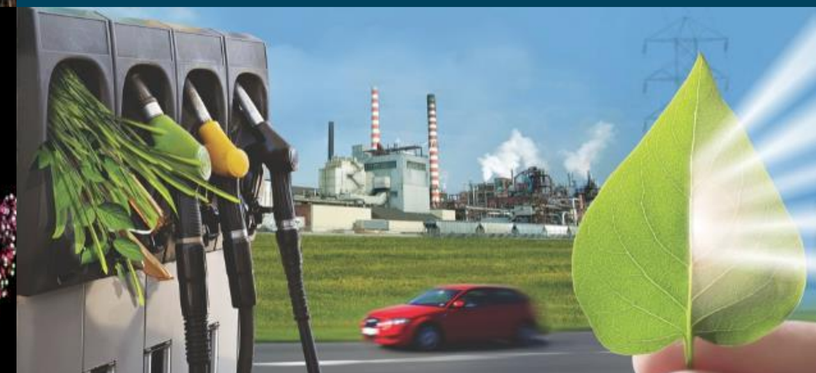

U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Feedstock Supply and Logistics

Wednesday, March 6, 2019
Hilton Denver City Center—Denver, CO

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WBS 1.2.1.1: Sensors and Measurement in Harvest & Collection for Rapid Quality Control of Corn Stover

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Goal Statement & Outcomes

- *The project goal is to demonstrate a logistics system design that uses compositional data, storage performance projections, and local climate data to reduce variations in biomass moisture, carbohydrate, and ash that negatively impact processing and conversion performance.*
- *Outcomes include:*
  - *Near-infrared spectroscopic (NIRS) analytical methods for moisture, carbohydrates, and total ash in baled corn stover and switchgrass (< 3 min/bale; ± 5% relative to lab analyses).*
  - *Development of "first-principles" models describing moisture migration, heat flow/energy balances, and dry matter loss in storage (bulk MC & DML ±5% of measured values from storage trials), and*
  - *Demonstration of a logistics system design that uses composition, storage performance projections, and climate data to reduce variations in as-delivered MC, glucan, xylan, and ash (day-to-day average value ±5% of target values).*

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Quad Chart Overview

Timeline

- Project start: 10/1/2015
- Project end date: 9/30/2021
- Percent complete: 50%

Barriers addressed

- Ft-F. Storage Systems
  - Stability, moisture loss
- Ft-E. Feedstock Quality & Monitoring
  - Variations affecting performance

	Total Costs Pre FY17**	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$1.19 M	$1.19 M	$0.925 M	$3.3M
Project Cost Share*				

Partners: Antares Group – Corn stover harvesting & logistics; B Hames Consulting– NIRS modeling

Objective

Evaluate the major components of a data-driven biomass supply design that reduce harvesting- and storage-related quality variations over time

End of Project Goal

Develop a biomass logistics system that integrates real-time compositional characterization, storage performance projections, and local climate data to reduce feedstock variability and improve processing and conversion performance

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Project Overview

Corn Belt Demo '12

Cost Quality '15

Active Management '18

- <u>2012 Demonstration:</u> Collection efficiency, bale density & dry storage **improvements in high-yield area at target cost**
  - **<u>Challenges:</u>** High moisture content in storage results in dry matter losses; harvesting equipment entrains soil resulting in high ash. What's the cost?
- <u>2012-2015:</u> Impact of equipment and harvest and collection practices on yield, ash and cost; **impact of moisture content on dry matter loss** in storage
  - **<u>Challenges:</u>** Need timely information for on-the-fly decisions in harvest before storage and delivery to a biorefinery. How much can NIRS move from lab to field?
- <u>2015-2018:</u> Provide information at critical decision points in harvesting, storage and **queuing to reduce operational variations** in carbohydrate and ash content of delivered stover to meet processing needs
  - **<u>Challenges:</u>** How can NIRS (MC, carb, ash) and other information sources (weather, storage conditions) be interpreted to make valuable decisions?

Overview & Relevance

Bales reflect variations in:

- Field conditions/climate
- Equipment/operations
- Storage conditions

Time-related effects include:

- Dry matter loss (DML)
- Moisture migration

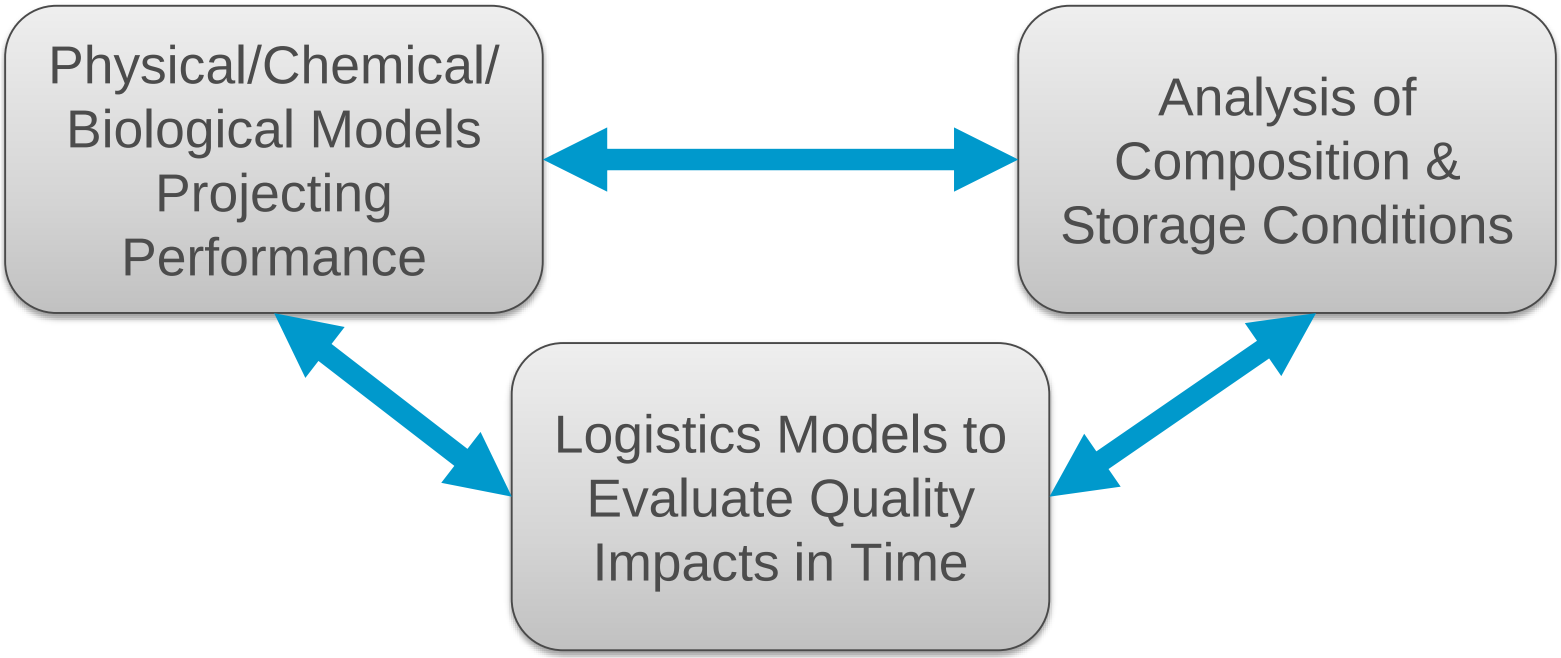
Not just averages but extremes…

- Example: Moisture in preprocessing

Management Approach

- From the field to the laboratory
  - Identify the problems, determine causes/effects, evaluate/quantify primary drivers, pose and test solutions at lab and stack scales
- Utilize programmatic strengths of **biomass analysis** and **PDU**; partner with others to fill the gaps
  - Antares Group—Logistics operations and commercial feedstocks
  - Dr. Bonnie Hames—Near infrared spectroscopy/chemometrics
- Go/No-Go decisions and milestones based on **measurable** and **relevant** goals
  - Milestones represent step-wise technical progression
  - Go/No-Go decisions to evaluate critical decisions/divergent pathways using technical and/or technical objectives
- Peer-Reviewed 3-Year AOPs
  - Solicit external input as an independent check on research relevance and progress towards realistic goals
- Quarterly meetings with FSL and FSL management

Technical Approach



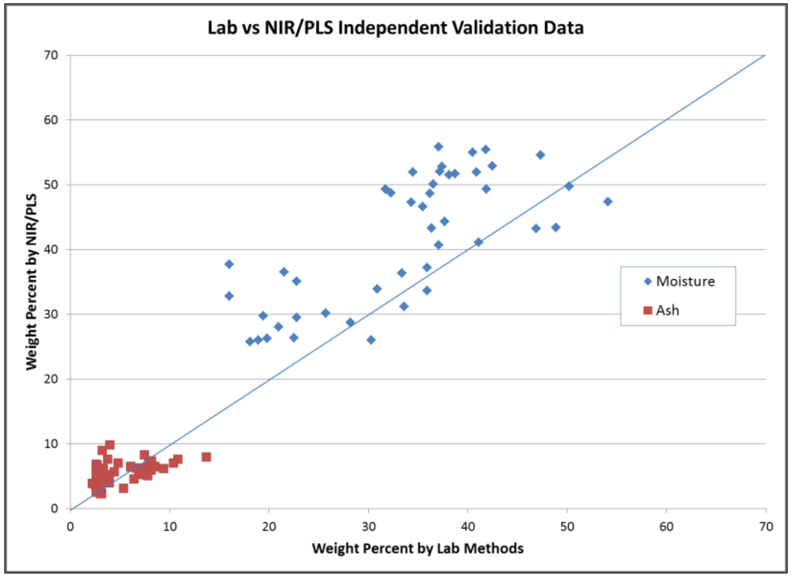
- **Go/No-Go:** *Evaluate modeled operational performance of actively-managed storage systems. Go: Active systems reduce moisture to <20% in 90d within 1.25x 2017 SOT cost (w/ DML).* **March FY20**
- **End of Project Milestone:** *Show at laboratory scale and with techno-economic analysis, the individual components of an engineered harvesting, storage, and delivery system capable of supplying an 800,000 DMT/yr biorefinery with baled corn stover and switchgrass that meet BETO biochemical conversion in-feed quality targets for structural stability, moisture, ash, and carbohydrates at the lowest achievable cost.* **September FY21**

Technical Approach, cont.

- **Observe what's limiting** efficiency/reliability for stover (IBRs).
  - Challenge: best management practices result in highly-variable ash and moisture contents; active management intends to reduce this variation.
  - Controlling moisture/ash in bales means measuring it, quickly/cheaply.
- **Focus on the show-stoppers**: soil/ash and moisture.
  - Challenge: IBRs have problems with biomass quality in preprocessing.
  - Prioritize efforts based on program goals, industry challenges, and analysis results, i.e., most downstream impact/least cost and effort.
- **Research the fundamentals** across process-relevant ranges.
  - Challenge: variations span broad and poorly-defined ranges; measuring "everything" is impractical. **Focus on the "why" of the problems that gives rise to the "how" of the solutions.**
- **Define success factors**
  - Incorporation of research results within and **across** BETO programs & labs.
  - Increasing commercial interest in research; partnerships in FOAs/CRADAs.
  - Ultimate Goal: Industry adoption of ash/moisture avoidance practices, analytical tools, and biomass storage management practices/tools.

Technical Accomplishments, Progress, and Results

- Near infrared spectroscopy/bale probe **transitioned from "BALESS" high-tonnage logistics project into 1.2.1.1** to include glucan, xylan, and moisture models (along with ash) in stover.
- Current ash models (version 4) include higher MC & ash (total).

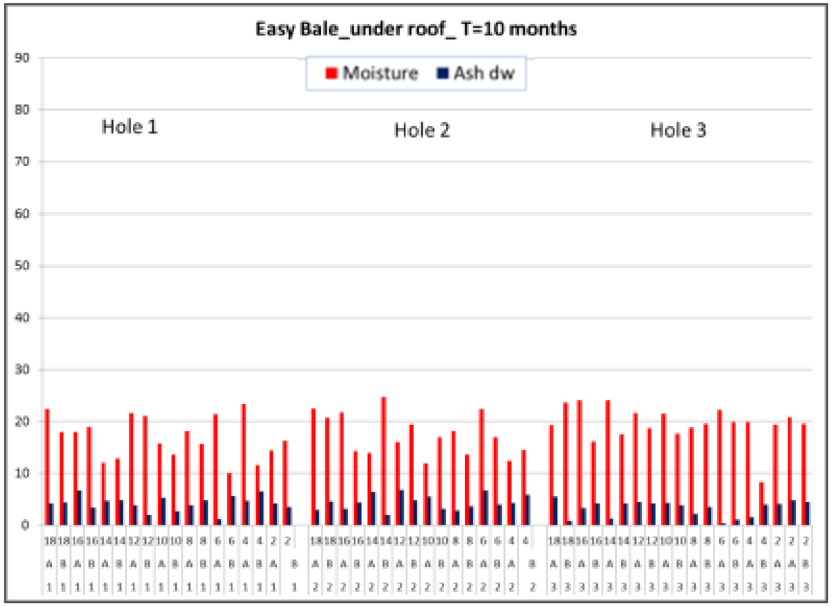


- Two **working probes and spectrometers** (Antares' and INL's) to test model transfer and maintenance (a large part of future scope).
- Dr. John Cundiff and students at Penn State University have researched **mechanical insertion** and control methods for the probe to safely apply the ~1,500 lbf needed.

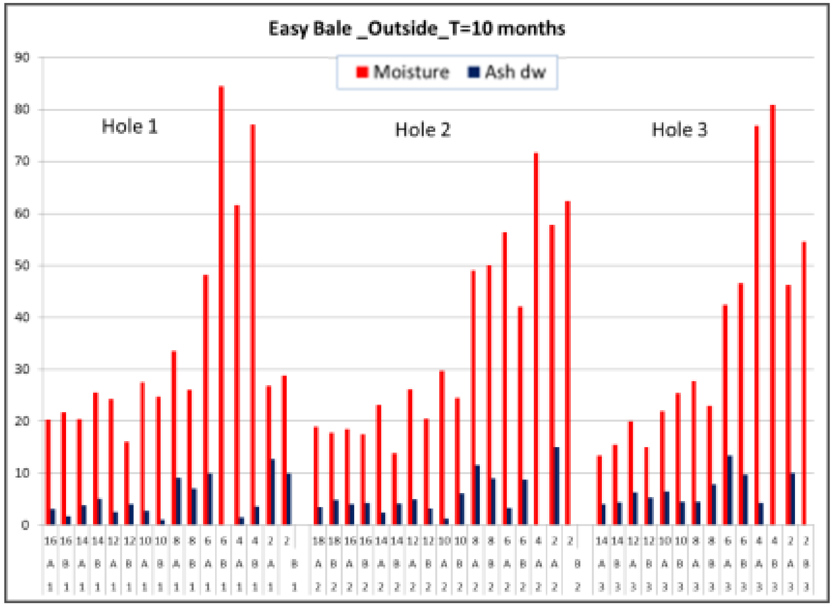
Technical Accomplishments, Progress, and Results, cont.

- Compositional summary by depth allows spatial/volumetric evaluation of an individual bale in < 10 min/bale (~60 scans/bale).

Covered Storage



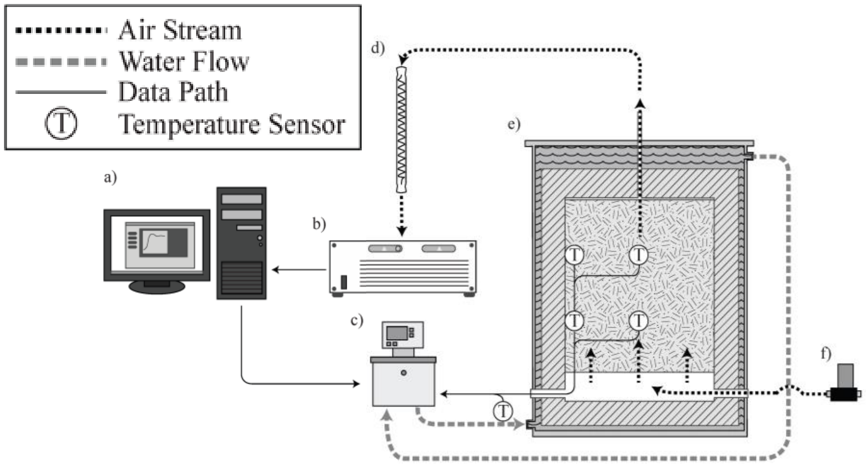
Outside Storage

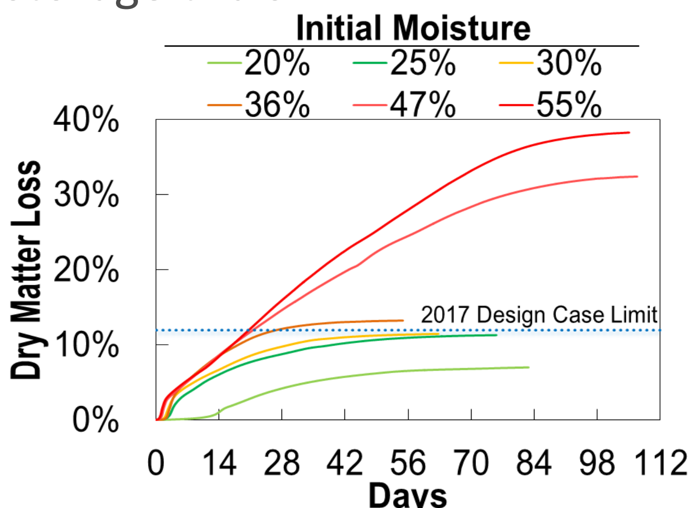


- Example shows how moisture and ash vary after outdoor storage.
  - Moisture content increases; soluble ash moves from surface to wet layer.

Technical Accomplishments, Progress, and Results, cont.

- Biological Activity, Moisture Dynamics, and Dry Matter Loss.
  - Quantify losses in real time under controlled conditions (temp/air/moisture).
  - Collect data for **predictive modeling**: airflow, heating, moisture loss.
  - Compare **lab to field** data—past and present storage trials.





  - Use storage reactors to examine sensitivity of drying to…
    - Air temperature and relative humidity (climate/regional effects).
    - Gas transport rate through material (density/storage conditions).
    - Respirative heating and dry matter loss dependence on temperature.
    - Impact of different anatomical fractions/conditions on DML & MC.

Technical Accomplishments, Progress, and Results, cont.

Numerical simulation—using and applying reactor results

- Analytical methods for bulk drying do not capture biological effects of:
  - **Internal heating** associated with biological activity, and
  - **Dry matter loss** associated with air addition.
- Commercial general, 1D, 2D, & 3D, PDE solver, COMSOL Multiphysics.
- Combined equations describe drying and…
  - Heat transfer
  - H_2O transport/drying
  - O_2 transport
  - Respiration/DML
- Address questions:
  - How much DML?
  - Where? When?
  - Control strategies?

PDEs

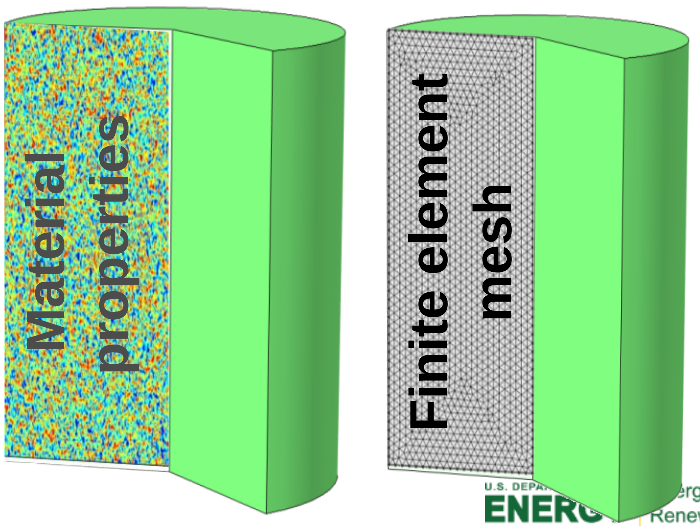
$$\frac{\partial X_p}{\partial t} = -(X_p - X_{eq})\frac{\pi^2}{9}a_p^2 D_c$$

$$\varepsilon\frac{\partial X_a}{\partial t} + V_a\frac{\partial X_a}{\partial x} = -\frac{\rho_{dp}}{\rho_{da}}\frac{\partial X_p}{\partial t}$$

$$\rho_a\left(c_{p_{da}} + c_{p_v}X_p\right)\left(\frac{\partial T_a}{\partial t} + \frac{V_a}{\varepsilon}\frac{\partial T_a}{\partial x}\right) = -\frac{h_t a_p}{\varepsilon}(T_a - T_p)$$

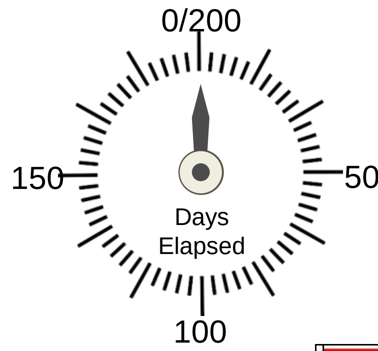
$$\rho_{dp}\left(c_{p_{pd}} + c_{p_w}X_p\right)\left(\frac{\partial T_a}{\partial t}\right) = \left[h_t a_p(T_a - T_p) - \rho_a V_a\frac{\partial X_a}{\partial x}\left(L_v + c_{p_v}(T_a - T_p)\right)\right]$$

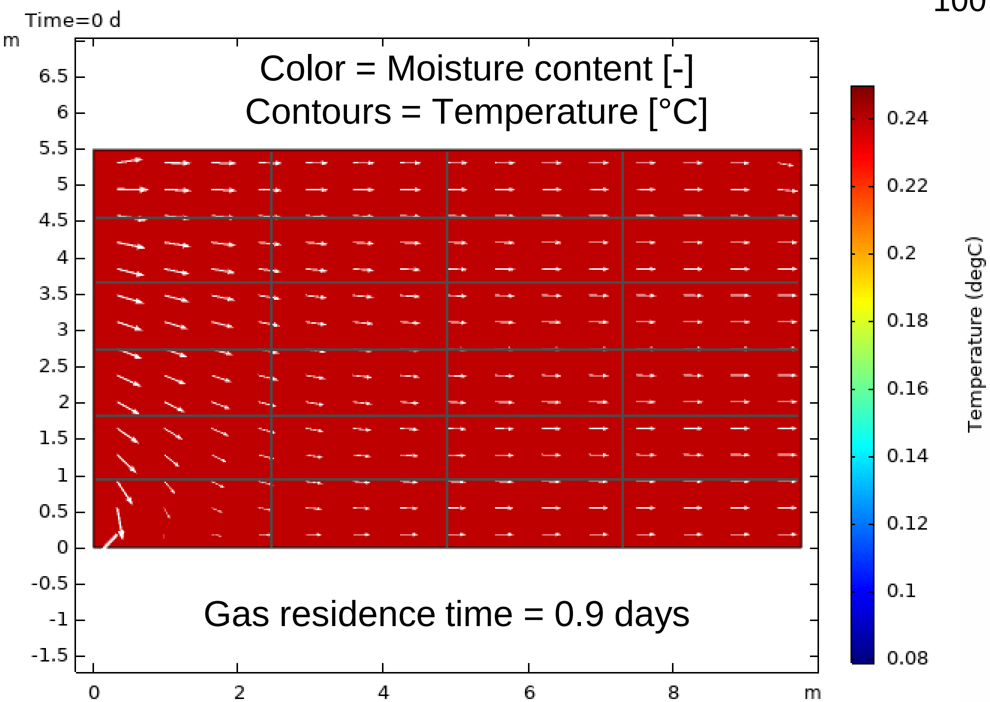
Numerical Model Domain

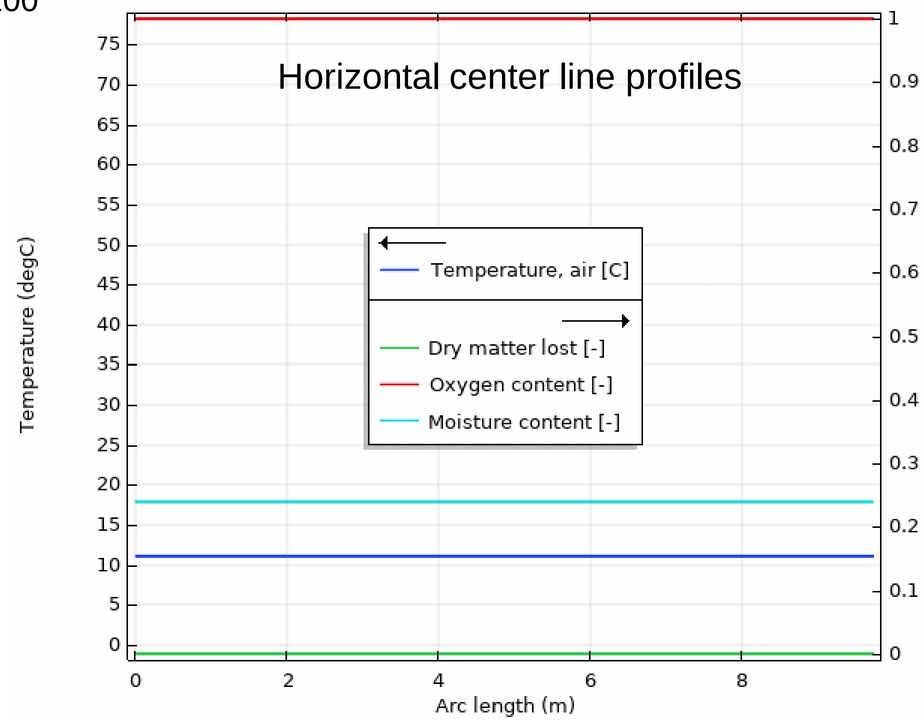


Storm Lake animated output: Initial MC = 24%

- Advective flow through stack
- Oxygen never limiting
- Drying front/temp moves through
- Dry matter loss stemmed by drying







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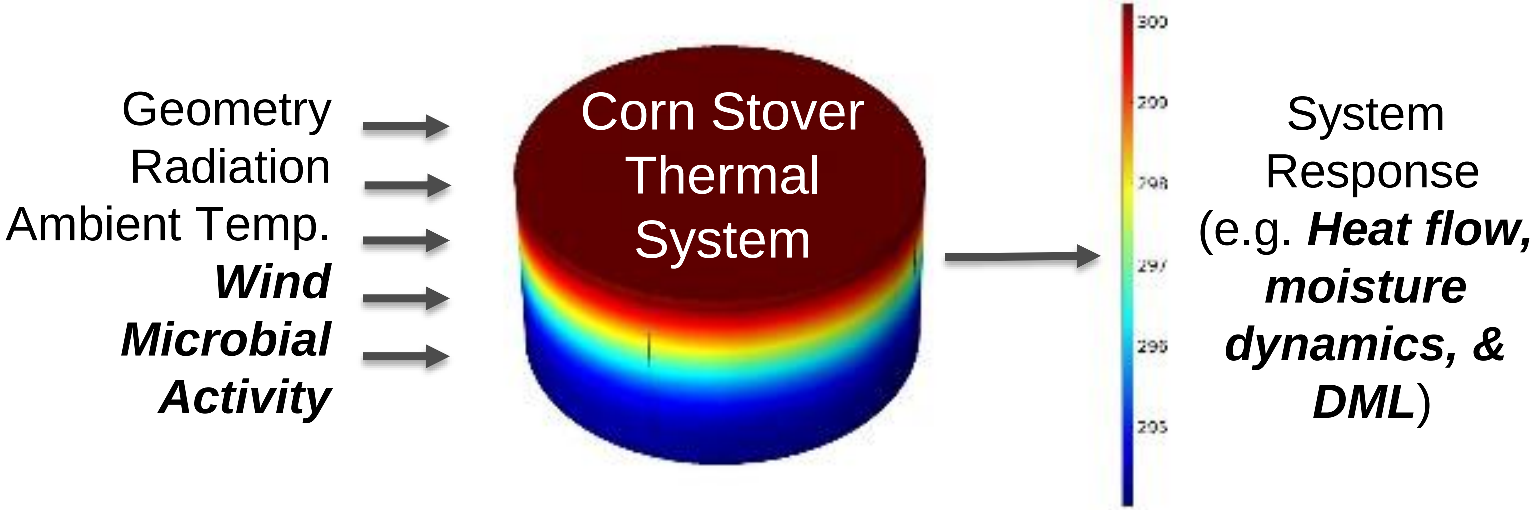
Technical Accomplishments, Progress, and Results, cont.

Dynamic thermal modeling

- Example: Advection resulting from ambient wind exposure.

Wind flow regimes play a role in the dynamics of ***heat transfer, moisture, and*** the ***degradation of organic matter*** in corn stover bale stacks.

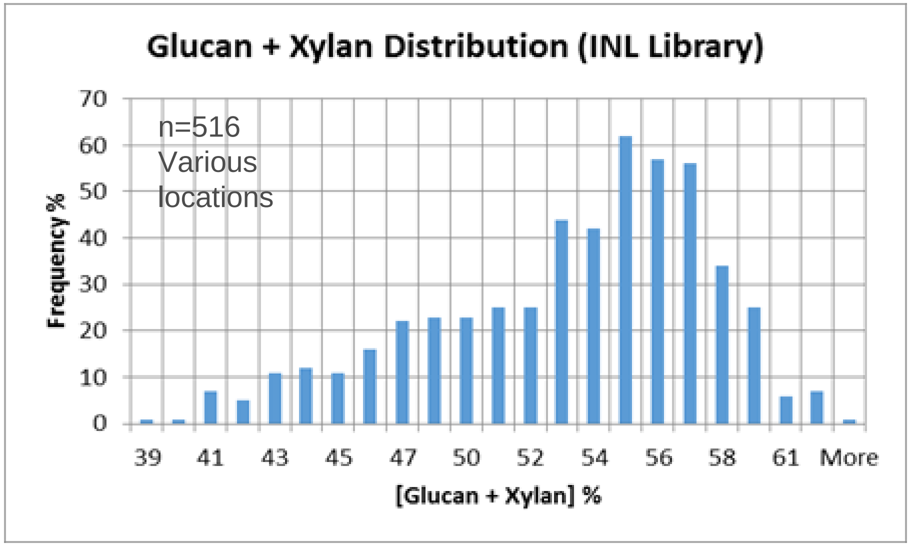


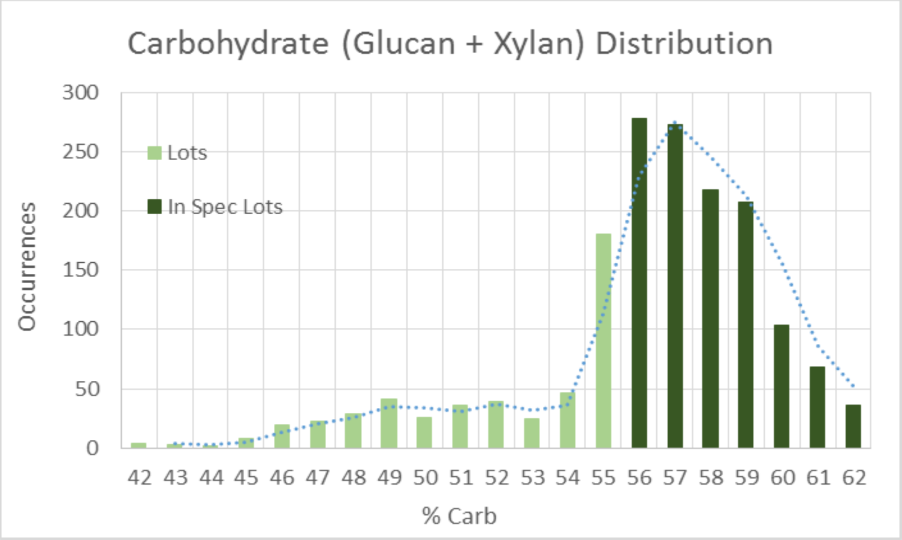
- Modeled results can be compared to tracer tests and storage simulation reactors' results for evaluation and model improvement.
- Results will show relative performance improvements based on a wider range of storage conditions than could ever be tested.

Technical Accomplishments, Progress, and Results, cont.

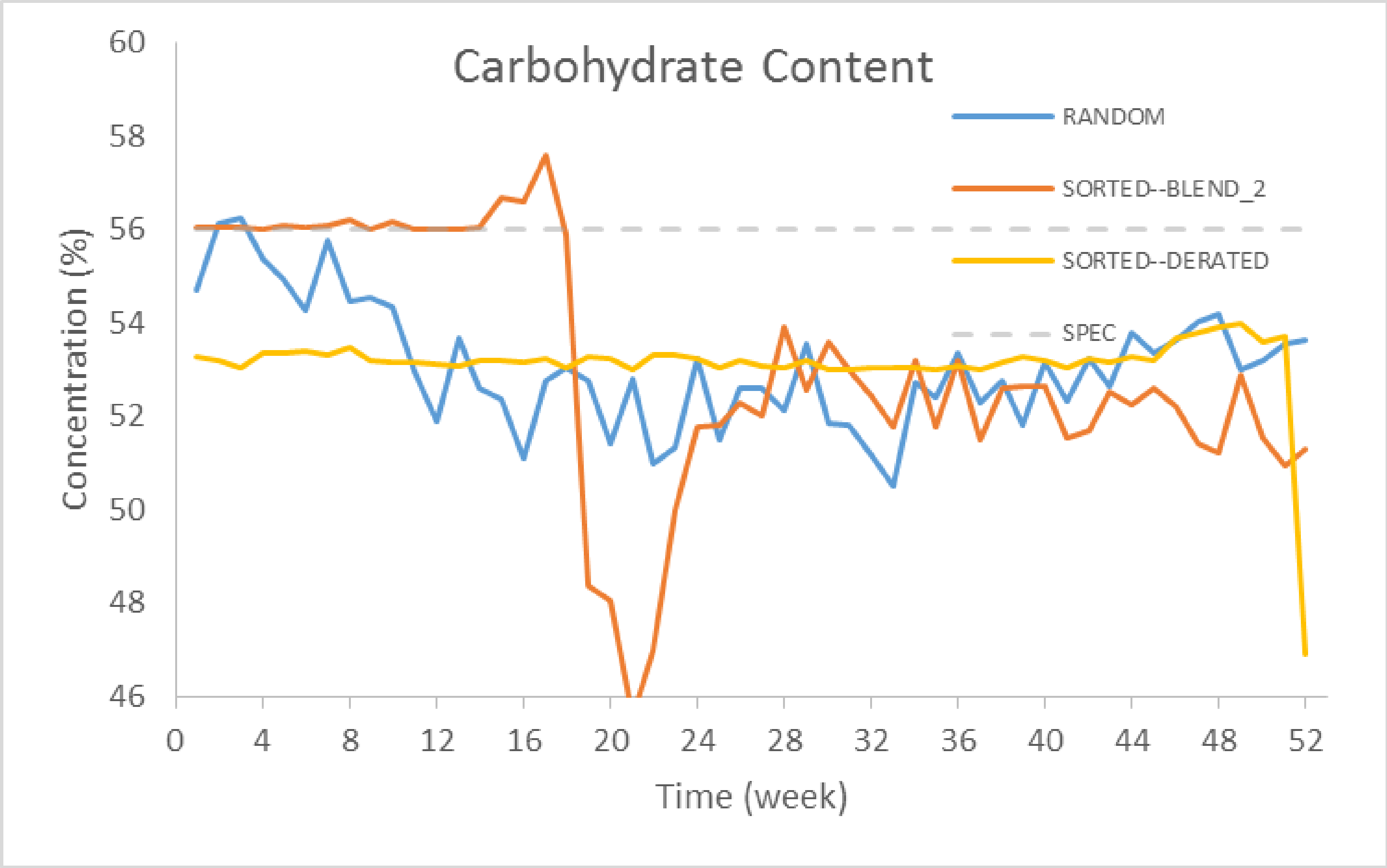
Logistics simulations

- 3 components: structural carbs, moisture, & ash.
- Monte Carlo distributions **based on INL Library results.**
- 2 harvests: wet & dry.
- 4 climates: cool/wet, warm/wet; cool/dry, hot/dry.
- Projected moisture loss **based on vapor pressure deficit and equilibrium moisture content.**
- Projected storage losses based on moisture/DML relations **measured at INL.**





Technical Accomplishments, Progress, and Results, cont.



- Simulation of storage in northwest Iowa after a dry harvest
- Random draw vs. sorting and blending, and de-rating sorting & blending
- Sorting meets spec for up to 20 weeks but remaining carb in storage drops
- **De-rating based on average at harvest ensures carb content consistency**

Relevance

- The project goal is to demonstrate a logistics system design that uses compositional data, storage performance projections, and local climate data to reduce variations in biomass moisture, carbohydrate, and ash that negatively impact processing and conversion performance.
  - Near-infrared spectroscopic (NIRS) analytical methods…
    - Ft-E. Feedstock Quality & Monitoring
    - Enables rapid screening of biomass in storage and at plant
  - Development of numerical models of storage dynamics…
    - Ft-F. Storage Systems
    - Provides scientific basis for storage system design/performance
  - Demonstration of a logistics system design…
    - Ft-E. Feedstock Quality & Monitoring
    - Reduces biomass variations affecting preprocessing/conversion

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Future Work

- Quantify DML, self-heating, and drying relationships in high-moisture corn stover (>25% MC) at two airflow rates (0.25 LPM, 1.0 LPM) in lab storage reactors.
  - The goal is to replicate in-stack conditions during storage to inform numerical modeling work in progress to FY20 Go/No-Go and FY21 final milestone.
- Use 3-D physical models to show how moisture and DML migrate over time by diffusion and advection in multi-bale stacks.
  - The model(s) will describe moisture migration and DML in bales across a range of moisture contents from 15% to 70% (saturation) and predict within-bale dry matter losses over the course of one year.
- Expand NIRS probe chemometric calibrations to include greater physiological variability such as anatomical fractions, drought-affected samples, and various states of preservation/degradation.
  - Switchgrass will be added in FY20.
- Complete baseline TEA of as-built storage units evaluating bales ranging from 18% to 30% moisture and 30-year average climate conditions from central Iowa. Compare 1-year material, labor, and DML costs relative to 2017 SOT.

Summary

- Variable biomass quality (moisture, composition, physical condition) reduces downstream operational reliability, limits throughput, increases startup risks, and is a barrier to “Gen 2”.
  - Baled biomass composition reflects in-field, operational, and storage-induced variations in moisture, carbohydrates, and ash
  - Gross compositional variations can be measured rapidly—field-side and in storage in whole bales—via NIRS/probe/chemometrics
- Moisture promotes biodegradation leading to loss of valuable/increase in non-value components i.e., ash (soil).
  - Understanding how moisture drives biodegradation and how moisture moves in storage lets us predict rates/extents of DML and moisture loss over time
  - Storage environments may be modified to enhance drying/stability
- Starting composition, storage environment, climate, and storage duration can be used with predictions of storage stability and heuristics for lot selection to reduce variations in daily average component values and meet specific infeed specifications.

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Dr. Bonnie Hames

<u>…And Others…</u>

Dr. Doug Karlen, USDA-ARS
Prof John Cundiff, VT
Bill Couser, Couser Cattle
James Straeter & Case NH
Alan Kadolph

Supplemental Slides

Response to Reviewer’s Comments

- “Would like to see how this corn stover work supports other feedstocks.”
  - We are focusing FIRST on corn stover—a result of its availability and its current commercial use. Because grain rather than stover drives harvest operations it comes with problems i.e. moisture and ash (soil) that are less problematic in dedicated energy crops.
  - Stover represents a challenge to NIRS, storage, and preprocessing. Diverse anatomical fractions respond differently to moisture over time. These morphological fractions have related but often different compositions and storage stability. Operations influence their relative abundance in a bale. By solving these challenges we are in better standing to adapt our methods to additional biomass sources/formats that have fewer of these heterogeneities.
  - We are projected to complete a switchgrass bale probe model by end of FY21 and have written several proposals for using the probe in coppice and chipped softwood.

Response to Reviewer's Comments

- "As would be appropriate for any project on assessing quality parameters, both accuracy and repeatability of the estimates must be determined and reported."
  - Current NIRS chemometric models include an estimate of standard error of estimate based on a "leave one out…" cross validation. As our standard sets grow, we can break our calibrations into "calibration sets" and "validation sets", which is planned in upcoming FY19-FY21 work.
- "The project should consider developing best management practices that preserve the quality of biomass feedstock that can be delivered to a biorefinery for smooth operation."
  - We have attempted to do so with our current Logistics/Queuing simulation, which will continue to improve and expand as we work to meet our FY21 goals.

Presentations, Publications, & Patents

- Kenney, Kevin, et al. (2014). Biomass Logistics. Bioprocessing of Renewable Resources to Commodity Bioproducts. V. S. Bisaria and A. Kondo. Hoboken, New Jersey, John Wiley & Sons, Inc.: 29-41.
- Wendt, Lynn., et al. (2014). "Influence of Airflow on Laboratory Storage of High Moisture Corn Stover." Bioenergy Research: 1-11.
- Smith, William, et al. "Characterizing Biomass Within the Supply Chain." Advanced Bioeconomy Feedstocks Conference, June 10, 2015, New Orleans, LA.
- Murphy, Austin, et al. "Evaluation of Bulk, High Moisture Corn Stover in Anaerobic Storage." American Institute of Chemical Engineers Annual Meeting, November 8, 2015. Salt Lake City, UT.
- Bonner, Ian, et al. (2015). A Laboratory Scale Reactor for Simulating Biomass Storage for Bioenergy. 2015 ASABE Annual International Meeting. New Orleans, Louisiana, American Society of Agricultural and Biological Engineer: 11.
- Smith, William, et al. "Getting the Right Information at the Right Time." Agricultural Equipment Technology Conference, February 8, 2016, Louisville, KY.
- Smith, William, et al. "Outdoor Storage Performance of Chopped Switchgrass for Bioenergy Use." Symposium on Biotechnology for Fuels and Chemicals, April 28, 2016, Baltimore, MD.
- INL Invention Disclosure Record No. BA-935. Smith, William A, Bonnie R Hames, Kevin S Comer, Jason Peoples. "Direct-Push Near Infra-Red Spectroscopic Bale Probe and Chemometric Models for Biomass Feedstock Composition." Date Accepted: 10/10/2016.