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Milestone Title:	Complete interview survey of a minimum of 10 institutions that feed biomass into pilot-scale or larger conversion equipment. From the survey prepare a report describing major challenges experienced in feeding biomass into conversion reactors and also what properties, equipment or failures associated with the feeding process incur the greatest cost.
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Key Words:	Biofuels, feeding, rheology

Milestone Status/Purpose

Approximately 20 institutions were contacted by telephone and/or electronic mail and requested to provide responses to a survey on feeding biomass feedstock materials (see Table 1). Fourteen individuals responded. Responses from the participants, including information that was offered in addition to answers to the survey questions are summarized in this report, which fully meets the requirements of the milestone.

Table 1. Biomass Handling and Feeding Survey Questions

Biomass Handling and Feeding Questions	
Note: Your responses to these questions will be anonymous unless you specifically state permission otherwise.	
1.	Briefly describe a salient material feeding challenge that your institution has encountered. Please indicate the equipment type, the feedstock and the challenge.
2.	What feedstocks is your institution most interested in?
3.	Please rank the following list of feeding equipment according to their level of concern for your institution, with the item of greatest concern being first. ( ) Feeding problems inside gravity hoppers ( ) Feeding problems using screw augers, including feed rate variability ( ) Feeding problems using pneumatic conveying systems ( ) Feeding problems using belt conveyors ( ) Feeding material against a pressurized reactor
4.	Please rank the following list of material parameters that may cause feeding challenges according to their level of concern for your institution, with the item of greatest concern being first. ( ) Feeding problems associated with particle size disparities of feedstock ( ) Feeding problems associated with particle shape disparities of feedstock, such as extreme aspect ratios ( ) Feeding problems associated with feedstock moisture content, which can increase or decrease cohesion causing caking or free flow ( ) Feeding rate reliability of primary feedstock ( ) Maintenance requirements associated with feeding of primary feedstock ( ) Feeding problems associated with feeding materials with different physical properties, such as bulk density ( ) Any feeding problem not listed above (please describe).

5.	What type of assistance in material feeding would be most helpful to your institution? Possible examples are: – Comprehensive physical characterization of a wide range of potential biomass feedstocks including estimated feeding properties – Tests demonstrating enhancements of feeding behavior of different biomass feedstock due to amendment with small quantities flow enhancing additives – Detailed white paper describing the challenges of feeding various biomass materials in different feed systems.

Importance

Conversion of biomass into renewable fuels has been the topic of considerable research for many years because of its environmental and geopolitical benefits. The Billion-Ton Update released by the US Departments of Energy (DOE) and Agriculture (USDA) in August 2011 reports that there are more than a billion tons of biomass available annually in the United States alone, which could replace approximately 30% of domestic petroleum usage [1]. Approximately one-third of that material could come from perennial energy crops. Supply systems that can quickly and efficiently handling large volumes of feedstock will clearly be needed to deliver such large quantities of biomass. Importantly, it has been estimated that harvesting, transportation, storage, and preprocessing operations contribute up to 50% of feedstock cost at the refinery gate [2]. These handling costs can be reduced by improving handling efficiency throughout the supply system [3, 2]. Recent reviews of fast pyrolysis for producing bio-oils [4], gasification of biomass to produce syn-gas [5], combustion of biomass [5], and co-firing biomass with coal [6, 7] as well as the use distillers grains from the production of ethanol from corn [8] have all reported challenges associated with feeding and handling biomass feedstocks.

Unlike liquids and gases, bulk solid materials can sustain stresses without undergoing significant deformation. The amount of stress that bulk solids can support depends on their compression and stress history, and unlike liquids and gases, when a bulk solid does flow, the flow pattern is rarely uniform. Another important consideration is that the shear deformation (failure) of bulk solids can exhibit both plastic and elastic behavior. The complexity of the flow behavior of bulk solids make them much more challenging to handle than liquids and gases. Common problems include plugging, segregation, obstructed or limited discharge, erratic flow, sudden uncontrollable flow, and sticking of material to container walls which causes a loss of live storage and can lead to spoilage. In year 2000, Merrow [9] reported that bulk solids handling has improved due to years of experience and that industrial plants that handled bulk solids typically operated at 77% of design capacity, compared to 90% for processes that handle liquids or gases. In a perspective on solutions to handle biomass variability, Kenney et al. pointed out that solving biomass feeding problems will likely benefit from material conditioning or reformatting as well equipment optimization [9]. Of particular concern for systems that must handle biomass materials are the wide range of moisture contents (25 to 60%), large particle size distributions depending upon drying and grinding/chipping conditions, low energy densities (8 to 14 MJ/kg), and low bulk densities (60 to 100 kg/m^3) coupled with fibrous interlocking particles that tend to resist flow.

Summary of Survey Participants and Responses

This section summarizes the available information on the feed system of each participant (Table 2) and responses to the questions in the survey (Tables 3 through 7). From Table 2 it is apparent that the majority of the survey participant's primary work is in thermochemical conversion of biomass feedstocks, although some participants come from the biochemical conversion and forestry industries. In order to respect participant anonymity, the participants have each been assigned a letter alias using the letters A through N. Table 3 indicates that the greatest challenges that the participants have experienced pertain to material bridging in hoppers and lines and in feeding materials with augers. Other challenges that were mentioned multiple times include feeding materials with low densities, high fines content or stringy particles. Table 4 indicates that the highest interest is in woody materials (likely due to the fact that most of the survey participants come from biofuels thermochemical conversion and forestry industries), although substantial interest in agricultural residues, energy crops, noxious grasses, and municipal solid waste (MSW).

The responses summarized in Table 5 demonstrate that challenges associated with feeding materials through screw augers and gravity hoppers are the foremost concerns for the participants. A closely related issue of feeding material against a pressurized reactor (typically with a screw auger) also ranked high as a feeding challenge. Feeding problems associated with using pneumatic conveying also received attention, and in phone interviews multiple participants indicated that they had replaced pneumatic conveying systems with auger and belt conveying systems because of material incompatibilities. Table 6 compares responses from the participants regarding the behavior of difficult-to-feed materials. The greatest concerns of the participants were due to (1) the effects of moisture content that results in varying cohesion, including caking, (2) particles with extreme aspect ratios, such as stringy corn stover particles, and (3) differences in physical properties, such as bulk density, of different materials. Feeding challenges due to particle size disparities, feeding reliability and equipment maintenance associated with primary feedstocks were also noted as significant concerns.

The final question in the survey asked what type of assistance in material feeding would be most helpful to the participants and listed some examples. Nearly all of the participants expressed that more information would be beneficial, although the type of information varied according to the interest of the participant. Requests included detailed white papers describing (1) hardware characteristics for reliable feeding of a variety of feedstocks, (2) challenges, costs, maintenance requirements of feeding systems, (3) de-risking of feeding materials into pressurized systems, (4) mitigations for feeding materials that are abrasive, high moisture, or that have widely varying particles, (5) commercially relevant testing protocols and metrics for quantifying flowability, augerability, pneumatic transportability, and air lock performance. One participant noted that the primary goal of their institution was to develop and validate a biomass conversion technology, and that time and effort spent on troubleshooting feedstock handling issues decreases their available resources for their primary R&D.

Conclusions

The responses from the participants offer many areas for future research. Investigating means to improve the consistency and reliability of feeding a variety of materials using auger feeders, especially against pressurized reactors, appears to be a nearly universal concern and one that INL is well-positioned to address in the near term. INL recently set up a loss-in-weight bin feeder in which the instantaneous power usage can be recorded. The bin weight feeder has multiple sizes of augers and cylinders to feed a variety of materials, so that the feed rate consistency, maximum feed rate, and feeding power requirements can be assessed for materials with different particle sizes as functions of pretreatments or flow enhancing additives. Research on auger feeding of materials would naturally lead to journal articles and detailed white papers describing hardware characteristics, challenges, costs, and maintenance requirements for reliable feeding of materials into conversion reactors.

Table 2. Brief summary of available information regarding feed systems of participants.

Participant	*Feeder Description or feed specification*	*Approximate feed rate*
A	The solids feeder system, including lock hoppers, is designed to operate at gasification reactor pressures of 50-100 psi. The feeder is designed for 3/8 inch nominal stock.	10 kg/hr
B	Specification for commercial gasifier unit is 1 –inch minus and no more than 15% by wt of the feedstock can be smaller than 20 US Sieve or 841 microns in size. For the PDU, the top size is ½” equivalent.	50 kg/hr
C	Unknown	100+ kg/hr
D	Unknown	100+ kg/hr
E	Commercial pulp chip production yard	25,000+ tons/yr
F	Commercial and PDU gasifiers	100 kg/hr
G	PDU gasifier	50 kg/hr
H	4” fluidized bed fast pyrolysis system	1 kg/hr
I	Biomass feedstock comminution process	10-100 kg/hr
J	2” fluid bed gasifier	2 kg/hr
K	4” fluid bed gasifier	10 kg/hr
L	Crop harvesting equipment	500 kg/hr
M	Dual lock-hopper pyrolysis system	200 kg/hr
N	Biomass preprocessing	5-200 kg/hr

Table 3. Participant responses to survey question 1.

Question	Briefly describe a salient material feeding challenge that your institution has encountered. Please indicate the equipment type, the feedstock and the challenge.

Difficulty described	*Participants reporting difficulty*
Material bridging in hoppers or lines	A, B, C, D, M, N
Difficulties associated feeding using augers	A, D, F, H, M, N
Difficulties with fine particles	B, H
Difficulties with stringy particles	B (bridging), I (tangles), N
Difficulties with low density materials	G, J, K
Mechanical wear	E
Corrosion from hot product	E
Specific challenge with woody material	A,B
Specific challenge with herbaceous material	B, L (cutting & collecting grasses)
Specific challenge with reactive materials	F (low volatile temp materials volatize just prior to insertion into the reactor) H (lignin-based materials melt in injection line) J (plastic materials form a plug on the end of the feeder)

Table 4. Participant responses to survey question 2.

Question	What feedstocks is your institution most interested in?

Material class	*Participants reporting difficulty*
Agricultural residues such as corn stover	B, C, H,I,K,N; Pelletized: A, D
Energy crops such as switchgrass	B, C, H,I,K,N; Pelletized: A, D
Woody materials	A, B, C,I, D, E, F,G,H,J,K,N
Noxious grasses	J,K,L,N;
MSW	B,C,F,I,N; Densified: D

Table 5. Participant responses to survey question 3.

Question	Please rank the following list of feeding challenges with numbers 1 through 5 according to their level of concern for your institution, with the item of greatest concern being first.

Feeding challenge	*Occurrences of rankings*					*Score**
	1's	*2's*	*3's*	*4's*	*5's*	
Feeding problems inside gravity hoppers	4	3	5	1	0	48
Feeding problems using screw augers, including feed rate variability	4	8	1	1	0	56
Feeding problems using pneumatic conveying systems	0	2	1	6	1	24
Feeding problems using belt conveyors	0	0	1	1	8	13
Feeding material against a pressurized reactor	4	4	3	0	0	44

* The score for each question is calculated by reversing the rankings (rankings of 1 receive point values of 5, rankings of 5 receive point values of 1, and so forth) and then summing the point values.

Table 6. Participant responses to survey question 4.

Question	Please rank the following list of material parameters that may cause feeding challenges with numbers 1 through 6 according to their level of concern for your institution, with the item of greatest concern being first.

Feeding challenge	*Occurrences of rankings*						*Score**
	1's	*2's*	*3's*	*4's*	*5's*	6's	
Feeding problems associated with particle size disparities of feedstock	0	4	0	4	3	1	39
Feeding problems associated with particle shape disparities of feedstock, such as extreme aspect ratios	3	2	3	3	1	0	51
Feeding problems associated with feedstock moisture content, which can increase or decrease cohesion causing caking or free flow	1	4	4	1	2	2	51
Feeding rate reliability of primary feedstock	2	1	1	4	2	1	38
Maintenance requirements associated with feeding of primary feedstock	1	1	4	1	1	3	35
Feeding problems associated with feeding materials with different physical properties, such as bulk density	3	2	0	4	1	2	44
Any feeding problem not listed above (please describe).	0	0	1[a]	0	0	0	4

* The score for each question is calculated by reversing the rankings (rankings of 1 receive point values of 6, rankings of 6 receive point values of 1, and so forth) and then summing the point values.
[a] Separation of post processed solute from solids in a field environment.

Table 7. Participant responses to survey question 5. Ideas for feeding assistance specifically suggested by participants are listed as notes.

Question	What type of assistance in material feeding would be most helpful to your institution? Possible examples are:

Possible examples listed in survey:	*# in agreement*
• Comprehensive physical characterization of a wide range of potential biomass feedstocks including estimated feeding properties	1
• Tests demonstrating enhancements of feeding behavior of different biomass feedstocks due to amendment with small quantities flow enhancing additives	1
• Detailed white paper describing the challenges of feeding various biomass materials in different feed systems.	4

[a] Detailed white paper describing typical hardware characteristics that result in reliable feeding for a variety of feedstocks.

[b] A white paper describing and comparing the challenges, costs, reliability, process constraints and maintenance requirements of various feeding systems would be valuable. Particularly important is showing how each feeder system performs long term with various feedstocks. A short test does not provide the reliability and maintenance data and so this information would aid in feeder selection. Particularly important would be a comparison of how long the wear parts of the feeding system(s) are guaranteed to last. Certainly, comprehensive physical characterization of diverse feedstocks and feedstock blends with different properties and identification and demonstration of feed-enhancement additives will be very helpful.

[c] Detailed white paper de-risking or investigating challenges associated with solids handling into pressurized systems. Several systems exist to move solids such as slurry pumping, extrusion or auger, "bunker flow" or fluidized movement but each has unique challenges. One challenge common to several of these solids handling systems is the abrasive nature of the biomass and how that impacts the equipment. Moisture impacts in these systems as well as particle size would also be beneficial.

[d] Cost effective and reliable feed systems that can purge air/oxygen and provide pre-heated feed (100 C) to a slightly pressurized oxygen-free reactor vessel. Feed mechanism must be able to handle feedstock mixes with wide variety of bulk density and particle sizes, all sized at 2" minus. Desired system would minimize use of inert purge gas such as nitrogen and prevent fuel volatilization back into the feed system.

[e] Pumpable stable slurry formulation with max solid content that can be stored in storage tanks.

[f] Particle size distributions of the feedstocks, along with a simple, fast, and effective method for removing fines, would be most beneficial. This may include actual preparation of the feedstocks to meet the size requirements of our system.

[g] (1) Commercially relevant testing protocols and metrics for quantifying the flowability, augerability, minimum pneumatic transport tube diameter and air velocities, airlock performance, etc. There are many ad hoc and academic measures of flowability such as Hausner ratio, angle of repose, internal shear, etc. that only vaguely relate to commercially relevant decisions about how feedstock X will work in material handling process Y. (2) Need a comprehensive on-site industry evaluation of material feeding design needs, issues experienced, and heuristics and a workshop or panel of experts white paper to define the research and engineering standards/methods pathway to make feedstock feeding more of a science and less art.

[h] A consortium of groups who feed solids and their approaches, challenges, and solutions would be extremely helpful. From this type of consortium, we might be able to derive correlations or other helpful mathematical relationships between feeding and the systems we use to feed.

[i] (1) Testing of alternatives technologies for cutting and feeding of grasses grown on marginal and uneven lands. (2) An economic comparison of processing grasses and/or energy crops in the field for long range transport of sugars versus process (pelleting, etc) storage, transportation, and negative opportunity costs of current biomass systems modeled by DOE.

[j] Our primary goal in regards to feedstock is proper handling and preparation so we can take delivery of materials that we have a high level of confidence will work in our system. The goal of our R&D program is to develop and validate a biomass conversion technology for advanced biofuels. The more time and effort we spend on troubleshooting feedstock handling issues the less time and money we have available for R&D.

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