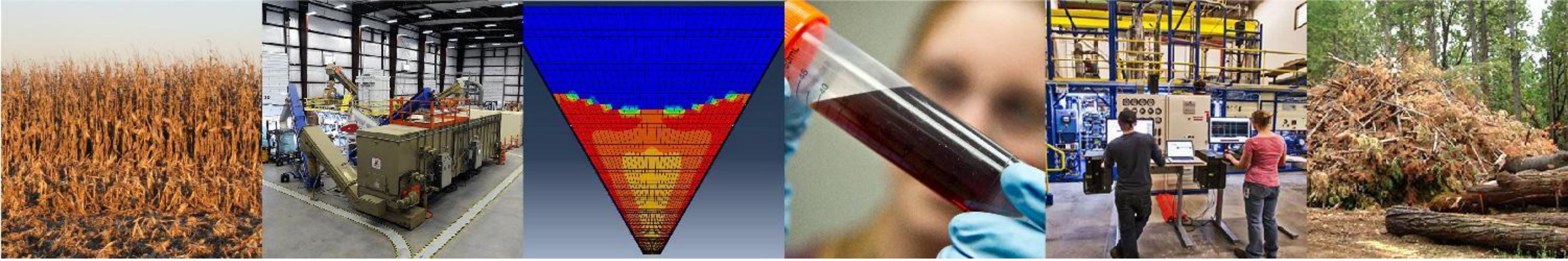


DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Process Control and Optimization (PCO)
WBS# 3. 3. 1. 10X

March 7, 2019

PI: Quang Nguyen

Process Control & Optimization Team

Preprocessing

- Quang Nguyen (PI)
- Patrick Bonebright (Control)
- Robert Kinoshita (Sensors)
- William Smith (Sensors)
- Neal Yancey (Operation)

Primary Deconstruction

- Richard Elander (Lead – Low Temp)
- Kristin Smith (Lead – High Temp)
- David Sievers (Control & Sensors)
- Katie Gaston (Control & Sensors)
- Dan Carpenter (Integration – High Temp)
- Raymond Hansen (Operation)

Goal of the Consortium

Identify and address the impacts of feedstock variability – chemical, physical, and mechanical – on biomass preprocessing and conversion equipment and system performance, to move towards 90% operational reliability.

Goal Statement

Project Goal:

Identify relationships between feedstock bulk properties and equipment performance to develop robust Adaptive Process Control Systems for achieving stable operation.

Outcome (FY18):

An Adaptive Process Control System utilizes **feedforward** control (using predictive models based on historical performance data of unit operations, and on properties of input materials) and **feedback** control to achieve stable operation of a 2-stage biomass grinding system.

Relevance:

Pioneer biorefineries had difficulties achieving the plant design throughput due to inadequate control of biomass preprocessing and conversion equipment.

Quad Chart Overview

Timeline

- Project Start Date: November 2017
- Project End Date : September 2018
- Percent Complete: 100%

	Total Costs Pre FY17	FY 17 Costs	FY 18 Costs ($)*	Total Planned Funding (FY 19-Project End Date)
DOE Funded	N.A.	N.A.	**1,178,117**	N.A.
Project Cost Share	N.A.	N.A.	N.A.	

*** Partners: INL 75%; NREL 25%**

Barriers addressed

Ct-A. Feedstock Variability, Ct-B. Reactor Feed Introduction, Ct-C. Efficient Preprocessing, Ct-D. Efficient Pretreatment, Ct-J. Process Integration , Ct-N. Materials Compatibility and Reactor Design and Optimization Integration, Ft-E. Terrestrial Feedstock Quality, Monitoring, Ft-G. Biomass Physical State Alteration and Impact on Conversion Performance Ft-I. Overall Integration and Scale-Up , Im-A. Inadequate Supply Chain Infrastructure, It-B. Risk of First-of-a-Kind Technology, It-C. Technical Risk of Scaling

FY18 Objective

Verify that an Autonomous Adaptive Process Control System can achieve 90% operational reliability for a two-stage grinding system using 15 tons of corn stover bales with varying moisture content.

FY18 Project Goal

- Identify relationships between feedstock properties and process & equipment performance.
- Identify potential control parameters for improving the operational reliability and feedstock quality.

1. Project Overview

Task 1: Adaptive Process Control System Development

Objectives:

- Improve operational reliability
- Achieve consistent feedstock properties

1.1 Adaptive Control Logics (e.g., predictive models, **feedforward & feedback control**)

1.2 In-line NIR sensor for measuring moisture, total ash, glucan, and xylan of milled corn stover. Image analyzer for particle size & shape.

1.3 Relationships between properties of input and output materials and process control parameters. This information is necessary for developing **effective control logics** and **equipment design criteria.**

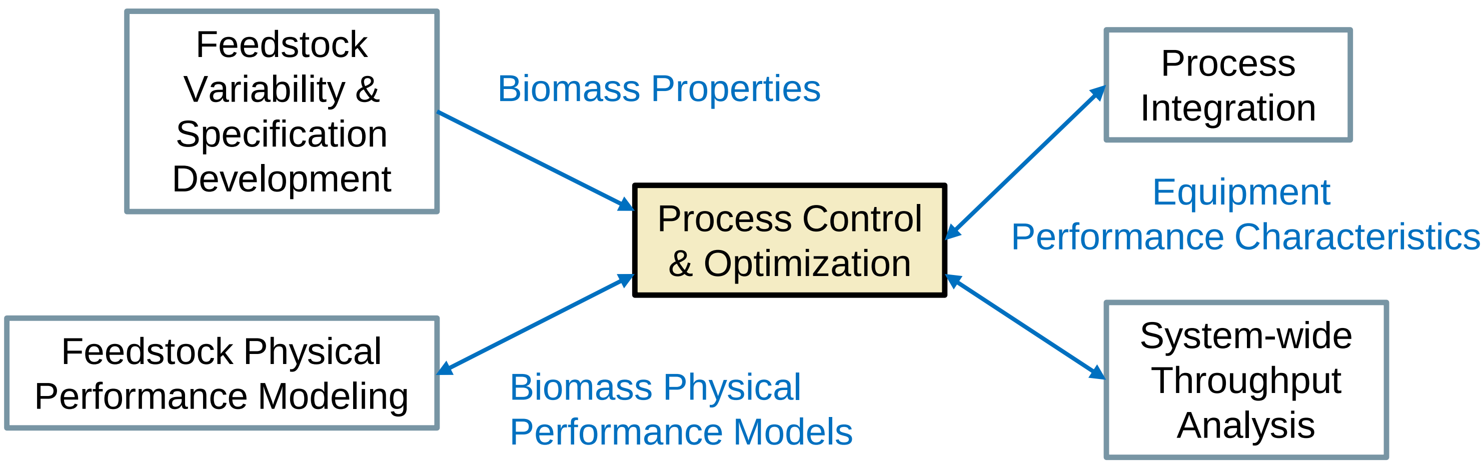
Task 2: In-line sensor for measuring high moisture (>25%) corn stover bales: low-frequency radio wave (work did not start).

2. Approach (Management)

1. Feedstock Preprocessing (INL)

2. Primary Deconstruction – Low Temp. & High Temp. (NREL)

3. Bi-weekly meeting (PCO team and FCIC)



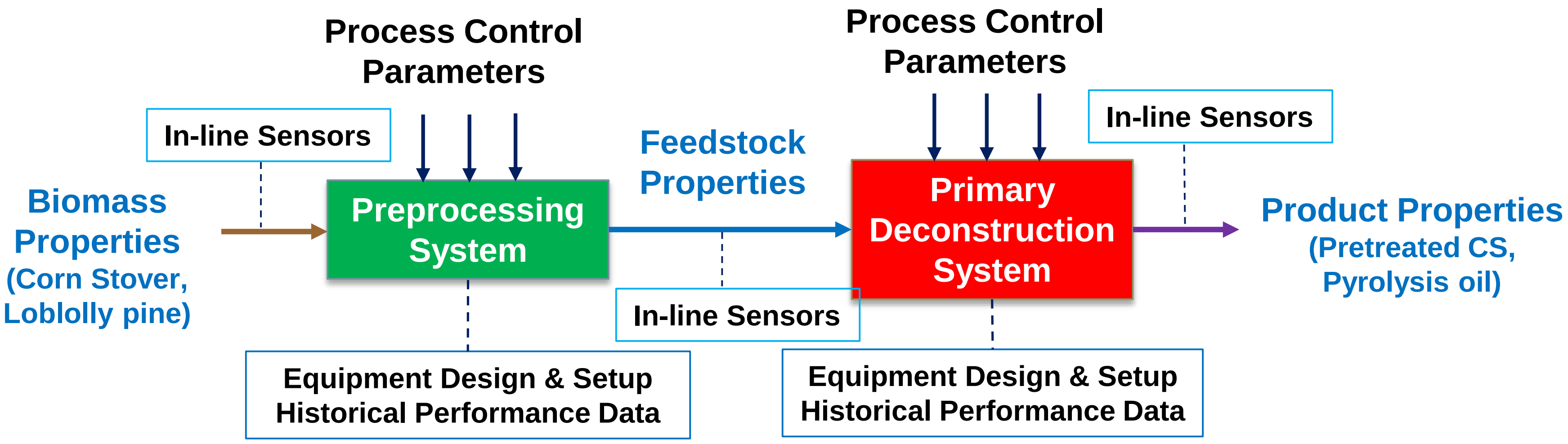
Interaction between PCO task and other FCIC tasks

2. Approach (Technical)

- Adaptive Process Control System
  - Leverage methodologies and results from the previous User Facility Control Project (completed in FY17).
  - Leverage work on in-line NIR sensor from the Feedstock Harvesting & Storage Project (WBS 1.2.1.1).
  - Utilize historical data and data from baseline runs.
- Identify relationship between critical material properties, process/equipment control parameters and output material properties
  - Focus on the performance of single unit operation.
  - Critical properties that impact operational reliability: moisture, total ash, particle size & shape, chemical composition, and acid loading (pH).
- Critical success factors
  - Repeatable in-line sensors for measuring critical properties.
  - Correlate critical properties that cannot be readily measured by in-line sensors (compacted bulk density, internal friction, impact/shear strength, etc.) to measurable bulk properties.

Approach (Technical) (Cont.)

Adaptive Process Control System comprises: Predictive / Feedforward / Feedback Control and In-line Sensors



Relationship between input material and output material properties and process control parameters

Background: Existing In-line Sensors for Measuring Bulk Properties

Gazeeka Bale Moisture Sensor on Conveyor feeding the 1st-Stage Grinder

- **Measures moisture content of corn stover bale up to 25%**

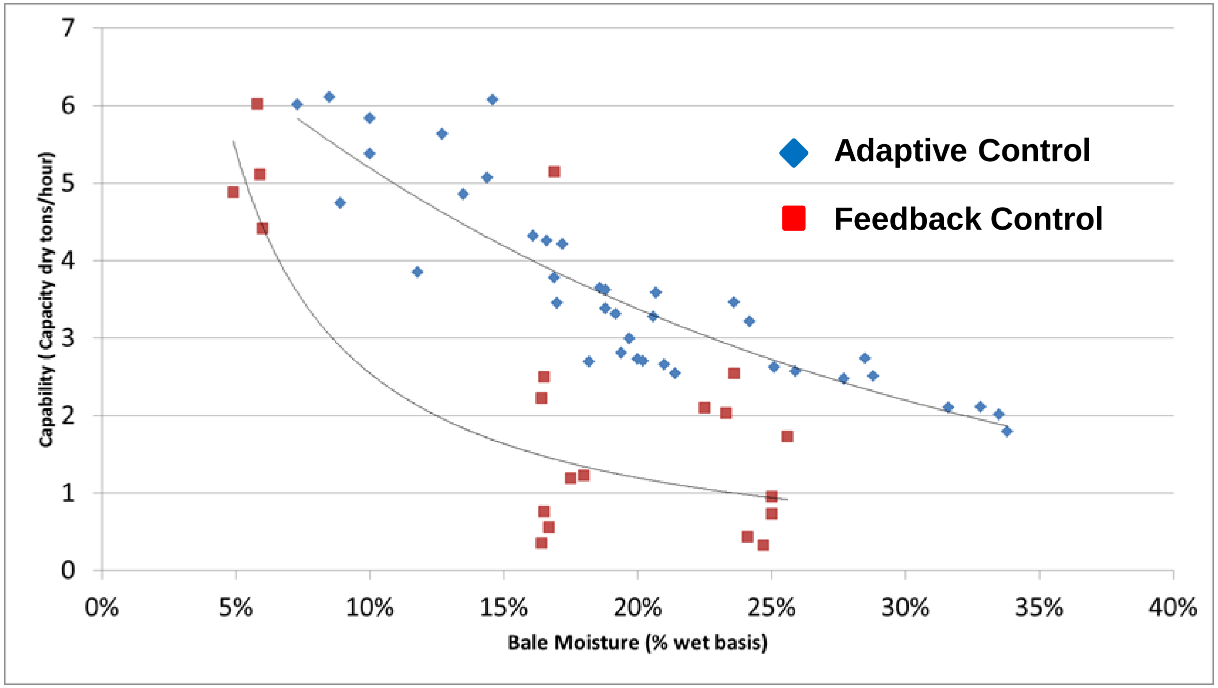
In-line NIR Probe on Drag Chain Conveyor feeding the 2nd-Stage Grinder.

- **Measures moisture, ash, glucan and xylan content of milled CS**

Background – User Facility Control Project

Leverages methodologies from a 20-ton (7 hr duration) run in FY17:

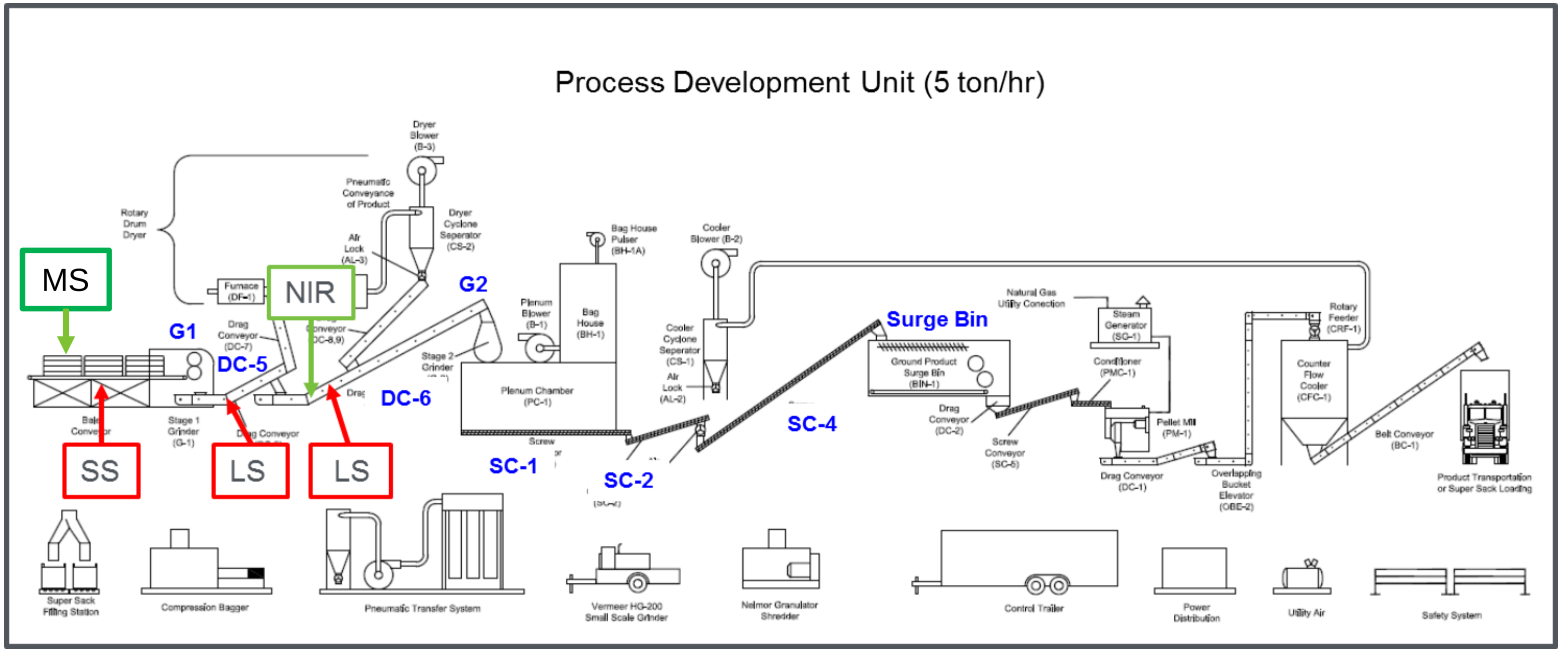
Human-in-the-loop Adaptive Process Control System achieved **96% operational reliability** (on-stream time) for a 2-stage grinding system compared to **63%** (using **feedback control**) using 7% - 34% moisture corn stover bales.



Impact of bale moisture on throughput of 2-stage grinding

3. Technical Accomplishments – Feedstock Preprocessing

Conducted a 6-hr test of an **Autonomous Adaptive Process Control System** (i.e., no human-in-the-loop) of a two-stage grinding system using 25 bales (15 tons) with moisture ranging from 12% to 35% with **no down time**.

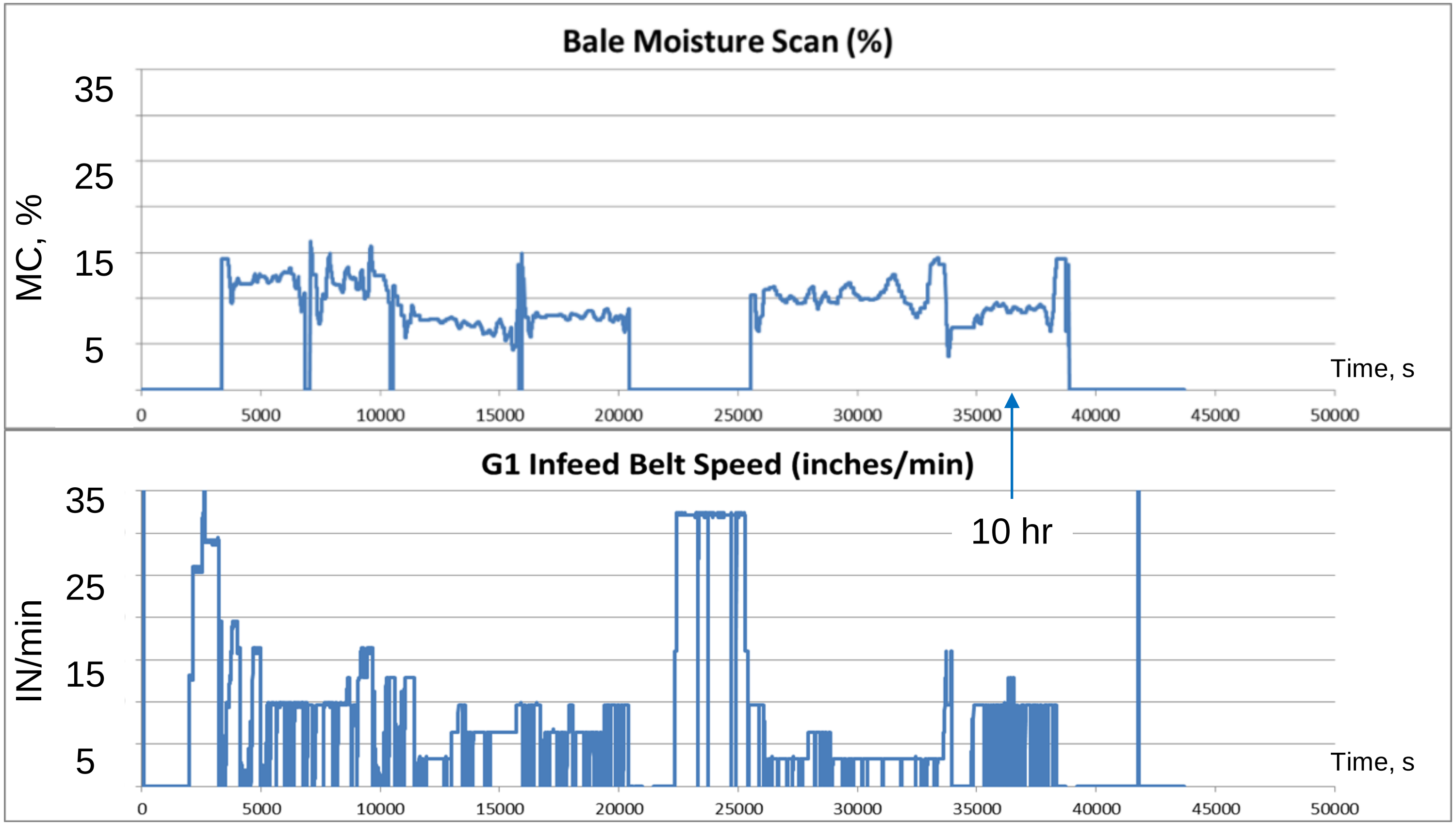


SS	Speed Sensor	MS	Gazeeka Moisture Sensor	**G**: Grinder
LS	Level Sensor			**DC**: Drag Chain Conveyor
NIR	NIR Probe			**SC**: Screw Conveyor

Block Flow Diagram of 2-stage grinding

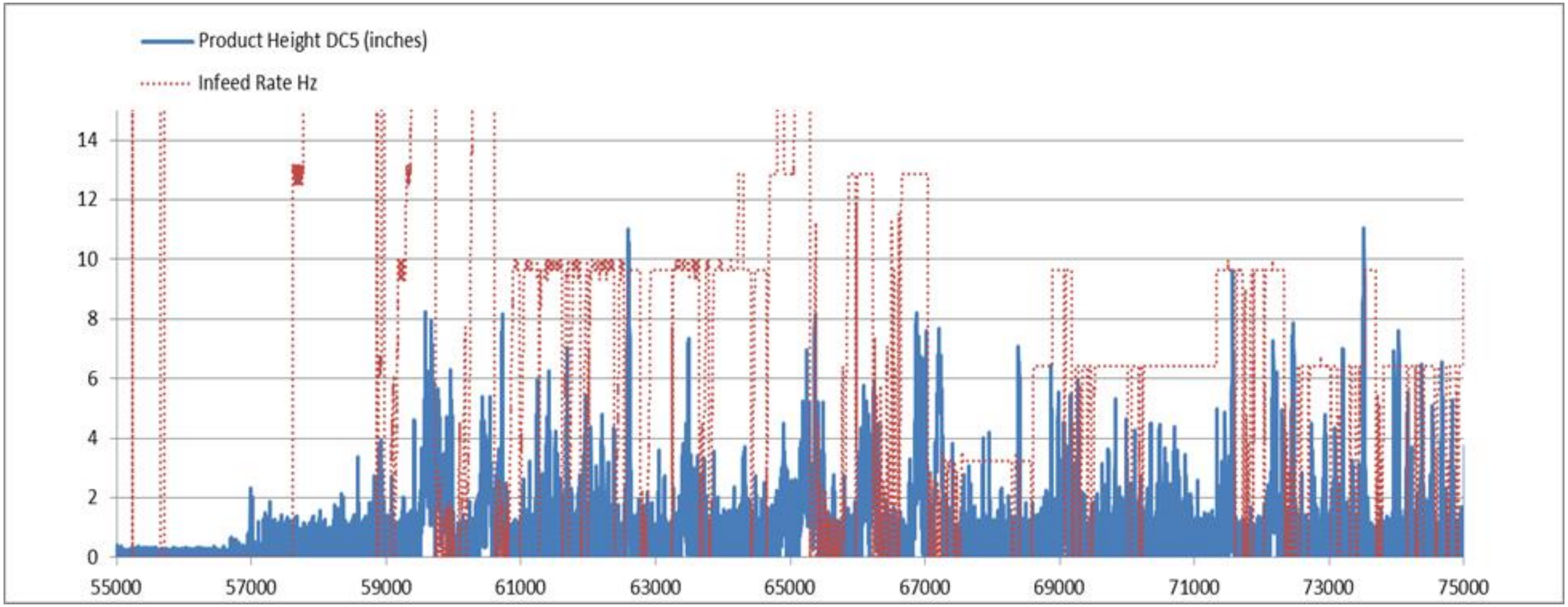
Technical Accomplishments – Feedstock Preprocessing (Cont.)

Feedforward Control: Automated response of Bale Grinder (G1) feed rate based on bale moisture content to achieve stable operation



Technical Accomplishments – Feedstock Preprocessing (Cont.)

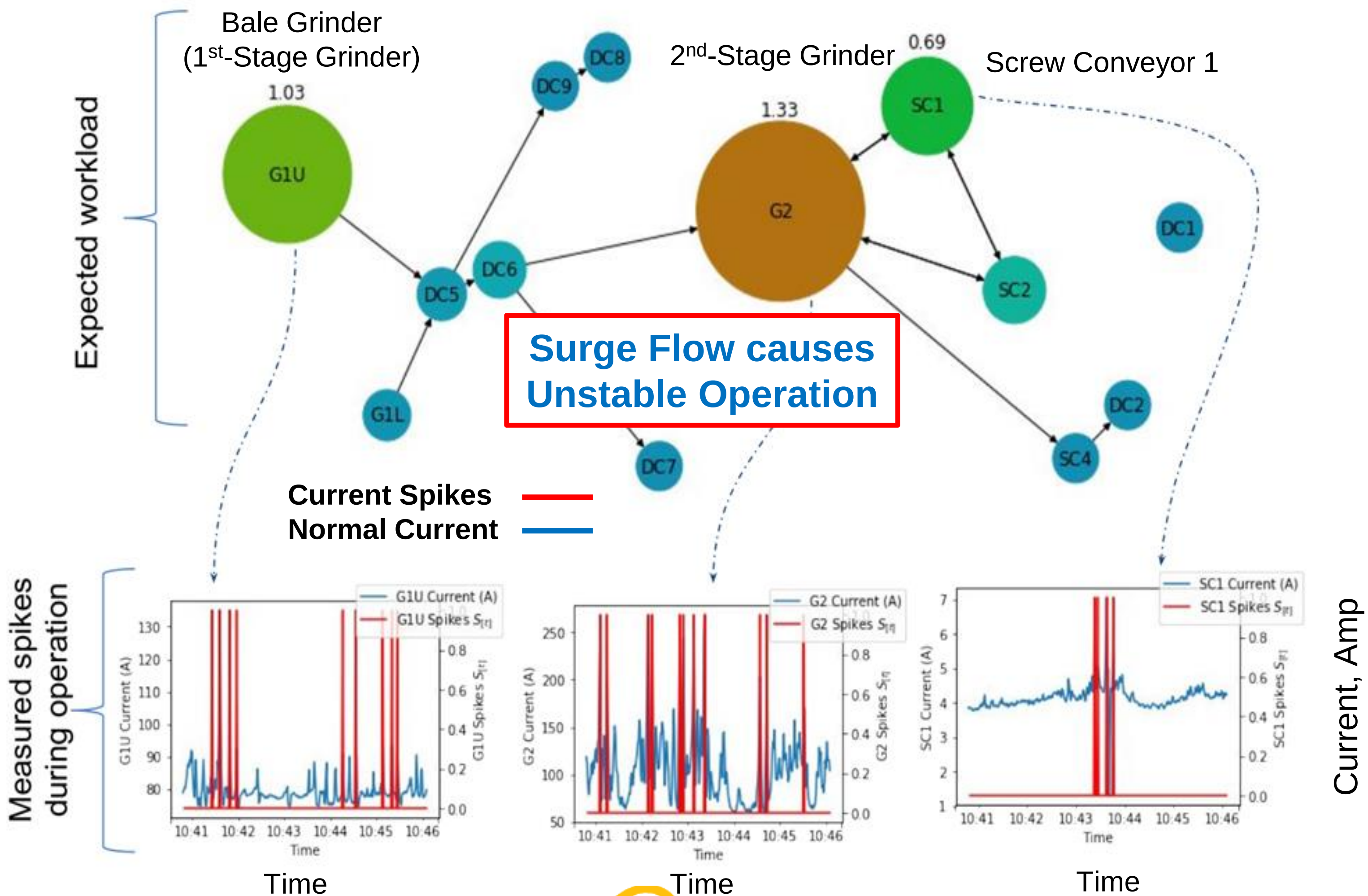
Feedback Control: Automated response of bale grinder feed rate based on feedstock level on the outlet conveyor to achieve stable operation



0 hr Time, second 5.5 hr

Technical Accomplishments – Feedstock Preprocessing (Cont.)

Unstable operation of 2nd-stage grinder & SC1 due to surge flow from the bale grinder



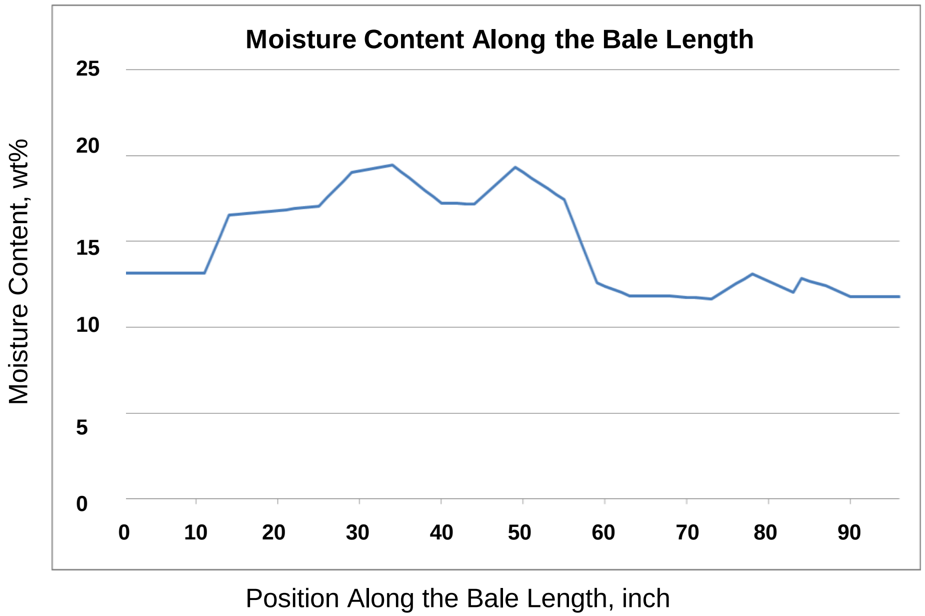
Corn Stover Bale Characteristics

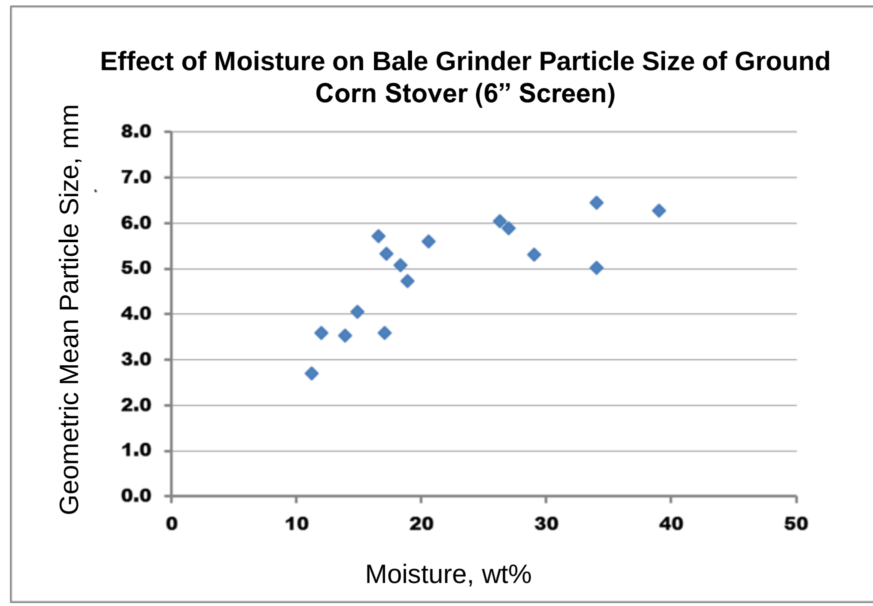
Varying properties within a bale cause surged output from the bale grinder

**High Moisture/
Heat Damaged**

Technical Accomplishments – Feedstock Preprocessing (Cont.)

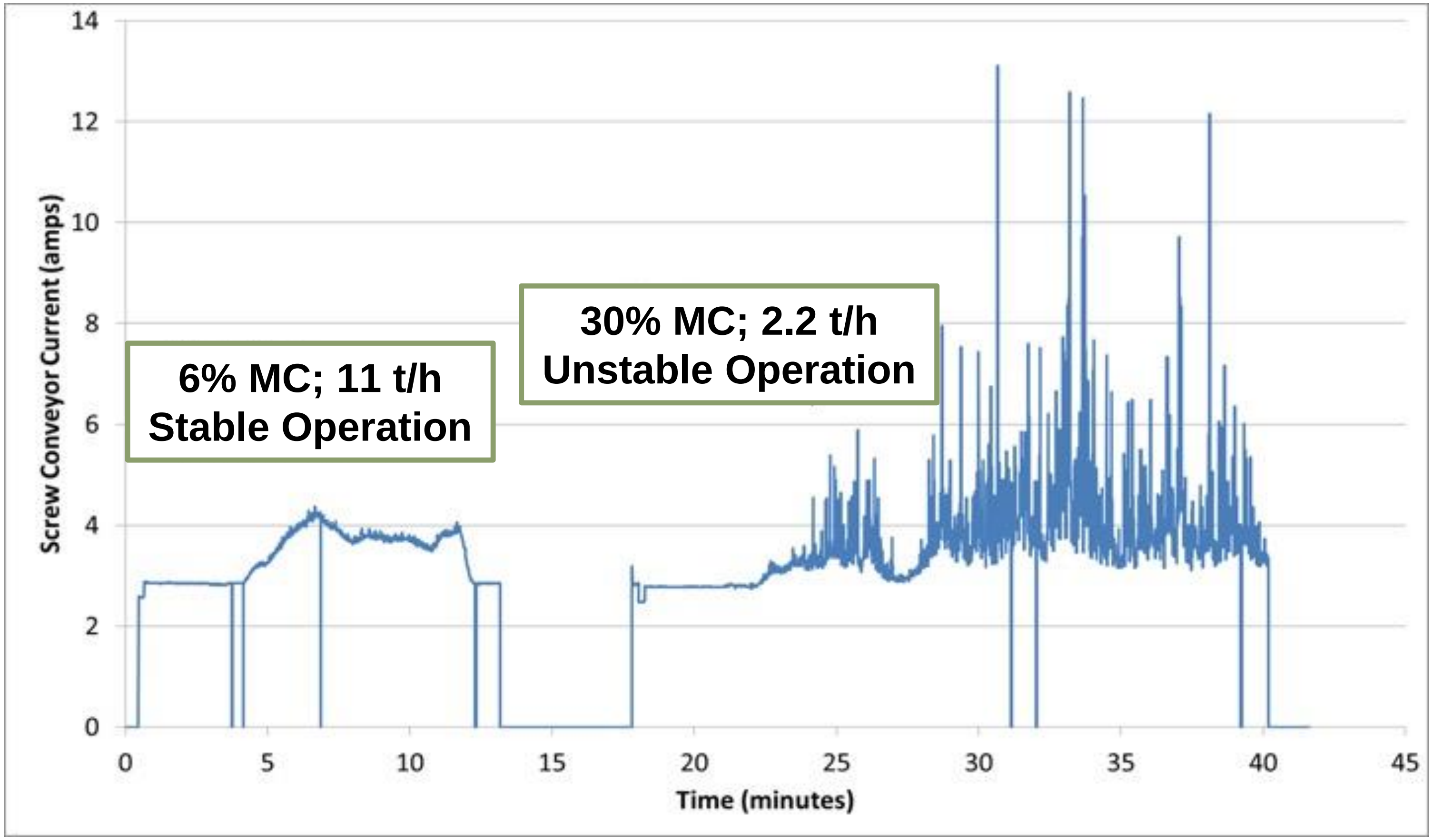
Higher Moisture leads to Larger Particle Size of Corn Stover





Technical Accomplishments – Feedstock Preprocessing (Cont.)

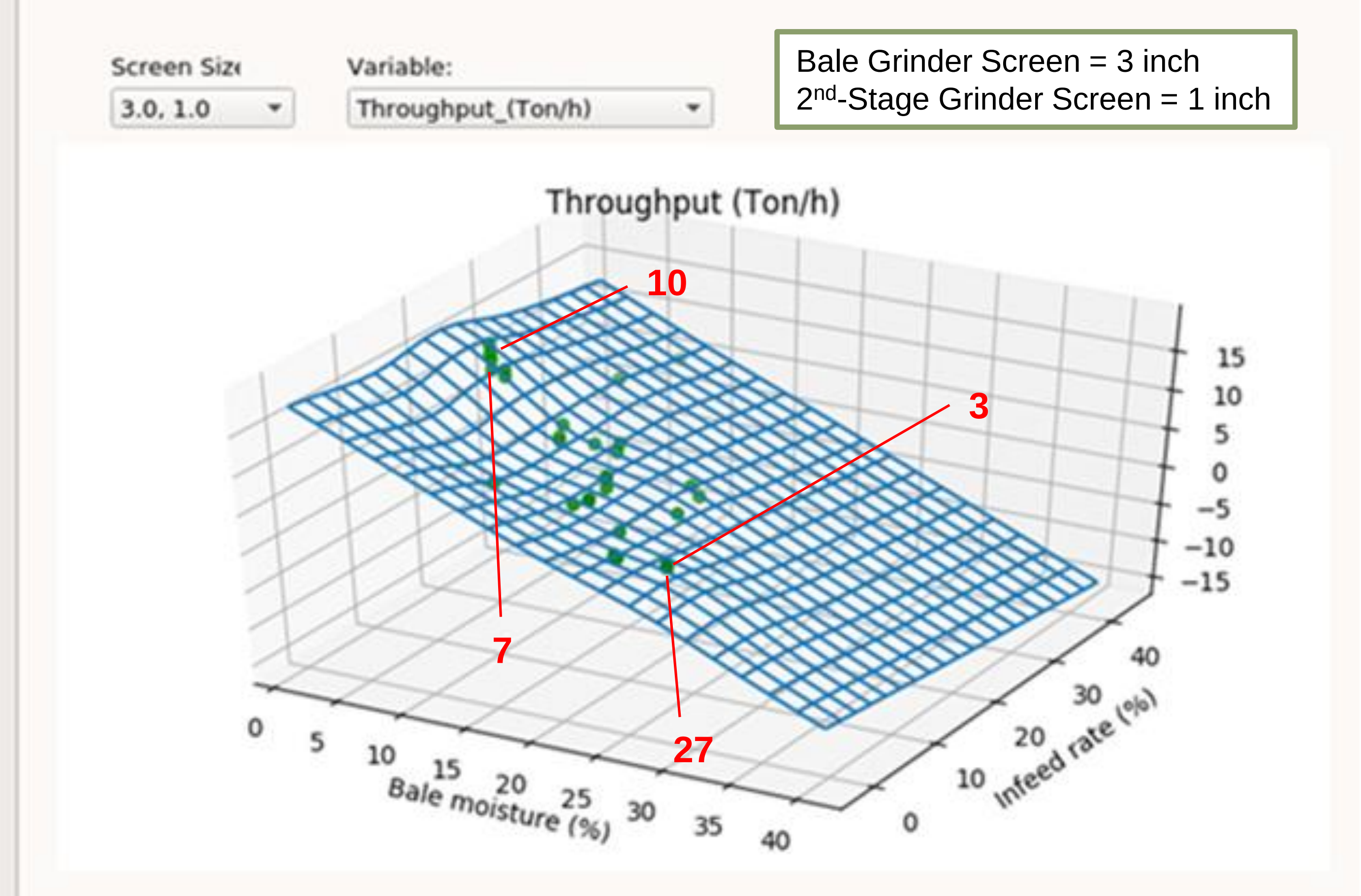
Higher Moisture leads to Lower Screw Conveying Throughput



Effect of Moisture of 1" Milled Corn Stover on Helical Screw Conveyor Performance

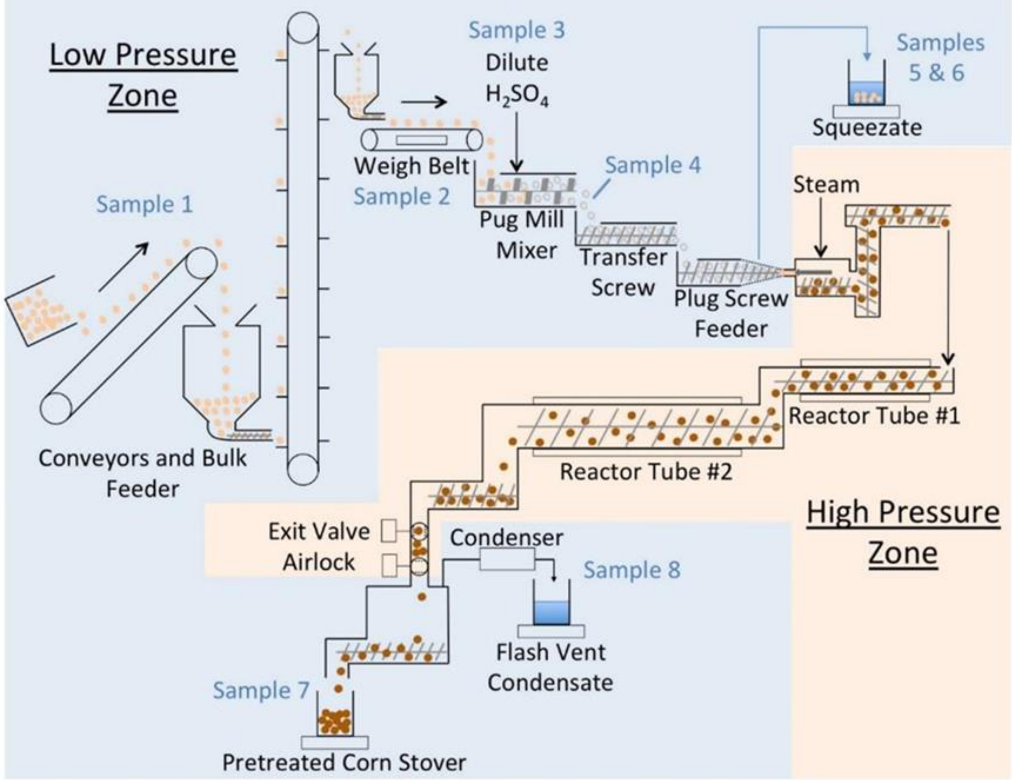
Technical Accomplishments – Feedstock Preprocessing (Cont.)

Higher Moisture leads to Lower System Throughput



3. Technical Accomplishments – Low-Temp Primary Deconstruction

Key properties:
- Input biomass: moisture, ash, particle size & shape
- Process control parameters: feed rate, acid addition
- Output: pH of squeezate, sugar and furan yields



Pretreatment system of the low-temperature conversion pathway

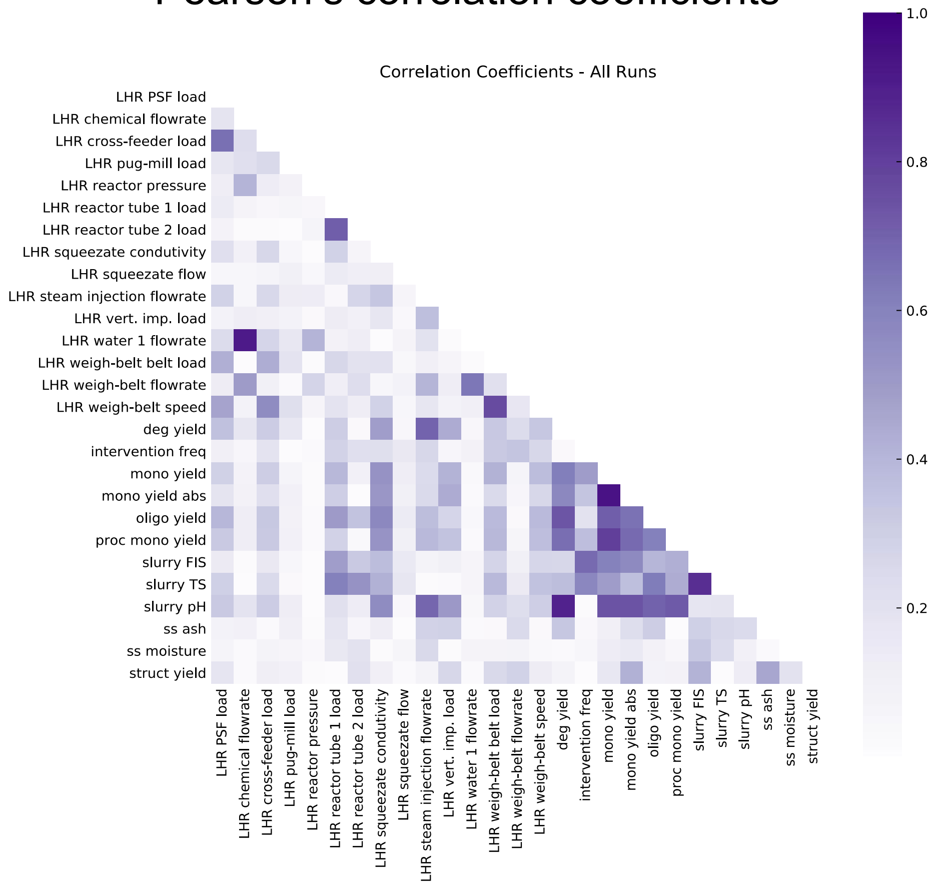
Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Dilute acid steam pretreatment

- NREL ran four baseline runs using corn stover feedstock in the low-temperature conversion reactor—the Metso 500 kg/d pretreatment reactor.
- The corn stover feedstock was first processed at INL:
  - Low-ash, low-moisture (LALM) – Run 1
  - High-ash, low-moisture (HALM) – Run 2
  - High-ash, high-moisture (HAHM) – Run 3
  - Low-ash, high-moisture (LAHM) – Run 4

Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Baseline run absolute values of Pearson's correlation coefficients



Correlations

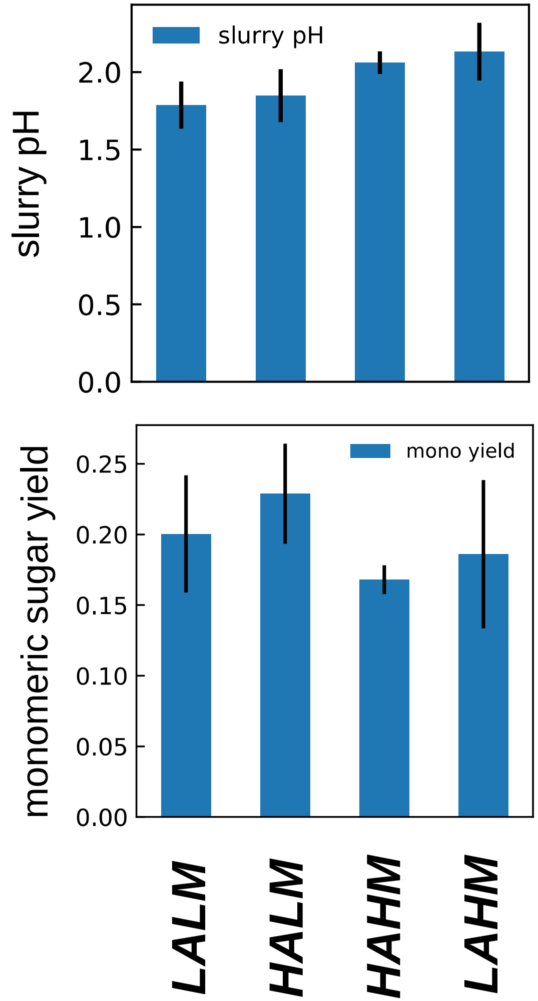
- Plug-screw-feeder (PSF) motor load (torque)
- Cross-feeder motor load (torque)
- Weigh-belt belt load (kg/m of moving belt)
- Feedstock particle variation (subjective)

- Conversion yields
- Reactor pH

Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Effect of feedstock moisture:

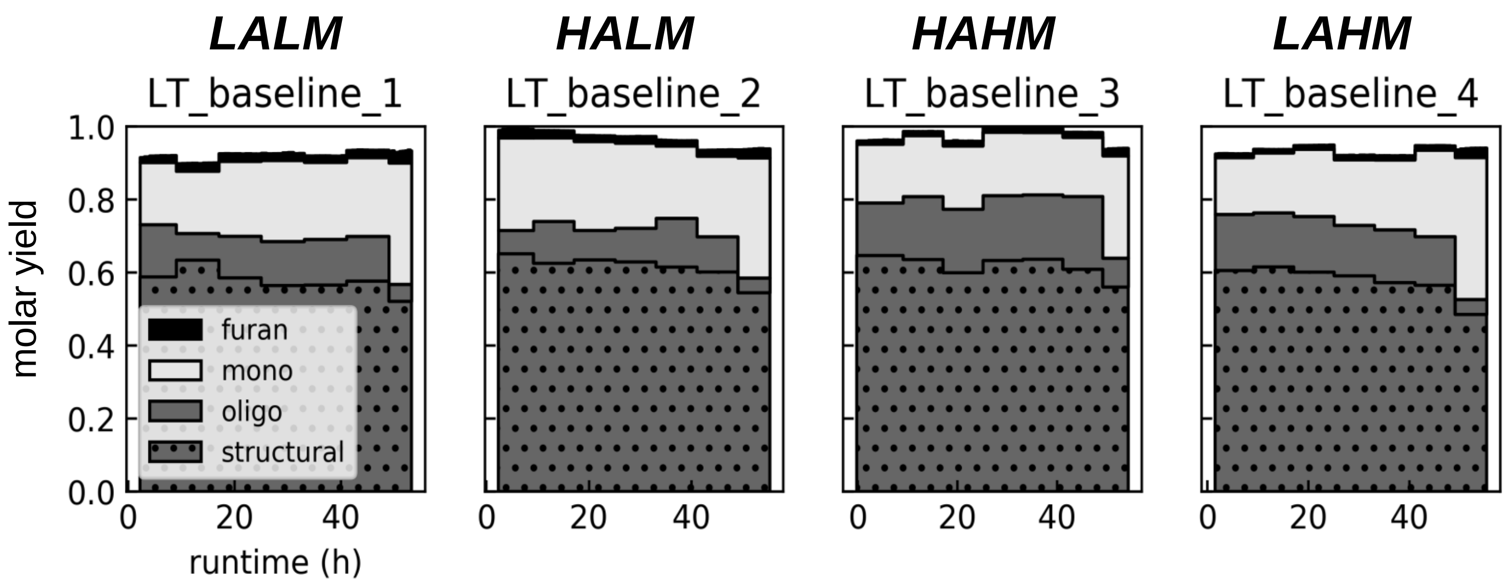
- High-moisture (***HM)*** materials resulted in **higher pH** of pretreated corn stover slurry and **lower monomeric xylose yields**.



Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Effect of acid loading

- **Higher acid** conditions at end of each run resulted in **higher monomer** and **lower oligomer yields**, slightly lower structural carbohydrate yield, and **slightly higher furan** (C5 sugars degradation) yield.



Baseline conversion molar sugar yields.

Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Effect of feedstock ash variation: Ash may change the neutralization capacity, which will alter the pH in the reactor and affect yields.

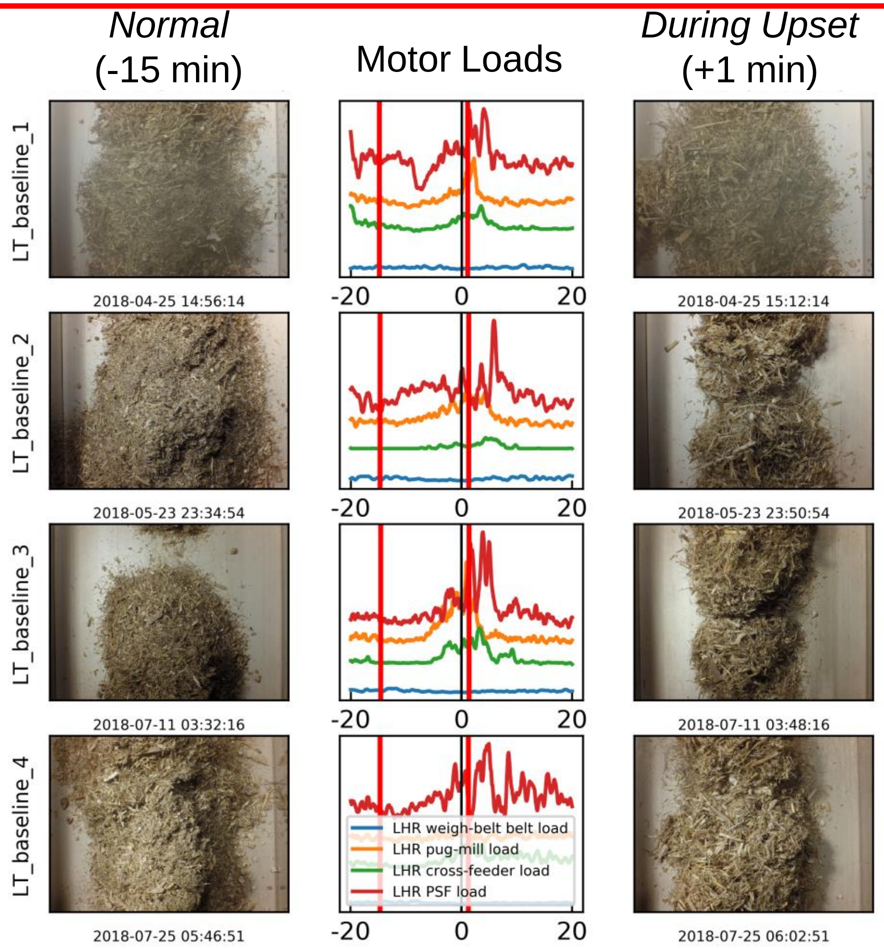
- Variation in monomeric sugar yield relative to *HA* and *LA* runs indicates **ash effects are insignificant** with this particular feedstock.

Effect of feedstock particle size distribution:

- Reactor Feeder and Plug Screw Feeder motor loads fluctuate with subjectively-evaluated feedstock particle properties. Operator observations noted that **"lighter" and "stringier" feedstock** tended to **coincide with** downstream **feeder motor load spikes**.

Technical Accomplishments – Low-Temp Primary Deconstruction (Cont.)

Motor load upsets occur when the high aspect-ratio material is present



Images of feedstock on weigh-belt before and after upstream hopper-feeder refill startup events (t = 0 min).

The images at +1 min qualitatively present more long aspect-ratio particles than the *normal* images at -15 min. The center row plots motor loads and red vertical bars for when the before and after images were taken

- Weigh Belt
- Pug Mill (acid addition)
- Cross Feeder
- Plug Screw Feeder

3. Technical Accomplishments – High-Temp Primary Deconstruction

Historical data mining and analysis of the baseline runs for high-temperature conversion identified operability problems and mitigation strategies.

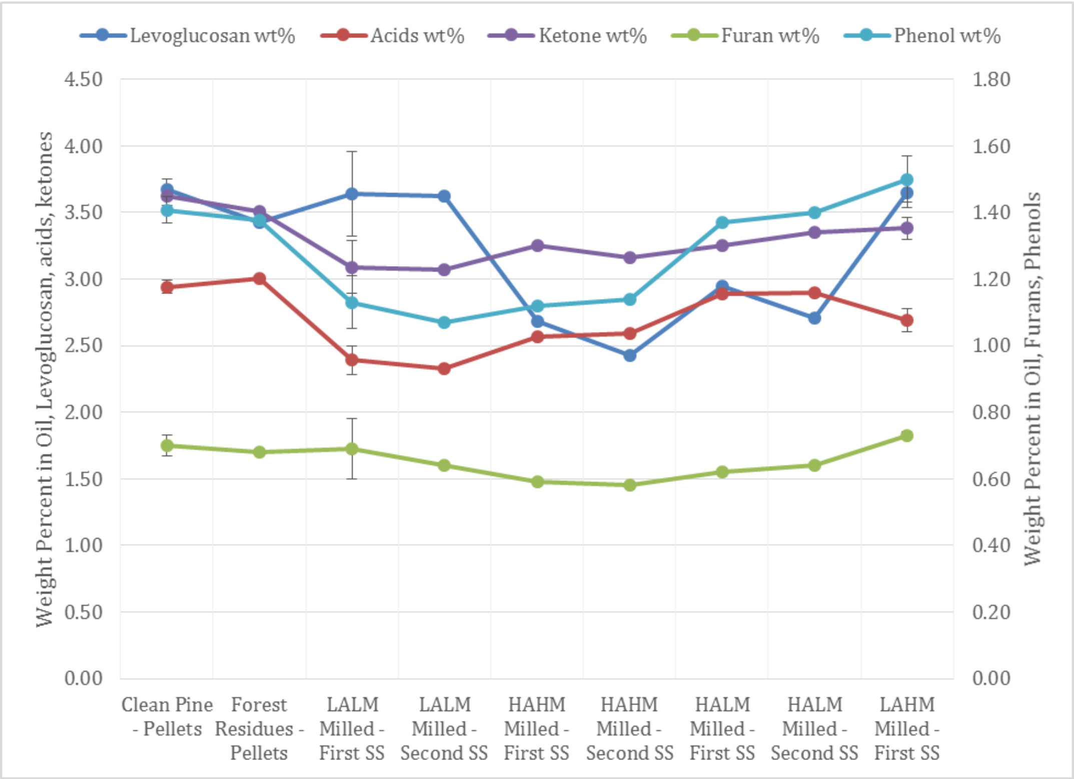
- **Effect of biomass particle size**
  - Problem: Feedstock particle-size distribution (PSD) will change the heat transfer rates to the particles within the pyrolyzer and affect product yields.
  - Mitigation: Automatically adjusting the residence-time or biomass feedrate into the pyrolyzer to optimize heat transfer for the particle-size distribution.
- **Effect of ash content**
  - Problem: Feedstock ash variation will change the reactions occurring within the pyrolyzer and affect product yields.
  - Mitigation: Automatically adjusting the nitrogen purge rate on the feed train to remove finer particles (which has higher ash content).

Technical Accomplishments – High-Temp Primary Deconstruction (Cont.)

- The FCIC baseline runs provided Supervisory Control and Data Acquisition (SCADA) process real-time data, offline analytical samples, and operator notes.
- Feed slugging is dropping the reactor temperature and thereby affecting component yields in the product oil.
- An online sensor to measure solids loading is necessary to implement an adaptive process control strategy to mitigate the slugging behavior.
- Historical data indicates that certain ash species are well correlated to higher water content in the oil, as well as shifting the oil levoglucosan, acids, and phenol composition.

Technical Accomplishments – High-Temp Primary Deconstruction (Cont.)

Clean pine and forest residue behave differently when milled vs. pelletized (Oils from milled materials have lower phenol, ketone and acids content)



Component yields as measured by GC-MS for historical and baseline feedstocks. 95% confidence intervals are shown for data sets that have sufficient points to calculate them

4. Relevance

Project Goal

Identify relationships between feedstock bulk properties and equipment performance to develop robust Adaptive Process Control systems for achieving stable operation.

Contribution to FCIC goal

- Support the FCIC goal of addressing the impacts of variability in feedstock properties on biomass preprocessing and conversion equipment and system performance to move towards 90% operational reliability.
- Identified key bulk properties that impact equipment performance: moisture, particle size & shape, total ash.
- Successfully tested the inline Gazeeka bale moisture sensor (up to 25%) and a prototype NIR probe for measuring moisture, ash, glucan and xylan content of milled corn stover.
- Verified an Adaptive Process Control System using predictive, feedforward and feedback control improves the operational reliability (on-stream time) of a 2-stage biomass grinding system. The same control logic should work for conversion unit operations.

Summary

1. Overview: The project objective is to improve equipment operability and product yield and quality challenges caused by variability in properties of input biomass materials.
2. Approach for this project:
   - Develop relationships between input & out properties and process control parameters of key unit operations, and apply Adaptive Process Control Systems.
3. Technical Accomplishments
   - Achieved no down time in 2-stage grinding of 25 corn stover bales using Autonomous Adaptive Process Control System (i.e., no human-in-the loop control).
   - Identify key control parameters:
     - ➢ Moisture content and particle size & shapes of input biomass materials for preprocessing and low-temperature conversion.
     - ➢ Ash content and particle size and density for high-temperature conversion.
4. Relevance: This work shows that we were on the right track in developing an Adaptive Process Control System for improving the operational reliability and selecting appropriate equipment design for preprocessing and conversion.

Thank You