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.

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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
$ft\text{-}lb_f$	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
MWe	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

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)

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.

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

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

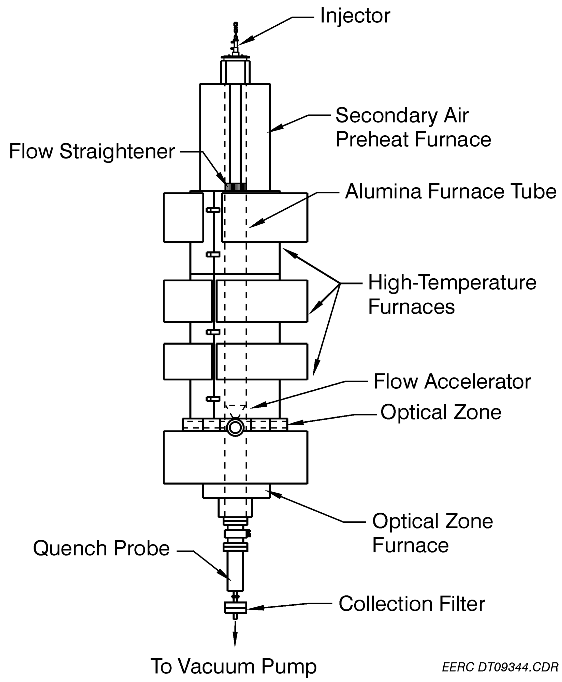

Figure 4. EERC optical drop-tube furnace.

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.

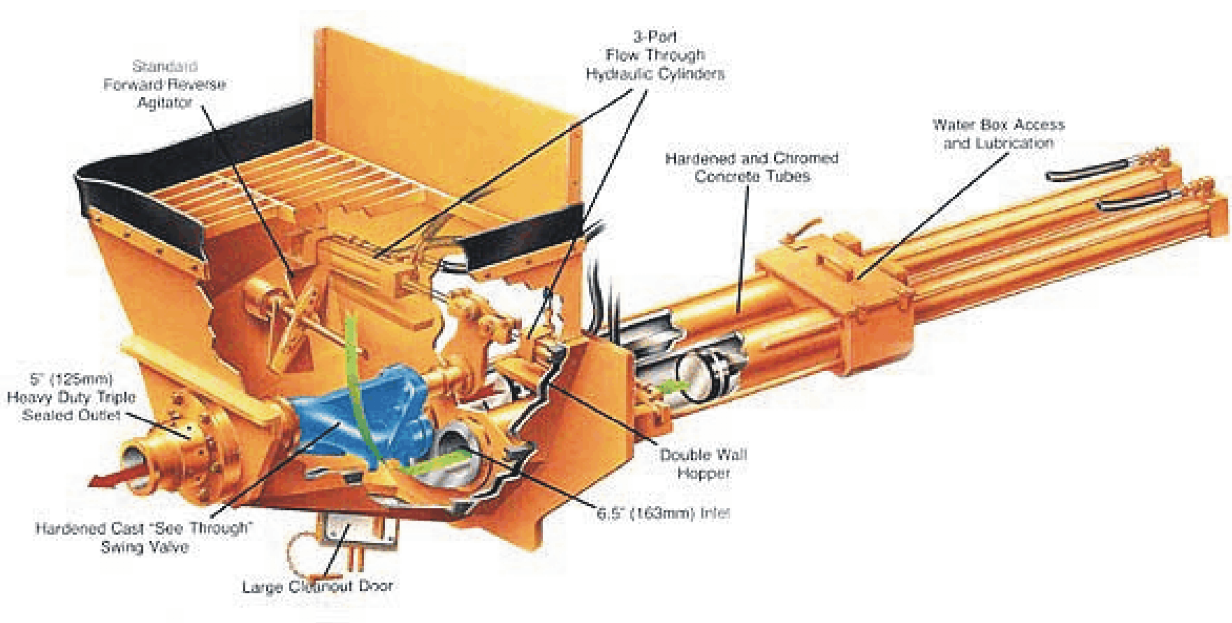

Figure 6. Cutaway diagram of Morgen Mustang concrete pump.

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).

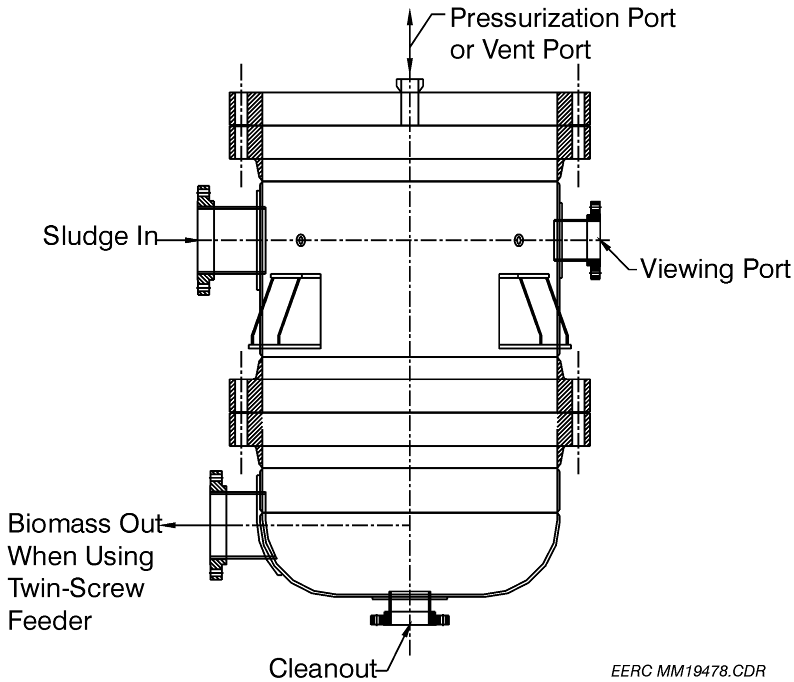

Figure 7. Large pressure vessel for elevated-pressure sludge system.

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

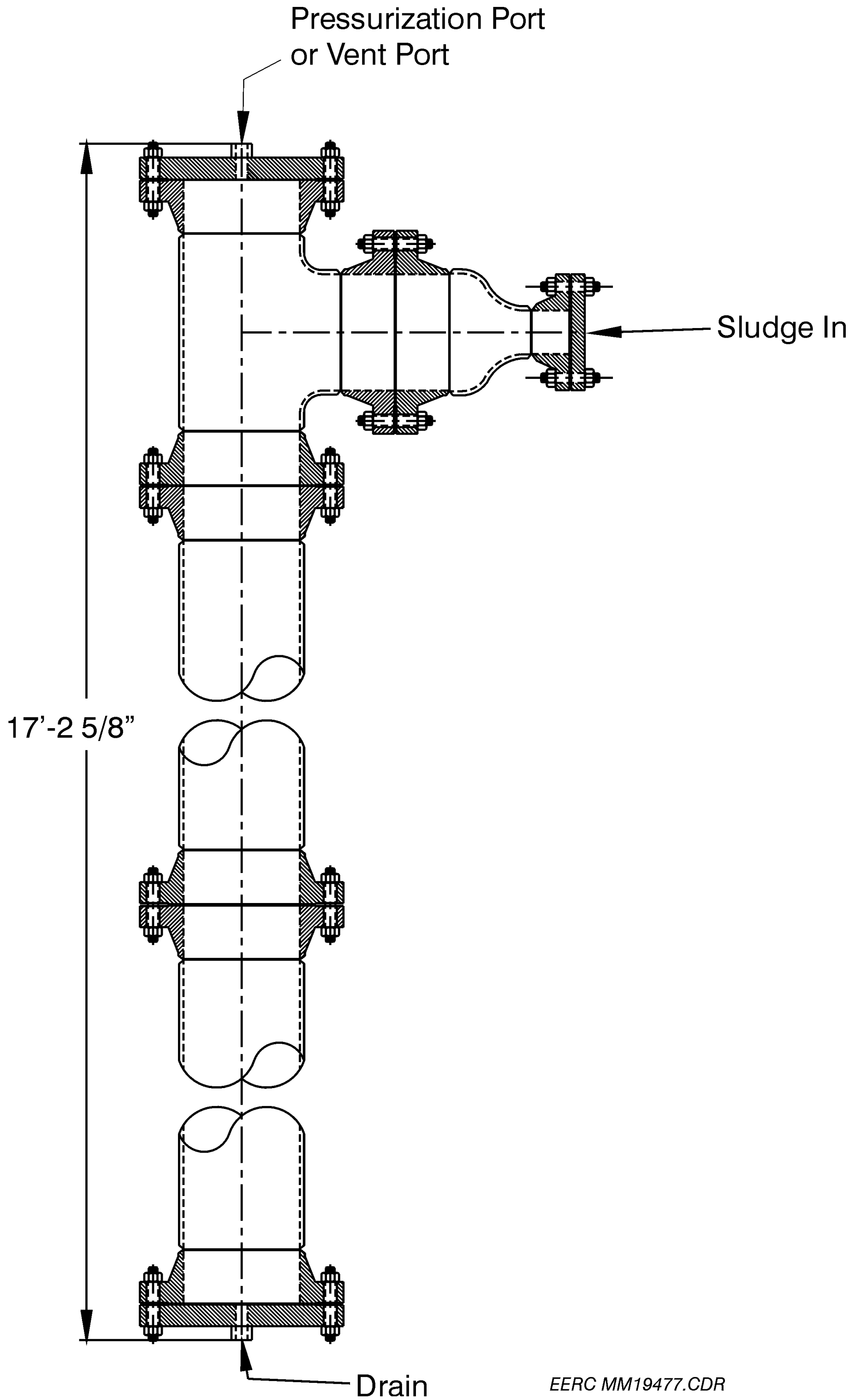

Figure 8. Pressure piping system for elevated-pressure sludge pump testing.

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

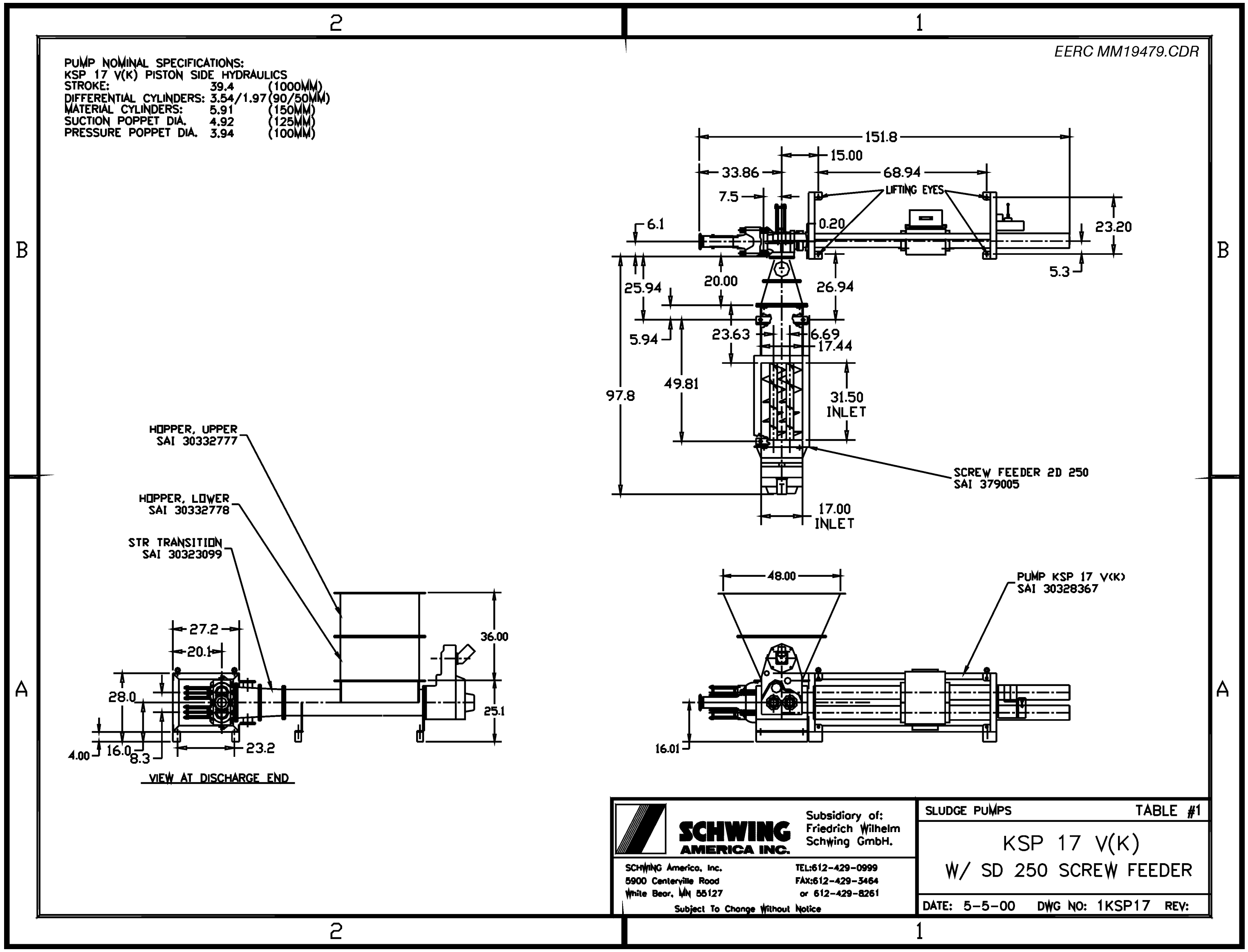

Figure 9. Schwing America high-solids sludge pump with twin-screw feeder.

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.

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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.