
Iron	2.2	3.7				
Titanium	0.1	1.7				
Phosphorus	7.6	0.8				
Calcium	22.6	16.3				
Magnesium	10.7	3.0				
Sodium	0.0	6.6				
Potassium	44.2	1.6				
Sulfur	1.8	4.5				

Table 30 shows the air velocities evaluated. The volume rate of air flow for three baffle settings was determined using a calibrated pitot. Preliminary calculations, performed for sewage sludge entrainment calculations, showed that for ambient conditions, a velocity of 30 ft/sec would simulate the conditions for an entrained-flow gasifier. The results indicate that even at 8 m/sec (26 ft/sec) all of the select biomass materials, except RDF, would be entrained. Even at a lower velocity of 2.6 m/sec (8 ft/sec), the entrainability is almost 90 wt%. The 25 wt% of RDF not entrained at 8 m/sec (26 ft/sec) corresponds roughly with the amount of undesirables (glass, ferrous, aluminum) plus compacted paper/cardboard wads that would ideally be removed prior to utilization.

Table 29. Bulk Density Determinations for Various Biomass Feedstocks

Material	Density, lb/ft^3	Compaction
Cedar Sawdust	3.8–6.3	Spill
E-Grass		
⅛-inch Screen	9.3–10.4	Spill
Cedar Shavings	2.4–4.2	Spill
Western White Wood Mulch	11.6	Spill
Urban Wood Waste		
Mulch	10.4	Spill
¼-inch Screen	8.2–9.6	Spill
Switchgrass		
As-Received		Bale fragment
¼-inch Screen	10.9–11.5	Spill
½-inch Screen	8.3–8.9	Spill
1-inch Screen	5.2–5.3	Spill
Corn Stover		
As-Received		
¼-inch Screen	6.2–6.8	Spill
½-inch Screen	4.7–5.3	Spill
Soybean Hulls		
Whole	6.5	Spill
Chopped	20.7	Spill
Pellet	42.8	Spill
Pellet	73.6	Specific density of pellet
Chopped Pellet	28.2	Spill
Wheat Straw		
Refiner product	4.3	Spill
Pellet	39.7	Spill
Pellet	69.8	Specific density of pellet
RDF		
−4 inch	5.5–6.9	Spill
	7.8	Loose in barrel
	13.4	Compressed in shipping bag
Coarse	2.6–3.1	Spill
Wet Sawdust	16.2	Spill

Table 30. Production of Heavies During Air Entrainment Tests for Various Biomass Feedstocks

	Air Velocity, m/sec (ft/sec)		
Material	2.6 (8.5)	8 (26)	15 (49)
Corn Stover			
¼-inch Screen	<5	0	NA
½-inch Screen	12.5		NA
Urban Wood Waste			
¼-inch Screen	<5	0	NA
Switchgrass			
¼-inch Screen	<5	0	NA
½-inch Screen	12.5		NA
1-inch Screen	12.5		NA
E-Grass			
⅛-inch Screen	12.5	0	NA
RDF (−4 inch)	89	25	6

The application of the air classifier for upgrading RDF to a more feed-system-tolerant material is discussed in a latter section.

An attempt was also made to determine approximate power requirements for reduction of the biomass materials to these entrainable sizes. Samples were sent to one of the industry leaders in size reduction technology to provide a rough judgment for power requirements. This vendor indicated that installed horsepower could range from 50 to 75 hp per ton/hour of biomass processed, including primary and secondary size reduction. The high end number, for example, is encountered in the preparation of −20-mesh wood flour that is pressed into consumer products such as toilet seats. Other related projects that have amassed some operating time in the size reduction of biomass include the Hawaiian Biomass Gasification Facility processing bagasse and the switchgrass-firing project at the Ottumwa generating station (87, 88). Power requirements for size reduction of bagasse (at 45% moisture) through a 25.4-mm (1-inch)-round opening screen were about 55 to 66 hp per ton/hour but decreased significantly to about 20 hp per ton/hour with a slotted screen. For the switchgrass-firing project, at capacities of 11 to 14 metric tons/hr (12 to 15 short tons/hr), the actual power draw was about 75 kW (100 hp) for a 7% moisture feedstock, although the installed motor power was 450 kW (600 hp). Actual testing would have to be performed on multiton quantities of biomass to more closely estimate power requirements to allow system design.

Feed System Approaches to Pursue

Plug-Screw Feeder

Relative to any high-pressure biomass feeding system, the plug-screw feeder has had the most significant operating history and track record. The plug-screw feeder has also been utilized in two separate systems for feeding biomass to gasification systems. The first instance involved the application of a plug-screw feeder with a 1.6-MPa fluid-bed gasifier operated during development of the Biosyn process at the University of Sherbrooke (Quebec, Canada) (89). Attempts at obtaining public information on the success of the utilization of the plug-screw feeder were unsuccessful. Presently, the rights to the process are held by Enerkem (90). The plug-screw feeder was also tested in the Phase 1 testing of the Hawaiian BGF, which was intended to demonstrate the GTI Renugas gasification technology with sugarcane bagasse. Unfortunately, no public report exists for the Phase 1 testing to discern the operability of the plug-screw feeder. Discussions with personnel involved in the project indicated that the feeder performed acceptably after a period of shakedown testing. Both persons indicated that the plug-screw feeder is a technology worth pursuing for high-pressure biomass feeding.

To this end, contacts were established with engineers at Metso paper, including those knowledgeable about the Hawaiian project, and at Andritz/Ahlstrom. Select feedstock samples were sent to Metso and Andritz to obtain feedback on the potential for feeding these materials with a plug-screw feeder to a gasifier system operating at up to 3.1 MPa (450 psig). Both manufacturers believed that the plug-screw feeder would work for such an application. Metso offered a ranking of the respective feedstocks, shown in Table 31, with respect to most to least desirable. Metso felt that the larger the feedstock, the better, concerning the ability to produce a plug with sufficient integrity to resist backflow of gas. The most desirable feedstocks reviewed were the corn stover processed through a ½-inch screen and the switchgrass processed through a 1-inch screen. RDF and urban

Table 31. Metso Corporation Ranking of Suitability of Biomass for Feeding with Plug-Screw Feeder

Material	Ranking (10 being best)
RDF (−4 inch)	6
Sawdust	4
E-grass (⅛-inch screen)	3
Corn Stover (½-inch screen)	7
Switchgrass (¼-inch screen)	5
Switchgrass (1-inch screen)	7
Urban Wood Waste (¼-inch screen)	6

wood waste (processed with ¼-inch screen) were given favorable rankings. At too small a particle size, the thought was that the material would become too dense, and the feed would not have enough resistance to the shearing force required to move the material forward; instead, the material would spin with the screw. Andritz had little reservation regardless of the feedstock size.

Metso and Andritz both offered similar visions of what a possible feed system approach would look like. A feed system concept provided by Metso for feeding RDF is presented in Table 32. The major unit operations of the proposed system included 1) a precompression or stuffing screw; 2) a series arrangement of two plug-screw feeder/tee pipes, separated by a safety valve; and 3) a shredding conveyor for "delumping" of the material plug. Each tee pipe would be equipped with a blow-back damper. Metso suggested that a single line with 500-mm (20-inch) plug-screw feeders would be sufficient for 40 tons/hour of RDF. The installed power requirement for the system is approximately 1350 kW (1800 hp).

Table 32. Metso Corporation Proposed Feed System for RDF

Unit Operation	Description
Metering Conveyor – 26" Diameter	Conveys material to precompression screw
CDS-630 Precompression Screw with Atmospheric Housing and 100-hp Motor	Compresses loose material to keep bulk density above 100 kg/m^3 (9 lb/ft^3) at 70% consistency
ADI-500 Atmospheric Plug-screw Feeder with 800-hp Motor	Feeds material to #1 T-pipe at 100 to 120 rpm maximum
#1 T-pipe with Blow-Back Damper	Receives compressed material from ADI-500 feeder; pressure at this point 200 to 250 psig; blow-back damper breaks up plug and acts as safety device for pressurized gas escape
Safety Cutoff Valve – 24" Diameter	Can be closed as an extra safety precaution in case of detected blow back
ADI-500 Pressurized Plug Screw Feeder with 800-hp Motor	Feeds material to #2 T-pipe at 100 to 120 rpm maximum
#2 T-pipe with Blow-back Damper	Receives compressed material from ADI-500 feeder; pressure at this point 450 psig maximum; blow-back damper breaks up plug and acts as safety device for pressurized gas escape; maximum temperature allowable is 260°C (500°F)
Shredder/feed Conveyor – 15" Diameter with 100-hp Motor	Feeds biomass directly to process or to metering/surge bin; functions to break up compressed material plug; water-cooled shaft and housing

Both manufacturers were confident that the shredding screw would decrepitate the plug fragments essentially back to the consistency of the as-fed material. Several pellets were prepared from select feedstocks using a manual pellet press with a 31.8-mm (1.25-inch) die at maximum press pressure of 56.2 MPa (8150 psig). Densities of the pellets are presented in Table 33, and photos of the pellets are shown in Appendix F. For these materials, the bulk density of an individual pellet was approximately 5 to 7 times the bulk density of the as-pelleted material. These compression ratios may approach that required with the plug-screw feeder and are lower than those claimed for the TK Energi piston feeder where biomass densities of 1000 to 1700 kg/m^3 (62 to 106 lb/ft^3) are apparently achieved. The corn stover, wood waste, and E-grass pellets retained a sharp-edged form after preparation, while the switchgrass pellet began to easily decrepitate around the edges. The sawdust and RDF pellets sprang apart immediately upon their removal from the press die. Actual testing would have to be performed to determine the ease at which the compressed fuels are broken down by any shredding screw.

Table 33. Density of Pellets Made with Various Biomass Materials (simulating possible conditions of plug-forming feeders)

Material	Pellet Density, kg/m^3 (lb/ft^3)
E-Grass	
⅛-inch Screen	785 (49.0)
Corn Stover	
¼-inch Screen	820 (51.2)
Urban Wood Waste	
¼-inch Screen	865 (54.0)
Switchgrass	
¼-inch Screen	755 (47.1)
RDF (−4 inch)	Did not form cohesive pellet
Sawdust	Did not form cohesive pellet

EERC Design for Non-Plug-Forming Feeder

Feeding biomass into pressurized atmospheres up to 2.93 MPa (425 psig) using a plug-screw feeder or possibly the CO-AX feeder may be successful in the near term. However, as mentioned previously, the question remains as to the suitability for feeding biomass to entrained-flow or fast fluid-bed gasifiers where the particles must be of a sufficiently small size to be carried upward in the reacting gas stream. These systems may be unsuitable if degradation of the densified biomass "plug" back to a size near that of the feedstock cannot be achieved. Particle size may not be as critical with a down-fired gasifier as long as the reactor length is sufficient to achieve complete fuel reaction. With a down-fired gasifier, however, the choices of feed system approach may be more limited owing to the necessity of having the feed system located at the top of the gasifier.

To this end, preliminary consideration was given to a feed system that will not irreversibly densify the feedstock and is applicable across a range of biomass types. What is proposed is actually a conjoining of two developmental systems: the Ingersoll–Rand coaxial piston feeder and the Fortum Piston Feeder (Figures 52 and 53, respectively). Further, based on reported data for these two systems, the specific power requirements may be considerably less that required with a plug-forming system. A conceptual drawing of the proposed system is presented in Figure 56 and includes a metering-type bin that is used for feedstock surge capacity and controlled delivery of fuel to the gasifier.

In an attempt to present the functionality of the proposed feed system, a three-dimensional image was created using AutoCad with movement of the parts imparted using Visual Nastran 4D. A movie clip animation was then produced to show the complete fuel charging and high-pressure feeding sequence. An animation of the proposed feed system can be found at the following link: http://www.undeerc.org/clips/FeederConcept.avi.

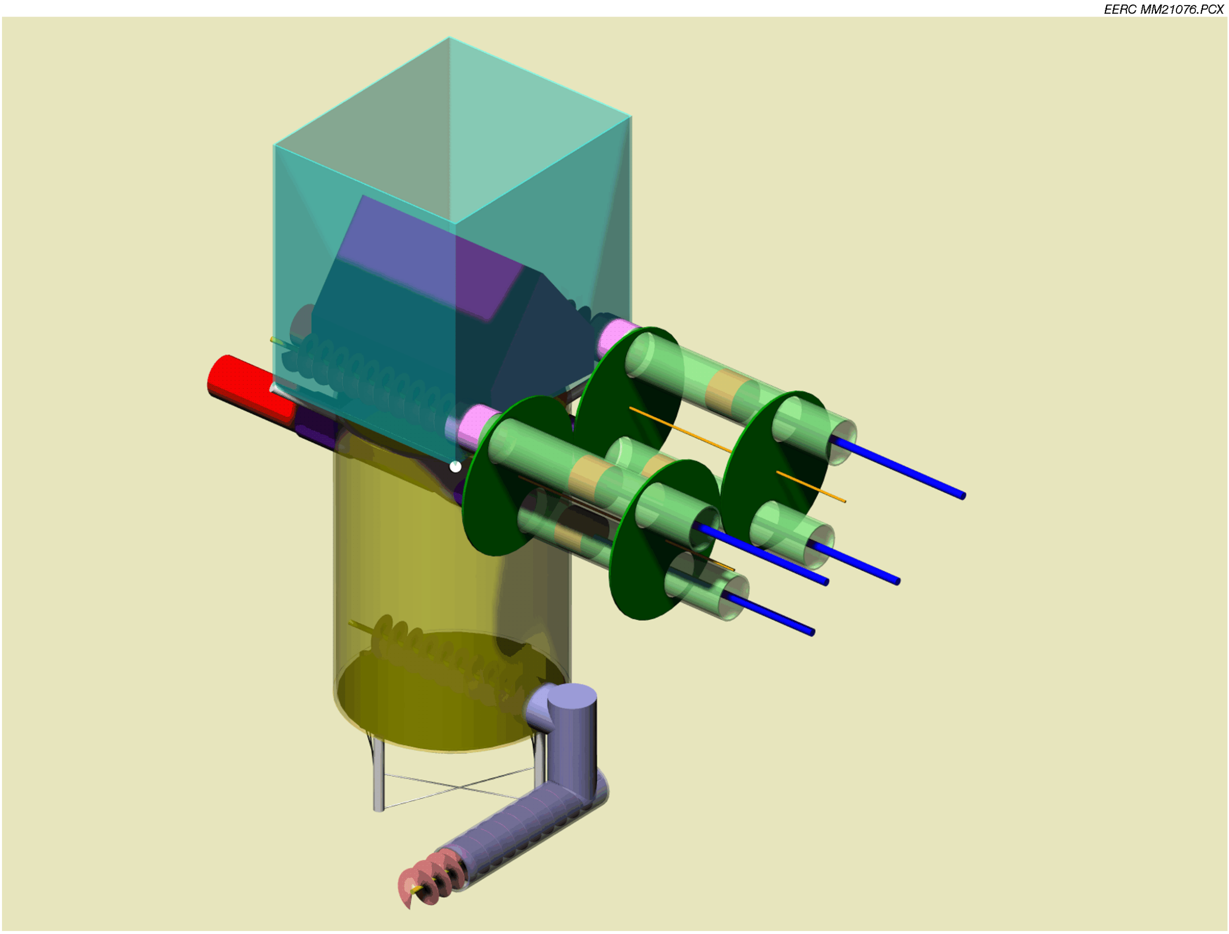

Figure 56. Proposed high-pressure feed system for biomass.

Theoretically, the Ingersoll–Rand coaxial piston feeder would seem, by itself, to be a good system for additional developmental activities with biomass. The perceived drawback of the coa xial feeder (according to the author) would be the inability to reliably charge the nonflowable, cohesive and, often times, stringy biomass materials into the material cylinder using the existing gravity-feed system. The system would require dense, granular materials such as briquetted or pelleted fuels or, possibly, wood chips (but not mulch) – fuels not suitable for entrained-flow or fast fluid-bed systems. The Fortum Piston Feeder, as previously described, has similar functionality to the coaxial feeder but uses a precompression screw to force the biomass into the material cylinder.

The perceived drawback to the Fortum feeder (according to the author) is the use of a valve to provide pressure sealing between the metering-type bin and the material cylinder. For this process, there appears to be a period in which the piston is just clearing the valve, but the valve is still open. During this period, gas pressure would have a chance to backflow from the metering bin. The density of any biomass still in the pipe between the valve and the metering bin would be insufficient to prevent gas backflow. Further, the reliability of a valve gate or ball to "cut through" a biomass charge in the material cylinder, and still provide pressure sealing, may be low.

The proposed system incorporates the "gas exclusion" piston of the coaxial feeder to replace the valve of the Fortum feeder. With two pistons in use, the sequencing of fuel charging and feeding across the pressure boundary will always be such that one piston is always positioned in the material cylinder (on the metering bin) to prevent gas backflow. The "gas exclusion" piston would be used to introduce pressure equalization gas, although the Fortum system claimed it is not needed. Further, it is envisioned that the metal surfaces at the interface between the material cylinder on the metering bin and the rotating material cylinders will be constructed of a highly wear-resistant material that may actually "wear in" during cycling to maintain a good gas seal. This wear-resistant material would also be required to "clip" the biomass, as necessary, during rotation of the material cylinders. The enclosure at the interface would be equipped with a gas vent or vacuum system to control small emissions of mostly inert gas.

The system presented in Figure 56 incorporates two parallel charging systems feeding a single metering bin. The metering bin is coupled to the gasifier via a high-speed injection auger for final fuel delivery. Based on assumed cylinder dimensions of 406-mm (16-inch) ID × 2-m (6.6-ft) length, the total mass rate for a 160-kg/m^3 (10-lb/ft^3) bulk density, 15,900-kJ/kg (6800-Btu/lb) heating value biomass would be 14.5 metric ton/hr (15.9 short tons/hr), sufficient to provide 10% of the thermal input to a Wabash River-sized gasifier. The cycle time to complete fuel charging and feeding across the pressure boundary would be approximately 20 seconds, with approximately 5 of those seconds required for a 406-mm (16-inch) screw rotating at 60 rpm to precompress the fuel into the material cylinder.

It should be noted that aside from the ⅛-inch E-grass and the ¼-inch switchgrass, the biomass feedstocks sized for feeding to entrained-flow or fast fluid-bed gasifiers would have spill densities below 160 kg/m^3 (10 lb/ft^3) – see Table 29. The utility of the precompression screw to achieve this density was demonstrated with a simple system, shown in Figures 57 to 60. The system utilized a 76.2-mm (3-inch)-diameter standard-pitch screw in a carbon steel pipe housing to charge and compress select biomass feedstocks into a 0.91-m (3-ft)-long transparent PVC pipe. The screw was

EERC MM21054.PCX

Figure 57. Precompression screw apparatus – discharge of compression screw.

EERC MM21055.PCX

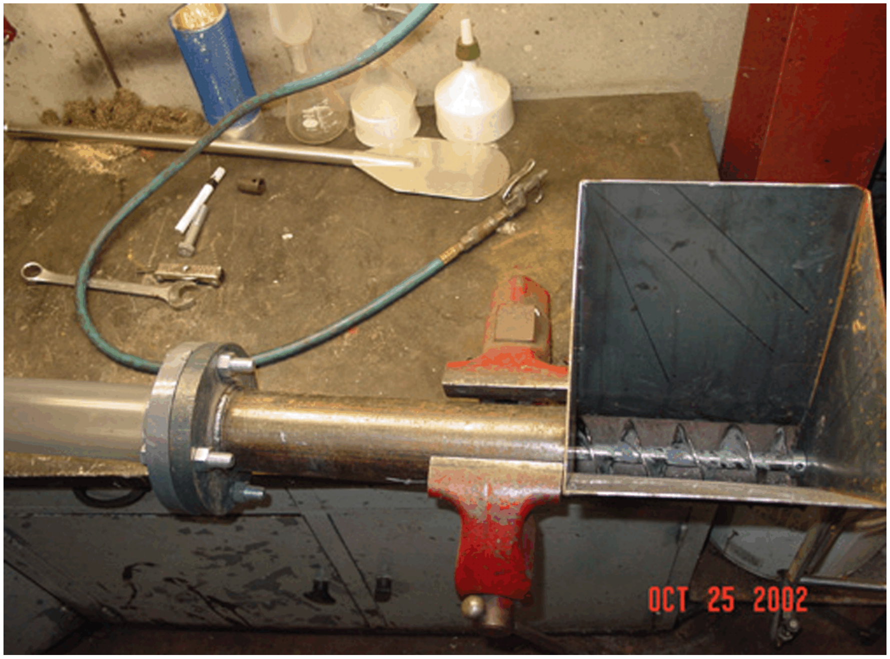

Figure 58. Precompression screw apparatus – feed hopper and compression screw.

Figure 59. Precompression screw apparatus – transparent material cylinder.

Figure 60. Precompression screw apparatus – handle for manual operation.

manually turned, with feeding stopped when the screw became difficult to turn with one hand. The original intention was to utilize a torque-wrench to measure the maximum torque required for the measured level of densification, but this was not done. The bulk density of the compressed biomass was calculated from the volume of the transparent pipe and the measured weight of the biomass compressed within. The results in Table 34 indicate the calculated bulk densities for almost all biomass materials attained or exceeded the nominal 160 kg/m^3 (10 lb/ft^3). The increase in bulk density ranged from as low as 52% with ¼ switchgrass to over 100% with one sample of sawdust. Any increase in bulk density over 160 kg/m^3 (10 lb/ft^3) would also produce a proportional decrease in feed system size or cycle rate. Another benefit to precompression of the biomass is a theoretical reduction in pressure equalization gas over that required, for example, with a lock hopper system. The reduction in pressurization gas would be directly proportional to the increase in the biomass bulk density due to precompression relative to the spill bulk density that would characterize the biomass in a lock hopper.

Design and Cost Analysis for RDF Preparation and Feed System

A fuel preparation and feed system, based on the use of −4-inch RDF, was designed with RDF selected as a fuel because of the significant availability of municipal refuse. It was assumed, for this preliminary design effort, that the RDF preparation facility was adjacent to or in close proximity to a Wabash River-sized gasifier.

Estimation of RDF-Processing Rate

To facilitate sizing and eventual capital cost estimation of the RDF processing and high-pressure feeding equipment, the mass rate of RDF was estimated. For purposes of calculation, the following assumptions were made:

As-received RDF heating value	5500 Btu/lb
Fuel input	40 tons/hr (20% of Wabash River thermal input)

The mass rate of 40 tons/hr was used as the throughput of all major unit operations, and no corrections were made for losses during subsequent cleaning, size reduction, or thermal drying.

Major Unit Operations

Based on visual inspection of the RDF and assumed fuel properties necessary for feeding, the following major unit operations were incorporated into the proposed feed system design:

- Nonferrous removal – to principally remove and recover aluminum. Recovery of aluminum, which is present in high concentration (1 wt%), would provide an added revenue stream as well as reduce any operational problems that could be associated with this low-melting-temperature material.

Table 34. Compaction of Various Biomass Feedstocks Using Precompression Screw

Material	Density, lb/ft^3	Level of Compaction
Corn Stover		
¼-inch Screen	6.7	Loose
	8.4	Shaken
	11.3	Compressed
½-inch Screen	4.8	Loose
	7.3	Shaken
	8.1	Compressed
Switchgrass		
¼-inch Screen	10.0	Loose
	13.2	Shaken
	15.2	Compressed
½-inch Screen	7.9	Loose
	11.8	Shaken
	12.2	Compressed
Urban Wood Waste		
¼-inch Screen	8.0	Loose
	12.5	Shaken
	13.9	Compressed
Cedar Sawdust	7.3	Shaken
	9.8	Compressed
E-Grass	9.8	Loose
	13.9	Shaken
	16.1	Compressed
Wet Sawdust	12.9	Loose
	23.7	Shaken
	25.2	Compressed
Sawdust/Shavings	7.0	Loose
	11.9	Shaken
	15.0	Compressed

- Gravity separation – to remove glass, ceramic, rock, and ferrous items that contribute to wear of downstream unit operations such as mills, rotating equipment, and high-pressure feeders. Further, glass is a low-melting temperature material that could result in slagging and other agglomeration issues.

- Size reduction – to reduce the material from a nominal size of minus 4 inches to minus 2 inches to improve utilization within rotating equipment such as screws and to improve entrainability.

- Thermal drying (may be excluded) – to reduce moisture content of the RDF from a nominal 30 wt% to less than 15 wt%.

- High-pressure feeding – to move RDF at a controlled rate from ambient pressure to across the pressure boundary (425 psig).

- Metering bin – to provide surge capacity and uniform metered feeding of biomass to the process.

Other unit operations that are required are conveyors for transporting RDF between major processing steps and a system for measuring mass flow rate or providing total mass.

Vendor Discussions

One or more vendors were approached for each of the major unit operations. For each vendor, the following specifications were provided:

- RDF processing rate: 40 tons/hour
- Primary constituents: paper, cardboard, plastic film (such as that from grocery store bags)
- Minor constituents: glass (2%), wood (3%), dense plastic (3.5%), grit (2%), aluminum (1%), ferrous (1%)
- Moisture content: 30 wt%
- Input size: minus 4 inch for cleaning and size reduction, minus 2 inch for thermal drying and feeding
- Spill bulk density: 6 to 8 lb/ft^3

The information desired from each vendor included the following:

- Cost per system (including controls)
- Power requirements
- Annual maintenance cost
- Frequency of major repair
- Turnaround time for major repair

In addition, drying system vendors required submission of a detailed questionnaire. The major unit operations and the respective vendors contacted were as follows:

- Non-ferrous removal

  - Eriez Magnetics – marketer of eddy current separation systems

- Gravity separation

  - General Kinematics – marketer of Gravity Destoner with Single Air Knife
  - Forsberg, Inc. – marketer of Air Classifer
  - Karl W. Schmidt & Associates, Inc. – marketer of Air Classifier Vacuum Separator

- Size Reduction

  - American Pulverizer Company
  - Marathon Equipment Company
  - Williams Patent Crusher & Pulverizer Co.

- Thermal Drying

  - Heyl & Patterson, Renneburg Division
  - Barr-Rosin, Inc.

- High-Pressure Feeding

  - Metso Corporation – marketer of plug-screw feeders (formerly Sunds Defibrator) for continuous thermochemical wood pulping

  - Stake Technology Ltd. – marketer of CO-AX Feeder for thermomechnical wood pulping

  - Fortum – technology rights holder for “Piston Feeder for Solid Fuels”; developed by company formerly known as Imatran Voima Oy

  - TR Miles Technical Consultants Inc. – marketer of lock hopper system with metering bin

Not all vendors, unfortunately, were entirely enthused or complete with respect to the data request. Estimates for capital and annual maintenance costs as well as for power and other utilities (e.g., Btus for fuel drying) are presented in Table 35. The cost estimate from TR Miles is presented in Appendix G. The range of costs for size reduction reflects the essentially nonexistent experience within the United States concerning preparation of material to 51 mm (2 inches) and under. The lowest value of 225 kW (300 hp) is based on the use of a low-speed shear shredder. The highest capital high-pressure feeder would be the plug-screw feeder system (+$3 million) and the CO-AX feeder system ($4.9 to $6.6 million) where three to four CO-AX feeders would be required. The lock hopper system proposed by Miles has the lowest quoted capital cost, but this excludes the capital cost for a potentially necessary predensification system. The sophistication of the Fortum feeder would suggest a price comparable to the plug-screw feeder or the TK Energi three-stage piston feeder at $2.5 to $3.0 million for a two-parallel feed-line system. The horsepower for the high-pressure feed system would range from 525 kW (700 hp) for the lock hopper system to 1350 kW (1800 hp) for the plug-screw feeder. The power requirement for the CO-AX feeder may be a third or less of that of the plug-screw feeder. The majority of the power requirement for the lock hopper

Table 35. Cost and Utility Estimates for Major Unit Operations in RDF Feed System

Unit Operation	Capital Cost, $1000	Maintenance Cost, $1000	Power, hp (kW)	Btu/hr
Non-Ferrous Removal	300	10–20	(50)	NA[1]
Gravity Separation	92	4–5	106	NA
Size Reduction	782–1680	53–239	300–2400	NA
Thermal Drying	1480	74	350	30 MM
High-Pressure Feeding	1660–6600	82–330	700–1800	NA
Conveyors/Metering Hoppers	1000–1200	4–5	100	NA

[1] Not applicable.

system is for compression and recycling of pressurization gas. Data from Fortum suggests that the power requirement for a two-parallel feed-line system would be approximately 200 kW (270 hp), not including pressurization gas. A 40% reduction in pressurization gas volume owing to precompression of the fuel with the Fortum system would produce a power requirement similar to that of the lock hopper system.

Alternative Processing Methods for MSW/RDF

The processes discussed for upgrading RDF to a viable gasification feedstock may not provide the best or only option for use with entrained-flow or fast fluid-type gasifiers. Two processes for producing RDF that warrant further investigation include the solid waste energy recycling facility (SWERF) process being advanced by Brightstar Environmental (91) and the Spiralclave process being advanced by Komar Industries (92). Both processes are being touted for application to a mixed refuse stream, that is unsorted waste. The intent would be to eliminate curbside sorting or the utilization of separate material recovery facilities (XRF) to separate recyclables from the municipal waste stream.

The description of both processes is similar. The waste, including all recyclables, is batch-processed using saturated steam at temperatures around 140°C (285°F) to essentially "sterilize" the waste. The degraded, "pulp-like" material is then subjected to traditional size and gravity separation techniques to recover glass, ferrous, aluminum, and plastic. Brightstar Environmental intends to employ the SWERF process in conjunction with their own gasification technology to produce power. Presently, the process is being employed in Australia and the UK where high landfilling costs provide economic justification to the process.

The attractiveness of the process for this respective study is that the pulp-like product may be of a size consistency more readily applied to entrained-flow or fast fluid-bed gasifiers. Although the process descriptions for both processes are vague, the mechanical processing (without size reduction), sterilization, and pulp drying may produce an entrainable material. Both companies were contacted to provide a sample of their respective products as well as economic information, but neither were able or willing to assist in this regard (93, 94).

CONCLUSIONS

- Several potential alternative fuels were evaluated as potential feedstocks, including sewage sludge, used railroad ties, UWW, MSW, and used waste tires/TDF. Fuels with potential tipping fees were considered the most favorable feedstocks.

- Based on the feedstock assessment, sewage sludge was selected as one of the primary feedstocks for consideration at the Wabash Plant. The results show that MSW, UWW, and railroad ties could also provide an equivalent thermal input as a gasification feedstock, although the availability of zero to negative value feedstock would presumably be substantially higher with the MSW. This would require a dry feed system which could process the RDF/UWW down to sizes small enough to be entrained in the second stage of the E-Gas gasifier. The cost of processing these types of fuels to a $^{-}$3/16 inch size or smaller could increase the fuel costs to as much as \$2/MMBtu, however, thereby precluding their economic utilization.

- Because of the limited waste heat available for drying and the need for the gasifier to operate with alternative feedstocks at up to 80% moisture, a decision was made to investigate a pumping system for delivering the as-received fuel across the pressure boundary.

- High-temperature drop-tube furnace tests were conducted to determine if explosive fragmentation of high-moisture sludge droplets could be expected, but testing showed that these droplets underwent a shrinking and densification process that implies that the sludge will have to be well dispersed when injected into the gasifier.

- A high-pressure feed pump and fuel dispersion nozzles were tested for their ability to cross the pressure boundary and adequately disperse the sludge into the second stage of the gasifier. The results suggest that it is technically feasible to get the sludge dispersed to an appropriate size into the second stage of the gasifier although the recycle syngas pressure needed to disperse the sludge would be higher than originally desired.

- The installed capital costs for a system located at Wabash River were estimated at approximately \$9.7 million, within an accuracy of ±10%. An economic analysis indicates that in order to justify the additional capital cost of the system, Global Energy would have to receive a tipping fee of \$12.40 per wet ton of municipal sludge delivered. This is based on operation with petroleum coke as the primary fuel. Similarly, with coal as the primary fuel, a minimum tipping of \$16.70 would be required. The availability of delivered sludge from Indianapolis, Indiana in this tipping fee range is unlikely; however, given the higher treatment costs associated with the sludge treatment in Chicago, Illinois, delivery of sludge from that area, given adequate rail access, might be economically viable.