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Review and Assessment of Commercial Vendors/Options for Feeding and Pumping Biomass Slurries for Hydrothermal Liquefaction

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CW Enderlin
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November 2012

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Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

The National Advanced Biofuels Consortium (NABC) is working to develop improved methods for producing high-value hydrocarbon fuels. The development of one such method, the hydrothermal liquefaction (HTL) process, is being led by the Pacific Northwest National Laboratory (PNNL). The HTL process uses a wet biomass slurry at elevated temperatures (i.e., 570 to 680°F [300 to 360°C]) and pressures above the vapor pressure of water (i.e., 2200 to 2900 psi [150 to 200 bar] at these temperatures) to facilitate a condensed-phase reaction medium. The process has been successfully tested at bench-scale and development and testing at a larger scale is required to prove the viability of the process at production levels. Near-term development plans include advancing the process to pilot-scale readiness.

A significant challenge to the scale-up of the HTL process is feeding a highly viscous fibrous biomass wood/corn stover feedstock into a pump system that provides the required pressure for downstream processing at ~3000 psi (206 bar). In October 2011, PNNL began investigating commercial feed and pumping options that would meet these HTL process requirements. Initial efforts focused on generating a HTL feed and pump specification titled “PNNL Biomass Process Feed & Pump Equipment Needs” (see Appendix C). That specification was provided to prospective vendors to determine the suitability of their pumps for the pilot-scale (i.e., 1 dry metric tons per day [DMTPD] production rate or 0.5 to 2 gpm at 15 wt% solids and 3000 psi) and production-scale plants (i.e., 2000 DMTPD production rate or 2300 gpm at 15 wt% solids and 3000 psi). Figure ES.1 presents the problem statement diagram used in the specification.

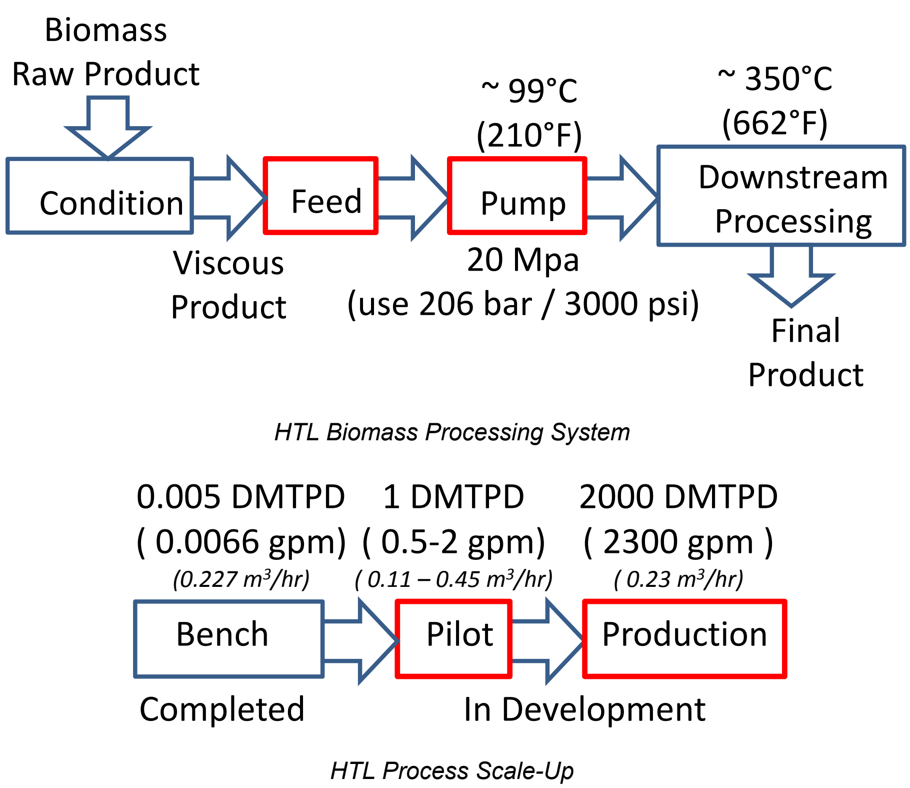

Figure ES.1. Problem Statement Diagram Provided to Pump Vendors

By December 2011, many vendors had responded to PNNL's inquiries. Six vendors (Table ES.1) were identified that could provide viable equipment to meet HTL feed and/or pump needs. Those six vendors provided options consisting three types of positive displacement pumps (i.e., diaphragm, piston, and lobe pumps).

Vendors provided capabilities and equipment related to HTL needs (see Appendix C). This information was collected, assessed, and summarized in individual reports and used as the basis of this report. The six chosen vendors and their equipment are compared as a group and assessed as related to HTL application. A PNNL HTL pump vendor summary comparison is shown in Appendix A. Vendor contact information is provided in Appendix B.

Table ES.1. Vendors Identified in Pumpability Assessment

Vendor (Location)	Pump Equipment Type	Overall Summary Information
ABEL (Germany)	diaphragm – hydraulic membrane	Appendix A (Pump Vendor Comparison) Appendix B (Vendor Contact Details)
FELUWA (Germany)	diaphragm – hydraulic hose	
Putzmeister Holding GmbH (Germany)	piston – hydraulic dual piston	
Schwing Bioset (USA)		
Weir Minerals (Netherlands)		
Zeilfelder Pumpen (Germany)	lobe – rotary	

Feeding and pumping HTL biomass appears to be viable with commercial off-the-shelf equipment and specialized designs. All vendors were confident of feeding and pumping a flowable biomass like the HTL finely ground (0.0012-in./30-micron/0.03-mm) wood feedstock at 15 wt% dry solids with a measured 4-in. (102-mm) slump (see Figure ES 2). Other HTL feedstock with less slump and/or larger particle sizes can likely be pumped; however, feed and pump testing will be required.

Because biomass feedstock can have many variables (e.g., type, particle size, moisture content), pumpability testing is highly recommended for any new biomass feedstock, including HTL feedstock. Pumpability, pump selection, and required feed and pump options need to be verified. Past success with feeding and pumping HTL biomass at high pressures has been limited. However, new feed and pumping options from the vendors presented in Table ES.1 and recent vendor experience pumping very challenging feedstock media gives new optimism for successfully pumping high-pressure HTL biomass.

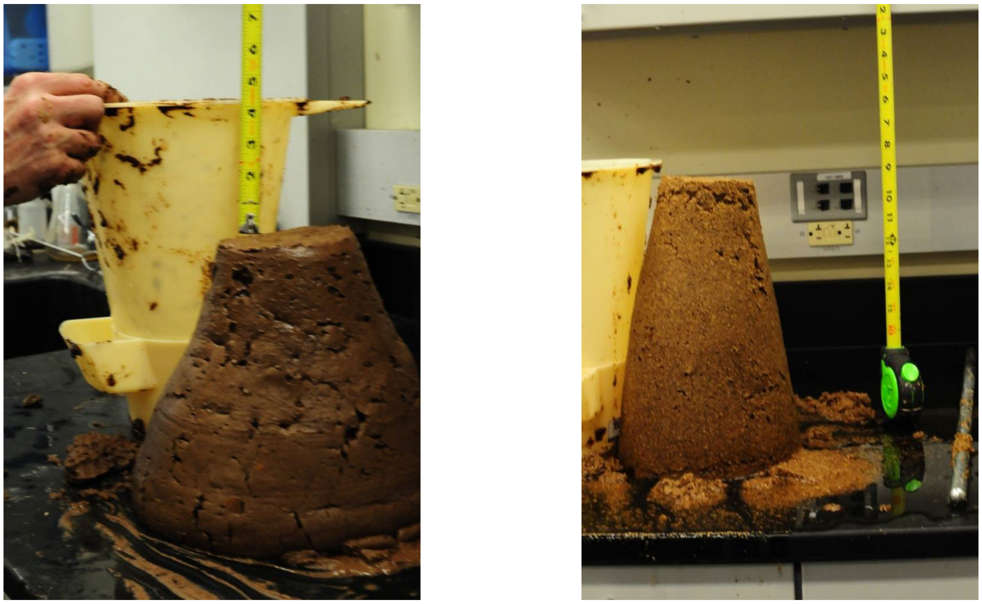

Figure ES 2. Slump Testing of HTL Feedstock. Left: 0.0012-in. (0.0-mm) immersion milled wood feedstock, 13 wt% solids, after 2.5 minutes, 4 in. (102 mm) of slump. Right: minus 0.0625-in. (1.59-mm) wet wood feedstock, 18 wt% solids, after 4 minutes, 0.5 in. (13 mm) of slump. Further dewatering is evident.

Acknowledgments

This work was supported by the National Advanced Biofuels Consortium, which is funded by the U.S. Department of Energy's Office of Biomass Program with funds from the American Recovery and Reinvestment Act.

Acronyms and Abbreviations

COTS	commercial off-the-shelf
DMTPD	dry metric tons per day
HTL	hydrothermal liquefaction
NABC	National Advanced Biofuels Consortium
NPSH	net positive suction head
PNNL	Pacific Northwest National Laboratory
PWR	Pratt & Whitney Rocketdyne
ROM	rough order of magnitude
TEA	technical economic analysis
CAT-HTR	Catalytic Hydrothermal Reactor
HTU®	Hydro-Thermal Upgrading

Symbols and Units

µm	micron/micrometer (10^{-6} meter)
gpm	gallons per minute
HP	horsepower
in.	inch
kW	kilowatts
m^3/hr	cubic meters per hour
mm	millimeter
MPa	mega Pascals (1 x 10^6 Pa)
Na_2CO_3	sodium carbonate
Pas	Pascal second
psi (psig and psia)	pounds per square inch

Conversion Factors

flow	1 gpm = 0.227 m^3/hour; 1 m^3/hour = 4.403 gpm
length	1 in. = 25.4 mm = 25400 micron; 1 mm = 1000 micron = 0.0394 in.
pressure	1 psi = 0.0069 MPa = 0.069 bar; 1 MPa = 145 psi = 10 bar
power	1 HP = 0.747 kW; 1 kW = 1.341 HP
viscosity (dynamic)	1 Pas = 1000 centipoise

Contents

Summary iii
Acknowledgments vii
Acronyms and Abbreviations ix
Symbols and Units ix
1.0 Introduction 1.1
1.1 Background 1.1
1.2 Objective of Assessment 1.1
2.0 Pump Vendor Assessment 2.1
2.1 Relevant Vendors Identified 2.1
2.2 Vendor Equipment Capabilities/Equipment Types 2.1
2.3 Vendor Biomass Experience 2.1
2.4 Vendor Pumpability of HTL Feedstock 2.2
2.5 Vendor Pump Capabilities, Features, Assessment 2.3
3.0 Description of Pumps 3.1
3.1 Diaphragm Membrane Pump (ABEL) 3.1
3.1.1 Description 3.1
3.1.2 Operation 3.1
3.1.3 Vendors Identified 3.2
3.1.4 Vendor Capabilities for HTL Application 3.2
3.1.5 Assessment for HTL Application 3.3
3.2 Diaphragm Hose Pump (FELUWA) 3.3
3.2.1 Description 3.3
3.2.2 Operation 3.4
3.2.3 Vendors Identified 3.4
3.2.4 Vendor Capabilities for HTL Applciation 3.5
3.2.5 Assessment for HTL Application 3.6
3.3 Solids Piston Pump (Schwing Bioset, Weir Minerals, Putzmeister) 3.6
3.3.1 Description 3.6
3.3.2 Operation 3.7
3.3.3 Vendors Identified 3.8
3.3.4 Vendor Capabilities for HTL Application 3.8
3.3.5 Assessment for HTL Application 3.9
3.4 Rotary Lobe Pump (Zeilfelder Pumpen) 3.10
3.4.1 Description 3.10
3.4.2 Operation 3.10
3.4.3 Vendor Capabilities for HTL Application 3.11

3.4.4 Assessment for HTL Application 3.12
4.0 Pump and Feeding System Components 4.1
4.1 Valves 4.1
4.1.1 Poppet Cone Valves 4.1
4.1.2 Ball Valves 4.1
4.1.3 Swing Pipe Valves 4.2
4.2 Drives 4.3
4.3 Pump Feeding Equipment 4.3
4.3.1 Screw Feeders/Augers 4.3
4.3.2 Raw Feedstock Storage and Transport Systems 4.4
4.4 Specialized Component 4.5
4.4.1 Pipeline Injection System 4.5
5.0 Feed and Pump System HTL Application 5.1
5.1 HTL Processing Parameter Considerations 5.1
5.1.1 Pressure 5.1
5.1.2 Temperature 5.1
5.1.3 Flow Rate 5.1
5.1.4 Particle Size 5.2
5.1.5 Weight Percent Solid Concentration 5.3
5.1.6 Fibrous Nature 5.3
5.1.7 Abrasive Material 5.3
5.2 Vendor Summary – Pumpability Assessment 5.3
5.3 Vendor Summary – Pilot Plant 5.4
5.4 Vendor Summary – Production Plant 5.4
5.5 Suggested HTL Configuration and Options to Consider 5.5
6.0 Conclusion 6.1
Appendix A – Pump Vendor Comparison Summary A.1
Appendix B – Pump Vendor Contact Details B.1
Appendix C – “PNNL Biomass Process Feed & Pump Equipment Needs” dated November 3, 2011 .... C.1
Appendix D – “Pumpability Assessment Query by PNNL to Vendors” dated early December, 2011 .... D.1
Appendix E – Other Vendors Explored/Contacted/Summary Results E.1

Figures

1.1 Overview of HTL Process 1.1
3.1 Diaphragm Membrane Pump – Schematic 3.1
3.2 Triplex Diaphragm Membrane Pump – ABEL HTM Series 3.2
3.3 MULTISAFE Double Hose-Membrane Pump – Schematic 3.4
3.4 MULTISAFE Triplex Double Hose-Membrane Pump 3.5
3.5 Solids Piston Pump – Dual Cylinder 3.7
3.6 Solids Piston Pump – Dual Cylinder 3.7
3.7 Rotary Lobe Shapes Convex and Concave 3.10
3.8 Rotary Lobe Pump – T-Rex 3.11
4.1 Poppet Cone Valves 4.2
4.2 Swing Tube Valve 4.2
4.3 Twin Screw Feeder 4.3
4.4 Push Floor 4.4
4.5 Sliding Frame 4.5
4.6 Pipeline Injection System 4.5
5.1 Biomass Pumping Application 5.5

Tables

1.1 Pumpability Assessment Objective and Resolutions 1.2
2.1 Comparison of Pump Types 2.4

1.0 Introduction

1.1 Background

Pacific Northwest National Laboratory (PNNL), working as a partner in the National Advanced Biofuels Consortium (NABC), has the lead role in developing the hydrothermal liquefaction (HTL) process for converting biomass to biofuels.[1] A technical-economic analysis (TEA) of the HTL process confirmed its high carbon yields and desirable biofuel product distribution; however, questions remained regarding scalability to a pilot- or production-plant with respect to pumping and reactor design. This assessment was conducted to address those questions by identifying commercially available pumping systems suitable for a production-scale plant.

In the HTL process application being investigated, fibrous base raw biomass feedstock, pine wood chips, or corn stover particles are mixed with water to form a paste-type slurry (nominally 15% dry weight solids). The slurry is highly viscous with non-Newtonian flow properties. Small amounts of other material (e.g., Na_2CO_3) may be added to this biomass feedstock to aid (e.g., adjust the pH) in downstream processing. In the pilot- and production-scale systems, an aqueous stream (process recycle) containing ~5% weight organic acids and alcohols (e.g., glycolic acid, acetic acid, methanol, ethylene glycol) will be used as the makeup water for the biomass slurry. The slurry is pumped to 15–20 MPa (2200–2900 psi/150-200 bar) and then heated to 300–350°C (570–662°F). The pressure is maintained above the vapor pressure of water to facilitate a condensed-phase reaction medium. The biomass solids are converted to a bio-oil, and the bio-oil is separated from the solids and aqueous phase. The generated bio-oil can then be upgraded (via hydrotreating) to produce a hydrocarbon product. Figure 1.1 presents a simplified sketch of the process.

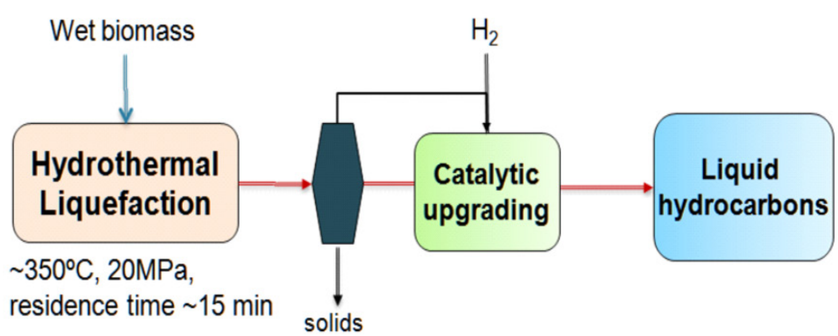

Figure 1.1. Overview of HTL Process

1.2 Objective of Assessment

The goal of this assessment is to identify viable industrial feed system and pump options for a 2000 dry metric tons per day (DMTPD) production-scale HTL plant. The key objectives of this assessment and their resolutions are summarized in Table 1.1.

[1] for more information see http://www.nabcprojects.org/hydrothermal liquefaction.html

Table 1.1. Pumpability Assessment Objective and Resolutions

Objective	Resolution
Identify relevant applications and industries operating at comparable scales	Pump and bulk material handling vendors were identified in the following industries: • biomass pelletization and briquetting (biomass feed systems) • concrete pumping (abrasive slurry) • industrial pumping – high-pressure and viscous material pumping • municipal sludge handling/treatment – biomass feed and pumping • pulp and paper industry – biomass feed and pumping.
Interact with commercial vendors and pursue integration between vendors	Vendor searches within the relevant industries were conducted. Vendors were contacted and information exchanged. Further discussions were pursued when viable HTL vendors were found. Six vendors were identified, offering three pump types and various feeder systems. Time and budget limitations did not allow the pursuit of integration between vendors.
Take advantage of commercial off-the-shelf (COTS) technology	All six vendors could provide COTS technology but would customize the equipment for HTL application.
Supply and support vendor needs for biomass feedstock rheology characterization	Some rheology testing was conducted at PNNL. Additional rheology testing was performed at the request of a vendor for slump test. HTL feedstock samples were shipped to vendors at their request for pumpability assessment that could include rheology testing.
Provide vendors with process requirements to support selection of conceptual design for feedstock handing and pump system.	The document "PNNL Biomass Process Feed & Pump Equipment Needs," dated November 3, 2011 was generated by PNNL and supplied to vendors (see Appendix C). This document included process requirements and initial feedstock and rheology data.
Obtain cost data to the extent possible from equipment vendors to support the TEA.	Cost data was received from the six vendors and passed along for TEA incorporation.
Identify issues associated scale-up.	Scale-up issues are addressed by vendor submittals of pilot- and production-scale equipment. In addition, a pump assessment query to vendors (see Appendix D) addressed scale-up. Scale-up discussions and concerns from vendors are noted.

2.0 Pump Vendor Assessment

2.1 Relevant Vendors Identified

The majority of vendors found to have feed and pump equipment suitable for HTL application are located in Europe—four in Germany and one in the Netherlands. Only one viable vendor is based in the United States. However, some of the European companies have U.S. subsidiaries. The larger European vendor base is believed to be the result of Europe's longer term and more extensive investment in biomass processes compared to the United States. Further, Europe has historically been a manufacturer of heavy-duty pumps for the world market. A summary of the relevant vendors selected for this assessment is provided in Appendix A. Vendor contact information is provided in Appendix B.

All viable vendors provide equipment for large industrial applications. Each vendor has at least 20 years of experience in biomass pumping or similar, difficult, pumping applications. Vendor company sizes range from large (e.g., Weir Minerals, Putzmeister), to medium (e.g., FELUWA, ABEL, Schwing Bioset), to small (e.g., Zeilfelder Pumpen) and, in general, the larger companies are equipped to provide full turnkey feed and pump systems whereas the small company is more focused on component supply (e.g., pumps). It should be noted that the medium-sized companies were very specialized to biomass or difficult pumping applications and may be considered equivalent to specialized groups within the large companies. The large vendors likely have more capital and resources available to develop specialized pumping applications. However, they may also have less enthusiasm for smaller, specialized applications like HTL unless they see a potential market.

Many vendors were explored in the search for viable HTL pump vendors. Appendix E summarizes vendor contacts that were identified, but not selected, for detailed assessment.

2.2 Vendor Equipment Capabilities/Equipment Types

All six viable vendors provide positive displacement pumps of various types (i.e., diaphragm, piston, and rotary lobe) to meet HTL application needs. Full feed system equipment, from raw stock storage (e.g., silos, bins, hoppers) to material handling (e.g., push floors, sliding frames) to the pump inlet were available as integrated systems from both large and at least one medium company (Schwing Bioset). Local feed systems connected to the pump (generally twin screw augers) are routinely provided as needed for the application. In addition, downstream components (e.g., line injection systems for reducing pipe friction) are provided by many of the vendors (i.e., ABEL, Putzmeister, Weir Minerals).

Further details regarding the various equipment offered by vendors and relative comparisons are presented throughout this assessment.

2.3 Vendor Biomass Experience

The wood chips and corn stover (i.e., dried, chopped corn stalks) biomass HTL feedstock is a difficult material to pump; especially at solids loadings above 15 wt%. This type of biomass feedstock tends to form bridges in opening, especially when larger particle sizes are involved. In addition, it can pack/plug at a constriction when under pressure; especially if dewatering occurs. However, some recent pumping application developments show great promise for pumping this feedstock. New equipment and process configurations allow pumping of materials that, in the past, were impossible to pump. The vendors included in this assessment are specialized in this type of application and use rheology, characterization test (e.g. slump test, dewatering test, etc.) and past experience to solve new pumping applications, including biomass.

The typical biomass application of all vendors is the pumping of dewatered sewage sludge, which has different pumping characteristics than the HTL feedstock of wood chips and corn stover. Putzmeister has direct experience pumping biomass with its solids piston pumps at HTL pressures and has supplied the pumps for a condensed-phase liquefaction pilot-plant demonstration. Schwing Bioset has direct experience pumping wood chips in several testing applications with its solids piston pumps, but likely at pressures below 500 psi (34 bar). Other non-sewage biomass experience includes FELUWA pumping agriculture mixtures with its diaphragm hose pump and Zeilfelder Pumpen pumping silage with its rotary lobe pump with chopping blades. The vendor information presented in this report was extracted from more detailed PNNL write-ups; those write-ups are not publicly available and for NABC use only.

Pumping HTL-type feedstock at pressures of 3000 psi (206 bar) is likely a new application for most vendors. In general, vendors that have direct application with HTL-type feedstock pump at much lower pressures (e.g., ≤725 psi [50 bar]). Although the selected vendors may not have pumped biomass exactly like that used in HTL, they have specialized in pumping difficult materials and understand the issues associated with pumping HTL feedstock. In all cases, vendors recommended pumpability testing to verify pump designs and suggested that production-scale equipment is likely to be more successful than pilot-scale equipment.

2.4 Vendor Pumpability of HTL Feedstock

The target HTL biomass feedstock are at the extreme edge of pumpability, especially at higher solid concentrations (above 15% weight dry solids) and larger particle sizes 0.08 to 0.2 in. (2 to 6 mm). Biomass feedstock, with its fibrous nature, tends to adhere to itself, entangle, and bridge across openings, which makes it difficult to feed and pump. However, the vendors were extremely confident that the finely ground (0.0012-in/30-micron/0.03-mm.) wood feedstock at 15% weight dry solids with a measured 4-in. (102-mm) slump is a pumpable biomass material.

Vendor experience indicated that biomass feedstock needs to be tested for pumpability if it is not flowable (i.e., slump less than 4 in. [102 mm]) and/or has one or more of the following conditions: contains little moisture; dewaters easily; has large particles. Feedstock testing may include rheology testing on small feedstock samples or pump testing on actual material. PNNL has performed rheology tests on some HTL feedstock and two vendors have the capability to perform rheology tests (FELUWA, Weir Minerals). Tests involving actual pumping of the feedstock material using full-scale equipment are ultimately what determine if a feedstock can be pumped. Vendors cautioned that pump testing on a smaller-than-production scale could return false results that the feedstock is “not pumpable,” when in fact it could be pumped at production scale. When it comes to feeding and pumping biomass, larger openings and pipe sizes are generally preferred to limit feedstock bridging and thus enhance feedstock pumpability.

Vendors can employ various methods to enhance feedstock pumpability (e.g., pump speed adjustment, screw feeder and mixers, feedstock size reduction equipment [like macerators], and line injectors that coat surfaces with fluid to reduce friction). Equipment is likely to need adjustment for each feedstock to achieve flow through the system and optimize performance and efficiency. Only testing will show which equipment combinations and operating parameters can be used to successfully pump the more challenging HTL feedstock and feedstock conditions (i.e., type, particle size, wt% dry solids).

Finally, there appears to be a renewed interest worldwide in developing applications like HTL to convert biomass to biofuels. In our vendor queries for HTL, some vendors responded that they had similar pumping requests to HTL for pumping biomass and HTL biomass feedstock but must maintain confidentiality about the inquiring organizations and their associated processes. In some of these processes, like the Steeper Energy's proprietary technology Hydrofaction™ process, the required pumping pressures are much higher than HTL. Further, other HTL-like processes (e.g., Licella's CAT-HTR and the older HTU® process) in various states of development have had success in pumping HTL biomass material at HTL pressures or higher. In addition, many biomass gasifier processes exist for pumping HTL-type feedstock, but generally at pressures below 500 psi (34 bar).

2.5 Vendor Pump Capabilities, Features, Assessment

During these HTL biomass pumpability investigations, three types of positive displacement pumps (i.e., diaphragm, solid piston, and rotary lobe) were identified to pump the HTL feedstock of wood chips and corn stover to 3000 psi (206 bar) and 2300 gpm (637 m^3/hr). Vendors were most confident in their ability to pump HTL feedstock finely ground in an immersion mill and exhibiting a slump of at least 4 in. (102 mm). Each type of pump has advantages and disadvantages for pumping HTL biomass. Table 2.1 compares each pump type, provides the operating principles for each pump type, and lists features that can be employed with the pumps to enhance pumpability.

It should be noted that one of the criteria of our investigation into HTL biomass pumping was that the pump be scalable (i.e., the pilot plant pump could be scaled up for the production plant). All six vendors were able to offer scalable pumps, but generally the pumps had flow rates appreciable larger than required for a 1 DMTPD pilot plant. Smaller pumps that scale up to the production plant scale are not available. Therefore, to maintain pump scalability between the pilot- and production-scale plants, either the pilot plant will need be larger or pumped product will have to be bled off in a slipstream arrangement to meet pilot-plant flow requirements and the excess product flow recycled.

Table 2.1. Comparison of Pump Types

Pump Type	Positive Displacement — Diaphragm — Membrane	Positive Displacement — Diaphragm — Hose	Positive Displacement — Piston	Positive Displacement — Rotary Lobe
Vendor	ABEL	FELUWA	Putzmeister, Schwing Bioset, Weir Minerals	Zeilfelder Pumpen
Key Advantages	Pressure obtained in a single stage – 3625 psi (250 bar) exceeds HTL pressure requirement Minimal contact of components with feedstock Minimal pulsation	High viscosity handling Pressure obtained in a single stage up to 4600 psi (320 bar) greatly exceeds HTL pressure requirement Large particle handling to 3 in. (75 mm) Minimal contact of components with feedstock Rupture of hose diaphragm is protected by a second hose diaphragm Minimal pulsation	Highest viscosity handling Pressure obtained in a single stage – 3000to 4350 psi (206 to 300 bar) Large particle handling to 2 in. (51 mm) with swing tube valve Flow rate adjustable over large range Proven in past applications similar to HTL Low stroke rate	Simple design Operation to 842°F (450°C) Lobe blades chop fiber material Largest particle size handling to 4 in. (102 mm) High viscosity handling High solids content, Pressure up to 3625 psi (250 bar) possible No valving required, No pulsation Run backwards as a generator to recover power Low maintenance Replaceable wear components
Key Disadvantages	Solids content limited to around 10% Lower viscosity handling than piston pumps Rupture of diaphragm exposes process media to hydraulic fluid Higher stroke rates than piston pumps Suction feed requires sufficient net positive suction head (NPSH) available	Viscosity handling may be slightly lower than piston pumps Higher stroke rates than piston pumps Suction feed requires sufficient NPSH available	Possible flow pulsation Available Putzmeister pumps limited to 1885 psi (130 bar) Use of cone valves may limits particle size to 0.5 in. (12.7 mm), Highest maintenance	Multiple stages required to build pressure – 710 psi (50 bar) per stage Suction feed requires sufficient NPSH available

3.0 Description of Pumps

3.1 Diaphragm Membrane Pump (ABEL)

3.1.1 Description

Diaphragm membrane pumps (subsequently referred to as membrane pumps) are positive displacement pumps. A pump cavity is formed by a suction valve on the inlet side and a discharge valve on the outlet side. A moveable membrane between these valves can alter the volume of the pump cavity. Movement of the membrane is typically actuated by a piston connected directly to the membrane or by using an intermediate mechanism like hydraulic fluid to transfer pressure to the membrane. Membrane pumps come in various configurations, but are often ganged together in duplex, triplex, or quadplex configurations to increase total flow and/or reduce pulsation peaks by offsetting the timing between ganged pumps. This offset is typically defined by the drive system, which consists of an engine-type crankshaft, rods, and pistons.

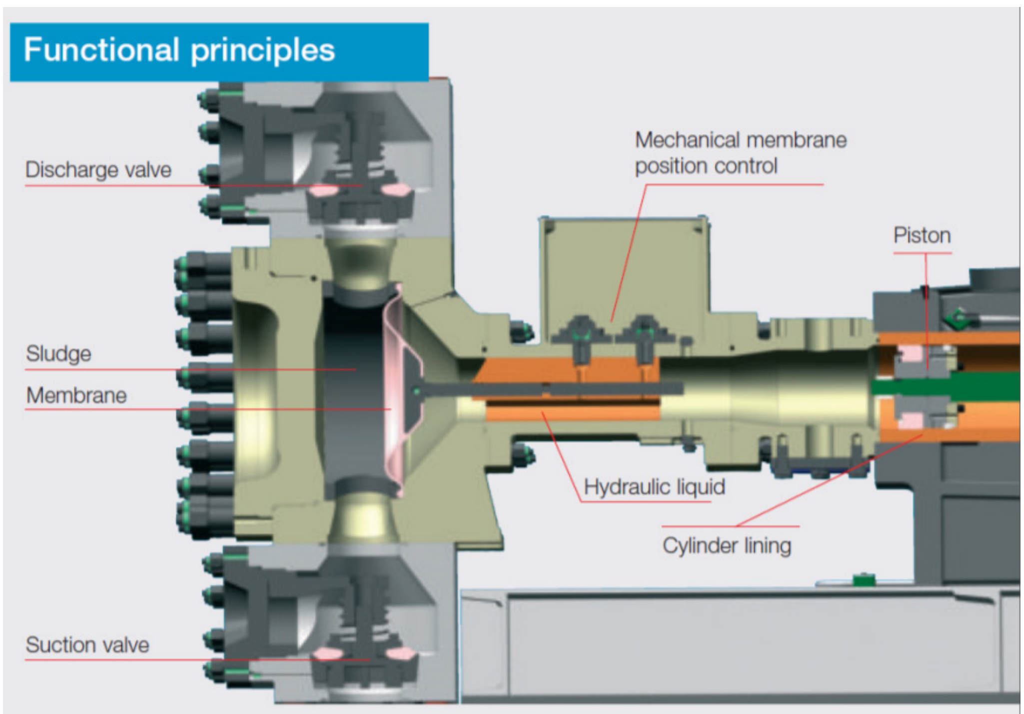

Figure 3.1. Diaphragm Membrane Pump – Schematic (information from ABEL literature)

3.1.2 Operation

Material to be pumped is drawn into the pump cavity by suction force by first closing the discharge valve, then opening the suction valve, and then moving the membrane to increase the cavity volume (i.e., suction). When full cavity volume is obtained by membrane movement, the suction valve closes, the discharge valve opens, and membrane moves to decrease pump cavity volume and thus push materials out of the pump with increasing pressure. This synchronous process is repeated to create continuous pump flow. Pump flow can be adjusting by varying the stroke rate.

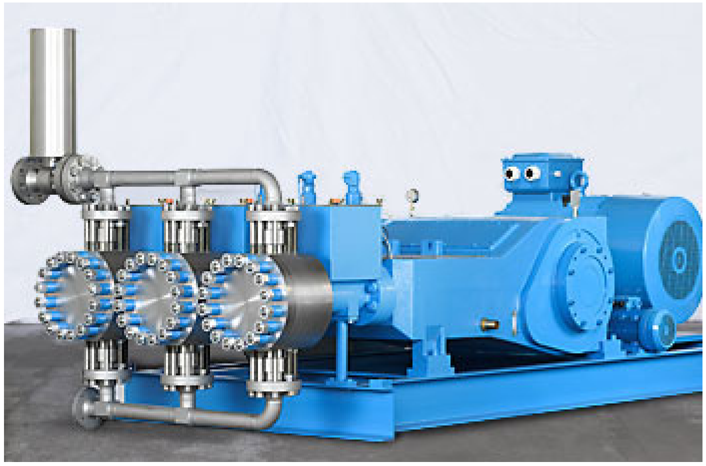

Figure 3.2. Triplex Diaphragm Membrane Pump – ABEL HTM Series (information from ABEL literature)

3.1.3 Vendors Identified

Many manufacturers build membrane pumps; however, those identified for consideration in HTL application are ABEL, FELUWA, and Weir Minerals. FELUWA and Weir Mineral membrane pumps have similar capabilites to the ABEL pump and likely would be viable substitutes. To simplify the discussion, only the ABEL membrane pump will be discussed. ABEL was the sole manufacturer to propose a membrane pump for HTL application.

3.1.4 Vendor Capabilities for HTL Application

The ABEL membrane pump is a robust pump built for industial application and continous operation. ABEL custom designs each pump for the application and, therefore, long lead times can be expected. ABEL has designed a pre-formed membrane for its pumps that does not stretch during stroking action; this is advantageous to longivity of ABEL membrane pumps compared to similar membrane pumps. The piston is isolated from the membrane by using a hydraulic liquid interface. The ABEL membrane pump can operate at temperatures up to 392°F (200°C) with standard materials and up to 572°F (300°C) with available customizations.

ABEL has specified a triplex pump for HTL application that should produce a continous flow with small pulsation variations. Pumps are sychronized 120 degrees apart. If required, pulsation variations can be reduced further with pulsation dampers. ABEL has stated that use of this pump in biomass applications may be limited to solid concentrations of around 10 wt% (more if the medium is flowable) and that the pump is often used in biomass solid concentrations in the 5 wt% or lower range—usually sewage wastewater or similar. The check valves on this pump, suction and discharge, are spring loaded cone valves typically specified for high-pressure operation with fibrous material. Hydraulically operated cone valves are not available with this pump type. The pump requires that the media be flowable. The pump cavity suction feed requires sufficient NPSH, which might require a screw feeder with HTL feedstock.

ABEL's biomass pumping experience primarily includes biosolids related to sewage treatment and feedstock that may be more fibrous (e.g., wine lees and sugar beet slurries). ABEL did provide an example of wood chip pumping using an ABEL membrane pump (EM series); however, details and applicability of this process to HTL were not ascertained. Recently, ABEL used its solids piston pump to pump biosolids at the Enertech biomass plant producing SlurryCarb^{TM}.

3.1.5 Assessment for HTL Application

The ABEL membrane pump appears to be applicable to flowable feedstock, but not all HTL feedstocks are expected to be flowable. Biomass solid concentrations above 10 wt% may be challenging, and, unlike the other pump options explored in this report, may require preprocessing of the feed to a smaller particle sizes. ABEL indicated that if the feedstock can be made to flow into the pump, the membrane pump is preferrable to the solids piston pump because it is more efficient, easier to maintain, and does not require a standalone hydraulic system.

Finally, ABEL literature states that their HTM series pump is designed for hydraulic solids transfer, including pumping suspensions with high dry substance content and high specific weight. However, HTL feedstocks typically have a low specific weight, especially when compared to mine slurries. If fine grain material is being pumped with solids loading around 10 wt% or less, the ABEL membrane pump is a pump to consider.

References

More details related to the ABEL membrane pump discussed in this section can be found at the ABEL website: http://www.abel.de.

3.2 Diaphragm Hose Pump (FELUWA)

3.2.1 Description

Diaphragm hose pumps (subsequently referred to as hose pumps) are positive displacement pumps. This pump works like a typical membrane pump (see description in Section 3.1), but instead of a membrane (flat) surface, the diaphragm surface is cylindrical and, during pumping, squeezes the media in a similar fashion to a human vein pumping blood (Figure 3.3). Hose pump membranes are moved by a hydraulic action; typically using a crankshaft-driven piston to displace the hydraulic fluid, which in turn moves the hose diaphragm. Hose pumps come in various configurations, but are often ganged together in duplex, triplex, and quinplex configurations to increase the total flow and/or reduce the pulsation peaks by offsetting the timing between ganged pumps. This offset is typically defined by a drive system, which consists of an engine-type crankshaft, rods, and pistons.

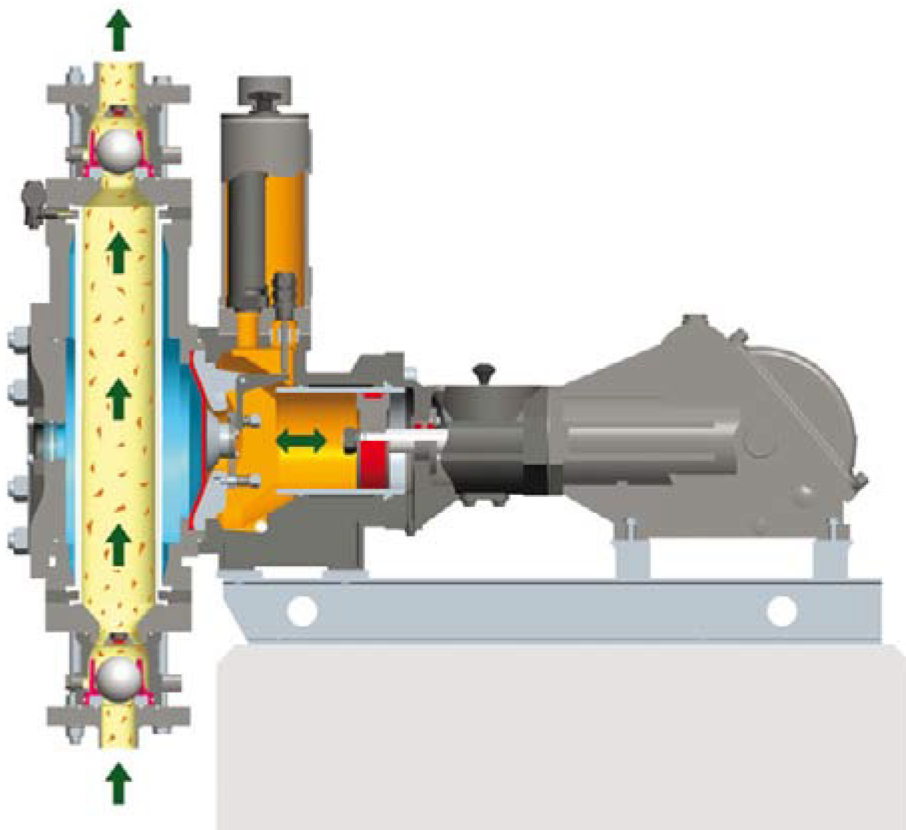

Figure 3.3. MULTISAFE Double Hose-Membrane Pump – Schematic (information from FELUWA literature)

3.2.2 Operation

Material to be pumped is drawn into the pump cavity by the suction force of first closing the discharge valve, then opening the suction valve, and then moving the membrane to increase the cavity volume (i.e., suction). When full cavity volume is obtained by membrane movement, the suction valve closes, the discharge valve opens, and membrane is moved to decrease pump cavity volume and thus push materials out of the pump with increasing pressure. This synchronous process is repeated to create continuous pump flow. Pump flow can be adjusting by varying the stroke rate.

3.2.3 Vendors Identified

Hose pumps discussed here for industrial applications are much less common than membrane pumps. Peristaltic hose pumps are different than diaphragm hose pumps because peristalic pumps use a mechanical roller to deform a hose against a hard surface to move material instead of the constricting action used by the diaphragm hose pump. Diaphragm hose pump manufacturers identified for consideration in HTL application are FELUWA and Weir Minerals. The FELUWA hose pump is fully developed to meet HTL applications. The Weir Mineral hose pump is not developed at this time to meet HTL applciation requirements, but could, in the future, be an option to consider becuase of some unique features that may be useful for HTL biomass pumping. To simplify the discussion, only the FELUWA hose pump will be discussed. FELUWA was the sole vendor to propose a hose pump for HTL application.

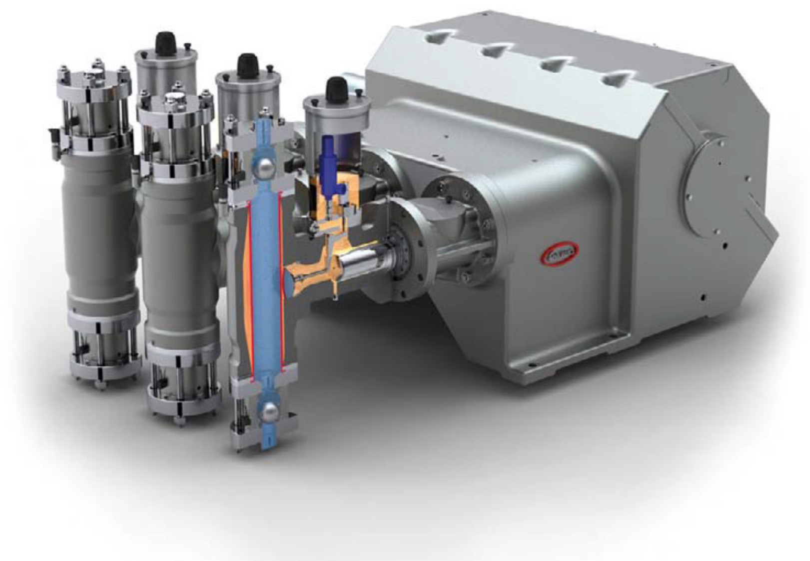

Figure 3.4. MULTISAFE Triplex Double Hose-Membrane Pump (information from FELUWA literature)

3.2.4 Vendor Capabilities for HTL Applciation

The FELUWA hose pump is a robust pump built for industial application and continous operation. FELUWA custom designs each pump and associated equipment for the application and, therefore, long lead times can be expected. FELUWA offers two types of hose pumps. Both use a double diaphragm design where the inner diaphragm is driven by the outer diaphragm with a small volume of hydraulic fluid in between. FELUWA's standard hose pump uses a diaphragm membrane pump to activate the inner hose diaphragm. FELUWA's specialized, but more expensive, MULTISAFE pump uses a double hose configuration with the membrane diaphragm in its standard hose pump replaced with a hose diaphragm so that the outer hose diaphragm is driving the inner hose diaphragm through an intermediate hydraulic fluid. These hose pumps are slightly more complex than standard diaphragm pumps, but offer several advantages, including the ability to pump more viscous material and increased reliability due to the fact that the pump can still operate with a rupture of the inner hose diaphragm. FELUWA has indicated that its MULTISAFE hose pump is preferrable if any abrasive material is expected in the HTL feedstock. These hose pumps can operate at 257°F (125°C) with standard diaphragm materials and up to 392°F (200°C) with special diaphragm membrane materials.

FELUWA has specified a quinplex MULTISAFE diaphragm hose pump for HTL application that should produce a continous flow with small pulsation variations. Pumps are sychronized 72 degrees apart. If required, pulsation variations can be reduced further with pulsation dampers. This pump was recommended because it is highly reliable, has increased flexibility to handle various types of feedstock, and handles abrasive material. The hose pump requires valves to operate and FELUWA promotes its experience in the design of process-specific valves, including free-floating, spring-loaded, and forced-control (e.g., hydraulically activated) valves. The details of pump valve configuration for HTL application requires further investigation; however, one option that should be considered is hydraulically actuated ball valves.

FELUWA states that for the hose pump to operate, the conveying fluid needs to arrive and be injected into the pump chamber. FELUWA considers a pumpable media to have a viscosity less than 5 Pas (5000 times the viscosity of water). Media with viscosities above 5 Pas can be pumped, but often require the addition of forced-control valves (e.g., hydraulically activated ball valves) and worm feed (e.g., screw conveyor) to inject the media into the pump chamber. FELUWA has stated that more challenging HTL feedstock will require these additional components.

This assessment has verified that FELUWA's biomass pumping experience includes primary biosolids related to sewage treatment and feedstock that may be more fibrous (e.g., a ground corn mixture). FELUWA confirmed that its hose pumps should be capable of pumping HTL feedstock concentrations of 15 wt% or higher.

3.2.5 Assessment for HTL Application

The FELUWA hose pump is an exellent candidate for HTL application. The FELUWA hose pump is unique and it is likely this type of pump has not been considered previously in the biomass community for high-pressure biomass pumping. The FELUWA hose pump is capable of the highest maximum pressure (4600 psi [320 bar]) among the vendors and equipment assessed in this report. This hose pump appears to be capable of pumping HTL-type biomass feedstock with solid loading beyond 15 wt%. FELUWA's rheology testing on HTL samples gives additional creedence to its pump assessment. The FELUWA hose pump appears to be elogant, highly reliable, and compares favorably to other pump types. In addition, maintenance requirements are less than those of solids piston pumps. However, hose pumps may not handle more viscous biomass feedstock as well as solids piston pumps.

Because of the hose pump's ability to handle higher solid content feedstock, it appears to exhibit greater flexiblity than the membrane pump for HTL application. Transporting material into the pump chamber is likely easier with a solids piston pump than with a hose pump. Finally, solids piston pumps have been used historically for hard-to-pump applications and have an advantage in techology maturity and available knowledgebase.

References

More details related to the FELUWA diaphragm hose pump discussed in this section can be found at the FELUWA website: http://www.feluwa.de/en/news/.

3.3 Solids Piston Pump (Schwing Bioset, Weir Minerals, Putzmeister)

3.3.1 Description

Solids piston pumps are positive displacement pumps. Piston pumps work on the principle of filling the piston chamber with media as the piston is retracted (suction stroke) and then forcing the media out of the piston chamber on the return stroke (discharge stroke) (Figure 3.5). Valves (see Section 4.1.3), are used to isolate and open the piston pump chamber to the discharge line during the piston stroking action. In single-acting pumps, the media being pumped is only exposed to one side of the piston. On double acting pumps, the media is exposed to both sides of the piston and suction/discharge is occurring simultaneously on different sides of the piston. Piston pumps come in various configurations. In general, in larger applications, either a single-piston or dual-piston chamber is used. More than two pistons are used in some applications; however, it is uncommon.

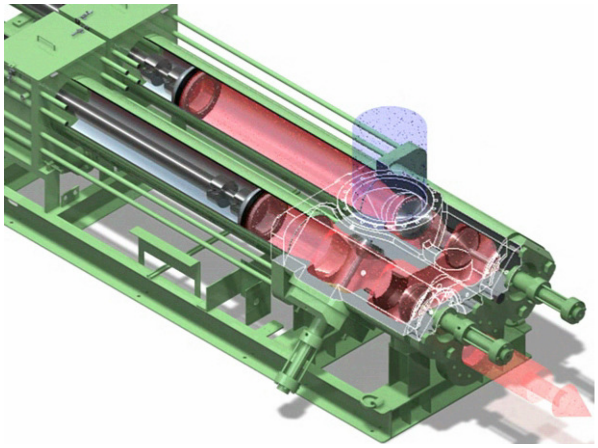

Figure 3.5. Solids Piston Pump – Dual Cylinder (information from Weir Minerals literature)

3.3.2 Operation

Media to be pumped is first drawn into the pump cavity by sealing off the discharge line (closing the discharge valve or moving the S-swing pipe), then opening the material feed (suction valve or equivalent). The piston is moved to increase the cavity volume and media is drawn into the pump by the resulting suction, gravity, and/or optional feeder system. In cases where more viscous material is being pumped, the cylinder chamber fill is aided by a feeder system (e.g., twin screw feeder) that pushes the media into the chamber. When full cavity volume is obtained by piston movement, the material feed is isolated (suction valve is closed or equivalent) and the discharge line is opened (opening the discharge valve or moving the S-swing pipe). The piston is moved to decrease pump cavity volume and thus push materials out of the pump with increasing pressure. This synchronous process is repeated to create continuous pump flow. Pump flow can be varied by adjusting the stroke rate. In general, the flow pulsation from piston pumps is higher than comparable diaphragm or rotary pumps.

The pumps considered for HTL application are all single-acting pumps but in a dual cylinder application (Figure 3.5 and Figure 3.6) where two pistons are operated 180 degrees out of phase, both discharge into a single output pipeline. In this configuration, the dual pump chambers are alternately being filled and emptied, creating a steady output flow. Single-acting pumps in a single-cylinder application offer no advantage over the dual-cylinder application and have the disadvantage of large flow pulsations. [Note that that the continuous flow HTL bench-scale development testing uses two positive displacement Teledyne ISCO metering pumps operating in a similar manners the dual cylinder piston pump].

Figure 3.6. Solids Piston Pump – Dual Cylinder (information from Schwing Bioset literature)

3.3.3 Vendors Identified

Solids piston pumps are made by many manufacturers. Those identified for consideration in HTL application are manufactured by Schwing Bioset and Weir Minerals. ABEL and Putzmeister also supply solids piston pumps, but the solids piston pumps in their product lines did not have the capability to generate the required HTL pressure of 3000 psi (206 bar) and, therefore, were not offered for HTL application. Weir Minerals also offers diaphragm pumps, but elected to specify its solids piston pump because it can handle more viscous materials. To simplify the discussion, the Schwing Bioset and Weir Minerals pumps will be the main focus of the following discussions because both vendors proposed solids piston pumps for HTL application that could meet all HTL design requirements.

3.3.4 Vendor Capabilities for HTL Application

All vendors offering solids piston pumps provide robust solids piston pumps built for industrial application and continuous operation. These vendors customize their standard solids piston pump designs for specialized applications by specifying various options (e.g., feeders and valves) and materials. All vendors have the capability of providing new baseline solids piston pump designs, but it is costly and schedule-prohibitive compared to adapting their baseline unit. In general, the pumps described in this section are built as needed and therefore long lead times can be expected; especially with large volume pumps customized with specific options (e.g., feeders and forced-control valving).

Both Schwing Bioset and Weir Minerals have proposed similar solids piston pumps and have similar pump options including valves and feeder systems. On the feed side, ABEL, Putzmeister, Schwing Bioset, and Weir Minerals offer twin screw feeders that operate in a similar manner but can be configured in different orientations. On the discharge side, various types of check valves are offered to channel the media out of the pump chamber to the discharge line.

Check valves are either free-floating or forced-control (Section 4.1). Forced-control valves have been specified by Schwing Bioset and Weir Minerals for HTL application. The hydraulically activated swing pipe valve system allows the passage of the largest particle sizes (e.g., up to ~2 in. [50.8 mm]). However, only Schwing Bioset offers this valve to work up to the HTL design pressure of 3000 psi (206 bar). Hydraulically activated poppet valves, offered by all solids piston pump vendors, limit the maximum particle size to approximately 0.5 in. (12.8 mm). However, this valve system can operate at higher pressures than the swing tube valve and can take advantage of Weir Minerals higher pump pressure capabilities if needed.

In general, the maximum pressure capabilities of these solids piston pumps are less than comparably sized membrane or hose pumps. However, two solids piston pump manufacturers (i.e., Schwing Bioset and Weir Minerals) were able to meet or exceed the HTL pressure requirement of 3000 psi (206 bar). Schwing Bioset's solids piston pump achieves the HTL design pressure of 3000 psi (206 bar) but has no excess pressure capacity without specialized design. Schwing Bioset offers its large opening S-Turn swing pipe valve design at HTL pressures, whereas, the similar valve from Weir Minerals does not. Therefore, Weir Minerals only offered its hydraulically operated poppet valves for HTL application. Schwing Bioset has investigated designs for increasing the pressure of its solids piston pumps to 3200–3600 psi (220–248 bar), but to date has not built a pump in this pressure range.

The maximum operation temperatures of these pumps are similar and are limited by the rubberized material used on the piston ram. All pumps from these vendors can meet the HTL temperature requirement of 210°F (99°C) even though Putzmeister states the maximum temperature of its pump is just slightly below this requirement. The use of specialized rubber materials, such as Viton, on the ram allows the Putzmeister piston pump to operate at a slightly higher temperature in the range of 250 to 260°F (121 to 130°C).

These vendors have been verified to have biomass experience including wood chips, wood dust, paper sludge, corn stover, and straw, all of which are similar in nature to the HTL biomass feed streams. In general, vendors offering multiple pump types specify solids piston pumps for the toughest pumping conditions, especially for extreme slurries, sludge, and paste with high viscosity, fiber content, and large particle sizes.

According to solids piston pump vendors, organic/biomass-type material in excess of 15 wt% dry solids is routinely pumped. The largest biomass application of solids piston pumps among the vendors is the pumping of dewatered sewage/municipal sludge. All vendors with solids piston pumps were confident of pumping the HTL media with 4-in. slump and small particle size; however, HTL feedstock with high solid content and minimal slump (non-flowable) would be more difficult to pump and pumpability testing would be required.

3.3.5 Assessment for HTL Application

Solids piston pumps are among the best candidates for HTL application primarily because they routinely handle material that is difficult to pump. Solids piston pumps have been proven effective in varied applications, including biomass, and have been proven to operate reliably over a number of years in industrial sludge pumping. Schwing Bioset and Weir Mineral make very similar, high-quality pumps that meet HTL requirements. Either pump would be acceptable. For HTL application, Weir Mineral picked the solids piston pump over its equivalent diaphragm membrane pump and its centrifugal pump. Putzmeister has proven that solids piston pumps can pump a variety of biomass and highly viscous materials, but like ABEL, it cannot currently meet the HTL pressure requirement

For HTL application, the key advantage of solids piston pumps over diaphragm and rotary lobe pumps, is the proven ability of solids piston pumps to feed/pump highly viscous material. Disadvantages of solids piston pumps include a more complex design and more rigorous maintenance requirements.

References

More details related to the solids piston pumps discussed in this section can be found at the vendor websites:

- Schwing Bioset: http://www.schwingbioset.com
- Weir Minerals: http://www.weirminerals.com
- Putzmeister: http://www.putzmeister.com
- ABEL: http://www.abel.de

3.4 Rotary Lobe Pump (Zeilfelder Pumpen)

3.4.1 Description

Rotary lobe pumps are positive displacement pumps. The media being pumped flows around the interior of the pump casing in the lobe cavity. However, the lobes do not make contact with each other like gear pumps do. The lobes rotate on a pump shaft that is typically connected to a gear box and driven by a motor. Rotary lobe pumps do not require valves to operate, unlike membrane/hose diaphragm and solids piston pumps. Rotary lobe pumps do require pressure relief valves to prevent over-pressurization. Rotary lobe pumps come in a number of lobe (also called wing) configurations including single and multiple lobes. The lobes can be concave or convex (Figure 3.7) depending on the application. The flow rate of the pump is adjusted by changing the rotation speed of the lobes. These pumps typically can be run at very slow speeds (less than 10 rpm). Typical rotary lobe pumps can run dry for a period of time and be rotated in either direction. They are manufactured using a variety of materials to allow many specialized applications.

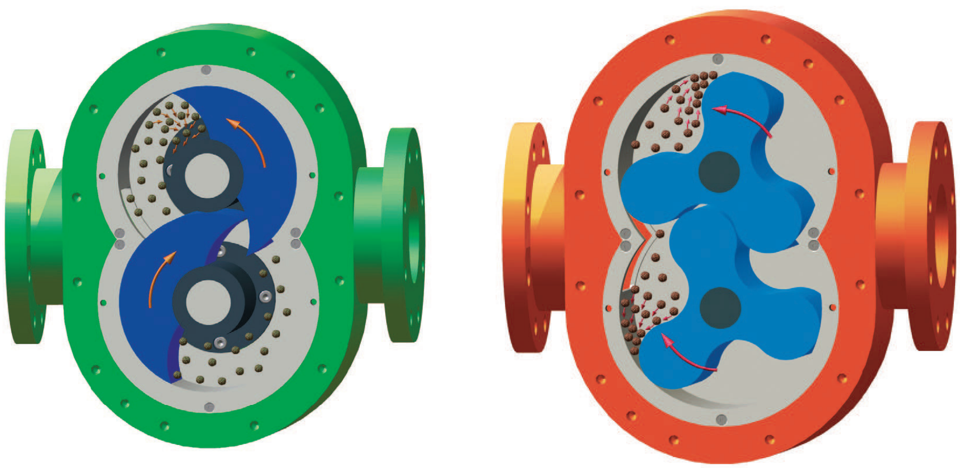

Figure 3.7. Rotary Lobe Shapes Convex (left) and Concave (right) (information from Zeilfelder Pumpen literature)

3.4.2 Operation

As the lobes rotate, pump cavity volume simultaneously increases on the inlet side of the pump and decreases on the outlet side of the pump. When the lobes are creating an expanding volume (coming out of mesh) on the inlet side of the pump, media flows into the pump cavity and is trapped by the lobes as they continue to rotate. The media travels around the interior casing of the pump in a pocket between the lobes and the casing; no media passes between the lobes. Finally, the volume of the cavity is decreased by the meshing of the lobes which forces the media through the outlet port under pressure. This process is repeated to create continuous pump flow. Pump flow can be adjusted by varying the rate of rotation of the lobes.

Rotary lobe pumps are made by many manufacturers but the only one identified for consideration in HTL application is by Zeilfelder Pumpen. Zeilfelder Pumpen has specialized the rotary lobe pump for biomass applications and high temperature. The specializations make this pump rather unique.

3.4.3 Vendor Capabilities for HTL Application

Zeilfelder Pumpen's new T-Rex series rotary lobe pump has been proposed for HTL application (Figure 3.8). This pump is a robust rotary lobe pump and built for industrial applications and continuous operation. Zeilfelder Pumpen custom designs each pump for each application and therefore long lead times can be expected. The T-Rex rotary lobe pump comes with convex chopper lobes (Figure 3.7a) that are designed to handle coarse, fiber-containing media such as the more challenging HTL feedstock. These specialized lobes chop and push the media through the pump, whereas the more common concave lobes tend to squeeze the media, resulting in additional component wear. In addition, the T-Rex rotary lobe pump has replaceable wear components, including the convex lobe cutting edge, that extend the life and maintainability of the pump.

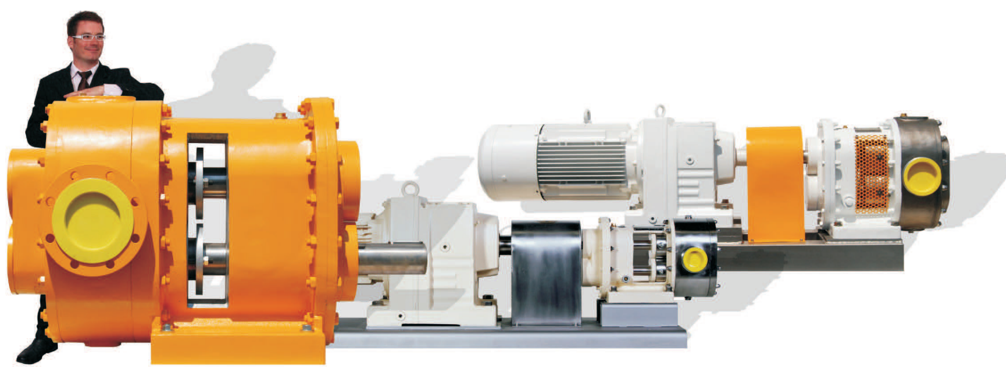

Figure 3.8. Rotary Lobe Pump – T-Rex (information from Zeilfelder Pumpen literature)

The rotary lobe pump has unique features not available on the other pumps reviewed that may be useful in HTL operations. With special materials, this pump can operate at temperatures as high 842°F (450°C), which is significantly higher than any of the other pumps reviewed and allows this pump to operated at HTL process temperature (662°F [350°C]) with a margin of safety. Using its high temperature capacity, this rotary lobe pump can also be considered for use as an in-process booster pump to maintain the required HTL pressure that may otherwise be lost to process pipe wall friction or other pressure reducing processes. The other unique feature is the ability of this rotary lobe pump to run backwards from high pressure to low pressure. When connected to a generator, this rotary lobe pump can recover energy. For HTL, as the high-pressure process completes, the energy efficiency of the process could be enhanced by recovering energy as the product is brought down to atmospheric pressure.

Zeilfelder Pumpen rotary lobe pumps are limited to pressure increases of 710 psi (50 bar). To reach higher pressures, the pumps are staged in series. In staged pumping, operating pressures as high as 3625 psi (250 bar) can be achieved. To reach the HTL design pressure of 3000 psi (206 bar), six pumps would be used. Flow pulsations from this pump are minimal and likely less than the other types of pumps that are not benefiting from specialized pulse-damping accessories.

The T-Rex rotary lobe pump has the ability to pump biomass and silage containing up to 90 wt% fibers and solids. Its rotor design can chop through solid and fibrous material. This type of pump is being used for biomass feed to gasifiers. The optional changeable wear elements on this pump allow handling of abrasive materials.

3.4.4 Assessment for HTL Application

The rotary lobe pump with chopper lobes is an excellent candidate for HTL application. With its ability to operate at HTL process temperatures, the rotary lobe pump could also serve as booster pump, if necessary, to make up pressure losses in the downstream HTL reactor. Key advantages of this pump are its simple design and its specialization for handling fibrous material. Another key operational advantage is the fact that it is operated without check valves. The key disadvantage of this pump is the added complexity associated with having multiple pumps in series to achieve pressures above 710 psi (50 bar). Another considerations is that Zeilfelder Pumpen only supplies pumps and the intergration of multiple pumps, along with accessories (e.g., feeders, pressure relief valves, integrated pump control) would require using other vendors. Finally, because the inlet of the pump requires material to be drawn into the pump chamber, it is expected that some flow of the material or feeder system would be required–similar to the diaphragm pumps.

References

More details related to the Zeilfelder Pumpen rotary lobe pump discussed in this section can be found at the Zeilfelder Pumpen website: http://www.zeilfelder-pumpen.com/

4.0 Pump and Feeding System Components

4.1 Valves

All pumps, except for the rotary lobe pump, require check-type valves to operate. Valve operation is a concern in biomass operations because the larger, fibrous material tends to hang up, bridge, and pack at locations where constrictions are smaller or force is not sufficient to fully close and seal the valve. Because the rotary lobe pump does not require valves other than auxiliary pressure relief valves, this type of pump does not have this problem.

For pumps that require valves, forced-control valves are generally specified over free-floating valves. Free-floating valves depend on pumped media pressure changes to open and close the valves. Free-floating valves are typical in diaphragm pump operation and, though uncommon, can also be used with solids piston pumps. Free-floating valves commonly use floating balls which are a concern when dealing with fibrous material and larger particle size. In general, forced-control valves are hydraulically operated and require a separate hydraulic pump and controller, which brings additional complexity. Less aggressive forced-control valves may use a spring force similar to an engine valve.

Forced-control valves proposed by pump vendors include the following types: 1) poppet cone valves; 2) ball valves; and 3) swing pipe valves. The forced-control ball and swing pipe valves have large openings capable of handling the largest particle sizes among the valve types. Each of the three types of forced-control valves is discussed below.

4.1.1 Poppet Cone Valves

Poppet cone valves operate like the valves on an engine. For the dual cylinder/ram solids piston pumps, valves are used to direct feed into each individual charge cylinder and then out to a single discharge line. In general, poppet valves are hydraulically operated and with a very positive open and close actuation that will not move against pump pressure. Because the poppet cone valve has a limited opening size, it limits the size of material it can pass (i.e., typically a maximum of 0.5 in. [50.8 mm]) for HTL-sized pumps. Fibrous material likely can be caught in the valve seat. The forced action of the valve most likely will either cut the material or smash the material on the seat to provide a sufficient seal, although the possibility exists that material could build up on the valve seat if the pumping action does not clear out the material each time. The Weir Minerals poppet valve design (Figure 4.1) incorporates smooth surfaces and gentle bends to maximize the ability of pumped material to pass through the valve system and valve seat.

4.1.2 Ball Valves

The ball valve, as described by FELUWA, is an option for forced-control valving on its diaphragm hose pump to handle the more challenging, viscous, fibrous HTL feedstock. These valves operate on the principle of a rotation action that is hydraulically activated. The ball valve design should have a very positive closure capable of high pressures and tend to cut material as it closes and opens. [Note, forced control ball valves are used in the system for the HTL process development testing.]

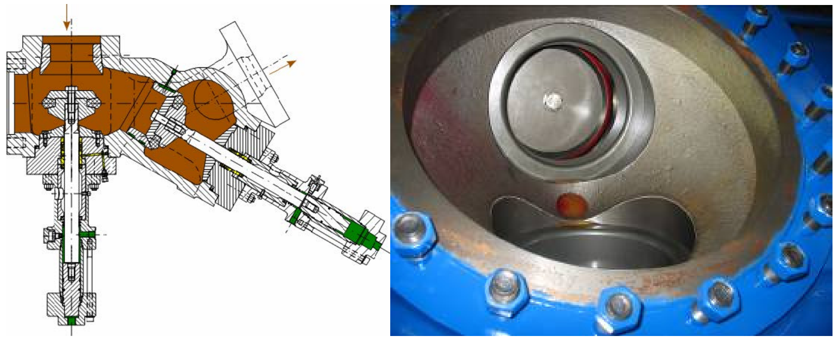

Figure 4.1. Poppet Cone Valves (information from Wier Minerals literature)

4.1.3 Swing Pipe Valves

The swing pipe valve is referred to by many different names from different vendors (e.g., rock valve, s-tube) and may be considered a valve-less design. In this document, we have arbitrarily called this design a swing pipe valve to best describe it function. The swing pipe valve was initially developed for dual cylinder piston pumps for pumping concrete with minimal back pressure and restriction. The swing pipe valve is typically hydraulically activated.

The swing pipe valve is essentially a bent pipe or tube, designed such that one side maintains its position on the discharge line but on the other side moves (i.e., swings) between the two piston pump chamber discharge openings. As the swing pipe valve switches between piston chambers, it opens the discharge line to one piston pump chamber as it seals off the other piston pump chamber. This movement is timed to correspond with the dual cylinder piston pump's charge and discharge cycles. Seals along the pivoting surfaces of the swing valve are used to maintain pressure. The edge of the swing pipe valve, as it pivots between the two piston pump chambers, provides cutting action for fibrous and large materials.

Swing pipe valve designs may have some limitations that affect HTL application. Schwing Bioset was the only vendor that proposed the use of the swing pipe valve (i.e., rock valve, see Figure 4.2) up to, but not above, HTL design pressures of 3000 psi (206 bar). This maximum pressure may have been a limitation on the piston pump design and not the swing pipe valve design. Some swing pipe valve designs are susceptible to a condition wherein pipe movement between cylinders exposes the pipe to both piston pump chambers for a moment, creating a "short circuit" that is not suitable for installations with a static or process pressure in the discharge line.

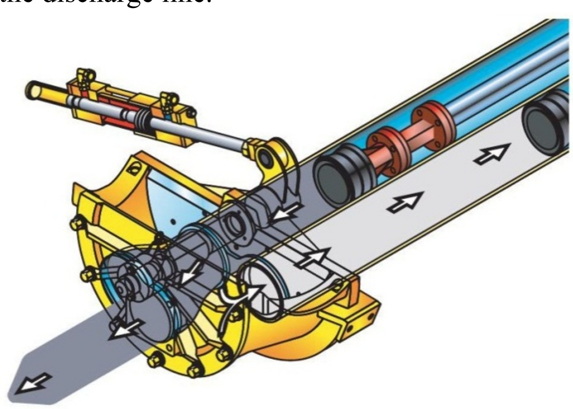

Figure 4.2. Swing Tube Valve (information from Schwing Bioset literature – "Rock Valve")

4.2 Drives

The pump vendors in general seemed to prefer hydraulic drive systems for pumps; however, other drive options are available. For the HTL production scale system of 2300 gpm (522 m^3/hour) and 3000 psi (206 bar), the estimated power requirement is between 5000 and 10,000 kW (6700 and 13,400 HP) based on values received from the diaphragm and solids piston pump vendors.

4.3 Pump Feeding Equipment

HTL feedstock cannot be pumped unless the feedstock can be moved from the local storage location to the pump and subsequently fed into the pump. Biomass, being a fibrous substance, can be a challenge to move because of its high viscosity, its tendency to stick together, and bridging. HTL feedstock pump feeding may be challenging due to HTL process needs, including 1) maximizing the wt% solids in the HTL feedstock to increase process efficiency and 2) waste conditioning, such as adding a recycle water stream and process additives, which will likely need to take place at some point in the feed and pumping process.

The pump vendors in this review were limited in scope to local feeding of HTL feedstock feed into the pump. In all cases, the vendors proposed or discussed screw feeders at the pump to assist in feeding the material to be pumped into the pumping chamber. Screw feeders are discussed in the following section.

4.3.1 Screw Feeders/Augers

Screw feeders or augers are used to assist in feeding less flowable media, like biomass, into the pump cavity. In general, all pump types provide some suction force (or use gravity) to help draw feedstock into the pump chamber. However, assistance is required for some highly viscous and difficult to move feedstock. For efficient pumping, pump cavity fill in the range of 70 to 80 percent or more is desired. Screw feeders and augers can be used to move media into the pump and to increase the fill in the pump chamber. In general, for solids piston pumps, twin screw feeders were specified for HTL application. Screw feeders and augers can have many configurations (e.g., single, twin) but for HTL application, the twin screw feeder was most often discussed. Some vendors discussed feeder applications where the feed auger entered into the pump as far as possible to aid in pump cavity fill. Schwing Bioset and Weir Minerals both proposed twin screw feeders for their solids piston pump for HTL application. FELUWA discussed using screw feeders, as required, with its diaphragm hose pump. Zeilfelder Pumpen has also proposed using a screw feeder with its rotary lobe pump.

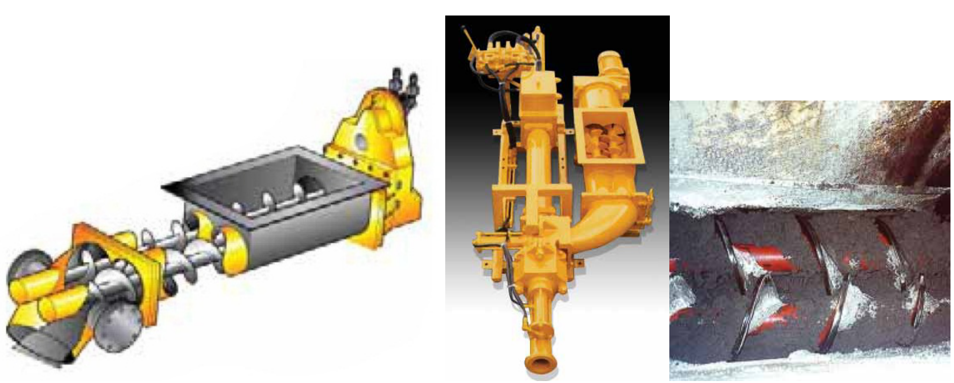

Figure 4.3. Twin Screw Feeder (information from Schwing Bioset literature)

Incorporation of a localized feed system is strongly recommended for any HTL pump application to maintain the maximum flexibility for dealing with variable feedstock. No downsides were identified for including a feeder, other than the additional cost.

4.3.2 Raw Feedstock Storage and Transport Systems

Methods for transporting biomass feedstock from local storage to the pump were reviewed outside pump vendor interactions. One pump vendor, Schwing Bioset, provides biomass transport equipment (e.g., silos, hoppers, push floors, sliding frames), which would allow it to provide a full turnkey system from feedstock storage to pumping. Other pump vendors may also be able to provide biomass transport systems and equipment. Investigations into bulk biomass transport found that the biomass pelletizing, briquetting, and cubing industries routinely move bulk biomass in process similar to what would be required for a HTL process production facility. The pelletizing/briquetting industry is well established throughout the world and many companies that provide the biomass transport equipment and/or full turnkey systems for that industry could be used for HTL.

4.3.2.1 Push Floor

Push floors (Figure 4.4) are proven systems for moving a variety of non-free-flowing and difficult to handle bulk solid materials, from dry silage and wood chips to wet sludge. In general, push floors are designed for square and rectangular storage bunkers. Push floors function by moving a number of parallel ladder structures in reciprocating motion across the bunker floor to dig into feedstock/material and move it to a screw conveyor or other equipment.

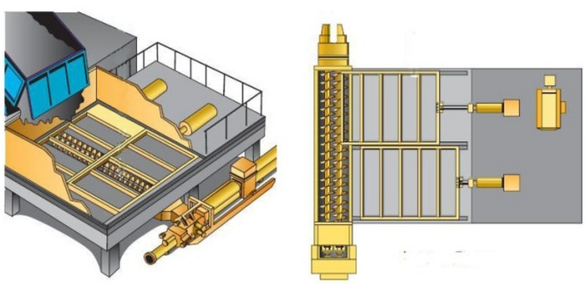

Figure 4.4. Push Floor (information from Schwing Bioset literature)

4.3.2.2 Sliding Frame

Sliding frames perform a similar function as push floor but are designed for flat bottom silos, as shown in Figure 4.5.

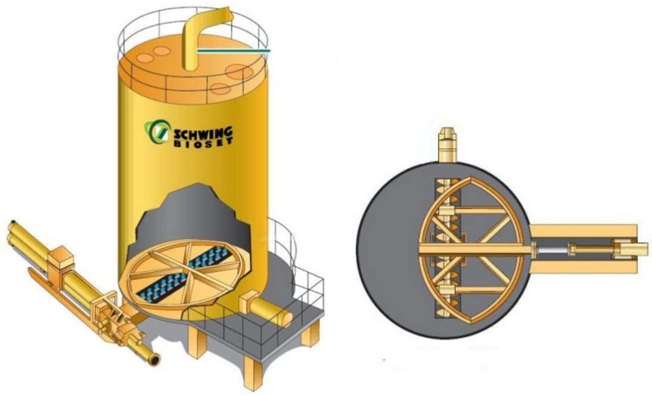

Figure 4.5. Sliding Frame (information from Schwing Bioset literature)

4.4 Specialized Component

4.4.1 Pipeline Injection System

One downstream component that may be useful for HTL pumping is a pipeline injection system (also called pipeline grease rings and other similar terms). Injection systems can be used when hard-flowing materials or material conveyed over long distance causes excessive pressure loss and possibly exceeds available pumping capability. Injection systems introduce a small amount of fluid along the pipe wall to reduce friction, which results in less downstream pressure loss. Various lubricants can be used, including water, grease, oil, and polymers.

Per Putzmeister literature, “With special lubricants, it is possible to reduce the pressure in the delivery line by up to 2% of the initial value.” In discussions with Putzmeister, lubricant amounts between 0.5 percent and 2 percent by volume are injected. An ideal lubricant would act as a boundary layer, and not be absorbed into the material too fast. Water is very cheap and polymer is quite expensive. In the past, with lower organic content cake, water alone would provide a good pressure reduction. Currently, the trend is that higher organic content is expected and water alone helps a lot less than it used to; thus, a polymer blend is much more helpful. For installations where lubricant is absorbed into the pumped media, more pipeline injection systems may be required. To inject lubricant into the pipeline, the injection system needs to exceed the pipeline pressure. For high-pressure applications, clean lubricating fluid is required.

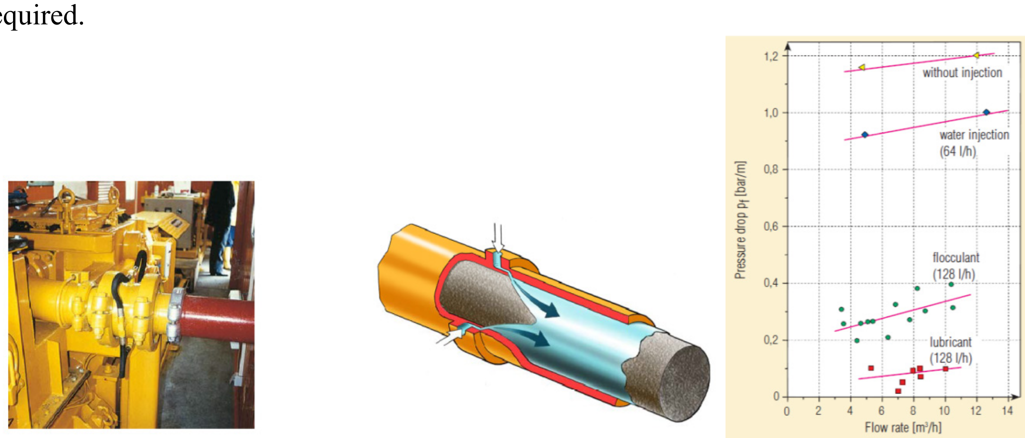

Figure 4.6. Pipeline Injection System (information from Putzmeister literature)

5.0 Feed and Pump System HTL Application

5.1 HTL Processing Parameter Considerations

5.1.1 Pressure

The HTL pressure requirement of 3000 psi (206 bar) can be met by a number of pump vendors and different pump types. Solids piston pumps and diaphragm pumps (membrane and hose) can reach the requirement in a single stage. The rotary lobe pump cannot reach HTL pressure requirement in a single stage; multiple pumps in series are required to obtain the HTL pressure. Some vendors' pumps are able to exceed the HTL pressure requirement by over 45 percent (1351 psi [94 bar]), for a maximum pressure of 4350 psi (300 bar). Additional pressure may be beneficial for HTL to accommodate expected high downstream pipe pressure losses. However, running a pump at higher pressures is countered by 1) a possible reduction in maximum flow rate and 2) higher cost related to the required power increase of the drive system to generate pressure and the corresponding increased pressure rating required of downstream equipment. Reduced flow rate from pumps running at higher pressure may necessitate more pumps to maintain maximum flow rate. Maximum pressure for many of the pumps may be limited more by the capacity of the drive unit's hydraulic pump than by the structural strength of the working fluid pump body.

5.1.2 Temperature

The HTL temperature requirement for the front end pumping of the HTL process is 210°F (99°C) and can be met by a number of pump vendors and different pump types. Downstream of this front end pumping, the temperature is increased to 662°F (350°C) to meet HTL in-process temperature requirements. For the diaphragm and piston pumps, the HTL temperature requirement for front end pumping could be exceeded, but not substantially, using specialized seals/rubber products. The rotary lobe pump was the only pump type assessed that could operate at HTL in-process temperatures (662°F [350°C]) and above (up to 842°F [450 °C]).

5.1.3 Flow Rate

The HTL production plant flow rate requirement of 2300 gpm (522 m^3/hour) can be met by all evaluated pump types. However, because no single pump can meet this flow rate, multiple pumps in parallel configurations are required. The flow of all pump types in this review can be adjusted under operational conditions by changing the operating frequency. There are limitations to pump flow adjustability; however, the diaphragm and solids piston pumps allow the widest range of flow rate variation. The flow rate on the rotary lobe pump is adjusted by changing the operating frequency (i.e., rotation speed). Such applications for pumps in series are often realized using master/slave configurations for the variable frequency drives.

Various production plant operations and flow rate requirements may affect the overall pump design for the HTL process. Some plant operations to consider include the following:

- Operations at reduced capacity: Because feedstock supplies may not always be available to run the plant at maximum flow rate, the plant should have the flexibility to operate at lower flow rates. This could be accomplished by shutting down pump lines where pumps are configured in parallel or by adjusting pump flow rates.

- Plant maintenance: Maintenance on the pump and pump lines without process shutdown would require standby pump lines or configurations with parallel pumps where a single pump line could be shut down with a corresponding reduction in throughput.
- Critical operating conditions: A fixed flow rate or flow rate range may be required to make the HTL process work efficiently at a prescribed residence time. Further, a minimum transport velocity may be required to avoid solids deposition (i.e., keep heavy materials from settling) or stratification. This type of requirement has the potential to constrain the HTL pumping operations more than any other requirements.

5.1.4 Particle Size

Particle size can affect the HTL process in many ways. HTL raw feedstock can be large (up to 3 in. [76 mm]) with potentially large aspect ratios due to fibrous material. Reducing the size of biomass can be difficult, especially when trying to maintain consistency in grainy, fibrous, high-moisture material. In addition, operations to reduce biomass size can be energy intensive and costly, especially reduction to the small sizes (~0.0012-in / 30 micron / 0.03 mm) currently needed for laboratory-scale pumpability. Larger particle sizes (i.e., on the order of 0.079 to 0.24 [2 to 6 mm]) are expected to be processed in pilot and production plants. Batch studies indicate that the quality of the HTL product (oil) is independent of material particle size; however, this would need to be validated in pilot-scale studies.

Rheology testing on HTL wood feedstock has shown that several adverse trends appear with increased particle size, including 1) less flowable feedstock, 2) dewatering of slurry (i.e., separation) under pressure, and 3) a potential increase in bridging effects. As particle sizes increase above approximately 0.079 to 0.10 in. (2 to 4 mm), standardized rheology testing becomes difficult due to the dimensions associated with the test instrumentation. Custom setups or flow loops are needed to obtain rheological characterization. In addition, as particle sizes increase, the effective scales associated with the rheology change. As the ratio between particle size and characteristic geometry (e.g., pipe diameter) becomes larger, particles no longer behave as part of a homogenous continuum consisting of both solids and liquid. Particle behavior become distinguishable from the behavior of the carrier fluid. Figure ES-1 shows slump test changes as particle size is increased from laboratory-scale (0.0012 in./30 micron/0.03 mm) to a size estimated to be near production scale (0.079 to 102 in. [2 to 4 mm]).

Size reduction of HTL feedstock was outside the scope of the HTL pump investigation. However, many systems can reduce particle size. Pump vendors discussed providing size-reduction equipment upstream of the pump and have had success in similar applications where size reduction was needed.

Of the pump types reviewed in this HTL assessment, the rotary lobe pump and diaphragm hose pump can pass the largest particle sizes (i.e., up to ~3 in. [~78 mm]). Solids piston pumps with swing pipe valves can accommodate particle size up to 2 in. (50.8 mm). Solids piston pumps with poppet cone valves and diaphragm membrane pumps are limited to a maximum particle size of around 0.25 to 0.5 in. (6 to 13 mm). For transport of biomass material, it is beneficial to have a mixture of particle sizes (i.e., particle gradation) on the order of 30 percent of mixture with 30 micron (0.0012-in./0.03-mm) grain size or smaller for best pumping and to avoid deposition/sedimentation in the pipeline. Pumps should be tested to prove operation at maximum particle size with representative size distributions.

5.1.5 Weight Percent Solid Concentration

The highest possible weight percent solids concentration in the feedstock is desirable for HTL process efficiency. Discussions with pump vendors indicate that 10 to 15 wt% dry solid concentration biomass feedstock typically can be pumped, but higher solid concentrations are more difficult and generally require specialized design. PNNL's bench-scale testing of HTL feedstock found the upper limit for pumpability to be on the order of 15 wt% suspended solids with wood chip and corn stover feedstock. Pump vendors claim success in pumping organic materials with concentrations up to 40 wt% solids but this material may not be indicative of fibrous, low density HTL feedstock. Vendors claim to pump inorganic materials up to 80–90 wt% solids but this is likely with heavy granular material unlike HTL feedstock. Pump testing will be required to prove the applicability and limits of weight percent solid concentration with various HTL feedstock and particle sizes.

5.1.6 Fibrous Nature

The fibrous nature of biomass material creates unique flow and pumpability challenges that require attention in feeding and pumping system design. These challenges are associated with the characteristics of particles generated from fibrous material, which tend to be cohesive (i.e., stick together), easily entangled, non-uniform in shape and size, and compacted and dewatered under pressure. These characteristics result in slurries where solids are readily segregated and sometimes difficult to re-disperse via fluid turbulence.

Locations with constriction or obstructions are major area of concern with fibrous HTL feedstock. These locations can cause fibrous material to hang up, resulting in significant bridging, which can lead to flow restrictions and even plugging. Even if the material breaks free, it often does so in a clump/agglomeration that can be significantly larger than the individual particles. In the past, valve systems on diaphragm and solids piston pumps have had problems handling fibrous biomass; especially free-floating valve systems with balls at valve seats. Forced-control valve systems, proposed by most all vendors, should handle fibrous material in HTL application as detailed in Section 4.1.

5.1.7 Abrasive Material

HTL biomass feedstock is expected to contain some abrasive material (e.g., dirt, sand, rocks) due to its outdoor harvesting, transport, and storage. HTL pump systems will need to handle such materials. All reviewed pump vendors can provide pumps that deal with abrasive materials (e.g., concrete) using specific pump options (e.g., material selection and replaceable wear parts).

5.2 Vendor Summary – Pumpability Assessment

Pump vendors were asked about providing pumps for an HTL pumpability assessment (see Appendix D). All vendors indicated that pump testing was required to prove the pumpability of HTL feedstock and determine actual pump performance and corresponding limits of feedstock variables (e.g., weight percent solid concentration, particle size). No vendors had testing capabilities appropriate for

HTL conditions at their facility or at third-party facilities. No detailed estimate has been made for a full pump assessment program to test HTL feedstock and variables but rough estimates indicate the cost is likely to exceed $1 million.

One pump assessment option proposed by a vendor was using a pump that did not meet full HTL pressure requirements. The vendor's engineers concluded that a pump assessment at near 50 percent HTL pressure should indicate the success/failure of higher pressure pumping. Pump testing at lower pressures to assess the pumpability of a material (biomass in this case) is not an uncommon practice and is often done to evaluate the feasibility of putting pumps in series. However, lower pressure pump testing requires the assessment of higher pressure phenomena (e.g., dewatering). Because pumps are available that can reach full HTL pressure for a pumpability assessment, low pressure testing may be too risky, especially when dealing with a variety of HTL feedstock types and variables.

A full-scale pumping system is recommended for any pump assessment. For HTL application where multiple pumps are in parallel, testing of a single pump line would be considered full scale. See Section 5.3 for further information about why a full-scale test is recommended.

5.3 Vendor Summary – Pilot Plant

HTL pilot plant systems (including two solids piston pumps, a diaphragm membrane pump, a diaphragm hose pump, and a rotary lobe pump) were offered by five of the six vendors. Putzmeister did not propose a pilot plant system because it could not offer a system that could meet the HTL pressure requirement of 3000 psi (206 bar). The most complete systems, both solids piston pumps including screw feeders, were provided by Schwing Bioset and Weir Minerals. In addition, the diaphragm pump vendors FELUWA and ABEL could provide similar complete systems. Pump cost ranged from <$100,000 to ~$600,000 depending on the flow rate and pump features provided. Delivery times ranged from 20 to 60 weeks.

One vendor warned against pilot-scale testing. That vendor's experience indicated that it is difficult to pump feedstock like HTL in small-scale pilot-plant testing like that proposed by PNNL for HTL demonstration. Pump systems do not scale well because certain factors (e.g., pump clearances, internal strain rates) for a given pump design do not scale. Reduced-scale testing can indicate process failure in a viable production-scale design. Revisiting the HTL pilot-plant scale may be warranted to assess how to minimize a false conclusion for scale-up to a production plant relative to pump/transport system design. For pump systems with multiple pumps in parallel, the testing of one line of pumps could be considered a full-scale test.

5.4 Vendor Summary – Production Plant

HTL production plant systems (including three solids piston pumps, a diaphragm membrane pump, a diaphragm hose pump, and a rotary lobe pump) were offered by all six vendors. Putzmeister, in its production plant system proposal, added additional cost to upgrade its pumps to meet the HTL pressure requirement of 3000 psi (206 bar). All costs for these systems were budgetary and ranged from $4 to 10 million with some variations on pump and pump options being provided. Delivery times ranged from 26 to 60 weeks.

5.5 Suggested HTL Configuration and Options to Consider

This assessment has located reputable, viable vendors that can provide a variety of pump systems and pump types to meet HTL application.

The dual cylinder piston pump is the most proven pump system to meet HTL application requirements and one vendor has experience with a pilot demonstration of a similar HTL process. A twin screw feeder or similar feed system is recommended to ensure a wide variety of HTL-type biomass materials can be moved into the pump chambers to aid in pumping and pumping efficiency. Putzmeister manufactures a piston pump setup close to that chosen for HTL application. The setup includes a biomass feed, recycled process liquid, a twin screw feeder, and a dual cylinder solids piston pump; see Figure 5.1.

The FELUWA hose pump is a very unique pump that should be further assessed for HTL application. The Zeilfelder Pumpen rotary lobe pump has many unique features not available from any of the other pump vendors, including 1) operation at high temperature, allowing it to be used as an HTL booster pump and 2) the ability to run backwards for process energy recovery; for HTL a single stage unit likely would be used for both of these options.

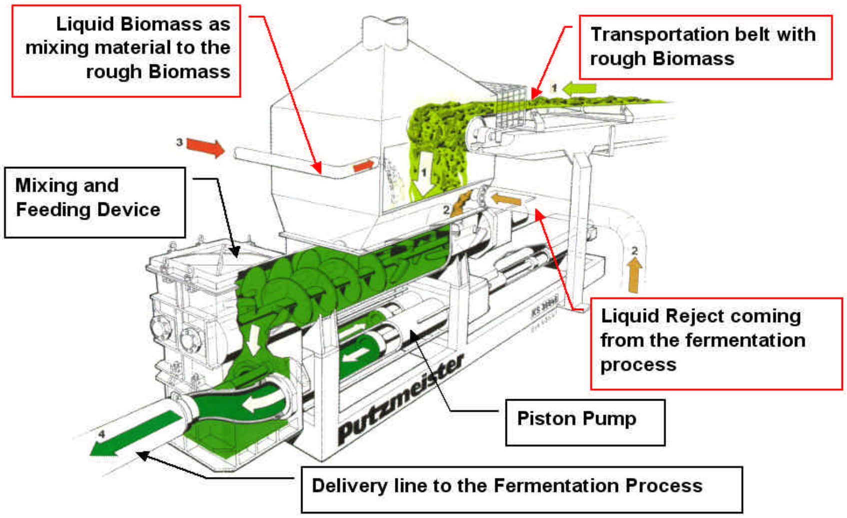

Figure 5.1. Biomass Pumping Application (information from Putzmeister literature)

6.0 Conclusion

Feeding and pumping HTL biomass appears to be viable with COTS equipment and specialized designs. All evaluated pumping vendors were confident of feeding and pumping a flowable biomass like the HTL finely ground (0.0012-in./30-micron/0.03-mm) wood feedstock at 15 wt% dry solids with the measured 4-in. (101-mm) slump used to perform laboratory bench-scale testing. HTL feedstock for the pilot and production plants likely will be more challenging to pump because of the desire to maximize the economics of the overall HTL process resulting in biomass feedstock with larger particle size estimated on the order of 0.08 to 0.16 in. (2 to 4 mm) or greater. All pump vendors concur that specialized design of the feed/pump system followed by pump testing is necessary to validate and optimize the biomass pumping at HTL pressure and temperature operating conditions.

A key economic factor to consider with pumping is the size reduction (i.e., grinding) of raw HTL feedstock as large as 3 in. (76 mm), which is energy intensive and costly. Size reduction was outside of the scope of this pump assessment; however, all biomass pumps have particle size limitations. Larger particles may be more difficult to pump because of various operating phenomena (e.g., biomass feedstock dewatering in the pump cavity) that result in decrease flowability and pumpability of the biomass material. Size-reduction costs increase as target particle size decreases and some discussions indicate that costs may increase significantly once a threshold is reached (e.g., 0.08 in. [2 mm] and smaller). HTL scoping tests conducted using specific particle sizes in a batch autoclave indicate similar HTL process yields of oil, gas, and solids for particle sizes in the range of 0.08 to 0.24 in. (2 to 6 mm). Therefore, the progression to larger size particles is not expected to affect the process chemistry.

Because biomass feedstock can have many variables (e.g., type, particle size, moisture content), pumpability testing is highly recommended for any new biomass feedstock, including HTL feedstock, for pump selection and required feed and pump options. For many materials, pumpability assessments can be made at operating pressures below the maximum. This is often done in instances where a series of pumps are required to obtain the desired final operating pressure. The assessment is first performed using a single pump to determine pump performance. In the case of coarse (i.e., large particle) biomass slurries, dewatering (i.e., material segregation) within the pump can become a factor at higher operating pressures. Therefore, the assessment of the pumpability of a biomass feedstock at reduced pressure introduces/increases technical risk with an increase in the particle size that is not experienced with other materials. A pumpability assessment at full-scale and maximum operating pressure is recommended.

For this HTL pumping application, solids piston pumps are well-proven designs and likely the base choice to be considered. Diaphragm pumps, especially the hose pump, should be considered due to unique pumping characteristics that may be favorable in this pumping application. The rotary lobe pump with chopper blades is unique and lends itself well to the front-end HTL pumping application and to in-process applications at HTL temperatures as a booster pump. In addition, it can be configured in reverse for energy recovery via pressure letdown. Past success with feeding and pumping HTL-type biomass at high pressures has been limited and at reduced scale. Various new feed and pumping options (i.e., piston, diaphragm, and rotary lobe) from the vendors assessed in this report and recent successes in pumping challenging feedstock command renewed optimism for the pumpability of high-pressure HTL biomass feedstock.

Appendices

Appendix A – Pump Vendor Comparison Summary
Appendix B – Pump Vendor Contact Details
Appendix C – "PNNL Biomass Process Feed & Pump Equipment Needs" dated November 3, 2011
Appendix D – "Pumpability Assessment Query by PNNL to Vendors" dated early December, 2011
Appendix E – Other Vendors Explored/Contacted/Summary Results

Appendix A

Pump Vendor Comparison Summary

Appendix A

Pump Vendor Comparison Summary

	Putzmeister	Schwing Bioset	Weir Minerals	FELUWA	ABEL	Zeilfelder Pumpen
PUMP PROPOSED						
Pump Type	Piston	Piston	Piston	Diaphragm (Hose)	Diaphragm (Membrane)	Lobe (Specialized Chopper)
Pump Cylinders	Two	Two	Two	NA	NA	NA
Stroke Rate (strokes/minute)	Typically less than 10		Varies, High up to 50, Low down to less than 10, Typical 15 – 35		NA (Rotary)	
PUMP CHARACTERISTICS						
Pressure (continuous)	1885 psi (130 bar) [c]	3000 psi (206 bar)	3200 psi (220 bar)	3000 psi (206 bar)	3625 psi (250 bar)	3625 psi (250 bar) / 710 psi (50 bar) per stage
Max Pressure (continuous) Available	1885 psi (130 bar) [c]	3000 psi (206 bar)	4350 psi (300 bar)	4600 psi (320 bar)	3625 psi (250 bar)	3625 psi (250 bar) / 710 psi (50 bar) per stage
Temperature (Normal)	194°F (90°C) [c]	210°F (99°C)	210°F (99°C)	257°F (125°C)	392 °F (200 °C), elastomer limit	99°C (210° F) to less than 350° C (662° F)
Temperature (High) Special Materials	212 – 221 °F (100-105 °C)	250°F (121°C)	266°F (130°C)	392°F (200°C)	572 °F (300 °C)	450°C (842°F)
Maximum Particle Size (Proposed)	0.315 in. (8 mm / 8000 microns)	2 in. (50.8 mm / 50,800 microns)	0.5 in. (12.7 mm / 12,700 microns)	Large 3+ in. (75 mm / 75,000 microns)	0.25 in. (6.35 mm / 6500 microns)	4 in. (101 mm / 101,000 microns)
Maximum Solid Content – Biomass	45% (biosolids)	40% (biosolids)	22% (organic sludge)	15% + [a]	up to 10%; more if flowable	up to 18%
Maximum Solid Content – Other	up to 85%	up to 80%	up to 85% (coal slurry)	up to 80%	up to 75%	up to 90%
Identified Fibrous Biomass Experience	paper sludge, corn stover, straw	wood chips, wood dust	None identified (sewage sludge)	ground corn mixture	wine lees, wood chips?	grass, straw, corn silage
Vendors Offering Similar Pumps	Schwing Bioset, Weir Minerals, ABEL	Weir Minerals, Putzmeister, ABEL	Schwing Bioset, Putzmeister, ABEL	Weir Minerals (Undeveloped for biomass)	FELUWA, Weir Minerals	None
PUMP VALVES						
Valve Proposed	Poppet (i.e., Disk)	Swing Tube (i.e., Rock Valve)	Poppet (i.e., Poppet Cone)	Poppet or Special Design	Poppet (Cone Valve)	None Required (Only Pressure Relief)
Valve Force	Hydraulic	Hydraulic	Hydraulic	Hydraulic	Spring	NA
BIOMASS PUMPING ASSESSMENT						
Pump Base HTL Feedstock[a]?	Yes	Yes	Yes	Yes	Yes (solid content around 10%)	Yes
COMPANY						
Company Location (Country)	Germany	USA	Netherlands	Germany	Germany	Germany
Company Size (employees)	Large	Small	Large	Medium	Medium	Small
Years In Pumping Business	25+	20+	50+	50+	50+	50+
RELATED FEED/PUMP EQUIPMENT						
Screw Feeders Available?	Yes	Yes	Yes	Yes	Yes	Yes, External Purchase
Turnkey System Available?	Yes	Yes	Yes	Yes	Yes	No

	Putzmeister	Schwing Bioset	Weir Minerals	FELUWA	ABEL	Zeilfelder Pumpen
Other Pump Type Options Available?	Unknown	No	Yes, Diaphragm (Hose & Membrane)	Yes, Diaphragm (Membrane)	Yes, Piston Pump	Gear
PILOT PLANT INFORMATION						
Cost	None (No proposal)			Ranging from \$100,000 to \$750,000[(b)]		
Pump Model	None (No proposal)	KSP 65 H(HD)R	DHC 10180	ZGL 30/130 – K 56 – DS 4 HD	HMT-Q-100-0060	T-REX 32 & T-REX 50
Number of Pumps	None (No proposal)	1	1	1	1	6 in series to achieve pressure
Flow rate	None (No proposal)	30 gpm (6.81 m^3/hr)	0.5 – 40 gpm (0.114 – 9.1 m^3/hr)	0.5-3 gpm (0.14 – 0.83 m^3/hr)	44 gpm (12.2 m^3/hr)	4.23-39.63 gpm (1.17 – 10.98 m^3/hr)
Total Power Required	None (No proposal)	250 HP (186 kW)	160 HP (120 kW)	40 HP (30 kW)	125 HP (93 kW)	151 HP (113 kW)
Estimated Lead Time	None (No proposal)			20 – 60 weeks		
PRODUCTION PLANT INFORMATION						
Cost	Ranging from \$4 to 10 million[(b)]					
Pump Model	HSP 25100 HP or HSP 2180 HP	KSP 65 H(HD)R	DHC 26280	QGK 1000/500	HMT-Q-1000-2000	T-Rex 50 / T-REX 80
Number of Pumps	7	12 [(S1)]	6	2	3	6 in series to achieve pressure, maybe 2 lines
Total Power Required	Some Unknown, Others Ranging from 6000 to 8000 HP (4500 – 6000 kW)					
Estimated Lead Time	Some Unknown, Others 24 – 60 weeks					

(a) HTL finely ground (30 micron) wood feedstock at 15% weight dry solids with a measured 4-in. slump
(b Cost conversion base on September 2012 average of \$US 1.29/EURO.
(c) Does not meet minimum HTL requirements – Reference: "PNNL Biomass Process Feed & Pump Equipment Needs" of November 3, 2011

gpm – gallons per minute; HP – horsepower; HTL – hydrothermal liquefaction; kW – kilowatt; m – meter; mm – millimeter

Appendix B

Pump Vendor Contact Details

Appendix B

Pump Vendor Contact Details

Contact Information	ABEL	FELUWA	Putzmeister	Schwing Bioset	Weir Minerals	Zeilfelder Pumpen
Contact	Rick Kesler	Heinz Naegel	Robert "Bob" Liebermann (Pumpaction Corp.)	Joshua R. Di Valentino	Charilos Karambalis	Christian Bornstein
Contact Title	Area Sales Manager	Managing Director	Western US Sales Manager at Pumpaction Corporation	Western Reginal Sales Manager	Product Manager GEHO Pumps	Owner
Contact E-mail	rkesler@abelpumps.com	Naegel@feluwa.de	bliebermann@pumpaction.com	jdivalentino@schwingbioset.com	c.karambalis@weirminerals.com	bornstein@zeilfelder-pumpen.com
Contact Phone	(303) 278-2550	+49 6594 / 10 215	(714) 377-9348	(715) 247-3433	+31 77 3895 135	+ 49 (53 08) 69 38 11 2
Contact Cell Phone	(303) 895-8858		(714) 580-9106	(612) 867-4429	+31 650 663 208	+ 49 (1 74) 90 88 86 6
Website	www.abelpumps.com	www.FELUWA.com	http://www.putzmeister-solid-pumps.com/enu/index.htm	http://www.schwingbioset.com	www.weirminerals.com	www.zeilfelder-pumpen.com
Company Name	ABEL Pumps, L.P.	FELUWA Pumpen GmbH	Putzmeister Holding GmbH	Schwing Bioset Inc.	Weir Minerals Netherland b.v.	Zeilfelder Pumpen – part of – ASM Dimatec Deutschland GmbH
Company Location	USA	Germany	Germany	USA	Netherlands	Germany
Company Address	17778 W. 59th Place Golden, Colorado 80403	Beulertweg 10 D-54570 Murlenbach	Max-Eyth-Str. 10 72631 Aichtal Germany	350 SMC Drive Somerset, WI 54025	Egtenrayseweg 9 – 5928 PH Venlo – The Netherlands P.O. Box 249 – 5900 AE Venlo – The Netherlands	Lehmkuhlenfeld 2 Wolfsburg 38444 Bundesrepublik Deutschland

Appendix C

"PNNL Biomass Process Feed & Pump Equipment Needs" dated November 3, 2011

Appendix C

"PNNL Biomass Process Feed & Pump Equipment Needs" dated November 3, 2011

PNNL Biomass Process Feed & Pump Equipment Needs

Problem Statement:
An equipment solution for the front end portion of the biomass processing system, consisting of a **Feed** and **Pump** system (see Figure 1), is needed to move a biomass feedstock to a downstream process for both a **Pilot** and a **Productio**n scale system (See Figure 2).

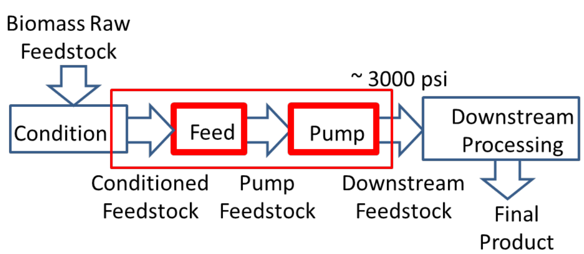

Figure 1 – Biomass Processing System

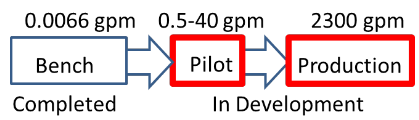

Figure 2 – Biomass Process Scale-up

Bench scale testing of a biomass processing system has been successfully completed (see History) and larger scale development and testing is required to prove the process at production levels. Near term development is a **Pilot** scale system on the order of 0.5 to 40 gpm followed by a larger **Production** scale system on the order of 2300 gpm (raw feedstock rate at 2000 DMTPD). The challenge is to **Feed** a highly viscous fibrous biomass wood / corn stover feedstock into a **Pump** system that subsequently provides the required 3000 psi of pressure for downstream processing. The pumping system developed for the Pilot scale must be scalable to Production scale. Feed and Pump requirements as well as associated process variances that can be considered are described in Attachment 1-Table 1.

Near Term Needs From Vendor:

1. Provide a conceptual feed and pump system to meet the requirements for the Pilot and Production facilities. Include specifications/cutsheets of proposed equipment and any related options to consider.
2. Provide a rough order of magnitude (ROM) cost estimate for the proposed systems, Pilot and Production, that we can use in our technical economic analysis (TEA).

The following would be helpful in evaluating the proposed conceptual system

3. Past Experience - Describe / show any experience in similar applications at pressure; flow rate is not as important as multiple units can be used. Describe any applications that were specifically related to using biomass.
4. Extended Capabilities of System
    a. Pressure verses Flow – Range of pressure / flow rates available with pumping system(s). Other pump sizes or pump options can be presented.
    b. Particle Size – Describe the largest particle size that can be handled.
    c. Solids Loading – Describe the highest solid loading (% dry weight) that can be handled.

   d. Impact of Rheology Variance – Describe extent system may react to slight variances to the rheology described for the biomass feedstock.

5. For Proposed System (Pilot & Production Scale)
   a. Feed Options – Describe any feed options to consider for biomass material.
   b. Fibrous Material Handling – Describe any special feature supplied to handle the fibrous biomass material. Check valves are of special concern.
   c. Power Usage – Describe power consumption at the flow rate ranges for the pilot scale and production scale systems.
   d. Space Requirements – Describe the space requirement for the feed and pump system including any ancillary equipment for the pilot scale and production scale systems.
   e. Supporting Utilities – Describe the various outside connections (power, water, etc.) required for system operation.

Future Applications:

The activities are part of a multi-year, multi-million dollar, effort being executed by a national consortium comprised of 17 industry, national laboratory, and university partners, under the direction of the U.S. Department of Energy. The effort is focused on the development and commercial deployment of technologies to convert lignocellulosic biomass feed stocks to biofuels that are compatible with the existing transportation infrastructure. The consortium will integrate these technologies with existing refineries and distribution networks.

Near term (<2 years) activities include pilot-scale pump ability demonstrations, and the development of a pilot ready process. Longer term objectives include the commissioning of a 2000 dry metric ton per day (DMTPD) production plant, which will be followed by distributed industrial applications.
Successful demonstration of this biomass conversion process at the prototype and production phases will likely follow with industrial applications at multiple locations in the USA and beyond.

Feed & Pump Process Description: (Reference Figure 1 and Attachment 1 - Table 1)

Raw biomass feedstock is obtained from the harvesting of wood and corn. The raw wood feedstock is forest-type materials that have been size reduced by a chipper or grinder and the raw corn stover feedstock is dried corn stalks that have been chopped. Biomass feedstock is shipped to the processing plant and staged until used. Further condition may be done at the plant prior to feeding and may include further size reduction and the addition of water to lower the solid content. Some final biomass feedstock conditioning steps that use recycled process "water" and small volumes of process materials are described under Biomass Feedstock Properties and Characteristics.

The feed system acquires the biomass feedstock by either a batch or continuous loading process and then continuously feeds the biomass feedstock to the pump inlet. From the pump inlet, the pump internally pressurizes the biomass feedstock to the required downstream system pressure and passes the biomass feedstock into the downstream processing piping.

Note: A batch loading process could consist of using a feed hopper that is supplied with biomass feedstock from a front end loader bucket or a conveyor. Some final biomass feedstock conditioning steps may be best performed as part of the feed and pump system.

Biomass Feedstock Properties and Characteristics: (Reference Attachment 1-Table 1, Attachment 2-Biomass Feedstock Info)

The fibrous base raw feedstock is pine wood chips (45% dry weight solids) OR corn stover (90 weight % dry solids) mixed with water to form a paste-type mixture (nominally 15% dry weight solids) that is highly viscous with non-Newtonian flow properties. Small amounts of other material may be added to this biomass feedstock to aid in downstream processing such as adjusting the pH, etc. (i.e., Na_2CO_3, added at about 1% weight on slurry). In the prototype and production scale systems, an aqueous stream (process recycle) containing ~5% weight organic acids and alcohols (glycolic acid, acetic acid, methanol, ethylene glycol) will be used as the make-up water for the biomass slurry.

Current available information about the biomass feedstock is summarized in Table 1. Attachment 2 contains current information and references related to the biomass raw feedstock and biomass conditioned feedstock. Rheological characterization is still in progress for some of the biomass feedstock and variables being considered. Key process variables are particle size and solid loading % dry weight. Other process variables to be considered are pressure and temperature.

History – Bench Scale Testing:

Laboratory bench-scale testing has been successfully completed. The feed system for the bench scale system was to mechanically batch load the pine wood / water mixture (20 micron grind) into vertical cylinders that were pressurized with 30 psi air to move the material through piping to the pumping system. The pumping system utilized two small syringe pumps operating alternately in tandem to achieve the 3000 psi pressure and continuous flow. The syringe pumps are not scalable to production scale so therefore are not being considered for prototype / production testing. Flow rate of the bench-scale system ranged from 0.5 to 4 liters/hour with a nominal flow rate of 1.5 liters/hour. After pressurization, the approximate slurry velocity in the 0.37 inch ID process tubing is approximately 1 cm/sec. Significantly higher velocities are being targeted in the prototype and production scale systems.

Process Enhancements Desired:

Reduction in cost of the overall process is highly desirable and may include some of the following that could affect the feed and pumping systems:

1. Accept Larger Particle Size – Currently larger raw feedstock requires additional cost to further reduce the particle size down to as small as 20 micron by chopping, grinding, and milling operations. This size reduction is done to aid in biomass feedstock flowability and consistency to the downstream processes. Less particle size reduction or particle size blending should reduce feedstock conditioning cost and may reduce overall capitol and operational cost. Downstream processing is unaffected by particle size, however, the feedstock rheology and consistency changes due to larger and/or blended particle sizes is unknown.
2. Accept Higher Solids Loading – Currently raw feedstock solids loading, ranging from 45 to 90% dry weight solids, is reduced to as low as 13% dry weight solids to increase feedstock flowability and consistency. Lower solid content reduces the downstream process efficiency. Solids loading above 18% dry weight solids or more likely would result is lower finished product cost. Very high solids loading on the order of 20 – 35%+ dry weight solids would be highly desirable for process efficiency. Feedstock rheology changes and consistency changes due to increased solid loading is unknown but is expected to make the feedstock much more viscous, dry, and sticky.

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Attachment 1

Table 1- Feed & Pump Requirements

	Bench Scale	**Pilot Scale**	**Production Scale**	**Notes:**
Process Variables	**(Reference Only)**	**(Near Term)**	**(Future)**	
Biomass Raw Feedstock - (As Shipped)	a. Woody Chips (with bark) - Size: Length (2 -8 inches) by Width (1- 2 inches) by Thickness (up to 0.5 inch); 45 - 50% dry weight solids. b. Corn stover (dried corn stalks) - Size: Smaller than woody chips; 95% dry weight solids.			As received raw material with no processing and no size reduction. Shipped dry bulk. [See tab "Wood&CornFeedstock-AsReceived"]
Biomass Conditioned Feedstock	Feedstock to be sized reduced and % dry solid weight concentration adjusted to meet process and / or pumping requirements. Processing steps can occur before feed system, as part of feed system, or in pump. Solids concentration will be lowered by the addition process recycled water and additional make-up water as needed.			Required feedstock processing from received raw material. Recycled water supplied at around 50 psi at approximately 200 °F. Some process material, like Na_2CO^3 ~1% weight, may be added to aid downstream processing.
Biomass Feedstock - Downstream Feedstock	Sized reduced and solid concentration has occurred to make a pumpable slurry or paste.			Feedstock at outlet of pump.
Particle Size - Size Reduction	20 microns (0.000787 inch)	Estimates of material size reduction required to meet flow and/or pumping range from 0.25 inch (6 mm) down to 0.03125 inch (less than 1 mm).		Minimal processing of raw feedstock is desired based on economics. Blending of particle sizes is acceptable and may have benefits for minimizing voids / air entrainment. Downstream processing is not affected by particle size.
Solids Concentration	10 - 18% dry weight solids	Nominally 15% dry weight solids. Maximum 20% dry weight solids or more as limited by flowability. Moisture content is estimated at 98% water with 2% organics acids and alcohols.		Higher % dry solids weight is desired based on economics. Higher solids concentration may be limited by resulting pumpability. Based on past experience, limit of solids concentration may be on the order of 20 – 25% dry weight solids. Downstream processing is not affected by increased solids concentration.

Feed System	Raw or pre-processed feedstock is piled and stored at the facility prior to use. Feedstock is then moved to the feed system by various means that could include batch and/or continuous processes. Production scale feed is 2000 dry metric tons per day.			Simplest initial feed process is likely a loader moving material from the pile to a hopper or conveyance belt.
Feed Pressure (psi)	As needed.			Various feed system may require pressure or other mechanisms to feed feedstock to the high pressure pump; this could include lower pressure pumping systems.
General Feedstock Properties	pH Range: 5 - 8 Abrasitivity: Up to 3% weight ash content			Feedstock ranges from neutral to slightly acidic. Abrasitivity is mild. Fibrous materials based from wood feedstock (chopped forest growth) and corn feedstock (dried corn stalk and husks).
Rheology - In Process Material	For wood feedstock see Datasheet WP (20 micron). For corn stover feedstock see Datasheet CP(???).	Rheology data is in progress. For wood feedstock see Datasheets WP (???) For corn stover feedstock see Datasheets CP (???)		Material to be pumped is highly vicious and exhibits non-Newtonian flow properties. The rheology will be affected by the variances in particle size/distribution, solids concentration, and to some extent temperature. Specific gravity is > 1 but generally not more than 1.05.
Pump System	Feedstock is fed to the pump inlet by the Feed System. Air entrainment should be minimized. Some flow pulsation likely can be tolerated. Continuous pumping of feedstock is required at pump outlet to downstream process.			The pump can contain all or part of the Feed System.
Pump Outlet Pressure	3000 psi (206 bar)	2700 - 3200 psi (186 -220 bar)	3000 - 3200 psi (206 - 220 bar)	Maintaining high pressure is required for the downstream process to convert and maintain the biomass and water media to a liquid phase. Liquefaction of biomass occurs at 300°C and above. For water to remain a liquid, the temperature of the water must remain below its critical temperature of 374°C. The expected 350°C processing temperature with a 10°C error margin requires 2,800 psi to keep water in its liquid phase. Maximum pressure of 3200 psi is used to allow for up to 500 psi downstream pressure loss.

Pump Temperature	NA	210 °F (99 °C)		Estimated based on mixed temperature of ambient feedstock and recycled process water supplied at 230 - 240 °F and 50 psi.
Flow Rate (gpm) of 15% dry weight solids	0.0066 (0.0245 liters/min)	0.5 - 40 (2 - 150 liters/min)	2300 (8706 liters/min)	Flow rate can be obtained by using multiple pump units. For the pilot scale, a split flow can be used to meet flow rate. Flow rate can be reduced for higher solids loadings.
Flow Velocity	Scale up from Bench may require the flow to reach turbulent conditions.			Flow velocity can be adjusted by downstream process pipe sizing as required.
Estimated Maximum Pipe Diameter Downstream of Pump (inches)	NA	0.75 - 1.00 (19 - 25 mm)	2.0 - 4.0 (51 - 102 mm)	Estimated only. This should not influence pump outlet size. Downstream piping may vary depending on process requirements including manifolding up or down for multiple process streams.
Equipment Operation	Continuous	Continuous with 90% on stream		Feed system is allowed batch processing as long as feedstock exiting pump to process is continuous.
Plant Resources	NA	Power, Water, Steam		Power > 240V, 1 or 3 Phase/60Hz (480V likely available at Production scale) Water > As Needed Steam > Likely at Production scale

Attachment 2

Biomass Feedstock Information

1. **Biomass Feedstock Currently Under Consideration for Use In Process**

   a. **Wood Feedstock**
      i. Raw Feedstock – Southern Pine Residual Forest Product (RFP)
         1. See Raw Feedstock Description
      ii. Conditioned Feedstock – Made from Raw Feedstock
         1. Immersion Milled Pine Slurry - Finely Ground to 20 micron. In small bench scale testing, after feed preparations (immersion milling and water addition) for a solids loading of 13% dry weight solids, the pine wood mixture has flow properties similar to play dough (i.e. when a small ball of material is squeezed in a hand the material will uniformly squeeze out between the fingers). Particle size is primarily 20 microns or less (D50) with some particles as large as 400 microns (D99) scattered in the mix.
            a. See Rheology Testing
               i. Shear
               ii. Slump
            b. See Particle Size Distribution
         2. -1/16-in. Pine Slurry – Mill to pass through a 1/16- inch screen
         3. -1/4-in. Pine Slurry – Mill to pass through a 1/4- inch screen

   b. **Corn Feedstock**
      i. Raw Feedstock
         1. See Raw Feedstock Description
      ii. Conditioned Feedstock – Made from Raw Feedstock
         1. Corn Stover-200 to 400 microns
         2. Some rheology for the corn stover mixture has been published (Stickel et al. 2009, Viamajala et al., 2009)

   c. **Reference Material** (* downloadable from Internet)
      i. *Article - Particle Concentration and Yield Stress of Biomass Slurries During Enzymatic Hydrolysis at High-Solids Loadings (Christine M. Roche, Clare J. Dibble, Jeffrey S. Knutsen, Jonathan J. Stickel, Matthew W. Liberatore) Published online 27 April 2009 in Wiley InterScience (www.interscience.wiley.com) DOI 10.1002/bit.22381
      ii. *Report - Particle Morphology Characterization and Manipulation in Biomass Slurries and the Effect on Rheological Properties and Enzymatic Conversion (Clare J. Dibble, Tatyana A. Shatova, Jennie L. Jorgenson, and Jonathan J. Stickel) DOI 10.1002/btpr.669, Published online in Wiley Online Library (wileyonlinelibrary.com).
      iii. *Report - PNNL- 16079, 3.1.1.2 Feed Processing and Handling DL2 Final Report (DC Elliott, JK Magnuson, CF Wend) September 2000
      iv. *Article - Rheological Study of Comingled Biomass and Coal Slurries with Hydrothermal Pretreatment (Wei He, Chan S. Park, and Joseph M. Norbeck), Energy Fuels 2009, 23, 4763–4767 : DOI:10.1021/ef9000852, Published on Web 05/26/2009
      v. *Report - Rheology of corn stover slurries at high solids concentrations – Effects of saccharification and particle size (Sridhar Viamajala, James D. McMillan, Daniel J. Schell, Richard T. Elander), Bioresource Technology
      vi. * Report - Rheology measurements of a biomass slurry: an inter-laboratory study (Jonathan J. Stickel, Jeffrey S. Knutsen, Matthew W. Liberatore, Wing Luu,DouglasW. Bousfield, Daniel J. Klingenberg · C. Tim Scott, Thatcher W. Root, Max R. Ehrhardt, Thomas O. Monz) Rheol Acta (2009) 48:1005–1015 DOI 10.1007/s00397-009-0382-8

vii. *Article - Rheology and extrusion of high-solids biomass (C.Timothy Scott, Joseph R. Samaniuk, Daniel J. Klingenberg) MAY 2011 | TAPPI JOURNAL
viii. *Article - Physical Pretreatment – Woody Biomass Size Reduction – for Forest Biorefinery - In Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass; Zhu, J., et al.; ACS Symposium Series; American Chemical Society: Washington, DC, 2011
ix. *Article - Particle Morphology Characterization and Manipulation in Biomass Slurries and the Effect on Rheological Properties and Enzymatic Conversion (Clare J. Dibble, Tatyana A. Shatova, Jennie L. Jorgenson, and Jonathan J. Stickel) DOI 10.1002/btpr.669 Published online in Wiley Online Library (wileyonlinelibrary.com)

2. Raw Feedstock Description

a. Wood Feedstock

b. Corn Feedstock

Figure B2. Photographs of raw stover material collected from rear of combine with row crop head and prototype shear type chopper. Material collected over 7.62 cm screen (A), 5.08 cm screen (B), 2.54 cm screen (C), 1.27 cm screen (D), 0.635 cm screen (E) and above pan (F), are shown.

3. Conditioned Feedstock Description

   a. **Size Reduction Steps**

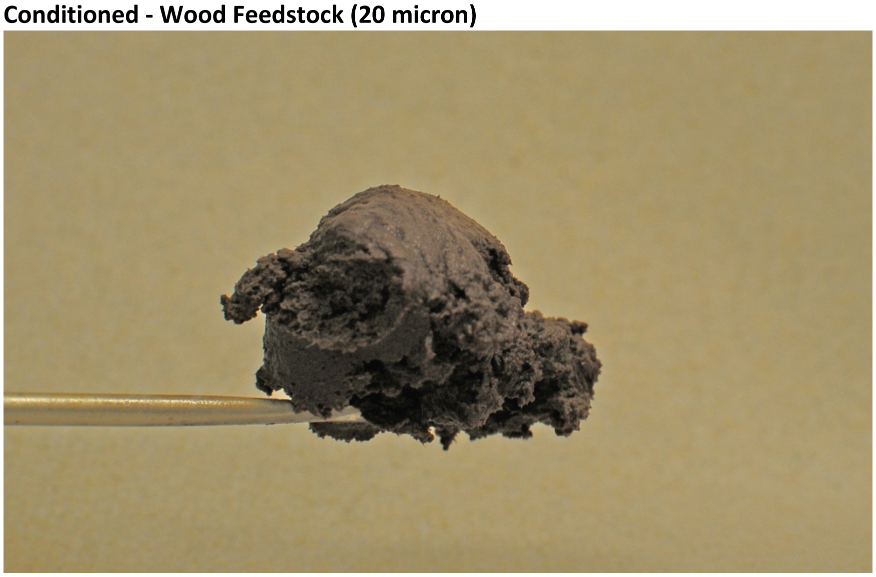
   The conditioned feedstock material sent to PNNL was not sieved pan material. After collection and drying all material (wood and stover) was ground using an Arts-Way Hammer mill through a ¼ inch screen, and placed in 220 gal bulk containers.

   Further size reduction of the material was carried out with Schutte-Buffalo Circ-U-Flow model 18-7-300 Hammer mill (capacity 200 lbs./hour). To reduce material to the 0.5-1.5mm feedstock specifications, 20 mesh screen (0.853 mm opening) was utilized and for the 200-400 micron specifications, the 20 mesh screen was replaced with a screen with approximately 400 micron screen opening.

   Therefore all material sent was not screened material, it was the complete material sized to by initial reduction in the Arts-Way to 1/4 inch then further reduction to the smaller sizes using the Schutte-Buffalo.

   The corn stover and wood chips were treated to the same size reduction methods, although how they responded was very different. In general, the wood chips produced a much narrower size distribution and lower fines (and therefore less dust), while the corn stover had much greater particle size distribution and produced much more fines particularly when dry.

   b. **Conditioned - Wood Feedstock (20 micron)**



   c. **Conditioned - Corn Feedstock**

   No photo available at this time.

4. **Rheology Testing -** Wood Feedstock (20 micron)

Biomass RHEOLOGY Update - October 20, 2011

Background: A series of rheology tests have been planned for the two different biomass feedstocks of wood product & corn stover. The feedstock parameters to be varied in these tests include particle size (up to 400 micron), moisture content (above 20 weight % solids), and in some cases temperature (up to 80 °C). Rheology testing will include shear vane, rheograms, and slump.

Rheology Test Results:

These are preliminary results. Plans call for additional rheology testing including constant strain rate tests and slump test. These results will be passed along as soon as they are available.

Biomass Feedstock Tested: Wood Product - Forest Product Run (FPR) Post Immersion Mill, ~ 13 weight % Solids, Particle Size ~ 20 micron d(0.5). See photo and particle size distribution information / figures following. Note: The Pilot and Production application is expected to have larger particle size (400 micron or greater) but may have a similar solid loading (12 – 15 weight % solids or greater).

Two types of rheology tests were performed: 1) shear vane tests for direct measurement of shear strength and 2) rheogram for shear rates between 200 and 500 s^{-1}. This data was used to model the material as a Bingham plastic:

$\tau = \gamma\mu + Y_s$ where:

τ = applied shear stress (Pa)

γ = shear rate (s^{-1})

μ = plastic viscosity (Pa s)

Y_s = Yield stress in shear

This results in a plastic viscosity on the order of **0.8 to 1** Pa s and Yield stress in shear of approximately **650** Pa. Rheograms for shear rates from **0 to 200** s^{-1} indicate a shear thinning behavior.

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Photo - Biomass Wood Product

Particle Size Distribution Analysis (Two Runs)

Result: Average d(0.1) = 4.0 microns, d(0.5) = 19 microns d(0.9) = 75 microns

5. **Slump Testing –** Wood Feedstock (20 micron)

PNNL Biomass Product Slump Testing - October 26, 2011

A. Preparation of Slurries of Biomass Product (wet Pine) for Slump Test Updated 10-27-11

Objective: Prepare samples of wet (undried) pine Forest Product Residual (FPR) to evaluate character of material for slump test

Slump Test Conducted with 2 Slurries on 10-26-11:
1) Left over Feed from Wood 8/9: Immersion milled, wt% solids = 13.02 wt% before Na2CO3 added
2) Wet Pine ~15wt%, as prepared below. Minus 1/16 inch material used. Na2CO3 added.

Required volume	339.292	in3
	5.55943	L
Need ~25% excess	7.412573	L
Assumed final density	1.03	g/ml

Final Slurry Target 7634.95 grams 76.3495 Add 4 gram of Na2CO3 to each sample

Sample ID	wet pine	15%	wt% Solids in Slurry		Size (micron)
	Wt% solids in wood	Dry Wood (grams)	Wet Pine (grams)	Water (grams)	
Wet Pine 1/4 inch, Xwt%	43.4%	1145.243	2636.80	4998.15	6350
Wet Pine 1/16 inch, X wt%	56.1%	1145.243	2041.21	5593.74	1587.5
Wet Pine 1/32 inch, wt%	63.1%	1145.243	1815.87	5819.08	793.75
Corn Stover 200 to 400μ, Xwt%	90.3%	1145.243	1267.70	6367.25	

Notes
Sample prepared on 10/26/11, and slump test performed. During loading the slump test system, significant dewatering was observed.
Actual Make up of Sample for Slump Test ***As Prepared:*** ***Wt% Solids, As tested (some dewatering was observed)***

Sample ID	15% Wet Pine	Water	Na2CO3	wt% Solids
Wet Pine 1/4 inch, 15wt%				
Wet Pine 1/16 inch, 15wt%	2041.5	5595	76.35	15.84%
Wet Pine 1/32 inch, 15wt%				
Corn Stover 200 to 400μ, 15wt%				

125.88	Tare, g
174.652	Tare+ Sample Wet
134.82	Tare+ Sample
18.3%	Wt% Solids Tested

(Actual as tested - from post test sampling)

B. Slump Testing Setup:

Slump Test Procedures: Slump testing procedures were based on ASTM C143/C143 M – 10 a "Standard Test Method for Slump of Hydraulic-Cement Concrete". The test apparatus consisted of a cone (12 inches tall, 8 inch diameter base, 4 inch diameter top) and tamping rod that met these ASTM standards.

Test procedures were modified to limit dewatering cause by the ASTM procedure for tamping. Test procedure modification involved inverting the cone during filling to minimize voids, with some tamping and tapping on the side. Next the cone was rapidly flipped over. Tamping and tapping were performed, and refilling of the top of the cone of material that oozed out at the bottom. For these feed materials, tapping the side of the cone was more effective at removing voids than tamping with the rod. This was the case in the two primary tests. In the very first tests (test depicted in two small photos), failure to tap on the side of the cone during cone lifting did not give good release of the product from the cone walls.

1 of 3

PNNL Biomass Product Slump Testing - October 26, 2011

C. Slump Testing:

C1. Immersion Milled Wood, Size 20 micron (Dp50):

C1a: Initial Slump Test with Immersion Milled Wood, Size 20 micron (Dp50), 13 Wt% Solids, Result > Repeat Test in C1b

Note: Test is not valid because cone did not release well when lifting and was repeated as C1b below.

Initial Slump Test with Immersion Milled Wood 13 wt%.
Left, 1 minute; Right, 2 minutes, No Slump Data Resulted

C1b: Slump Test with Immersion Milled Wood, Size 20 micron (Dp50), 13 Wt% Solids > Result: 4 inch of Slump

Note: Repeat test after C1a test failure. Material from C1a was reused and this time successfully released from the cone was achieved by additional tapping/vibrating of the cone when lifting.

Slump Test, Immersion Milled Wood Feed, 13wt% Solids, Start of test

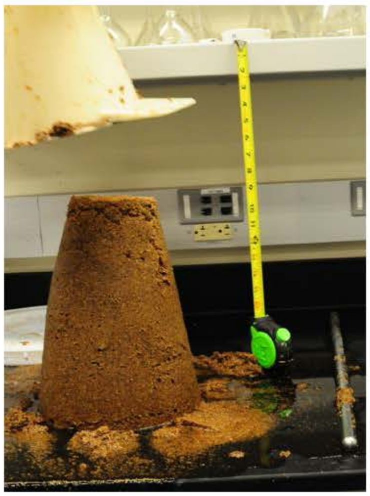
Slump Test, Immersion Milled Wood Feed, 13wt% Solids, 1 minute.

Slump Test, Immersion Milled Wood Feed, 13wt% Solids, 2.5 minutes, 4 inches of slump.

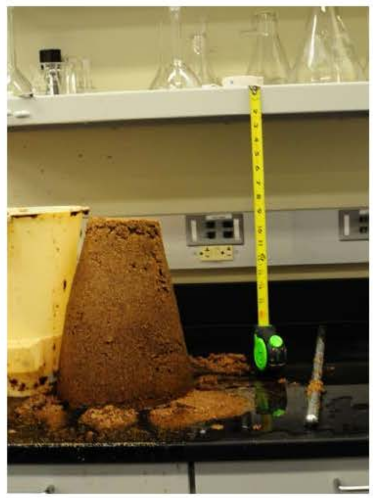
PNNL Biomass Product Slump Testing - October 26, 2011

C2. Minus 1/16 - inch Wet Wood

C2a: Slump Test, Performed with Minus 1/16 - inch Wet Wood (18.3 wt% post-test) > Result: 0.5 inch of Slump
Note 1: Solid content of material was measured at 15.84 wt% pre-test and remeasured after test as 18.3 wt%. Higher solid content after test from dewatering during test setup and continued dewatering during testing. Tamping material during test setup exacerbated the dewatering so tamping was reduced. Additional dewatering was visible during slump test time of 4 minutes.
Note 2: If a handful of this material is squeezed in hand, some dewatering will occur.



Slump Test, -1/16-in. Wet Wood, 18% Solids, Start of Test. (Note dewatering of Material)



Slump Test, -1/16-in. Wet Wood, 18% Solids, After 4 minutes, 0.5 inches of slump. Further dewatering is evident.

6. Particle Size Distribution – Wood Feedstock (20 micron)

MALVERN INSTRUMENTS

MASTERSIZER 2000

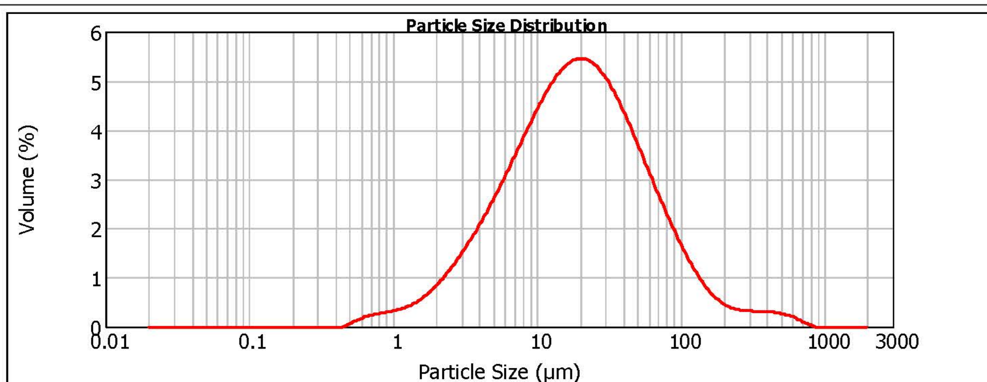
Result Analysis Report

Sample Name: FPR Slurry Feed-1-Unsonicated - Average	**SOP Name:**	**Measured:** Monday, September 19, 2011 4:50:37 PM
Sample Source & type:	**Measured by:** D3M966	**Analysed:** Monday, September 19, 2011 4:50:39 PM
Sample bulk lot ref:	**Result Source:** Averaged	

Particle Name: Sawdust	**Accessory Name:** Hydro 2000G (A)	**Analysis model:** General purpose	**Sensitivity:** Normal
Particle RI: 1.530	**Absorption:** 0.1	**Size range:** 0.020 to 2000.000 um	**Obscuration:** 9.42 %
Dispersant Name: Water	**Dispersant RI:** 1.330	**Weighted Residual:** 0.801 %	**Result Emulation:** Off

Concentration: 0.0123 %Vol	**Span :** 3.944	**Uniformity:** 1.52	**Result units:** Volume
Specific Surface Area: 0.656 m²/g	**Surface Weighted Mean D[3,2]:** 9.143 um	**Vol. Weighted Mean D[4,3]:** 37.761 um	

d(0.1): 4.090 um **d(0.5):** 18.928 um **d(0.9):** 78.751 um



Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %	Size (µm)	Volume In %
0.020	0.00	0.142	0.00	1.002	0.25	7.096	2.75	50.238	2.66	355.656	0.23
0.022	0.00	0.159	0.00	1.125	0.29	7.962	2.99	56.368	2.40	399.052	0.23
0.025	0.00	0.178	0.00	1.262	0.33	8.934	3.22	63.246	2.13	447.744	0.21
0.028	0.00	0.200	0.00	1.416	0.39	10.024	3.44	70.963	1.87	502.377	0.19
0.032	0.00	0.224	0.00	1.589	0.48	11.247	3.63	79.621	1.62	563.677	0.16
0.036	0.00	0.252	0.00	1.783	0.58	12.619	3.81	89.337	1.38	632.456	0.10
0.040	0.00	0.283	0.00	2.000	0.69	14.159	3.95	100.237	1.16	709.627	0.05
0.045	0.00	0.317	0.00	2.244	0.82	15.887	4.04	112.468	0.95	796.214	0.00
0.050	0.00	0.356	0.00	2.518	0.96	17.825	4.10	126.191	0.77	893.367	0.00
0.056	0.00	0.399	0.00	2.825	1.12	20.000	4.10	141.589	0.60	1002.374	0.00
0.063	0.00	0.448	0.01	3.170	1.28	22.440	4.06	158.866	0.48	1124.683	0.00
0.071	0.00	0.502	0.07	3.557	1.46	25.179	3.96	178.250	0.38	1261.915	0.00
0.080	0.00	0.564	0.12	3.991	1.65	28.251	3.82	200.000	0.31	1415.892	0.00
0.089	0.00	0.632	0.16	4.477	1.85	31.698	3.64	224.404	0.27	1588.656	0.00
0.100	0.00	0.710	0.19	5.024	2.07	35.566	3.43	251.785	0.25	1782.502	0.00
0.112	0.00	0.796	0.21	5.637	2.29	39.905	3.19	282.508	0.24	2000.000	
0.126	0.00	0.893	0.23	6.325	2.52	44.774	2.93	316.979	0.24		
0.142		1.002		7.096		50.238		355.656			

Operator notes:

Malvern Instruments Ltd.
Malvern, UK
Tel := +[44] (0) 1684-892456 Fax +[44] (0) 1684-892789

Mastersizer 2000 Ver. 5.60
Serial Number : MAL1019545

File name: Biomass sample AJS.mea
Record Number: 4
9/19/2011 4:58:45 PM

MALVERN INSTRUMENTS

MASTERSIZER 2000

Result Analysis Report

Sample Name:
FPR Slurry Feed-1-Sonicated - Average

SOP Name:

Measured:
Monday, September 19, 2011 4:54:19 PM

Sample Source & type:

Measured by:
D3M966

Analysed:
Monday, September 19, 2011 4:54:20 PM

Sample bulk lot ref:

Result Source:
Averaged

Particle Name: Sawdust
Accessory Name: Hydro 2000G (A)
Analysis model: General purpose
Sensitivity: Normal

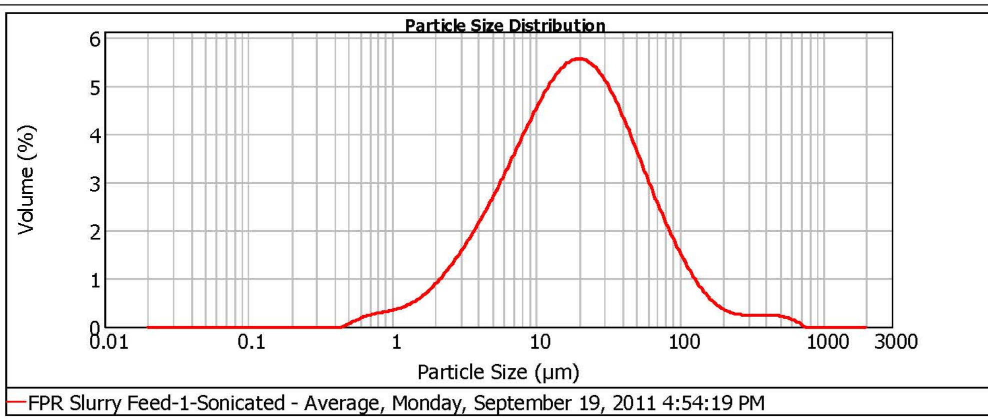
Particle RI: 1.530
Absorption: 0.1
Size range: 0.020 to 2000.000 um
Obscuration: 9.51 %

Dispersant Name: Water
Dispersant RI: 1.330
Weighted Residual: 0.821 %
Result Emulation: Off

Concentration: 0.0120 %Vol
Span : 3.748
Uniformity: 1.41
Result units: Volume

Specific Surface Area: 0.678 m²/g
Surface Weighted Mean D[3,2]: 8.845 um
Vol. Weighted Mean D[4,3]: 34.373 um

d(0.1): 3.959 um **d(0.5):** 18.219 um **d(0.9):** 72.240 um



Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %	Size (μm)	Volume In %
0.020	0.00	0.142	0.00	1.002	0.27	7.096	2.82	50.238	2.61	355.656	0.19
0.022	0.00	0.159	0.00	1.125	0.30	7.962	3.06	56.368	2.32	399.052	0.18
0.025	0.00	0.178	0.00	1.262	0.35	8.934	3.29	63.246	2.04	447.744	0.17
0.028	0.00	0.200	0.00	1.416	0.42	10.024	3.51	70.963	1.77	502.377	0.15
0.032	0.00	0.224	0.00	1.589	0.50	11.247	3.71	79.621	1.52	563.677	0.11
0.036	0.00	0.252	0.00	1.783	0.61	12.619	3.88	89.337	1.28	632.456	0.07
0.040	0.00	0.283	0.00	2.000	0.73	14.159	4.03	100.237	1.06	709.627	0.00
0.045	0.00	0.317	0.00	2.244	0.86	15.887	4.12	112.468	0.86	796.214	0.00
0.050	0.00	0.356	0.00	2.518	1.00	17.825	4.18	126.191	0.68	893.367	0.00
0.056	0.00	0.399	0.00	2.825	1.16	20.000	4.18	141.589	0.53	1002.374	0.00
0.063	0.00	0.448	0.02	3.170	1.33	22.440	4.12	158.866	0.40	1124.683	0.00
0.071	0.00	0.502	0.07	3.557	1.52	25.179	4.02	178.250	0.31	1261.915	0.00
0.080	0.00	0.564	0.13	3.991	1.71	28.251	3.87	200.000	0.25	1415.892	0.00
0.089	0.00	0.632	0.17	4.477	1.91	31.698	3.67	224.404	0.21	1588.656	0.00
0.100	0.00	0.710	0.20	5.024	2.13	35.566	3.44	251.785	0.19	1782.502	0.00
0.112	0.00	0.796	0.22	5.637	2.35	39.905	3.17	282.508	0.18	2000.000	
0.126	0.00	0.893	0.25	6.325	2.58	44.774	2.90	316.979	0.18		
0.142		1.002		7.096		50.238		355.656			

Operator notes:

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Appendix D

"Pumpability Assessment Query by PNNL to Vendors" dated early December, 2011

Appendix D

"Pumpability Assessment Query by PNNL to Vendors" dated early December, 2011

We are now seriously considering performing a near term pumpability assessment. In this pumpability assessment we would be looking for:

- reassurance that our fibrous feedstock material can be introduced and pumped with your equipment;
- determining any special feed/pump features or upgrades that may need to be incorporated into the equipment for:
    - PILOT – Short term demonstration
    - PRODUCTION – Full scale, long term plant success

We would anticipate testing some variations in the feedstock (type, particle size, moisture content) to determine ability to feed/pump the feedstock, as well as process limits and tradeoffs for overall process efficiency.

For this pumpability assessment, the ability to start testing quickly (3-6 month time frame) and to minimize cost may take some innovative thinking. Various options could be considered including using an existing test apparatus, testing at a facility with an installed pumping system, or providing a feed/pump system that could be installed at a third-party testing facility or PNNL.

1. What options can you provide that would allow a pump assessment to be performed?
2. What is the smallest pump you have available that you believe could adequately address feedstock pumpability and scale-up to the PILOT/PRODUCTION flow rates?
3. What parameters/metrics would you consider most important to verify during pumpability assessment for your equipment performance in the PNNL application to minimize uncertainty in the assessment of scale-up.
4. What unique features* are available in your equipment to address possible problems that may arise during the pumpability assessment that may need to be included for either the PILOT or PRODUCTION scale equipment?

* Unique features include seal types, valve types, material of construction, replaceable wear components, alternate/addition components, etc. Parameters that may require additional features to be incorporated would include fibrous nature of biomass material, dealing with abrasive materials in the feedstock (e.g. ash, sand, dirt), reducing biomass feedstock transport friction to minimize pressure loss, eliminating material bridging during pump feeding, running dry, and eliminating air induction that could cause pump cavitation.

If you have any better ideas we would appreciate this information for consideration. This may include not using your specific equipment but the same type of equipment available at a smaller scale or at a facility. A larger scale system will be considered if positive tradeoff between schedule and additional cost (e.g. additional feedstock, scale of testing, etc.). PNNL is interested in identifying partners for both collaboration and investment in this endeavor though the National Advanced Biofuels Consortium (NABC). Information about the NABC can be found at website http://www.nabcprojects.org/.

Appendix E

Other Vendors Explored/Contacted/Summary Results

Appendix E

Other Vendors Explored/Contacted/Summary Results

Vendor	Equipment	Notes	Contact/Related Websites
Aker Wirth GmbH	• Piston Pumps • Diaphragm Pumps • High Temperature Slurry Pumps	No vendor response to e-mail. Makes a variety of pumps for the mining industry.	akerwirth.info@akersolutions.com martina.rohe@wirth-europe.com Address: Koelner Strasse 71- 73 Erkelenz 41812 Germany Related Website(s): www.akersolutions.com/akerwirth www.wirth-europe.com
ANDRITZ INC	MSD Impressafiner / Plug Screw Feeder	High-pressure feeder for a variety of feed material types ranging from wood chips (high bulk density) to wheat straw (low bulk density) Vendor Response: Andritz biomass feeding and pumping systems are unfortunately not designed for the pressures you need. We can currently only handle up to 25 bar (~360 psig) with some exceptions at lower design pressures. We have expertise in pumping wood fibers at lower pressures, and can reach maybe 15 to 16% dry solids content with difficulty. The friction losses at higher solids make engineering and operation of the pumping system very difficult, so we use rotary valve, plug screw feeder, or lock-hopper systems instead. Particle size and particle characteristics will, of course, influence the behavior of the suspension, but water inclusion in the fiber walls and hydrogen bonding are tough to overcome.	Bertil Stromberg ANDRITZ PULP AND PAPER Fiber and Chemical Division Vice President, Biofuel Bertil.Stromberg@andritz.com Address: 13 Pruyn's Island Dr. Glens Falls, NY 12801, USA Related Website(s): http://www.andritz.com/ANONIDZ42B1DFB7798CE26B/reactorfeedequipment-msdimpressafiner
BMA Braunschweigische Maschinenbauanstalt AG	"Steam-drying" biomass processing	Located in Germany No response	sales@bma-de.com Address: Am Alten Bahnhof 5 38122 Braunschweig Germany Related Website(s): http://www.bma-worldwide.com/products/biomass.html

Vendor	Equipment	Notes	Contact/Related Websites
Boerger, LLC	Rotary Lobe Pump	This pump operates at a relatively low pressure so it would have to be used as a feeder pump. Vendor Response: We have pumps that can go as low as 5 gpm on up to 5000 gpm. The only difference is that on the pumps at the lower end of the flow range we do not offer replaceable radial liners.	Steve Doyle sdo@boerger-pumps.com T: 612-435-7327 Address: 2860 Water Tower Place Chanhassen, MN 55317 USA Related Website(s): www.boerger-pumps.com
ChemGrout	• Grout Pump Progressive • Cavity Plunger Pump	Generally less than 500 psi. The primary pumps in this line are progressive cavity pumps. The highest pressure pump available is plunger pump with an upper pressure range of 1000 to 2000 psi.	Related Website(s): http://www.chemgrout.com/groutpumps.htm
Coperion GmbH	Twin Screw Extruder	Twin screw feeder/extruder in Germany	info@coperion.com Tel.: +49 (0) 711 897-0 Address: Theodorstraße 10 70469 Stuttgart Germany Related Website(s): http://www.coperion.com/en/
Delta Industries Inc.,	Progressive Cavity Pump	Application A: Moyno pump was used for a biomass application see PNNL-16079 pages 11&12. It appears a positive displacement pump after the Moyno pump was used to boost the pressure. Key Moyno excerpts from the attached document include: "RIT used a Moyno pump to feed slurry to a standard piston pump with rather big check valves; the ball being 11 mm in diameter." "Tests were performed in a pumping rig including a low-pressure Moyno pump and a high-pressure plunger pump with 9.5 mm balls in its check valves." "In these tests a progressing cavity (Moyno) pump was used as the low-pressure feed to the high-pressure reciprocating plunger pump." Application B: A Moyno 2000 HS pump and twin auger feed system to move some grain dust paste in a brewery (http://impeller.net/magazine/news_en/doc3619x.asp). Vendor Response: Moyno does not have a pump that will produce 2700 to 3000 PSI. The most they can do is a theoretical 1500 PSI with a 17 stage pump. Vendor Response: One thing I do need to point out is that to pump 2300 GPM you will likely need to use at least four pumps in parallel.	Mike Foteff mike.foteff@deltaindustriesinc.com Phone 503-288-5011 Toll Free: 800-242-5011 Fax: (503) 288-5014 Address: 16142 N.E. Mason Street, Portland, OR 97230 Related Website(s): http://www.moyno.com/ http://www.deltaindustriesinc.com/
Discflo Corporation	Disc Pump	Discflo is best known for its innovative Disc Pump technology, a unique laminar-flow, non-impingement pumping system that cuts maintenance and downtime, while increasing pump life. The Disc Pump has been proven to: pump abrasives with minimal wear, pump efficiently at viscosities over 10,000 cPs, handle large or stringy solids without clogging, and pump water/oil fluids without emulsifying. Not a metering pump as flow varies unless a check valve is introduced. Check valves are a problem with highly vicious materials. Will pump very viscous material up to maybe 400 psi but higher than that then pumps need to be put in series and this is complicated with highly vicious material as elbows are required that have high friction losses. Material to be pumped has to flow into the pump. Cost-effective alternative to centrifugal, progressive cavity, lobe, and screw pumps.	No response discflo@discflo.com Address: 10850 Hartley Rd Santee, CA 92071 USA Related Website(s): http://www.discflo.com/

Vendor	Equipment	Notes	Contact/Related Websites
Inno Engineered Products Pte Ltd	Positive Lobe Pump	Durrex Lobe Pump – Located in Singapore (http://www.innopumps.com/positive_lobe.htm#http://www.innopumps.com/positive_lobe.htm#) one of the stated features was "capable to pump the viscous material below 2 million cp and pulp with the solid volume of 60%." Vendor Response: Will not work for HTL application.	Simon Han simon@innopumps.com Address: 48 Siglap Drive Singapore 456173 Related Website(s): http://www.innopumps.com/index.htm
LEWA GmbH	Diaphragm Pump	No vendor response to e-mail. http://www.lewa.com/main/en/3710 Examples for the use of LEWA pumps and systems for biofuel production of the second (synthetic fuels) and third (hydrogen) generation: LEWA ecoflow and triplex for metering of additives and conveying of hydrocarbons and deionates in high-pressure processes: LEWA triplex process pumps as supply pumps for oil, 100-2400 l/h, up to 250 bar, up to 100°C. LEWA triplex process pump for methanol metering, 100-2400 l/h, up to 250 bar, up to 100°C	Technical Inquires: lewa@lewa.de Phone: +49 7152 14-0 Address: Ulmer Straße 10 71229 Leonberg Germany Related Website(s): www.lewa.de
LF Pumping (Europe) Ltd.	Material Handling	Biomass and wood chip, pellets and shavings drying – http://www.lfpumping.com/biomass-and-wood-chips.php	Technical Enquiries – info@lfpumping.com Related Website(s): http://www.lfpumping.com
LobePro Rotary Pumps	Rotary Lobe Pump	Vendor Response: Our rotary lobe pumps are rated up to max. 175 psi continuous differential pressure only.	Nico Ramos nicor@lobepro.com Tel. 912.466.0304 Address: 2610 Sidney Lanier Drive, Brunswick, Georgia 31525 Related Website(s): http://www.lobepro.com/eng-data-sludge-engineering.php
Liberty Process Equipment	Progressive Cavity	Have a variety of pumps specializing in progressive cavity pumps. Looks like maximum discharge pressure is 800 psi.	(847) 640-7867 Related Website(s): http://www.libertyprocess.com
LSM Pumps USA	Peristaltic hose pump	LSM manufacture Hose Pumps in all sizes from 3/8" to 8". The LSM size 8" is the World's Largest Peristaltic Pump. Vendor Responses: Second Response: The factory has decided that this media is not suitable for our pumps. We think it will only create problems as it is too viscous to flow into the pump by the suction created when the rollers run over the hose. We think that a piston pump would be better. Please look at a supplier as	Louis Gundorph Moller louisgm@aol.com Phone: (713) 893-7413 Address: 14655 Champion Forest Dr.

Vendor	Equipment	Notes	Contact/Related Websites
		Putzmeister or similar. www.putzmeisteramericas.com First Response: We do not have that much experience with wood chips. We have pumped it but the condition of the chips we have seen so far varies quite a bit. We do pump numerous different materials as chopped hay, remains from slaughterhouses (blood, fat and chopped solid remains), chicken and cattle manure, grass and hay in different stages/solutions, Urine from hogs and cattle, molasses, waste from the fishing industry and other similar by-products. In Europe they use little corn as biomass, but they use all the remains from production at flour mills (husks etc.) as well. There must be some liquid present in the media pumped. Peels from sugar beets, leftover from sugar production etc. are also used frequently matter. We have also pumped concrete with stones, chewing gum, mining slurry, and other crazy fluids – some with extreme viscosities.	Unit 701 Houston, TX 77069 Related Website(s): www.lsmpumpsusa.com
Megator Corporation	Rotary Lobe Pump	Vendor Responses: Second Response: The Sliding Shoe design is limited to a maximum pressure of 110 PSI and the product must be free flowing and be free from abrasive particle. The Rotary Lobe design can handle up to 400 PSI but is dependent upon a product with high viscosity. First Response: Regrets but the design requirements exceed our maximum pressure.	Lou Beatty lou@megator.com (412) 963-9200 Address: 1721 Main Street Pittsburgh PA 15215, USA Related Website(s): http://www.megator.com/solutions/ http://www.megator.com/lobe_pumps.htm
Milton Roy	Metering Pumps	Milton Roy has supplied these pumps for use on the Renmatix project it which biomass solids at fairly high viscosity and up to near 20% dry weight solid content is being achieved. I do believe their pilot-scale process is less than 43 gpm so therefore the Milton Roy pump capacity fits their application. Vendor Responses: Milton Roy (and all metering pumps) live in the GPH world (not GPM). Also, high viscosity fluids with high solids contents are not a good fit for these pumps. Basically, the scope of your project is outside of our capabilities. The largest pumps we can offer are 2600 GPH (43 gpm). The pressure ratings are no problem….we go up to 30,000 PSI. I believe there are other styles of pumps that would be better suited to your application.	Henri Bouscaren henri@finelineinstrument.com Fine Line Instrument T: 425-861-1110 Address: 201 Ivyland Road Ivyland, PA 18974 Phone: 215-441-0800 Related Website(s): www.miltonroy.com
MURPHY & DICKEY, INC.	Feeder Pump – Type ?	Vendor Response Voice Message: Have provided some feed pumps for Viron Technologies out of Madison, WN but only up to 1800 psi.	Mark L. (847) 778-4269 630.655.1080 Address: 930 N.York Road Suite 205 Hinsdale, IL 60521 Related Website(s): http://www.murphyanddickey.com/PUMPS.htm l
Neptune	Metering Pumps	Meets temperature 180 F and 3000 psi, and 1 gpm requirements but is limited to 10% solids with	Tim Fegin

Vendor	Equipment	Notes	Contact/Related Websites
		metering tubular pump (http://www.neptune1.com/pumps/tubpump.htm)	(215) 699-8700 pump@neptune1.com Related Website(s): http://www.neptune1.com/pumps/index.htm
NETZSCH Pumps North America, LLC	Progressive Cavity Pump Rotary Lobe Pump	Information related to biomass pumping at http://www.netzschusa.com/company_brochure_pages/Nemo/2008_Brochures/Water%20Brochure.pdf	No Response Back John Sands E-mail: john.sands@netzsch.com Address: 6078 Highway Z P. O. Box 339 Spring Green, WI 53588 Related Website(s): http://www.netzschusa.com
PCM (USA Contact)	Progressive Cavity Pump	PCM is one of the world's leading manufacturers of positive displacement pumps and advanced fluid-handling equipment. The company was founded in 1932 by René Moineau, the inventor of the Progressing Cavity Pump. Vendor Response: Unfortunately we must decline your application due to the extreme pressure and flow ratings (prod scale). We can manage Bench and Pilot required flow rates but not the pressures. Unless your pressure ratings are drastically reduced, we cannot offer a solution.	Paul Pilisi Tel. : (713) 896-4888 Ext. 108 ppilisi@pcm.eu Address: 11940 Brittmoore Park Drive Houston, TX 77041 Related Website(s): http://www.pcm.eu/
Pratt & Whitney Rocketdyne (PWR)	Dry Biomass Pump	Developing a high-pressure dry feed pump, including the detailed design, construction, and testing of a 600 ton-per-day (tpd) prototype. The PWR feed pump has the potential to significantly improve the availability and efficiency of feeding dry coal/petcoke/biomass into high-pressure gasifiers.	Contact: K. David Lyons (NETL Project Manager) k.david.lyons@netl.doe.gov Related Website(s): http://www.netl.doe.gov/publications/factsheets/project/FE42237-PWR.pdf
Pulsafeeder Engineered Products Operation (EPO)	High-Pressure Pumps	Never received a response back after sending Problem Statement. Earlier Vendor Response: I had Pulsafeeder look at this application and they are unsure if their high-pressure pump can handle the high viscosity fluid. At this time they decline to bid as they feel that their pump cannot handle the viscosity. They have a Foster Vane type pump that could handle the fluid, but it is not a high-pressure pump. http://www.pulsa.com/products/foster/	Craig Janett cjanett@unitprocess.com Cell 509-750-0921 Tel: (585) 292-8000 Address: 2883 Brighton-Henrietta Townline Road Rochester, NY 14623 Related Website(s): http://www.pulsa.com/ Distributor:

Vendor	Equipment	Notes	Contact/Related Websites
			http://www.unitprocess.com/
Roper Pump Company	Gear Pump	Vendor Response: From the look of it the pressure is too high for our gear pumps. Roper Pumps appreciates the opportunity to evaluate your application needs. However, we regret to inform you that we do not have a pump that we could confidentially recommend to best suit your application. Roper Pumps offers a wide range of pumps designed to meet our customer's needs but will not recommend one unless we know it will satisfy our customer's application parameters.	Sam McFall Applications Engineer Roper Pumps/ Dynamco Office: 706-336-3341 Tel: 706.335.5551 Address: 3475 Old Maysville Road Commerce, GA 30529 Related Website(s): http://www.roperpumps.com
Saxlund International GmbH	• Solids piston pump • Bulk Feed Systems	Provides a variety of products including: Solids Pumps, Sliding Frame, Push Floor, Rotor Tubefeeder, Chain Conveyor, Screw Conveyor, Elevator, Rotary Valve Vendor Response: After studying your specification we see that the required pump pressure is 3000 psi (206 bar). The max pressure of our pumps is 100 bar (1451 psi) That means the Saxlund pump will not work for your application.	Michael Brehmer michael.brehmer@saxlund.de Address: Heidberg G 1, 4 + 5 29614 SOLTAU-HARBER Germany Related Website(s): http://www.saxlund-international.de/products.html?L=1
Seepex GmbH	Progressive Cavity Pump	Provides progressive cavity pumps. Will not reach HTL pressure requirement.	Max Rupert, Territory Manager - West Seepex Inc. Tel: (503) 307-5378 mrupert@seepex.net Distributor Address: 12498 SE Ashley St Clackamas, OR 97015 Corporate Address: Postfach 10 15 64 D-46215 Bottrop Scharnhölzstraße 344 Tel +49 2041.996-0 Related Website(s): http://www.seepex.com/
Stamet Inc.	Rotary Solids Pump	Posimetric solids pump technology. Coal/biomass mix. Pressures up to 500 psi. Technology acquired by GE Energy in 2007.	Derek Aldred, Timoth Sanders Phone: (310)719-7110 Address: 17244 S. Main St., Gardena, CA, 90248 Related Website(s): No website found

Vendor	Equipment	Notes	Contact/Related Websites
Sulzer Pumps (US) Inc	Pumps	Never received a response back after sending Problem Statement.	Bob McCain, Sales Director Canada, Western US and Export Cellular: +1.925.998.4413 Bob.McCain@Sulzer.com Address: 200 SW Market Street Portland, OR 97201 Phone: 1.503.205.3731 Related Website(s): No website found
TK Energi A/S	Pressurized Feeding of • Solid Materials • Screw and Plug Feeders • Piston Plug Feeders • High-Pressure Feeders	Vendor Response: The principle design will consist of a pressurization stage and a dosing stage. The requirements to these stages must be determined in accordance with process conditions and the physical properties of the fuel. Paste with 15 % can be pumped by a high-pressure piston feeder and continuous dosing can be obtained by having two separate parallel pumping systems. The safety in such a system is handled by metal valves. We have such a system operating against 80 bar with a capacity of 6-8 tons pr hour here at our workshop. For pressurization of non-newtonian solids – bacically all the biomass shown in the attached document we would recommend our solids feeder that is attached in the flyer. If you are pressuring non-newtonian solids the issue of dosing is much more complex as you face the risk of bridging and blocking. Thus you need a pressurization stage and then a dosing stage. Pressure compensation in liquid systems is then an issue that has to be taken care of according to the process requirements. For the paste feeding systems the principles are the same for small and large scale feeders – but for solid biomass – where you will seea high degree of non-newtonian behavior – it can be extremely difficult to get the principles downscaled. Bridging does happens more often ion small dimensions than in large and a screw conveyer for straw biomass will work without problems in a diameter of 400 mm but bridge and give trouble if it is 200 mm in diameter. You will find lots of similar "rules of thumb" that work 75-90 % of the time. As you have already indicated you are aware that no commercial solutions are available and you will need some development work. TK Energi is specialized in handling and feeding of all sorts of solids – biomass-waste-coal etc- into pressurized thermal processes. One recent contract is mentioned here – http://cleanindex.se/startups/article/danish-tk-energi-signs-billion-dkk-gasification-technology-license-agreemen – and an American project – http://www.netl.doe.gov/publications/factsheets/project/NT0006523.pdf – http://www.gasification.org/uploads/downloads/Conferences/2011/37KOCH.pdf As you can see we have had a very good cooperation with U.S. Department of Energy-supported projects in the past and I can assure you that we can also develop an elegant solution for your application.	Thomas Koch, CEO tk@tke.dk phone + 45 22611047 Address: Værftsvej 8 4300 Køge Denmark Related Website(s): www.tke.dk

Vendor	Equipment	Notes	Contact/Related Websites
Verder Inc.	Progressive Cavity Pump	Application: Verderpro VPR feed hopper pump for high viscous (http://www.verder.com/Liquidshandling/Pumps/Progressing_cavity_pumps/Verderpro_VPR). Vendor Response: Unfortunately, we do not carry the products or equipment you are seeking. The product you are asking about is only sold in Europe at this time. We only sell the Verder lines mentioned above, which are unable to reach the parameters you have supplied us with.	Ryan Mellinger Application Engineer P: (877) 476-3569 Address: 110 Gateway Drive Macon, GA 31210 Tel: (478) 471 7327 Related Website(s): http://www.verder-us.com/
Vogelsang	• Rotary Lobe Pump • Rotacut • Biocut	Rotary lobe pumps and grinders.	Address: P.O. Box 751 7966 State Route 44 Ravenna, OH 44266 (800) 984-9400 Related Website(s): http://vogelsangusa.com/
Wagen Pumps	Progressive Cavity Pump	Vendor Response: We are manufacturers of progressive cavity pumps and also very successful in the field of biogas. We regret however that your inquiry does not fit in our manufacturing program.	Michael Leise m.leise@wangen.com Address: Pumpenfabrik Wangen GmbH Simoniusstraße 17 D-88239 Wangen im Allgäu Tel. +49 7522 997 – 240 Fax +49 7522 997 – 148 Related Website(s): www.wangen.com
Wastecorp Pumps	• Diaphragm Pump • Pumps	Industrial pumps. No vendor response to e-mail.	Address: P.O. Box 70 Grand Island, NY 14072 Tel: 888.829.2783 Related Website(s): http://www.wastecorp.com/

Vendor	Equipment	Notes	Contact/Related Websites
Wright Flow Technologies (IDEX) (formerly Johnson Pumps/ formerly Viking Pump)	Rotary Lobe Pump	Vendor Response: To follow up with our conversation it appears we cannot help you out with this application. Not high-pressure pumps.	Wrightflow Technologies Limited – IDEX Sanitary Group Highfield Industrial Estate Edison Road Eastbourne East Sussex BN23 6PT United Kingdom Tel: +44 (0)1323 509211 Related Website(s): http://www.wrightflowtechnologies.com/en/products/byTech.html Rotary Lobe Pumps: http://www.wrightflowtechnologies.com/en/products/technology/rotaryLobe.html
The pumps below are more related to concrete/grout pumping applications			
Airplaco	Concrete Pump	Will not meet HTL pressure of 3000 psi (206 bar). Shotcrete pumps have higher pressures. The Procretor has a 1300 psi capacity. The Shotcrete pumps 536 and 636 have lower pressures in the 800 – 900 psi range.	Related Website(s): http://www.airplaco.com/index.html
Blackjack	Grout Pump	Normal 0 – 625 psi with 1200 psi option. Upper volume range of 50 to 100 gpm. This is a piston style pump with a 5 in. diameter bore and 8 in. travel. Each stroke will take in .33 cubic feet of material. Because of rubber seals a none caustic feed is preferred. The piston style pump will be most effective at delivering product at high pressure with largest aggerate size. The ChemGrout pump uses an auger style pump and is less forgiving and has much lower pressures.	Perry Hochkammer (800) 834-2566) Related Website(s): http://www.blackjackgroutpumps.com/index.htm
HMI	Concrete Pump	HMI mudjacking pumps range from 150 – 750 psi and up to 17 and 34 gpm	Related Website(s): http://mudpumps1.reachlocal.net/equipment/mudjacking/pumps
Reed Concrete Pumps & Gunite Machines	Concrete Pump	Suggested the B20 2100 psi as highest pressure pump.	Duane Remus (Engineer) (909) 287-2104 Cell (591) 312-0747 Related Website(s): http://www.reedpumps.com/

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ENERGY

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