previously discussed. The municipal sludge from the PAD could possibly be slurried and fed using existing equipment at Wabash River. Consequently, Dr. Alan Propp of Gulftex Environmental was contacted to determine the availability of PAD-produced municipal sludge to perform slurry tests at the EERC (60). However, they did not have any material available and, further, did not have an existing pilot facility to perform any drying tests.

A technology similar to the PAD is also being applied by a company called Creative Waste Management (61). This company may actually utilize the PAD and perform contract waste remediation services.

DRY BIOMASS FEED SYSTEM

High-Pressure Feeding Systems: Classification and Status

A number of commercial and developmental systems have been implemented for feeding materials across pressure boundaries into reactors or processing systems that operate at elevated pressures. Some of these systems have their origination in the processing of coal while others have been commercially used for processing of wood or agricultural fibers in the pulp and paper industry. Several of these systems have been utilized at the demonstration scale in biomass gasification systems both in North America and abroad. An attempt has been made to provide an overview of the main classifications of high-pressure feed systems that have been designed and utilized at the pilot or demonstration scale. Within these classifications, specific systems will be described. Background information has recently been compiled by the National Renewable Energy Laboratory (NREL) as part of an effort to determine feeding equipment that may be applicable to biomass hydrolysis systems (62). The study built off of a Technical Research Centre of Finland (VTT) study (63). Information on systems that were not discussed within or developed subsequent to these two studies has been added in this report.

For the purposes of this project, the four primary categories of pressurized feed systems include:

- Lock hoppers
- Rotary feeders
- Plug-forming feeders
- Non-plug-forming feeders

The classifications of feeder systems as presented by NREL and the VTT included piston feeders and screw feeders as distinct and separate categories; discussion of their functionality follows in a later section. Review of all screw feeders indicated their method of pressure sealing, through the formation of dense, mostly imperable plug, to be akin to that of several of the piston feeders. Further, some of the piston feeders incorporated both piston and screw functionalities. The remainder of the piston feeders did not rely on the formation of a pressure sealing plug but rather on the sealing of the piston surface against the material cylinder in which they operated. A further advantage of the reclassification used herein was to separate systems that may be limited to specific pressurized gasification/combustion systems, e.g., fluid bed, fast or circulating fluid bed, or entrained flow. It should be stated that a one-size-fits-all approach to feeding is probably not attainable, but the selection of feed system will be driven by the available feedstock, its physical properties, and the conversion process being fed.

Consequently, Table 24 presents four feed system categories, as identified by the author, and specific examples and vendors for the systems. The commercial or developmental status, as understood by the author of this report, is also indicated. The advantages and disadvantages of each feed system, as advanced by the Elander study and modified in light of updated feed system information, are presented in Table 25. Applications of several of these systems with respect to elevated pressure biomass gasification or combustion are discussed in a later section.

Lock Hopper Systems

Lock hopper systems operate on the principle of intermittent charging or feeding across the pressure boundary, typically by the staged opening and closing of valves on the top and bottom of the charged pressure vessel. For this system, the top valve is opened to receive material into the lock hopper while the bottom valve is maintained in a closed position. After the top valve is closed, the lock hopper is brought to or above system pressure, typically with an inert gas. Following pressurization, the bottom valve is opened, and the material is allowed to discharge to the process. Following emptying of the lock hopper, the bottom valve is closed and the vessel depressurized to allow another cycle. Dual or parallel lock hoppers may be employed to allow one lock hopper to be on-line, that is, discharging at pressure to the process, and allow the other lock hopper to be in the filling and pressurizing modes.

Original lock hopper designs were based on gravity discharge of a mostly free-flowing, dense, granular, dry material, such as coal (pulverized or crushed), chipped wood (not hogged), or pelleted fuel. Lurgi employs a conical valve system for the fixed-bed coal gasification systems. The Macawber Engineering Controlveyor™, shown in Figure 37, is actually a component within a pneumatic conveying/injection system (64). Again developed for dense, free-flowing powder, granular, or lump materials, Macawber claims feeding accuracies of 0.5%, applicability for powders to lumps (<50 mm), and delivery into system pressures up to 450 psig. Feed rate capacities range from less than a pound per minute to more than 1 ton per minute. The system has been used in the metal industry for applications such as fuel feeding to cupolas and blast furnaces. Discussions with the vendor (and its European counterpart Mactenn), however, revealed no experience with biomass regardless (65), and Macawber has no systems in development for pressures over 150 psig. As the system incorporates a series of conically shaped hoppers, the likelihood of reliable flow between hoppers with stringy, cohesive, bridging biomass is probably low. Macawber does not have Controlveyor systems for off-site evaluation. Testing capabilities at Macawber do not include actual demonstration with a Controlveyor system but rather consist of evaluation of parameters for pneumatic conveying of the selected materials.

Table 24. Classifications of Pressure Feed Systems

Classification/System Example	Application	Comment
Lock Hopper		
Lurgi	Coarse coal, 450 to over 1000 psig	Commercial
Macawber Controlveyor (pneumatic injection)	Coal, minerals, over 100 psig	Commercial
Miles Biomass System	Low-density, biomass, designs to 450 psig, 10 tons/hr	Commercial
Cratech Biomass System	Low-density, biomass, 150 psig, current 1 ton/hr	Developmental
Rotary Feeders		
Andritz Rotary Valve	Sawdust, up to 200 psig, +40 tons/hr	Commercial
Asthma Feeder	Sawdust, 150 psig, 50 tons/hr	Commercial
Plug-Forming		
Stake Technology CO-AX Feeder	Wood chips (15 tons/hr), straw chips (9 tons/hr), 180 to 400 psig	Commercial
TK Energi 3 Stage Piston Feeder	Wood chips (8 tons/hr), straw (4 tons/hr), 350 to 600 psig	Developmental
Plug Screw Feeder	Wood fiber (+20 tons/hr), wood chip (50 tons/hr), 150 psig	Commercial
Ingersoll-Rand Reciprocating Screw Feeder	Coal, less than 3 tons/hr, 725 psig	Developmental
Vattenfall Screw-Piston Feeder	Straw and peat, less than 4 tons/hour, 350 psig	Developmental
Werner and Pfleiderer Feeder	Coal (+15 tons/hr), sawdust (tested at 2 tons/day), 1500 psig	Commercial
Sugar Research Institute (Australia)	Bagasse	Developmental
Posimetric Feeder	Coal (near ambient, tested to 210 psig), minerals	Commercial
Non-Plug-Forming Feeders		
Ingersoll-Rand Co-Axial Piston Feeder	Coal up to 1", 2.5 tons/hour, 500 psig (tests), 1500 psig (design)	Developmental
Fortum Piston Feeder for Solid Fuels	Wood chips, 3.5 tons/hour, 350 psig	Developmental
Foster-Miller Linear Pocket Feeder	Coal up to 1", 5 tons/hour, 1000 psig	Developmental

Table 25. Advantages and Disadvantages of Feed Systems

Classification	Advantages	Disadvantages	Comment
Lock Hopper	Simple Does not compact feed Can handle wide-ranging particle size Low power consumption for associated valves and screws	Large (tall) vessels due to long cycle times Pressurization gas required with "high" compression cost Noncontinuous feed Poor lock valve reliability with dusty, wet feed stocks	Most effective with flowable feedstocks such as chips and pelleted fuel Recent designs (e.g., Miles) can reduce gas consumption
Rotary Feeder	More continuous feed with good rate control Small size relative to throughput Low power consumption Can handle a variety of feedstocks	Feed bridging above valve Pressurization gas required Sticking of fuel in pockets can require "chasing" to dislodge feed leading to higher gas consumption	Less use of pressurization gas due to recirculation
Plug-Forming Feeder	Continuous to near-continuous feeding Can handle wet, sticky, and low-density materials No to little consumption of pressurization gas	High frictional forces leading to wear and high specific power consumption (kW/ton per hr) Densification of fuel may lead to agglomerates too large for utilization in the process	Specific power consumption for piston-type systems appears lower than screw-type
Non-Plug-Forming Feeder	No agglomeration of fuel, leaving particle density/size intact	Pressurization gas required in some designs Noncontinuous feeding	Pressurization gas less than lock hoppers and rotary valves owing to fuel compression Probable lower specific power consumption and wear relative to plug-forming feeders

Figure 37. Macawber Controlveyor pneumatic feed system.

For less or non-free-flowing materials, the Miles lock hopper system has been developed (Figure 38). This system employs diverging (bottom opening is larger than top opening) wall lock hoppers that resemble long, narrow pipes rather than short pressure vessels with conical bottoms. In the Miles system, the cycle of material filling, pressurization, and discharge is as previously described. However, the material discharges into a "metering bin" which functions to provide surge capacity, flow leveling, and isolation from the process. A series of metering screws function to provide "calibrated" discharge of material to a water-cooled injection auger which delivers the fuel to the process. The Miles system was designed specifically for feeding biomass to gasification and combustion processes. The Miles system has been successfully used in a number of gasification applications, including the feeding of wood chips at 3.1 MPa (450 psig) to a 7-ton/hour system in Clamecy, France, and has been used in conjunction with several developmental and demonstration gasifiers of the Gas Technology Institute (GTI) (66). A more recent application has been in conjunction with a sugarcane bagasse gasification project in Hawaii (67). Miles has estimated specific power requirements for a double lock hopper system operating at 3.1 MPa (450 psig) to be approximately 20 hp per ton/hour of biomass processed based on a feedstock bulk density of 160 kg/m^3 (10 lb/ft^3); the volume rate of gas is 69 scfm per ton/hr. These values increase by approximately 50% when using a single lock hopper system.

Another lock hopper system under development is that of Cratech (Figure 39). Cratech has been developing a biomass integrated gasification gas turbine (BIGGT) for about 10 years. They

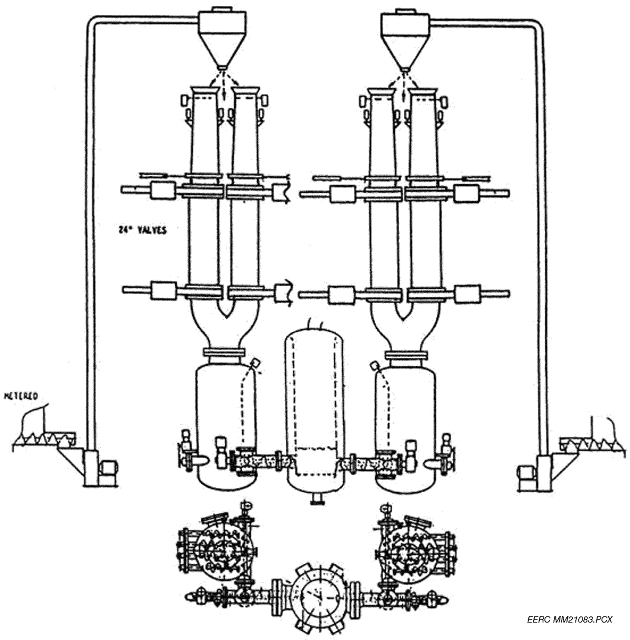

Figure 38. Miles biomass lock hopper feed system.

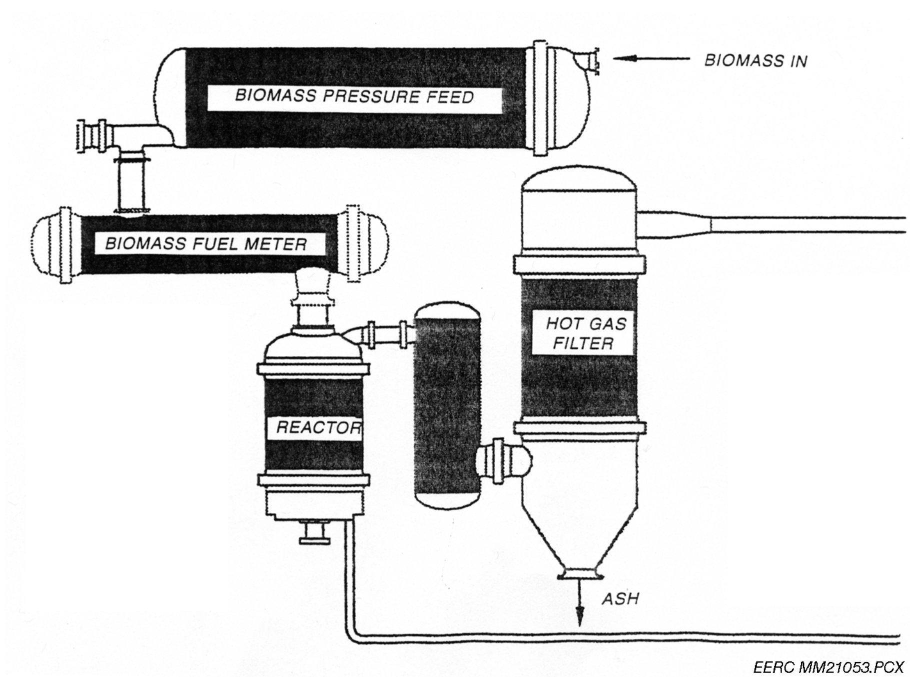

Figure 39. Cratech biomass feed system.

currently have an operating gasifier that can handle fuel at about 909 kg/hr (2000 lb/hr) and operate at 150 psig with a max 200-psig operating pressure. Cratech intends to develop a system for feeding 20 tons per hour of biomass material, with minimum density of about 110 kg/m^3 (7 lb/ft^3) into a 300-psig pressure vessel (68). They believe that higher feed rates and pressures could be attained. Cratech has logged 350 hours on cotton gin trash and about 60 hours on wood chips. The system consists of pressurized feed hoppers, gasifier, and metal filters for hot-gas cleanup.

All testing to date has been carried out at 2 atmospheres. The system includes a horizontal lock hopper with a screw auger for positive mechanical discharge. The biomass is pneumatically charged to the lock hopper; air flow rates of 20 ft^3 per minute for each pound/minute of biomass throughput is required for pneumatic conveyance. The lock hopper discharges to a horizontal metering bin that can incorporate a weigh belt feeder for biomass conveyance and mass rate control; the method of conveyance from the metering bin can also be a screw conveyor (69). Discussion of the Cratech system can be found in U.S. Patent 5,666,890.

Rotary Feeders

Rotary feeders and variants called star valves are simple devices used for both dry solid and slurry feeding across pressure boundaries. These systems incorporate a single to multivaned/pocketed rotor within a pressure-containing housing. Pressure sealing is achieved by metal-to-metal contact between the vanes and the valve housing. Feed material is charged through an opening in the top of the housing with the throughput controlled by the rotational speed of the rotor. Pressure equalization with the process is typically accomplished by adding a fluid at or above system pressure. As these feeders find their primary application in the wood (chip and sawdust) pulping industry, the pressurization gas is typically steam, a necessary component of downstream processing. Intermediate gas pressures are attained by recovering vent gas from the "back" of the valve and recycling to the filled pocket or pressure-building side. When the pockets are aligned above the bottom discharge on the housing, the material falls via gravity; a steam "chase" may be necessary to clear out the pockets when feeding sticky materials.

The feeder that has the most relevance to the current activities includes the Andritz/Ahlstrom rotary feeder, shown in Figure 40 (70). This feeder is used on the M&D inclined digestor (for sawdust pulping) and is used for pressure differentials of 150 to 170 psig. Pictures of a rotary valve are shown in Figures 41–43. This system, employed at a West Coast pulp and paper facility, is capable of feeding approximately 200 dry tons per day of sawdust. A feature of this rotary feeder is the longitudinal taper of the rotor and housing; that is, the rotor forms a plug within the housing. This geometry allows the user to maintain an "effective" seal even as the rotor and housing "wear in." As the rotor and housing wear, the rotor can be incrementally adjusted along the axis within the housing to maintain a proper metal-to-metal seal. The torque of the drive motor for the rotor is continually monitored; operational experience is used to relate the motor torque to the level of back leakage. The adjustment of the rotor within the housing can be completed remotely (from the control room) without human intervention. Discussions with an Andritz representative indicated that valve designs are available for 1.38 MPa (200 psig) differential at up to 500 tons/hr. The company has not performed any development with series-staging of rotary valves but thought that a rotary valve/screw

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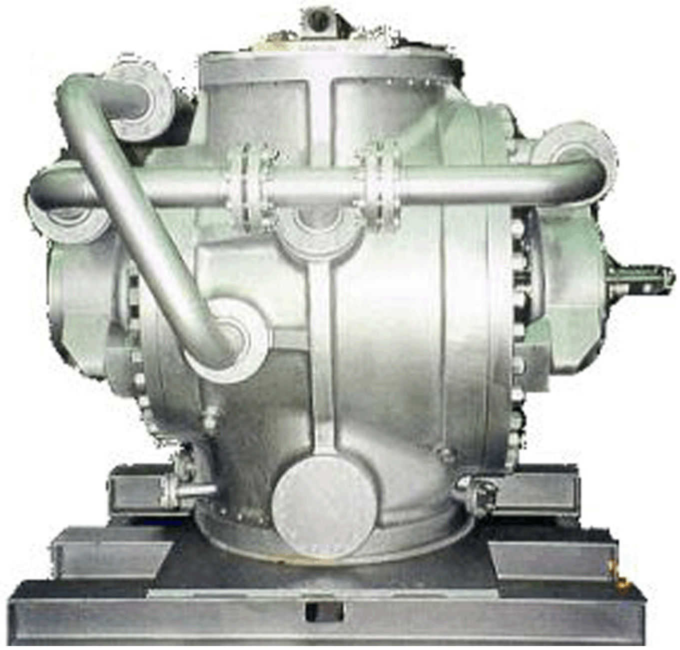

Figure 40. Andritz rotary feeder.

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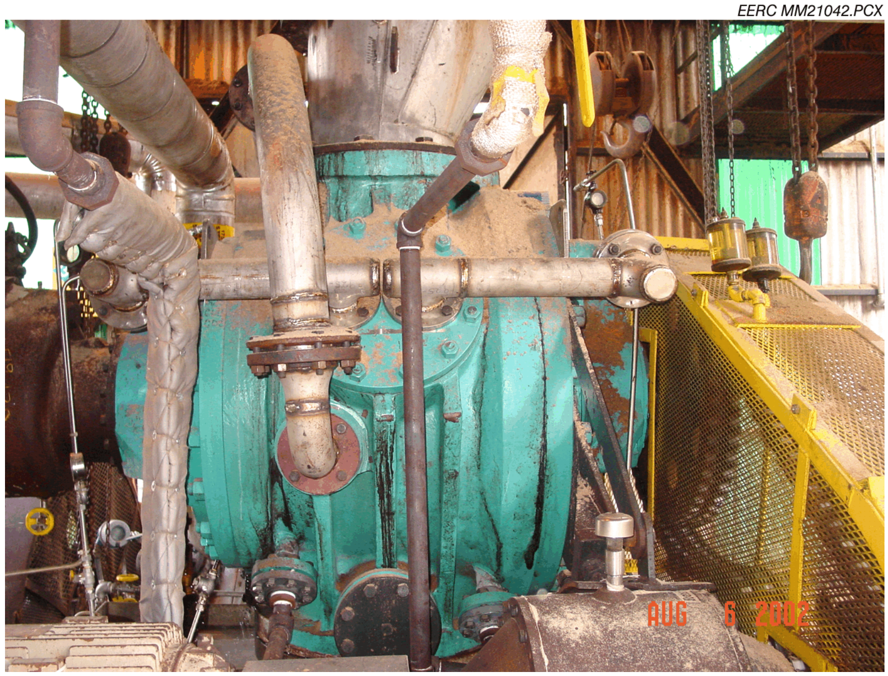

Figure 41. Rotary feeder used in sawdust pulping process – side view.

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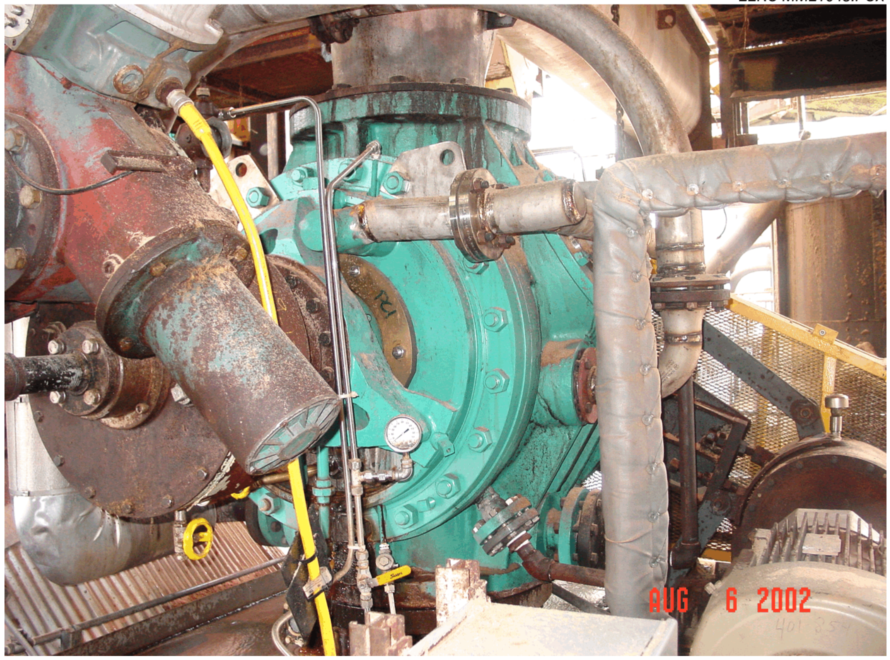

Figure 42. Rotary feeder used in sawdust pulping process – end view.

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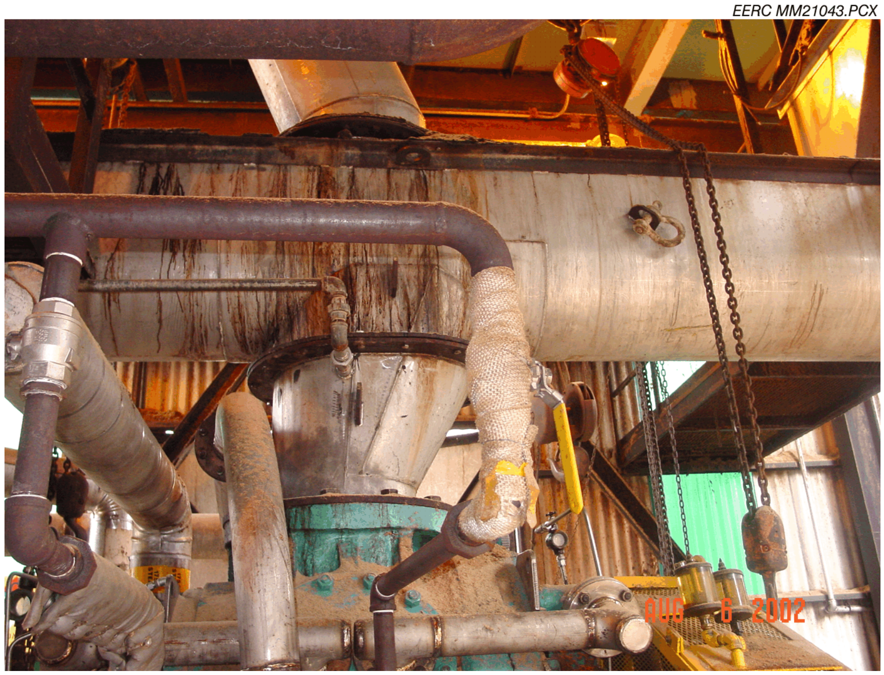

Figure 43. Rotary feeder used in sawdust pulping process – view of sawdust charging system.

combination could be possible. An issue with the rotary valves at high pressure included machine deflection. A rotary valve feeding 20 dry-tons/hr of sawdust at 20 rpm weighs between 9090 and 11,400 kg (20,000 to 25,000 lb) and costs approximately $500,000 (71).

One additional design of the rotary valve is the asthma feeder, a single-pocket design. The asthma feeder, typically used with sawdust, requires a high-pressure steam chase to empty the cavity. Material discharge is discontinuous owing to the single pocket.

Plug-Forming Feeders

The plug-forming feeders comprise the group with the most significant commercial application and developmental activities in systems for the feeding of dry solids to processes operating at elevated pressure. Current commercial application of the plug-forming feeders is strictly within the biomass industry, i.e., pulping of woody or herbaceous materials for paper production. Systems such as the Metso Corporation (formerly Sunds Defibrator) and Andritz/Ahlstrom plug screw feeders are commonly used in conjunction with continuous digesters in the wood-pulping industry. These systems are applied to both wood chips and lower density wood fiber. Development activities exist to use plug-forming feeders in the newly emerging biomass hydrolysis (for ethanol production) industry, although current designs will apparently utilize commercial plug-screw feeders.

Figure 44 presents a schematic cutaway diagram of a Metso Corporation plug-screw feeder (72). This and the Andritz system are variable area feeders that rely on the taper of the screw and "throat" to densify the feed. Pictures of a plug-screw feeder operating at a West Coast pulp and paper plant are shown in Figure 45. Feed to these systems is accomplished via gravity in the case of wood chip feeding (Figure 46) and by vertical "stuffing" screws in the case of low-density wood fiber. After entering the feeder, the screw advances the chips (or fiber) through the throat causing the densification force to partially dewater the feed; in the case of chips, the as-fed moisture content may be 50 wt%, some of it surface moisture. The throat is typically equipped with removable perforated plates to allow moisture drainage (Figure 47). Further, the throat is equipped with a vent to allow moisture vapor and gas escape. After passing through the throat, the feed enters a cylindrical plug pipe (Figure 48) where additional moisture drainage and densification occur. The resistance in the plug pipe to cause additional densification is provided by a device called the blow back damper. The additional densification imparted by the resistance of the damper is depicted in Figure 49. The acting end of the damper is conically shaped and rides on the face of the feed plug. As the cantilevered screw extends to the end of the plug pipe, the biomass exits with a "doughnut" shape. In case the plug loses its "integrity" (i.e., density), the resisting force of the blow back damper is sufficient to compress the plug to the point where the damper closes against the plug pipe exit and seals against backflow of gas and steam. The damper also functions to break up the biomass plug.

Plug-screw feeders produced by Metso and Andritz range in capacity from 500 tons/day for 400 mm (16 inch), 800 tons/day for 500 mm (20 inch), to 1200 to 1800 tons/day for 600-mm (24 inch) systems feeding wood chips. For lower-density fibers, such as waste from medium-density fiberboard (MDF) plants, capacities for the 16- and 24-inch feeders drop to 300 to 500 tons/day, respectively.