FEED SYSTEM INNOVATION FOR GASIFICATION OF LOCALLY ECONOMICAL ALTERNATIVE FUELS (FIGLEAF)

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FEED SYSTEM INNOVATION FOR GASIFICATION OF LOCALLY ECONOMICAL ALTERNATIVE FUELS (FIGLEAF)

ABSTRACT

The Feed System Innovation for Gasification of Locally Economical Alternative Fuels (FIGLEAF) project was conducted by the Energy & Environmental Research Center and Gasification Engineering Corporation of Houston, Texas (a subsidiary of Global Energy Inc., Cincinnati, Ohio), with 80% cofunding from the U.S. Department of Energy (DOE). The goal of the project was to identify and evaluate low-value fuels that could serve as alternative feedstocks and to develop a feed system to facilitate their use in integrated gasification combined-cycle and gasification coproduction facilities. The long-term goal, to be accomplished in a subsequent project, is to install a feed system for the selected fuel(s) at Global Energy's commercial-scale 262-MW Wabash River Coal Gasification Facility in West Terre Haute, Indiana.

The feasibility study undertaken for the project consisted of identifying and evaluating the economic feasibility of potential fuel sources, developing a feed system design capable of providing a fuel at 400 psig to the second stage of the E-Gas (Destec) gasifier to be cogasified with coal, performing bench- and pilot-scale testing to verify concepts and clarify decision-based options, reviewing information on high-pressure feed system designs, and determining the economics of cofeeding alternative feedstocks with the conceptual feed system design.

A preliminary assessment of feedstock availability within Indiana and Illinois was conducted. Feedstocks evaluated included those with potential tipping fees to offset processing cost:sewage sludge, municipal solid waste, used railroad ties, urban wood waste (UWW), and used tires/tire-derived fuel. Agricultural residues and dedicated energy crop fuels were not considered since they would have a net positive cost to the plant. Based on the feedstock assessment, sewage sludge was selected as the primary feedstock for consideration at the Wabash River Plant. Because of the limited waste heat available for drying and the ability of 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 into the second stage of 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. These 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.

A preliminary design was prepared for a sludge-receiving, storage, and high-pressure feeding system at the Wabash River Plant. The installed capital costs were estimated at approximately $9.7 million, within an accuracy of ±10%. An economic analysis using DOE's IGCC Model, Version 3 spreadsheet 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 sludge treatment in Chicago, Illinois, delivery of sludge from Chicago, given adequate rail access, might be economically viable.

TABLE OF CONTENTS

ABSTRACT

Continued. . .

TABLE OF CONTENTS (continued)

Continued. . .

TABLE OF CONTENTS (continued)

LIST OF FIGURES

Continued. . .

LIST OF FIGURES (continued)

Continued. . .

LIST OF FIGURES (continued)

LIST OF TABLES

Continued. . .

LIST OF TABLES (continued)

ACRONYMS

ASTM	American Society for Testing and Materials
ASME	American Society of Mechanical Engineers
ATR	advanced transport reactor
BIGGT	biomass integrated gasification gas turbine
BNSF	Burlington Northern Sante Fe
C&D	construction and demolition
DOE	Department of Energy
EERC	Energy & Environmental Research Center
EPA	Environmental Protection Agency
E-Gas	tradename for Gasification Engineering Corporation's entrained-flow gasifier
FIGLEAF	Feed System Innovation for Gasification of Locally Economical Alternative Fuels
GEC	Gasification Engineering Corporation
GTI	Gas Technology Institute
IGCC	integrated gasification Combined Cycle
IGCP	integrated gasification coproduction
IPP	independent power producer
MDF	medium density fiberboard
MIG	metal inert gas
MSW	municipal solid waste
MWRD	metropolitan water reclamation district
NA	not applicable
NETL	National Energy Technology Laboratory
NPV	net present value
NREL	National Renewable Energy Laboratory
NS	Norfolk Southern
ORNL	Oak Ridge National Laboratory
PAD	pulverizing air dryer
PLC	programmable logic controller
PPI	Pressure Products Industries
PSDF	power systems development facility
PVC	polyvinyl chloride
RDF	refuse-derived fuel
SFMS™	Sludge Flow Measuring System (trademark of Schwing America)
SS	stainless steel
SWERF	solid waste energy recycling facility
TDF	tire-derived fuel
TIG	tungsten inert gas
TRDU	transport reactor development unit
UK	United Kingdom
U.S.	United States
USDA	United States Department of Agriculture
UWW	urban wood waste

VTT	Technical Research Center of Finland
WREP	Whitewater River Environmental Partnership
WTE	waste to energy
WWTP	waste water treatment plant
XRF	X-ray fluorescence

ABBREVIATIONS

acfh	actual cubic feet per hour
Btu	British thermal unit
CO_2	carbon dioxide
cP	centipoise
ft^3	cubic feet
m^3	cubic meter
yd^3	cubic yard
ft	feet
ft-lb_f	foot pound force
gpm	gallons per minute
hp	horsepower
hr	hour
ID	inside diameter
μg/g	microgram per gram
Hg	mercury
kg	kilogram
kJ	kilojoule
km	kilometer
kWh	kilowatt hour
L	liter
m	meter
min	minute
mm	millimeter
MMBtu	million Btu
mgd	million gallon per day
MPa	megapascal
MW	megawatt
MW_e	megawatt electrical
N-m	Newton meter
NO_x	nitrogen oxides
ppmv	parts per million by volume
lb	pound
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
rpm	rotations (or revolutions) per minute
scfh	standard cubic feet per hour

scfm	standard cubic feet per minute
SO_x	sulfur oxides
vol%	volume percent
wt%	weight percent

EQUATION PARAMETERS

d_p^*	dimensionless particle size
d_p	particle size
ρ_g	gas density
ρ_s	particle density
g	gravitational constant
μ	gas viscosity
u_t^*	dimensionless terminal velocity
Φ	sphericity
u_t	terminal velocity
$C\upsilon$	valve flow coefficient
P_1	absolute upstream pressure
P_2	absolute downstream pressure
Q	gas flow rate at standard pressure and temperature
T	absolute temperature
SG	gas specific gravity
dP	differential pressure

FEED SYSTEM INNOVATION FOR GASIFICATION OF LOCALLY ECONOMICAL ALTERNATIVE FUELS (FIGLEAF)

EXECUTIVE SUMMARY

The Feed System Innovation for Gasification of Locally Economical Alternative Fuels (FIGLEAF) project was conducted by the Energy & Environmental Research Center (EERC) and Gasification Engineering Corporation of Houston, Texas (a subsidiary of Global Energy Inc., Cincinnati, Ohio), with cofunding from the U.S. Department of Energy (DOE). The goal of the project was to identify and evaluate low-value fuels that could serve as alternative feedstocks and to develop a feed system to facilitate their use in integrated gasification combined-cycle and gasification coproduction facilities. The long-term goal, to be accomplished in a subsequent project, is to install a feed system for the selected fuel(s) at Global Energy's commercial-scale 262-MW Wabash River Coal Gasification Facility in West Terre Haute, Indiana.

The feasibility study undertaken for the project consisted of identifying and evaluating the economic feasibility of potential fuel sources, developing a feed system design capable of providing a fuel at 2.80 MPa (400 psig) to the second stage of the E-Gas (Destec) gasifier to be cogasified with coal, performing bench- and pilot-scale testing to verify concepts and clarify decision-based options, reviewing information on high-pressure feed system designs, and determining the economics of cofeeding alternative feedstocks with the conceptual feed system design.

Project activities included identifying potential alternative feedstocks for use at Global Energy's Wabash River (Terre Haute, Indiana) gasification plant. Estimates were developed for the availability of sewage sludge, used railroad ties, urban wood waste (UWW), municipal solid waste (MSW), and waste tire fuel. Nationwide estimates were also determined for these fuels based on their availability in the 38 largest metropolitan areas of the United States with populations over approximately 1.1 million people. Supplemental information was provided for availability of agricultural residues.

The resource assessment showed that within an approximately 80-km (50-mile) radius, MSW is available in sufficient quantity to provide up to 10% of the thermal input to the Wabash River gasifier. Vigo County, which contains Terre Haute, could provide 7.6%, while the 15 counties with borders within 50 straight-line miles of Terre Haute could provide an additional 20% thermal input. For UWW, transport distances would be up to 120 km (75 miles) to attain 10% or more of the thermal input, with only 2% of the input sustainable by available UWW within the Vigo County area. The availability of sewage sludge is more limited, with Indianapolis, Indiana (approximately 120 km from Terre Haute), able to supply up to 5% of the gasifier thermal input.

Nationwide estimates show a similar trend of availability for MSW and UWW, with metropolitan areas with 1 million people being able to provide approximately 22% and 20%, respectively, of the Wabash River gasifier thermal input. For undigested sewage sludge, a metropolitan region of approximately 2.75 million people could provide 10% of the thermal input.

Fuels with potential tipping fees were considered the most ideal feedstock. Because utilization of railroad ties, MSW, UWW, and waste tires would require processing down to sizes small enough to be entrained in the second stage of the Wabash River gasifier, the estimated costs of as much as \$2/MMBtu precluded their economic utilization. Based on the feedstock assessment, sewage sludge was selected as the primary feedstock for consideration at the Wabash River Plant. Because of the limited waste heat available for drying and the ability for the gasifier to operate with alternative feedstocks at up to 80% moisture, a decision was made to investigate a system for delivering the as-received fuel (~23.5 wt% solids) 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 commercial, high-pressure feed pump was leased and tested for its ability to feed the sludge cross the 2.93-MPa (425-psia) pressure boundary. The EERC also procured, constructed, and tested several fuel dispersion nozzles for potentially dispersing 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.

A preliminary design was prepared for a sludge-receiving, storage, and high-pressure feeding system at the Wabash River Plant. The installed capital costs were estimated at approximately \$9.7 million, within an accuracy of ±10%. An economic analysis using DOE's IGCC Model, Version 3 spreadsheet 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 Chicago, given adequate rail access, might be economically viable.

Recommendations for future work on this project should concentrate on further clarifying the economics and demonstrating the long-term feed system performance. This would include further clarification of the sludge tipping fees; transportation costs for receiving sludge should be pursued with both the Whitewater River Environmental Partnership (WREP) of Indianapolis and the Metropolitan Water Reclamation District (MWRD) of Greater Chicago. The delivered on-site cost of the sludge is going to be the principal driver for determining the economics for installing such a feed system.

Further testing of improved dual-fluid dispersion nozzles should also occur. Pilot-scale tests should be performed at the Wabash River facility to refine system concepts for a Phase II commercial demonstration. The design of the EERC nozzles was continually improving and had not reached near-optimum conditions. As near-optimum conditions are achieved, better diagnostics for measuring the sludge droplet size will be needed to discern minor improvements in performance.

Further work should be completed to determine the effects of preheating the sludge and preheating the recycle syngas on the nozzle performance. Preheating the sludge and recycle syngas should help improve the nozzle performance. Sources of low-cost waste heat from the gasifier should be identified and investigated for their suitability to preheat the sludge. Preheating the recycle syngas will occur naturally in the boost compressor. These tests should also be conducted in a pressure vessel operating at full system operating pressure in order to determine the appropriate flow rates and pressure ratios that will optimize the performance of the dispersion nozzle. These tests should also incorporate the second control block and modified PLC logic to verify that the pulsing flow experienced with a double-piston pump can be eliminated. Longer-term nozzle wear tests should also be performed to determine the expected wear rates and life expectancy for these nozzles given the use of hardened parts.

FEED SYSTEM INNOVATION FOR GASIFICATION OF LOCALLY ECONOMICAL ALTERNATIVE FUELS (FIGLEAF)

INTRODUCTION

The power generation landscape in the United States will soon be dominated by two seemingly polar directives: reduction of electricity costs and reduction of greenhouse gas and other emissions. The shrinking availability of landfill for municipal and utility wastes is also becoming a factor. Currently, this is leading utilities and independent power producers (IPPs) to install a wave of natural gas-fired turbine units, so much that virtually all of the generation in the United States that is less than 10 years old is natural gas-based and is dependent on the relatively volatile natural gas market for its competitive position.

Over half of the electrical power generated in the United States has historically come from the combustion of coal. Coal is the most plentiful domestic fuel and must be America's lead choice for future power generation needs. It is typically utilized in conventional boiler–steam turbine plants with postcombustion particulate removal and other emission treatments. Many of these plants, over 35,000 MW in just the Northeast and Midwest for instance, are over 40 years old. These older plants will be severely challenged by increasingly stringent emission limits for SO_x, NO_x, Hg, and CO_2, as well as increasing costs for disposal of scrubber wastes and combustion ashes.

Gasification for power generation is an environmentally superior means to utilize domestic coal resources, matching the emissions of natural gas combined-cycle facilities. But the coal-to-power economics for integrated gasification combined-cycle (IGCC) facilities do not result in equivalent costs of electricity in most situations, and coal-based IGCC is not expected to penetrate this market in the near term. Neither the environmental benefits or fuel flexibility diversification will be realized on this route.

The solutions to achieving these goals are 1) coproduction at the end of the gasification process, to produce higher-value products such as transportation fuels and 2) utilization of renewable feedstocks at the front end to reduce plant fuel costs as well as enhance the overall environmental performance. The U.S. Department of Energy's (DOE) Vision 21 Program embodies the application of these concepts. At the Vision 21 Program Definition Meeting held at the National Energy Technology Laboratory (NETL) in December 1998, the development of feed systems for alternative feedstocks for gasifiers was identified as one of the major technical barriers to advance Vision 21 coproduction plants. The use of lower-quality, less expensive feedstocks represents the best near-term opportunities for early entry IGCP (integrated gasification co-production) plants. However, the major gasification technologies developed to commercial availability have limited fuel flexibility, primarily as a result of their feed systems. In most cases when alternative feedstocks are cofed, the secondary fuel is likely to be significantly different in physical and chemical properties from the primary coal fuel. Discontinuities and nonuniformities in handling and feeding the differing materials can be expected in some of the feed mechanisms. Consequently, in order to expedite IGCC and IGCP applications, the development of feed systems for nonconventional and renewable fuels, especially biomass, is needed.

The Wabash River Facility was designed for operation with high-sulfur bituminous coal, utilizing about 2500 tpd. The E-Gas (formerly Destec) technology gasifier is a two-stage gasifier which normally sees coal slurry fed both in the first stage and second-stage. Utilizing biomass or other renewables for the second stage feed could have an enormous positive financial implication, thereby leading to increased gasification opportunities.

This project was conducted by the Energy & Environmental Research Center (EERC) and Gasification Engineering Corporation of Houston, Texas (a subsidiary of Global Energy Inc., Cincinnati, Ohio). The EERC is one of the world's major energy and environmental research organizations, employing more than 250 full-time scientists, engineers, technicians, and support staff to conduct research, testing, and evaluation of fuels, combustion, gasification, and emission control technologies. Global Energy is a world leader in gasification for power generation, with over 60,000 hours of coal gasification operational experience and nearly 600 person years of gasification expertise among its employees. Global Energy's E-Gas (Destec) technology gasification facility, the Wabash River Coal Gasification Repowering Project, is currently the largest single-train gasification facility operating in the western hemisphere as well as the cleanest coal-fired plant of any kind in the world.

This program was cofunded with \$460,000 of funding from the DOE (80% of the cost of the project) and \$115,000 of industrial cost share. The goal of the Feed System Innovation for Gasification of Locally Economical Alternative Fuels (FIGLEAF) project was to 1) identify and evaluate low-value fuels that could serve as alternative feedstocks and 2) develop a feed system to facilitate their cofeeding with coal in integrated gasification combined cycle and gasification coproduction facilities. For this research program, cofeeding was defined as feeding a mixture of up to 30% alternative resource separately from the primary fuel (e.g., coal) into a single gasifier of existing commercially available design. Feedstocks for cofeeding were envisioned to include, but not be limited to, biomass, municipal solid waste (MSW), municipal or industrial sludges, and nonhazardous industrial wastes.

Based on a preliminary review of the Wabash River fuel delivery requirements, it was determined that a separate feed system in which the fuel would enter the second stage of the Wabash gasifier would be the best approach, and the following design considerations were determined:

- Limit fuel preparation costs
- Minimize capital investment
- Present a reasonable technical risk
- Handle a wide variety of fuel and size
- Feed across a 400-psi pressure boundary

To this end, the FIGLEAF project assessed the development of a novel feed system for gasification of a select alternative feedstock under elevated pressure. This research program included a feasibility study followed by the evaluation of a new feed system design. The feasibility study included the identification and assessment of those issues associated with the alternative feedstock and determined the applicability to broadly based markets. Limited lab and pilot testing was used to provide a base of design information for potential scaleup and demonstration. The long-term goal of a subsequent project would be to install a feed system for these selected fuels at Global Energy's commercial-scale 262-MW Wabash River Coal Gasification Facility in West Terre Haute, Indiana.

RESOURCE ASSESSMENT

Sewage Sludge

Indianapolis

The Whitewater River Environmental Partnership (WREP) operates two wastewater treatment plants (WWTPs) for the municipality of Indianapolis, treating approximately 200 million gallons/day (MGD) of wastewater (1–3). Approximately 711 wet tons/day of sludge is produced at a solids content of 22 to 23 wt%. Primary and waste-activated sludges are combined and dewatered at the Belmont WWTP site, with sludge being transported 7 miles by pipeline between sites. The dewatered sludge is then incinerated at Belmont in a rotary hearth furnace, with the ash residue landfilled as a Type 3 special waste. The elimination of a stabilization or treatment (e.g., digestion) step preserves heating value and reduces the quantity of supplemental fuel (natural gas) required to sustain combustion and achieve proper destruction.

At the time of discussions with Indianapolis contacts, the municipality was pursuing other options for disposal of the sludge. Although incineration is currently cost-competitive with landfilling—the tipping fee would be about \$13/wet ton at the adjacent Southside landfill, and transportation costs would be about \$2/wet ton—negotiations were under way with Southside to allow landfilling of the sludge at only \$5 to \$6/wet ton. The landfill operators would benefit from enhanced landfill gas production, owing to the wet, biologically active sludge. It was revealed that the sludge could be obtained from Indianapolis if no more than \$15 to \$16/wet ton was paid to the procurer.

Truck haul would be the most probable method of sludge transport between Indianapolis and Terre Haute. The truck haul option would require up to 35 loads per day (at ~20 tons/truck) over a one-way haul distance of approximately 75 miles. The Belmont site, where sludge dewatering is performed, lacks rail access.

Truck haul cost estimates were received from two cartage companies for transporting 23 wt% undigested sludge from the Belmont site to Terre Haute (4, 5). The estimates ranged from \$26 to \$30/wet ton, which would more than consume the tipping fee that could be obtained from WREP.

Subsequent to conversations with WREP personnel, the EERC developed a protocol for handling and shipping undigested sewage sludge. The protocol and shipping container were air-freighted to the Belmont WWTP, and a 1-gallon sample of combined undigested primary-waste-activated sludge was taken from the discharge of the belt filter press. This material was next-day air-freighted back to the EERC for analysis (proximate, ultimate, heating value, ash x-ray fluorescence [XRF], and total chloride). Analysis results are shown in Table 1 for the Indianapolis sewage sludge.

Table 1. Analysis Results for Indianapolis Sewage Sludge

	As-Received	Moisture-Free
Proximate, wt%		
Moisture	77.70	NA
Volatile Matter	14.71	65.96
Fixed Carbon	1.68	7.54
Ash	5.91	26.5
Ultimate, wt%		
Hydrogen	9.90	5.67
Carbon	8.76	39.27
Nitrogen	1.05	4.69
Sulfur	0.16	0.73
Oxygen	74.23	23.14
Ash	5.91	26.5
Heating Value, Btu/lb	1736	7783
Chloride, µg/g	400	1790
XRF, wt% as oxide		
Silicon		29.3
Aluminum		22.2
Iron		9.0
Titanium		0.9
Phosphorus		18.4
Calcium		9.7
Magnesium		2.8
Sodium		1.1
Potassium		1.7
Sulfur		4.9

Based on a thermal input of 52.0 billion Btu/day to the Wabash River gasifier, the Indianapolis sludge would provide about 4.8% of the thermal input. This thermal input value is close to the FIGLEAF project design basis value of 5% to 10%.

Metropolitan Water Reclamation District of Greater Chicago

The Metropolitan Water Reclamation District (MWRD) of Greater Chicago serves an equivalent population of over 10.1 million people—5.1 million real people, a commercial/ industrial equivalent of 4.5 million people, and a combined sewer overflow equivalent to 0.5 million people (6). The district treats over 1400 MGD of wastewater at seven WWTPs, producing approximately 190,000 dry tons/year of Class B stabilized (anaerobically digested) sludge, called biosolids by the

"District" (7). The treated sludges produced at the Stickney site (151,000 dry tons/year) and the Calumet site (30,000 dry tons/year) account for over 90% of the sludge produced by the District (8, 9).

The District produces biosolids at two solids contents: 25 and 65 wt%. The 25 wt% solids sludge represents approximately 11% (dry basis) of the total treated sludge produced. All of this material is used for beneficial reuse (application to farmland). The 65 wt% solids sludge represents the remaining 89% (dry basis) of the total treated sludge produced. The biosolids are used for a variety of applications, as shown in Table 2. The processing costs include those for digestion, aging, transportation, and tipping (if applicable).

Table 2. Disposal Methods for 65 wt% Treated Sludge (biosolids) from the Chicago MWRD

Disposal Method	% of Total	Processing Cost, $/dry ton
Daily Cover	18	54–98
Final Cover	33	54–98
Controlled Solids Distribution	10	68–110
Landfilling	30	120
Fulton County	9	99–123

Controlled solids distribution includes a soil amendment on golf courses and athletic fields. This application is possible because the digested sewage sludge is allowed to age in drying ponds for up to 3 years, effectively destroying all pathogens and increasing the solids content to 65 wt% via natural drying. Disposal in Fulton County entails trucking sludge 162 miles for utilization in a former mine land reclamation program. The majority of the remaining sludge is disposed of within 15 miles of the WWTPs.

Possible modes for the 200-mile sludge transport from Chicago to Terre Haute would include rail haul or truck haul. Rail access is available at the sludge-aging site; however, the rail siding can only handle the light traffic of the side-dump cars that move fresh sludge from the WWTPs to the aging ponds. District personnel believe that significant upgrades would be required to handle daily rail load-out.

The cost of sludge processing through digestion is approximately $75/dry ton, while aging adds another $11/dry ton. Haulage via truck to Fulton County adds the greatest incremental cost—about $37/dry ton or about $475 per loaded truck at approximately 20 wet tons/truck.

Based on an assumed heating value of 4500 Btu/lb (10) for the aged sludge, approximately 9.1% of the thermal input of the Wabash River (or similarly sized) gasifier could be achieved with 190,000 dry tons/year of sludge. A scenario with higher potential may be to obtain the 39% (66,000 dry tons/year) of aged sludge that is diverted to landfill and Fulton County, although this quantity of sludge would provide only 3.2% of the gasifier thermal input. The avoided cost of landfilling or transporting the sludge to Fulton County may provide the procurer $34 to $37/dry ton ($22 to $24/wet ton) which, according to a quote from one cartage company ($20 to $23/wet ton), may be sufficient to offset the transport cost to Terre Haute (11). Cost data were not available for rail haul.

At the time of discussions, the District was preparing a request for proposals to attract bids on the development of a sludge pelletization process to convert at least 50% of the sludge into a higher-value Class A product. This would significantly reduce the sludge available for use in Terre Haute, and the higher-cost disposal options (landfilling and trucking to Fulton County) would probably be eliminated first.

Regional Cities

Table 3 lists several other cities within approximately 100 miles of Terre Haute that were contacted to determine quantities and disposition of municipal sewage sludge. These cities all produce digested sewage sludge but in insufficient quantity to be a viable fuel source for Wabash River. The electrical power production potential is below 0.5 MW for any of these cities, assuming 5000 Btu/lb and 35% overall efficiency.

Table 3. Sludge Available from Regional Cities

City	Population, thousands	Distance, miles	Sludge, dry tons/year	Sludge Solids, wt%	Disposition
Evansville, IN	126	112	–	–	Land-applied
Decatur, IL (12)	80	106	4690	4.5	Land-applied
Lafayette, IN (13)	70	92	2500	5.0	Land-applied
Champaign, IL[1] (14)	97	106	3600	20.0	Land-applied
Bloomington, IN (15)	61	57	2920	40.0	Daily cover
Danville, IL	36	57	–	–	–

[1] Includes the city of Urbana, Illinois.

Nationwide

Based on a per capita factor of 0.25 dry lb/day (16), the production of raw or untreated sewage sludge solids was estimated for the 38 U.S. metropolitan areas with populations over 1 million. The results are presented in Table 4. Using a heating value similar to that of undigested Indianapolis sewage sludge—7780 Btu/lb—further estimates show that sludge from 16 of the metro areas could provide 10% or more of the thermal input to a Wabash River-sized gasifier. The population base required to achieve the 10% value is approximately 3 million. The remaining metro areas would provide between 5% and 10% of the thermal input. Population data were based on preliminary results from the year 2000 census (17).

Table 4. Estimated Generation of Undigested Sewage Sludge for the 38 Largest U.S. Metropolitan Areas

City	Population, millions	Sludge, thousand dry tons/year	% of Gasifier Thermal Input
New York, NY	15.000	684	56.1
Los Angeles, CA	13.000	593	48.6
Chicago, IL	8.008	365	30.0
Philadelphia, PA	4.95	225	18.5
Dallas–Ft. Worth, TX	4.910	224	18.4
Washington, D.C.	4.740	216	17.7
Detroit, MI	4.475	204	16.7
San Francisco–Oakland, CA	4.035	184	15.1
Houston, TX	4.011	183	15.0
Atlanta, GA	3.857	176	14.4
Miami–Ft. Lauderdale, FL	3.711	169	13.9
Boston, MA	3.297	150	12.3
Seattle–Tacoma, WA	3.260	149	12.2
Phoenix–Mesa, AZ	3.014	138	11.3
Minneapolis–St. Paul, MN	2.872	131	10.7
San Diego, CA	2.821	129	10.6
St. Louis, MO	2.569	117	9.6
Baltimore, MD	2.491	114	9.3
Pittsburgh, PA	2.331	106	8.7
Tampa–St. Petersburg, FL	2.278	104	8.5
Cleveland, OH	2.221	101	8.3
Denver, CO	1.979	90.3	7.4
Portland, OR–Vancouver, WA	1.846	84.2	6.9
Kansas City, MO	1.756	80.1	6.6
San Jose, CA	1.647	75.1	6.2
Cincinnati, OH	1.628	74.3	6.1
Sacramento, CA	1.585	72.3	5.9
San Antonio, TX	1.565	71.4	5.9
Norfolk–Virginia Beach, VA	1.563	71.3	5.8
Indianapolis, IN	1.537	70.1	5.7
Orlando, FL	1.535	70.0	5.7
Columbus, OH	1.489	67.9	5.6
Milwaukee, WI	1.462	66.7	5.5
Charlotte–Gastonia, NC	1.417	64.7	5.3
Las Vegas, NV	1.381	63	5.2
New Orleans, LA	1.305	59.5	4.9
Salt Lake–Ogden, UT	1.275	58.2	4.8
Hartford, CT	1.147	52.3	4.3
Total Metropolitan United States	123.968		

It should be noted that metropolitan Chicago in Table 4 shows about 8 million people relative to the 5 million people served by the MWRD of Chicago. The six counties within Illinois that surround Cook County contribute the additional 3 million people. The results also show that significantly greater thermal input can be achieved using undigested sludge relative to the digested, aged sludge of the MWRD. Utilizing the undigested sludge would have the benefit of increasing the quantity and heating value of the fuel. Presuming that undigested sludge can be obtained, the avoided cost of digestion would translate into a greater tipping fee for the sludge recipient.

Used Railroad Ties

Wood tie replacement by Class I railroads over the last several years has ranged from approximately 10.5 to 12.0 million ties, while wood tie replacement for short-line/regional railroads has ranged from 3.5 to almost 4.5 million ties (18, 19). Class I railroads operate 170,000 miles of track in the United States. Four railroads—Norfolk Southern (NS), Burlington Northern Sante Fe (BNSF), Union Pacific, and CSX Corporation—operate the majority of the track (20). Approximately 425 smaller operators—short-line and regional railroads—operate about 50,000 miles of track.

NS and CSX each have an annual tie replacement of about 2.5 million, including ties replaced on Conrail lines under joint NS–CSX ownership. Union Pacific has annual tie replacement approaching 3 million (21, 22). Although information was not available, it is presumed that BNSF tie replacement would be similar in quantity to the other operators. The amount of used ties produced by any one short-line/regional railroad would be small in comparison.

Depending upon moisture content, 1 to 1.5 million used ties are equivalent to about 100,000 tons of used ties (23). At approximately 6800 Btu/lb, 140,000 tons, or 1.7 million ties, would be required annually to supply 10% of the thermal input to a Wabash River-sized gasifier. This represents about 15% of the annual used-tie production potential from Class I railroads. However, even though the quantity for a Wabash River-sized gasifier would seemingly be easily satisfied, competition for the used ties appears strong, and utilization in secondary markets appears very high.

As indicated by discussions with railroad personnel, railroads are not in the business of finding markets for the used ties. Separate used-tie contractors bid for long-term contracts to follow tie replacement gangs and collect the used ties. Two railroads that would disclose information about their tie replacement activities indicated that the contractors pay for the used ties. Further, one railroad had as many as 12 bidders for three separate contracts to recover used ties. The contractors must operate their own equipment for collecting, stockpiling, and hauling away the used ties. The number of quality ties that can be sold for reuse largely drives the ability of the contractor to economically operate. Wholesale prices for good used ties range from $5 to $10 per tie.

RailWorks Wood Waste Energy and Tampa International are two major used-tie contractors. They were contacted to discuss markets for their used ties and get information on tie-processing costs (23, 24). RailWorks handles approximately 60% of the entire Class I used tie market, while Tampa International handles 95% of used CSX ties. Both companies indicated that their primary market (by volume) is chipped-tie fuel, while the secondary market consists of good used ties for landscaping (typically sold to garden centers and building supply companies).

RailWorks indicated that within the Indiana area there is an "above-average" availability of used ties, which could open a new market of 1.0 to 1.5 million ties per year. RailWorks could also deliver whole ties rather than the customarily processed (hogged) ties. RailWorks currently operates tie-processing facilities in Minnesota, North Carolina, Mississippi, and Arkansas. These facilities are typically set up within a few miles of the fuel customer. RailWorks hauls whole ties to the chipping facilities via rail and prepares a nominal 3-inch minus mulchlike fuel using a hammermill. Depending upon the rail bed conditions where the used ties were removed, the tie moisture content may range from 10 to 50 wt%. Tampa International operates similar facilities. Neither RailWorks nor Tampa International would disclose the production cost or selling price for a typical processed-tie fuel. However, personnel at CMS Generation indicated that they are currently paying $2.50/ton delivered for a 3-inch minus used-tie fuel (25).

The cost of further processing for use in an entrained-flow or similar conversion system may be cost-prohibitive. RailWorks indicated that it assisted the Tennessee Valley Authority in the development of a codrying/hogging operation to produce a 3/16-inch minus product for cofiring in a suspension-fired boiler. The cost of production, at $2/MMBtu, was very high. RailWorks believes that preparation costs would be similar for used-tie fuel sized for an entrained-flow gasifier.

Urban, Mill, and Forest Wood Residues

Indiana

A resource assessment completed in 1995 indicated that the state of Indiana has a significant number of sawmills, furniture manufacturers, and pallet manufacturers that, in combination with tree-trimming and construction/demolition (C&D) industries, generate large quantities of wood waste (26). At the time of the assessment, 66% of all UWW was being landfilled or given away. The study reviewed 11 metropolitan regions that encompassed 80% of Indiana's then 5.5 million people.

The assessment identified approximately 1650 generators of wood waste within the state. The generators were divided into five primary categories: secondary wood processors, pallet manufacturers/recyclers, urban tree and landscape residue generators, primary wood processors, and C&D residue generators. Within the 11 regions, the generation of UWW was estimated to be 1,130,000 dry tons/year, while the quantity available was approximately 743,000 dry tons/year.

The difference between generated and available UWW (i.e., 387,000 dry tons/year) represents the quantity that was 1) sold, 2) used captively by the generator for fuel, or 3) reused or recycled. Secondary wood processors sell sawdust, chips, and bark as mulch, commanding typically high prices ($40/dry ton at the time of the study). Pallet manufacturers/recyclers also sell or captively use a large fraction of the generated waste. Almost 80% of the UWW from primary wood processors is used to supply wood fiber for the local pulp/paper industry or is used captively as a fuel. Procurement of these UWW fractions as fuel would require paying prices substantially above those typically paid ($/MMBtu) for traditional fossil fuels or petroleum coke.

The available UWW, 743,000 dry tons/year, was the amount landfilled or given away. This material represents potential fuel that could be obtained at zero or negative cost (excluding transportation). Urban tree and landscape residue plus C&D residue made up 55 and 23 wt%, respectively, of all available UWW in Indiana. The reuse and recycle options are fewer for these two waste fractions, owing to their typically less desirable properties: variability in physical and chemical properties (as in the case of tree and landscape residue), the possible presence of hazardous materials, and the requirement for sorting (as in the case of demolition debris).

Table 5 presents the estimates for available UWW for the 11 regions. Within Region 8, which contains Terre Haute, the amount of UWW available is quite limited. At approximately 25,400 dry tons/year and assuming about 8000 Btu/lb (dry basis), this amount of UWW would supply 2.1% of the Wabash River gasifier thermal input. Approximately 78% of the UWW comprises tree trimming/landscaping residue and C&D debris. Although Region 8 has a substantial primary wood-processing industry, 87% of the wood waste (23,300 dry tons/year) from this sector is recycled or reused.

Table 5. Estimate of Available Urban Wood Waste Within Indiana (weight in thousands of tons)

Region No.	Region Name	Population, thousands	UWW Available, dry tons/year	% of Wabash River Thermal Input
1	Indianapolis	1249	189.3	16.0
2	Fort Wayne	364	76.5	6.4
3	Evansville	339	63.9	5.4
4	Gary/Hammond	712	84.4	7.1
5	South Bend/Elkhart	403	95.0	8.0
6	Muncie/Anderson	298	72.3	6.1
7	Bloomington	267	45.2	3.8
8	Terre Haute	161	25.4	2.1
9	Kokomo/Marion	265	33.4	2.8
10	Richmond	98	15.4	1.3
11	New Albany	227	42.3	3.6

Regions 1 and 3, which are substantially more populous than Region 8, could possibly provide 16% and 5.4%, respectively, of the Wabash River gasifier thermal input. Again, the potential fuel load would largely comprise urban tree/landscape residue and C&D debris. However, transport distances would become an issue, as the population centers for Regions 1 and 3 are 77 and 112 miles, respectively, from Terre Haute. Region 7, whose population center of Bloomington is only 57 miles from Terre Haute, has the potential to raise the available fuel load to about 70,600 dry tons/year or 5.8% of the thermal input.

Illinois

A similar analysis of UWW resource data for the neighboring state of Illinois was not performed, as the nearest major population centers (Decatur and Champaign–Urbana) are over 100 miles distant.

Nationwide

A state-level analysis of urban, mill, and forest wood residue availability was prepared by the Oak Ridge National Laboratory (ORNL) for the year 1999 (27). Urban wood waste included that disposed with MSW (yard trimmings, site-clearing waste, pallets, wood packaging, and miscellaneous wood) and that disposed in C&D landfills. Previous survey data for MSW and C&D quantities as well as the estimated fraction of wood within these two disposal streams were used to produce crude estimates of MSW and C&D wood. Mill wood residue data for the ORNL study were compiled by the USDA Forest Service and include waste from primary wood mills:lumber, pulp, veneer, and composite wood fiber materials. The availability and cost for forest wood residues—logging residues and salvageable deadwood—were estimated by a model that utilizes equipment retrieval limitations, road access, and site slope to provide adjustment. For all categories, a nominal charge for haulage, $8/dry ton, was added. Estimates for annual supply (quantity versus delivered price) are presented in Table 6 for the states of Illinois and Indiana for urban, mill, and forest wood residues.

The data of the ORNL study appear to significantly agree with the 1995 study of UWW available in Indiana. The sum of the urban and mill waste at $50 dry/ton, 1.23 million dry ton per year, in the ORNL study compares to 1.13 million dry tons/yr generated according to the Indiana study. This presumes that all wood waste, even that captively used by a generator, can be purchased for no more than $50/dry ton. Significant quantities of the higher-quality mill wood waste would only be available at a cost over $20/dry ton or $1.20 per million Btu.

Nationwide, the trend for availability of wood waste versus delivered price mirrors that for Indiana and Illinois. At a price up to $20/dry ton, sufficient urban residue would be available nationwide to provide 10% of the thermal input to 190 Wabash River-sized gasifiers. At a cost up to $30/dry ton, the availability of urban residue would increase 68%.

Wiltsee completed a study for the National Renewable Energy Laboratory in 1998 that analyzed the UWW resources of 30 randomly selected metropolitan U.S. areas with populations ranging from 84,000 to almost 4,000,000 people (28). The waste resources were classified as MSW wood, industrial wood, and C&D wood. MSW wood comprises the nonrecoverable fraction of wood wastes disposed with MSW (assumed in the study to be 3 to 5 wt% of MSW) and the wood waste diverted from the MSW stream. Wood diverted from the MSW stream included private tree trimmings and yard waste and the debris removed by utility and private tree services. Industrial wood included scrap and sawdust from pallet recycling, woodworking shops, and lumberyards. C&D wood included wood debris from C&D activities as well as debris from land clearing (i.e., preparation for new construction). These classifications were consistent with those used in the Indiana UWW resource assessment.

Table 6. Supply Data for Urban, Mill, and Forest Wood Residues Within Indiana and Illinois (1000 dry tons delivered)

	< \$20/dry ton	< \$30/dry ton	< \$40/dry ton	< \$50/dry ton
Indiana				
Urban Residue	317	528	528	528
Mill Residue	31	213	NA	699
Forest Residue	NA	253	367	470
Illinois				
Urban Residue	416	693	693	693
Mill Residue	19	117	NA	282
Forest Residue	NA	228	330	423
U.S. Total				
Urban Residue	22040	36847	36847	36847
Mill Residue	1780	41459	NA	90418
Forest Residue	NA	23747	34771	44872

Based on the total quantities of wood waste in each of the three categories, the study developed weighted average coefficients for tons (with moisture included) of UWW generated per annum per person. The generation factors (wet tons/year/person) for MSW wood, industrial wood, and C&D wood were estimated to be 0.209, 0.048, and 0.076, respectively. The total UWW generation factor was 0.333 wet tons/year/person.

These coefficients were used here to predict the quantity of UWW generated by each of the 38 metropolitan areas of the United States with a population over 1 million people. The results are presented in Table 7 for each of the three UWW categories and for the total UWW. Values were converted to a dry tons/year basis assuming an average UWW solids content of 65 wt%. The percentage of thermal input to a Wabash River-sized gasifier was estimated assuming a dry wood heating value of 8000 Btu/lb. Approximately 120,000 dry tons/year of UWW would be required to provide 10% of the thermal input.

The results show that the quantity of generated wood may be substantial, with population centers over 5 million people theoretically being capable of providing 100% or more of the thermal input to a Wabash River-sized gasifier. However, the UWW available for use as fuel would be more limited. Although somewhat higher than the 66 wt% value identified in the Indiana resource

Table 7. Estimated Generation of Urban Wood Waste for the 38 Largest U.S. Metropolitan Areas (weight in thousands of tons)

City	Population, millions	MSW Wood, dry tons/year	Industrial Wood, dry tons/year	C&D Wood, dry tons/year	Total UWW, dry tons/year	% of Gasifier Thermal Input
New York, NY	15.000	2040	468	741	3250	274
Los Angeles, CA	13.000	1770	406	642	2810	237
Chicago, IL	8.008	1090	250	396	1730	146
Philadelphia, PA	4.95	672	154	244	1070	90.3
Dallas–Ft. Worth, TX	4.910	667	153	243	1060	89.6
Washington, D.C.	4.740	644	148	234	1030	86.5
Detroit, MI	4.475	608	140	221	969	81.7
San Francisco–Oakland, CA	4.035	548	126	199	873	73.6
Houston, TX	4.011	545	125	198	868	73.2
Atlanta, GA	3.857	524	120	191	835	70.4
Miami–Ft. Lauderdale, FL	3.711	504	116	183	803	67.7
Boston, MA	3.297	448	103	163	714	60.2
Seattle–Tacoma, WA	3.260	443	102	161	706	59.5
Phoenix–Mesa, AZ	3.014	409	94.0	149	652	55.0
Minneapolis–St. Paul, MN	2.872	390	89.6	142	622	52.4
San Diego, CA	2.821	383	88.0	139	611	51.5
St. Louis, MO	2.569	349	80.2	127	556	46.9
Baltimore, MD	2.491	338	77.7	123	539	45.5
Pittsburgh, PA	2.331	317	72.7	115	505	42.5
Tampa–St. Petersburg, FL	2.278	309	71.1	113	493	41.6
Cleveland, OH	2.221	302	69.3	110	481	40.5
Denver, CO	1.979	269	61.7	97.8	428	36.1
Portland, OR–Vancouver, WA	1.846	251	57.6	91.2	400	33.7
Kansas City, MO	1.756	239	54.8	86.7	380	32.0
San Jose, CA	1.647	224	51.4	81.4	356	30.1
Cincinnati, OH	1.628	221	50.8	80.4	352	29.7
Sacramento, CA	1.585	215	49.5	78.3	343	28.9
San Antonio, TX	1.565	213	48.8	77.3	339	28.6
Norfolk–Virginia Beach, VA	1.563	212	48.8	77.2	338	28.5
Indianapolis, IN	1.537	209	48.0	75.9	333	28.0
Orlando, FL	1.535	209	47.9	75.8	332	28.0
Columbus, OH	1.489	202	46.5	73.6	322	27.2
Milwaukee, WI	1.462	199	45.6	72.2	316	26.7
Charlotte–Gastonia, NC	1.417	192	44.2	70.0	307	25.9
Las Vegas, NV	1.381	188	43.1	68.2	299	25.2
New Orleans, LA	1.305	177	40.7	64.5	282	23.8
Salt Lake–Ogden, UT	1.275	173	39.8	63	276	23.3
Hartford, CT	1.147	156	35.8	56.6	248	20.9
Total Metropolitan United States	123.968					

assessment, the Wiltsee study found that, on average, the 30 metropolitan areas landfilled/incinerated or gave away as mulch about 73% of the UWW. Again, this material is made up primarily of MSW wood and C&D wood. However, opportunities may be available to provide between 5% and 10% of the thermal input using the higher-quality industrial wood. The Wiltsee report shows the production of industrial wood to be quite variable among the 30 municipalities studied, with the average disposition of industrial wood by landfilling/incineration or mulch being about 33%.

It should be noted that UWW actually available for use as a fuel within a specific metropolitan area or region will be dictated by landfill tipping fees, regulations concerning dumping/burning, public policy/attitude with regard to reuse and recycling, and the proximity to and competition from other large wood waste users.

Municipal Solid Waste

Indiana

Data for the generation and disposal of MSW, C&D debris, and other solid waste within Indiana were obtained from the Indiana Department of Environmental Management 1999 summary data report on the operation of solid waste facilities (29). Solid waste facilities include landfills, transfer stations, and incinerators. The solid waste data were presented in terms of both the county of origin and the facility of disposition.

To determine the potential availability of MSW for utilization by the Wabash River gasifier, the quantity of MSW generated within Vigo County (which contains Terre Haute) and within adjacent Indiana counties was determined. The results are presented in Table 8 for Vigo County and 15 other counties with borders that are within approximately 50 straight-line miles of Terre Haute. The values for MSW represent material that is destined for landfilling or incineration and has had recyclables already removed by curbside or transfer station recovery. Assuming a heating value of 4500 Btu/lb for the MSW, the percentage of thermal input to the Wabash River gasifier was estimated for each county of MSW origin.

Approximately 210,000 tons/year of unsorted MSW would be required to achieve a target thermal input value of 10%. Among the 16 counties, the largest quantity of MSW, 160,000 tons/year, is generated in Vigo County. Presently, 95% of Vigo County MSW stays within the county, being disposed of at a landfill near Terre Haute. This quantity of MSW is alone sufficient to provide 7.6% of the gasifier thermal input. Monroe County could theoretically supply an additional 4.6% of the thermal input for a total of 12.2%. The remaining 14 counties could more than double the available MSW to 568,000 tons/year, achieving a thermal input of almost 27%.

The tipping fee charged by Wabash River would dictate the MSW that can become available for use as a gasifier fuel at Wabash River. The proximity to the current landfill would suggest high potential to compete for the MSW resource within Vigo County. The ability to attract MSW from surrounding counties (and communities) would further be influenced by the combined transportation and tipping fees currently being paid by surrounding cities or solid waste management districts.

Table 8. MSW Resource Available Within Indiana Counties Adjacent to Terre Haute

County	MSW, ton/year	% of Thermal Input to Wabash River Gasifier	Cumulative % of Thermal Input
Vigo	160,250	7.6	7.6
Monroe	97,190	4.6	12.2
Montgomery	73,630	3.5	15.7
Hendricks	67,950	3.2	18.9
Morgan	39,410	1.9	20.8
Putnam	24,690	1.2	22.0
Clay	23,930	1.1	23.1
Knox	17,420	0.8	23.9
Greene	16,290	0.8	24.7
Vermillion	12,530	0.6	25.3
Sullivan	12,410	0.6	25.9
Parke	7370	0.3	26.2
Owen	7200	0.3	26.6
Daviess	6100	0.3	26.9
Warren	1290	0.1	26.9
Fountain	550	0.0	27.0

Illinois

Data for the generation and disposal of MSW within Illinois were obtained from the Illinois Environmental Protection Agency (EPA) 1998 Annual Report on Nonhazardous Solid Waste Management and Landfill Capacity (30). Subsequent to the initial data review, an annual report was published by the Illinois EPA covering the year 1999 (31).

Similar to the exercise with Indiana MSW data, the potential availability of MSW within adjacent Illinois for utilization by the Wabash River gasifier was determined. The results are presented in Table 9 for 11 Illinois counties whose county lines are within approximately 50 straight-line miles of Terre Haute. Again, the MSW quantities represent material that remains after recyclables recovery and is destined for landfilling or incineration. Assuming a heating value of 4500 Btu/lb for the MSW, the percentage of thermal input to the Wabash River gasifier was estimated for each county of MSW origin.

Among the 11 counties, the largest quantity of MSW, 150,600 tons/year, is generated in Champaign County. This quantity of MSW is alone sufficient to provide about 7% of the gasifier thermal input. However, the majority of this MSW would be from Champaign–Urbana, which is about 100 highway miles from Terre Haute. The remaining ten counties could provide an additional 240,000 tons/year or slightly more than 11% of the thermal input.

Table 9. MSW Resource Available Within Illinois Counties Adjacent to Terre Haute

County	MSW, ton/yr	% of Thermal Input to Wabash River Gasifier	Cumulative % of Thermal Input
Champaign	150,620	7.1	7.1
Vermilion	73,410	3.5	10.6
Coles	63,290	3.0	13.6
Edgar	21,250	1.0	14.6
Clark	17,580	0.8	15.4
Crawford	13,450	0.6	16.1
Richland	12,320	0.6	16.6
Douglas	12,080	0.6	17.2
Cumberland	11,830	0.6	17.8
Lawrence	11,420	0.5	18.3
Jasper	3320	0.2	18.5

Nationwide

Data for the nationwide generation, recovery, and disposal of MSW were obtained from two sources: 1) EPA (32) and 2) *Biocycle* (33), an organics composting and recycling journal. Data for the year 2000 are presented in Table 10.

Table 10. MSW Generation, Recovery, and Disposal Rates and Percentages for the United States in the Year 2000, million tons/yr (%)

	EPA	Biocycle
Generated	231.9 (100)	409.0 (100)
Recovered[1]	69.9 (30.1)	130.5 (31.9)
Incinerated	33.7 (14.5)	28.2 (6.9)
Landfilled	128.3 (55.3)	250.3 (61.2)

[1] Includes materials recycled and composted.

Between approaches, there is reasonably good agreement concerning the quantity of MSW incinerated. However, the variation in landfilling and recovery data components can be partially attributed to the methods of data estimation. The EPA figures are generated using the *material flows method*, i.e., a mass balance approach that takes into account the quantities of physical goods (food, clothing, appliances, etc.) purchased. These purchased goods are the precursors of the generated waste. Corrections are made based on imports and exports and assumed life of a product. Data sources include industry and business (including their representative associations), other governmental agencies, and surveys performed by industry, government, or the press. MSW for EPA purposes includes "those materials from municipal sources sent to municipal landfills." C&D residue is not included in the MSW stream. Municipal sources are considered to include homes, institutions (schools, prisons), commercial (small business, offices, restaurants) and, to a limited extent, industry.

The *Biocycle* "State of Garbage" report, conducted yearly for the past 13 years, relies on questionnaires sent to solid waste management and recycling officials in all 50 states and the District of Columbia. Participation is high with all entities except Montana represented in the current survey. Data gleaned include MSW generation, recycling, incineration, and landfilling rates. Sources and types of waste counted as MSW are similar to the EPA approach with several notable inclusions in the *Biocycle* data: C&D debris (29 states), industrial waste (24 states), and agricultural waste (14 states). The contribution from each of these three categories to the total MSW generated is not ascertainable within the *Biocycle* data.

Using the more conservative EPA numbers for landfilled MSW, an average nationwide factor (0.467 tons/yr-person) was used to estimate the quantity of MSW available within 38 metropolitan areas of the United States with population over 1 million people. It was assumed that MSW currently incinerated would not be available and only MSW going to landfill would be ascertainable as a gasification feedstock. The results are presented in Table 11. Further, by assuming a heating value of 4500 Btu/lb for the MSW, the percentage of total thermal input to the Wabash River gasifier was estimated.

The estimates show the available MSW to range from approximately half-million tons/yr (Hartford, Connecticut) to 7 million tons/yr (New York). A city of 1 million people would provide 22% of the thermal input to a Wabash River-sized gasifier, while the entire thermal input could be achieved from a metropolitan area of over 4.5 million people. The total thermal input from these 38 metropolitan areas, representing approximately 45% of the U.S. population, would be 520 trillion Btu per year.

It should be noted, however, that the actual MSW available (after recovery and incineration) in any area might be substantially higher or lower than the estimates made using a nationwide average. For example, Minneapolis and St. Paul, Minnesota; Indianapolis, Indiana; and Hartford, Connecticut, have waste-to-energy (WTE) facilities that already consume a significant fraction of the available MSW. Conversely, the approximately 30 million tons per year of MSW currently incinerated could provide additional **net** generation capacity owing to the higher thermal efficiency of the gasification combined-cycle systems. Assuming thermal efficiencies of 40% gasification combined-cycle versus ~20% for mass burn, an additional 1800 MW could be attained. Also, the current trend of stabilized recycling rates and a growing population should allow even greater generation capacity from MSW.

Within the midwestern United States, which includes Indiana and Illinois, the average MSW tipping fee was $34/ton in 2002 (34). Tipping fees were as high as $69/ton at landfills in the northeast and as low as about $23/ton in the south central and west cental U.S. The national average is almost $34/ton.

Table 11. Estimated Generation of Municipal Solid Waste for the 38 Largest U.S. Metropolitan Areas (weights in thousands of tons)

City	Population, millions	Municipal Solid Waste, 1000 tons/year	% of Gasifier Thermal Input
New York, NY	15.000	7005	332
Los Angeles, CA	13.000	6071	288
Chicago, IL	8.008	3740	177
Philadelphia, PA	4.95	2312	110
Dallas–Ft. Worth, TX	4.910	2293	109
Washington, D.C.	4.740	2214	105
Detroit, MI	4.475	2090	99.1
San Francisco–Oakland, CA	4.035	1884	89.4
Houston, TX	4.011	1873	88.8
Atlanta, GA	3.857	1801	85.4
Miami–Ft. Lauderdale, FL	3.711	1733	82.2
Boston, MA	3.297	1540	73
Seattle–Tacoma, WA	3.260	1522	72.2
Phoenix–Mesa, AZ	3.014	1408	66.7
Minneapolis–St. Paul, MN	2.872	1341	63.6
San Diego, CA	2.821	1317	62.5
St. Louis, MO	2.569	1200	56.9
Baltimore, MD	2.491	1163	55.2
Pittsburgh, PA	2.331	1089	51.6
Tampa–St. Petersburg, FL	2.278	1064	50.4
Cleveland, OH	2.221	1037	49.2
Denver, CO	1.979	924	43.8
Portland, OR–Vancouver, WA	1.846	862	40.9
Kansas City, MO	1.756	820	38.9
San Jose, CA	1.647	769	36.5
Cincinnati, OH	1.628	760	36.1
Sacramento, CA	1.585	740	35.1
San Antonio, TX	1.565	731	34.7
Norfolk–Virginia Beach, VA	1.563	730	34.6
Indianapolis, IN	1.537	718	34
Orlando, FL	1.535	717	34
Columbus, OH	1.489	695	33
Milwaukee, WI	1.462	683	32.4
Charlotte–Gastonia, NC	1.417	662	31.4
Las Vegas, NV	1.381	645	30.6
New Orleans, LA	1.305	609	28.9
Salt Lake–Ogden, UT	1.275	595	28.2
Hartford, CT	1.147	536	25.4
Total Metropolitan United States	123.968	57893	

Waste Tires/Tire-Derived Fuel

Indiana

Based on the Indiana 1999 State of the Environment Report (35), Indiana generated about 5.5 million additional waste tires in 1999 or about 1 tire per person. At about 15,000 Btu/lb and 20 lb per tire (passenger), all of the used tires produced yearly in Indiana would only provide 8.7% of the fuel input to the Wabash River gasifier. In 1997, approximately 18.5 million scrap tires remained in illegal dumps within Indiana, with this number being reduced by about 1 million tires per year through state-funded cleanup efforts. The state has two large tire dumps containing over 1 million tires each, but these dumps are located between 140 and 170 miles distant in Dearborn and Kosciusko Counties. Several dozen tire dumps are located within about 50 straight-line miles of Terre Haute, but these are smaller, containing several hundred thousand or fewer tires.

The potential availability of tire-derived fuel (TDF) was discussed with the president of Auburndale Recycling Center (36). Auburndale has tire-processing facilities in Wisconsin but also collects tires from Indiana and four other Great Lakes and midwestern states (37). This company could immediately provide 50,000 tons of 2-inch × 2-inch TDF. This product would sell for about \$20/ton; a ¾-inch to 1.25-inch TDF is sold to a local utility for \$27/ton delivered. The heat content can range from 12,500 to 16,500 Btu/lb, depending upon the level of metal separation. The Auburndale company president indicated that processing a tire completely to a ¾-inch minus size would be cost-prohibitive for TDF applications.

Illinois

A similar search of scrap tire availability was not performed for the state of Illinois.

Nationwide

According to *Waste Age*, 270 million scrap tires were generated in 1998 within the United States, essentially one for each U.S. inhabitant (38). Through 1998, 500 million tires remained in 2800 stockpiles, legal and illegal. In 1997, it was estimated that over 70% of scrap tires were reused, with TDF being the largest secondary market. The remaining 30% of scrap tires, or about 80 million tires/year, represents a significant resource for use as a fuel but this would be a widely dispersed commodity.

The cost for producing a fuel for use in an entrained-flow gasifier appears to be unfavorable. The typical market prices for tire-derived materials indicate that tire chips, both 1 inch and 2 inch, used as fuel range from \$10 to \$45 per ton (39). Further, market prices for ¼-inch and 3/8-inch material range from \$200 to \$220 per ton.

Agricultural Residues

Estimates were prepared for the potential availability of agricultural residues within Indiana and Illinois for utilization as feedstocks within the Wabash River gasifier. The residues of interest included corn stover, soybean hulls, and wheat straw. Residue estimates were generated from the harvested acres of corn and wheat and the harvested bushels of soybeans and factors relating the amount of residue per recovery of commodity products. Data for the commodity yields were obtained from the Indiana Agricultural Statistics Service (40) and the Illinois Agricultural Statistics Service (41). The following factors (and reference source) for residue yield were used:

1. Corn stover: 1.57 dry tons per harvested acre of corn (28)
2. Wheat straw: 0.42 dry tons per harvested acre of wheat (28)
3. Soybean hulls: 3.4 lbs per 60-lb bushels of soybean (42)

The factor used for corn stover recovery is actually conservative with values twice this possible, depending upon the method of stover recovery and the amount to be tilled back into the soil (43). The wheat straw estimate agrees quite well with a value estimated from the wheat straw used by a local straw board plant operator. This plant processes approximately 36,000 tons/yr of wheat straw and obtains its entire supply within a 25-mile radius. Further, they require only 25% of the wheat straw within that 25-mile radius. Soybean hulls are not actually left in the field after recovery of the soybean but are generally produced in a concentrated stream at a soybean-processing facility. Consequently, the potential availability of soybean hulls represents that available from one or more processors, probably within a 50- to 100-mile range of the farm.

Tables 12 and 13 present the estimated availability of corn stover and soybean hulls within, respectively, the Indiana and Illinois Counties adjacent to Terre Haute. As corn is a very large commodity crop in these two states, the potential availability of corn stover is significant. At an estimated dry heating value of 8000 Btu/lb, the 3.86 million dry tons of corn stover from these 27 counties could provide over 300% of the gasifier thermal input. Vigo County, producing 82,000 short tons/yr, alone could provide almost 8%. Soybean hulls could provide 196,000 dry tons/year or 17% of the thermal input between the 27 counties. Results are not presented for wheat straw, as the amount among the 27 counties totaled only 36,000 dry tons/year or about 3% of the total thermal input of the Wabash River gasifier.

The previously discussed ORNL study and others (44) have generated estimates for delivered prices for corn stover on a statewide basis. The results show that within Indiana and Illinois (as with all states except Oklahoma) prices would have to exceed \$30/dry ton and probably approach \$40/dry ton to take delivery of corn stover and compete against uses as bedding, insulating material, particleboard, and chemicals. Approximately \$10 to \$15 of the cost is for farmer compensation; \$5 is for transportation (assuming 50-mile delivery); and the balance for mowing, raking, baling, and loading.

FEED SYSTEM DEVELOPMENT FOR MUNICIPAL SEWAGE SLUDGE

Municipal sewage sludge, for reasons previously discussed, was selected as the feedstock of choice around which initial feed system developments, for the Wabash River gasifier, were undertaken. Modeling calculations performed by Global Energy defined the range of sewage sludge properties that would impart minimal economic and operational penalties on Wabash River gasifier performance. These same modeling efforts indicated that mechanically dewatered sewage sludge

Table 12. Corn Stover and Soybean Hull Resources Available Within Indiana Counties Adjacent to Terre Haute

	Corn Stover		Soybean Hulls	
County	Estimated Available (1000 dry tons)	% Thermal Input to Wabash River Gasifier	Estimated Available (1000 dry tons)	% Thermal Input to Wabash River Gasifier
Clay	95	8.8	5.25	0.5
Daviess	136	12.6	5.18	0.5
Fountain	155	14.5	8.28	0.7
Greene	74	6.9	3.37	0.3
Hendricks	113	10.5	6.26	0.6
Knox[1, 2]	200	18.7	9.02	0.8
Monroe	9	0.8	0.52	0
Montgomery[1, 2]	186	17.3	10.24	0.9
Morgan	76	7.1	3.72	0.3
Owen	28	2.6	1.53	0.1
Parke	99	9.2	4.95	0.4
Putnam	105	9.8	5.91	0.5
Sullivan	116	10.8	5.48	0.5
Vermillion	61	5.7	1.87	0.2
Vigo	82	7.7	3.97	0.4
Warren	134	12.5	7.06	0.6
Total	1668	155.5	82.6	7.3

[1] Top 10 state producer corn.

[2] Top 10 state producer soybean.

would, theoretically, not need preprocessing (e.g., additional dewatering or drying), thus removing one potential barrier to technical and near-term project success.

Although a source or sources of municipal sewage sludge for utilization at Wabash River were not contractually secured, the sludge from Indianapolis, Indiana, was considered to be representative of a nominal sludge fuel, at least with respect to as-received moisture content and heating value.

Table 13. Corn Stover and Soybean Hull Resources Available Within Illinois Counties Adjacent to Terre Haute

	Corn Stover		Soybean Hulls	
County	Estimated Available (1000 dry tons)	% Thermal Input to Wabash River Gasifier	Estimated Available (1000 dry tons)	% Thermal Input to Wabash River Gasifier
Champaign[1, 2]	428	39.9	20.5	1.8
Clark	162	15.1	8.4	0.7
Coles	182	17	9.72	0.9
Crawford	128	11.9	6.52	0.6
Cumberland	110	10.3	5.26	0.5
Douglas	190	17.8	10.26	0.9
Edgar	251	23.4	12.84	1.1
Jasper	151	14.1	9.15	0.8
Lawrence	124	11.6	5.87	0.5
Richland	123	11.4	6.49	0.6
Vermilion[1, 2]	342	31.9	18.62	1.7
Total	2191	204.3	113.6	10.1

[1] Top 10 state producer corn.

[2] Top 10 state producer soybean.

Actual testing with Indianapolis sludge was limited to chemical analysis and drop-tube furnace testing (discussed in the following section). Owing to the limited processing (i.e., no stabilization through digestion, or chemical or thermal processing), the Indianapolis sludge has a relatively short "shelf life" even when refrigerated. Based on the perceived course of feed system development and testing, the attendant risk to personnel (from potential exposure to elevated levels of pathogens) was considered too high.

Consequently, the majority of feed system development activities were conducted using a digested sewage sludge (considered a Class B biosolid) produced by the municipality of Fargo, North Dakota. This sludge was used as a surrogate principally because of the nearness (75 miles distant), availability (the Fargo WWTP was very willing to help our testing), and biological stability relative to the Indianapolis sludge. At the time of testing, the city of Grand Forks did not yet have an operational mechanical plant that could produce a stabilized, dewatered sludge.

A picture of the Fargo sludge is shown in Figure 1 as it was being discharged from the belt filter presses at approximately 23.5 wt% solids into rolloffs for landfill disposal. As further evidenced by Figure 2, mechanically dewatered sewage sludge at moisture contents greater than 75 wt% exhibits a physical appearance and properties closer to that of a solid rather than a fluid. The mechanically dewatered sewage sludge is essentially nonflowable under it own weight and is not self-leveling even after long periods of storage. Comparative analysis of the Indianapolis and Fargo sewage sludges is presented in Table 14.

The Indianapolis and Fargo sludges had similar physical appearances and were characterized by visible pieces of hair and paper fiber. An attempt was made to characterize the discrete particles that were retained on an 8-mesh (2.4-mm, 0.0937-inch)-square-opening screen. Respective samples of each sludge were thinned with a large excess of water and then poured onto the screen. The screen was partially immersed in water and then agitated to facilitate passing of material through the screen openings. The recovered wet solids were then oven-dried and ashed. These tests indicated that the content of large, discrete particles is low for both sludges. On an as-fed basis, the +8-mesh solids content was 0.138 and 0.0596 wt% for the Indianapolis and Fargo sludges, respectively. The Indianapolis sludge solids were principally comprised of paper fibers, grass fibers (<25-mm, 1-inch), small flat rubber pieces, seeds, and some grit (<3-mm, ⅛-inch). The Fargo sludge had considerably more hair and rubber pieces, no seeds, and little grit.

Procurement of Fargo Sludge for Pilot Testing

Large quantities of Fargo sewage sludge were obtained on three separate dates, coinciding with initiation of distinct phases of pilot-scale testing. For each test phase, six to eight 210-liter

EERC MM21027.JPG

Figure 1. Fargo municipal sewage sludge discharging from belt-filter press.

EERC MM21085.PCX

Figure 2. Photo of Fargo municipal sewage sludge.

(55-gallon) plastic barrels (shown in Figure 3), with a loaded capacity of approximately 160 to 180 kg (350 to 400 lb), were obtained. The barrels were held with the bucket of a small loader and positioned under the belt-filter press discharge auger to capture the "fresh" sludge. The barrels were sealed, washed down to remove excess sludge, and labeled. A pickup truck was used to haul the barrels between Fargo and Grand Forks.

Estimation of Particle Size for Entrainment

Estimates were made for the maximum particle size that could be entrained at conditions within the E-Gas gasifier operated at Wabash River. The maximum particle size would dictate the method(s) and economics for processing different biomass to sizes suitable for feeding to the gasifier.

The estimated entrainment velocity was made by calculating the terminal free-fall velocity of a particle of assumed diameter and sphericity. The maximum particle size would be that which produces a terminal velocity less than or equal to the gas velocity within the second stage of the gasifier.

The method proposed by Haider and Levenspiel (45) was used to calculate terminal velocity. Equations 1–3, shown below, indicate the sequence for first calculating a dimensionless particle size, then using the dimensionless particle size to calculate a dimensionless terminal velocity and, finally, converting the dimensionless terminal velocity to an actual terminal velocity. The equations are

Table 14. Comparison of Analysis Results for Indianapolis and Fargo Sewage Sludge

	Fargo Sewage Sludge		Indianapolis Sewage Sludge	
	As-Received	Moisture-Free	As-Received	Moisture-Free
Proximate, wt%				
Moisture	76.48	NA	77.70	NA
Volatile Matter	11.90	50.58	14.71	65.96
Fixed Carbon	0.88	3.74	1.68	7.54
Ash	10.74	45.68	5.91	26.50
Ultimate, wt%				
Hydrogen	9.38	3.78	9.90	5.67
Carbon	6.68	28.41	8.76	39.27
Nitrogen	0.80	3.42	1.05	4.69
Sulfur	0.78	3.31	0.16	0.73
Oxygen	71.61	15.40	74.23	23.14
Ash	10.74	45.68	5.91	26.50
Heating Value, Btu/lb	1184	5034	1736	7783
Chloride, µg/g	169	720	400	1794
Ash XRF, wt% as oxide				
Silicon		31.4		29.3
Aluminum		8.8		22.2
Iron		18.7		9.0
Titanium		1.0		0.9
Phosphorus		11.2		18.4
Calcium		14.2		9.7
Magnesium		3.0		2.8
Sodium		0.7		1.1
Potassium		1.2		1.7
Sulfur		9.7		4.9

EERC MM21028.JPG

Figure 3. Barrels for transporting Fargo municipal sewage sludge.

applicable to a wide range of particle shapes, including spherical, cubical, cylindrical, disklike, or irregular; very flat shapes with a width 10 times that of the height or thickness are not covered.

$$d^*_p = d_p \left[\frac{\rho_g (\rho_s - \rho_g) g}{\mu^2} \right]^{1/3} \qquad \text{[Eq. 1]}$$

$$u^*_t = \left[\frac{18}{(d^*_p)^2} + \frac{2.335 - 1.744\Phi_s}{(d^*_p)^{0.5}} \right]^{-1} \quad \text{for } 0.5 < \Phi_s < 1 \qquad \text{[Eq. 2]}$$

$$u_t = u^*_t \left[\frac{\mu (\rho_s - \rho_g) g}{\rho_g^{\,2}} \right]^{1/3} \qquad \text{[Eq. 3]}$$

Parameters for the calculations are described in Appendix A. The gas viscosity was obtained from published data (46) and was based on operating conditions provided by Global Energy. Calculations were performed over two ranges of particle specific densities: 480 to 720 Kg/m^3 (30 to 45 lb/ft^3) and 960 to 1440 kg/m^3 (60 to 90 lb/ft^3). The former range represents that typical for wood and agricultural residues, while the latter range represents densities typical for plastic, rubber, and leather (47). The density for sewage sludge was measured to be approximately 1090 Kg/m^3 (68 lb/ft^3), thus falling in the latter range.

Estimations of terminal velocities for various biomass feedstocks indicate that the maximum particle size of sewage sludge for entrainment will be no larger than about 2.5 to 5.0 mm (0.1 to 0.2 inches) at the known operating conditions of the gasifier.

Drop-Tube Furnace Testing

In support of the determination of proper sewage sludge size for injection into the Wabash River gasifier, it was hypothesized that the presence of large quantities of moisture within the sewage sludge may aid in its dispersion and rapid conversion. It was thought that exposure to the high-temperature gas (approximately 1370°C [2500°F]) of the second stage and the large amount of radiant energy from the refractory lining may cause the bound moisture to rapidly expand and vaporize. The expansion and vaporization would ideally be violent enough to cause the sludge particles to disintegrate into many smaller, more easily entrained particles. Therefore, the dispersion requirements of the sludge-feeding device would not be as rigorous.

To test the ability of the sewage sludge to violently disintegrate, the EERC's optical drop- tube furnace was used as the radiant heat source. The furnace, shown schematically in Figure 4, was reconfigured by removing the injector (for pulverized fuels), flow straightener, quench probe, and collection filter. The injector was replaced with a dairy flange cap. The quench probe and filter were replaced with a stainless steel collection pot lined with high-temperature glass insulation. The insulation functioned to provide a cushion for dropped sludge pellets. With the preheat furnace, high-temperature furnaces, and optical-zone furnace, the heated length measures 6 feet.

For all tests, the preheat furnace was maintained at 1000°C (1800°F) (the maximum for the heater), and the remaining furnaces were maintained at approximately 1400°C. This setting was sufficient to achieve a maximum furnace temperature of 1370°C (2500°F) as measured by a thermocouple positioned within the furnace. Nitrogen at approximately 1.4L/min (3 ft^3/hour) was injected from the top to provide an inert atmosphere within the furnace and inhibit sludge combustion.

Undigested sewage sludge from Indianapolis, Indiana, was used in all tests. Pieces of sludge were rolled by hand into spheres of ⅛ inch to ¼ inch. During a test, a sludge sphere was weighed and then dropped into the furnace after lifting the removable dairy fitting cap. The collection pot at the bottom was then removed to inspect the condition of the spherical sludge. Two tests with spherical sludge showed that the pellets stayed intact and did not exhibit a tendency to violently disintegrate. Rather, upon repeated drops, the pellets remained spherical in shape but shrank in size and mass. For one test, the pellet was reduced in mass by only 50 wt% after 12 drops through the furnace. A similar test was performed with a button-shaped pellet of 15.6 mm (⅝-inch) diameter and

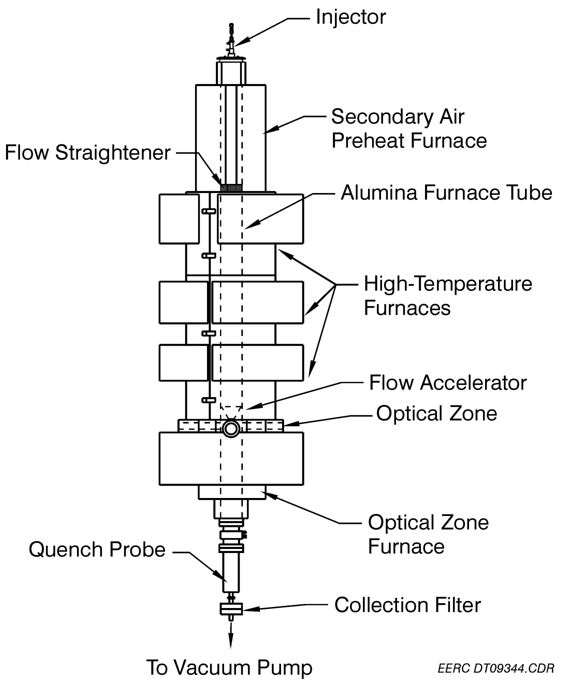

Figure 4. EERC optical drop-tube furnace.

3.2 mm (⅛-inch) thickness. The button-shaped pellet remained intact after losing 49 wt% of its mass through 13 drops.

Several tests were performed by introducing spherical pellets on a ceramic tube into the heated zone through the optical ports. A videocamera was used to view and record the effect on the pellets during an approximately 3-second hold time in the 1370°C (2500°F) zone. Several repeat tests with new pellets showed that in real time the pellets would just shrink in size without falling apart. Measurements with one pellet showed that the mass loss was approximately proportional to the reduction in pellet volume. For all tests performed, the drying actually functioned to produce a relatively firm pellet.

These preliminary tests suggest that without explosive fragmentation of the injected sludge mass, the particle size at injection will be that required for entrainment owing to an apparent low drying rate. This testing, however, did not provide for the effect of material reactivity which presumably will be superior to that of the currently injected fuel. It can be envisioned that with a sufficiently high reactivity at temperatures around 1370°C (2500°F), the consumption of the sludge mass may occur at a high enough rate that the downward particle decent is short and that an entrainable particle size is quickly reached. A properly positioned injection device could produce a sludge particle trajectory(ies) that help negate a resulting parabolic particle path after injection.

Feeding Across the Pressure Boundary

As previously discussed, Global Energy modeling efforts indicated that mechanically dewatered sewage sludge would, theoretically, not need additional dewatering or drying (unless proven cost-effective) prior to feeding. However, preliminary system design intentions precluded any drying of the sludge because of the uncertainty regarding the net tipping fee received at the Wabash River site. Consequently, pumping was considered to be a logical first selection for breaching the pressure boundary (2.830 MPa [410 psig]) of the Wabash River gasifier, presuming that sludge could be charged to the pump.

Based on an assumed density of 1000 kg/m^3 (62.4 lb/ft^3) and a daily sludge processing rate of 1000 wet-tons/day, the normal pumping rate was estimated to be about 10.7 L/sec (170 gpm). Without having performed any pump or sludge dispersion evaluations, preliminary minimum pump pressure requirements were assumed to be at least 3.450 MPa (500 psig) to overcome system operating pressure 2.830 MPa (410 pisg) and nominal line friction losses.

Pump Vendor Discussions

Through review of print and on-line product literature and direct contact with representatives and vendors, several commercial pump options were identified that could potentially provide near-term applicability for feeding viscous, nonflowable sludge into a pressurized atmosphere. Pump configurations included piston and progressive-cavity pumps and a novel pump utilizing nonimpingement boundary layer and viscous drag. The pump types and manufacturers are listed in Table 15.

The pumps offered by Schwing America (48) and Putzmeister (49) are based on concrete pump designs, reconfigured for the pipe/pipeline transport of highly dewatered municipal and industrial sludges. Typical applications include transferring dewatered sludges to haulage trucks or incinerators located several hundred feet from the sludge-dewatering facility. These pumps can achieve pressures up to 2000 psig and capacities of 500 gallons per minute (gpm). However, as the maximum values for pressure and pumping rate are not mutually attainable within a single system, multiple systems may be required to achieve both maximums.

Both Schwing and Putzmeister claim the ability to pump municipal sludges with solids contents up to 40 wt%. As opposed to traditional centrifugal and even positive displacement pumps, these specialized pumps require high-torque, twin-screw feeders to maintain high pump-filling efficiency by forcing the highly viscous sludge into the piston chambers. Both manufacturers offer pumps that have a method of backflow control, typically hydraulically actuated seat or poppet valves. Each piston chamber has a seat valve for the inlet and outlet that opens and closes with each filling and pumping cycle. This feature would appear to be desirable from the standpoint of providing a positive method for preventing uncontrolled backflow of gasifier contents upon suspension of sludge feeding. The pumps and screw feeders in these systems are powered by a stand-alone electrically driven hydraulic power pack.

Table 15. Pump Manufacturers and Pump Type

Manufacturer	Type
Schwing America	Double piston
Putzmeister	Double piston
Moyno	Progressive cavity
Discflo	Nonimpingement
Alfa Laval	Progressive cavity
Seepex	Progressive cavity

At the time of first contact with a representative, Moyno was just entering the dewatered sludge-pumping market with its HS 2000 series of progressive cavity pumps (50). As a consequence, the demonstrated operating history for Moyno pumps with highly dewatered municipal sludge was essentially nonexistent. As with the piston pumps, the Moyno HS series is equipped with twin-screw feeders to achieve pump filling. One advantage of the Moyno pump over piston pumps is the ability to produce a continuous, nonpulsating flow whereas piston pumps have a slight pulsation between piston strokes, with the pulse duration dependent upon the stroke rate. Perceived drawbacks of the Moyno pumps, with respect to the potential environment of utilization, include a 175°C (350°F) temperature limit on the pump stator and the absence of a positive means of backflow prevention. The low temperature limit on the stator may restrict sludge preheating as a potential option for reducing sludge viscosity.

The novel pump marketed by Discflo (51) does not rely on centrifugal force or a screw, lobe, or impeller to move the fluid. The Discflo pump relies on boundary layer and viscous drag forces created between one or more rotating disks and a high-viscosity fluid to achieve pumping. This nonimpingement design is touted to derive its advantage over conventional pumps largely through its greatly reduced maintenance and parts replacement costs. Application of Discflo pumps in the dewatered municipal sewage sludge area was essentially nonexistent, however.

The first four pump manufacturers listed in Table 15 were asked to provide 1) capital and estimated operating costs (including maintenance) for a commercial system designed to supply 10.7 L/sec (170 gpm) of sludge to the Wabash River gasifier and 2) a sample agreement and estimated cost for leasing a demonstration pump for testing at the EERC.

The capital and operating cost data were used to perform a present value analysis based on a 20-year life and a 5% discount rate. The analysis spreadsheet is shown in Table 16. The Discflo pump, although having an installed cost of less than half of the other pumps, was severely disadvantaged by a high horsepower requirement and, consequently, a high annual electrical operating cost. The Moyno pump appeared to have the most favorable present value, although the vendor quote for horsepower requirement was based on a fluid with a viscosity of 1 centipoise.

In contrast to the compliance with the request for capital and operating cost data, the degree of interest and the ability to provide a lease pump varied considerably among vendors/

Table 16. Present Value Analysis for Sludge Pump Systems

Company:	Discflo	Putzmeister	Schwing	Moyno HS
Pump Type	Disk	Dual-piston	Dual-piston	Progressive-cavity
Viscocity, cP	100,000	100,000	100,000	100,000
Sludge Solids, wt%	21.4	21.4	21.4	23
Head, psig	514	514	514	514
Flow, gpm	170	170	170	170
hp	600	150	200	100
Cost	$74,525	$149,450	$163,480	$59,739
Cost/hp	$124	$996	$817	$597
Cost/Flow	$438	$879	$962	$351
hp/Flow	3.5	0.9	1.2	0.6
Life	5 times greater than centrifugal	Pistons (5000 hr)	Pistons (5000 hr)	Rotor every 2 years, stator every year
Annual Parts Cost	$2,500	$27,089	$27,089	$28,400
Major Replacement Part	Rotor	Main drive cylinders	Main drive cylinders	Rotor, stator
Annual Labor Time	5 hours	80 hours	80 hours	16
Annual Labor Cost	$500	$8000	$8000	$1600
Annual Operating Time	7884	7884	7884	7884
Annual Operating Cost, $0.07/kWh	$248,346	$62,087	$82,782	$41,391
Total Annual Operating	**$251,346**	**$97,176**	**$117,871**	**$71,391**
Auger Feed Pump	$19,000	$46,550	$50,920	
Control Panel		$44,100	$48,240	
Power Unit		$56,350	$61,640	
Miscellaneous Equipment		$4900	$5360	$128,083
Total Package Costs	$93,525	$245,000	$268,000	$187,822
Notes	Discflo seemed to think we would only need a 600-hp pump. The results at 100,000 cP indicate a 900-hp requirement.	Pump price only includes the hydraulic power unit and the pump.	Pump price only includes the hydraulic power unit and the pump.	Pump price only includes the pump, drive, and base; misc. equipment includes twin-screw feed with drive, suction/discharge pressure sensors, and SRI metering station.
Life, years	20	20	20	20
Discount Rate	5%	5%	5%	5%
Present Value	($3,190,603)	($1,363,684)	($1,635,927)	($1,006,724)

manufacturers. At the time of inquiry, Putzmeister did not offer for lease a pump equipped with the seat or poppet valves. Discflo was equally encumbered by its inability to release a pump for testing and its lack of a pump model that could achieve operating pressures even up to 2.830 MPa (410 psig). Further, its pumps were not equipped with a twin-screw feeder, and the vendor verified after inspection of a sample that the pump could not draw in the dewatered sludge without a precharging mechanism such as a screw feeder.

Moyno, after repeated inquiries, did not produce an affirmative response to the ability to lease a pump. Initial vendor claims for the HS series pump were capacities up to 160 L/sec (2500 gpm) and maximum pumping pressures of 6.90 MPa (1000 psi). After the first series of pump trials were completed, Moyno was approached again about pump availability. Follow-up discussions with Moyno revealed, however, that aside from not having a pump for lease testing, the HS series pumps were only able to attain a maximum pumping pressure of 3.450 MPa (500 psig). This was subsequently deemed an inadequate pumping pressure. Concurrent inquiries were made with Alfa Laval and Seepex, both providers of progressive-cavity pumps to the municipal sludge treatment industry, and again the same pump limitations were revealed.

Leading up to the pump trials, only Schwing America was able to provide a pump with a positive means of backflow prevention – poppet valves. However, prior to making a commitment to leasing a pump system, it was determined that an EERC associate owned a Morgen Mustang (52) concrete pump that works on the same principle as the Schwing and Putzmeister sludge pumps. A picture of a similar pump is shown in Figure 5, and a cutaway schematic is shown in Figure 6. This diesel-operated pump uses dual pistons to deliver up to 31 m^3/hr (40 yd^3/hr) of concrete. The trailer-mounted concrete pump differs from the sludge pumps in that it is not equipped with poppet valves for positive backflow prevention nor is it equipped with a twin-screw auger for positive feeding of sludge to the pistons.

EERC MM19482.CDR

Figure 5. Morgen Mustang trailer-mounted concrete pump.

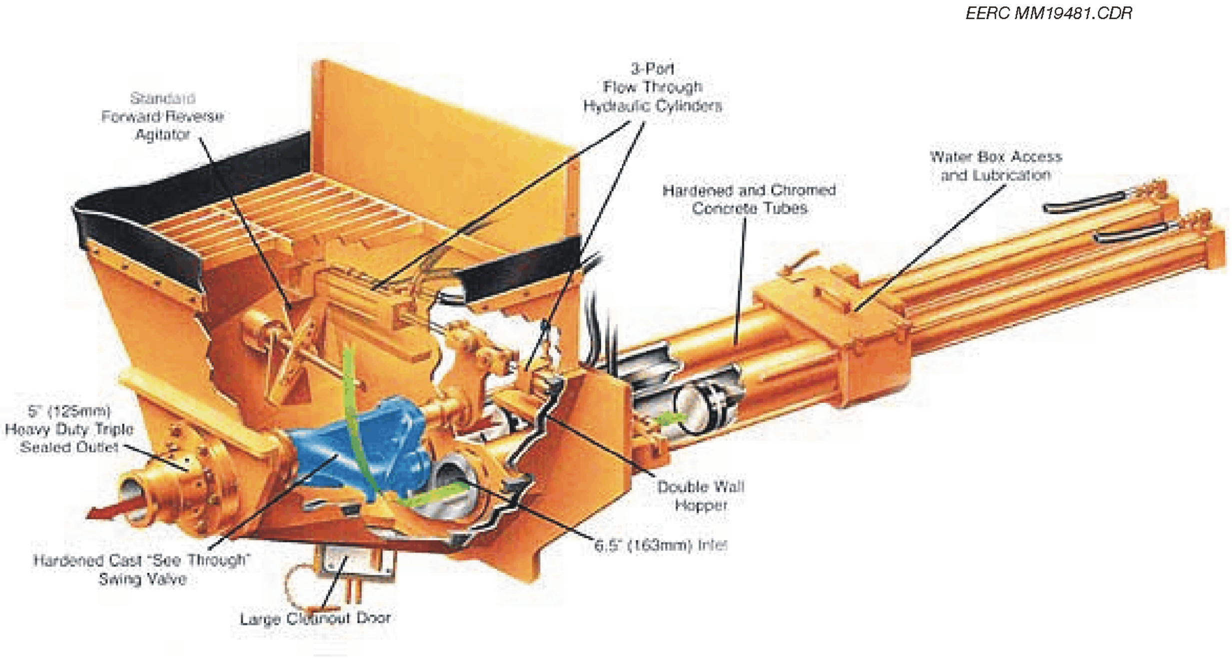

Figure 6. Cutaway diagram of Morgen Mustang concrete pump.

This pump uses a "swing" valve that switches between piston chambers to allow simultaneous filling of one chamber and delivery of fluid from the other chamber. Filling of the material chambers is facilitated by a vacuum created on the fluid within the feed hopper during the retraction of the piston within the "filling" chamber. A floating seal ring on the swing valve maintains a seal against the wear plate around the piston chamber outlets.

Pressure Vessel/Piping for Pump Testing

Two separate systems were designed for testing the ability of the piston pumps to deliver sludge into a 2.830 MPa (410 psig) pressurized atmosphere. The first design was based on a dual-purpose pressure vessel, shown in Figure 7. This 1.2-m (4-ft) -diameter, 2.4-m (8-ft) -long vessel was intended firstly as a receiving vessel for sludge and, secondly, as a biomass feed vessel for potential demonstration with the EERC transport reactor development unit (TRDU). The TRDU is a pilot-scale version of the Advanced Transport Reactor (ATR) system being tested at the Wilsonville, Alabama, Power System Development Facility (PSDF). The lower section of the pressure vessel was to be unbolted to remove the sludge between tests. The upper nozzle was the point at which sludge would be introduced into the vessel. The nozzle was sized to also allow attachment of a pressurized twin-screw auger for sludge feeding. The lower nozzle would be the point at which dry biomass would be withdrawn if the vessel were used as a pressurized hopper/feeder. The vessel size was based on the volume requirement for 1-hour capacity of biomass with a bulk density of 160 kg/m^3 (10 lb/ft^3).

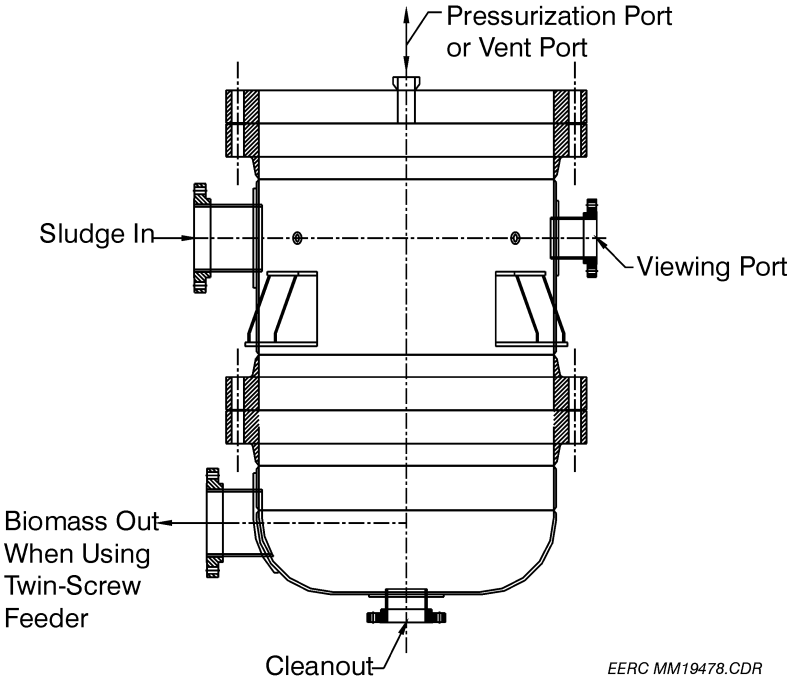

Figure 7. Large pressure vessel for elevated-pressure sludge system.

Four fabrication shops with American Society for Testing and Materials (ASTM) certification for pressure vessel construction were contacted to provide a quote for cost and construction time. Three shops provided bids, and the fourth declined to participate. Bid prices ranged from $20,000 to $41,000, with vessel delivery periods ranging from 10 to 12 weeks. The cost and delivery periods were considered excessive. Additionally, because of the vessel size and pressure requirements, the weight of the vessel was estimated by the shops at 6½ tons. This weight would present significant challenges with respect to unbolting and moving flanges to recover sludge, let alone movement and placement of the vessel within the gasifier structure. Based on the unacceptable cost, delivery period, and weight, this pressure vessel concept was shelved.

A second smaller pressure vessel option was pursued and eventually implemented, principally for the demonstration of pumping against 2.830-MPa (410-psig) pressure. The vessel was considered to potentially have a secondary use as the pressure containment vessel for a twin-screw auger that could be demonstrated with dry biomass materials on the TRDU. Figure 8 shows a shop construction drawing for the 254-mm (10-inch)-diameter carbon steel pressure vessel. The vessel was sized for 10 minutes of sludge pumping at a nominal feed rate of 0.38 L/sec (6 gpm). Estimations for proper pipe thickness and class or rating for the flanges and pipe tee were performed following ASME B31.3-90 pressure piping and Section VIII Division 1 pressure vessel codes.

The vessel consisted of two stacked 2.1-m (7-ft) pipe sections with a wall thickness of 9.53 mm (0.375 inch). The pressure pipe sections were designed with a volume under 0.11m^3 (4 ft^3) to allow vessel construction to be performed at the EERC. A 254-mm (10-inch) standard class tee was attached to the top pipe section. Flanges were of Class 300 rating. The lower section was

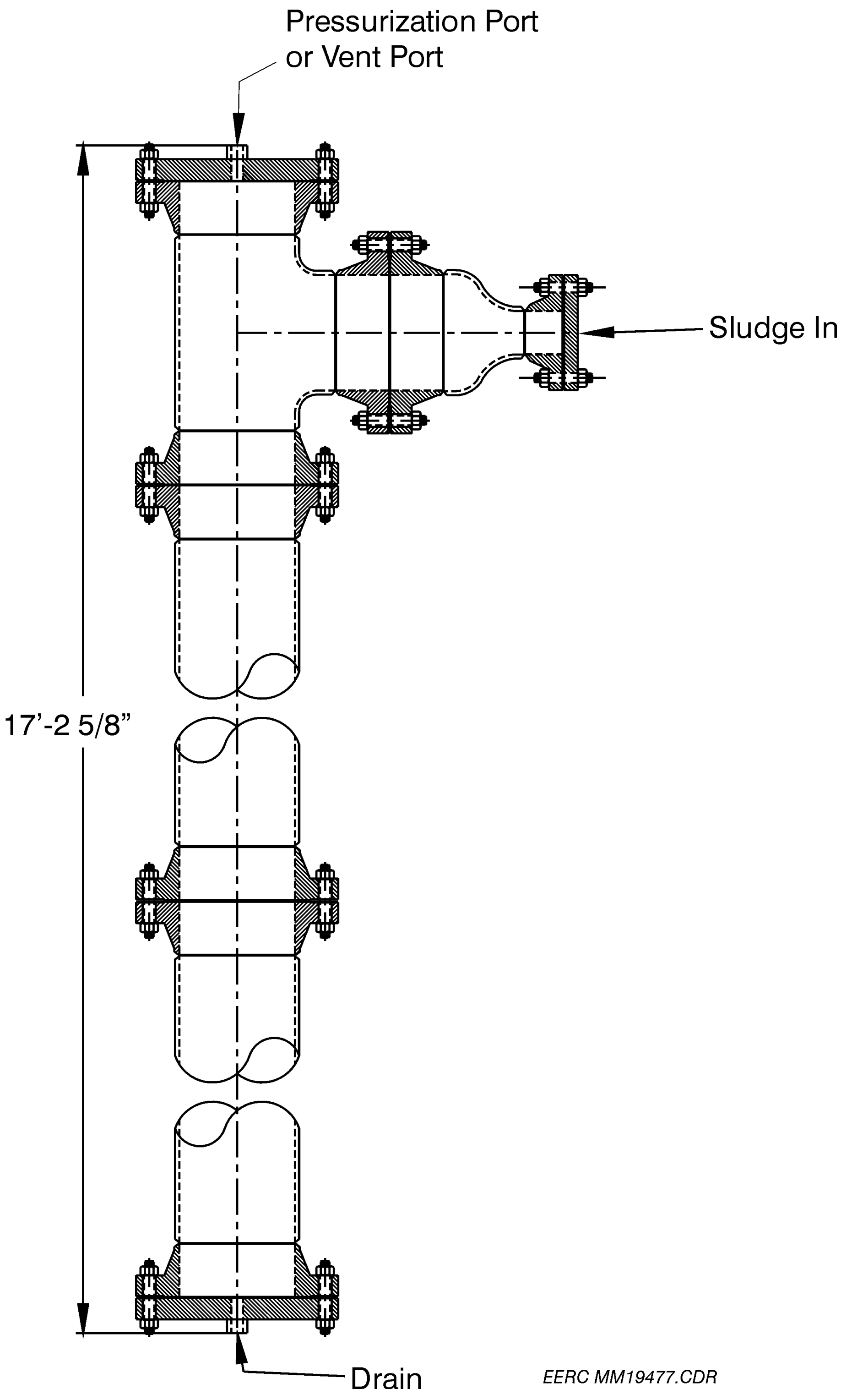

Figure 8. Pressure piping system for elevated-pressure sludge pump testing.

outfitted with box tubing support legs. The top flange on the pipe tee was center-bored and outfitted with a 25.4-mm (1-inch) coupling to allow attachment of gas charging/venting accessories. These accessories consisted of a safety relief valve, back-pressure control valve, manual vent ball valve, and a pressure gauge. The side flange on the pipe tee was attached to a 254-mm (10-inch) × 102-mm (4-inch) concentric reducing pipe spool. A Jamesbury Class 300 flanged 102-mm (4-inch) full-port ball valve was hung from the reducing spool.

Testing Pump Options

Prior to demonstration of pumping against the 2.830-MPa (410-psig) pressure barrier, the Morgen concrete pump was brought on-site and dry- and wet-tested. Dry testing consisted of starting the pump (after getting a new battery) and assessing for system defects. Wet testing consisted of first pumping water and then attempting to pump Fargo sewage sludge. The sewage sludge was shoveled from barrels to the feed hopper in such a manner to ensure that the intake ends of the material cylinders were completely covered and to facilitate establishment of a vacuum during the fill stroke. Unfortunately, the Morgen pump was unable to draw the nominal 23 wt% solids sludge into the material cylinders.

Consideration was given to trying to preheat the sludge (66°C [150°F] was the chosen target temperature) to reduce viscosity and improve flowability. However, tests conducted by immersing a steam-heated coil in a barrel of sludge showed that the coil would quickly scale with hard, dry sludge. The immersion barrel mixer system, equipped with a marine-type mixer blade, would only spin in the bottom of the barrel, cutting through the sludge without providing any agitation. The tenacity of the sludge indicated that a screw system with internally heated, self-cleaning flights would probably be one of the few ways to agitate and heat the sludge prior to utilization.

As a consequence of the unsuitability of the Morgen pump for handling sewage sludge, a Schwing America piston pump system was leased. Prior to the EERC receiving the pump, the manufacturing plant in White Bear Lake, Minnesota was visited to get a first-hand look at the system that would be tested. The total system, weighing approximately 4000 kg (8800 lb) was received via flat-bed truck. A schematic diagram of the pump with twin-screw feed auger is presented in Figure 9. A photo of the pump system is presented in Figure 10. The leased pump system consisted of the following components:

- KSP 17VK high-solids piston pump; 152-mm (6-inch)-diameter pumping cylinder; 991-mm (39-inch) ram stroke; 152-mm (6-inch) diameter discharge

- SD350 twin-screw feeder; 4000 N-m (2950 ft-lb$_f$) torque rating

- 50-hp electrically driven hydraulic power pack

The KSP 17VK pump, the smallest leased by Schwing, is a commercial pump with a maximum pumping capacity of 6.9 L/sec (110 gpm) and a max pumping pressure of 9.0 MPa (1300 psig). The pump consists of one material/hydraulic cylinder pair superposed over another pair. The material and hydraulic cylinders are separated by a water-filled stuffing box which functions to clean and cool

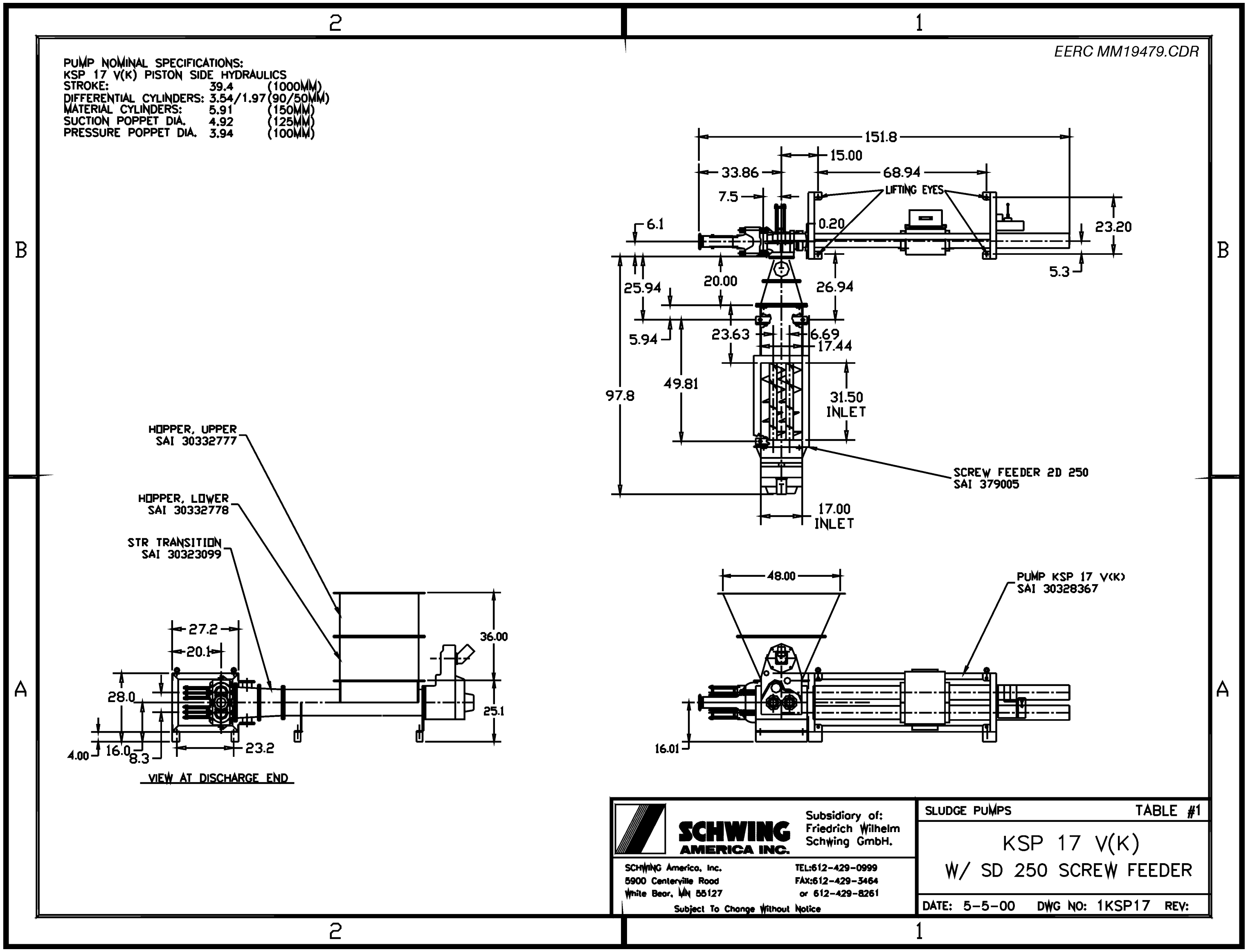

Figure 9. Schwing America high-solids sludge pump with twin-screw feeder.

EERC MM21029.JPG

Figure 10. High-solids sludge pump, twin-screw feeder, and power pack used at the EERC.

the material cylinder pistons. The pump is equipped with four hydraulically actuated poppet valves, one each on the suction side of the pump and one each on the discharge or pressure side of the pump. The reversible poppet valve heads rely on metal-to-metal knife-edge sealing to prevent backflow of material under elevated pumping pressures. The 152-mm (6-inch) discharge was modified to allow attachment to 63.5-mm (2.5-inch) heavy-duty concrete hose connections.

The twin-screw feeder functions to force-feed the sludge to the pump when the pump suction side poppets are open. In the lease configuration, the twin-screw feeder attached to the pump at a 90 degree angle. Other space-saving options are available where the pump and feeder are parallel to each other and connected through a curved transition. One version has the feeder atop the pump for maximum accessability. A photo of the screws within the feed hopper on the SD350 is shown in Figure 11. The screws consist of intermeshing, cut-flighting that functions to minimize lost capacity resulting from the build up of the sticky sludge on the shafts or flighting.

The power pack functions to provide hydraulic power, simultaneously, to the pump and twin-screw feeder. The power pack contains a single electric motor outfitted with multiple gear pump heads (one each for the sludge pump and twin-screw feeder) on the motor shaft. The power pack also contains the electronics that control the timing and sequencing of poppet valve function, the sludge pump stroke rate, and the rotational speed of the twin-screw feeder augers. Three-way valves at the power pack and the sludge pump allow these systems to be run in reverse to allow emptying of the pipeline in a controlled manner or to reduce pipeline pressure in the instance of an obstruction.

EERC MM21030.JPG

Figure 11. Hopper and overlapping augers of twin-screw feeder.

The sludge pump functions in a cyclical manner with one material cylinder in a pressure building/discharge mode and the second material cylinder in a filling mode. At the start of a cycle, the suction and discharge poppets on Cylinder 1 (the feeding cylinder) are in the closed position while the suction poppet is open and the discharge poppet is closed on Cylinder 2 (the filling cylinder). As the piston "compresses" the sludge against the closed poppets in Cylinder 1, the pressure on the sludge increases, and after reaching the desired line pressure, the discharge poppet opens, and the sludge is expelled by the piston. Concurrent to this, the retraction of the piston in Cylinder 2 plus the "stuffing" action of the twin-screw feeder causes the sludge to fill the cylinder. At the end of the piston stroke, the suction poppet closes to begin pressurization and feeding. The pump stroke rate and cylinder filling efficiency dictate the level of sludge pulsation owing to the cyclical pumping action.

After setup of the pump system, several preliminary pumping tests at the low-end pumping capacity (0.38 L/sec [6 gpm]) were performed to familiarize EERC personnel with procedures for safe operation and postrun cleanup. Instruction was performed by a Schwing America technician who was on hand for several days of testing to provide assistance. During the preliminary pumping tests, it was estimated that a pressure of 1.93 MPa (280 psig) was required just to pump the sludge through a 63.5-mm (2.5-inch)-ID, 7.6-m (25-ft)-long high-pressure, flexible hose. The hose had a maximum working pressure of 4.130 MPa (600 psig) and a burst pressure of 16.5 MPa (2400 psig). Consequently, it was estimated that to stay within safe operation, the maximum pressure within the pressure vessel could be 2.2 MPa (320 psig) rather than 2.83 MPa (410 psig).

The Schwing pump system was connected to the 100-mm (4-inch) Jamesbury valve on the pressure vessel. Only the lower pipe section with support legs and pedestal was used for the pressure pumping test. Connections were made using 63.5-mm (2.5-inch) heavy-duty snap-type closures with a maximum pressure rating of 13.8 MPa (2000 psig). Photos of the pump system and pressure vessel configured for pressurized pumping testing are shown in Figures 12 and 13. The flexible hose was originally selected over a rigid pipe and flange connection system to minimize the requirement for field-fitting and to hasten initiation of testing. Further, the flexible hose and heavy duty connectors made it easier to reposition and clean process equipment.

Once the Schwing pump was connected to the pressure vessel, the back-pressure control valve was reset to a relief pressure of 2.2 MPa (320 psig); the safety relief valve was set at 3.1 MPa (450 psig). With the 100-mm (4-inch) ball valve in the closed position and the flexible hose full of sludge, the pressure vessel was brought up to 2.2 MPa (320 psig) with nitrogen. The screw feeder and sludge pump were then started, and almost immediately, the opening of the ball valve was initiated. Simultaneously, the back-pressure control valve started to relief, indicating positive flow of sludge against pressure into the vessel. The pump was allowed to feed for approximately 5 minutes during which time no evidence of backflow of sludge or nitrogen was detected. Even after shutting off the pump but before closing the ball valve, there was no backflow. The pumping test was considered a success, and it was felt that doing the same at 2.83 MPa (410 psig) would not present any problems.

Dispersion/Injection of Sewage Sludge

After breaching the pressure boundary, it was envisioned that the sludge would need to be dispersed at a sufficiently small particle size to ensure entrainment. These values were previously

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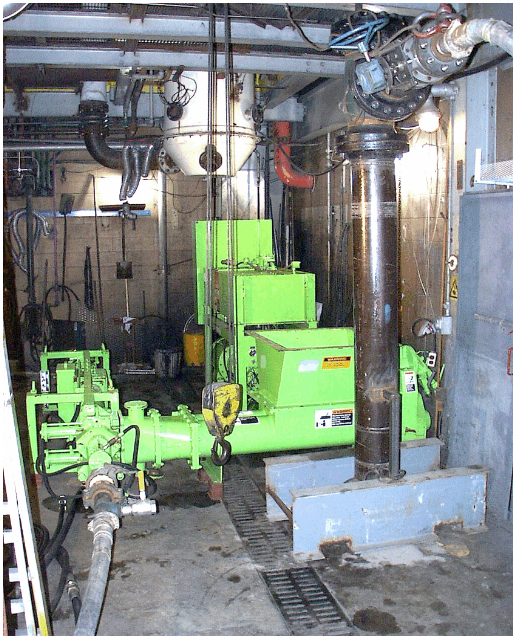

Figure 12. Pump system configured for pumping sludge into pressurized vessel – side view.

Figure 13. Pump system configured for pumping sludge into pressurized vessel – top view.

estimated to be in the range of 2.5 to 5.0 mm (0.1 to 0.2 inches). Three methods of injection/dispersion of sewage sludge into the Wabash River entrained-flow gasifier were considered: 1) mechanical dispersion, 2) screw-feeding with pneumatic dispersion, and 3) injection through a dual-fluid nozzle.

Mechanical Dispersion

Concepts considered for mechanical dispersion included 1) extrusion through a die followed by cutting the sludge extrudate with a high-speed rotational knife and 2) injection using a modified agricultural manure/sludge spreader. The spreader uses high-rotational-speed hammers (similar to a hammermill) or impellers to "project" the sludge, often at distances over 30 meters (100 ft). Screw augers are used to force feed the impellers or hammers. The spreader concept has a parallel in the sludge-drying industry. Fluid-bed systems used for producing thermally dried, pelletized (i.e., sphered: to form into a sphere) sludge as soil amendment use a "flinger" type feeder to propel small chunks of sludge into the dryer.

The principal drawbacks perceived to be associated with these systems included a short operating life and low reliability for rotating parts exposed to the high-temperature (approximately 1370°C [2500°F]) and potentially slagging atmosphere at the proposed injection point. Further, preliminary estimates indicate that rotational speeds for an impeller or hammers in a spreader-type system would be very high (several thousand rpm) again providing an equipment-reliability challenge, especially if thousands of continuous on-line hours for the feeder are required. The mechanical feeding/dispersion concept was not pursued further.

Screw Feeding with Pneumatic Dispersion

Principally because of the potential for sludge flow pulsation when a piston pump is used, screw feeding was considered as an option for leveling out sludge flow. Further, it was envisioned that the auger flights would provide an initial means of delumping the pumped sludge prior to using a directed stream of high-pressure gas from a dispersion nozzle to further size-reduce and convey the sludge into the flowing gas stream of the gasifier.

As part of proposed demonstrations, a design was developed for a twin-screw auger that would be coupled with a pump system. The twin-screw auger was sized based on an estimated maximum pumping rate of 0.76 L/sec (12 gpm). The proposed system consisted of twin overlapping screw flights, both with inward rotation. The overlapping flights would theoretically function to provide self-cleaning and inhibit buildup of sticky sludge. Pressure containment would be attained by housing the twin screws in a pipe/flange system rated for a minimum pressure of 410 psig.

Bid specifications for constructing a pilot-scale twin-screw auger were forwarded to six conveyor manufacturers. Five of the six vendors declined to participate. The remaining vendor, Unico Services (53), claimed experience in producing screw augers used for the controlled removal of high-temperature ash from two demonstration-scale gasifiers. The system quoted by Unico was $45,000, which was deemed excessive. Subsequent to the bid process, attention has focused on possibly building a system in-house with purchased components. Critical to the development of the pressurized-screw feeder was a shaft seal that can seal at 410 psig. Discussions with eight shaft seal vendors indicated that nothing was available off-the-shelf. The seal manufacturers would require significant engineering time to develop new or modify existing designs. Most vendors declined further involvement, knowing the request was for no more than two seals. One vendor offered a quote of $3000 per seal.

Dual-Fluid Nozzle Injection

After considering and rejecting mechanical dispersion and screw feeding with pneumatic dispersion, injection using a dual-fluid nozzle became the primary focus of sludge-feeding/dispersing options. Initial design options focused principally on the application of a shotcrete nozzle, a tool used for wet concrete “gunning.” Shotcrete nozzles intimately mix compressed air with concrete in a converging pipe, resulting in a high-velocity stream (100 to 200 ft/sec) of concrete that can be deposited on vertical services at distances up to approximately 6 meters (20 feet) or more from the nozzle. A photo of an application of a shotcrete nozzle is shown in Figure 14 (54). These nozzles can feed concrete with aggregate up to 19 mm (0.75 inch) in diameter. It was presumed that recycle syngas available at Wabash River could replace air as the pneumatic transport fluid. Preliminary estimations show that the sludge:syngas volume ratio available for the Wabash River gasifier is similar to the concrete:compressed air ratios normally achieved with the nozzle.

Several shotcrete nozzle manufacturers were identified. A 6.35-mm (2.5-inch) nozzle with a rated capacity of approximately 18.4 m^3/hr (24 yd3/hr) concrete was purchased from Shotcrete Technologies (55). A schematic of the nozzle is shown in Figure 15, and a photo of the nozzle is

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Figure 14. Shotcrete Technologies nozzle being used for concrete gunning.

EERC MM19480.CDR

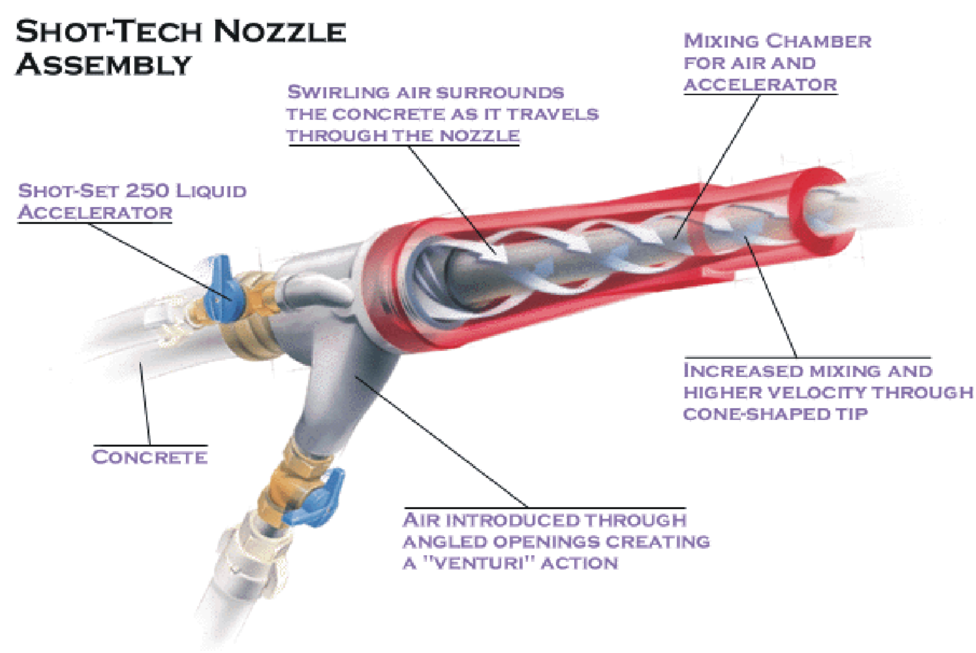

Figure 15. Cutaway diagram of Shotcrete Technologies shotcrete nozzle.

shown in Figure 16. This nozzle was equipped with 63.5-mm (2.5-inch) heavy-duty connection to allow easy mating to existing piping.

In addition to the shotcrete nozzle, a nozzle design was advanced that was based on a mechanical sludge dispersion system used by the Western Lake Superior Sanitary District (Duluth, Minnesota) (56) for feeding 16 wt% solids sludge to an, now inoperable, atmospheric-pressure fluid-bed incinerator. A schematic of this dispersion system, informally called a lance, is shown in Figure 17. The lance consisted of a solid rod with a solid metal cone attached at one end. The pipe and lance were suspended vertically with the sludge being forced through the annulus created by the cone and the 152-mm (6-inch) pipe. The thinning of the sludge allowed it to be more effectively dispersed and consumed within the fluid bed. The supported end of the rod was attached to a spring mechanism that allowed the lance to move downward, increasing the annular space in the event that a rag or similar potential obstruction was passed with the sludge.

As the requirements for sludge dispersion within the Wabash River gasifier were presumed to be much more severe, a dispersion nozzle with a lance-type insert was designed and constructed, with the principal design upgrade being the addition of perforations to the angled face of the cone. The perforations would allow the introduction of high-velocity jets of recycle syngas that would ideally disintegrate the sludge and carry the sludge into the gasifier. A shop construction drawing of the nozzle insert is shown in Figure 18, and a photo is shown in Figure 19. Initially, the confidence level in this design was less than that of the shotcrete nozzle, and consequently, the first nozzle system (EERC-1) was quite unrefined. The first nozzle insert consisted of two back-to-back concentric 25.4-mm × 50.8-mm (1-inch × 2-inch) reducers with one end sealed by a 25.4-mm (1-inch) cap. The opposite end was connected to a 25.4-mm (1-inch) pipe which supplied the

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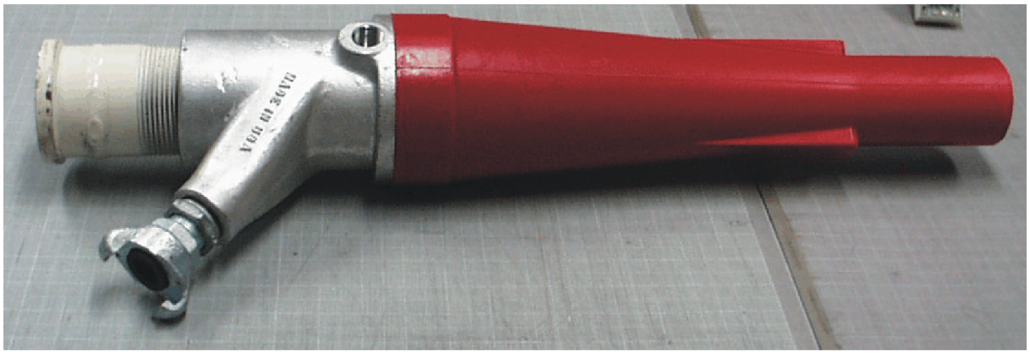


Figure 16. Shotcrete Technologies 2½-inch shotcrete nozzle.

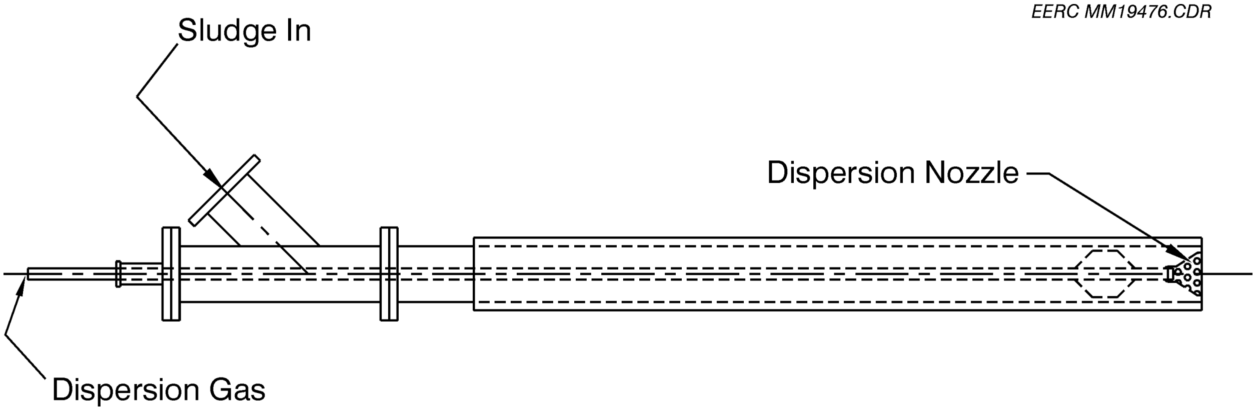


Figure 17. Sludge dispersion lance used in fluid-bed incinerator.

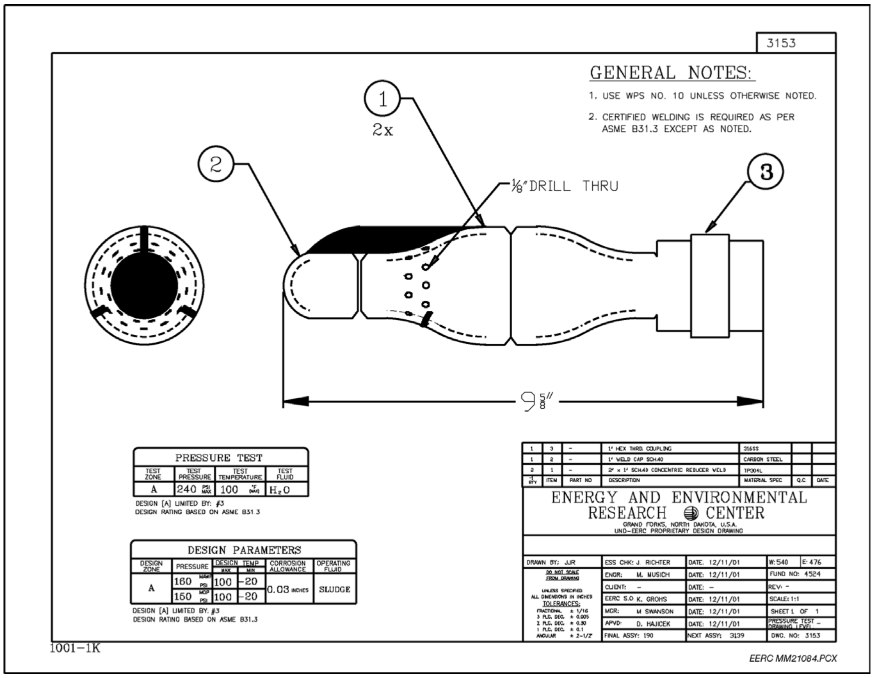


Figure 18. Shop drawing of the EERC-1 sludge dispersion nozzle.

EERC MM21082.PCX

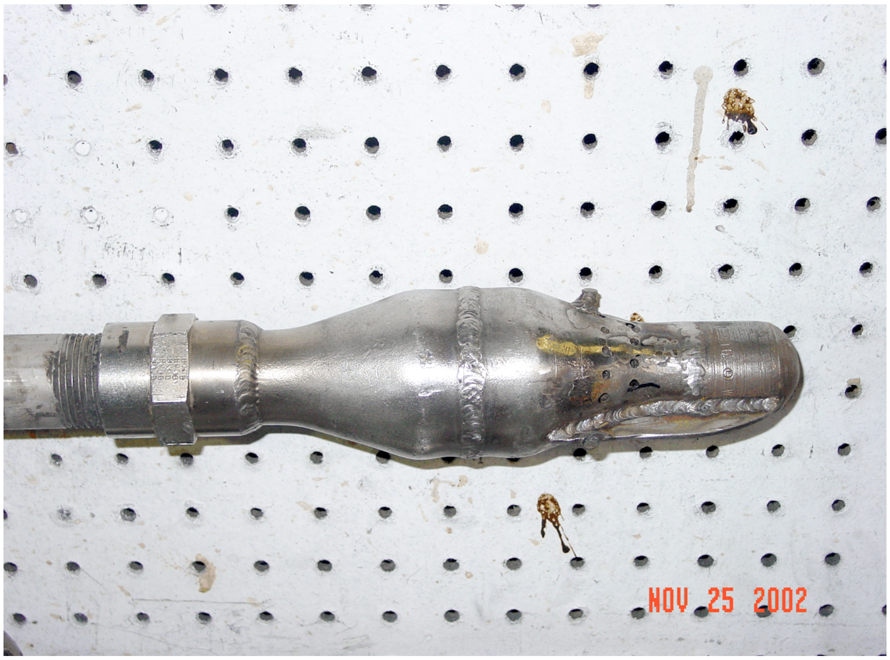
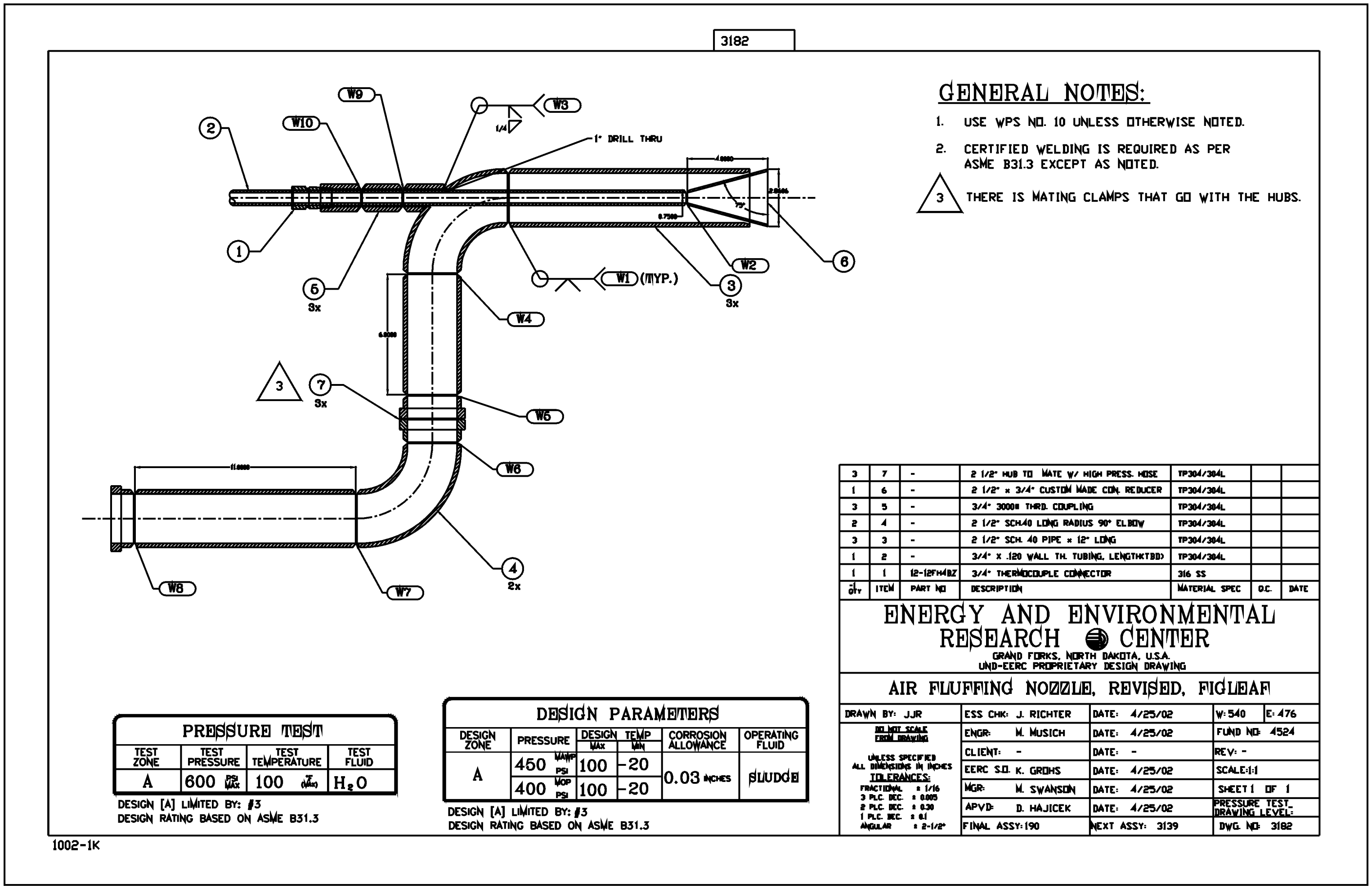


Figure 19. The EERC-1 sludge dispersion nozzle.

dispersion gas. Three alignment fins were attached approximately 120 degrees apart on the sloped face of the nozzle to help provide a uniform annular space around the circumference. A support system was constructed that allowed the EERC-1 nozzle to be held securely within the end of the 63.5-mm (2.5-inch), 7.6-m (25-ft)-long high-pressure, flexible hose. The support system allowed the nozzle to be moved in or out of the hose to change the width of the annular gap. The number of holes on the face of the upstream reducer was determined based on a desired velocity of 30 m/sec (100 ft/sec) through each hole at a total flow rate of 4400 scfh.

Subsequent to the evaluation of the shotcrete nozzle and the EERC-1 nozzle, a more refined version of the latter nozzle was designed, constructed, and tested. A shop drawing of the EERC-2 nozzle is shown in Figure 20, and photos of the nozzle are shown in Figures 21–23. The principal improvements in this nozzle were that the dispersion gas pipe ran down the center of the nozzle and that the pipe and cone were a singular, integral unit. A compression fitting with a Teflon ferrule was utilized to allow the 19.1-mm (0.75-inch)-OD dispersion gas pipe (with dispersion cone) to be moved in and out to change the width of the annular gap. A threaded-rod locking assembly was used to prevent the unwanted movement of the dispersion pipe. Initially, it was hoped that the rigidity of the heavy wall 19.1-mm (0.75-inch)-OD dispersion gas pipe would inhibit flexing and, consequently, nonuniformity of the annular gap width. The first shakedown tests indicated otherwise, and as with the EERC-1 nozzle, three alignment fins were added to help maintain proper gap. The end of the nozzle pipe was machined to a taper with an angle equivalent to that of the dispersion cone angle. The dispersion cone was machined from a piece of round stock and then sealed on the large end with flat stock. The number of holes on the dispersion cone was similar to that of the EERC-1 nozzle.

EERC MM20867a.CDR



QTY	ITEM	PART NO	DESCRIPTION	MATERIAL SPEC	O.C.	DATE
3	7	-	2 1/2" HUB TO MATE W/ HIGH PRESS. HOSE	TP304/304L		
1	6	-	2 1/2" x 3/4" CUSTOM MADE CON. REDUCER	TP304/304L		
3	5	-	3/4" 3000# THRD. COUPLING	TP304/304L		
2	4	-	2 1/2" SCH.40 LONG RADIUS 90° ELBOW	TP304/304L		
3	3	-	2 1/2" SCH. 40 PIPE x 12" LONG	TP304/304L		
1	2	-	3/4" X .120 WALL TH. TUBING, LENGTH(TBD)	TP304/304L		
1	1	12-12FH4BZ	3/4" THERMOCOUPLE CONNECTOR	316 SS		

PRESSURE TEST

TEST ZONE	TEST PRESSURE	TEST TEMPERATURE	TEST FLUID
A	600 PSI MAX	100 °F (MAX)	H_2O

DESIGN [A] LIMITED BY: #3
DESIGN RATING BASED ON ASME B31.3

DESIGN PARAMETERS

DESIGN ZONE	PRESSURE	DESIGN TEMP MAX	DESIGN TEMP MIN	CORROSION ALLOWANCE	OPERATING FLUID
A	450 MAWP PSI	100	-20	0.03 INCHES	SLUDGE
	400 MOP PSI	100	-20		

DESIGN [A] LIMITED BY: #3
DESIGN RATING BASED ON ASME B31.3

Figure 20. Shop drawing of the EERC-2 sludge dispersion nozzle.

EERC MM21034.JPG

Figure 21. The EERC-2 sludge dispersion nozzle.

EERC MM21035.JPG

Figure 22. The EERC-2 sludge dispersion nozzle – end view.

EERC MM21036.JPG


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Figure 23. The EERC-2 sludge dispersion nozzle – end view.

Containment System for Sludge Dispersion Testing

Two separate systems were initially designed for containment of the sludge during dispersion testing. The first system, shown in Figure 24, was intended to allow injection of the dispersed sludge into an entrainment column. The entrainment column would be fed at the bottom with air from a blower. Although operated at atmospheric pressure and ambient temperature, the flowing conditions of the entrainment tower would produce particle drag and lift essentially equivalent to those achieved in the Wabash River gasifier. The entrainment tower would be ported to allow attachment of a pneumatic dispersion device such as the shotcrete nozzle (or other) or a twin-screw conveyor.

The second system was designed principally for evaluation of the shotcrete nozzle. This system consisted of a 2.7-m (9-ft)-long, 483-mm (19-inch)-diameter carbon steel pipe with several ports along its length. The sludge pump was positioned with the attached shotcrete nozzle at or near the entrance of the horizontally oriented pipe. Sludge impacting on the end panel was to fall through the lower port. The side ports located within 0.76 m (2.5 ft) and 1.7 m (5.5 ft) of the entrance were covered with plexiglass to allow observation of the nozzle spray. The first shakedown tests with the shotcrete nozzle indicated this vessel to be unwieldy with respect to recovery of the sludge for subsequent tests. Consequently, a new system was developed that was used throughout all remaining atmospheric pressure dispersion tests.

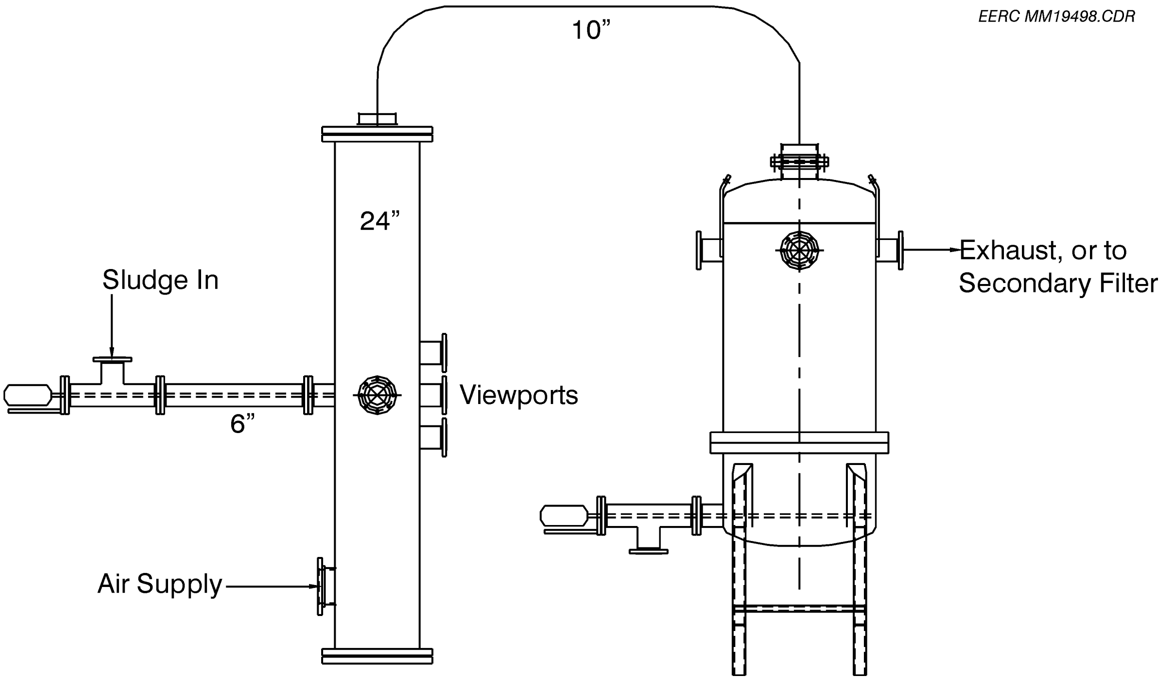

Figure 24. Sludge dispersion and entrainment column.

To facilitate more efficient utilization of the sludge and to minimize manual recovery of sludge from containers, a dispersion barricade or shroud (Figure 25) was placed above the opening to the twin-screw feeder. This four-and-a-half-sided shroud was constructed of steel plate and was clamped to the flange of the screw-feeder opening. The purpose of the shroud was to allow continual dispersion of sludge through a nozzle with the sludge impinging on the walls of the hood and then falling back to the screw feeder to be reused. Only periodic recharging of fresh sludge was required. The top side of the hood was equipped with a plexiglass-covered 0.30-m (12-inch)-diameter hole above which a halogen lamp was used to provide lighting within the hood. The dispersion nozzle was supported by a vice on a roller stand. The vice and stand could be moved to allow proper positioning of the dispersion nozzle over the twin-screw feeder hopper. The half-length side allowed simultaneous containment of the sludge and filming of the dispersed sludge spray. The distance between the nozzle tip and hood walls was about 0.61 m (2 ft).

Nozzle Testing

Excluding several shakedown tests, a total of 41 dual-fluid nozzle sludge dispersion tests were conducted at the EERC. Tests 1 to 29 were conducted in December of 2001, and Tests 30 to 41 were conducted in June of 2002. The first 20 tests were conducted with the shotcrete nozzle, while the latter tests were conducted with two different versions of the annular nozzle type as previously described.

EERC MM21078.PCX

Figure 25. Containment shroud on twin-screw feeder hopper.

As indicated in Table 17, the controlled variables included sludge rate, dispersion air rate, and nozzle configuration. Measured variables included the dispersion gas pressure at the nozzle and the hydraulic pressure for the pump.

Control of the sludge pump stroke rate was achieved through a manual rheostat located on the power pack. An analog gauge indicated the percentage of maximum pump stroke rate for the respective rheostat setting. The pump could be field-adjusted to increase the low-end and high-end pump stroke rates up to a maximum rate of about 24 strokes per minute to achieve a theoretical 6.9 L/sec (110 gpm). Control of the twin-screw auger speed (or feed rate) was similarly achieved with adjustments to low- and high-end speed made concurrently to changes in the pump stroke rate range. Maintaining a twin-screw auger speed at or 20% higher than the pump stroke rate setting was sufficient to achieve good pump filling. A few instances of poor filling, as evidenced by excessive pulsations in the sludge spray, were due to letting the feed hopper get too low on sludge.

The sludge-pumping rate was determined by measuring the mass of sludge pumped into a half-barrel over a specified period as recorded by a stop watch. Several calibrations were performed at each pump stroke setting and were found to differ by no more than a few percentages. Because the pump stroke rate is not affected by back pressure and filling efficiency is determined by the twin-screw auger, the sludge mass rate was presumed to be unaffected by changes in back pressure on the pump. Changes in back pressure at a constant pump rate would come from changing the gap size, for example, on the dispersion nozzles.

Table 17. Sludge Nozzle Test Conditions and Results

Test No.	Nozzle	Nozzle Configuration	Sludge Rate, lb/min	Air Rate, acfh	Velocity, ft/sec	Gauge Pressure, psig	Comments
1	Shotcrete	1.50" tip ID, Insert 1	225	4400	100	<10	Poor spray. large chunks
2	Shotcrete	1.50" tip ID, Insert 1	225	6600	150	<10	Better spray. smaller chunks
3	Shotcrete	1.50" tip ID, Insert 1	225	8800	200	<10	Improved spray. particles too large
4	Shotcrete	1.50" tip ID, Insert 2	225	8800	200	<10	No improvement from modified insert
5	Shotcrete	1.50" tip ID, Insert 2	225	11000	250	13	Wider spray angle. smaller particles
6	Shotcrete	1.50" tip ID, Insert 2	225	13300	300	17	
7	Shotcrete	1.50" tip ID, Insert 2	225	15500	350	20	Better distribution within spray cone
8	Shotcrete	1.50" tip ID, Insert 1	225	15500	350	20	Slight reduction in spray angle
9	Shotcrete	1.50" tip ID, Insert 1	120	15500	350		Less dense spray cone, wider angle
10	Shotcrete	0.96" tip ID, Insert 2	250	6300	350	45	Narrower spray cone, particles < 1/4"

Continued. . .

Table 17. Sludge Nozzle Test Conditions and Results (continued)

Test No.	Nozzle	Nozzle Configuration	Sludge Rate, lb/min	Air Rate, acfh	Velocity, ft/sec	Gauge Pressure, psig	Comments
12	Shotcrete	0.96" tip ID, Insert 2	250	8100	450	45	Poor camera view
13	Shotcrete	0.96" tip ID, Insert 2	250	3600	200	30	Sludge initially out as stream
14	Shotcrete	0.96" tip ID, Insert 2	250	3600	200		
15	Shotcrete	0.96" tip ID, Insert 2	250	1800	100		Same as 13, poor particle dispersion
16	Shotcrete	0.96" tip ID, Insert 2	250	5400	300	35	Similar to test 10
17	Shotcrete	0.96" tip ID, Insert 2	340	5400	300	50	Spray concentrated in middle of cone
18	Shotcrete	0.96" tip ID, Insert 2	340	7200	400		Good dispersion, better than 17
19	Shotcrete	0.96" tip ID, Insert 2	340	9000	500	65	Best spray cone, smallest particles
20	Shotcrete	0.96" tip ID, Insert 2	280	5400	300	35	Spray concentrated in middle of cone

Continued. . .

Table 17. Sludge Nozzle Test Conditions and Results (continued)

Test No.	Nozzle	Nozzle Configuration	Sludge Rate, lb/min	Air Rate, acfh	Velocity, ft/sec	Gauge Pressure, psig	Comments
21	EERC-1	0.18" annular gap	340	4400	130	25	Better dispersion, smaller particles than most shotcrete tests, ~ 0.20" particles
22	EERC-1	0.18" annular gap	340	6600	195	35	Finer particles (<0.20"), even distribution
23	EERC-1	0.25" annular gap	340	4400	95	10	Coarser spray, >0.25"
24	EERC-1	0.25" annular gap	340	6600	140	20	Slight reduction in particle size, worse than 21
25	EERC-1	0.18" annular gap	490	6600	195	45	Slightly better than 21
26	EERC-1	0.18" annular gap	490	4400	130		Coarser spray, comparable to 21
27	EERC-1	0.18" annular gap	575	6600	195	50	Slightly better than 21
28	EERC-1	0.18" annular gap	575	4400	130	40	Coarser spray, nozzle obstructions
29	EERC-1	0.18" annular gap	575	8800	255		Finest spray of first 29 tests, approaching 0.10"
30	EERC-2	0.125" annular gap	700	4400		100	Out as streams at start of stroke, smallest particles of first 30 tests, ~0.10"

Continued. . .

Table 17. Sludge Nozzle Test Conditions and Results (continued)

Test No.	Nozzle	Nozzle Configuration	Sludge Rate, lb/min	Air Rate, acfh	Velocity, ft/sec	Gauge Pressure, psig	Comments
31	EERC-2	0.125" annular gap	700	5200		85	Better spray, equally small particles
32	EERC-2	0.125" annular gap	700	5100		100	Comparable to previous two tests
33	EERC-2	0.18" annular gap	695	4400	130	45	Finer particles than 21, 26 and 28; 0.20" and less
34	EERC-2	0.18" annular gap	790	4400	130	56	Distinctly finer particles than 33; 0.10" to 0.20"
35	EERC-2	0.18" annular gap	850	4400	130	60	Comparable to 34
36	EERC-2	0.18" annular gap	850	2200	65	43	Poor distribution; starts as stream; not enough gas
37	EERC-2	0.18" annular gap	850	3300	98	45	Comparable to better than 33
38	EERC-2	0.22" annular gap	695	4400	123	35	Coarser particles, 0.20"
39	EERC-2	0.22" annular gap	850	4400	123	35	Comparable to 38
40	EERC-2	0.22" annular gap	695	3300	92	29	Poorer distribution, coarser particles than 38
41	EERC-2	0.22" annular gap	850	3300	92	29	Slightly better distribution but similar particle size to 40, 0.20 to 0.25"

The control and volume rate measurement of dispersion gas, for all tests air was used, was achieved by utilizing equipment from the TRDU gasifier at the EERC. A Baumann valve provided flow rate control with volume rate measurement provided by a Roots positive-displacement meter. The master computer for the TRDU was utilized to monitor flow rate and allow setpoint changes to the dispersion gas flow rate. The dispersion gas pressure at the nozzle was monitored using an analog gauge.

To perform a test, the tip of the respective sludge dispersion nozzle was positioned, as previously described, with respect to the containment shroud and the twin-screw feeder hopper. The dispersion gas flow rate was started and a setpoint entered into the control computer. The twin-screw feeder was started first and then the sludge pump. All tests were recorded using a Hi8 camcorder to allow comparative review of the tests. As the learning curve progressed, an attempt was made to capture images of the nozzle spray patterns at different angles.

Tests 1 to 20 were conducted with the Shotcrete Technologies nozzle. Tests with this system were less than encouraging. This nozzle produced a narrow, concentrated spray with a diverging cone angle estimated at about 12°. The first nine tests utilized the unmodified nozzle with a tip opening of 38.1 mm (1.5 inch) and the original gas–sludge mixing insert (Insert 1) as shown in Figure 26. The insert formed an annular region within the nozzle body. All gas entering the nozzle passed through holes located on the exterior ring of the insert. The holes were machined into the ring at an angle to impart a swirling action during contact with the sludge as it entered the nozzle through the center of the insert. Tests 4 to 7 were performed with a modified insert (Insert 2) as shown in Figure 27. This insert was modified by adding a number of holes along the insert wall and by adding a ring at the end of the insert to force the gas through the holes. The presumption was that this would allow earlier and more intense mixing of the dispersion gas with the sludge to produce smaller particles. There was no observed improvement to the sludge particle size or spray pattern. These initial tests with the shotcrete nozzle indicated that the dispersion gas- to-sludge ratios would be significantly above that available at Wabash River.

A more productive improvement to the shotcrete nozzle included the insertion of a cylindrical plug with a 24.4-mm (0.96-inch)-ID, shown in Figure 28, into the end of the nozzle. This plug resulted in a nearly 60% reduction of the cross-sectional area of the tip. The plug, while producing a narrower spray pattern, was effective at producing particles with sizes even better than those achieved with the 38.1-mm (1.5-inch) opening. This was accomplished at lower dispersion gas-to-sludge ratios. However, the dispersion gas-to-sludge ratios were still too high. There was no attempt to test an tip insert with a even smaller ID.

Tests 21 to 29 with the EERC-1 nozzle immediately followed the shotcrete nozzle testing. Based on the first test, this nozzle concept immediately appeared to be a better approach than the shotcrete nozzle. This improvement (reduction in particle size) was presumed to result from the more efficient degradation of the sludge stream as it was essentially extruded through the annulus around the dispersion cone. This was accomplished even though the cross-sectional area of the EERC-1 nozzle opening at 4.57 mm (0.18 inch) was almost 80% larger than the shotcrete nozzle using the 24.4-mm (0.96-inch) tip insert. Tests 23 and 24 showed that increasing the gap size to 6.35 mm (0.25 inch) resulted in an increase in particle size. Test 28, conducted at a dispersion gas-to-sludge

EERC MM21079.PCX

Figure 26. Mixing-Insert 1 for shotcrete nozzle body.

EERC MM21080.PCX

Figure 27. Mixing-Insert 2 for shotcrete nozzle body.

EERC MM21081.PCX


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Figure 28. Plug inserted into tip of shotcrete nozzle.

ratio 21% higher than desired, produced particles around 5.1 mm (0.20 inch) with significant reduction in particle size down to about 2.5 mm (0.10 inch) after doubling the dispersion gas rate in Test 29. Although the results of the last few tests of the series showed significant promise and would be achievable with recycle syngas resources available at Wabash River, the dispersion gas-to-sludge ratios were still higher than desired by Global Energy.

Consequently, the Schwing sludge pump system was leased for a second time after producing the, hopefully, more improved EERC-2 nozzle. The purpose of the last round of tests (30 to 41) were to evaluate the new nozzle at dispersion gas-to-sludge ratios near the maximum desired by Global Energy. In this round of tests, the highest sludge pumping rates were achieved, with rates ranging from 316 to 386 kg/min (695 to 850 lb/min), the latter value essentially being a maximum for the leased pump. As with tests with the EERC-1 nozzle, reductions in sludge particle size were attained by decreasing annular gap size and by increasing dispersion gas rate. It also appeared that, for a fixed dispersion gas rate, increasing sludge mass rate (over a small range) also decreased particle size.

In the first three tests with the EERC-2 nozzle, with a nozzle gap of 3.2 mm (0.125 inches), the smallest particles (approximately 2.5 mm [0.10 inch]) of all tests were produced. However, the concurrent effect was an increase in sludge dispersion gas pressure to 0.69 MPa (100 psig), the highest of all tests. Another positive development observed in tests with the EERC-2 nozzle was that at equivalent gap sizes (e.g., 4.6 mm [0.18 inches]) relative to tests with the EERC-1 nozzle, particle sizes achieved with the improved nozzle were comparable even at sludge mass rates twice these previously tested. For example, in Test 33 with the EERC-2 nozzle, the observed particle sizes were smaller than those achieved in Test 21 with the EERC-1 nozzle. Also, in Test 37, again conducted with a 4.6-mm (0.18-inch) nozzle gap, increasing the sludge mass 20% above that of Test 33 but at a 25% lower dispersion gas rate, produced comparable particle sizes with an equivalent dispersion gas pressure.

The improvement in performance with the EERC-2 nozzle compared to the EERC-1 nozzle may be partially explained by differences in construction. In the former nozzle, the sludge pipe containing the dispersion cone had a very slight bevel at its tip, forming essentially a sharp orifice with the cone. In the latter nozzle, the nozzle body tip had a bevel of approximately 9.53 mm (0.375 inch), perhaps providing additional length over which the sludge and dispersion gas could become intimately mixed. Further, the design of the second nozzle may have allowed the dispersion cone to be centered better within the nozzle body. An uneven annulus would have the effect of providing a larger flow gap around part of the nozzle, producing poorer sludge dispersion.

Photos of sludge dispersion spray from the shotcrete nozzle and EERC-1 and EERC-2 nozzles are presented in Appendix B. The photos were extracted form video recordings of the dispersion tests. A movie clip of the EERC-2 nozzle can be found at the following link: http://www.undeerc.org/clips/eerc2.wmv.

Dispersion Tests in Pressurized Vessel

A number of unsuccessful attempts were made at dispersing the sludge into a pressurized vessel. The purpose for trying these tests was to observe if injecting the sludge into a denser atmosphere, owing to the higher pressure of the gas in the pressure vessel, would cause additional shearing and degradation of the sludge particles. For this series of tests, the 254-mm (10-inch) pressure vessel was modified to allow insertion of the EERC-2 nozzle and to allow videotaping of the sludge spray pattern. Photos of the modified vessel are shown in Figures 29–31.

EERC MM21037.PCX

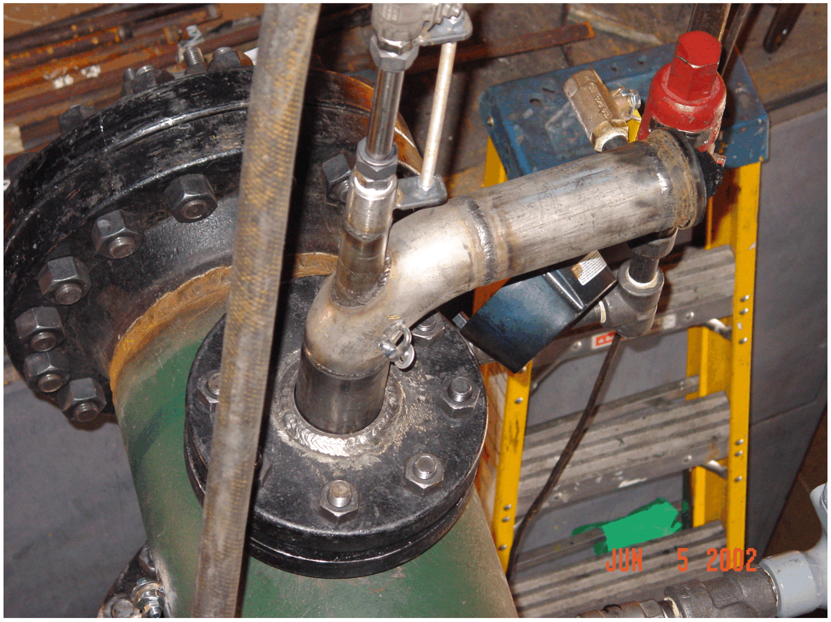


Figure 29. Pressurized sludge dispersion system – nozzle view.

EERC MM21038.PCX

Figure 30. Pressurized sludge dispersion system – tee assembly view.

EERC MM210039.PCX

Figure 31. Pressurized sludge dispersion system – sight port view.

To allow viewing and videotaping, the blind flanges on the tee were bored out and then outfitted with76.2-mm (3-inch) flanged pipe nozzles mated with a high-pressure glass site port. The ported flanges were arranged opposite each other on the tee to allow direct line-of-site viewing. One of the site port nozzles was equipped with a bracket to support the videocamera. A light source was hung at the other site port. An adjustable seal system, using square Teflon rope packing, was designed to allow vertical insertion of the dispersion nozzle to a select position between the site ports. The system was equipped with safety chains to prevent unwanted ejection of the sludge nozzle while at pressure. The bottom of the pressure vessel was equipped with a 63.5-mm (2.5-inch) full-ported ball valve to allow withdrawal of the sludge under pressure. The 254-mm (10-inch) tee was also ported to allow attachment of a safety relief valve and back-pressure control valve.

Based on the maximum available compressed air, it was determined that dispersion tests could be performed at vessel pressures up to 0.76 MPa (110 psig). To perform a test, the dispersion gas flow was started to bring the vessel up to pressure, with the back-pressure control continually relieving to maintain the desired pressure. The sludge flow was then started to begin the dispersion test. The sludge, however, demonstrated its tenacity toward stickiness and unflowability by impacting on the vessel wall near the nozzle tip and almost immediately bridging to obstruct the line of site between site ports. Further, the spray pattern blocked a significant portion of the light, not allowing good enough visibility to determine the impact of pressurized dispersion on sludge particle size. The nozzle was repositioned several times in an attempt to provide an impingement point where the sludge would fall, under its own weight, to the bottom of the pressure vessel. This was unsuccessful.

Alternative Nozzle Design

During the course of testing with the EERC-1 and EERC-2 nozzles, it was observed that the hair within the sludge could collect at the alignment fins and cause poor dispersion within the vicinity. A possible alternative design would be to have a flat, rectangular opening to the nozzle. This design would eliminate the cone insert (with alignment fins and hung-up hair) and the design issues for maintaining a uniform annular gap in the much more severe environment of a gasifier. In the instance of achieving a nozzle gap of 4.6 mm (0.18 inches), the nozzle width would be approximately 183 mm (7.2 inches). If this pipe width is too large to insert through existing gasifier ports, two 92-mm (3.6-inch) superposed nozzles could be used; however, even flow distribution may become an issue.

Estimation of Dispersion Gas Pressure Requirements

Results of the dispersion testing, specifically with EERC-2 nozzle, indicated that reasonable sludge dispersion results were obtained at 314 kg/min (690 lb/min): half that required for a 909 metric tons/day (1000 short tons/day) feed rate at Wabash River and half the maximum desired dispersion gas as estimated by Global Energy in its modeling efforts. Consequently, two dispersion nozzles would be used. Based on a sludge nozzle dispersion gas pressure of 0.31 MPa (45 psig), the actual recycle syngas pressure required for utilization at a gasifier pressure of 2.83 MPa (410 psig) was estimated. For this estimation, it was assumed that the annular nozzle gap would be the same when used at pressure as previously demonstrated in the sludge dispersion tests. Further, it was assumed that the annular gap area would have a C_v, much as a trim-seat combination for a control valve has a C_v for a specified set of flow conditions (i.e., temperature, pressure, pressure drop, and specific gravity). Consequently, the standard formula for flow coefficient calculation, shown in Equation 4 (57) was first utilized to calculate a C_v for the EERC-2 nozzle at atmospheric conditions and, with the same C_v, was then used to calculate P_1 (dispersion gas pressure upstream of the nozzle) as required at gasifier pressure:

$$Cv = \left[\frac{Q\sqrt{T} \cdot SG}{1360\sqrt{P_1 \cdot dP}} \right]$$

where P_1 = absolute upstream pressure, psia

P_2 = absolute downstream pressure, psia
Q = gas flow rate at standard pressure and temperature, scfh
T = absolute gas temperature, R
SG = gas specific gravity, relative to air
dP = ½ P_1, for critical flow where $P_1 - P_2 > ½P_1$

The conditions utilized in the calculations and resulting values are shown in Table 18.

Table 18. Conditions for Estimation of Dispersion Gas Pressure

Parameter	Atmospheric Conditions	Gasifier Conditions
P_1	60	1350[a]
Q	4400	135500
T	520	520
SG	1	0.729[b]
dP	30	675[a]
C_v	1.74[a]	1.74

[a] Calculated value.
[b] Calculated based on dry recycle syngas composition.

The results indicated that the recycle syngas pressure required for dispersion at gasifier conditions would be approximately 9.30 MPa (1350 psia). Because recycle syngas is available at a much lower pressure, 5.51 MPa (800 psig), boosting to dispersion pressure will be required. Consequently, seven gas compressor vendors were contacted to obtain a budgetary cost for a boost compressor. The following Syngas specifications were provided to the vendors:

Mass rate	15,000 lb/hr
Gas composition	
Carbon dioxide	15–16 vol%
Carbon monoxide	45 – 49 vol%
Hydrogen	33 – 34 vol%
Methane	0.5 – 2 vol%
Sulfur gases	<70 ppmv
Nitrogen, argon	Balance
Calculated molecular weight	21.6 lb/lb-mole
Pressure	800 psig

The information requested from compressor vendors included:

Number of compressors
Model or frame designation
Estimated capital cost (not installed)
Estimated annual maintenance cost
Power (hp or kW) requirements
Other utilities (cooling water, etc.)

Estimates were requested for boosting recycle syngas to 1500 and 2500 psig. Table 19 presents the recommended compressor and configuration plus capital cost and installed horsepower data. Only

Table 19. Compressor Systems for Dual-Fluid Sludge Dispersion Nozzle Gas Pressure Boost

Company	Model	Cost for 1500 psig, $1000	Cost for 2500 psig, $1000	Compressor Type	Comment
VR Systems					$1000–$1200 per hp
	Ariel JG/2, 200 hp	200–240		Reciprocating	
	Ariel JGH/2, 350 hp		350–420	Reciprocating	
Knox Western					
	Eagle 3245, 300 hp	171		Reciprocating	
	Eagle 3445, 500 hp		298	Reciprocating	Maximum pressure 2250 psig
PDC Machines, Inc.	13-1500-1500 duplex	240		Diaphragm	2 series machines
	13-1500-1500 duplex		240	Diaphragm	2 series machines
PPI					
	Frame 9X213	700		Diaphragm	7 parallel machines
	Frame 9X175		1400	Diaphragm	14 parallel machines
Gardner Denver					No systems
Elliott (Ebara Group)					Flow rate too low
Atlas Copco					Maximum pressure 1200 psig

four of seven vendors could provide compressor systems for this application. For a 1500-psig boosted recycle syngas pressure, the installed motor power rating ranged from 150 to 225 kW (200 to 300 hp). The approach suggested by PPI was considered unwieldy and overly costly. For the remaining responding vendors, the compressor cost ranged from $171,000 to $240,000. Power and cost each increased by approximately 70% for compressor systems capable of achieving 2500-psig recycle syngas pressure.

With the same compressor producing 1500 psig, it could also be possible to increase the sludge rate 20%, to 1090 metric tons (1200 short tons) per day, and decrease the dispersion gas rate 25%, to 5110 kg/hr (11,250 lb/hr), as indicated in Sludge Dispersion Test 37 previously described.

Sludge-Receiving, Storage, and High-Pressure Pumping Concept

Based on consultations with Global Energy concerning the layout and geology of the Wabash River site and with Schwing America concerning typical sludge industry approaches and equipment limitations, a concept for utilization of municipal sewage sludge at the Wabash River gasifier was developed. For this concept, it was further assumed that sludge would be received by truck. The sludge processing system was divided into three major facility areas:

1. Receiving station (and short-term storage)
2. Live storage
3. High-pressure feeding (with run tank)

A block flow diagram of the process is shown in Figure 32. Specifications were developed for the three major process steps and were presented to Schwing America for cost estimation. The specifications and information requested from Schwing are presented below.

Receiving Station

a. Receiving station should be enclosed
b. Enclosure should be ventilated with odor control and winter-heating capability
c. Facility should have capability to receive two trucks at a time
d. Sludge storage capacity should be 227 metric tons (250 short tons) or 6 hours of sludge feed
e. Transfer pump(s) and ancillary feeders/power packs should be enclosed in receiving station
f. Minimum transfer rate of 1000 tons per day (estimated 170 gpm)
g. Transfer piping should be heat-traced and insulated

Live Storage

a. Live-storage (including sliding frames, extraction screws/conveyors) silos should be enclosed in ventilated, odor-controlled, and winter-heated structure
b. Storage should be 1820 metric tons (2000 short-tons) or two days of sludge feed
c. Minimum transfer rate of 1000 tons per day (estimated 170 gpm)

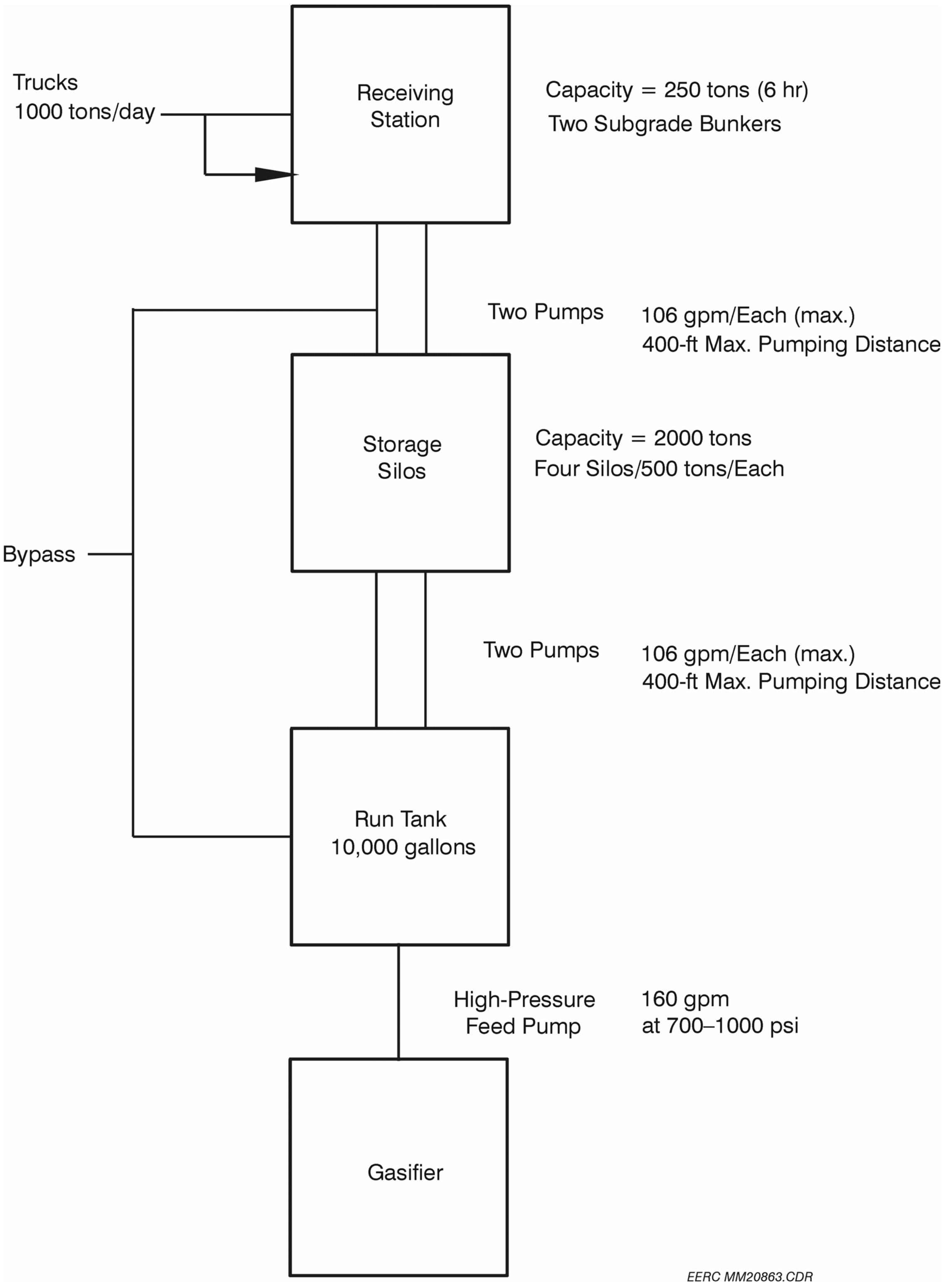


Figure 32. Block flow diagram of proposed sludge-processing system.

High-Pressure Feeding

a. Feed pump and ancillary twin-screw feeder and power pack should be enclosed
b. Minimum pumping rate of 1000 tons per day (estimated 170 gpm)
c. Sludge will be fed from 37,900-liter (10,000-gallon) run tank
d. Minimum pumping pressure of 700 to 1000 psig
e. Feed piping should be heat-traced and insulated

The information requested from Schwing America included:

1. Receiving station dimensions and estimated cost (excluding pumps) for storage capacity of 250 tons, including ancillary equipment such as push floor dischargers and conveyors.
2. Models and estimated costs for transfer pumps (including screw feeders and power packs) for moving sludge from receiving to live storage and from live storage to run tank.
3. Live-storage building dimensions and estimated cost (excluding pumps) for storage capacity of 2000 tons, including number and sizes of storage silos, sliding frame dischargers, and conveyors.
4. Model and estimated cost for high-pressure feed pump (including screw feeder and power pack).
5. Size and estimated cost for heat-traced piping.
6. Estimate for field erection cost.

Three additional capabilities requested for the pump systems provided by Schwing America were 1) sludge flow measuring system (SFMS), 2) self-diagnostics/monitoring, and 3) reduction of pulsation. The patented SFMS provides an accurate measurement of the volume of sludge being pumped, filling efficiency, speed of the pump, and the accumulated volume of sludge pumped over time. These pump performance readings can be used to monitor and track the pump's mechanical and hydraulic components, thus allowing early detection of component failure. For example, monitoring can be achieved for the wear of poppet valves, excessive internal oil leakage, and blockages at the pump suction side.

The reduction or elimination of pump pulsation may be a critical factor in gasifier operation, specifically with respect to gas cooling and operation of downstream unit operations. The duration of the pulse will depend upon the sludge pumping rate, with the pulse becoming shorter as the sludge-pumping rate increases. One option for eliminating the pulse is to use two control blocks instead of one to independently control each hydraulic cylinder of the sludge pump. The PLC logic would be modified to achieve this control and to compensate for any change in material cylinder-filling efficiency. Essentially, this approach would function to allow the pressurization stroke to begin on the second material cylinder before the first material cylinder piston has reached the end of its discharge stroke. Just as the first piston reaches the end of its stroke, the discharge poppet valve would open on the second cylinder to allow immediate sludge flow. The piston in the first material cylinder would then have to retract at a faster speed than its discharge stroke to allow filling with sludge and then pressurization. A similar approach is employed with dual discharge grout pumps used in underground tunneling applications.

The major components (and associated sizes and power requirements) that comprise each of the three process areas are presented in Tables 20–22. Two-dimensional drawings of the process area layouts, as provided by Schwing America, are presented in Figures 33–36. The drawings are generic and do not depict an actual layout at the Wabash River site.

Table 20. Receiving Station Equipment and Cost Information

Item	Designation/Size	Number Required
Push-Floor Bunkers	20' L × 9.5' W × 20' H	Two
Screw Feeders	SD350HD	Two
Sludge Pumps	KSP80V(HD)L	Two
Hydraulic Power Units	Model 1100 (200 hp)	Two
Budget Capital Cost	$1,300,000	
Average Annual Maintenance Cost	$2500	
Turnaround for Major Maintenance	One week	
Frequency of Major Repair	Every three years	

Table 21. Live-Storage Equipment and Cost Information

Item	Model/Size	Number Required
Sliding-Frame Silos	23' D × 46' H	Four
Hydraulic Power Units	Model 230 (25 hp)	Four
Extraction Conveyors	2' D × 32' L (20 hp)	Four
Screw Feeders	SD350HD	Two
Sludge Pumps	KSP80V(HD)L	Two
Hydraulic Power Units	Model 1100 (200 hp)	Two
Budget Capital Cost	$2,900,000	
Average Annual Maintenance Cost	$4500	
Turnaround for Major Maintenance	One week	
Frequency of Major Repair	Every two years	

Table 22. High-Pressure Feeding Equipment and Cost Information

Item	Model/Size	Number Required
Sliding Frame Silos	13.5' D × 12' H	One
Extraction Conveyors	2' D × 17' L (20 hp)	One
Screw Feeders	SD350HD	One
Sludge Pumps	KSP80V(HD)L	One
Hydraulic Power Units	Model 1100 (250 hp)	One
Budget Capital Cost	$700,000	
Average Annual Maintenance Cost	$2500	
Turnaround for Major Maintenance	One week	
Frequency of Major Repair	Every three years	

It should be noted that the quotes received by Schwing did not include buildings for the sludge- receiving station bunkers, the live-storage silos, or the run tank and high-pressure pump. Schwing America also provided a single cost for each of three process areas and did not provide a per component cost. The receiving station was comprised of two separate push-floor bunkers, each serviced by screw feeder/pump/power pack combination and was estimated to cost $1,300,000. For the live-storage facility, four 7.0-m (23-ft) diameter by 14.0-m (46-ft) high sliding frame silos will be required for 909 metric tons (1000 short tons) sludge storage capacity.

The silos in the proposed design are the largest manufactured and installed by Schwing. Each silo requires a separate extraction conveyor, but a single twin-screw feeder and pump combination can handle the discharge from two extraction conveyors. The entire live-storage cost was estimated at $2,900,000. For the high-pressure feeding area, a single pump (as requested by Global Energy) was utilized and was served by a single 4.1-m (13.5-ft)-diameter by 3.7-m (12-ft)-high sliding-frame silo (with extraction conveyor). The budget cost for this process area was $700,000.

The installed motor horsepower for the each of three process areas was 400, 580, and 270 hp, respectively, for a maximum power requirement of 938 kW (1250 hp). This is a specific power requirement of 22.5 kW per ton/hour, excluding gas compression power requirements. With gas compression, specific power requirements increases to approximately 26.2 kW per ton/hour assuming a minimum of 200 hp for the compressor motor.

Erection costs for a single 7.0-m (23-ft)-diameter by 14.0-m (46-ft)-high sliding-frame silo were estimated to be about $100,000 for ironworker trades. Installation of sludge-receiving bunkers would cost less. Millwright work for installation of each associated screw conveyor and slide frame is approximately $15,000. Interior coatings for each storage silo range from $50–$60,000, and

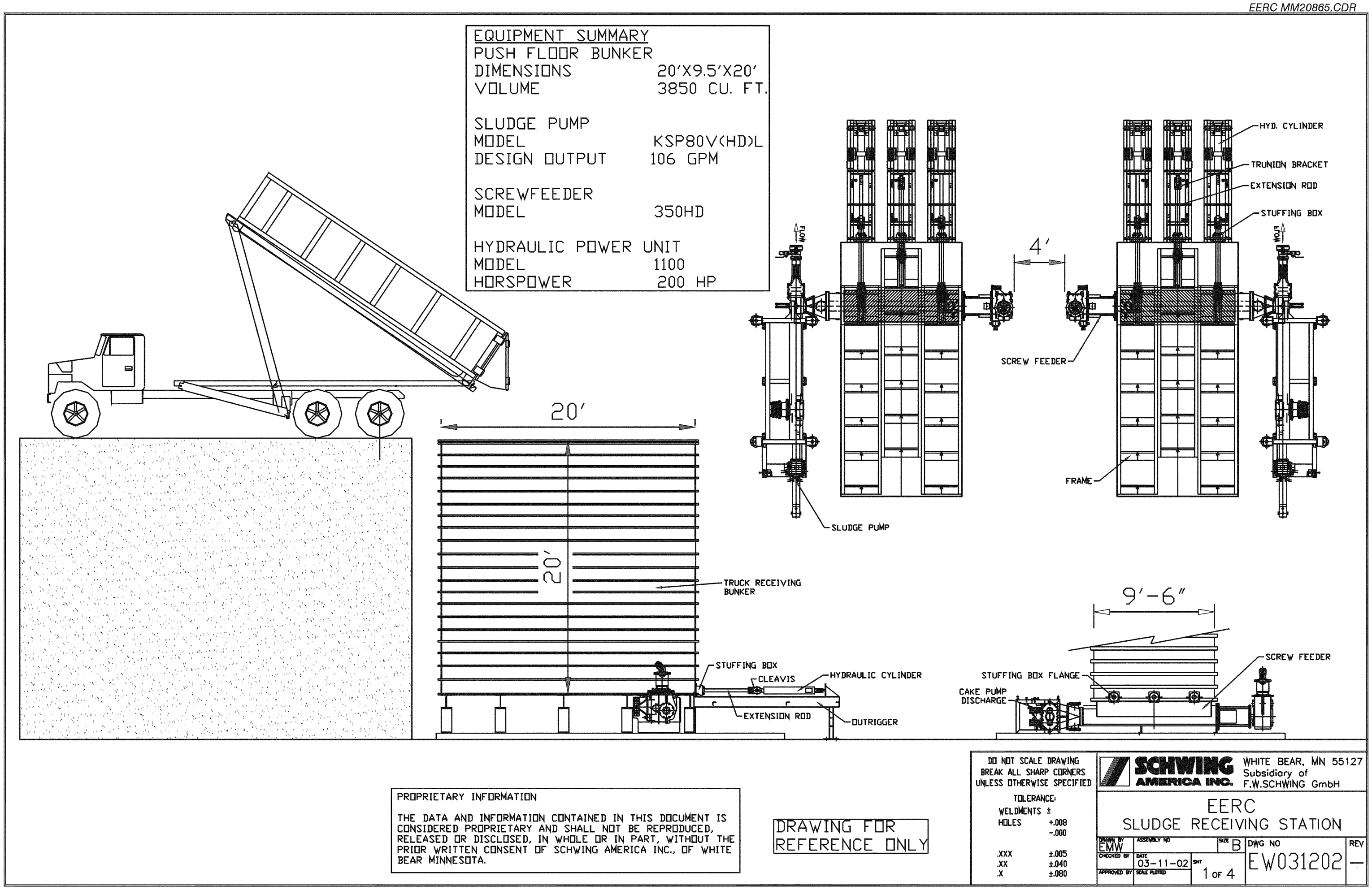
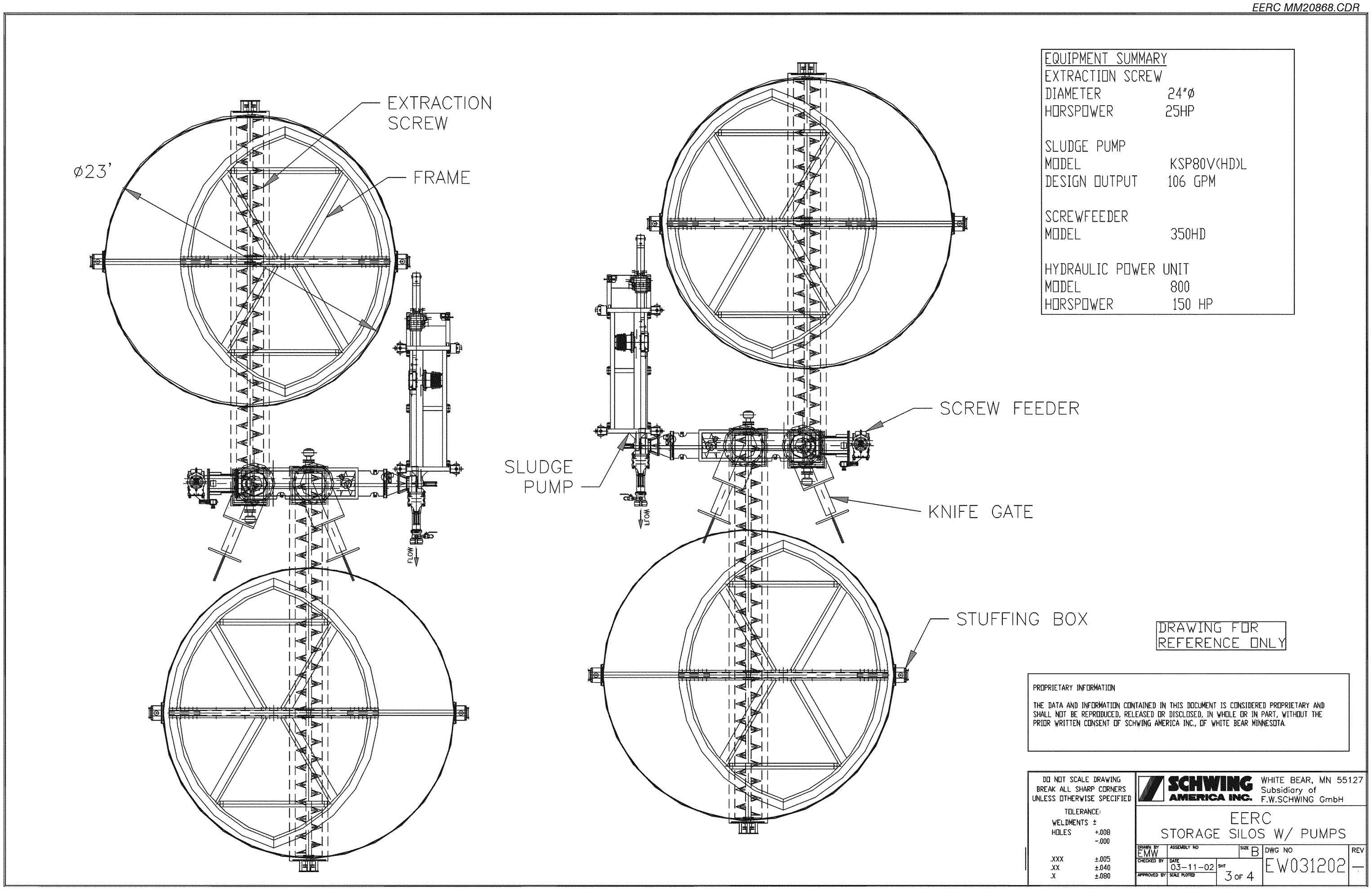


Figure 33. Schematic of sludge-receiving station.



EQUIPMENT SUMMARY	
EXTRACTION SCREW	
DIAMETER	24"ø
HORSPOWER	25HP
SLUDGE PUMP	
MODEL	KSP80V(HD)L
DESIGN OUTPUT	106 GPM
SCREWFEEDER	
MODEL	350HD
HYDRAULIC POWER UNIT	
MODEL	800
HORSPOWER	150 HP

PROPRIETARY INFORMATION

THE DATA AND INFORMATION CONTAINED IN THIS DOCUMENT IS CONSIDERED PROPRIETARY AND SHALL NOT BE REPRODUCED, RELEASED OR DISCLOSED, IN WHOLE OR IN PART, WITHOUT THE PRIOR WRITTEN CONSENT OF SCHWING AMERICA INC., OF WHITE BEAR MINNESOTA.

Figure 34. Schematic of live-storage system – top view.

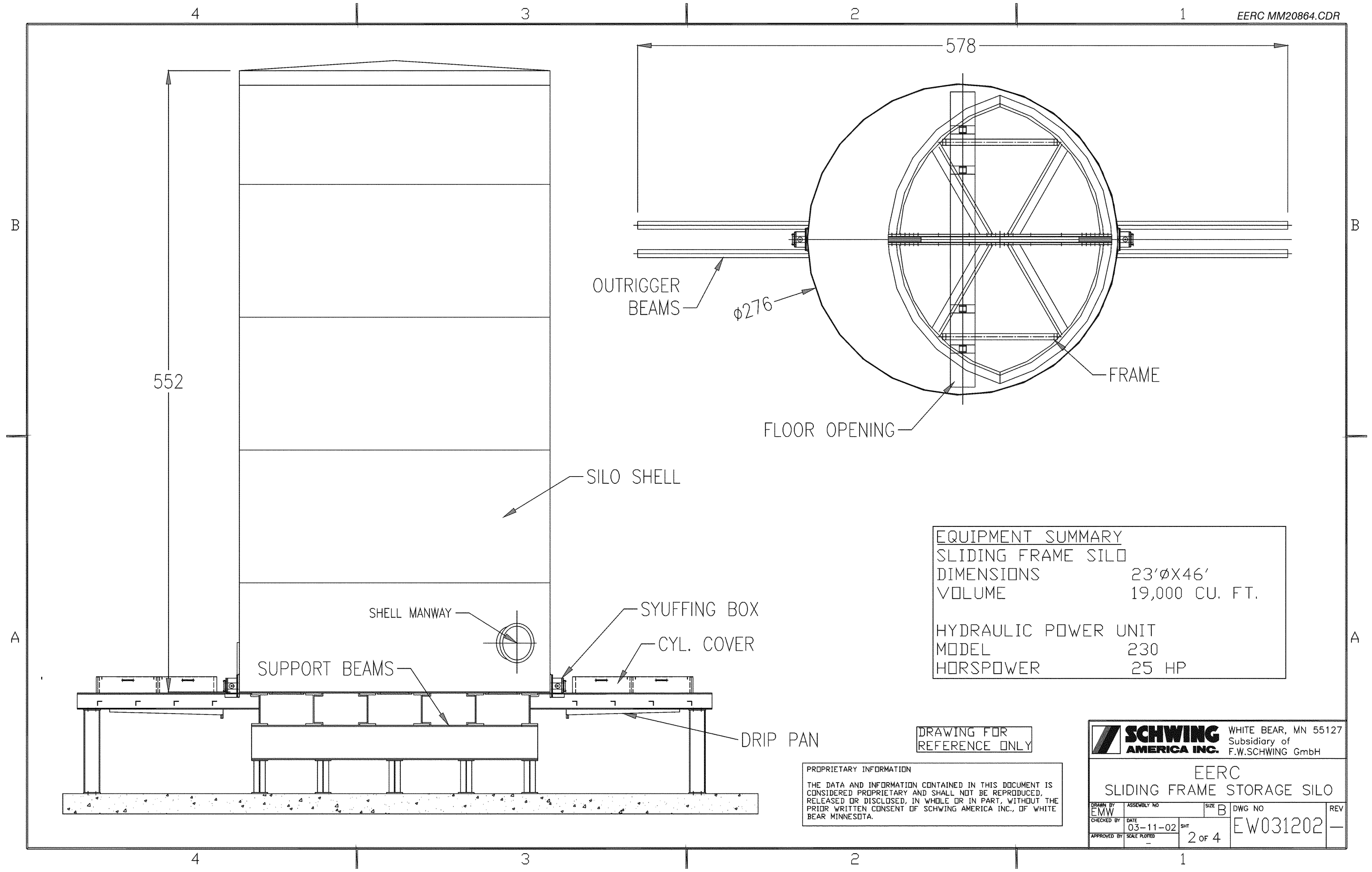


Figure 35. Schematic of live-storage system – side view.

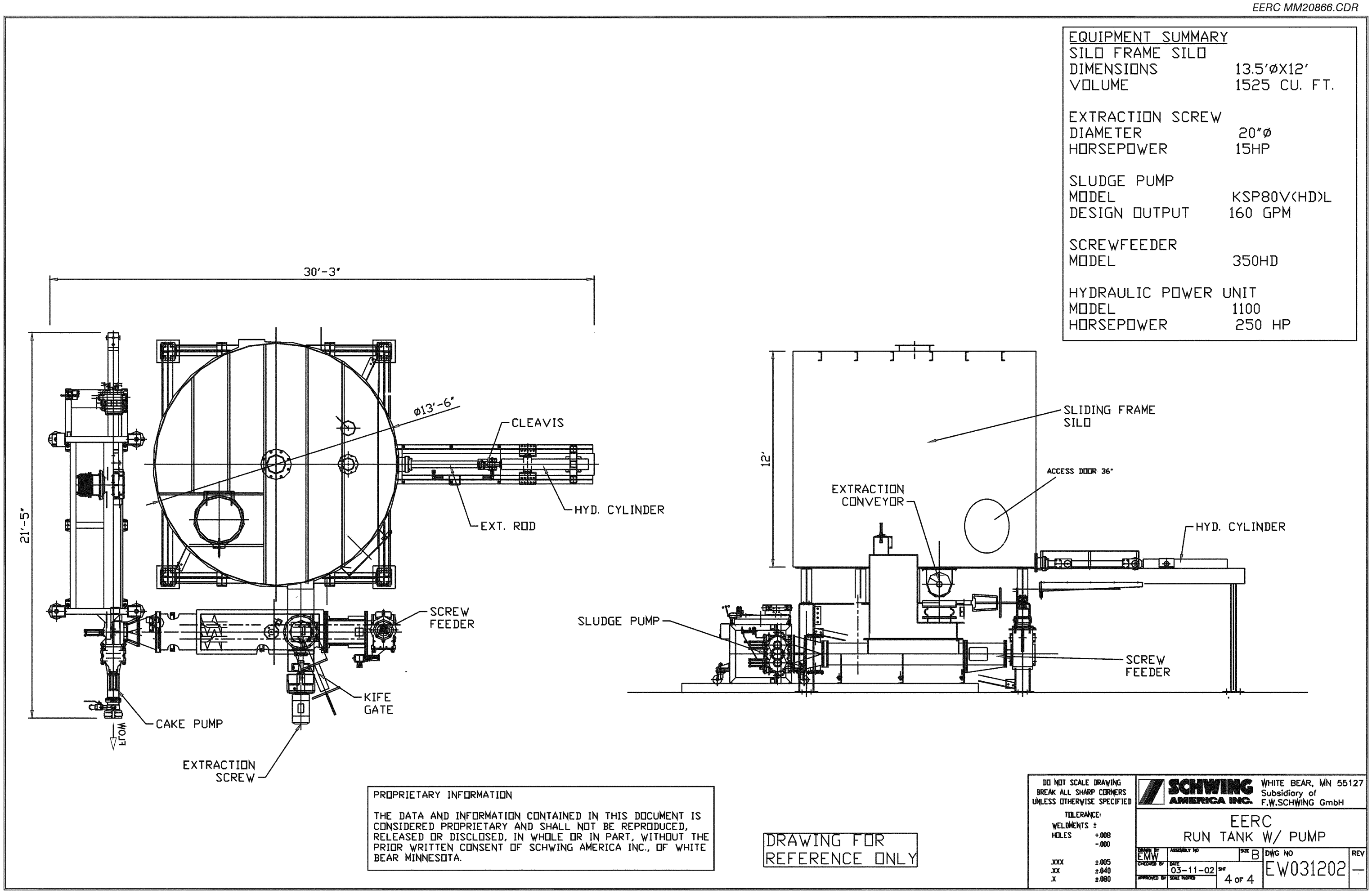


Figure 36. Schematic of high-pressure feeding system.

exterior coatings would cost about $30,000. Installation of a single pump/screw feeder/power pack system (including hydraulic tubing and wiring) would require about 160 staff-hours. Silos and bunkers would be in the largest reasonable shipping sizes and field-welded on-site. Pumps, power packs, screw feeders, and conveyors would be assembled (and tested) before they arrive on-site and would only require placement and interconnecting service (power, hydraulic, control wiring, water).

Sludge Preheating to Reduce Viscosity

Estimates were prepared for the quantity and cost of steam that would be required to increase the temperature of the sludge. It was assumed that modestly increasing the sludge temperature from 66° to 177°C (150° to 350°F) may produce significant reduction in sludge viscosity and improve atomization. Preheating of the sludge would take place under a pressurized state (presumably in the pipe feeding the gasifier) so that moisture is not released from the sludge. For the estimates, saturated steam at 3.0 MPa (440 psig) was assumed to be available for preheating 909 metric tons (1000 wet tons) per day of sludge at an initial temperature of 16°C (61°F). To preheat to 66°C (150°F), the steam requirement is 141 tons/day; to preheat to 177°C (350°F), the steam requirement is 412 tons/day. Assuming a steam cost of $5/1000 lb steam, the cost of the sludge would be increased $0.328 per million Btu to preheat to 66°C (150°F), and the cost of the sludge would be increased $1.07 per million Btu to preheat to 177°C (350°F). Costs would be lowered if excess heat from the gasifier could be transferred to the sludge through a heat exchanger.

Sludge Nozzle Design and Cost Estimation

Although the pilot-scale testing did not provide an opportunity to address the issues, consideration was given to possible materials for nozzle construction that may have suitable abrasive wear and high-temperature resistance. Referring to Figure 21, it is suggested that options for the nozzle body within the vicinity of the cone could include 310SS and Haynes HR160 alloy. This length of the nozzle body may range from several inches to 0.3 meters (12 inches) in length. The upstream pipe section would be constructed of a less costly material, e.g., 304SS or 316SS, and would be attached to the alloy tip section by welding; HR 160 is TIG and MIG weldable to dissimilar metals. The sacrificial tip section, in essence, would be cut off and replaced after irreparable wear, rather than reconstructing a complete nozzle assembly. The 310SS and HR 160 have Rockwell B hardness values of 85 and 88, respectively. The HR160 is machinable with carbide turning and facing bits and high-speed steel drill bits.

To enhance wear resistance in the instance of using 310SS, the nozzle body tip could be hard-faced with Stoodite 6 by Stoody Products. It is assumed that the air exiting the cone will tend to push the sludge toward the nozzle body and wear on the nozzle body surface, up to the point where the sludge exits the nozzle. At a minimum, the length of the nozzle body containing the cone would be hard-faced. The Stoodite 6 hard-facing comes as a bare rod and is applied with a welder in an argon environment. Stoodite 6 is good to 1150°C (2100°F) in an oxidizing atmosphere and can achieve Rockwell C hardness in the low 40s when two layers are applied. This hard-facing is machinable with carbide tools, thus allowing preparation of a surface finish that will achieve a uniform annular nozzle gap.

The cone of the nozzle would be constructed of HR 160 and would have a threaded connection to allow easy mating with the inner tube carrying the dispersion gas. The nozzle body tip may also include a cooling jacket for thermal protection during loss of sludge flow.

A 10-lb box of Stoodite 6, more than sufficient to prepare several nozzles, costs $474. The 310SS is comparable in price to 316SS tubular or pipe products with 63.5-mm (2.5-inch) Schedule 40 316SS pipe costing approximately $11 per foot. The HR 160 is available directly from Haynes, and a 63.5-mm (2.5-inch) Schedule 40 welded pipe costs about $273 per foot; a 63.5-mm (2.5-inch) round bar costs about $320 per foot.

Ceramics such as boride and alumina silicate products that are sintered may be viable. However, discussions with vendors indicated concerns for the proper material thickness required for structural and thermal integrity. An additional drawback to ceramics is that they are not amenable to field modification, such as addition of dispersion holes in the cone. The ceramic members would have to be initially cast with the desired perforations or other structural features.

An attempt was made to determine the cost of designing and producing a nozzle or nozzles for use in the Wabash River gasifier. As was indicated before, it is presumed that two nozzles would be used, each passing 454 metric tons (500 wet tons) per day of sludge. A spreadsheet, shown in Table 23, was constructed that utilized four variables: engineering design, drafting, parts, and fabrication to estimate cost. The engineering design and drafting costs were assumed to be spread among all nozzles produced. Further, a low-end and high-end estimate was prepared to reflect a possible range in labor effort (i.e., hours for the task) and labor rate ($/hour). In reality, if there are subsequent demonstration phases to this project, most of the engineering design and drafting will not be incurred in the preparation of a commercial nozzle.

Table 23. Cost Estimates for Dual-Fluid Sludge Nozzle

Cost Item	Low-End Cost			High-End Cost		
	Hours	Rate, $/hr	Cost, $	Hours	Rate, $/hr	Cost, $
Engineering	60	75	4500	60	100	6000
Drafting	24	55	1320	24	75	1800
Fabrication (per nozzle)	40	60	2400	60	85	5100
Parts (per nozzle)			1000			2000
Per Nozzle Cost						
One Nozzle			9220			14900
Two Nozzles			6310			11000
Three Nozzles			5340			9700

The per nozzle cost ranged from \$6300 to \$11,000 for producing two nozzles; the total cost for producing two nozzles would then be \$12,600 to \$22,000. This cost component is quite insignificant relative to the capital cost for sludge receiving, storage, and high-pressure feeding and recycle syngas compression.

Economic Analysis of the Sludge-Receiving, Storage, and Feeding System

A detailed capital estimate for implementing the sludge-receiving, storage, and feeding system at the Wabash River Coal Gasification Plant was conducted by Global Energy and was based on process conditions and equipment specifications previously described. The total capital cost was determined to be approximately \$9.7MM within an accuracy of ±10%. The economic analysis for a commercial-scale system processing approximately 1000 wet tons per day is presented in Appendix C.

To determine the economics of implementing the system, process simulation using Gasification Engineering Corporation's (GEC) proprietary computer software was run for petroleum coke and coal operation, with and without municipal sludge. Process information such as heat rate, steam and power output, utility consumption, etc., was determined. An economic analysis using DOE's IGCC Model, Version 3 spreadsheet was then conducted. Greenfield plants were assumed, using reasonable power prices to justify the petroleum coke and coal projects without sludge. Municipal sludge was then introduced for the respective cases to determine the allowable cost (or tipping fee) of the sludge to maintain the same net present value (NPV) for the project. The result shows that a tipping fee of \$12.40 and \$16.70 per wet ton of municipal sludge delivered to the plant site would be required for the petroleum coke and coal projects, respectively. A sensitivity analysis of the power price on the allowable cost of the municipal sludge was also performed.

Drying of Municipal Sewage Sludge

Thermal Drying

During the course of several bench-scale tests, it was observed that municipal sewage sludge produces a hard exterior as it dries from the outside inward. It was presumed that a flowable, spherical, or granular sludge form could be produced that would allow feeding in a manner similar to granular coal, e.g., using a lock hopper. Further evidence of the potential to produce such a material was based on the properties of the 65 wt% solids aged sludge produced by the Water Reclamation District of Chicago. The sample of this material taken from the drying beds had spherical particles and was not sticky. The freeze–thaw cycle during treatment of this sludge made it soil-like in consistency.

Consequently, it was hypothesized that a 3-to-1 reduction in sludge volume, that is, increasing the sludge solids content from a starting value of 23 to a final value of 70 wt% would produce a dry, flowable coal-like material. As Schwing America was the North American vendor for VA Tech Escher Wyss fluid-bed sludge-drying systems (58), they were approached to determine the feasibility of converting about 1000 wet tons/day of 23% solids undigested sludge into a 70 wt% solids product. VA Tech, however, indicated anticipated handling difficulties at this solids content. Plants are in operation that produce a 80 wt% solids product and more typically over 90 wt% solids.

Three drying lines would probably be required, although larger capacities have been achieved in two lines. These plants typically process digested sludge, but this would not eliminate the use of undigested sludge.

For a plant processing municipal sludge to 90% dry solids with three lines, the total capital cost would be approximately $16.5 to 20 million depending on how much wet cake and dry granulate storage would be needed. This gives operating flexibility but adds substantially to the cost. The price includes the dryers, coolers, all basic auxiliary equipment, and controls but does not include the system for supplying the drying energy (can be thermal oil system, steam, etc.).

The thermal energy delivered to the dryers, operating at 100% capacity, would be approximately 81.9 million kJ/hr (77.3 million Btu/hr), assuming 20°C (68°F) ambient conditions. A thermal efficiency of 92% can be reached depending on the heating system, with normal heat recovery. The electrical energy requirement would typically be in range of 1800 to 1950 kW (running all three lines at capacity). For sludge cooling (heat removal), approx. 21300 kW (72.7 million Btu/hr) is required. The capital cost and energy requirements would be lower for product with lower dry solids content.

Nonthermal Drying

A unique, more recent development that could be applied to municipal sewage sludge is the pulverizing air dryer (PAD), a patented, nonthermal drying process (59). Originally developed for drying agricultural products, this process has been applied to food waste, coal fines, manure, municipal sludge, mining ores, and pulp and paper sludge with moisture contents up to 85 wt%. The description of the process appears to be purposely vague to protect proprietary technology, but in essence, the wet material is fed to a high-velocity air stream, reaching speeds of 1280 km/hour (800 miles/hour). These high speeds produce attrition of the material through particle-to-particle collision with control of particle size achieved in a series of “conditioning” chambers. The description refers to centrifugal separation of solids and liquids, implying that moisture is not evaporated to a significant extent. The end product is a granule, with sizes ranging from minus 10 to minus 300 mesh depending upon the product use.

The technology can be brought to a site as trailer-mounted modules with increased processing capacity achieved by adding modules, typically in 10-ton/hour increments. Operating costs are claimed to be significantly less than thermal methods, being approximately $1.50 per ton of water removed compared to $5, $15, and $25 per ton of water removed when using, respectively, coal, natural gas, and electricity as the source of thermal energy. Capital costs for a 200-ton/day system are approximately $1.5 million versus, by Gulftex estimates, $4.5 to $10 million for competing thermal systems.

An intriguing claim of the process with municipal sewage sludge was the ability to make a granular product that could remain in suspension without redissolving. For this process, the sludge was dried to 15 wt% moisture in the PAD and then reduced to less than 200 mesh size. The purpose was to feed the processed sludge through a drip irrigation system. The potential in relation to this project, however, seemed to be to produce a slurried form of municipal sewage sludge at a much higher solids and heating value content relative to direct injection with the dual-fluid nozzles 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$^{\mathrm{TM}}$, 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

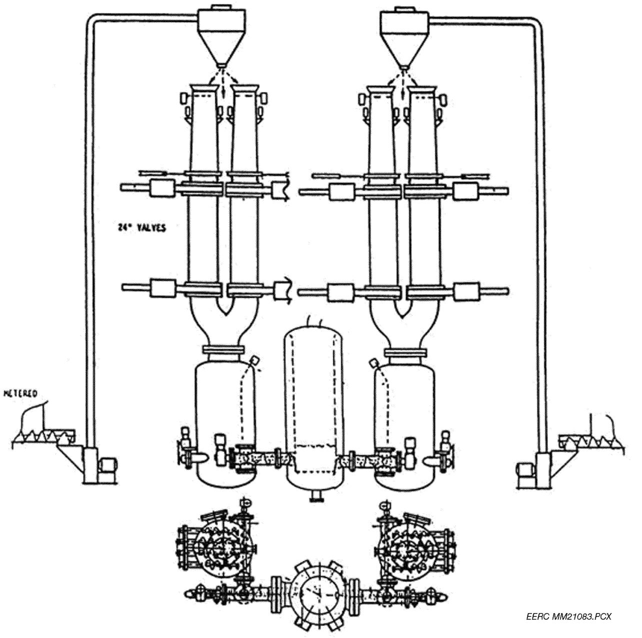


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Figure 38. Miles biomass lock hopper feed system.

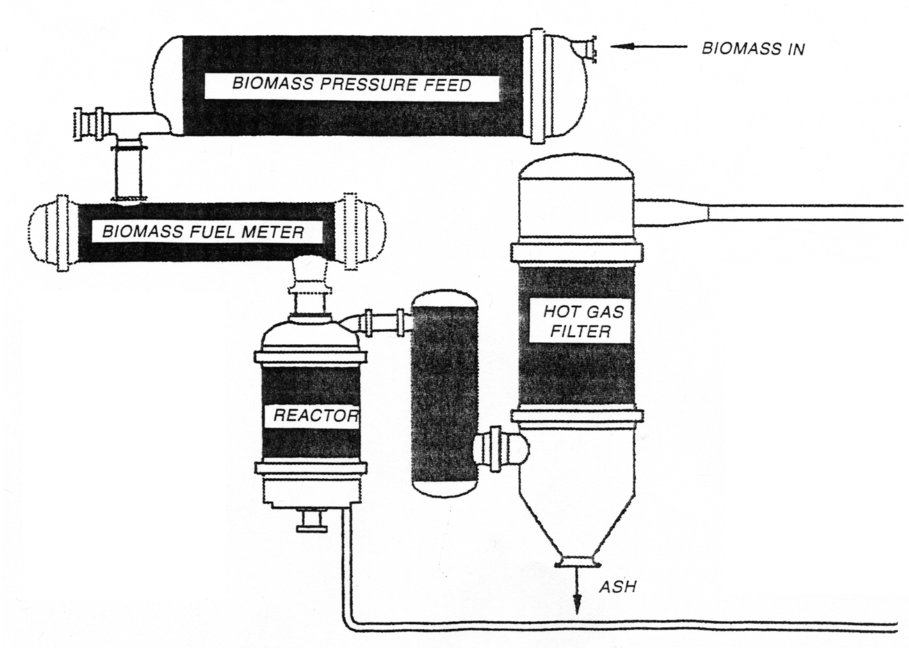

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Figure 39. Cratech biomass feed system.

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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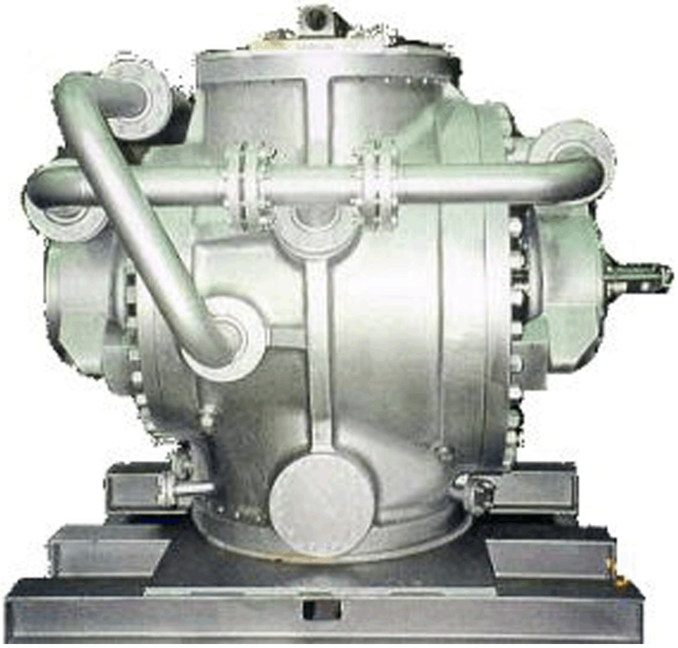

Figure 40. Andritz rotary feeder.

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

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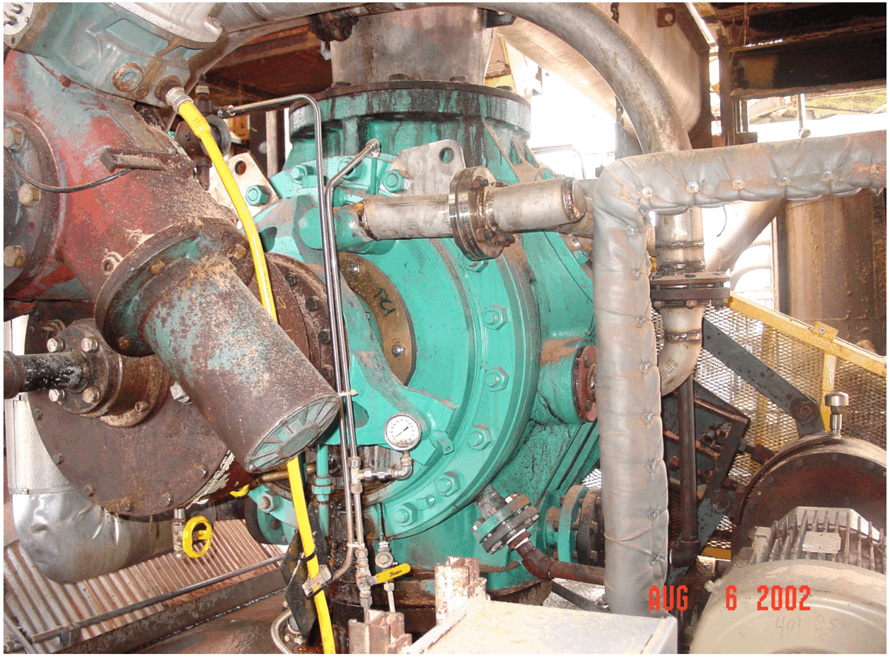

Figure 42. Rotary feeder used in sawdust pulping process – end view.

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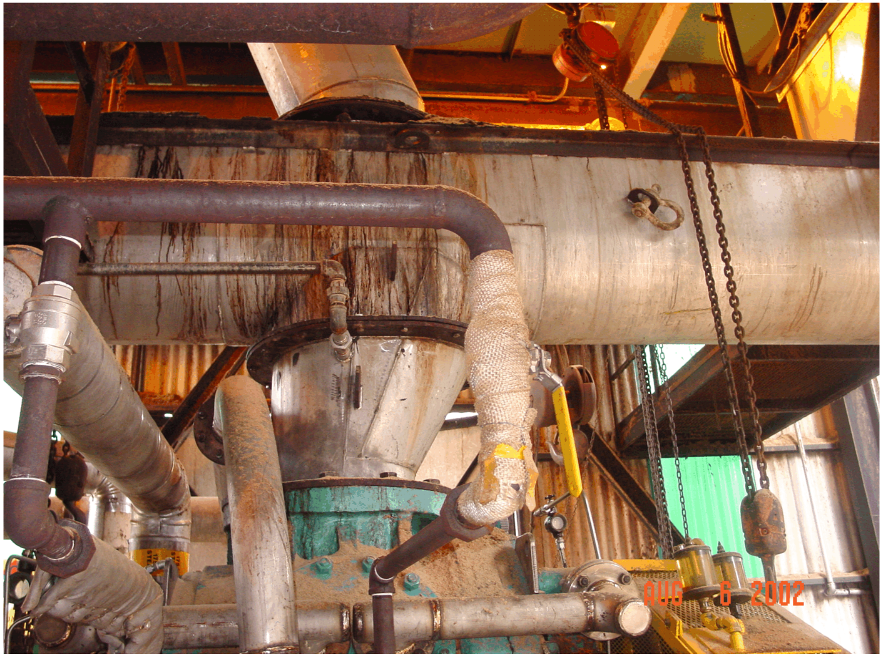

Figure 43. Rotary feeder used in sawdust pulping process – view of sawdust charging system.

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.

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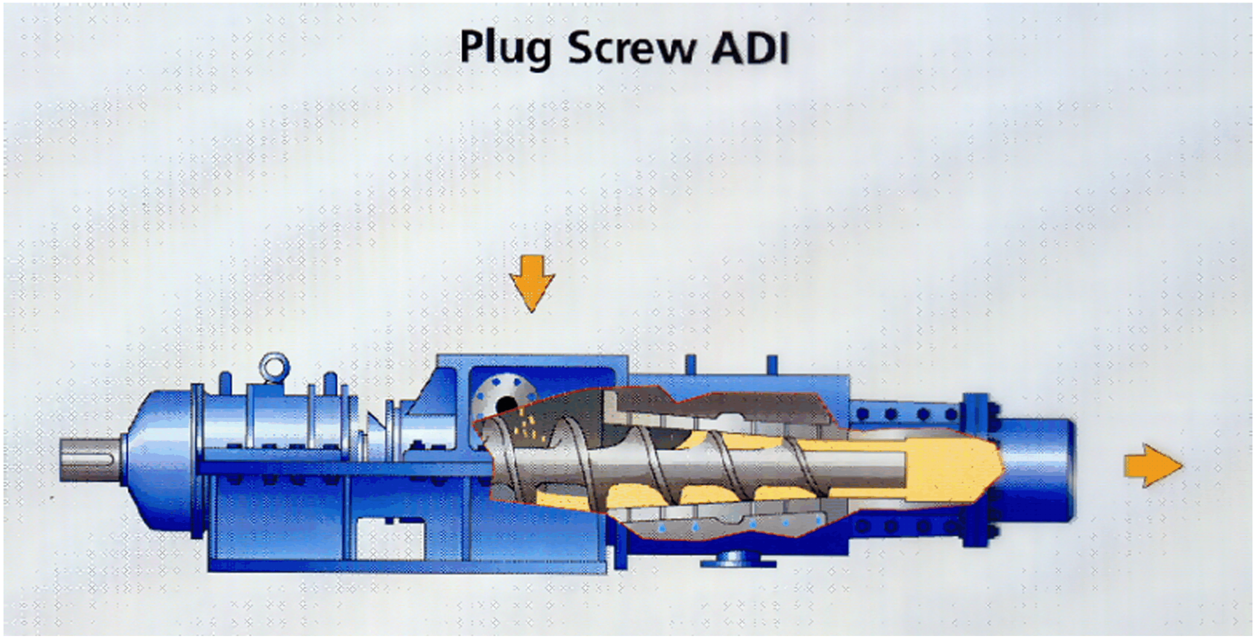

Figure 44. Cutaway diagram of Metso plug-screw feeder.

EERC MM21045.PCX

Figure 45. Plug-screw feeder system used in wood chip pulping process.

EERC MM21048.PCX

Figure 46. Wood chip-feeding system for plug-screw feeder.

EERC MM210046.PCX

Figure 47. Throat section of plug-screw feeder.

EERC MM21047.PCX

Figure 48. Plug-pipe section in plug-screw feeder.

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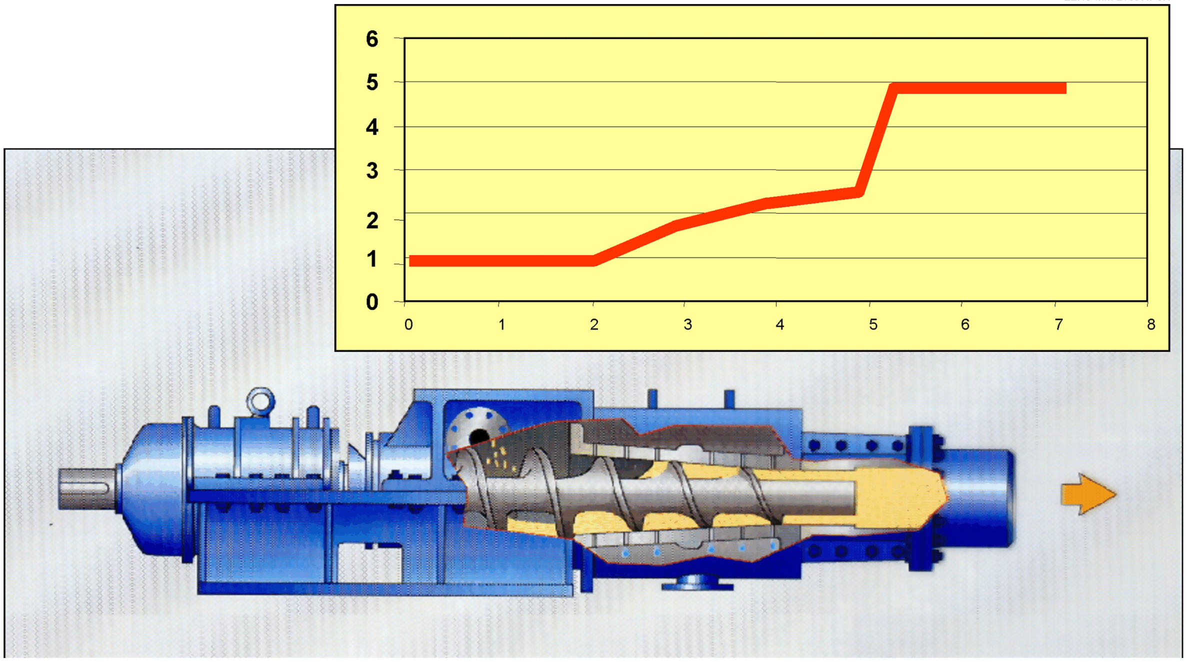


Figure 49. Diagram depicting wood chip densification with axial position in plug-screw feeder.

Another plug-forming feeder designed for the pulp-to-paper industry is the CO-AX feeder by Stake Technology Ltd. The CO-AX feeder is actually an integral component of Stake Technology's StakeTech steam explosion thermomechanical pulping system. The system has been utilized for wood chips and straw chips and claims continuous solids feeding for feedstocks with moisture contents of 10 to 65 wt% (73, 74). With the CO-AX feeder, material enters the feed chamber via a shallow-angle live-bottom hopper and is transferred to a precompression screw by two sets of twin screws. The feed is then conveyed by the precompression screw from the hopper discharge to the piston zone through a fluted tube. The precompression screw coaxial passes through the center of a ring piston, delivering the feedstock at the downstream face of the ring piston. The feedstock is compacted into a firm plug by the coaxial motion of the ring piston. Moisture expelled by the compaction is drained through a dewatering sleeve. The biomass plug is continuously advanced through a tapered compression tube to the steam explosion digester. The combination of compression tube taper and length dictates the plug density and, consequently, sealing against digester pressure. As with a plug screw feeder, the plug is forced against a conical choke that functions to break up the plug. The vendor claims adaptability to a variety of feedstocks, woody and nonwoody, and distinguishes itself from plug-screw feeders by lower specific power consumption. At 150 psig, for example, the power consumption is about 10 kWh/ton feedstock versus nearly 35 kWh/ton for a plug screw. The steam explosion technology with CO-AX feeder was utilized by Weyerhaeuser (Springfield, Oregon) at the demonstration scale (64 wet tons/day) for straw pulping at 200 psig. The process apparently was successful but was discontinued for nontechnical reasons (75). One requirement to operate properly was a feedstock moisture content of 35% to 45%, as free moisture was needed as a lubricant and to help reduce piston and compression tube wear.

The Ingersoll–Rand Reciprocating Screw Feeder, shown in Figure 50, and the Vattenfall Screw-Piston Feeder (76) are similar constant cross-section plug-forming feeders that utilize a screw to both advance and compact the feedstock. The former was developed and tested with coal while the latter was developed specifically for utilization with fibrous biomass.

In these systems, the feedstock is delivered via gravity to the compression-piston screw with the screw essentially functioning as the live bottom on the feed hopper. The screw advances the feedstock down the cylindrical material chamber until a sufficient amount of material is deposited adjacent to the existing plug. The screw than retracts and advances, compressing the fresh biomass against the downstream plug. With the Ingersoll–Rand system, the plug acts against a pressure valve that opens when the system pressure is exceeded. While not described, it is envisioned that a single distinct disc-shaped plug is expelled through the valve with each cycle. Compression of new feed against the previously formed plug produces a distinct nonbinding, noninterlocking interface between plugs. This is akin to reciprocating coal or mineral briquetting. The pressure-sealing component of the Vattenfall system is not adequately described. The description indicates that a single plug is formed within a "pressure chamber." This suggests that the pressure chamber is actually a lock hopper (completely filled by the biomass plug) and the densification to a plug is intended to reduce the consumption of pressurization gas. In fact, the developers claim 50% to 60% reduction in pressurization gas relative to a traditional lock hopper system.

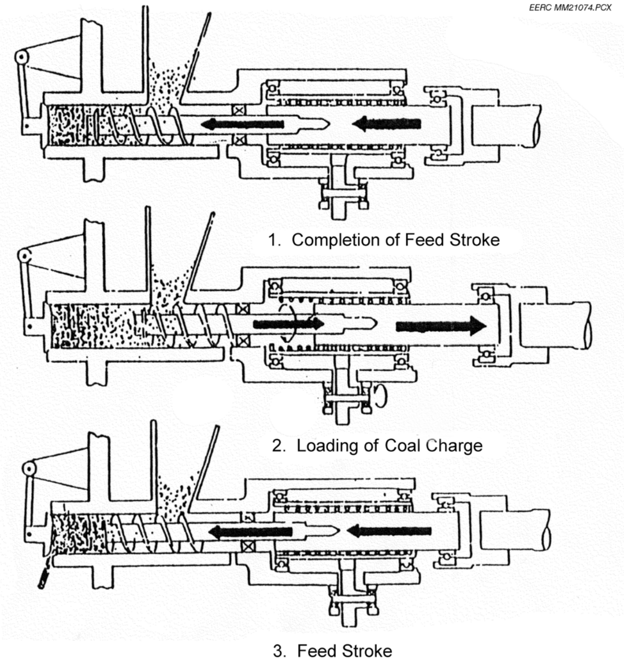


Figure 50. Ingersoll–Rand reciprocating screw feeder.

A most recent development in plug-forming feeders is that of TK Energi piston feeder, shown in Figure 51 (77). This system is a three-stage feeder with a rated capacity of almost 8 tons/hr of wood chip at 20% moisture. This system relies on the pistons to both compress and advance the biomass within the device. Within the feed hopper, the biomass falls in front of the retracted first piston and then is pressed into a "free space" in front of the second piston. After the first piston, biomass densities of 400 to 900 kg/m^3 (25 to 56 lb/ft^3) are attained. The second piston pushes the biomass plug downward into the free space ahead of the third piston. The third piston advances the biomass plug through the "sealing" section, with density within the sealing section determined by the "control" section. (This description appears to be purposely vague to protect intellectual property, but it suggests that there may be a tapered section or some restriction that provides resistance for plug formation). The plug density at discharge must be in the range of 1000 to 1700 kg/m^3 (62 to 106 lb/ft^3) for sealing. The third piston advances the plug to the plug breaker, a rotating cutting head, which functions to grind the plug. Safety against blow back of process gas is achieved by ensuring that at least one piston is positioned within the biomass flow path. The biomass charge will also function to inhibit backflow. The piston stroke rate is 1200 cycles per hour maximum. The system is designed to wear at the walls of the piston cylinders which will not affect plug densification. Add-on features include weigh belt feeder, dosing screw, and near infrared moisture measurement systems upstream of the feed hopper. Specific power consumption is presented as up to 100 kW for soft wood chips and up to 130 kW for hardwood chips, both fed at 6.5 tons/hr against 360 psig. The system is designed for biomass of 0 to 2 inches and input bulk densities of 150 to 250 kg/m^3 (about 9 to 16 lb/ft^3). TK Energi is in the process of patenting the feed system.

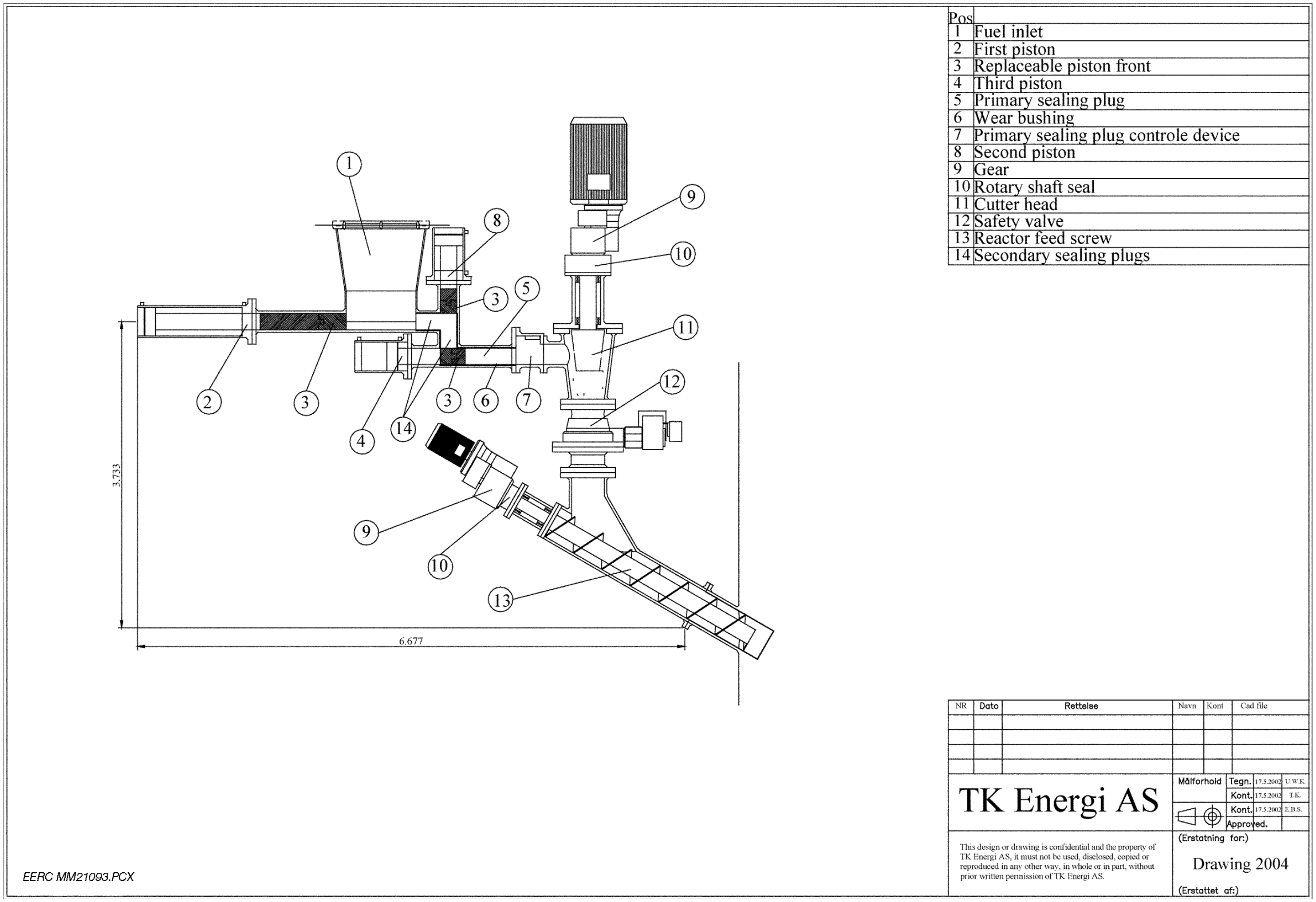


Figure 51. Schematic of TK Energi three-stage piston feeder for biomass.

The Sugar Research Institute (Mackay, Australia) is in the midst of development activities on a system for feeding sugarcane bagasse to pressurized gasifiers as part of biomass IGCC systems. Currently, the device has been developed to a capacity sufficient to feed a nominally 15-MWth gasifier (78). The organization envisions plants ranging in size from 50 to 120 MWe to match the bagasse/cane trash supply produced currently by Australian sugar mills. The Institute is currently proceeding with the filing and procurement of international patents and is targeting a December 2002 completion time frame. The system is purported to provide truly continuous feed across the pressure boundary and does rely on the formation of bagasse plug to achieve high-pressure sealing. However, the feeder does not incorporate pistons or screw-type devices to achieve the plug formation. The formation and action of the "sealing plug" were not described, but there appears to be a potentially complex interplay between the mechanical design of an associated "chamber" and the flow behavior of the bagasse plug. There is no indication of testing with materials other than bagasse, nor is there information on the expected pressure boundary for fuel delivery.

The Posimetric Feeder, currently marketed in North America by Pennsylvania Crusher (79, 80) was developed by Stamet with financial assistance from the DOE Small Business Innovation Research Program. Its principal application has been for the nonpulsating metered feeding of coal to crushers in coal-fired power plants. The feeder uses a spool-shaped disk to move solids through a partial rotation to the discharge. Fuel is gravity-fed to the top inlet of the feeder. The feeder relies on "bridging" of the fuel with the spool to achieve movement of the fuel from the feed inlet to the discharge. The fuel moves at the same rotational speed as the spool, resulting in very low wear rates. Further, "packing" of the fuel supposedly results in eliminated or greatly reduced backflow of process gas. At the discharge opening, the feed "plug" disengages from the spool and proceeds at an angle up the discharge chute. Stamet indicates that the Posimetric Feeder has been demonstrated to deliver coal into a 210-psig atmosphere. The literature seems to imply that the presence of fines and proper control of particle-size distribution are necessary for producing a pluglike seal. However, discussions with the vendor indicate that more recent tests show difficulties at maintaining a gas seal in tests at 250 psig. Further, no systems were in place or being developed for application at pressures approaching 410 psig.

Non-Plug-Forming Feeders

Two functionally similar non-plug-forming feeders include the Ingersoll–Rand coaxial piston feeder and the Fortum piston feeder for solid fuels, shown in Figures 52 and 53, respectively. Both systems rely on the sealing of the piston surface against the material cylinder to prevent gas leakage or backflow of process gas. The Ingersoll–Rand system, whose development was halted in the mid 1980s, was designed for feeding coarse coal to systems operating at pressures up to 1500 psig (81). Figure 54 shows the five distinct sequences for one complete cycle of fuel feeding. In the first sequence, coal is gravity-fed from a special dosing hopper to the space between the *transport* and *gas exclusion* pistons. In the second sequence, the space between the pistons is pressurized with an inert gas to a pressure at or above that of the process. Gas is introduced through ports in the face of the gas exclusion piston. Both pistons then move at the same speed toward the discharge opening. In the third sequence, the pistons move to a point above the discharge allowing the coal to gravity-feed to the process. In the fourth sequence, the gas exclusion piston moves to bring its face against the face of the transport piston. Gas trapped between the piston faces is vented through the ports in

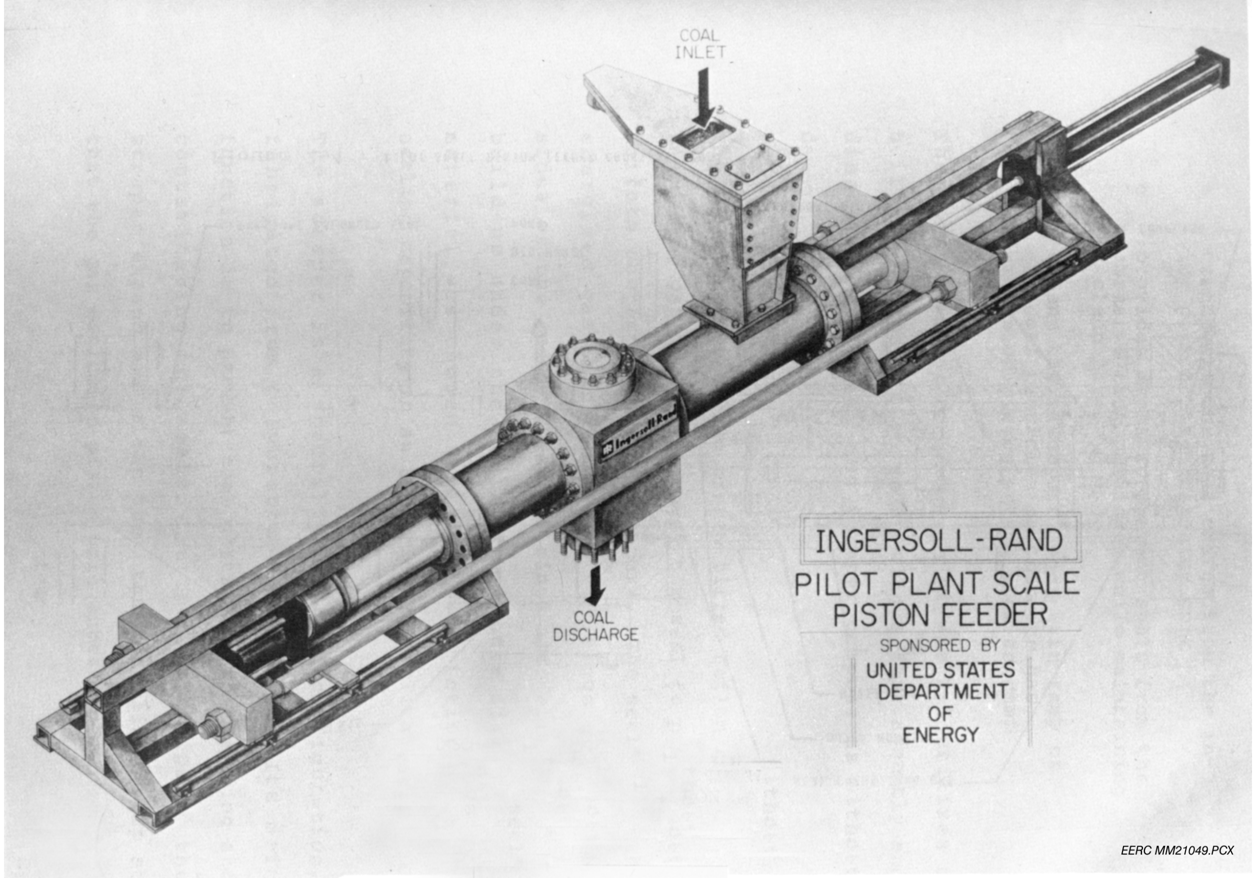
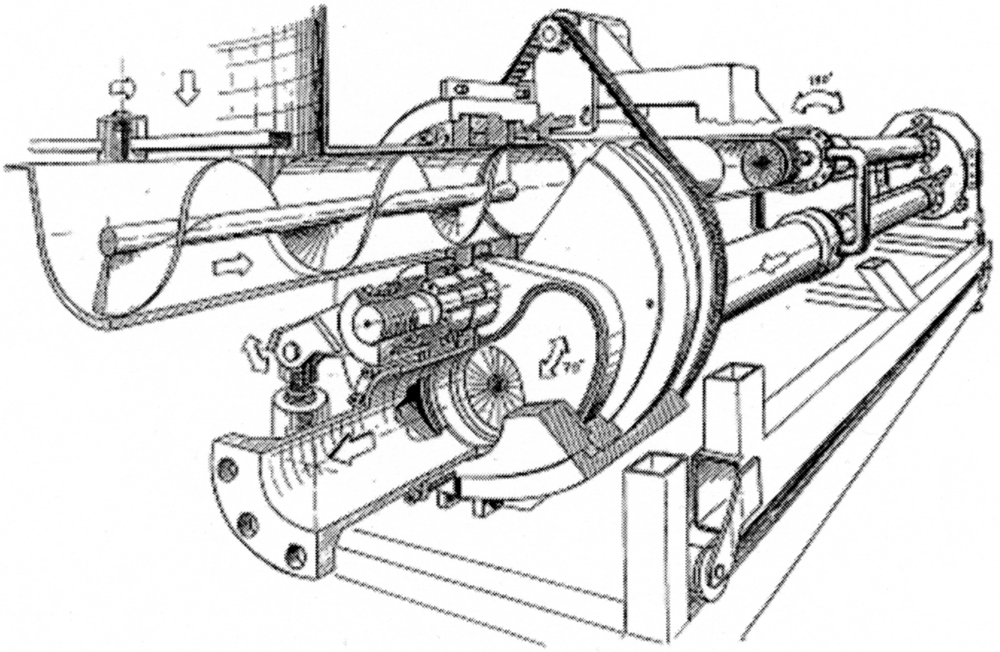


Figure 52. Schematic of Ingersoll–Rand coaxial piston feeder.

THE EXISTING PISTON FEEDER



THE PISTON FEEDER OF THE SECOND GENERATION

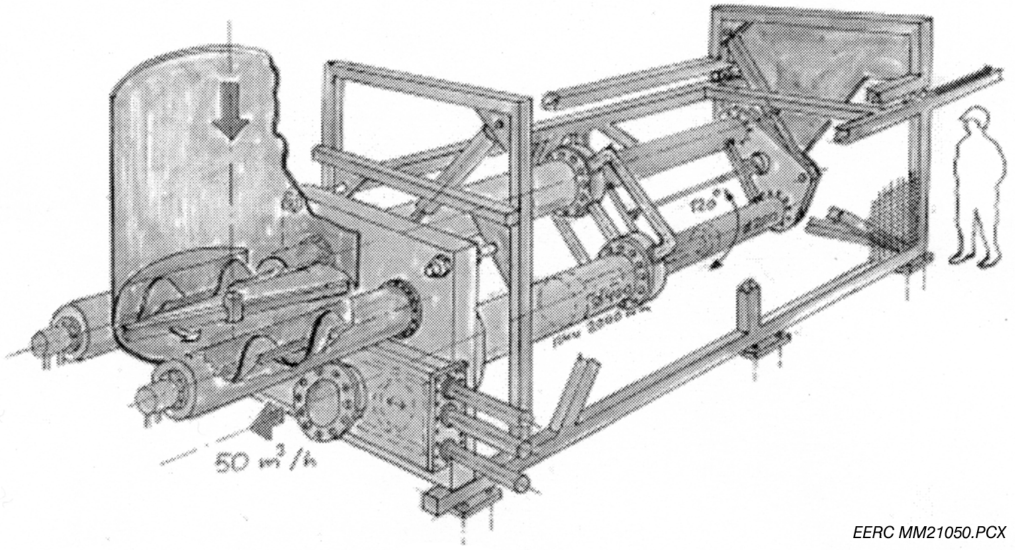


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Figure 53. Artist conception of Fortum piston feeder for solid fuels.

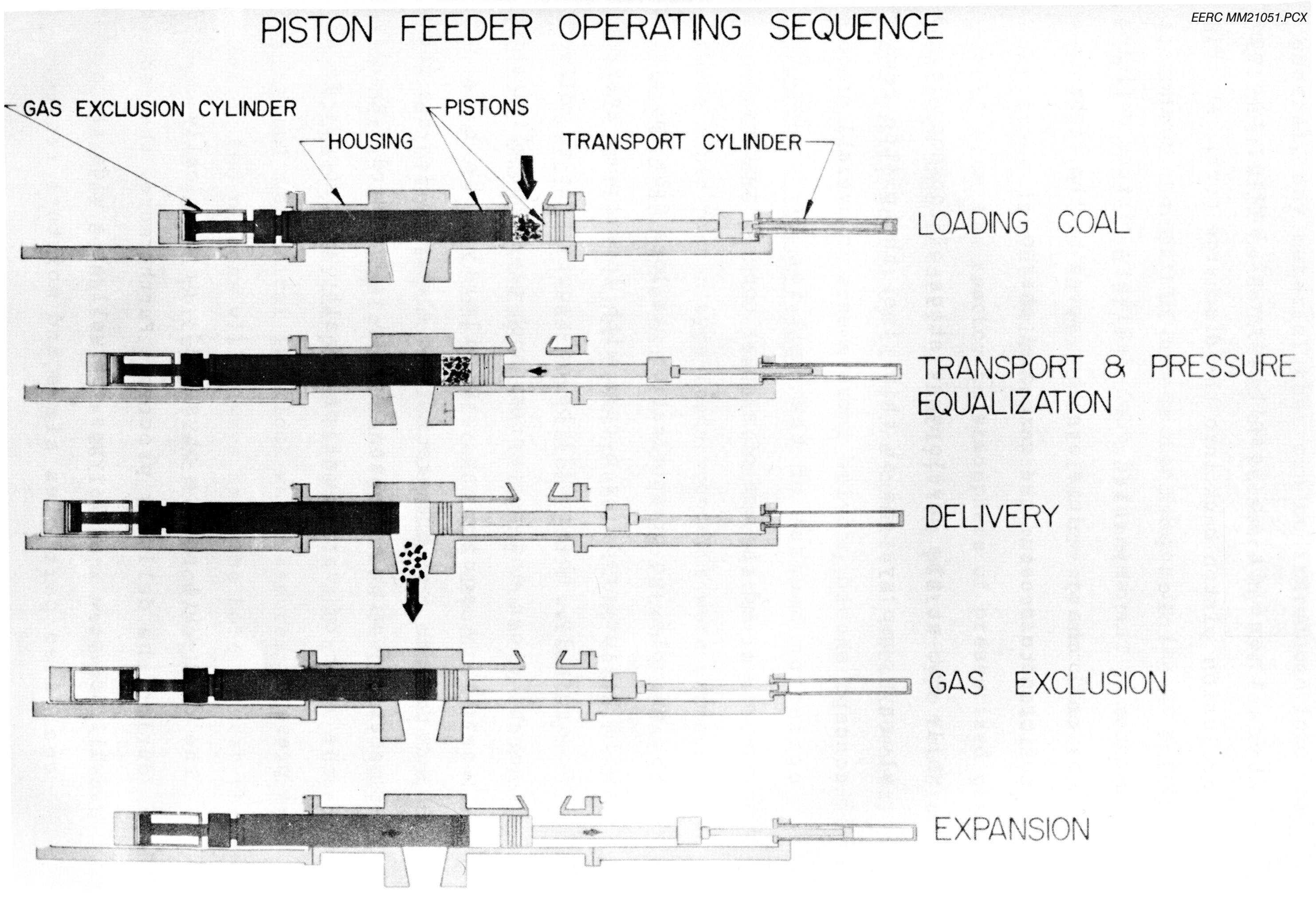

Figure 54. Five-stage feeding cycle with Ingersoll–Rand coaxial feeder.

the gas exclusion piston. In the fifth sequence, the pistons separate by the required face-to-face distance and then move back to the fuel charging opening to start the cycle over. The process used a system of inflatable piston seals to allow movement of the piston across discontinuities (e.g., feed charge opening) in the material cylinder. The developmental system utilized material cylinders of 9-inch ID to attain mass rates up to 2.5 tons/hr.

The Fortum system was designed specifically for feeding biomass to pressurized gasification and combustion systems. Materials tested included peat, wood chips, sawdust, and bark. Development activities were halted in 1995 after the developer (Imatran Voimas Oy) believed pressurized gasification to have a limited future (82). Foreign patents were apparently obtained, although the developer was not forthcoming with patent numbers or the estimated cost of the system.

The Fortum feed system comprises two primary components: the feed bin and piston feeder. The feed bin is equipped with a live-bottom screw that functions to meter the fuel into the material cylinders of the high-pressure piston feeder. The piston feeder consists of two horizontal material cylinders with one cylinder located above the other. Each material cylinder is equipped with its own hydraulically actuated piston. In the normal position, the upper material cylinder (and piston) is positioned to receive fuel from the feed bin, and the lower material cylinder (and piston) is positioned to feed fuel into the pressurized process. With the upper material cylinder positioned to receive fuel, the feed bin screw advances the fuel into the material cylinder, partially compressing the fuel against the retreating piston. Fuel charging stops after the piston reaches its fully retracted position. Simultaneously, the piston on the lower cylinder advances "until the pressure in the lower cylinder is raised to that of the process." The valve (pressure interlock) between the feeder and the process is opened, and the piston delivers the fuel to the process. After the valve closes, the upper and lower cylinders rotate 180° to continue the cycle. The pilot-scale feeder utilized a 200-mm (about 8-inch)-ID by 1-m (3.3-ft)-long material cylinder and was capable of feeding 10 m^3/hr (350 ft^3/hr) against 360 psig with a power consumption of 20 kW. Although not ever constructed or tested, a design was advanced for a commercial feeder with a capacity of 50 m^3/hr (1760 ft^3/hr), a cylinder with an ID of 400 mm (about 16 inches) and length of 2 m (6.6 ft), and a power consumption of 100 kW, again delivering against 360-psig process pressure. Although not part of the presented specifications, calculations indicate a cycle rate of 200 times an hour. Claims of the technology include no possibility of sudden pressure release through the feeder and no consumption of inert pressurization gas. The level of densification of biomass by the screw was not measured as it was the developer's intention to maintain "loose" biomass and avoid formation of pellets or briquettes.

The Foster–Miller linear pocket feeder, shown in Figure 55, was developed for feeding coal to fixed-bed, fluidized-bed, and entrained-flow gasifiers and was developed under DOE sponsorship (83). Performance tests were conducted with coarse and pulverized coal at pressures up to 6.89 MPa (1000 psig) and 4500 kg/hr (10,000 lb/hr). The feeder functions like a tube conveyor, with sealing pistons replacing the drag flights. The sealing pistons are connected by a chain, forming a series of pockets. The pockets are gravity-filled with coal and then the pistons pass through a "sphincter," a self-adjusting contact seal that functions to prevent backflow of gas to the atmospheric feed inlet. The pistons then pass through a sealing tube wherein the close tolerances between piston and tube wall function as a labyrinth seal to reduce the gas pressure acting at the "sphincter." The coal-laden

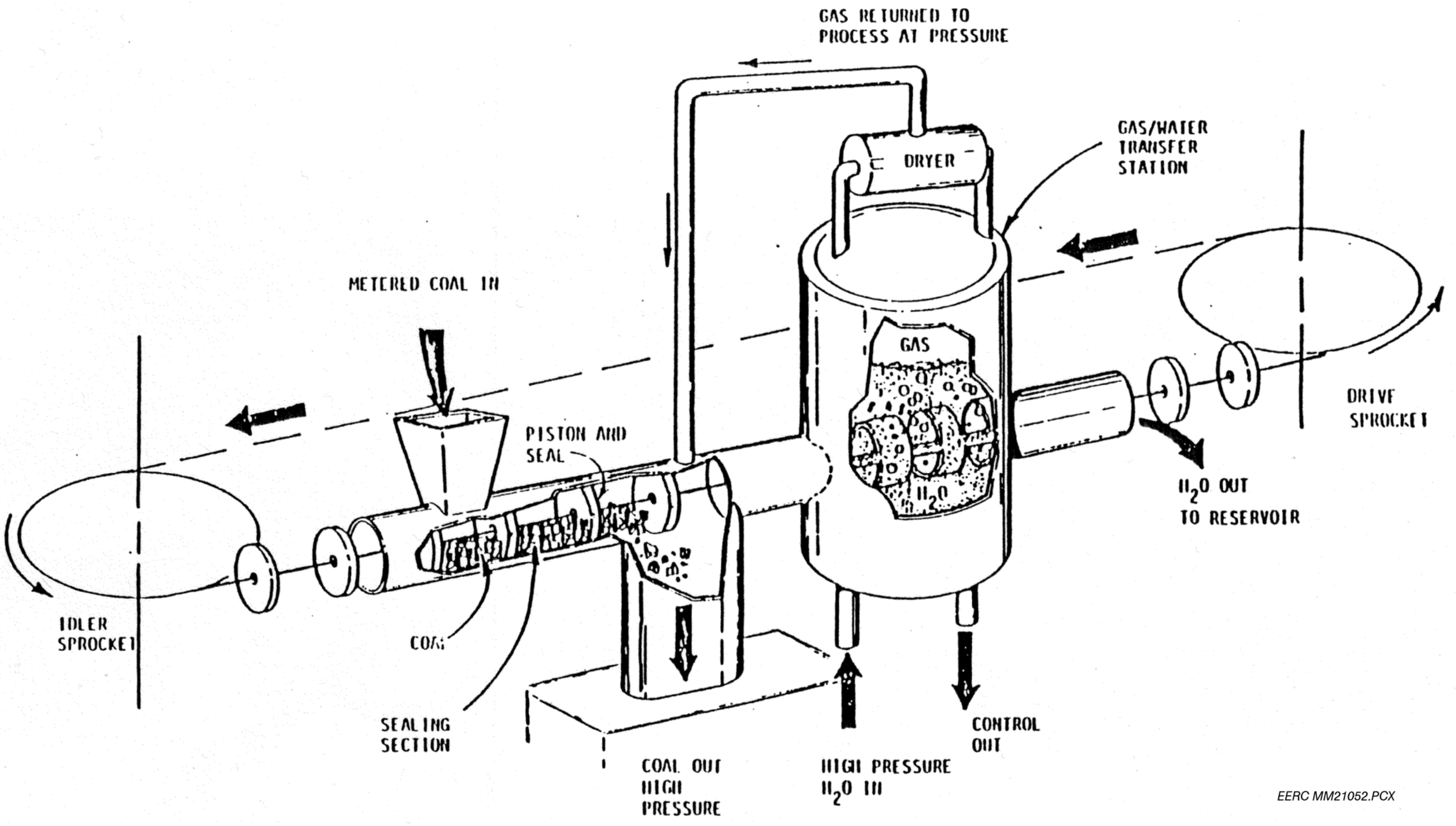

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Figure 55. Foster–Miller linear pocket feeder.

pockets then pass over the discharge with the coal then expelled via gravity. When pulverized coal is fed, a high-pressure gas “chase” may be necessary to efficiently discharge the coal. The gas-filled pockets enter the gas–water transfer station where the gas in the pockets is displaced by water. The displaced gas is returned to the process owing to the fact that the gas–water transfer station is maintained at a slightly higher pressure than the process. A proper water level is maintained in the transfer station using a high-pressure pump. The water contained within the pockets is discharged to an atmospheric pressure receiver for cleanup and reuse. Excess water on the chain and pistons are removed in a dryer section that uses a blower to induce a cross-draft air flow. The pocket-filling efficiency and the coal feed rate are controlled through the chain speed.

Patent Database Search for High-Pressure Solids Feed Systems

A Web-accessible database of U.S. and foreign patents (Delphion Intellectual Property Network, http://www.delphion.com/home) was searched to determine the status of dry feed systems for high-pressure applications (84). Queries were limited to U.S. patents only. A list of related patents is presented in Appendix D.

Review of the patents indicated that the systems were principally based on extrusion feeding of powdered or pulverized coal. A gas-tight pressure seal was apparently demonstrated to be achieved by one of two means: 1) attaining the plastic deformation state of the coal, resulting in void sealing or 2) adding an uncompressible filler/binder such as water or a hydrocarbon liquid to fill voids. The forces of extrusion, however, resulted in sufficient compaction of the coal to require the feed system to also incorporate a means of repulverizing or delumping the compact. This was typically achieved using a directed stream of high-pressure fluid (gas or liquid).

Procurement of Feedstock Samples

A number of feedstocks were procured to allow evaluation for potential utilization within several select commercial and developmental biomass feed systems. Feedstocks included corn stover, switchgrass, soybean hulls, RDF, wheat straw, E-grass, and wood waste. Corn stover was procured from Tom Schechinger of Biomass Agri Products (Harlan, Iowa). Switchgrass was obtained from Chariton Valley Resource Conservation and Development (CVRCD) of Centerville, Iowa. Corn stover has principally been evaluated for production of high-value products such as furfural, fibers, and ethanol. The corn stover consists of the stocks, leaves, and cobs left standing in the field after corn harvesting. Corn stover can be tilled back into the ground or harvested and baled for use as animal feed. Switchgrass is currently being promoted as a fast-growing, energy crop. Harvesting and bailing of corn stover and switchgrass can be performed using conventional farm equipment. For utilization as a fuel or chemical feedstock, the baling would be performed after the stover or switchgrass had field-dried to about 15 wt% or less moisture.

Soybean hulls (whole, shredded, and pelleted) were obtained from Darcy Ehmann of Ag Processing Inc. (Omaha, Nebraska). Soybean hulls are typically shredded and extruded into pellets as cattle feed, commanding prices between $50 and $70 per ton. The unpelleted soybean hulls would appear to be an ideal fuel for entrained-flow gasification in that they are of sufficiently small size and low density to preclude any requirement for size reduction. Cedar wood waste fractions were obtained from a local wood furniture manufacturer. The cedar sawdust would probably not need further processing for entrainment.

Samples of RDF were obtained from two separate producers. A coarse RDF material was procured from the Ramsey/Washington County Resource Recovery Facility (Newport, Minnesota), owned and operated by NRG Energy, Inc. (85). A smaller, nominally −4-inch RDF was obtained from a 2000-ton/day MSW processor on the East Coast. The NRG facility can process 1500 tons/day of MSW, which comprises 60% commercial waste and 40% residential waste. The facility achieves about 80% recovery as RDF. Approximately 5% of the MSW is recovered as ferrous using magnetic separation, and 1% is recovered as aluminum using eddy current separation. The Newport RDF facility was toured to observe the scale and complexity of the operation and to retrieve a sample of RDF. Fuels from both processors are consumed in WTE facilities.

RDF Sorting

An approximately 1.4-kg (3-lb) sample of the NRG RDF, filling a volume equivalent to three 5-gallon pails, was hand-sorted and classified into the following categories: cardboard, paper, plastic, textiles, wood, aluminum, ferrous, food waste, and glass/ceramic. A fluff fraction was also generated that appeared to consist primarily of paper fiber and grit that was apparently adhered to the RDF. The results of the sorting are presented in Table 26, and photos of the sorted fractions of the NRG RDF are presented in Appendix E.

Table 26. Coarse RDF Sorting Results

Material	Mass, grams	Weight Percent	Comment
Cardboard	238	11.3	
Paper	632	30.1	
Plastic	248	11.8	Mostly film plastic (from grocery bags or similar to envelope windows), styrofoam, pop jugs, little dense plastic
Textiles	146	7.0	Foam padding, carpet fibers, fiber fill for jackets, some rubber
Fluff	288	13.7	Material too small to sort by hand; estimate 90% paper
Wood	44	2.1	
Aluminum	16	0.8	6 grams of aluminum foil, 10 grams of aluminum castings or stamped product
Ferrous	3	0.1	Single piece of wire
Food Waste	4	0.2	Orange peel, dried bread chunks
Glass, Ceramic	8	0.4	
−4 × 10 mesh	157	7.5	Styrofoam beads, wood splinters, colored foil, glass/plastic fragments, paper fiber fluff
−10 × 20 mesh	136	6.5	Wood splinters, colored foil, glass/plastic fragments, paper fiber fluff, dirt?
−20 mesh	180	8.6	Paper fibers, dirt?, wood splinters, colored foil, glass/plastic fragments
Total	2100		

An 18-kg (40-lb) sample of −4-inch RDF was subjected to nondestructive physical analysis testing and manual sorting. First, the bulk density was determined at several compaction levels, including as-received, loose, and spill. The as-received density was determined from the mass and for the RDF after it was removed from the plastic package and then allowed to attain an expanded 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.

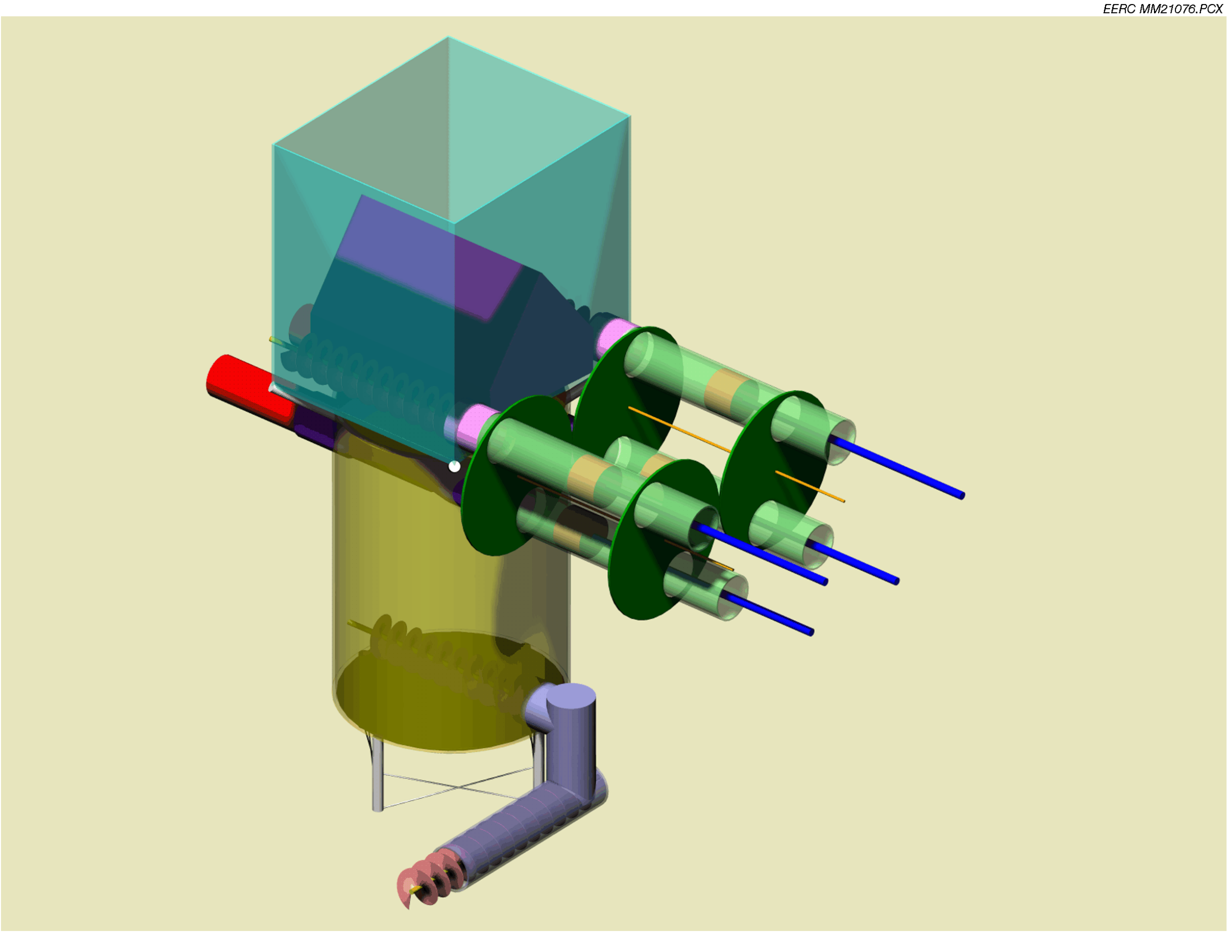

Figure 56. Proposed high-pressure feed system for biomass.

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

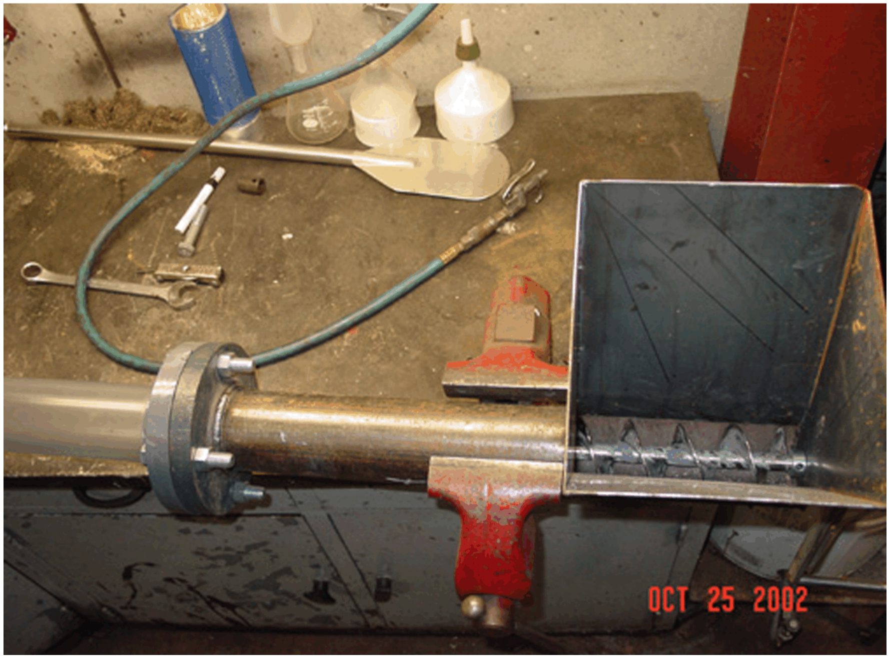

Figure 58. Precompression screw apparatus – feed hopper and compression screw.

EERC MM21056.PCX

OCT 25 2002

Figure 59. Precompression screw apparatus – transparent material cylinder.

EERC MM21057.PCX

OCT 25 2002

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.

RECOMMENDATIONS

- Further clarification of the sludge tipping fees and transportation costs for receiving sludge should be pursued with both the WREP of Indianapolis and the MWRD of Greater Chicago. The delivered on-site cost of the sludge is going to be the principal driver for determining the economics for installing such a feed system.

- Before this project would move to a commercial demonstration, sludge-associated issues concerning odors, noise, and traffic around the plant site should be addressed with the local community to minimize the negative feedback that might occur from such a project.

- Further testing of improved dual-fluid dispersion nozzles should occur. Pilot-scale tests should be performed at the Wabash River facility to refine system concepts for a Phase II commercial demonstration. The design of the EERC nozzles was continually improving and had not reached near-optimum conditions. As near-optimum conditions are achieved, better diagnostics for measuring the sludge droplet size will be needed to discern minor improvements in performance.

- Further work could be completed to determine the effects of preheating the sludge and preheating the recycle syngas on the nozzle performance. Preheating the sludge and recycle syngas should help improve the nozzle performance. Sources of low-cost waste heat from the gasifier should be identified and investigated for their suitability to preheat the sludge. Preheating the recycle syngas will occur naturally in the boost compressor.

- These tests should also be conducted in a pressure vessel operating at full system operating pressures in order to determine the appropriate flow rates and pressure ratios that will optimize the performance of the dispersion nozzle. These tests should also incorporate the second control block and modified PLC logic to verify that the pulsing flow experienced with leased equipment can be eliminated.

- Longer-term nozzle wear tests should also be performed to determine the expected wear rates and life expectancy for these nozzles given the use of hardened parts.

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APPENDIX A

PARAMETERS FOR TERMINAL VELOCITY EQUATIONS

PARAMETERS FOR TERMINAL VELOCITY EQUATIONS

d_p^*	Dimensionless particle size
d_p	Particle size, ft
ρ_g	Gas density, lb/ft^3
ρ_s	Particle density, lb/ft^3
g	Gravitational constant, 32.2 ft/sec^2
μ	Gas viscosity, lb/ft-sec
u_t^*	Dimensionless terminal velocity, ft/sec
Φ	Sphericity, dimensionless
u_t	Terminal velocity, ft/sec

APPENDIX B

NOZZLE TESTING PHOTOGRAPHS

EERC MM21088.PCX

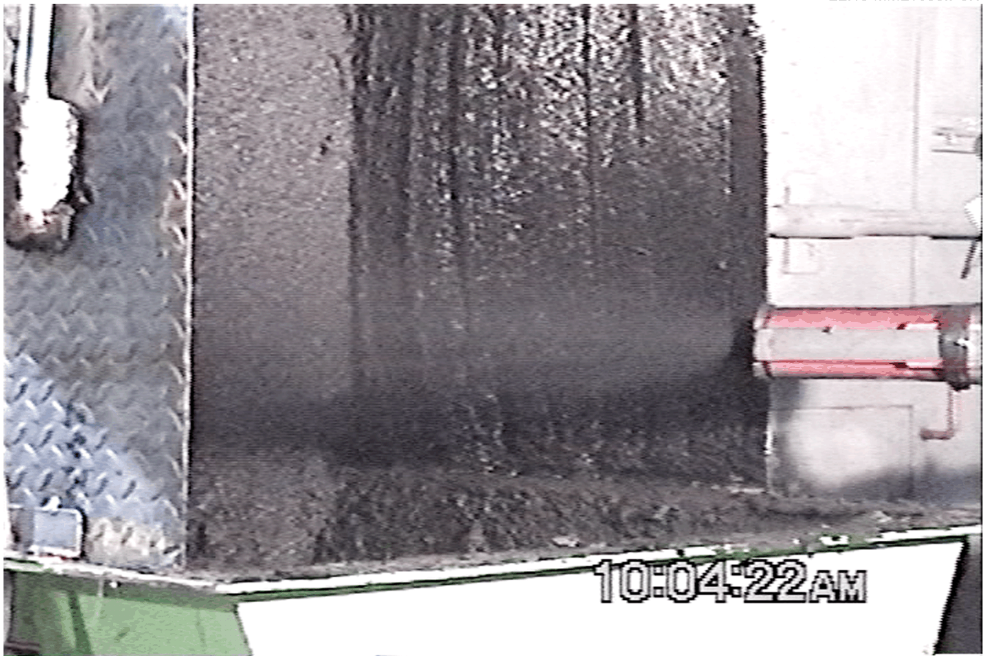
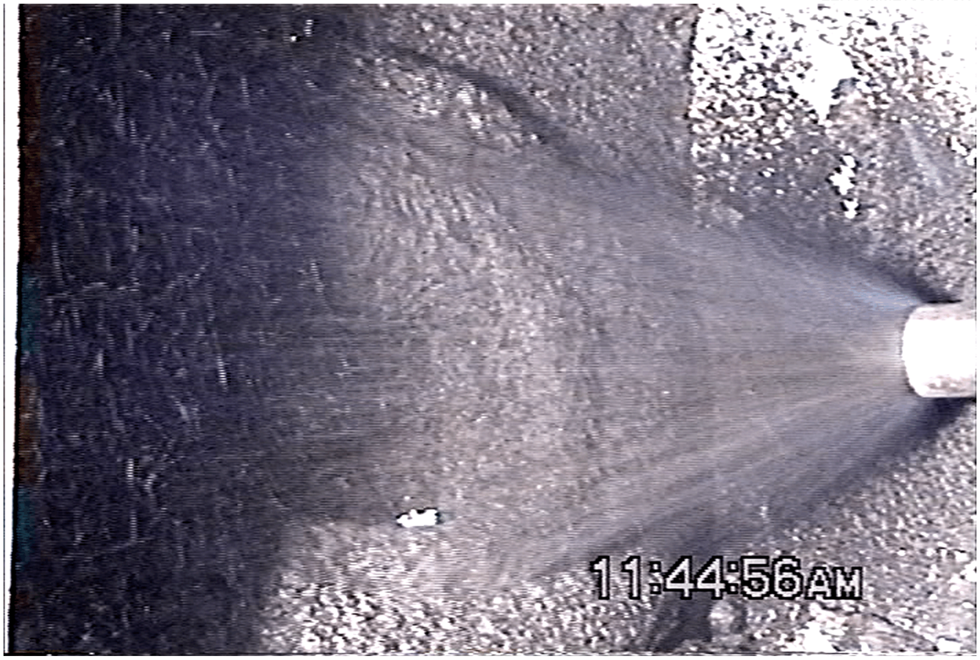


Figure B1. Sludge dispersion testing with shotcrete nozzle.

EERC MM21089.PCX

Figure B2. Sludge dispersion testing with EERC-1 nozzle.



EERC MM21090.PCX

Figure B3. Sludge dispersion testing with EERC-2 nozzle.

APPENDIX C

ECONOMIC ANALYSIS OF SLUDGE-RECEIVING, STORAGE, AND FEEDING SYSTEM

ECONOMICS OF THE FIGLEAF PROJECT

I. FIGLEAF Project – Capital Estimate

A. Basis for the Cost Estimate

Scope

The scope of work associated with the project consists of the equipment, systems, and bulk materials required to offload, store, forward, and feed sludge cake to the second stage of the gasifier located at the Wabash River Coal Gasification Repowering Project. The scope of work associated with the addition of this facility is described in the accompanying conceptual design documents, including:

- Design criteria document (Table I)
- Process flow diagrams (Figures 1 and 2)
- Equipment list (sized) (Table II)
- Plot plan (marked up) (Figure 3)
- Major equipment quotations (Please refer to EERC descriptions)

Generation of the cost estimate associated with this facility, is described below.

Major Equipment

Sizing and quotations for the major equipment were obtained by EERC from Schwing America Inc. These included an overall description, basic specification data, and drawings of the equipment. The remainder of equipment was estimated based on similar equipment in similar service, using capacity as a scale factor.

Bulk Material Costs

Bulk material pricing was based on a combination of actual unit costs and rates from Wabash (escalated to current day) and recent industry data for craft labor factors and material costs.

Bulk Material Quantities

- Earthwork – takeoff based on plot plan
- Concrete – manual takeoff based on conceptual design sketches for pads, unloading structure, etc.
- Steel – assumed a small tonnage for miscellaneous structures, pipe rack modification, and pipe supports
- Piping – manual takeoff based on the plot plan and PFD
- Instruments – basic count taken from the equipment quotation (installation only) and the PFDs (supply and installation)
- Electrical – feeder cable and switchgear sized as part of the conceptual design. Costs associated with cable and conduit were estimated by manual takeoff from the plot plan.

- Painting and insulation rough estimated based on piping takeoff
- Electrical heat tracing rough estimated based on piping takeoff

Subcontracts

Although representing a relatively small portion of the overall work, the scope and cost associated with subcontracted work was factored based on similar industry experience at other sites.

Construction

The direct hire component of the work was estimated based on union labor unit rates typical to the industry. The union labor rate employed in the estimate is a built up ("all in") rate, which includes compensation, fringes, taxes, and construction indirects which include non-manual staffing, temporary facilities, small tools and consumables, etc. An all-in labor rate of $61/hr should be representative of the craft mix, at this location, barring any unique market influences or weather impacts.

Sales Tax

Excluded

Equipment Supplier Field Service

Field service by the major equipment supplier, consisting of 17 days including travel and per diem, was included as part of the equipment quotes.

Freight

Freight is included as part of the major equipment quotation

Escalation

No escalation has been applied to the estimate, aside from the use of actual historic Wabash data referenced above. Therefore this estimate is current day.

Spares

No spares have been included.

Interest During Construction

None has been applied; therefore, the estimate assumes "overnight" construction.

Home Office (Eng./Proj. Mgmt./Admin.)

The cost for detailed engineering (including procurement) and design, as well as project management and administration are included to cover roughly 10,000 staff hours at current industry rates, plus an allowance for travel and other expenses.

Contingency

A 10% contingency has been added to cover omissions, design changes, and contractor profit.

B. Total Cost

The total cost was determined to be $9.71MM. The estimate is accurate to within 10%. An item by item breakdown of the estimate is shown in Table III.

Table I

FIGLEAF PROJECT DESIGN CRITERIA

Feed Rate: 1000 tpd

Feed Material: Sewage Sludge

Slurry: 23% solids (weight)

Slurry Density: 60 lb/ft^3

Storage Capacity: 2 days (4 tanks @ 19,000 ft^3/lb per tank)

Trucking Criteria: 30 yd^3 (25 tons)

II. FIGLEAF Economic Analysis

This economic analysis reviews the impact of addition of biosolids to the gasifier utilizing the FIGLEAF developed systems. Two plants are analyzed, a petcoke IGCC and a coal IGCC. Both plants are single train facilities, nominally 300 MW for the coke cases and nominally 250 MW for the coal cases.

In this review, a cost model based on Department of Energy IGCC Model, Version 3 spreadsheet was developed for the nominal coke/coal IGCC and a target rate of return (IRR) determined. The spreadsheet was then run with a second case reflecting the addition of the biosolids fuel to the second stage and the model was adjusted for the impacts on capital cost, output and heat rate. The required tipping fee for the biosolids was determined to maintain the same level of economic performance as measured by the IRR and NPV as the single primary fuel cases.

Major Parameters for Economic Analysis

	Petcoke	Coal
Fuel Cost, $/ton (coke/coal)	$12.00	$23.00
Electrical Power Price, $/MWH	$34.00	$ 42.89
Capital Cost for single fuel plant, $/kW (escalated)	1300	1350
Additional Cost for FIGLEAF system, MM$	9.71	9.71
Availability, %	85	80
Contract Life, Years	20	20
Financing, Debt/Equity/Interest	70/ 30/ 9%	70/ 30/ 9%
Return, IRR%	12	12
NPV, MM$ @ 10% discount rate	29.7	29.7

A. Petcoke & Petcoke-Bio-solids Cases:

	Petcoke IGCC	FIGLEAF
Petcoke, TPD	2292	2095
BioSolids, TPD	0	1042
Net Output, MW	301.4	291.3
Heat Rate, Btu/kWhr HHV	8690	8851

Results:

The Petcoke only plant showed a 12% IRR with a NPV of $29.7MM at a 10% discount rate.

At a power price of $34/MWH, the Petcoke-Bio-solids plant (FIGLEAF) must be able to obtain biosolids with a tipping fee of $12.40 per ton (i.e. feedstock must have negative value) to obtain the same economic performance.

The sensitivity of the required cost (or tipping fee) of the bio-solid to the variation in power price is shown in the following and in Figure 4:

Electrical Power Price $/MWH	Cost of Bio-Solid $/Wet Ton
30	-41.8
32	-27.1
34	-12.4
36	2.3
40	31.7

B. Coal & Coal-Bio-solids Cases:

	Coal IGCC	FIGLEAF
Coal, TPD	2710	2459
BioSolids, TPD	0	881
Net Output, MW	268.2	255.7
Heat Rate, Btu/kWhr HHV	8955	9187

Results:

The Coal-only IGCC plant showed a 12% IRR with a NPV of $29.7MM at a 10% discount rate (note that this is with a higher power price than the petcoke-only IGCC).

The Coal-Biosolids plant (FIGLEAF) must be able to obtain biosolids with a tipping fee of $16**.70 per ton** (i.e. feedstock must have negative value) to obtain the same economic performance.

The sensitivity of the required cost (or tipping fee) of the bio-solid to the variation in power price is shown in the following and in Figure 4:

Electrical Power Price $/MWH	Cost of Bio-Solid $/Wet Ton
32	-99.8
35	-76.9
40	-38.8
42.9	-16.7
46	7.1

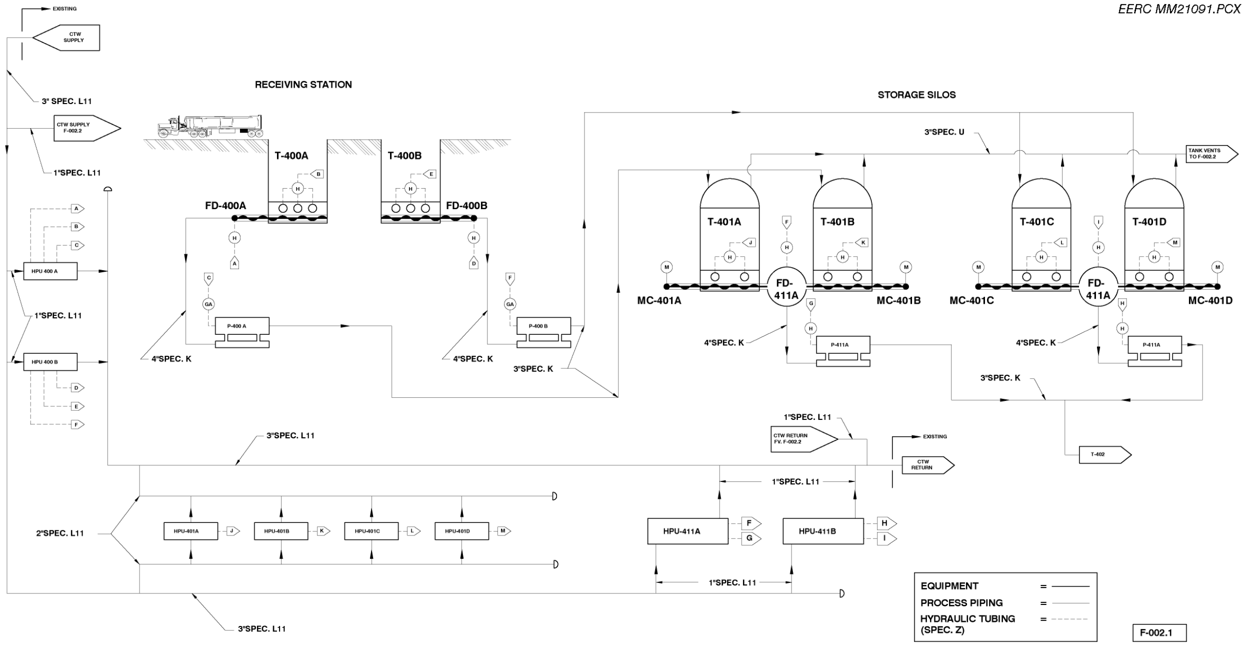


Figure C1. Process flow diagram for sludge receiving and storage systems.

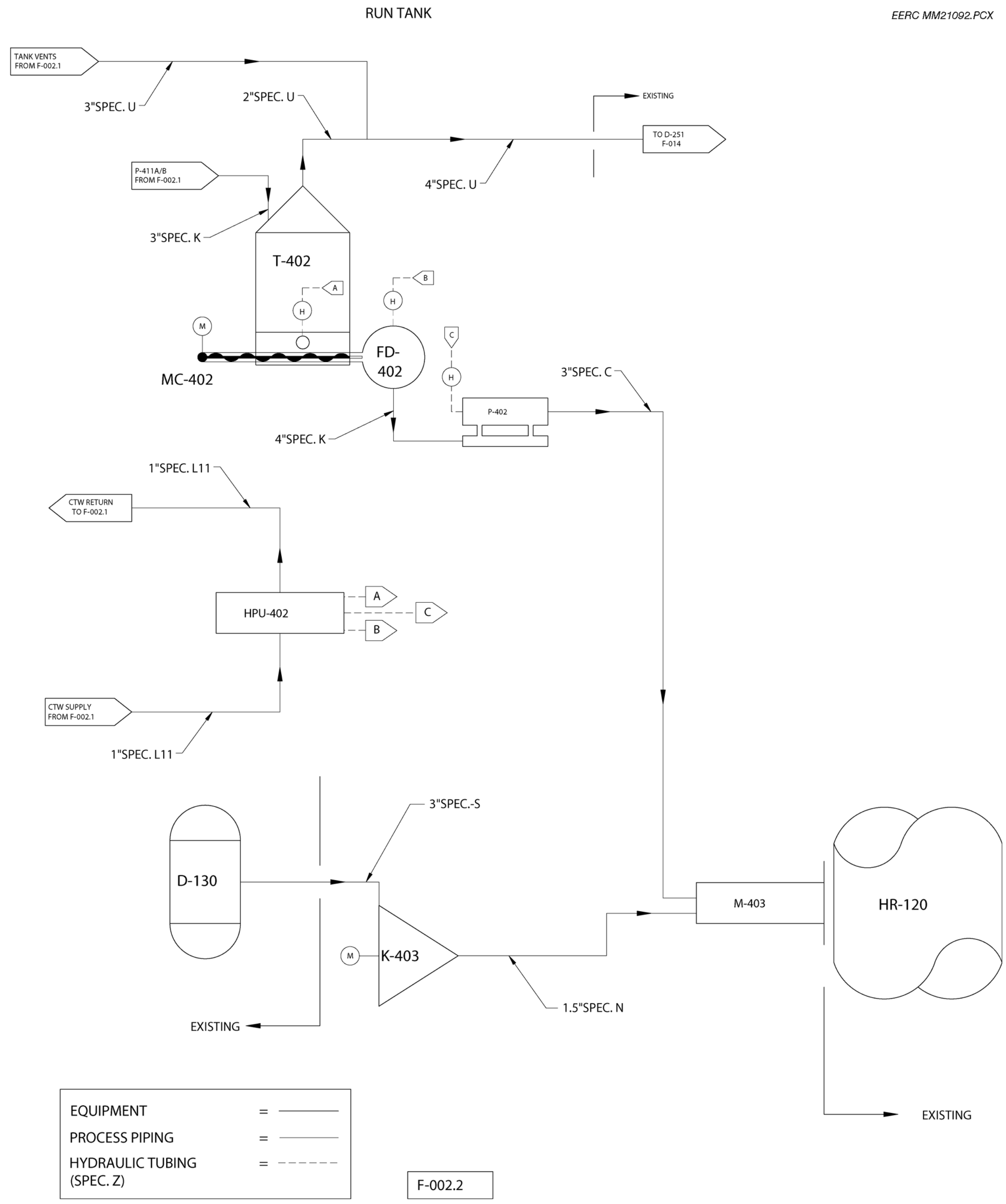


Figure C2. Process flow diagram for sludge high-pressure feeding system.

EERC MM20935.CDR

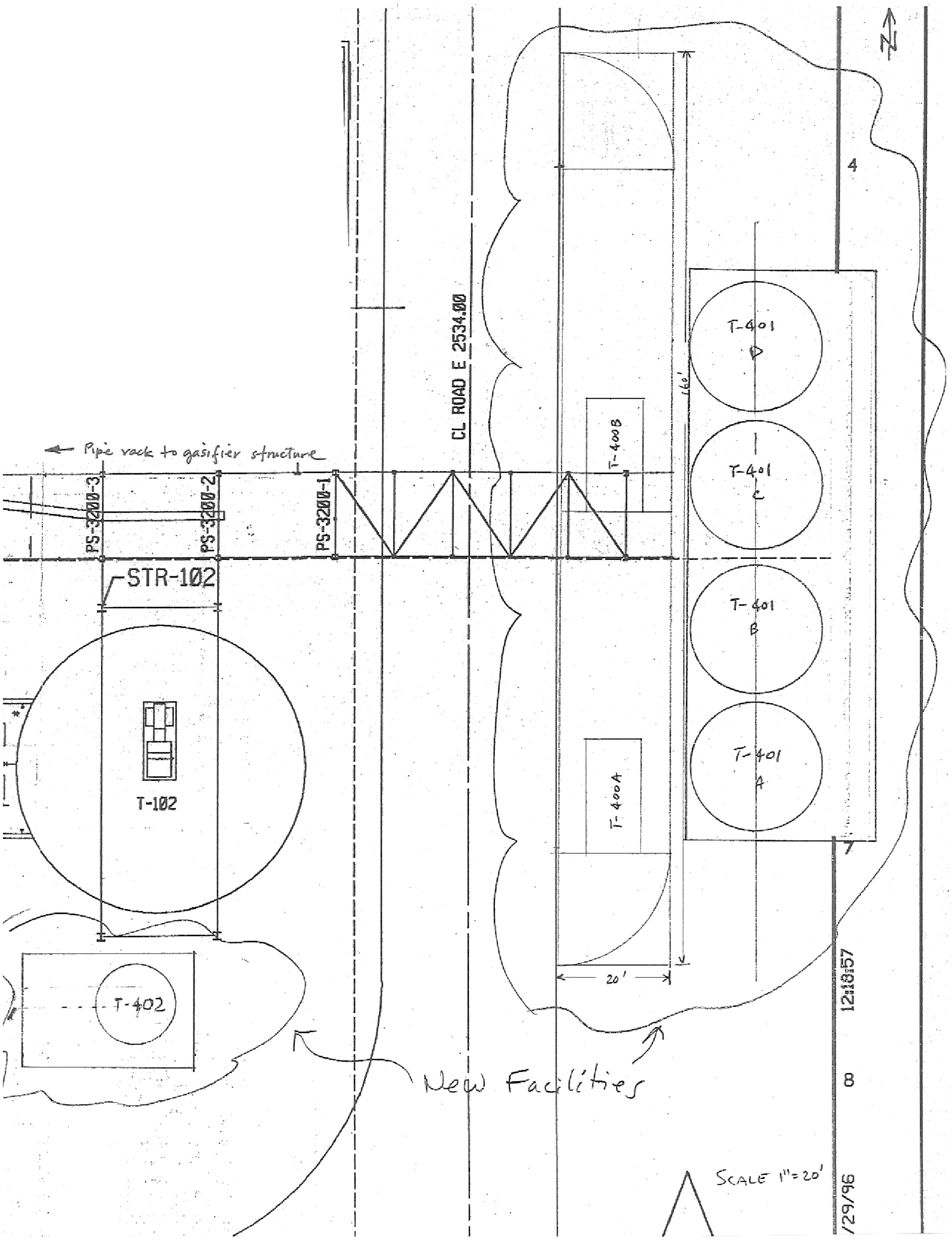


Figure C-3. Facility plot plan.

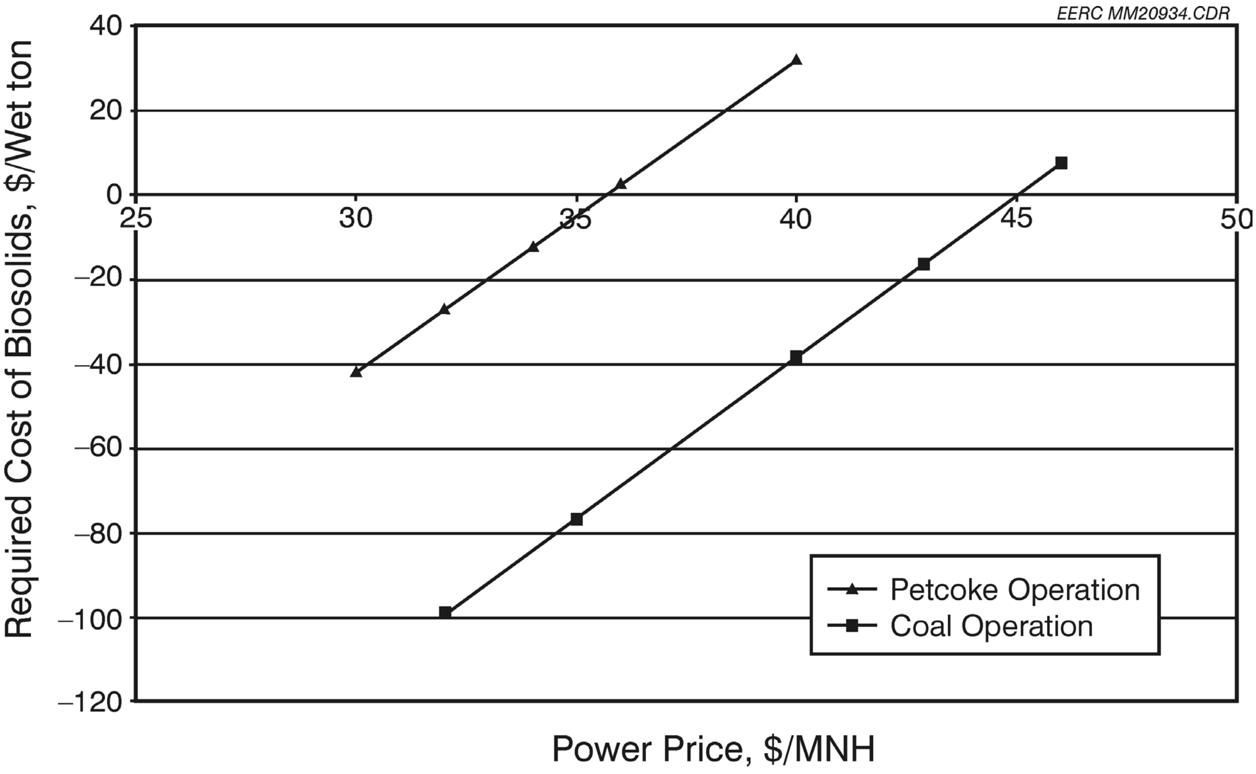


Figure C4. Municipal sludge cost vs. power price.

TABLE II

				Nominal Size				Conn.
FIGLEAF PROJECT - EQUIPMENT LIST [* = redundant equipment within train]								
Tag #	**Equipment Description**	**Qty**	**Materials of Constr.**	**Capacity 1**	**Units**	**Capacity 2**	**Units**	**hp**
T-400 A/B	Receiving Bunkers (w/ sliding frame bottom)	2	A-36 C-Stl	3,850	ft^3	20'L x 9.5'W x 20' H		hydraulic
FD-400 A/B	Screw Feeders	2						hydraulic
P-400 A/B	Sludge Pumps	2		160	gpm			hydraulic
HPU-400 A/B	Hydraulic Power Units	2						200
T-401 A-D	Storage Silos (w/ sliding frame bottom)	4	A-36 C-Stl	19,000	ft^3	23'D x 46'H		hydraulic
HPU-401 A-D	Hydraulic Power Units	4	[VFD]					25
MC-401A-D	Extraction Conveyors	4						25
FD-411 A/B	Screw Feeders	2						hydraulic
P-411 A/B	Sludge Pumps	2		160	gpm			hydraulic
HPU-411 A/B	Hydraulic Power Units	2						200
T-402	Run Tank (w/ sliding frame bottom)	1	A-36 C-Stl	1,718	ft^3	13.5' D x 12' H		hydraulic
MC-402	Extraction Conveyor	1						20
FD-402	Screw Feeder	1						hydraulic
P-402	Sludge Feed Pump	1		160	gpm			hydraulic
HPU-402	Hydraulic Power Unit	1						250
K-403	Recycle Syngas Booster Compressor	1	304L SS	15,000	lb/hr	800	psig	200
M-403	Sludge Mixer	1	High Nickle Alloy					

TABLE III

FIGLEAF - EQUIPMENT LIST & CAPITAL COST ESTIMATE

			EQUIPMENT/MATERIALS				LABOR				LINE
Cost Account	Tag #	Description	Qty	Units	Unit Cost	Total Cost	Qty	LF	Unit Cost	Total Cost	Total
Mech Equip.		*Receiving Station:*									
	T-400 A/B	Receiving Bunkers (w/ sliding frame bott	2			$0	440		$61	$53,680	
	FD-400 A/B	Screw Feeders	2			$0	80		$61	$9,760	
	P-400 A/B	Sludge Pumps	2			$0	40		$61	$4,880	
	HPU-400 A/B	Hydraulic Power Units	2			$0	40		$61	$4,880	
		Subtotal	1		$1,300,000	$1,300,000				$73,200	$1,373,200
		Storage Area:									
	T-401 A-D	Storage Silos (w/ sliding frame bottom)	4			$0	1421		$61	$346,773	
	HPU-401 A-D	Hydraulic Power Units	4			$0	40		$61	$9,760	
	MC-401A-D	Extraction Conveyors	4			$0	150		$61	$36,600	
	FD-411 A/B	Screw Feeders	2			$0	80		$61	$9,760	
	P-411 A/B	Sludge Pumps	2			$0	40		$61	$4,880	
	HPU-411 A/B	Hydraulic Power Units	2			$0	40		$61	$4,880	
		Subtotal	1		$2,900,000	$2,900,000				$412,653	$3,312,653
		Run Tank:									
	T-402	Run Tank (w/ sliding frame bottom)	1			$0	129		$61	$7,839	
	MC-402	Extraction Conveyor	1			$0	150		$61	$9,150	
	FD-402	Screw Feeder	1			$0	80		$61	$4,880	
	P-402	Sludge Feed Pump	1			$0	40		$61	$2,440	
	HPU-402	Hydraulic Power Unit	1			$0	40		$61	$2,440	
		Subtotal	1		$700,000	$700,000				$26,749	$726,749
		Other:									
	K-403	Recycle Syngas Booster Compressor	1		$240,000	$240,000	250		$61	$15,250	$255,250
	M-403	Sludge Mixer	1		$75,000	$75,000	20		$61	$1,220	$76,220
		Subtotal			$315,000	$315,000				$16,470	$331,470
		Account Subtotal									$5,744,072
Earthwork											
		Clear & Grub (s/c)	1			$0	2	ac	$2,400	$4,800	$4,800
		Cut & Fill (s/c)	1			$0	926	yd^3	$5	$4,676	$4,676
		Account Subtotal				$0				$9,476	$9,476
Concrete		Receiving Station [A-F]	892	yd^3	$170	$151,640	11		$61	$598,532	$750,172
		Storage Silos [G]	178	yd^3	$127	$22,606	14		$61	$152,012	$174,618
		Run Tank [H]	24	yd^3	$127	$3,048	14		$61	$20,496	$23,544
		Misc. [I]	17	yd^3	$101	$1,717	5.83		$61	$6,046	$7,763
		Account Subtotal	1111	yd^3		$179,011				$777,086	$956,097
Steel		Misc.	5	tons	$1,954	$9,770	27		$61	$8,235	$18,005
Piping											
	Spec C (3")	600# 304L SS	400	ft	$50	$20,000	2.3		$61	$56,120	$76,120
	Spec K (3")	150# 304L SS	520	ft	$64	$33,280	2.5		$61	$79,300	$112,580
	Spec K (4")	150# 304L SS	100	ft	$70	$7,000	2.8		$61	$17,080	$24,080
	Spec L11 (1")	150# CS	130	ft	$16	$2,080	1.3		$61	$10,309	$12,389
	Spec L11 (2")	150# CS	180	ft	$20	$3,600	1.5		$61	$16,470	$20,070
	Spec L11 (3")	150# CS	780	ft	$26	$20,280	1.8		$61	$85,644	$105,924
	Spec N (1.5")	900# 304L SS	335	ft	$40	$13,400	2		$61	$40,870	$54,270
	Spec S (3")	300# 304L SS	120	ft	$66	$7,920	2.6		$61	$19,032	$26,952

TABLE III (cont'd)

FIGLEAF - EQUIPMENT LIST & CAPITAL COST ESTIMATE											
Cost			EQUIPMENT/MATERIALS				LABOR				LINE
Account	Tag #	Description	Qty	Units	Unit Cost	Total Cost	Qty	LF	Unit Cost	Total Cost	Total
	Spec U (2")	150# 304L SS	80	ft	$60	$4,800	2.3		$61	$11,224	$16,024
	Spec U (3")	150# 304L SS	285	ft	$64	$18,240	2.5		$61	$43,463	$61,703
	Spec Z (.5")	150# 316L SS	255	ft	$20	$5,100	1.1		$61	$17,111	$22,211
		Account Subtotal	3185	ft		$135,700				$396,622	$532,322
Elect. Equip.											
	Motor Starters		14		$2,500	$35,000	4		$61	$3,416	$38,416
	MCC		14	sect.	$300	$4,200	4		$61	$3,416	$7,616
	Panels		2		$7,000	$14,000	12		$61	$1,464	$15,464
		Account Subtotal				$53,200				$8,296	$61,496
Cable & Raceway											
	3/c #12	2	560	ft	$0.4	$228	0.1		$61	$3,416	$3,644
	1/c 4/0	3	1290	ft	$1.0	$1,229	0.3		$61	$23,607	$24,836
	1/c 350 kcmil	3	50	ft	$1.6	$79	1		$61	$3,050	$3,129
	1/c 1000 kcmil	6	540	ft	$5.1	$2,765	2.1		$61	$69,174	$71,939
	1" RGS		500	ft	$18	$9,000	1.5		$61	$45,750	$54,750
	2" RGS		90	ft	$23	$2,070	2		$61	$10,980	$13,050
	3" RGS		290	ft	$30	$8,700	3.2		$61	$56,608	$65,308
	4" RGS		150	ft	$40	$6,000	4.8		$61	$43,920	$49,920
		Account Subtotal				$30,071				$256,505	$286,576
Instrumentation											
	PG	(included w/ equipment)	4			$0	1.5		$61	$366	$366
	PT	(included w/ equipment)	4			$0	9.6		$61	$2,342	$2,342
	HS	(included w/ equipment)	5			$0	7		$61	$2,135	$2,135
	LT	(included w/ equipment)	7			$0	12.6		$61	$5,380	$5,380
	TG		7		$480	$3,360	4		$61	$1,708	$5,068
	PS	(included w/ equipment)	7			$0	6.6		$61	$2,818	$2,818
	FT		2		$1,500	$3,000	2.6		$61	$317	$3,317
	MOV		2		$17,500	$35,000	5		$61	$610	$35,610
		Account Subtotal				$41,360				$15,677	$57,037
Painting & Insulation		(s/c)	1							$50,000	$100,000
Elec. Heat Trace		(s/c)	1							$100,000	$150,000
Metal Building		(s/c)	600	sf	$50	$30,000					$30,000
Engineering, PM											$840,000
Contingency											$921,000
		GRAND TOTAL									$9,706,081

APPENDIX D

PATENTED HIGH-PRESSURE COAL FEED SYSTEMS

PATENTED HIGH-PRESSURE COAL FEED SYSTEMS

US04206713	Continuous Coal-Processing Method
US04218222	Method of Charging Solids into Coal Gasification Reactor
US04302353	Method for the Production of Synthesis Gas
US04209304	Coal Gasification Method of Feeding Dry Coal
US04978369	Process for Feeding Carbonaceous Material into Reaction Spaces
US04255161	Apparatus for Introducing Solid Fuels into a Pressure Gasification Reactor
US03976548	Apparatus for Processing Coal and Like Material

APPENDIX E

RDF SORTING AND CLEANING PHOTOGRAPHS

Figure E1. Cardboard fractions in NRG RDF.

Figure E2. Paper fraction in NRG RDF.

Figure E3. Plastic fraction in NRG RDF.

Figure E4. Textiles fraction in NRG RDF.

EERC MM19533.CDR

Figure E5. Combined wood, aluminum, ferrous, food waste, glass fraction in NRG RDF.

EERC MM21058.PCX

Figure E6. Forsberg air-classifier used for RDF cleaning and biomass entrainment tests.

EERC MM21059.PCX

Figure E7. Upgraded −4-inch RDF from air-classifier cleaning.

EERC MM21060.PCX

Figure E8. Combustible fraction of heavies from air-classifier cleaning of −4-inch RDF.

EERC MM21061.PCX

Figure E9. Noncombustible fraction of heavies from air-classifier cleaning of −4-inch RDF.

EERC MM21062.PCX

Figure E10. Noncombustible fraction of lights from air-classifier cleaning of −4-inch RDF.

APPENDIX F

AS-RECEIVED AND SIZED BIOMASS PHOTOGRAPHS

EERC MM21063.PCX

Figure F1. Corn stover.

EERC MM21064.PCX

Figure F2. Corn stover hammer-milled with ¼-inch and ½-inch screens (note: left line below biomass is ¼-inch in length; right line below biomass is 1-inch in length).

EERC MM21065.PCX

Figure F3. Switchgrass.

EERC MM21066.PCX

Figure F4. Switchgrass hammer-milled with ¼-inch, ½-inch, and 1-inch screens.

EERC MM21067.PCX

Figure F5. Urban wood waste.

EERC MM21068.PCX

Figure F6. Urban wood waste hammer-milled with ¼-inch screen.

EERC MM21069.PCX

Figure F7. E-grass hammer-milled with ⅛-inch screen.

EERC MM21071.PCX

Figure F8. Cedar sawdust and cedar molder shavings.

EERC MM21072.PCX

Figure F9. Wet sawdust.

EERC MM21077.PCX

Figure F10. Soybean hulls.

EERC MM21073.PCX

Figure F11. Biomass pellets – clockwise from top right: corn stover, switchgrass, urban wood waste, and E-grass.

APPENDIX G

TR MILES DESIGN AND COST ESTIMATE FOR RDF LOCK HOPPER SYSTEM

TR MILES **Technical Consultants Inc.** Phone (503) 292-0107

Email: tmiles@trmiles.com 1470 SW Woodward Way Portland OR 97225 Fax (503) 292-2919

Fuel Feeding System

Technical Specification

1. SITE CONDITIONS

Fuel mass rate: 30,000 lb/hr per feed train (2 trains)
Feed Volume Required: 10,000 ft3/h at 3 lb/ft3; 3,000 ft3/h at 10 lb/ft3; 1,500 ft3/h at 20 lb/ft3
Reactor Pressure: up to 450 Psig
Temperature at Feed Point: up to about 2500° F

2. SCOPE OF FEED SYSTEM

The fuel feeding system is designed to feed finely divided loose feed to the gasifier. The system will continuously feed bulk solids into each of two inlets in the reactor. The feed system consists of two trains. Each train would have a dual lockhopper. Each lockhopper would have a precharge hopper with scale and lockhopper discharging alternately into a live bottom pressurized surge bin with metering screws and a feed screw. An alternative system would utilize a screw compactor to bring the solids to an intermediate pressure 260 psig, with a lockhopper raising pressure to 450 psig, or a series of screw compressors and rams that would fill the pressurized lockhopper at working pressures of 450 psig.

3. FEED PROCESS DESIGN DATA

2.1 General

Raw fuel will be RDF or agricultural residues with a base spill density of 3 lb/ft3, 12 % moisture content (MC), with a nominal size less than 2 inch, an ash content of less than 10 wt%, and a heating value of 7250 Btu/lb. It is anticipated that the fuel would be densified to a minimum of 10 lb/ft3 by using densification or pre-compression. Each of two feeders will have the following characteristics:

Feed rate, each train	3000	ft3/h
Precharge Hopper	50	ft3
Lockhopper, each	50	ft3
Meter/Surge Bin with Live Bottom	150	ft3
Metering Screws	500-3000	ft3/h
Injector screw Capacity	3000	ft3/h

3. DESIGN BASIS

This estimate is based on design experience up to 450 psig and operating experience with pressurized lockhopper systems up 5 tons per hour.

This estimate is based on separating the overall feeding function into three independently controlled steps of:

1. Lockhoppering to reactor pressure
2. Variable metering; and
3. Rapid injection into the reactor.

This design approach removes most of the feeding equipment from direct contact with the hot reactor.

FEEDSTOCKS

The reference feedstock for most gasification systems is a wood chip that will pass a 2-inch oscillating screen. RDF or agricultural residues specified here would have a spill density of about 3 lb/ft3. Feedstocks of this kind will require either densification or compaction prior to feeding. At 10 lb/ft3 feedstock will have 60% voidage permeable to gas that must be pressurized before feeding to the reactor.

The feedstock can be externally densified using cubing or pelleting equipment that in practice can increase the specific density up to 35 lb/ft3 and the bulk density to above 20 lb/ft3. Densification can add from $20-$45/ton to the cost of a feedstock. For RDF it is likely that the cost would be $25/ton including power costs equal to approximately 100 HP/ton/hr. Of this 50 HP/ton/hr is used in material preparation and 50 HP/ton/hr is used in densification.

An alternative to densification is the plug screw feeder that can be mounted directly onto the pressurized metering bin. Low-density RDF or loose agricultural residues are compressed in a tapered screw and fluffed at the outlet with a high-speed screw or chopper. A version made in the US has been operated on sugar cane bagasse at up to 150 psig per stage and 5 tons per hour at an installed energy cost of 80 hp/ton/hour. Another system under development in Denmark has achieved densities of 20-30 lb/ft3 up to 15 tons per hour but has not been used against significant pressure. The concept has the advantage of reducing the amount of purge gas necessary to pressurize the fuel charge to the reactor since the feeder could be operated at reactor pressure or at a reduced pressure with only partial pressurization from the lower pressure to reactor pressure.

LOCKHOPPERS AND VALVES

The use of lock hoppers is the most straightforward method of overcoming high-pressure differentials, provided that the system is isolated from the heat and that a suitable valve is available. Feedstock preparation to 10-20 lb/ft3 improves handling, metering and general flowability.

COMPRESSED GAS and power requirements for the lock hoppers estimated here are:

	Double Lockhopper No Gas Recovery	Double Lockhopper Gas recovered to receivers	Two Trains W/ Gas Recovery 12 lbft3	Two Trains W/Gas Recovery 20 lb/ft3
Feedrate	15 tph	15 tph	30 tph	30 tph
Feed density	12 lb/ft3	12 lb/ft3	12 lb/ft3	20 lb/ft3
SCFM	1422	924	1848	1108
SCFM/ton/hour	95	62	62	37
HP	320	208	416	250
HP/scf 450 psig	.225	.225	.225	.225
HP/ton/hour	21	14	14	8

These figures include both the gas to bring the lockhopper charge up to pressure and also gas to displace the solid fuel moving from the Meter bin into the reactor. The Double Lockhopper arrangement permits venting the just emptied Lockhopper at system pressure into the other charged but not pressurized Lockhopper to realize the power savings shown.

Lock gas recovery systems have not been tested extensively with biomass. In Hawaii at lock gas was recovered and filtered at atmospheric pressure then blended with inert gas, which was CO2 from an inert gas generator, and reused.

Fuel charging to the lock hoppers is accomplished by metering the feedstock by pneumatic or mechanical conveyor to a PRECHARGE HOPPER with level controls. The charge is then quickly transferred into the lockhopper as needed, saving filling time.

The use of large valves and non-restricted material passages insures free and rapid transfer of feedstock. The lock hopper is characteristically empty by the time the valve is fully open.

Valves estimated are MILES designed valves that overcome several problems of using standard gate vales for use with dry solids.

METER BIN

METER BIN VOLUME in the feed system is approximately 10 minutes of operation at full capacity. Increasing the length of the straight cylindrical metal bin shell can increase the material capacity.

METERING & INJECTOR SCREW drives are variable speed. Special shaft seals are used to prevent leakage at high pressures. Meter screws are designed to provide uniform feed to the injection screw that transfers the feedstock into the reactor.

INJECTOR SCREW

Injection into the reactor is an important part of the system. Injector screws are water cooled internally or externally as desired. High-speed screws transfer feedstock into the reactor without accumulating char at startup or shutdown. Purge gas from the METER BIN offsets the flow of gas that is displaced from the reactor as the solids flow into the reactor. The injector can be adjusted to penetrate the flow in the reactor.

TR MILES **Technical Consultants Inc.** Phone (503) 292-0107

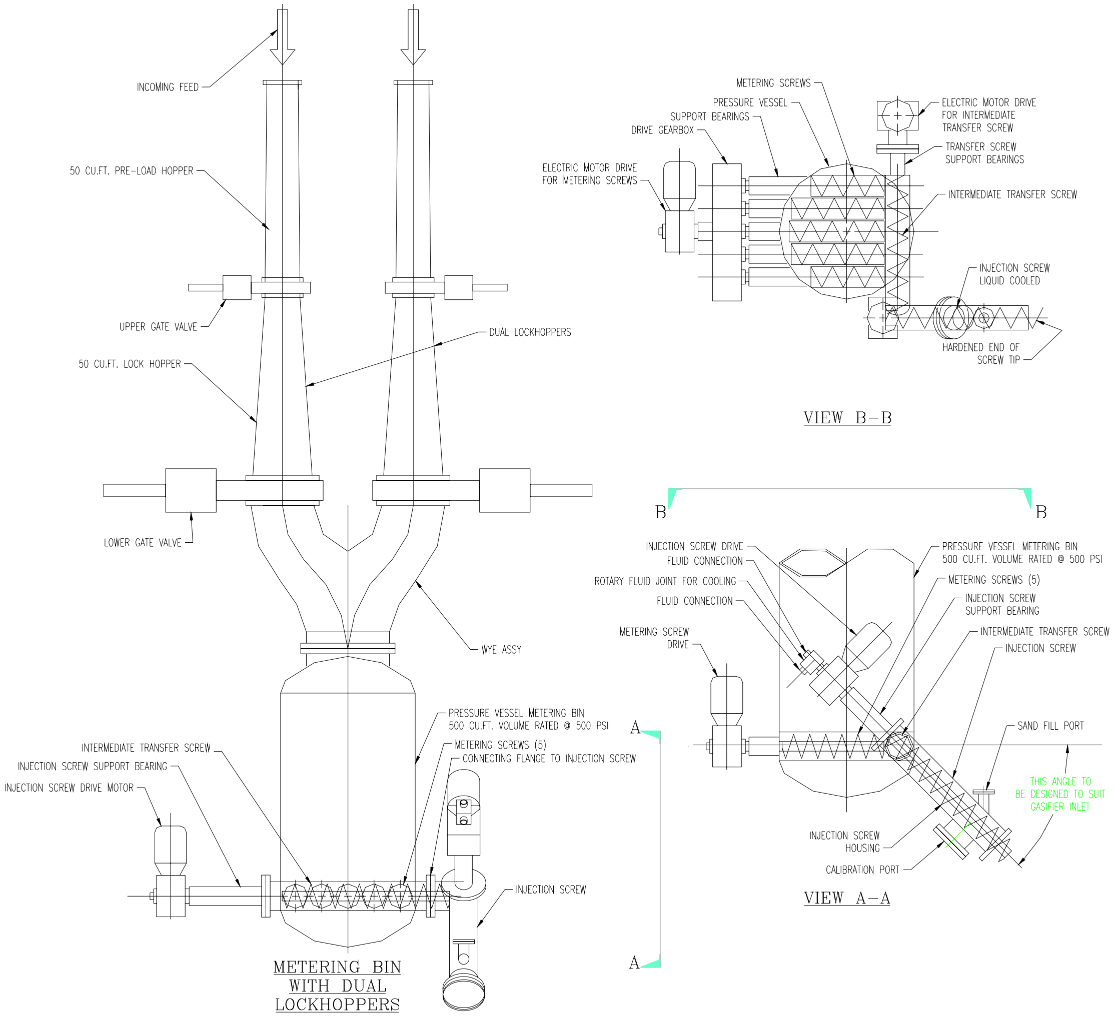
Email: tmiles@trmiles.com 1470 SW Woodward Way Portland OR 97225 Fax (503) 292-2919

Fuel Feeding System

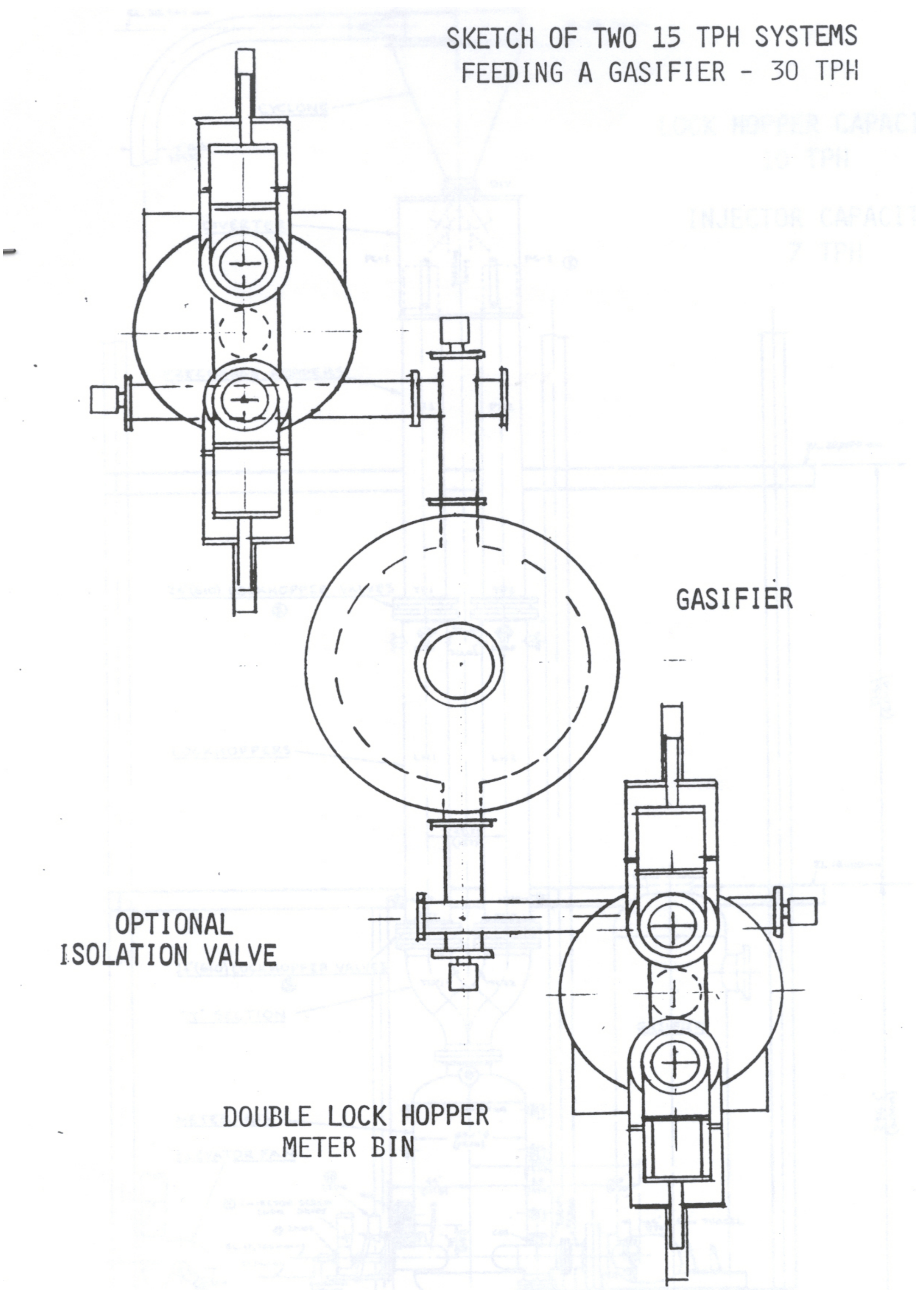
COST ESTIMATE, (2) 15 TPH TRAINS INSTALLED*

Feed System Equipment	
Lock hoppers and Valves	$ 837,000
Precharge Hopper with Scales	
Lock hoppers	
Gate Valves	
Transition to Meter Bin	
Meter Bins and Injectors	$ 629,000
Inert and Purge Gas Compression	$ 689,000
Total Feed Equipment (installed)	$ 2,115,500
Civil/Structural- equipment supports, foundations	$ 98,000
Mechanical Installation, piping and hoppers	$ 86,000
Electrical and Controls – Feed System	$ 69,000
Electrical and Controls, Purge Gas	$ 115,000
Miscellaneous, freight, spares	$ 155,000
Total Other	$ 523,000
Indirect Costs- mechanical and electrical engineering	$ 217,000
Total Feed System Construction Cost	$ 2,895,000
25% Contingency and allowance for unlisted items	$ 723,000
Total Estimated Capital Cost	$ 3,618,000

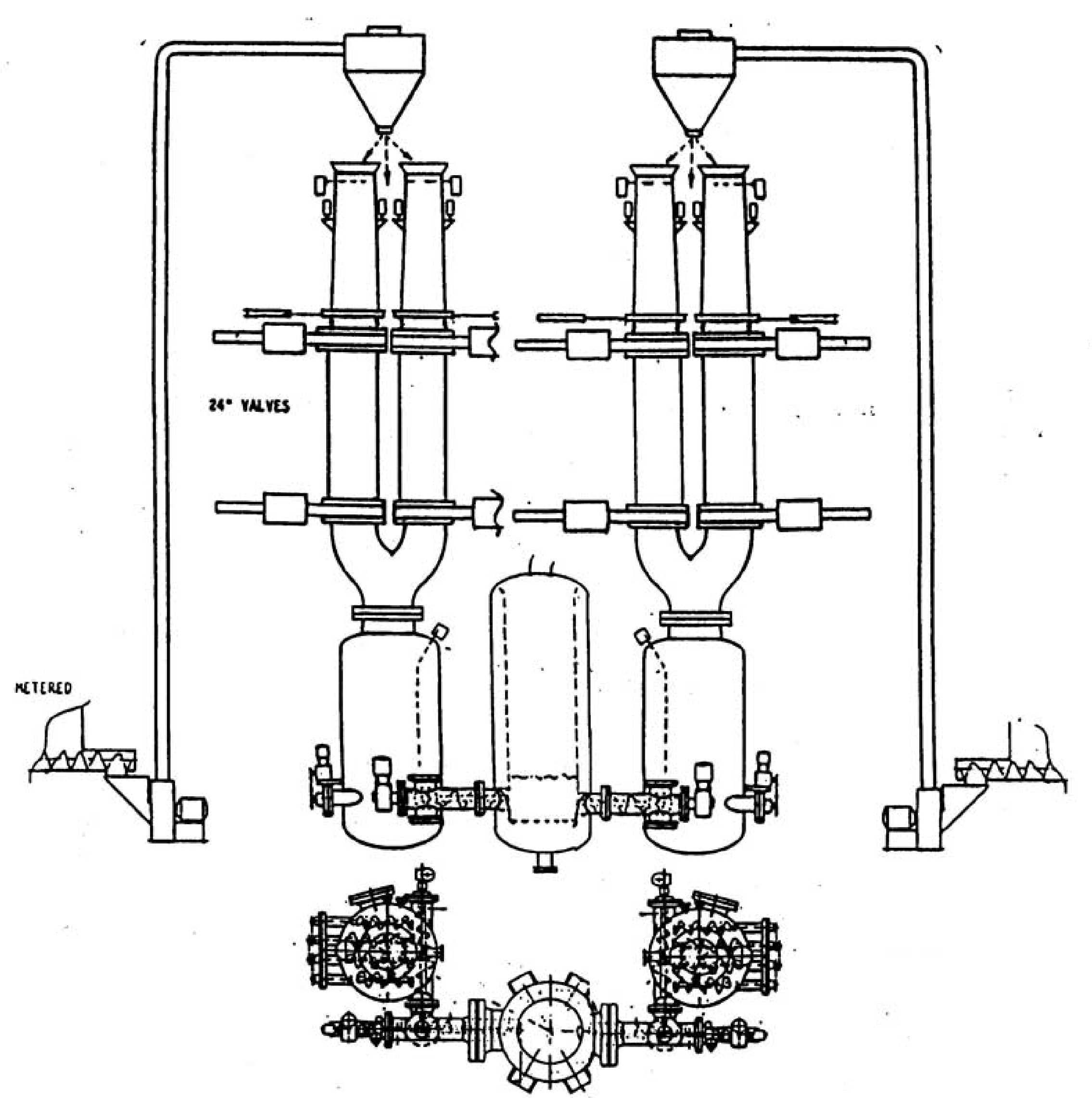
*Note: Installation costs are estimated at 30% of equipment costs.



DOUBLE LOCKHOPPER WITH METER BIN AND INJECTION SCREW 15 TPH



SKETCH OF TWO 15 TPH SYSTEMS
FEEDING A GASIFIER - 30 TPH



TWO DOUBLE LOCKHOPPERS FOR 30 TPH

APPENDIX H

PROJECT-RELATED WEBSITES

PROJECT-RELATED WEB SITES

Associations

http://www.wastexchange.org/Exchanges/default.cfm
http://www.rta.org/
http://www.preservedwood.com/
http://www.aar.org/

Biosolids

http://www.epa.gov/epaoswer/non-hw/compost/biosolid.pdf
http://www.mwrdgc.dst.il.us/

US Census Data

http://www.census.gov/population/estimates/metro-city/ma99-01.txt

City Offices

http://www.city.bloomington.in.us/
http://www.ci.champaign.il.us/
http://www.evansville.net/mayor/mainmenu.htm
http://www.ci.indianapolis.in.us/
http://www.city.lafayette.in.us/
http://www.ci.decatur.il.us/
http://www.indygov.org/dpw/dev/wastewater.htm
http://www.cityofdanville.org/

Energy Crops and Agricultural Residues

http://www.reap-canada.com/Reports/pelletaug2000.html
http://www.ott.doe.gov/biofuels/cornbridge.html
http://bioenergy.ornl.gov/papers/misc/switgrs.html
http://www.cvrcd.org/biomass.htm
http://www.eren.doe.gov/biopower/feedstocks/
http://www.ceassist.com/collection.htm
http://www.ianr.unl.edu/pubs/FieldCrops/nf310.htm
http://www.blueplanetbiomes.org/elephant_grass.htm
http://www.agry.purdue.edu/ext/corn/pubs/agry9509.htm
http://www.state.ia.us/government/dnr/energy/pubs/irerg/biomass2.htm
http://bioenergy.ornl.gov/papers/miscanthus/miscanthus.html
http://bioenergy.ornl.gov/oreccl/database.html
http://agproducts.unl.edu/corn/pricefar.htm
http://www.wisc.edu/cias/pubs/briefs/051.html

http://www.usda.gov/agency/oce/waob/jawf/profiles/html/usa/usasoy.html
http://www.producer.com/articles/20010104/production/20010104prod02.html

Equipment and Technology

Atmospheric Feeding

http://www.sarinc.com/weighbelt_beltscales.html
http://www.acrison.com/index00.htm
http://www.arbo-feeders.com/
http://www.belltechutility.com/html/sec/gravimet.htm
http://www.brabenderti.com/
http://www.zeppelin-usa.com/hrotary.html
http://www.ktron.com/
http://www.kamengo.com/approach04.html
http://www.merrick-inc.com/solutions.html
http://penncrusher.com/7feeders.html
http://www.accutechinc.com/

Bin Discharging

http://www.bmh.fi/
http://www.deckerindustries.com/silo_dischargers.html
http://www.hindon.com/roplex.html
http://www.metalfabinc.com/
http://www.wameng.com/dischargers.htm

Biosolids Processing

http://www.creativewaste.com/nonthermalsludge.html
http://www.sernagiotto.it/e_essicc.htm
http://www.enviroaccess.ca/fiches_5/F5-02-95a.html
http://www.mitchell-dryers.co.uk/
http://www.limus.de/etro.htm
http://www.komline.com/
http://www.roediger.com/p_sludgedryer.html
http://www.vatech.ch/images/Bars/Start_frame_e_VF.htm

Gas Compression

http://www.gascompressor.com/acidgas.htm
http://www.atlascopco.com/
http://www.burtoncorblin.com/recip.htm
http://www.tencarva.com/air/gas.htm
http://www.gotoppi.com/compressors/compressors.html

http://www.pdcmachines.com/diaphragm_compressors.asp
http://www.elliott-turbo.com/new/products_compressors.html
http://www.enerflex.com/html/comp_power/comp_power.htm
http://www.gardnerdenver.com/GDCorpPortal/
http://www.knox-western.com/
http://www.arielcorp.com/TECHDATA/TECHPAPER/AATECHPAPER.htm

Mechanical Conveying

http://www.4conveyors.com/
http://www.goodmanconveyor.com/
http://www.screwconveyors.com/
http://www.jervisbwebb.com/jbw/productsofjervisbwebbco3.htm
http://www.martinsprocket.com/
http://www.digitex.net/newtonconveyors/
http://www.summerlot.com/
http://www.thomasconveyor.com/
http://www.unicoservices.com/
http://www.feeco.com/

Drying

http://www.airpreheatercompany.com/thermproc.asp
http://www.barr-rosin.ca/products/b9.html
http://www.heylpatterson.com/products/Flashdryerren.asp
http://www.theonixcorp.com/dehydration.html

Flow Measurement

http://www.sarinc.com/weighbelt_beltscales.html
http://www.kanawhascales.com/standard/beltscale/default.htm
http://www.easterninstruments.com/solids_flow_measurement.htm
http://www.ramsey.it/impact-en.htm
http://www.merrick-inc.com/solutions.html
http://www.milltronics.com/product/product.asp?CFC=MMI
http://www.tecweigh.com/index.html
http://www.thayerscale.com/

High-Pressure Feeding

http://www.andritz.com/ANONIDZ52119F43/ppp/ppp-products/ppp-mechanicalfibre/ppp-mechanicalfibre-mainref/ppp-mechanicalfibre-mainref-psftpiec.htm
http://www.komarindustries.com/komarext.htm
http://www.fortum.com/main.asp?path=1
http://www.metso.com/

http://www.steamexplosion.com/
http://www.sri.org.au/home1.html
http://www.thermoselect.com/
http://www94.thomasregister.com/olc/asb/

Metering Bins

http://www.nbe-inc.com/photobook/conveying/photo-index.htm
http://www.sellbergs.se/brini/
http://www.hallco-mfg.com/
http://www.keith.nl/en/index.html
http://www.machinery.verville.com/
http://www.sherbrooke-oem.com/english/wood_pro.html

Pneumatic Conveying

http://www.enviro-engineering.com/kshoe.html
http://www.macawber.com/
http://www.mactenn.com/

Pumping

http://www.bornemannpumps.com/how.htm
http://www.discflo.com/
http://www.morgenmanufacturing.com/index.html
http://www.moyno.com/
http://www.putzmeister.com/
http://www.schwing.com/
http://www.seepex.com/english/frame_e.html

Shotcreting

http://www.shotcretetechnologies.com/
http://www.airplaco.com/equipment.htm
http://www.shotcretetechnologies.com/graphics/i_handappl.jpg
http://www.morgenmanufacturing.com/index.html
http://www.cfultratech.com/

Size Reduction

http://www.advancedrecyclingequip.com/
http://www.ampulverizer.com/
http://www.bliss-industries.com/htm/prodinfo.htm
http://www.cbi-inc.com/main.html
http://www.cuttercorp.com/

http://homepages.ihug.co.nz/~grain/grainA.html
http://www.newhouse-mfg.com/html/c5000.html
http://www.jeffreycompany.com/whatsnew.htm
http://www.pallmannpulverizers.com/pptmref.htm
http://www.rotogrind.com/
http://www.komarindustries.com/komarshr.htm
http://www.shred-tech.com/english/index.html
http://www.ssiworld.com/
http://www.sturtevantinc.com/Products/products.html
http://www.vecoplan.de/eng/Start.php3
http://64.224.66.115/home/welcome.asp?LNG=EN

Valves

http://www.everlastingvalveco.com/
http://www.hiltonvalve.com/showcase.htm
http://www.weyvalve.com/knifegate.html
http://info.jamesbury.com/public/home.asp

Wear-Resistant Materials

http://www.blastnozzles.com/welcome.htm
http://www.cartech.com/cpp/index.html
http://www.clevelandhardfacing.com/index.htm
http://www.stellite.com/en/default.asp
http://www.haynesintl.com/
http://www.malyn.com/nozzle.htm
http://www.xaloy.com/
http://www.ntktech.com/wear-resistant.htm
http://www.omegaslate.com/nozzles.htm
http://www.efunda.com/processes/surface/hardfacings.cfm
http://www.copelandind.com/valve_retrofits.htm
http://www.wallcolmonoy.com/
http://www.cruciblecompaction.com/wear.html
http://www.thomasregister.com/olc/ferrokilnfurn/wearres2.htm

MSW-RDF

Cleaning

http://www.sellbergs.se/brini/
http://www.forsbergs.com/mlmpd.html
http://www.eriez.com/
http://www.lovac.com/fuel.htm

http://www.karlschmidt.com/sort_classifier.htm

Thermal Processing

http://www.isr.gov.au/resources/netenergy/aen/aen10/10swerf.html
http://www.jxj.com/yearbook/iswa/2000/isrecycling_100_possible.html
http://www.interstatewastetechnologies.com/
http://www.mmc.co.jp/english/business/ecology08.html

Resource Information

http://www.winrock.org/reep/Publications/mswrpt/MSW2.html
http://www.epa.gov/epaoswer/non-hw/muncpl/facts.htm
http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm
http://www.epa.gov/epaoswer/non-hw/muncpl/states.htm
http://www.eia.doe.gov/cneaf/solar.renewables/renewable.energy.annual/chap03.html
http://www.swana.org/default.asp

Miscellaneous Processing Information

http://www.robson.co.uk/environment.html
http://www.hwest-equipment.com/
http://www.lundellmfgco.com/pef.html
http://www.marathon-equipment.com/
http://www.plasticsresource.com/recycling/ARC99/PEF_ARC99_PAPER_Final.htm
http://starfire.ne.uiuc.edu/ne201/course/topics/biomass/refuse.html
http://es.epa.gov/techinfo/facts/powrplnt.html
http://www.iclei.org/efacts/enrgywst.htm
http://www.co.ramsey.mn.us/recovery/Spring99_12.htm
http://www.co.ramsey.mn.us/recovery/trashtoday.htm

Federal Offices

http://www.epa.gov/owmitnet/mtb/biosolids/index.htm
http://www.cglg.org/projects/biomass/index.html
http://www.usda.gov/nass/pubs/agr02/acro02.htm
http://www.epa.gov/epaoswer/osw/
http://www.fe.doe.gov/
http://www.netl.doe.gov/
http://www.nrel.gov/
http://www.eia.doe.gov/

Gasification Web Sites

http://www.enerkem.com/

http://www.enviroaccess.ca/fiches_4/F4-11-96a.html
http://www.crest.org/index.html

Reports

http://bioenergy.ornl.gov/resourcedata/
http://tonto.eia.doe.gov/FTPROOT/features/biomass2002.pdf
http://www.eren.doe.gov/biopower/bplib/library/li_snowpapr.htm
http://bmf.osti.gov/cgi-bin/dexpldcgi?nrbmf.results;6
http://www.reap-canada.com/Reports/PelletSG.htm
http://bioenergy.ornl.gov/papers/bioam95/graham3.html
http://bioenergy.ornl.gov/papers/bioen96/mclaugh.html
http://www.afdc.doe.gov/pdfs/4809.pdf
http://www.afdc.doe.gov/pdfs/4902.pdf
http://www.nrel.gov/docs/fy99osti/25918.pdf
http://www.reap-canada.com/Reports/bioenergy2000Aug2.html
http://bioenergy.ornl.gov/papers/bioen96/noon1.html
http://www.cvrcd.org/deliverables.htm

State Offices

http://www.agstats.state.il.us/
http://www.agr.state.il.us/
http://www.epa.state.il.us/
http://www.nass.usda.gov/in/index.htm
http://www.in.gov/idem/
http://www.ai.org/oca/

Tires and Tire-Derived Fuel

http://www.auburndalerecycling.com/companyprofil.htm
http://www.scraptirenews.com/

Wood Fuel and Wood Waste

http://www.eren.doe.gov/biopower/feedstocks/
http://www.eren.doe.gov/biopower/feedstocks/fe_wood.htm
http://www.kppc.org/kwwrs/
http://www.srs4702.forprod.vt.edu/PUBSUBJ/abstract/ab9764.htm
http://www.ciwmb.ca.gov/Markets/StatusRpts/WoodWste.htm
http://www.ciwmb.ca.gov/ConDemo/Factsheets/UrbanWood.htm

Railroad Ties

http://www.tieyard.com/about_us/about_us1.htm

http://www.sites.onlinemac.com/andersonwhsl/index.htm
http://www.rta.org/pdf/tieanalysis.pdf
http://www.koppers.com/
http://www.railworks.com/sc/comp/rwks_wood.htm
http://www.preservedwood.com/aboutawpi.html

APPENDIX I

LIST OF CONTACTS

LIST OF CONTACTS

Entity	Location	Contact/Title	Phone/e-mail
Feedstock Resources Information			
A&K Railroad Materials	Portage, IN	Stacie	(219)882-1411
Auburndale Recycling Center	Auburndale, WI	Jerry Swensen	(715) 652-3622
Bartholonew County SWMD		Greg Hartwell	(812) 376-2614
BNSF	Topeka, KS	Mac Wiens	(705) 435-5882
Burlington Northern Sante Fe (BNSF) Railroad		Steven Forsberg, General Director Public Affairs	(913) 551-4479
Clay-Owen-Vigo Solid Waste Management District	Indiana	Janet Reed	(812) 443-0168
CMS Generation	New Bern, NC	Ray Bonner Jim Welborn	(252) 633-9525 (252) 633-9525
Conrail	Philadelphia, PA	Joe Sessa	(215) 209-2000 (856) 231-2015
CSX Transportation, Solid Waste Compliance Branch		Leah Foutty, Chief Solid Waste Rosemary Cantwell, Chief Special Waste	(317) 308-3104 (317) 308-3003
CSX Transportation			(904) 359-3100
CSX Transportation		Steve Watson	(317) 267-3003
CSX Corporation			(804) 782-1400
Daviess County Chamber of Commerce	Washington, IN	Dave Cox	(800) 449-5262
Exten Energy Project	Sterling, CT	Ken Wycherley	(860) 564-7000
Farm Bureau Coop	Monroe County, IN		(812) 332-4472
Great Lakes Regional Biomass Energy Program		Fred Kuzel	(312) 407-0177

GreenMan Technologies	Savage, MN	Phil Sherrier	(952) 894-5280
Illinois Department of Agriculture		John Herath Joe Saputo	(217) 524-2751
Illinois EPA		Gary Cima	(217) 785-8604
Illinois EPA		Jeff Hutton	(217) 780-0610
Illinois Department of Commerce & Community Affairs, Bureau of Energy & Recycling		Norm Marek	(217) 785-5082
Indiana Department of Environmental Management, Office of Land Quality		Bruce Palin	(317) 233-6591
Indiana Department of Environmental Management (IDEM)		Richard Worth	(317) 233-5156
Indiana Department of Commerce		Sarah Carney	(317) 232-8944 (219) 642-3677
Indiana Department of Agriculture		Kathy Altman	(317) 232-8765
Indiana Department of Commerce, Division of Energy Policy		Phil Powlick	(317) 232-8970
Indiana Department of Environmental Management		Jim McCurdy	(317) 232-8731
Indiana Department of Transportation, Railroad Section		Tom Beck	(317) 232-1478
Indy Pallet Company	Indianapolis, IN	Brad	(317) 780-0700
International Paper	Terre Haute, IN	Robert Sleeman	(812) 234-6688
Iowa Department of Natural Resources (DNR)		Lori McDaniel	(515) 281-8094
Kieffer Paper & Pulp Mill, Inc.	Brownstown, IN	Dennis Lankford	(812) 358-2413
Metropolitan Water Reclamation District of Greater Chicago Calumet Facility	Chicago, IL	John Sundera	(773) 256-3702

Metropolitan Water Reclamation District of Greater Chicago Stickney Facility	Chicago, IL	Bill Bergman	(708) 588-4305
Metropolitan Water Reclamation District of Greater Chicago	Chicago, IL	Hugh McMillan, General Superintendent	(312) 751-6635 fax
Metropolitan Water Reclamation District of Greater Chicago	Chicago, IL	Edmund Cook	(312) 751-5600 (312) 751-7828 fax
Monroe County Landfill	Bloomington, IN		(812) 349-2864
Monroe County Solid Waste Management District	Indiana	Mike Frey	(812) 349-2020
Norfolk Southern Railroad, Material Management		Material Management Gary Bible Dana Hellsly	(540) 981-3664 (540) 981-3886
NRG Energy		Joe Weinhold Manager Environmental Services	(612) 373-5431
Public Works	Bloomington, IN	Scott Dompke, Director of Operations for City Utilities	(812) 349-3661
Public Works	Bloomington, IN	Christina Fulton Services Coordinator	(812) 349-3410
Railworks Wood Waste Energy	Ballwin, MO	Greg Smith	(636) 207-8898
Railworks Western Tar Products	Terre Haute, IN	Sam Satopo	(888) 232-2384
Sanitary District	Urbana/Champaign, IL	Rod Fletcher	(217) 384-2355
Sanitary District	Decatur, IL	Greg Kuche, Director of Engineering	(217) 422-6931 ext. 217
Sanitation Department	Lafayette, IN	Ron Berryman	(765) 476-4570

Sewage Treatment	Evansville, IL	Harry Lawson Kenny Virgin, Plant Superintendent	(812) 428-0550
Solid Waste Management	Solid Waste Evansville, IN	Jim Daniels, Recycling Coordinator	(812) 436-7800 (812) 436-4926
Solid Waste Division, Mayors Action Committee (MAC)	Indianapolis/Marion County, IN	John Workman, Supervisor for Solid Waste	(317) 327-2372
Solid Waste Division	Decatur, IL	Hala Ahmed	(217) 424-2798
State of New York Department of Environmental Protection		Pedick Lai Assistant Chemical Engineer Beth Petrillo	(718) 595-6571 (718) 595-5064
Streets and Sanitation	Urbana/Champaign, IL	Ren Liman Dennis Schmidt	(217) 367-3409
Tampa International		Dave Johnson, General Manager	(800) 776-2028
Twin Bridges Recycling and Disposal Facility	Danville, IN	Jim Davis	(317) 745-2878 ext. 13
Union Pacific Railroad		Arlen Mafziger Keith Rawsen	(402) 930-1229 (402) 930-1232
Victory Environmental Landfill	Terre Haute, IN	Terry Moon	(812) 299-9227
Waste Water Treatment	Danville, IL	Phil Morgan	(217) 442-3193
Water Pollution Control	Lafayette, IN	Angela Andrews, Chief of Surveillance	(765) 476-4550
West Clinton Landfill	Clinton, IN	Ed Kanizer	(765) 832-6798
West Central Solid Waste Management District		Jane Collisi	(317) 745-2491
Whitewater River Environmental Partnership	Indianapolis, IN	Dave Smith	(317) 639-7145
Worthington Landfill	Worthington, IN		(812) 875-2545
Xcel Energy		Alma Allen Web Joe Brobjorg	(612) 330-5956 (612) 330-2856

Feedstock Supplier			
Ag Processing Inc. (AGP)	Omaha, NE	Darcy Ehmann	(402) 431-5027 (402) 492-3352 fax
American Woods	Grand Forks, ND	Ed Hippen Rick Waxvik	(701) 775-7388
Biomass Agri-Products	Harlan, IA	Tom Schechinger	(712) 744-3296 (712) 744-4296 (712) 755-5363
Biomass Industries	Gulf Breeze, FL	Kevin Mills	(850)916-1300
Chariton Valley Resource Conservation and Development (CVRCD)	Centerville, IA	Marty Braster John Sellers, Field Coordinator Velvet Glen Dora Guffy	(641) 437-4376 (641) 872-2657
Ramsey/Washington County Resource Recovery Project	Newport, MN	Gary White, Plant Superintendent Doug Germain, Duty Supervisor	(651) 458-1278
Whitewater River Environmental Partnership	Indianapolis, IN	Chris Holmes Kim Cussen	(317) 639-7051 (317) 639-7049
Haulage Companies			
Merrell Brothers	Kokomo, IN	Terry Merrell	(219) 699-7782
Oxcart Trucking		Joe Lambardo	(219) 933-9338 (219)933-9348 fax
Rebacz Trucking		Stan Rebacz	(708) 579-9750
Today Cartage	Plano, IL	Tom Klatt	(630) 552-4145
High-Pressure Feed System Supplier/Developer			
(Pennsylvania Crusher Posimetric Feeder vendor)			
Andritz/Ahlstrom	Muncy, PA	Joe Keller	(570) 546-1236
Andritz/Ahlstrom	Branford, Ontario CANADA	Larry Nemeth	(519) 754-4590
Andritz/Ahlstrom	Montreal, Quebec CANADA	Thomas Pschorn	(514) 731-0404

Fortum	Fortum, FINLAND	Pekka Jokela	Pekka.Jokela@fortum.com
Komar Industries	Groveport, OH	Mark Koenig	(614) 836-2366
Macawber Engineering	Maryville, TN	Preston Spalding	(865) 984-5286
Metso Paper	Atlanta, GA	Chris Kajzer Anders Mokvist	(770) 263-1589 (770) 263-1543
Stake Technology Ltd.	Norval, Ontario, CANADA	John Taylor, President	(905) 455-1990
Sugar Research Institute	Mackay, AUSTRALIA	James Joyce Terry Dixon	j.joyce@sri.org. aut.dixon@sri.org.au
TR Miles, Technical Consultants	Portland, OR	Tom Miles	(503) 292-0107
Current/Past Users of High-Pressure Feeders			
Boise Paper Solutions	Wallula, WA	Don Holmes, Engineer	(509) 546-3421
Duluth Western Lake Superior Sanitary District	Duluth, MN	Al Parela Dave Mattson	(218) 722-3336 ext. 247
Longview Fibre	Longview, WA	Pat Ortiez Doug Hinderager Tom Plamondon	(360) 425-1550 (360) 575-5397 (360) 575-4548
National Renewable Energy Laboratory (NREL)	Golden, CO	Andy Trenka Richard Bain	(303) 275-4745 (303) 275-2946
Pacific International Center for High Technology Research (PICHTR)	Honolulu, HI	Keith Matsumoto	(808) 258-9209
Weyerhaeuser	Springfield, OR	Wayne Nay	(541) 746-2511
Pump Vendors			
DiscFlo Corp.	San Diego, CA	John Pacello	(619) 596-3181
Morgen Manufacturing	Yankton, SD	Marlen Slagle	(605) 665-9654
Putzmeister	Sturtevant, WI	Scott Larkin	(412) 366-6303
Quality Flow Systems (Seepex and Alfa Laval vendor)	New Prague, MN	Pat Malay	(952) 758-9445

Schwing America	White Bear Lake, MN	Chuck Wanstrom Paul Katka	(651) 429-0999
VanBergen & Markson (Moyno vendor)		Gregg Nolt	(763) 546-4340
Wear-Resistant Materials			
Xaloy, Inc.	Pulaski, VA	Danny Porter	(540) 994-2219
Bin/Bin Discharging			
Hallco Floor Systems	Mooresville, NC	Stan Fisher	(770) 923-9118
Keith Walking Floor	Madras, OR	Jonathan Smith	(541) 475-3802
SITA Sverige AB	Solna, SWEDEN	Folke Giesen	Folke.Gieson@sita.se
Pressurized Screw Conveyor Vendor			
UNICO Services Inc.	Benicia, CA	Noland Nicdao	(707) 745-4540
Shotcrete Nozzle Vendor			
Shotcrete Technologies Inc.		Kristian Loevlie	(303) 567-4871
MSW/RDF Cleaning Vendors			
Environmental Services	Dickinson, ND	Doug Buckman	(701) 663-4069
Eriez Magnetics	Erie, PA	Al Gedgaudas	(814) 835-6000
Forsberg	Thief River Falls, MN	Denny Bakke Loren Holen	(218) 681-1927
General Kinematics	Barrington, IL	Ron Zorn	(847) 842-2067
Karl W. Schmidt & Associates	Denver, CO	Karl Schmidt	(303) 287-7400
Thermal Processor of RDF			
Brightstar Synfuels (SWERF Process)	Baton Rouge, LA	Ron Menville Jr.	(225) 769-9801
Interstate Waste Technologies (North American vendor for Thermoselect Technology)	Malvern, PA	Frank Campbell, President	(610) 644-1665
Komar Industries (Spiralclave System)	Groveport, OH	Mark Koenig	(614) 836-2366
Drier Vendors			

Barr Rosin	Boisbriand, Quebec CANADA	Kosta Kanellis	(450) 437-5252
Heyl & Patterson, Inc.	Canonsburg, PA	Jeff Morris	(724) 743-1000
Size-Reduction Vendors			
American Pulverizer	St. Louis, MO	James Holder	(314) 781-6100 ext. 32
Dynequip (rep for Williams Patent Crusher)	St. Paul, MN	Vince Anderson	(651) 776-1002
Marathon Equipment	Leeds, AL	Gary Krumweide Mike Mothersell	(253) 584-4744 (888) 733-8248
Williams Patent Crusher	St. Louis, MO	Harold Groves	(314) 621-3348
Pressure Vessel Fabrication Shops			
Arrow Tank & Engineering	Cambridge, MN	Lee Reese	(763) 689-3360
Lunseth Plumbing	Grand Forks, ND	Phillip Cramer	(701) 772-6631
Mid America Steel	Fargo, ND	Ron Peterson	(701) 232-8831
Wheeler Tank Manufacturing	Sioux Falls, SD	Chris Wheeler	(605) 332-2012
Compressor Vendors			
Elliott (Ebara Group)	Jeannette, PA	Jim Behovik	(724) 600-8171
Gardner Denver	Quincy, IL	Ed Heckle	(217) 221-8715
Knox Western	Erie, PA	Dave Sechrist	(800) 233-5208
PDC Machines	Warminster, PA	Osama Al-Qasem	(215) 443-9442 ext 105
Pressure Products Industries	Warminster, PA	Lee Coleman	(215) 675-1600
VR Systems (now part of Enerflex)	Odessa, TX	Jack Motley	(800) 478-0011
Miscellaneous			
OSHA (North Dakota)	Bismarck, ND	Keith Thompson	(701) 250-4521
Public Works	Grand Forks, ND	Mike Shea	(701) 746-2713 ext. 713