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2015 DOE Bioenergy Technologies Office (BETO) Project Peer Review

March 23-27, 2015

1.2.1.3 Biomass Engineering: Transportation & Handling

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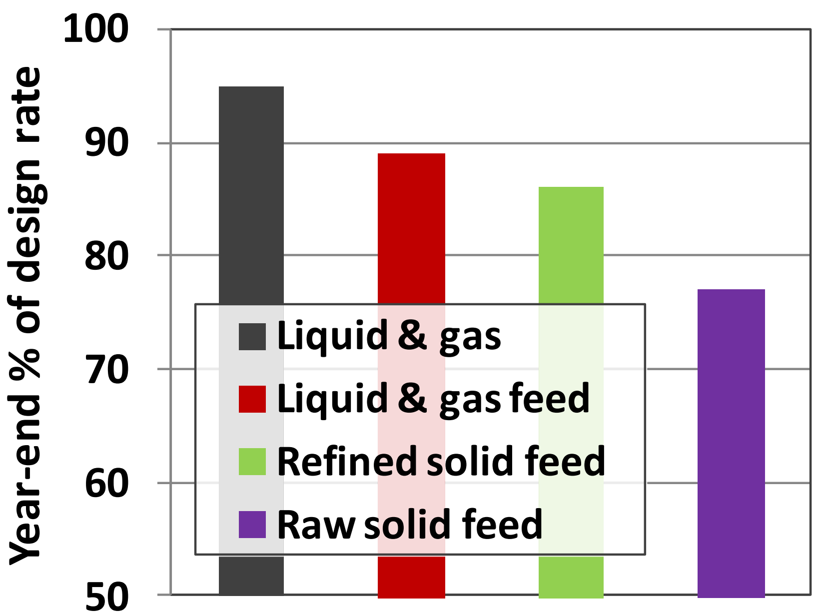
"Why 'flowability' doesn't work and how to fix it"

Goal Statement

Goal: Establish correlation between rheological properties of "high-impact" feedstocks and their feeding performance in hoppers and screw feeders

- Short-term: Provide data to ***avoid costly feeding problems*** during preprocessing and conversion tests

- Long-term: Achieve plant design capacity
  - Plants that handle bulk solids tend to operate ≈ 20% below design capacity. ***For biofuels, cost ≈ \$0.36/GGE*** (see supplemental slides)



Median performance of 508 new plants (Merrow, Chem Innov. Jan. 2000 for years 1996-1998)

High impact: component of blend with ~50 million ton/yr availability at ~\$80/ton

Project Quad Chart Overview

Timeline

- Start: October 2010
- End: September 2015

Budget

Total project funding: **$1,363K**

- DOE share: 100%

Funding in FY 2012-2014 ($1,000s)

WBS	2012	2013	2014	2015
1.3.1.4.D	250	225	0	0
1.2.1.3	**0**	**0**	**200**	**0**
1.2.1.2	0	0	0	188

Barriers

- Ft-G: Feedstock Quality & Monitoring
- Ft-J: Biomass Material Properties
- Ft-K: Biomass Physical State Alteration
- FT-L: Biomass Material Handling & Transportation
- Ft-M: Overall Integration and Scale-Up
- Tt-A: Feeding Dry Biomass

Partners & Roles

- NREL – Material feeding
- RTI – Material feeding

1 - Project Overview

Motivation: Rheological properties* are not available for many biomass feedstocks. In addition, equipment design criteria are not well understood (design is often based mainly upon experience)

Approach: Performed ***industry survey*** to determine feeding & handling needs. ***Evaluated properties and performance of materials*** from Feedstock Preprocessing & Interface Tasks

FY13: Hoppers

FY14: Screw feeders

FY15: Moisture & particle size effects in core project materials

FY16: Blending & feeding of blends, including MSW

History: Nucleated in Feedstocks Engineering Project in 2010 and became separate task in 2014. Expands on work performed for Development of Bulk-Format System for High-Tonnage Switchgrass (2010-2013)

* Primary rheological properties that impact handling are: bulk density, particle size/shape distributions, microstructure, compressibility, elastic recovery, shear strength ('flowability'), wall friction, and wettability (equilibrium moisture content).

2 - Approach (Managerial)

Task leadership: plan, prioritize, coordinate, review progress:

- Periodic inter-laboratory team meetings & visits
- Weekly progress and coordination meetings
- Quarterly BETO Review Meeting

Leverage related BETO sponsored work (feedstock, pyrolysis, gasification, test equipment):

- Share data with Feedstock Preprocessing Projects (data up to plant gate)
- Standardize test procedures, including tests at representative conversion conditions
- Data mining and assimilation of BETO program data into Biomass Resource Library

Create & follow approved project management plans

- Regular milestones (1/quarter) and deliverables (annual reports)

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2 - Approach (Technical)

Overall Approach

1. ***Test feeding performance*** of materials from Feedstock Preprocessing & Interface Tasks
2. Perform ***rheological characterization*** of same materials
3. Develop models to ***rank materials*** and ***predict flow performance***

Critical Success Factors

1. Demonstrate ***feedstock rankings*** and ***flow performance models*** based upon measureable rheological properties to avoid costly feeding and handling problems during preprocessing and conversion tests, especially 2017/2022 validations
2. Assess costs and effectiveness of different feeding and handling solutions (equipment maintenance, downtime, reliability, capital cost, etc.)

Top Potential Challenges

Coupling between

1. ***Diverse rheological properties*** of raw biomass and
2. ***Diverse equipment*** types

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2 - Technical Progress (Overview)

1. Feeding & handling interview/survey (14 institutions)
   1.1 Feedback on biomass feeding/handling experience & interests

2. Feeding & handling equipment performance tests
   2.1 Loss-in-weight screw feeder performance
   2.2 Hopper feeding performance
   - **Pine:** grinds = 1.6, 3, 6, 13, 25 mm; MCs = 10, 20, 30, 40%
   - **Switchgrass:** grinds = 3, 6, 9, 25 mm; MCs = 10, 20, 30%

3. Rheological properties characterizations
   3.1 Particle size/shape distributions
   3.2 Shear tests (unconfined yield strength & angle of internal friction)
   3.3 Compressibility and elasticity (springback)
   - **Same materials as above**

4. Flow performance models (still in development)

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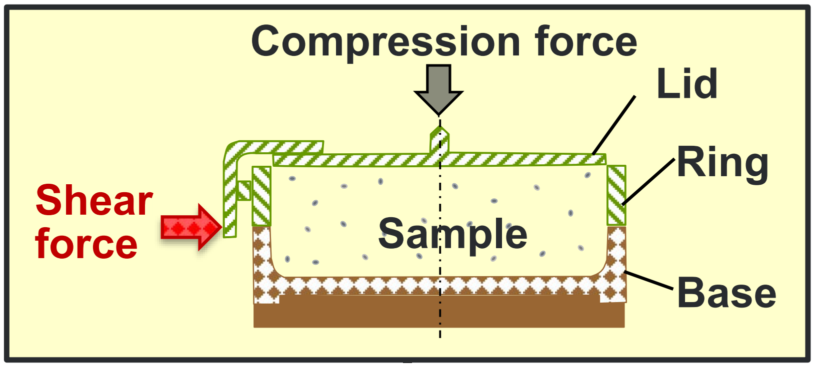
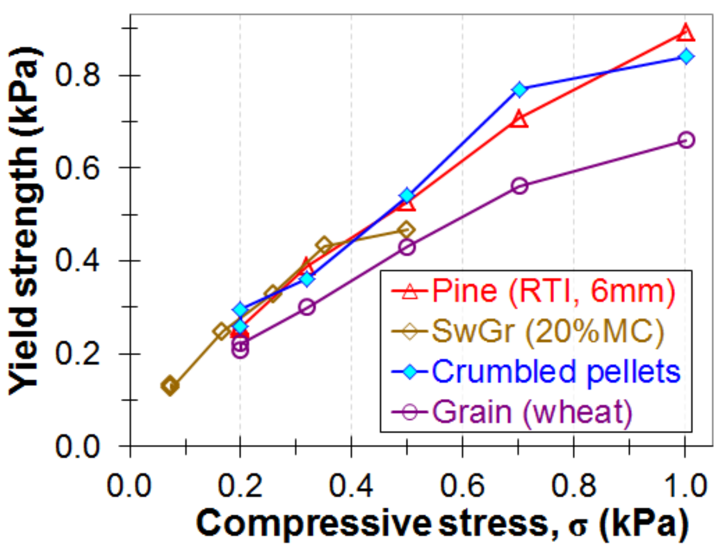
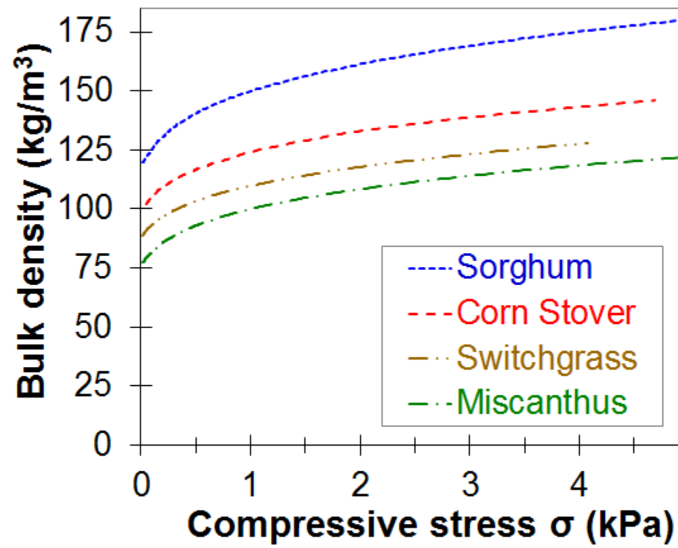
Focus Problem: Measurements of ‘Flowability’

4 so-called ‘direct flow parameters’

1. Bulk density (gravity or motor)
2. Compressibility
3. Elasticity
4. Shear strength (friction)

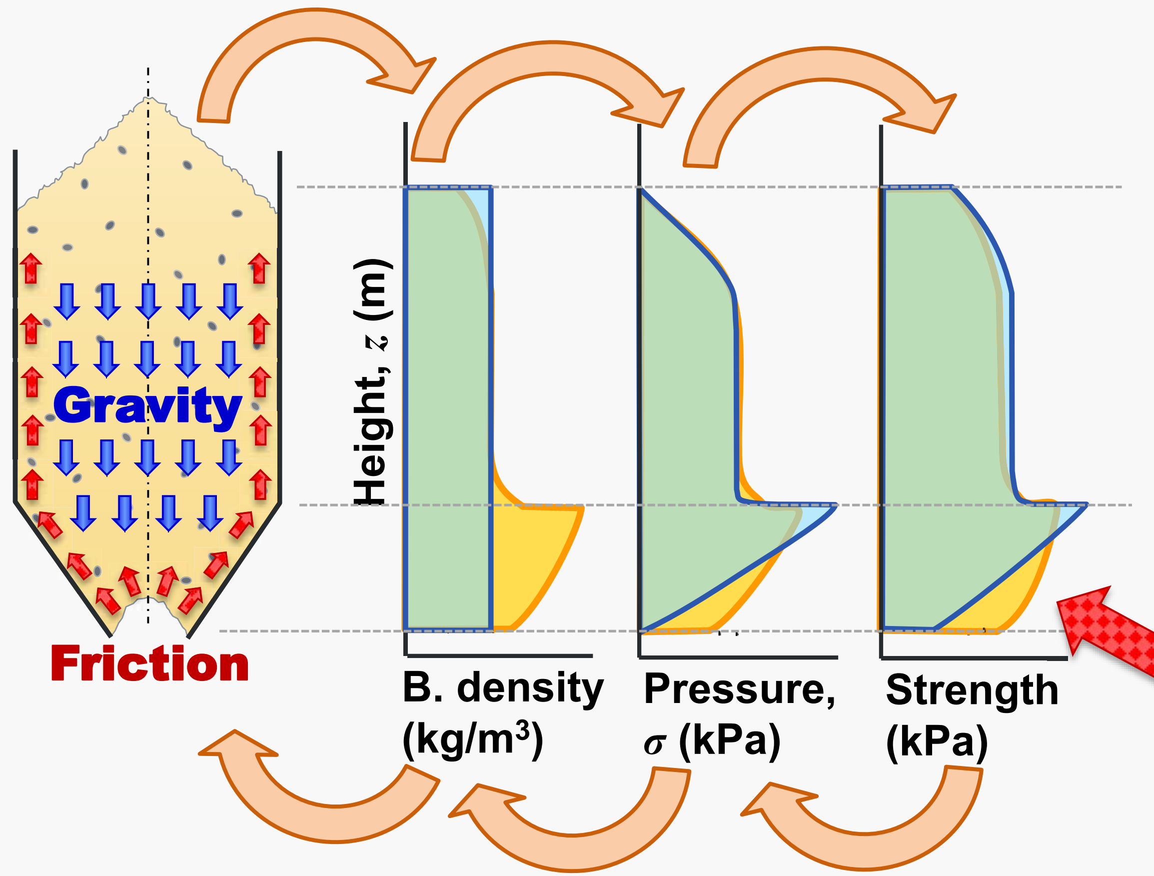




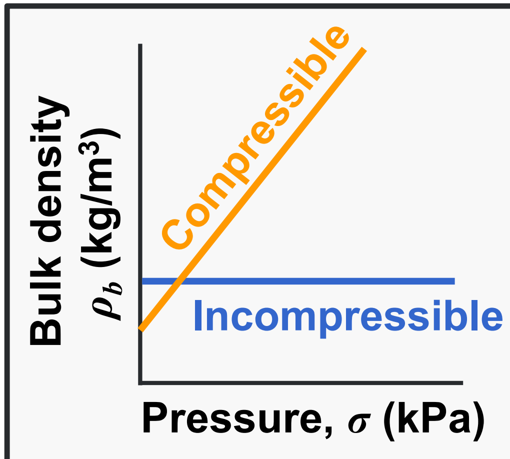


Strength & density both depend upon compressive stress but are treated separately

Focus Problem: Measurements of 'Flowability'



Bulk density, pressure and strength as functions of height in a bin/hopper for compressible & incompressible bulk solids



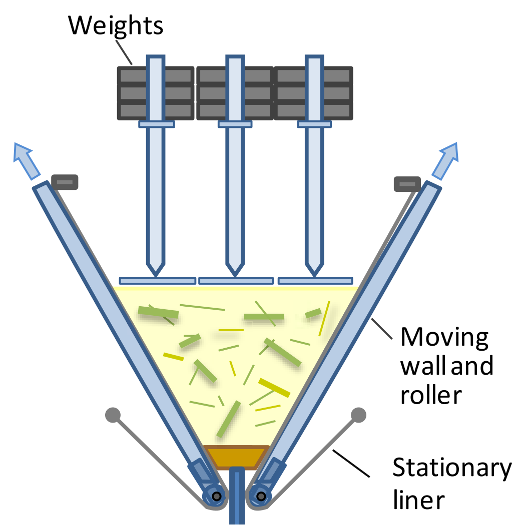
Compressible materials may have much greater strength at the opening

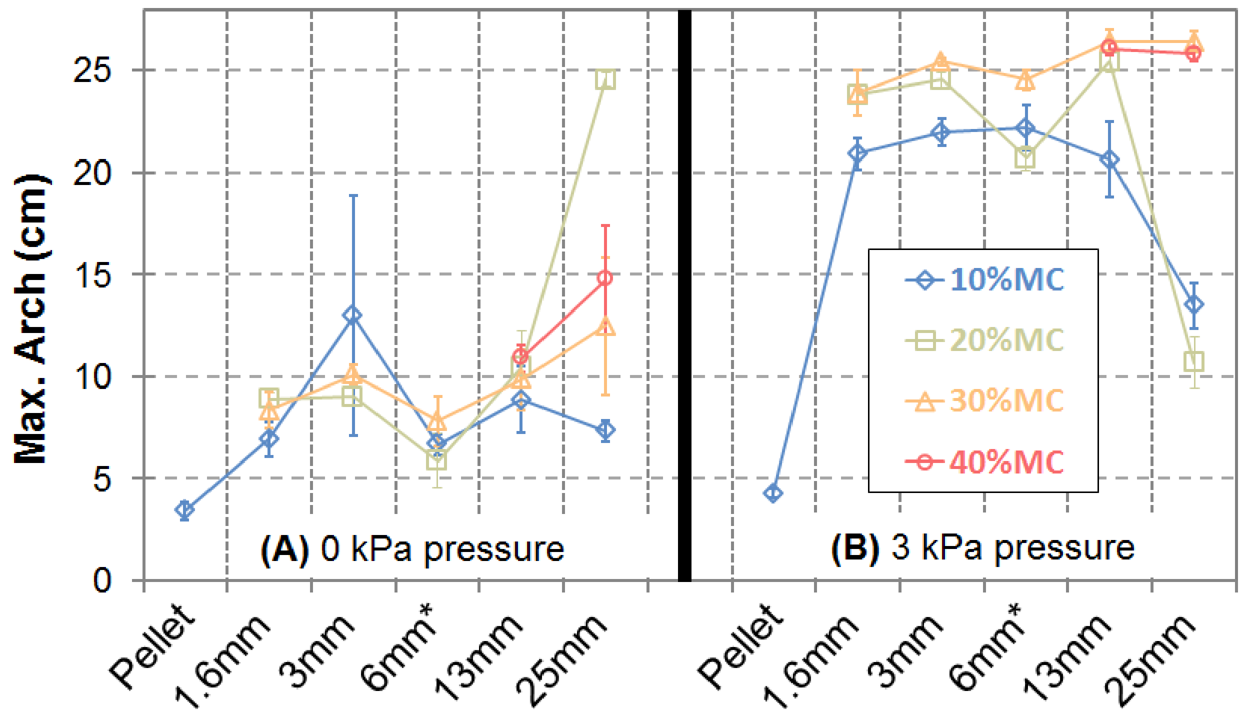
- Shear testers cannot account for this!

Measurements of bulk density, compressibility, elasticity and shear strength do not account for inter-dependence of the parameters in real systems!

2 - Technical Progress

Data for pine samples; similar data for switchgrass in additional slides

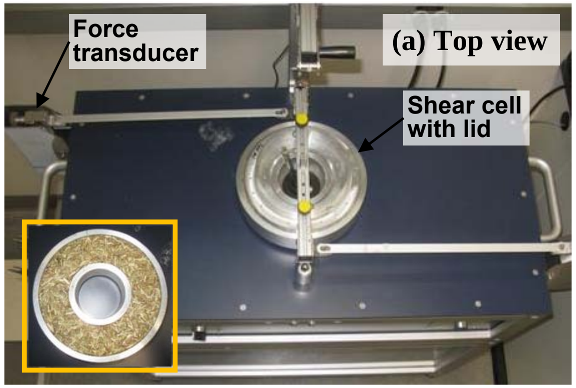




- *Hopper has moveable walls covered with stationary liner*
- *As walls are raised, size of hopper opening increases*
- *Material falls when hopper opening exceeds arching index (AI)*

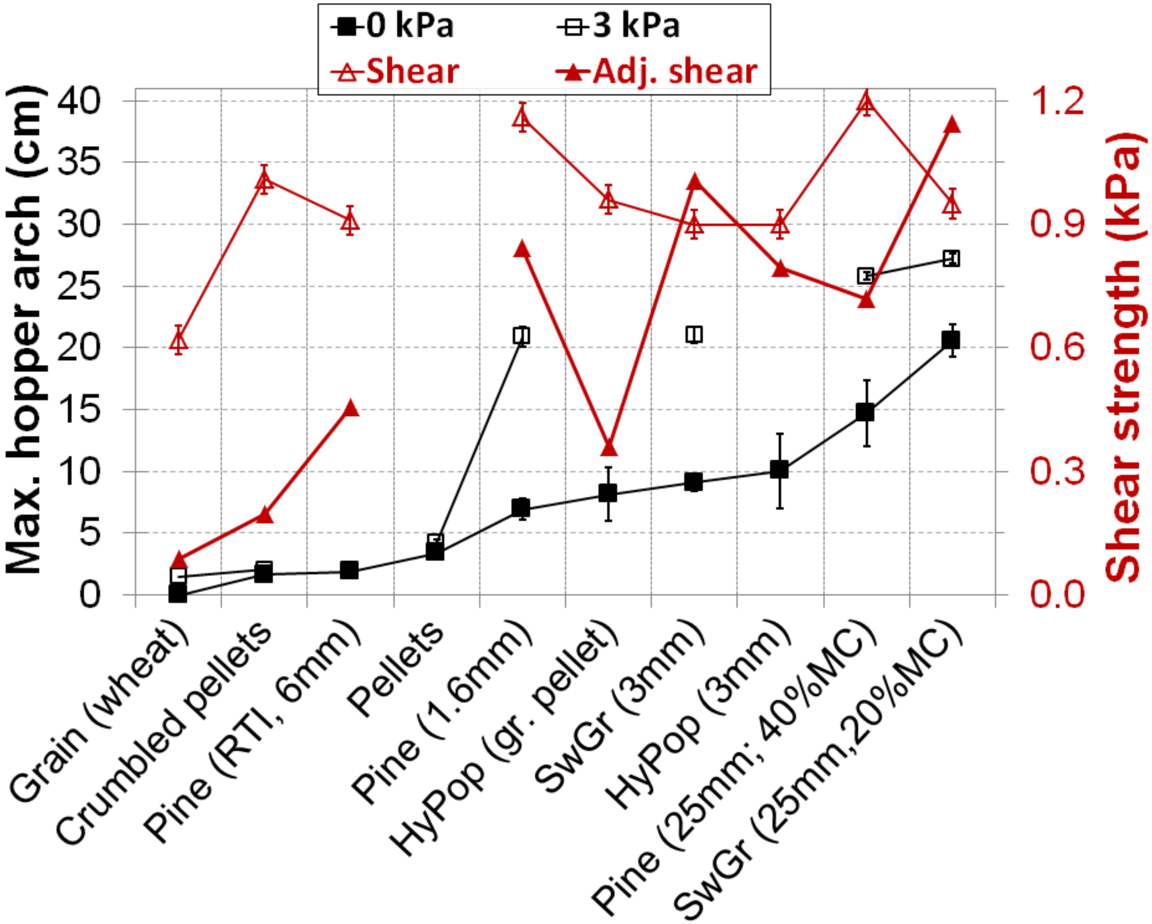
- ***AI*** is 5-15 cm for loose pine grinds
- ***AI*** increases to 20-30 cm upon mild compression
- *Pellets have lowest **AI** and do not compress*

2 - Technical Progress



Schulze ring shear tester. Inset: filled cell.

Hopper with adjustable opening



*Measured arching indices (**AIs**) and yield strengths of several materials*

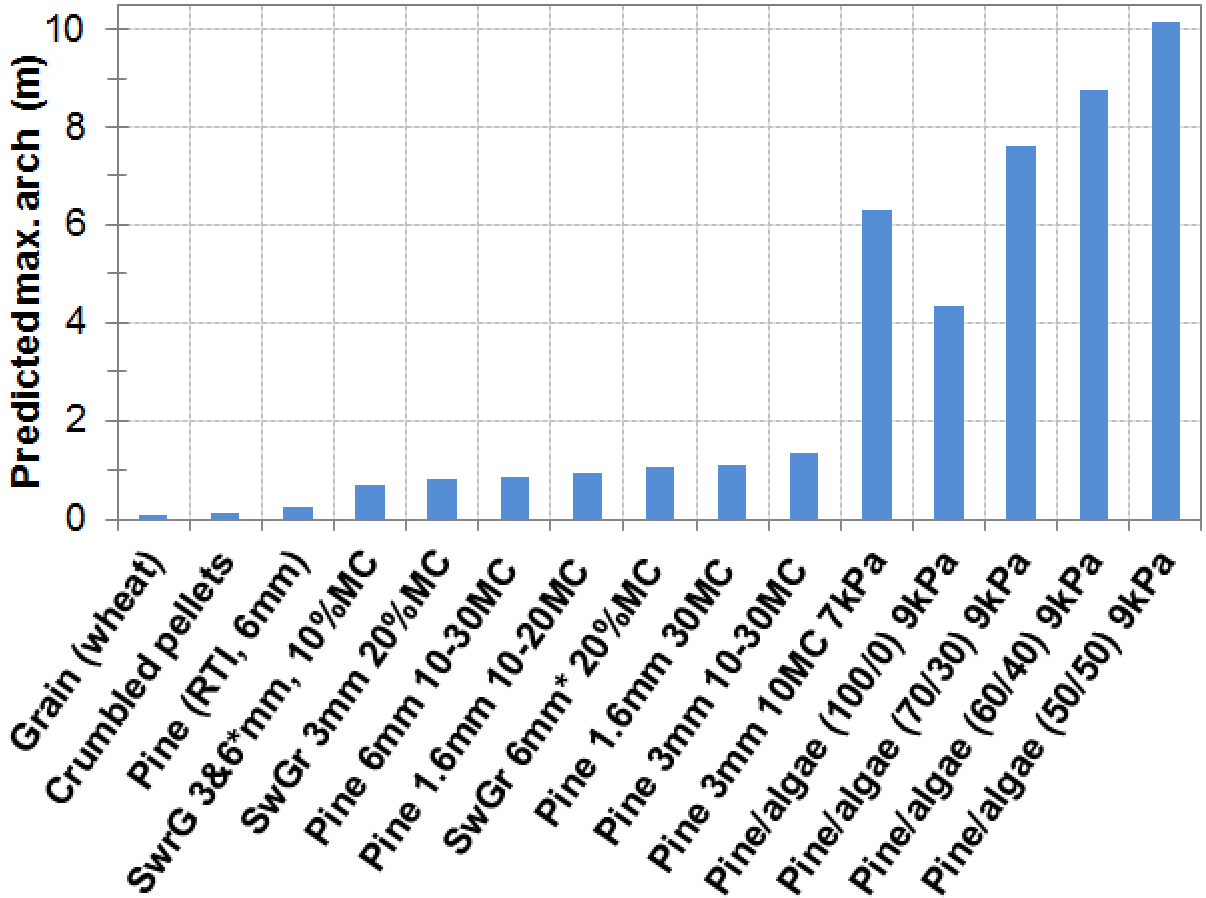
- *Adjusting strengths by bulk densities improves correlation – still not good*

2 - Technical Progress

Simple model: max. arch ≈ 2.2·$F_C/(g \cdot \rho)$, F_C = unconfined yield strength

Predictions:

- Grain: *AI* ≈ 0.08 m
- Dry SwGr powder *AI* ≈ 0.4 m
- *Wet pine & pine/algae blends: AI = 6-10 m! (still does not include increased strength due to elasticity)!*

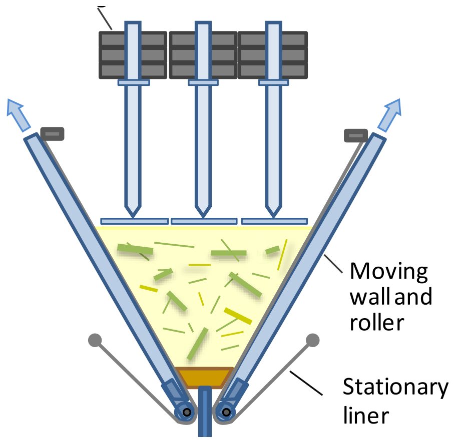


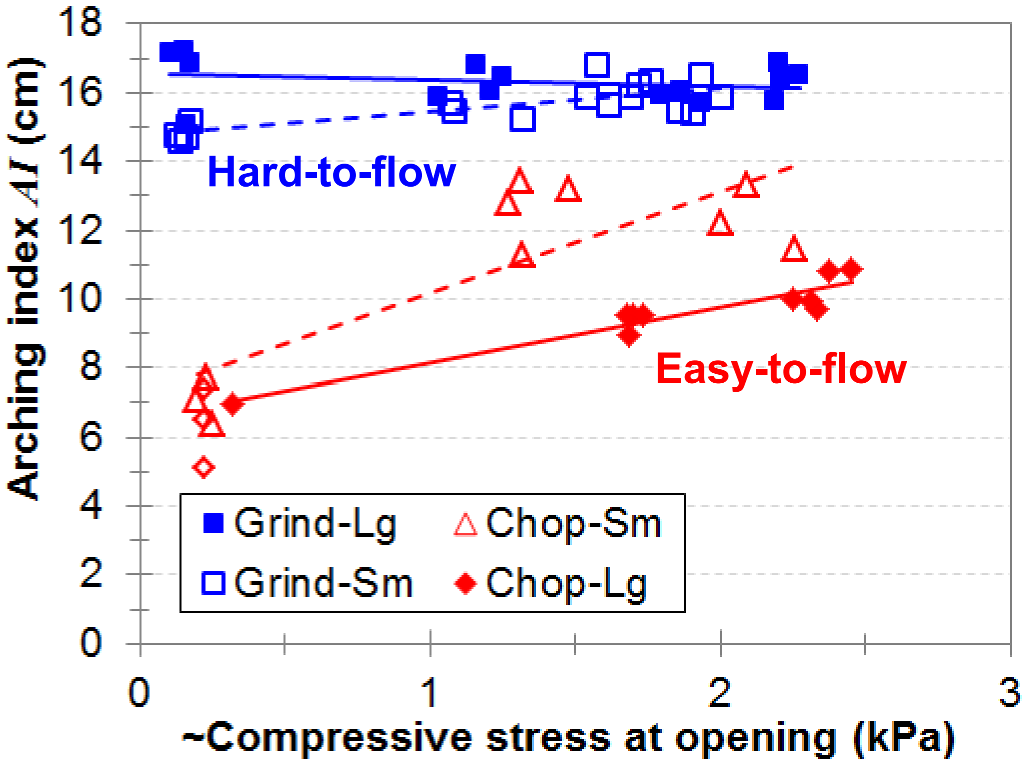
- **Equipment to handle material with *AI* >10m is not cost-effective**
- **Hypothesis (with some data): Most materials can be transformed into crumbled pellets (*AI* ≈13cm) for ≈$10/ton.**

Solution #1: **Use fast metric based upon all 4 direct flow parameters**

Already shown that yield stress & pressure at hopper opening depend upon all 4 direct flow parameters

- Yield stress
- Bulk density
- Compressibility
- Elasticity





Chopped and ground switchgrass from BETO Project: "Development of a bulk-format system to harvest, store, and deliver high-tonnage low-moisture switchgrass feedstock, 2011-2013

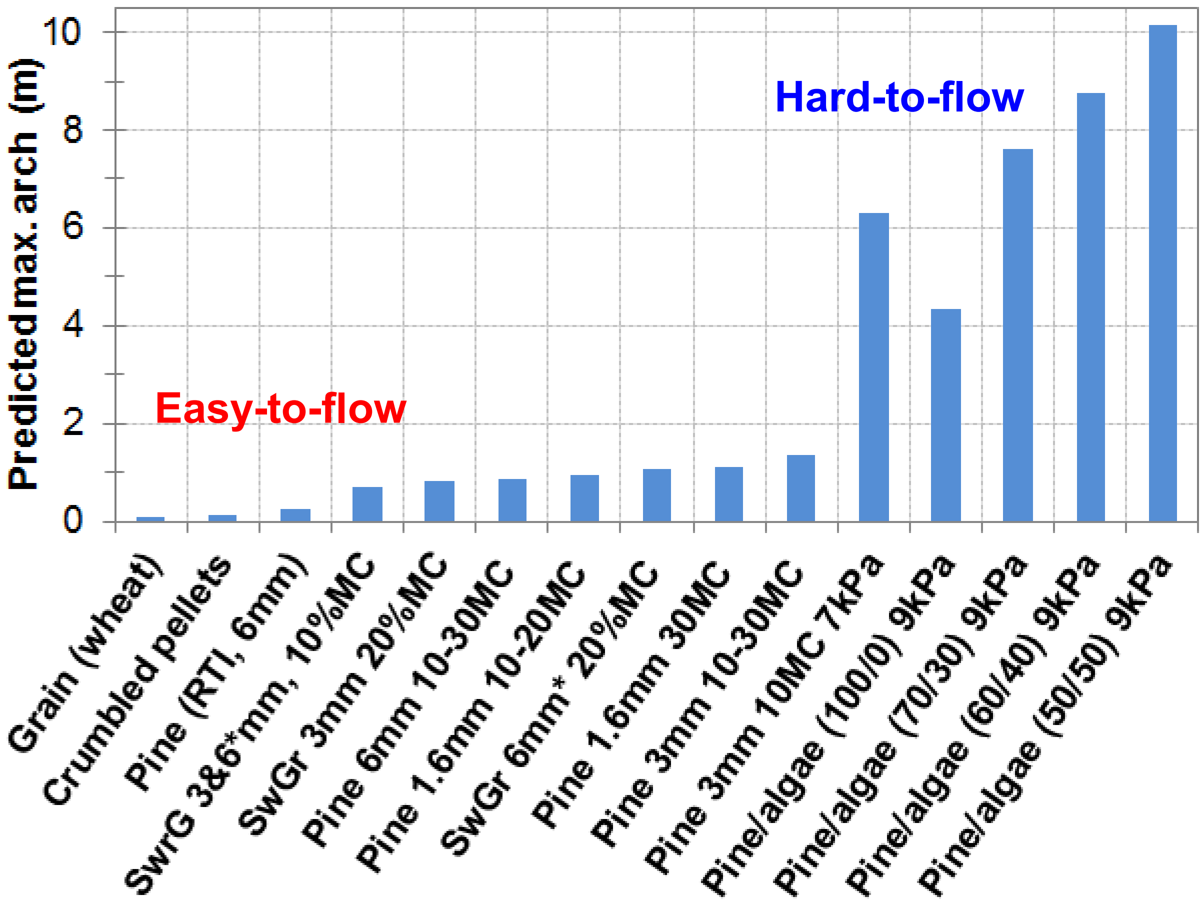
Hopper "arching index" measurements can be improved by measuring compressive stress at opening

- Tests can be extended to predict/understand flow for a range of conditions
- Two methods to measure compressive stress at opening under development

Solution #1: Use Fast Metric Based Upon all 4 Direct Flow Parameters

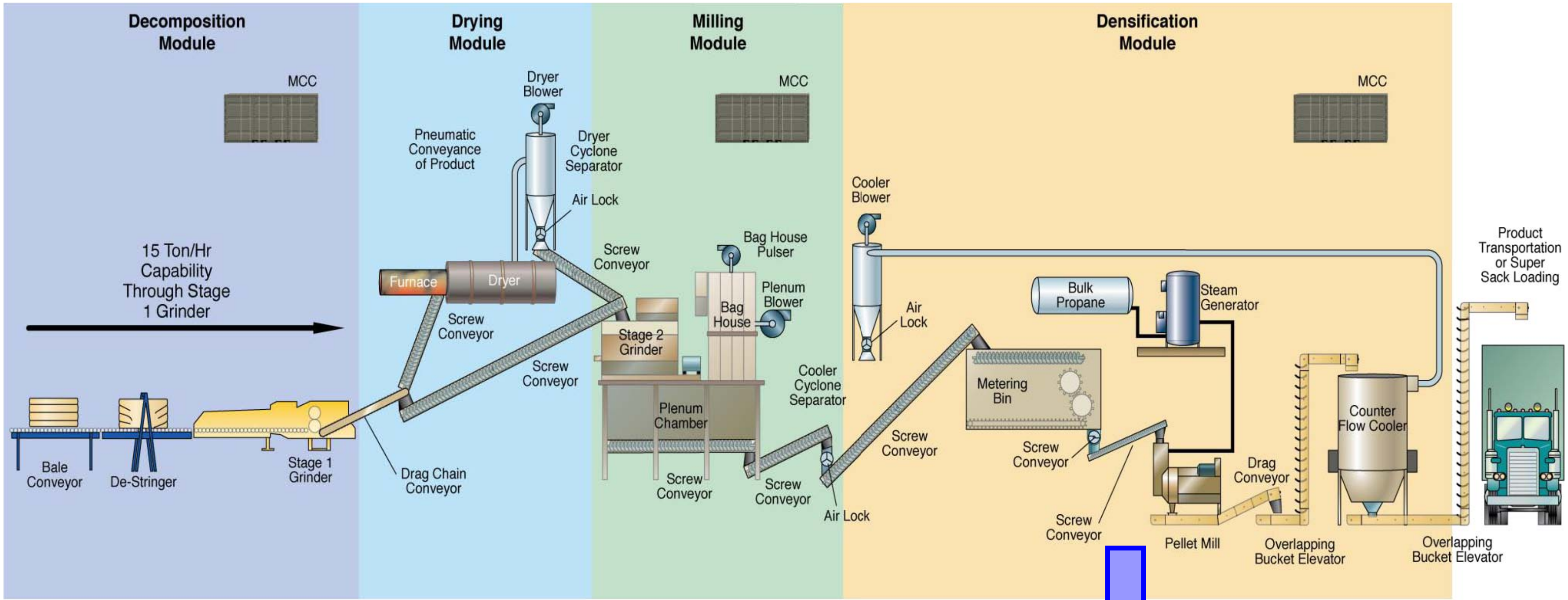
Innovation:

Measure improved flow metric continuously as material is produced or as material is fed into a reactor *(safety stop similar to overhead bar in a drive-through)*

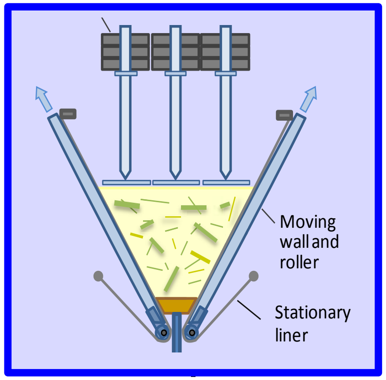


- New equipment can be designed based upon model predictions
- Performance of new feedstocks in existing equipment can be predicted based upon performance of known (reference feedstocks)
  - Flow predictions based upon reference feedstocks do not need specifics of feeder design, which may be proprietary

Solution #2: Active Control of Feedstock Preparation



Test feedstocks during production & adjust operating conditions in real-time to maintain “flowability” specification



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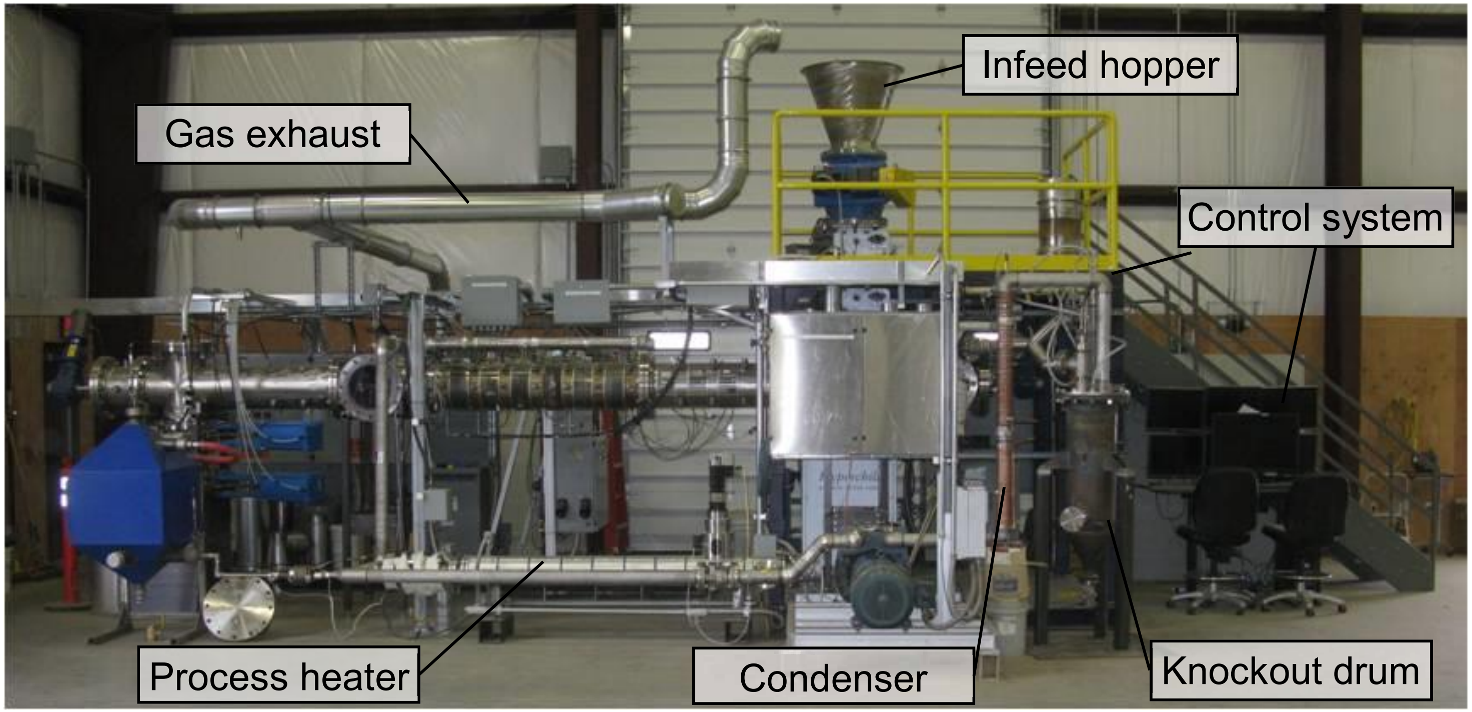
Solution #3: Understand Flowability At Reactor Conditions

Measurements of compressive stress, arching index, & yield stress can be set up in continuous-flow arrangement inside reactor conditions to understand feedstock flow performance at a range of temperatures, pressures and times.



Continuous feed thermal treatment system at INL (20 kg/hr)

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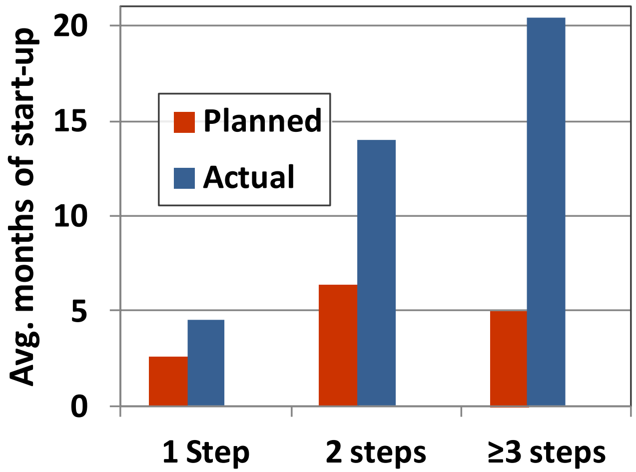
3 – Relevance

- Short-term: Provide data to ***avoid costly feeding problems*** during preprocessing and conversion tests
- Long-term: Achieve plant design capacity.
  - Plants that handle bulk solids tend to operate ≈ 20% below design capacity. ***For biofuels, cost ≈ $0.36/GGE*** (see supplemental slides)



Start-up time for process steps. Merrow, Chem Innov. Jan. 2000

Barriers

- Ft-K: Biomass Physical State Alteration
- FT-L: Biomass Material Handling & Transportation
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5 – Future Work

- **WBS 1.2.1.3 ended in 2014**
- **WBS 1.2.1.2 continues in 2015 (focuses on high moisture feedstock)**

Future work (In addition to Solutions 1-3 already proposed):

- Test feeding behavior of additional materials, including MSW fractions, hybrid poplar, corn stover, miscanthus, etc.
- Extend capabilities of current models, which do not properly account for material compressibility, elastic recovery (springback) or interlocking of large particles
- Test the feeding performance of more advanced equipment, such as a screw feeder feeding a pressurized reactor or a pneumatic conveying system

Summary

Short-term and long-term consequences are expensive in time and money if equipment cannot reliably feed material

- There is a strong need to be able to predict feeding performance of new materials because availability of 'standard' feedstocks depends upon many factors, including weather and changing demand

Rheological properties are inter-related and still not well understood

- Multiple properties must be evaluated, including bulk density, particle size/shape distributions, microstructure, compressibility, elastic recovery, shear strength, wall friction, and moisture content
- ***New test could evaluate all 4 direct flow parameters simultaneously***

In this work, the feeding performance of pine and switchgrass feedstocks have been evaluated in a screw feeder and a hopper as a function of particle size and moisture content

- Correlations have been observed between feeding performance and measured rheological properties

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Publications & Acknowledgements

Manuscripts

1. Westover, T L.; Phanphanich, M., Ryan, J C., I*mpact of chopping and grinding on the rheological properties of switchgrass*, Submitted to Biofuels.
2. Westover, T L.; Hernandez, S.; Matthew, A., Ryan, J. C., *Flowability and feeding characteristics of ground pine as functions of particle size and moisture content*, To be submitted.
3. Westover, T L.; Hernandez, S.; Matthew, A ., Ryan, J. C., *Flowability and feeding characteristics of ground switchgrass as functions of particle size and moisture content*, To be submitted.
4. Newby, D.; Wahlen, B.,; Stevens, D.; Lacey, J.; Roni, T.; Cafferty, K.; Anderson, L.; *Improved dewatering and hydrothermal liquefaction conversion of algae achieved by blending with pine*. To be submitted.

Acknowledgements

1. Sergio Hernandez
2. Austin Matthews
3. Manunya Phanphanich
4. J. Chad Ryan
5. Tyler L. Westover
6. C. Luke Williamson

Additional Slides

2 - Technical Progress (Overview)

1. Feeding & handling interview/survey (14 institutions)
    1.1 Feedback on biomass feeding/handling experience & interests

2. Feeding & handling performance tests
    2.1 Screw feeder performance
    2.2 Hopper feeding performance

3. Rheological properties characterizations
    3.1 Particle size/shape distributions
    3.2 Shear tests (unconfined yield strength and effective angle of internal friction)
    3.3 Compressibility and elastic recovery (springback)

4. Flow performance models (still in development)

2 - Technical Progress **Feeding survey**

03/14/15 Milestone: Interview/survey of >10 institutions that feed biomass in pilot-scale or larger equipment. Report challenges and factors that incur greatest cost.

ID	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

2 - Technical Progress **Feeding survey**

Material class	Participants reporting difficulty
Ag. 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

Feeding challenge	Rankings					Score*
	1st	2nd	3rd	4th	5th	
Screw augers	**4**	**8**	**1**	**1**	**0**	**56**
Gravity hoppers	**4**	**3**	**5**	**1**	**0**	**48**
Feeding against pressurized reactors	4	4	3	0	0	**44**
Pneumatic conveying systems	0	2	1	6	1	**24**
Belt conveyors	0	0	1	1	8	**13**

- Difficulties were reported for a wide range of materials
- Highest interest is in screw augers and gravity hoppers

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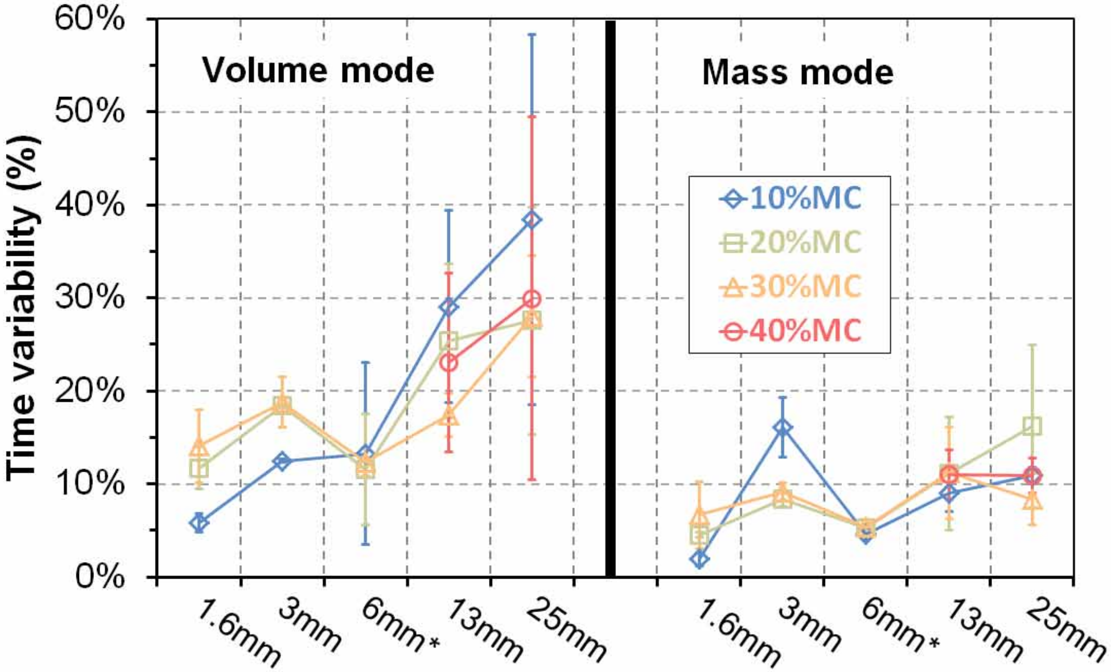
2 - Technical Progress

Screw auger performance

09/30/14 Milestone: Assess feeding performance of 12 clean ***pine samples*** in a ***screw feeder*** using three different screw configurations.



Time variability of feed rate (% of mean).

50 mm dia. auger

- *Volume mode tests at **20% max. speed***
- *Time variability increases with particle size but not with material cohesion*
- *Mass mode has lower time variability but higher cost & complexity*

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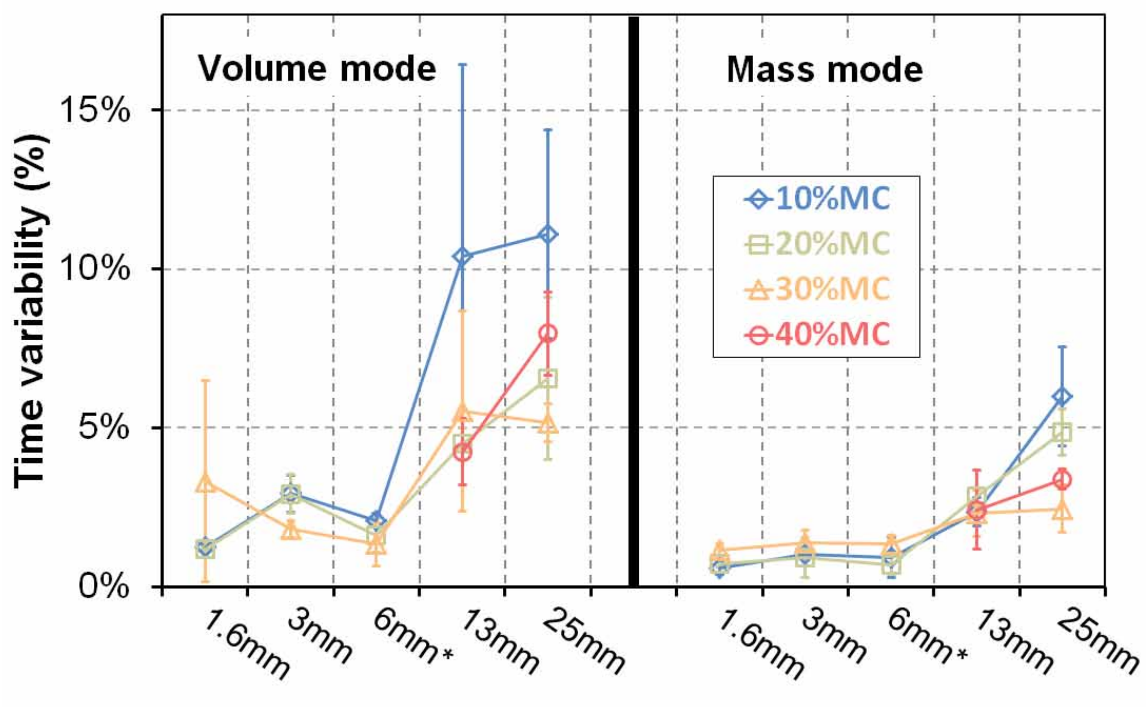
2 - Technical Progress

Screw auger performance



Time variability of feed rate (% of mean).

100 mm dia. auger

- *Volume feed tests at* **40% max. speed**
- *Power consumption measured (not shown)*
- *Larger auger has lower % time variation*
- *13 mm, 20%MC grind bent 1.5" dia. steel stirring rod*

Similar data recorded for switchgrass

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4. Flow performance models (still in development)

2 - Technical Progress

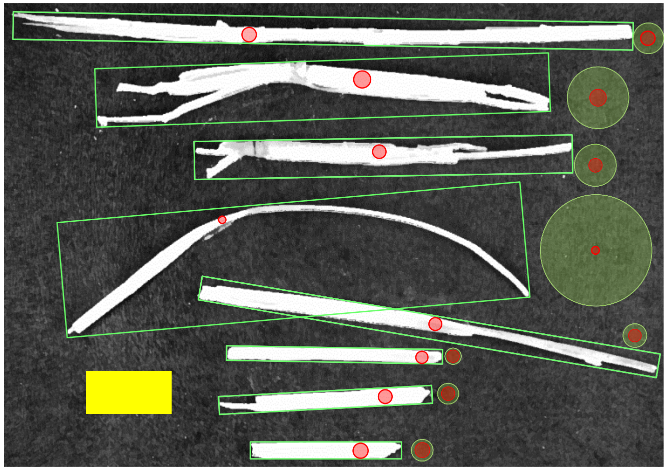
Particle size & shape distributions

Measurements of particle size and shape distributions of switchgrass samples

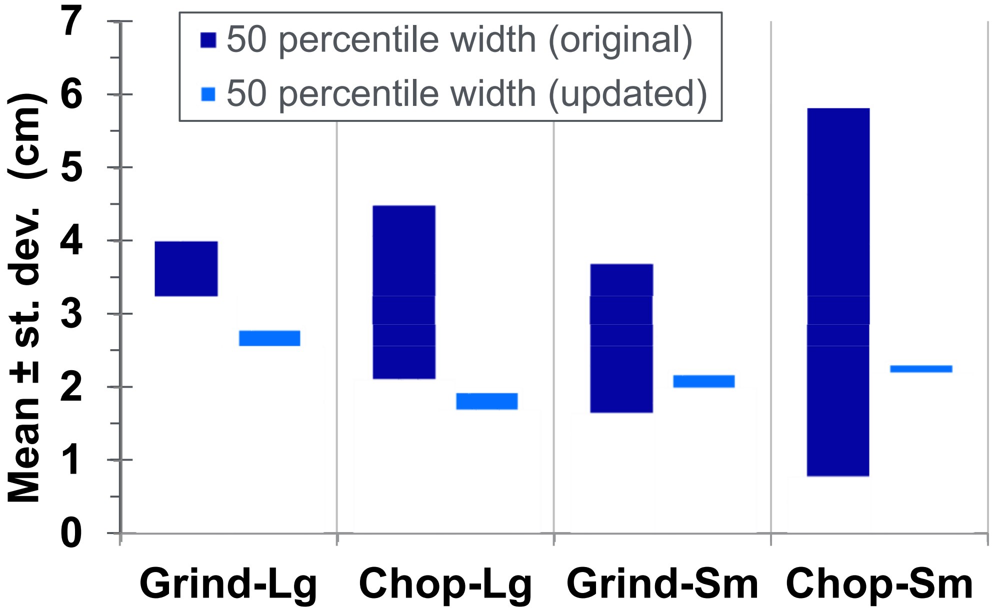
- Bulk-Format System for High-Tonnage Switchgrass (2010-2013)

> - Chopped material fed much better than ground.
> - <u>Is flowability due to sizes & shapes of particles?</u>

- Original: 8,000+ particles/replicate; placed by hand & imaged with digital camera
- Updated: 40,000+ particles/replicate; used automated camera with conveyor



Photos of example particles.
Yellow bar is 2 x 1 cm.

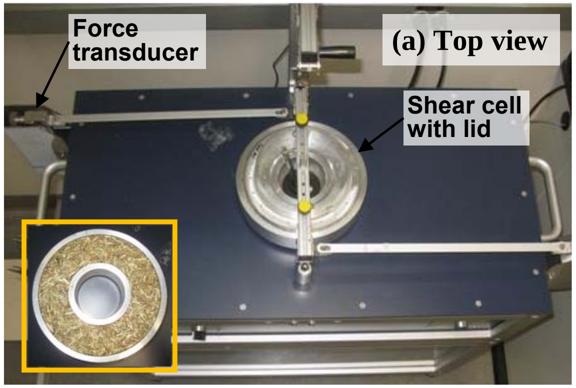


> - Updated results show materials have similar particles sizes and shapes.
> - Microscopy indicates that flowability at low compressive stresses depends primarily upon particle microstucture.

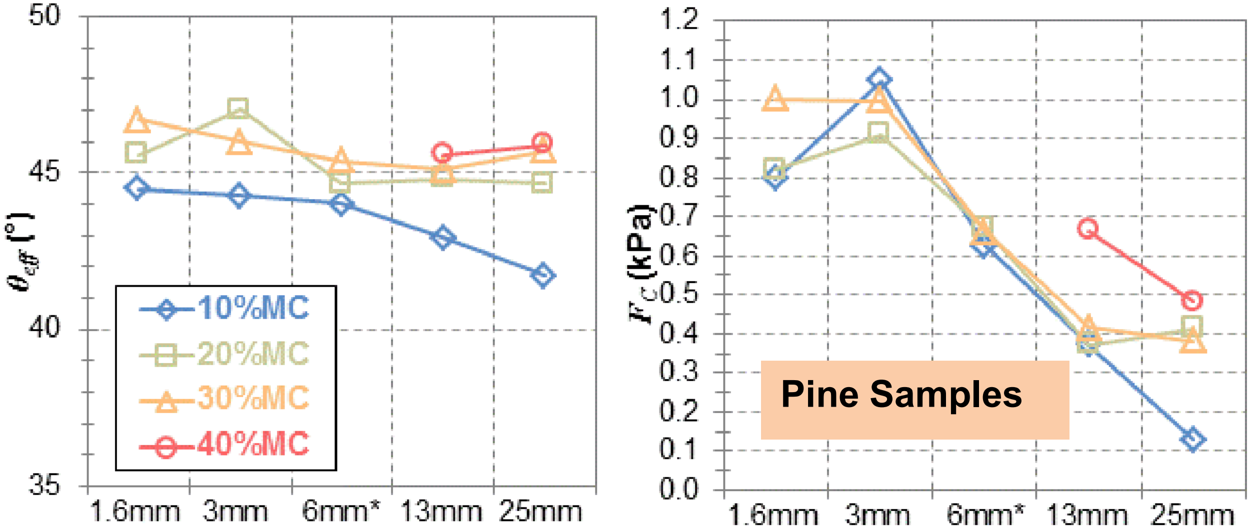
2 - Technical Progress **Shear tests (material strength)**

Schulze automated ring shear tester used to measure material strength

- Effective angle of internal friction θ_{eff} correlates to ***internal*** material strength
- Unconfined yield strength F_C measures ***strength at bridge*** (exposed face)
- Strength decreases with particle size and increases with moisture content



Schulze ring shear tester. Inset: filled cell.



Effective angle of internal friction θ_{eff} and unconfined yield strength F_C. Preshear stress = 2 kPa.

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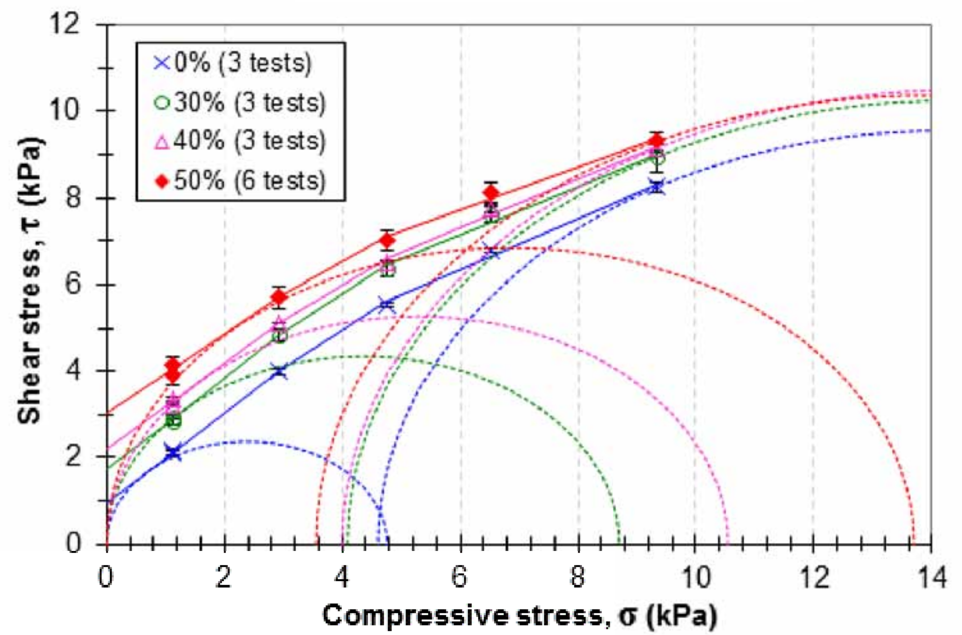
2 - Technical Progress

Shear tests (material strength)

Pine/Algae Samples



Shear tests of pine/algae blends

- Characterized flow properties of finely ground (0.2 mm) pine/algae blends (~40% MC)
- Finely ground, wet material has high strength
- **F_C increases with algae content**

Sample	f_c (kPa)	δ (°)
0% Algae	4.8 ± 8%	42.4 ± 1%
30% Algae	8.7 ± 5%	45.6 ± 2%
40% Algae	10.5 ± 1%	46.4 ± 0%
50% Algae	13.7 ± 8%	48.2 ± 2%

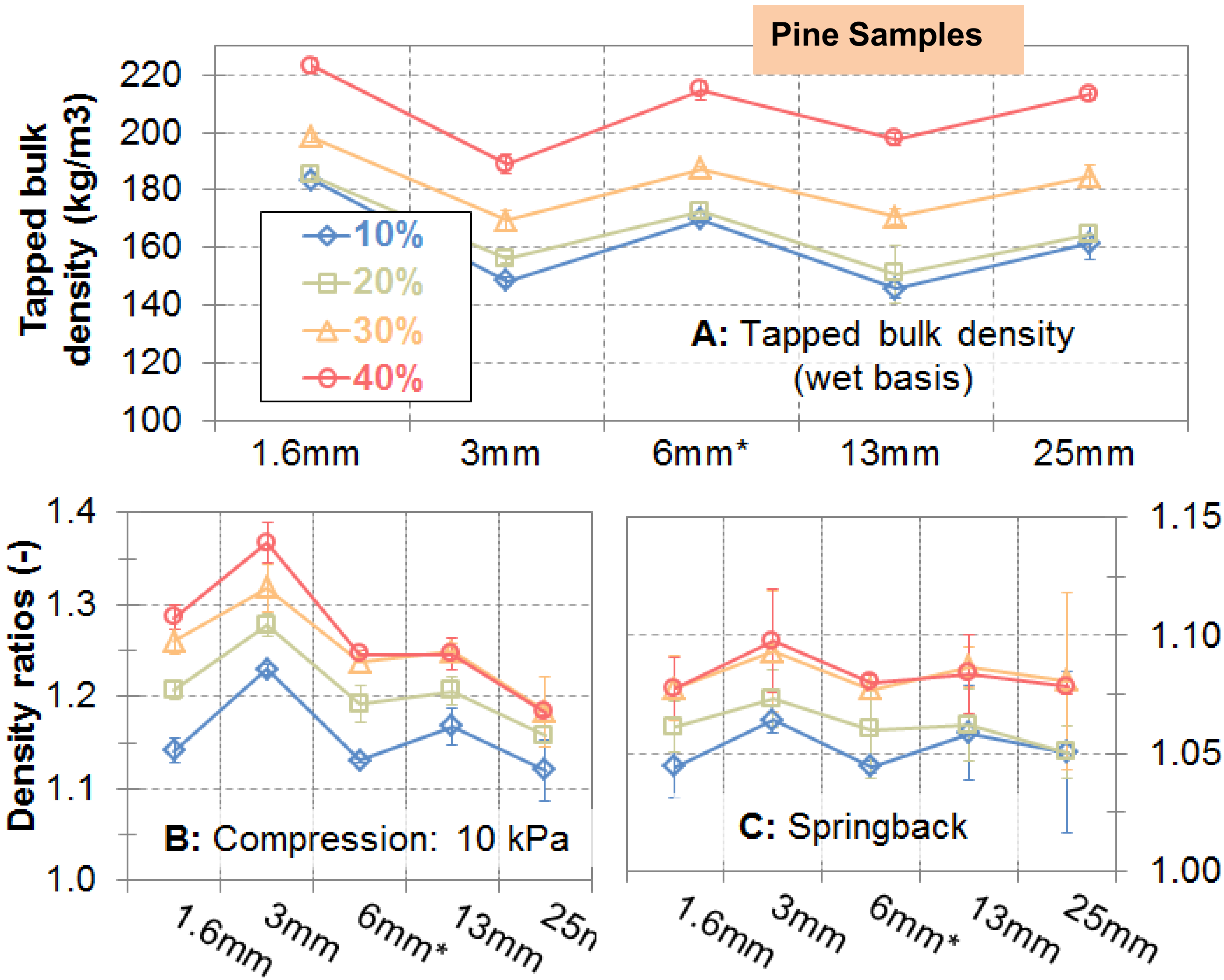
Photos of pine/algae blends. Left to right: pine only, 40%, 60%, and 100% algae.

2 - Technical Progress

Compression & elastic recovery

Compressibility tests (Instron load frame)

- 10% MC has small effect on bulk density
- 3 mm grind is most compressible
- Springback <10% for all samples



Additional Slides

Biomass Handling and Feeding Questions	
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.

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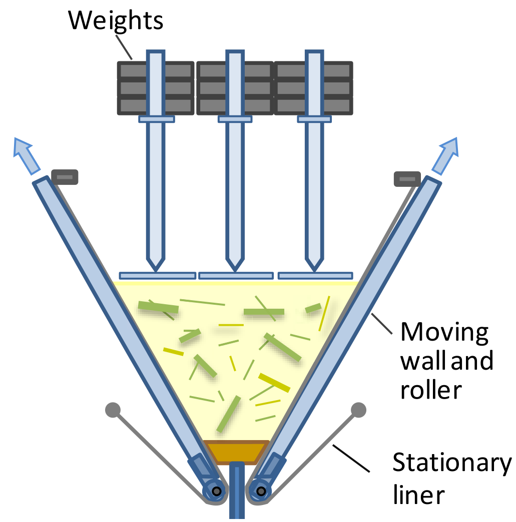
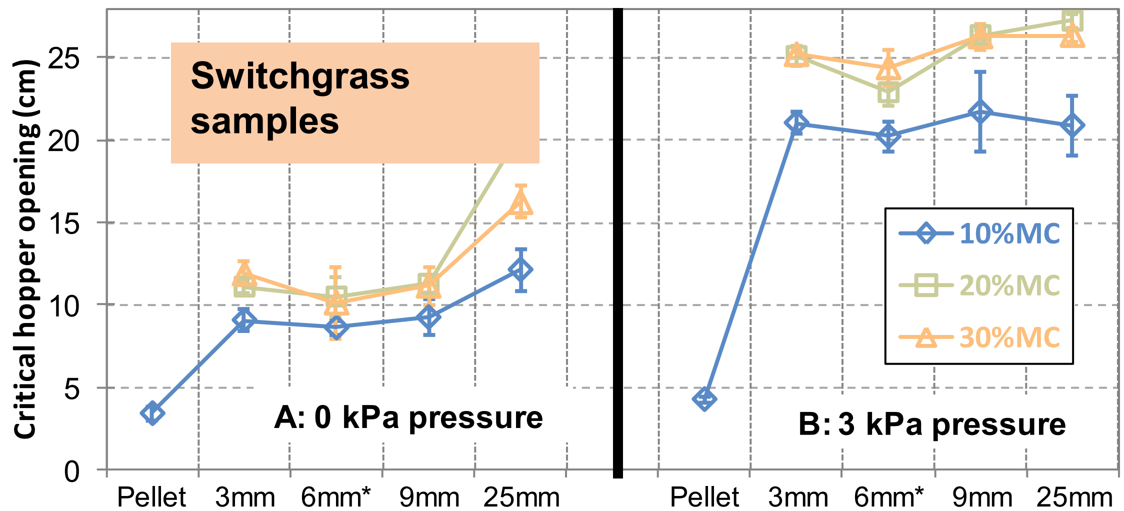
2 - Technical Progress

Hopper performance

06/30/14 Milestone: Assess feeding performance of 12 switchgrass samples in a screw feeder using three different screw configurations (*screw feeder data on next slides*)





- *Hopper has moveable walls covered with stationary liner;*
- *As walls raise, size of opening increases ;*
- *Critical hopper opening (L_{crit})I s determined when material falls free.*

- *Applying small pressure increases L_{crit} for most samples;*
- *Pellets have lowest L_{crit};*
- *Moisture has greatest influence on 25 mm grind.*

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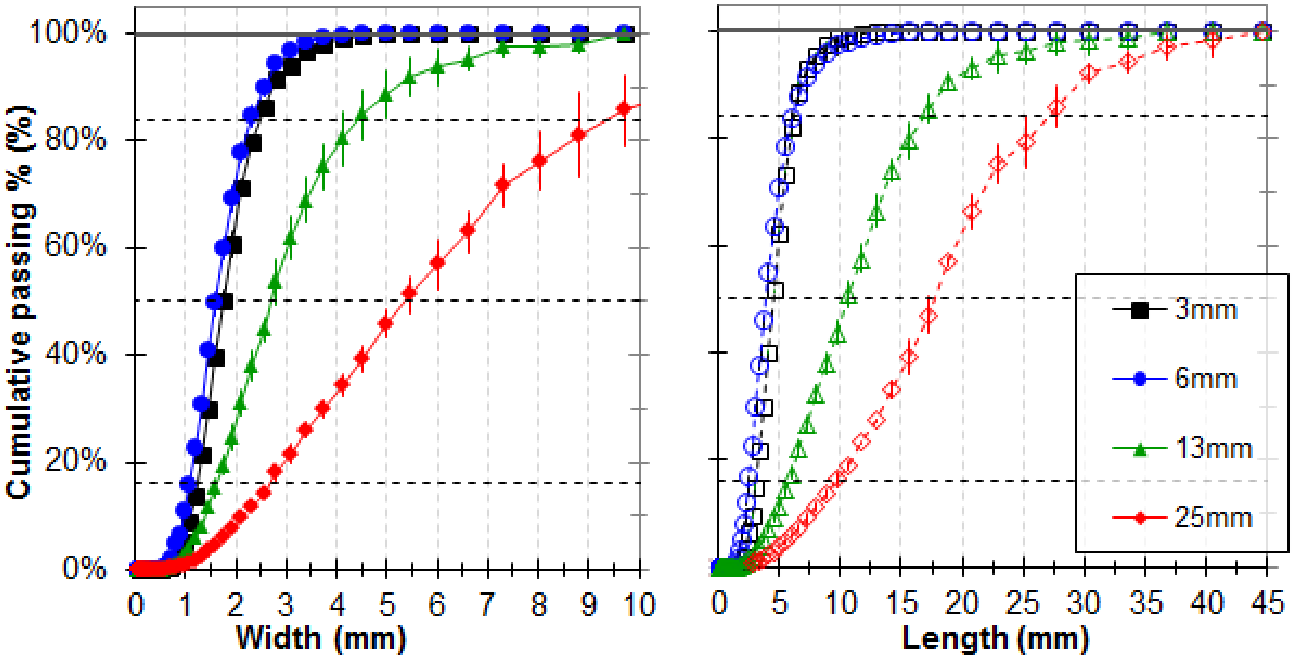
Particle size & shape distributions

Digital imaging system (Clemex P/E):

- Camera mounted above conveyor belt;
- Fed with vibratory feeder



- *3 mm hammer ground and 6 mm knife-ground materials are similar in terms of widths and lengths.*

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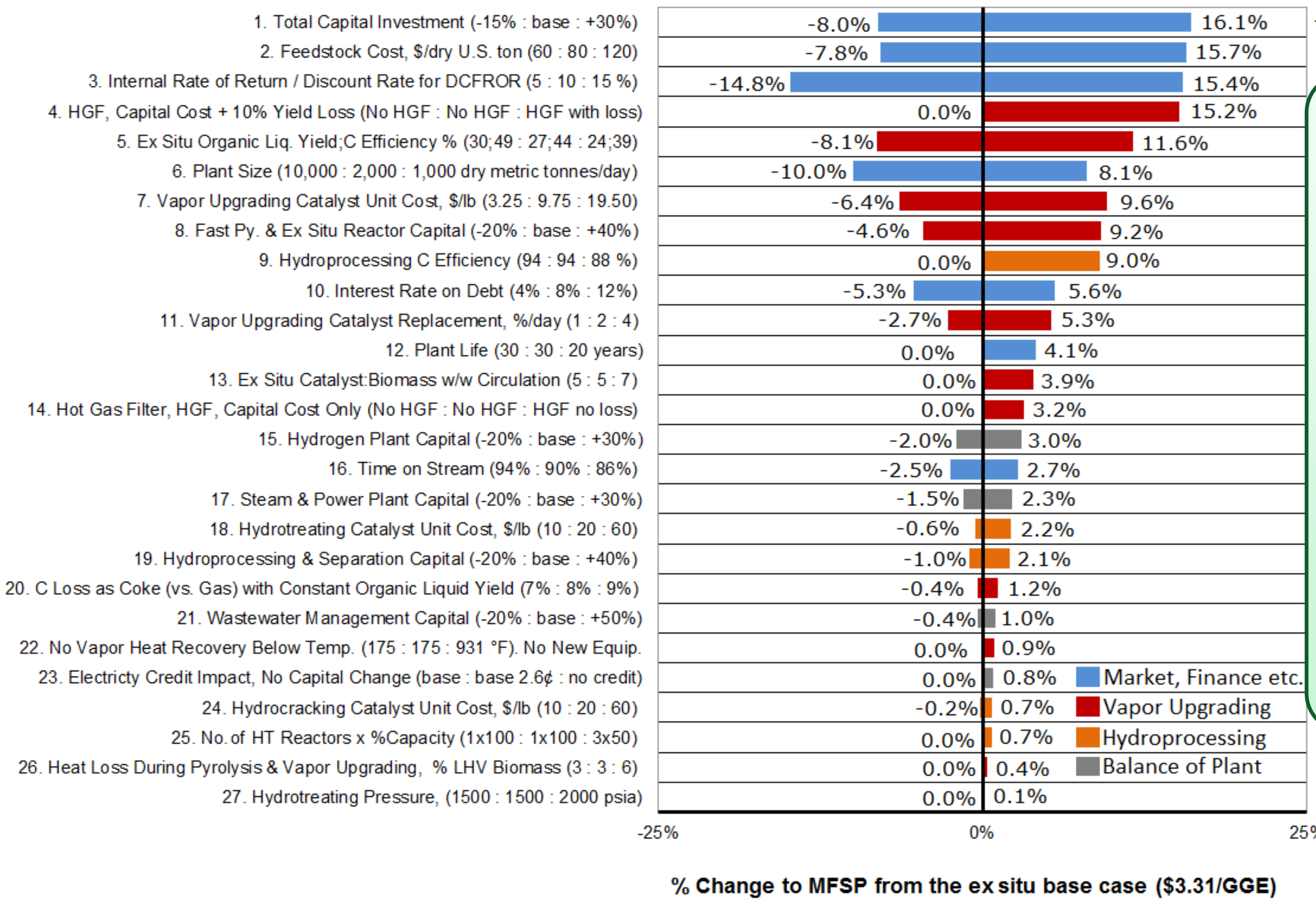
Relevance

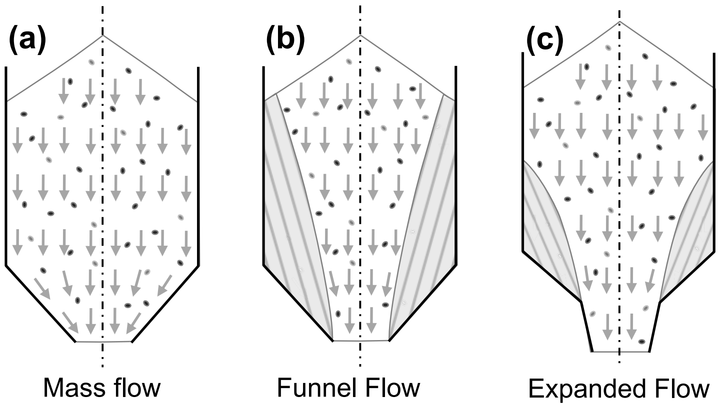
Cost sensitivities show potential impacts of feedstock on MFSP (*ex-situ* upgrading case).

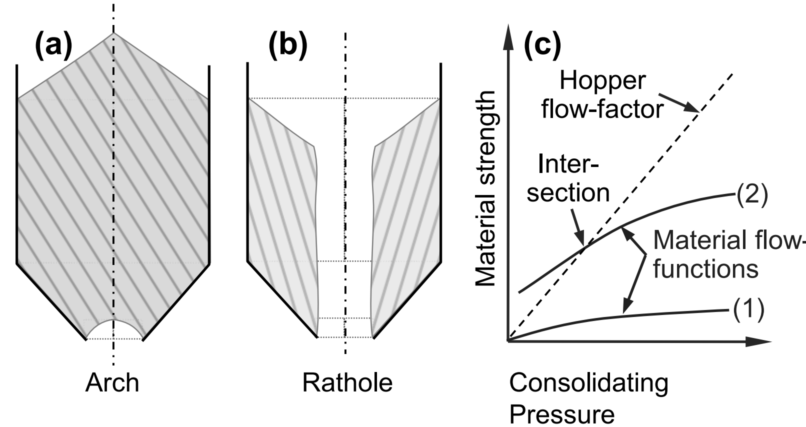


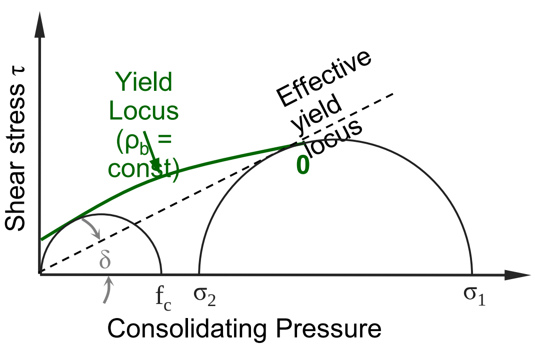
Capital investment

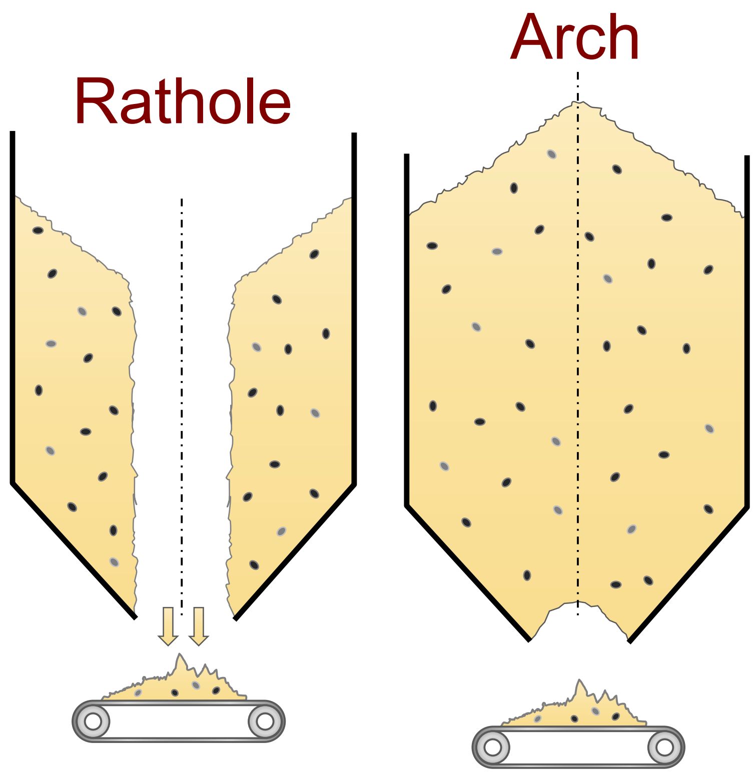
A 30% increase in plant size = 16.1% * $3.31/GGE = $0.53/GGE increase in fuel selling price.

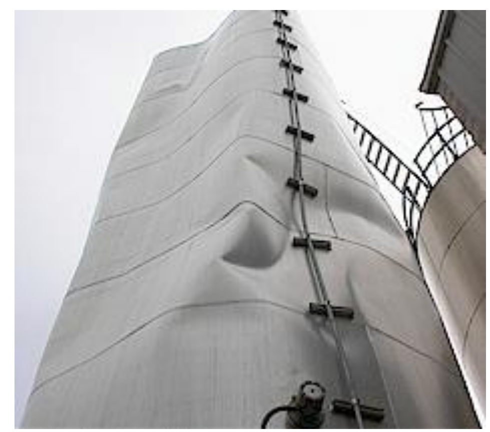
Scaling this value shows that increasing the plant size by 20% to compensate for production down time increases the fuel selling price by $0.36/GGE.











David Dick, "*Does your Silo Honk and Thump?*", Ask Joe! Article, Powder and Bulk Dot Com, Feb. 2006.

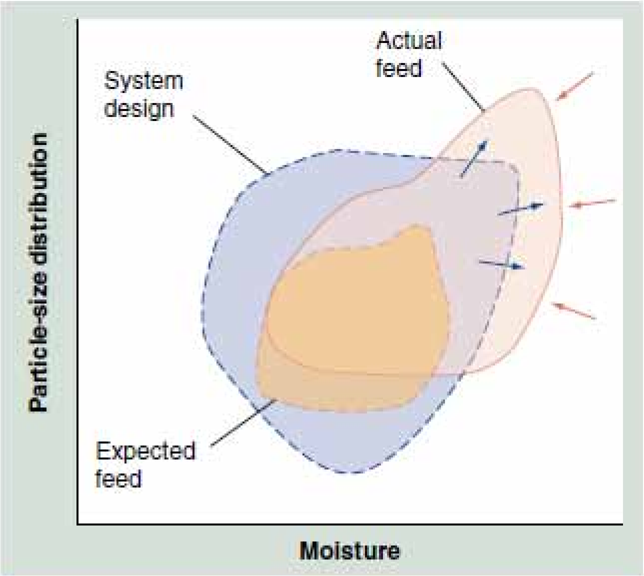


Figure 5. The combined approach for solving biomass handling and feeding problems through improved system design to expand equipment performance and improved preprocessing operations that constrain feedstock properties to conform to specifications.