DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Development of a Bulk-Format System to Harvest, Handle, Store, and Deliver High-Tonnage Low-Moisture Switchgrass Feedstock

March 25, 2015

Feedstock Supply & Logistics

Presenter: Sam Jackson, Genera Energy Inc.

Technical Lead: Al Womac, University of Tennessee

Lead Organization: TennEra LLC (formerly Genera Energy LLC)

Goal Statement

- *Develop and test bulk-format logistics for low-moisture switchgrass incorporating bulk-handled loose, bulk compacted with overburden, and bulk compacted with mechanical systems - comparing costs with round-bale logistics.*

- Supports "Advanced Uniform-Format Feedstock Supply System"
  - ✓ Distributed depots
  - ✓ Densification & Handling
  - ✓ Feedstock R&D harvesting, storage, handling & transportation for Ethanol Infrastructure
  - ✓ Perennial grass, dry herbaceous (<20% m.c. (w.b.))

- Results apply to bulk-format feedstock supply chain under U.S. permitting conditions for depot handling facility

- Important lessons learned that can be transferred to other feedstock supply systems include bulk handling after size reduction & densification relevant to U.S. truck transport.

Quad Chart Overview

Timeline

- Project start date: July 30, 2010
- Project end date: June 30, 2013
- Percent complete: 100%

Barriers

- Barriers addressed
  - Sustainable Harvesting
  - Biomass Storage Systems
  - Biomass Material Handling & Transportation

Budget

	Total Costs FY10-FY12	FY13 Costs	FY14 Costs	Total Planned Funding FY15-Project End Date (TOTAL)
DOE Funded	4.48M	313k	0	0 (4.800M)
Project Cost Share GENERA	4.73M	485k	0	0 (5.214M)

Partners

(Next Slide)

4%

0%

Collaborations /Project management

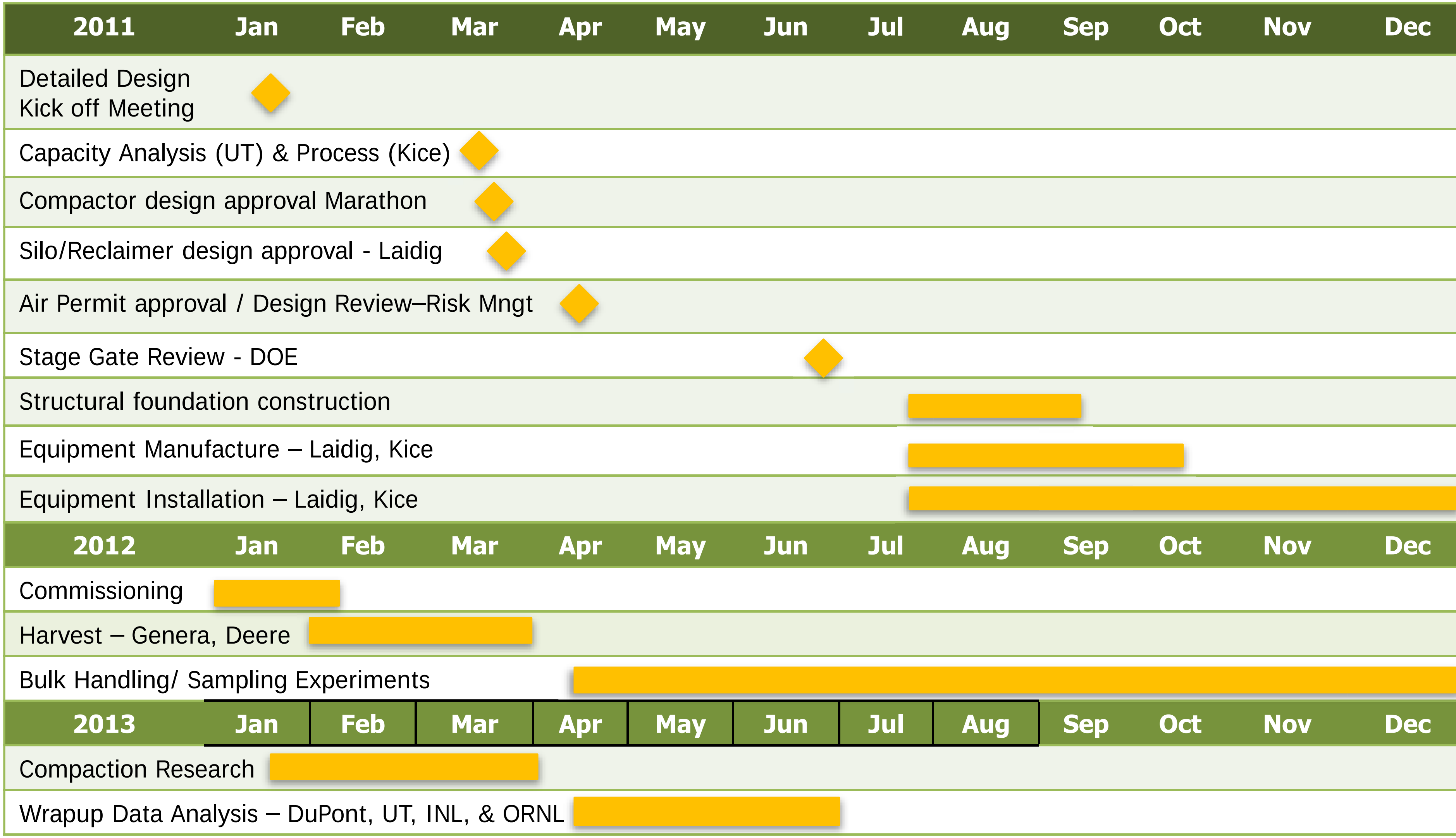
- Project Partners/Roles
  - **Genera Energy** – Switchgrass, farmers, storage and handling
  - **University of Tennessee** – Logistics analysis, reporting
  - **Laidig Systems** – Storage and reclaiming
  - **Marathon Equipment** – Bulk compaction
  - **Kice Industries** – Material conveyance and dust collection
  - **Deere & Co**. – Harvest equipment
  - **Idaho National Lab** –Material properties analysis (4%)
  - **Oak Ridge National Lab** – Independent cost analysis (0%)
  - **Dupont Cellulosic Ethanol** – Feedstock analysis
- Project Management
  - **Genera Energy** – Coordinates with partner input; permits, construction, and contracts

Project Overview - Objectives

Objectives

- Develop a bulk-based switchgrass harvest, handling, storage, compaction, transport, and off-load system to supply a demonstration biorefinery
- Determine switchgrass handling efficiencies of the bulk system and identify areas to improve efficiencies with respect to equipment investments and operators
- Determine switchgrass quality associated with the bulk system compared to the current bale system based on ethanol production and potential

Project Overview - History



1- Approach (Technical)

- Took broad viewpoint that "Logistics" spans field harvest to conveyance of a uniform, industrial milled product
- Lessons learned from storage bins with reclaim technology (direct application at biorefinery) – applicable to tall bulk piles (reclaim, bulk density, temperature stability, etc.) (depot) (Budget short for Stacker-Reclaimer)
- Size reduction for bulk format (w/forage harvester) & bales (w/tub grinder) examined for handling and cost comparison
- Unique bulk-format compaction integrated with reclaim process

Logistics spans Harvest to Representative Biorefinery receiving → Storage Bins = confining pressure & reclaim fundamentals of Bulk Stack → Logistics Design process with multiple partners, including preliminary tests with switchgrass → NEPA, State & Local Permits

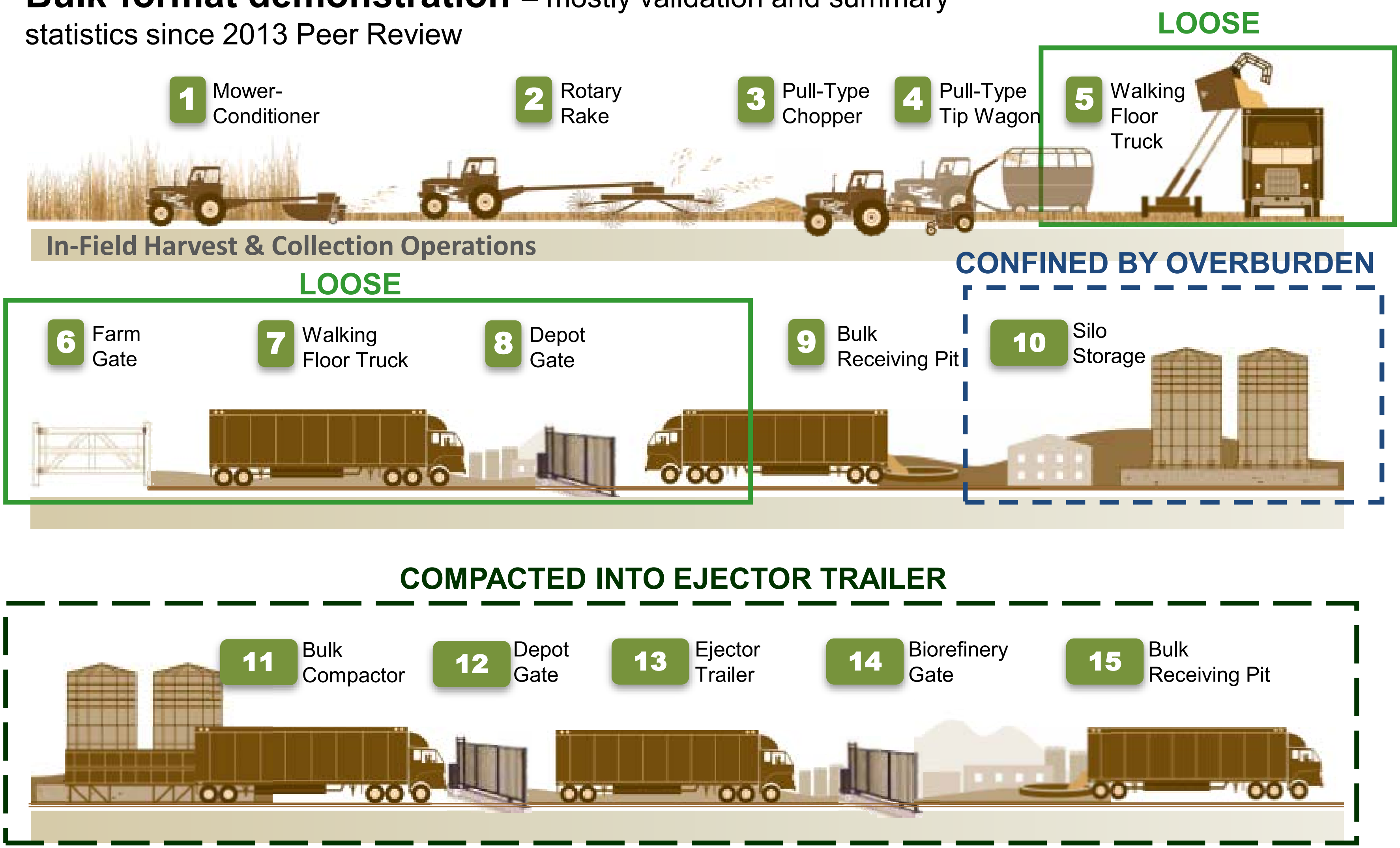
→ Construction and Commissioning → Harvest Campaign – GPS monitored → Conveyance, Handling, Reclaim, and Compaction Studies with 3 Particle Size distributions (Forage harvester bulk & 2 tub ground bales) → Data Analysis & Reporting

1- Approach (Management)

- Critical Success Factors
  - Technical – Improve bulk flow & handling capacity of equipment
  - Market – Biomass market & associated biomass specifications for sugar platform – but applicable to other markets
  - Business – Interaction of agricultural and commercial sectors
- Potential Challenges
  - Design, permit, & physically construct the system in timeframe
  - Coordination of partners typically accustomed to their sector
  - Working with a new commercial product (milled switchgrass)
- Management Structure
  - New company coordinate logistics involving sectors of agriculture and commercial systems operating with switchgrass product
  - Involve experts with milestones based on history with similar materials

2 - Technical Accomplishments

Bulk-format demonstration – mostly validation and summary statistics since 2013 Peer Review



2 – Technical Accomplishments

Detailed Equipment Tracking Logistics

- Simultaneous GPS monitoring of 7 pieces of equipment w/o in-cab researcher-distraction of experienced operators
- Researchers took non-intrusive field notes, such as tip wagon unload points
- Developed <u>custom, logical expressions</u> to categorize each equipment track log entry (1-Hz) by operation (for example: on-row, turning, waiting, unloading, etc.) – <u>verified w/ inspection of equipment interactions</u>
- <u>Calculated field efficiencies (%) or hauling utilization (%)</u>
- Various field geometries:
  - mo-co turn time from 1.83 to 7.97 min/ha
  - harvester turn time from 2.47 to 12.10 min/ha
- Results reinforced need for:
  - Increased crop yield
  - Improved field geometries for reduced turn times
  - Reduced in-field haul distances

2 – Technical Accomplishments

Range of harvest conditions, including field shape, terrain, distance, day & night

From GPS, GIS, On-site Truck Scales, etc.:

Demo-Scale*			Projected Commercial Scale**		
Operation	**Rate** *(per unit, Dton/h)*	**Efficiency or Utilization** *(%)*	**Operation**	**Rate** *(per unit, Dton/h)*	**Efficiency or Utilization** *(%)*
MoCo, 3-m (1 unit)	17.7	75.9	MoCo, 4-m (17 units)	88	80
Pull-type Forage Harvester (1 unit)	8.4	70.6	Self-propelled Forage Harvester (27 units)	44.6	70
Tip Wagons (3 units)	3.1	64.8			
Bulk-Trailer Trucks, 52 cu-yd, 3.8 Dton/load (2 units)	4.4	69.1	Bulk-Trailer Trucks, 133 cu-yd, 9.7 Dton/load (151 units)	7.8	75
Depot Receiving (1 unit)	8.8	36.6	Depot Receiving, 6 units/depot (30 units/5 depots)	50	90

* 2.85-3.61 Dton/ac

** 8 Dton/ac

** Supplying 410,000 Dton/y of Switchgrass to 32.8 Mgal/y Biorefinery

2 – Technical Accomplishments

Particle size	Wet Bulk Density* (lb/ft3) (@ 13% m.c.-w.b.)		Demo-Scale Loads* (tons)		Commercial-Scale Loads* (tons)	
	Loose	Compacted	52 yd^3 (Loose)	100 yd^3 (Compacted)	133 yd^3 (Loose)	108 yd^3 (Compacted)
Field Chop	6.20	10.64	4.35	14.36	11.13	15.51
Coarse Tub Grind**	4.90	8.61	3.44	11.62	8.80	12.55
Fine Tub Grind**	6.00	10.61	4.21	14.32	10.77	15.47

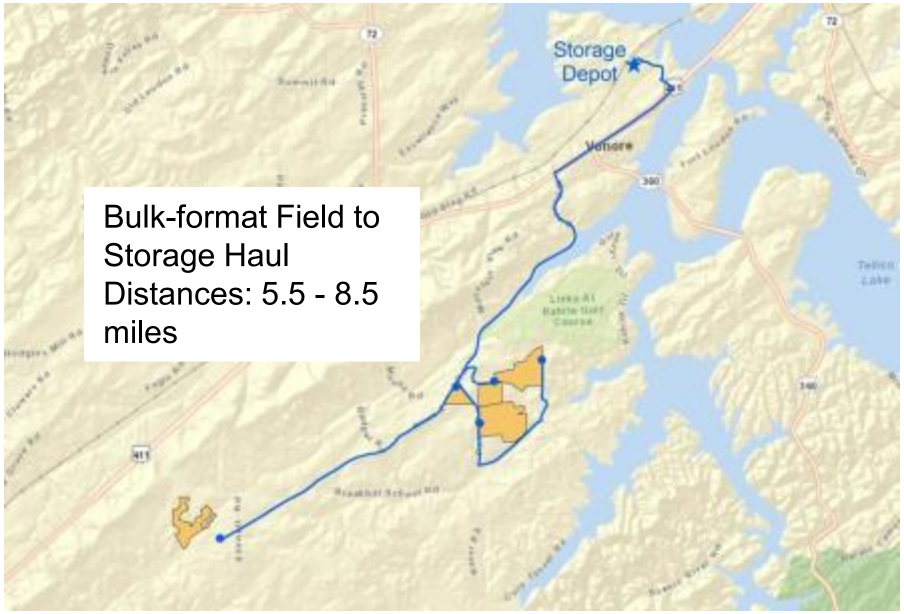
For Comparison With Bales

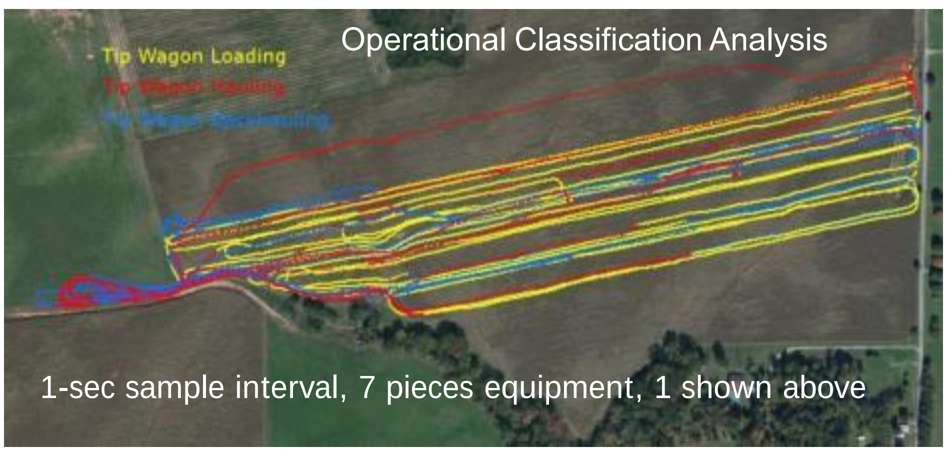
For Comparison With Bales

*In practice, fill efficiency affects loads and are taken into account.

**Tub grind used for bale-based system comparison (i.e. tub grind not applicable to bulk-format harvest)

2 – Technical Accomplishments





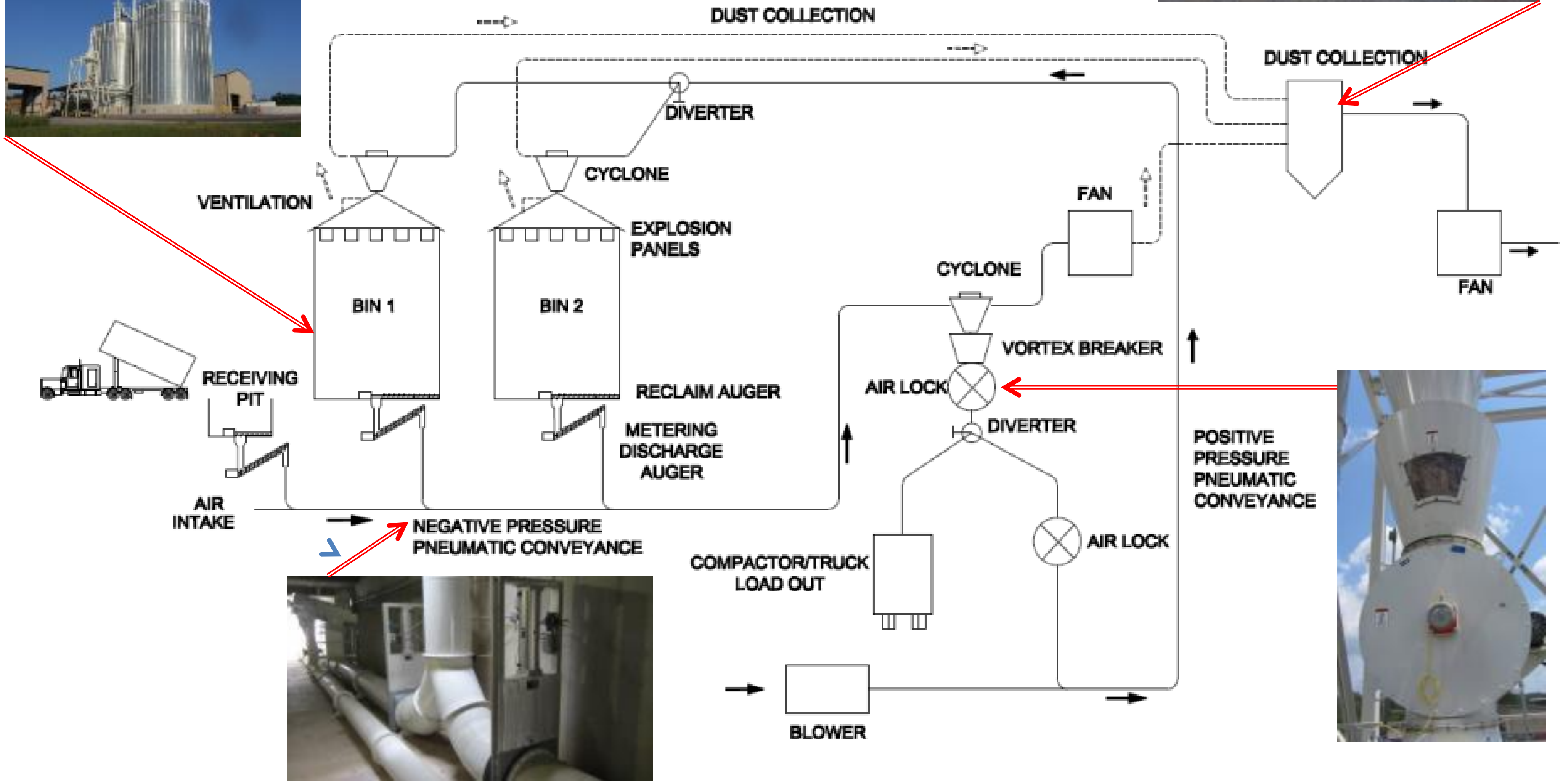
Limiting Factor During Harvest Logistics

	Daily Proportion of time (%) (Calc. for 1-sec resolution)		
	Min.	Avg.	Max.
Forage Harvester (1 unit)	74.3	88.7	97.0
Tip Wagons (3 units)	0.1	1.7	5.1
Trucks (2 units)	1.3	9.6	23.4*

* Caused by receiving startup delay on first day of harvest

2 – Technical Accomplishments

Bulk-format Receiving, Storage, Handling, & Dust collection



2 – Technical Accomplishments

Risk Management

- System design in accordance with appropriate codes
  - International Building Code (IBC)
  - International Fire Code (IFC)
  - National Electric Code (NEC)
  - National Fire Prevention Association (NFPA)
    - **NFPA 61** Standard for Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities
    - **NFPA 68** Standard on Explosion Protection by Deflagration Venting
- Compliance - local authority w/ jurisdiction
- Insurance Risk -Property Specialists review
- Operations – Standard Operating Procedures (SOPs) compliance & education

2 – Technical Accomplishments

Bin Load (field chop)	
93% Bin fill	874 tons (13.3% m.c.)
	756 Dtons
Bin top	5.4 Dlb/ft^3
Overall Avg.	8.4 Dlb/ft^3
Bin bottom (est.)	11.3 Dlb/ft^3

Factor	Reclaimer	
	Pit	Bin
Reclaimer Length (ft)	15	30
Max. Screw Reclaim Rate (cfm)	166	166
Max. Screw Reclaim Sweep Rate (ft^2/h, initial setting)	187	336
Max. DESIGN Screw Reclaim Rate (density of 5.5 Dlb/ft^3) (Dton/h)	27.4	27.4

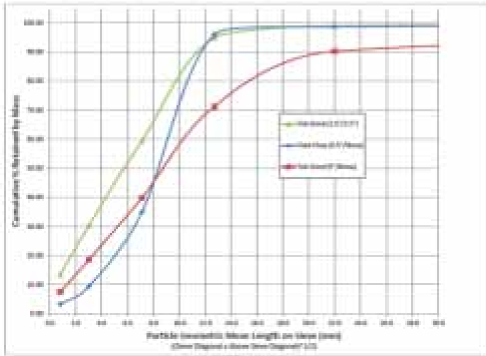
Lessons learned from Storage & Reclaim provide fundamental knowledge to implement increased-scale bulk storage stacks & applicable Stacker-Reclaim technology for piles

Receiving Pit

Bin

2 – Technical Accomplishments

3 unique particle sizes tested



Tub grind used for bale-based system comparison, (i.e. tub grind not applicable to bulk-format harvest)

Device	Material	Overburden (ft)	Avg. Reclaim Rate (Dton/h)	Reclaim Duty Cycle (%)
Bin 1	FC*	85	31.0**	0**
Bin 2	FC	16	29.8**	35**
Bin 2	CTG	19	4.9	99
Bin 2	FTG	16	11.0	75
Receiving Pit	FC	6	22.4	48
Receiving Pit	CTG	6	12.9	57
Receiving Pit	FTG	6	16.7	52

*FC – Field Chop CTG – Coarse Tub Grind FTG – Fine Tub Grind

**Influence of rushing, free-flowing FC bulk during bin discharge, as high as 40 Dton/h – exceeded reclaim design rate of 27 Dton/h

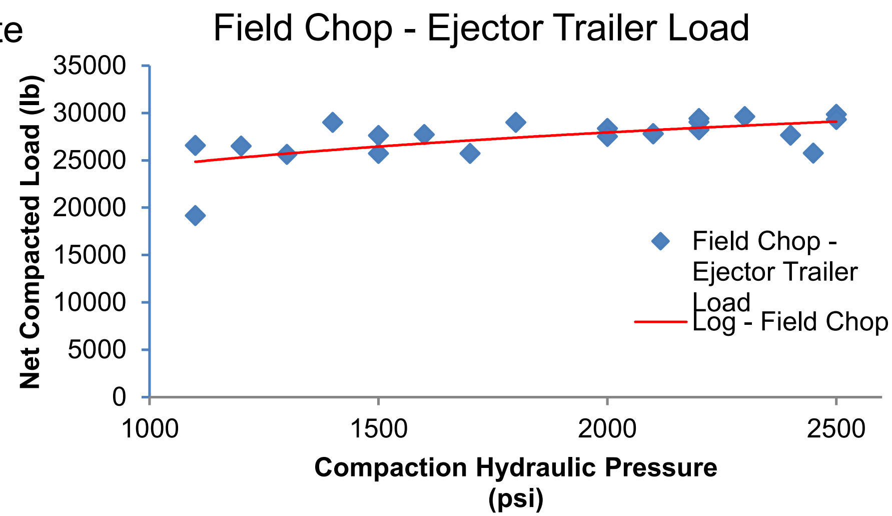
2 – Technical Accomplishments

Bulk Compaction - mobile

Material	Avg. Compaction Rate (Dton/h)	Avg. Ejector trailer Discharge Rate (Dton/h)	Dry Bulk Density (Dlb/ft^3)
Field Chop	34.6	142	9.23
Coarse Tub Grind	8.0*	113	7.49
Fine Tub Grind	10.63*	137	9.22

*Primarily limited by supply rate

Novel means to re-distribute compactor weight during transport



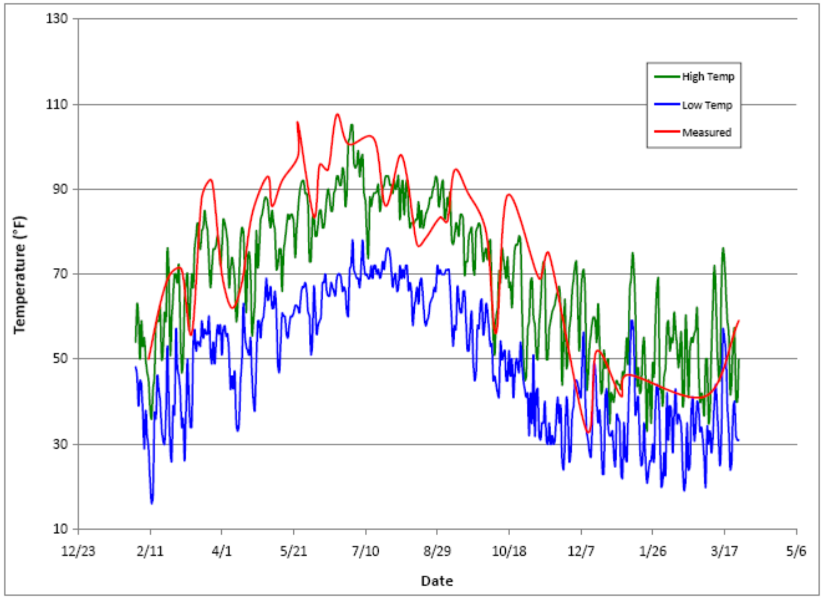
2 – Technical Accomplishments

Harvest
- Moisture content samples for decision to start harvest.

Delivery
- Moisture content samples from each delivered truck load.

Storage
- IR storage and ambient temperatures
- Moisture content and composition samples at storage discharge.

- No detected self-heating during storage & reclaim
- Management of moisture content
  - Forage Harvester (at harvest) ~13.3% (w.b.)
  - After Storage and Handling ~11.3% (w.b.)



2 – Technical Accomplishments

Bulk Flow/ Reclaim/ Handling Experiments

- Applicable to bulk-format & ground bales
- Randomized complete block
- Switchgrass re-circulation
- 3 particle sizes, 4 replications each
- 4-hour experimental unit
- 1-Hz data collection rate (14,400 repeated measures)
- 58-variables for handling system
- Focus on power-relations

Example for FC, CTG, & FTG combined data:

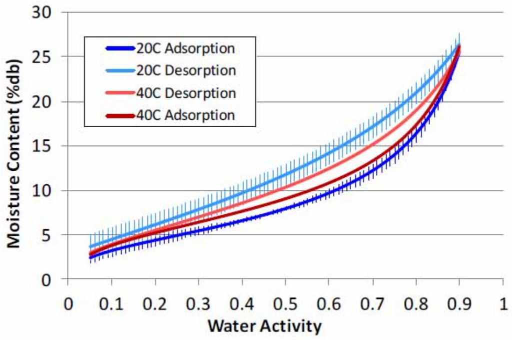
Conveyance Variable	Pearson Correlation Coeff. (P-level)		
	kW-positive Conveyance	kW-vacuum Conveyance	kW-dust Collection
kW-positive Conveyance	1.00	-0.87 ($p<0.0001$)	0.65 ($p<0.0001$)
kW-vacuum Conveyance	-0.87 ($p<0.0001$)	1.00	-0.49 ($p<0.0001$)
kW-dust Collection	0.65 ($p<0.0001$)	-0.49 ($p<0.0001$)	1.00

2 – Technical Accomplishments

- Kice bulk flow handling – pneumatic handling system
  - Vacuum (negative pressure) conveyance (safety in confined areas)
  - Pressure (blowing) conveyance (efficient tube size)
  - Dust collection integrally designed (safety and emissions)
  - Cyclone, Vortex chamber, Airlock concept
  - Initial tests with switchgrass stems up to 8-in length in scale system
  - Design details tweaked during commissioning
  - Current system throughput (ton/h) mostly limited by positive pressure conveyance leg

Underlying mechanism for free-flow FC* compared to CTG* or FTG* is not understood - active effort to find measurement that contrasts flow properties

- INL property measurements to understand rushing, free-flowing FC during bin unload
  - Compressibility
  - Springback
  - Wall friction
  - Flow indices
  - Water activity



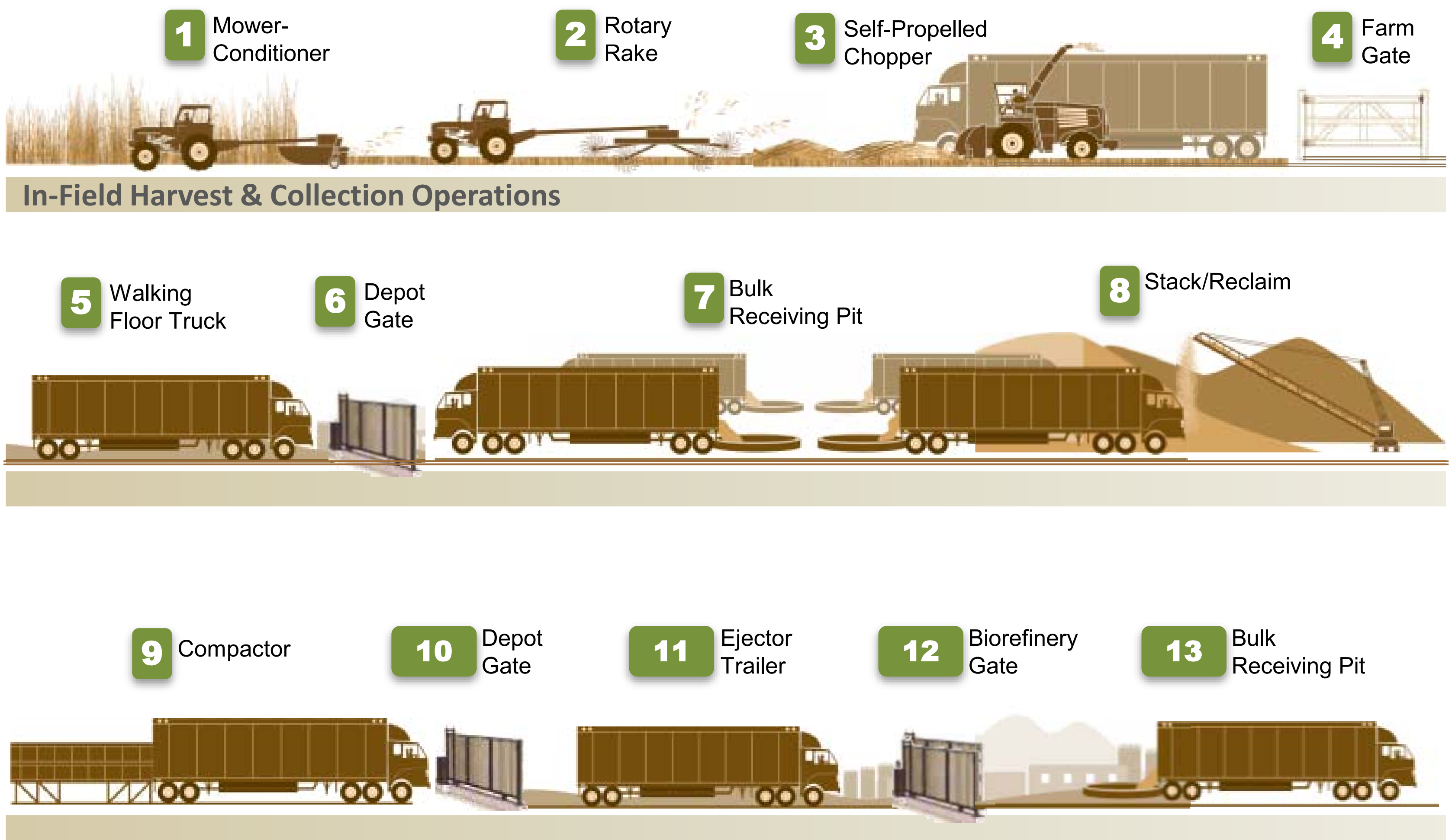
*FC – Field Chop CTG – Coarse Tub Grind FTG – Fine Tub Grind

2 – Technical Accomplishments

- DuPont assisted by evaluating switchgrass samples for compositional analysis and ethanol potential
    - Comparing bulk-format with baseline bale system
    - Evaluated temporal effect of storage time up to 1 year.
    - No surprises in results
    - Switchgrass composition from windrow during harvest are not affected by whether forage harvester or baler is picking up windrow
    - Switchgrass needs protection from extended exposure to moisture
    - Several publications document switchgrass potential

2 – Technical Accomplishments

Bulk-format for Commercial-Scale Stacker-Reclaimer



2 – Technical Accomplishments

Advantages of bulk-format go beyond cost – since supply of scalable large quantities of uniform, pre-processed feedstock at biorefinery specifications aides risk-management

Comparison of Feedstock Supply Chain Logistics
--Supplying 410,000 dton/y of Switchgrass to a 32.8 Mgal/y Biorefinery --
--Harvest Window of 371 h/y, Biorefinery Supply Window of 2000 h/y --

Round Bale, Distributed Roadside Storage, Truck Bales 45 miles to biorefinery, Tubground			**Forage Harvester-formatted Bulk**, Truck Loose Bulk 10 miles to 5 Depots, Truck Compacted Bulk 35 miles to Biorefinery		
Logistics Step	Units (n)	Cost ($/dton)	Logistics Step	Units (n)	Cost ($/dton)
Mower-Conditioner cut	17	1.32	Mower-Conditioner cut	17	1.32
Rake crop	17	0.75	Self-Propelled Forage Harvester	27	6.92
Round Bale crop, net wrap	31	6.38	Collect and haul loose bulk in van trailer	151	8.97
Self-load Bale wagon, bales to field edge	31	2.21	Depot Bulk Receiving Station	5	2.91
Tractor loader Stack Bales 3-2-1	31	1.37	Depot Conveyance Receiving	5	1.80
Field Edge Storage - 1-acre Rockbase/ tarp	244	12.11	Depot Conveyance Discharge	5	5.08
Truck field telehandlers to storage sites	1	0.41	Depot Dust Collection	5	2.95
Field telehandler load bales on Truck	5	0.98	Depot Storage - 6-acre Rockbase/ tarp	5	1.49
Truck bales to biorefinery	39	13.06	Depot Stacker/Reclaimer - Stacking	5	1.35
Biorefinery telehandler offload bales	6	1.18	Depot Stacker/Reclaimer - Reclaimer	5	8.19
Biorefinery telehandler - bales to grinder	6	1.18	Bulk Compactor	7	1.57
Tubgrind bales	12	13.51	Ejector Trailers for compacted bulk format	32	11.10
Dust collection	3	1.77	Biorefinery bulk receiving	1	0.73
			Dust collection	2	1.18
Total		56.23	Total		55.56

GENERA ENERGY · UT · LAIDIG · MARATHON · KICE · JOHN DEERE · INL Idaho National Laboratory · OAK RIDGE National Laboratory · DUPONT

3 – Relevance

1. Project tackles bulk-format logistics and handling - applicable to most feedstock supply systems
2. Downstream processing was incorporated early in the logistics system – to reduce often ignored issues with creating feedstock specifications for biorefinery needs
3. Depot format was incorporated into logistics system design
4. Novel densification was examined for economy of bulk handling
5. Bulk-format reclaimer and handling experiments provide detailed data previously not available for industrial scale up
6. A “model energy crop” of perennial grass at low moisture was examined through equipment systems that had limited or no prior experiences and/or data collection
7. Biomass selection, harvest time, and processing method were identified for fundamental advantages in handling opportunities
8. Techno-economic comparison between bulk-format and round bales

5 – Future Work

Project

- Project finished June 30, 2013; about 1 month after 2013 DOE peer review

Adoption/ Commercial Deployment

- Facility used to investigate other biomass selections as part of other funded projects
- Keeping an eye towards Stacker-reclaimer using track-less technology to facilitate mobile deployment for tall-stack storage, handling, and out-loading of transport units
- Tall stack and membrane technology for moisture management
- Further development of bulk format supply needs simultaneous deployment of moderate-scale biorefinery due to the needed scale to justify investment in stacker-reclaimer

Summary

1. Overview
   - Most comprehensive viewpoint that "Logistics" spans field harvest to conveyance of a uniform, industrial milled product.
2. Approach
   - Developed lessons learned from use of upright storage bins with reclaim technology (direct application at biorefinery) – to factors applicable to bulk piles (reclaim, bulk density, temperature stability, etc.) (supports depot)
3. Technical accomplishments
   - Classified GPS-tracked logistics operations with logical expressions
   - Lessons for development of advanced turn-key, feedstock supply systems
   - Contrast loose- versus compacted-bulk conditions
   - Biomass reclaiming and handling - discovery of free-flow field chop
4. Relevence
   - Results apply to most feedstock supply systems through bulk handling
5. Future Work
   - Project has ended. Future applications using uniform-format feedstock supply was identified for high-quantity handling with bulk stacker – reclaimer technology

Systems Matter!

GENERA ENERGY

UT

LAIDIG

MARATHON

KICE

JOHN DEERE

INL

OAK RIDGE
National Laboratory

DU PONT

Questions?

www.biomassprocessing.org

www.biomasslogistics.org

www.generaenergy.com

Additional Slides

Response to 2013 Review comments

- Overall Impressions:
  - Comment: “Methodical approach resulted in relevant findings. Working with producers and equipment manufacturers and providing the information to the public was excellent. More DOE-funded work to advance the industry is critical.”
  - Response: Thank you. All reviewer efforts and comments are highly appreciated.

Response to 2013 Review comments

- Overall Impressions:
  - Comment: "Moving from a harvest/delivery scenario to a harvest/depot preprocessing/compaction/delivery scenario. Flow rate problems were well documented, but economic impact was not calculated. Flow rate problems aren't solved, and so using a depot process for this situation is questionable. Since bins were used instead of piles (which are expected to be the commercial practice) for storage, what is the impact on the analysis outcome/results if storage piles are the likely way things would be done in a commercial-scale operation? Provided potentially useful negative results about the depot concept and bin storage, but no indication it was recognized as such."
  - Response: (Summarized) Economic analyses for bulk-format logistics was compared to bale-format logistics system. …The bale-format economic analysis used the reduced flowability values. The forage harvester was the most logical, energy-efficient method for creating the bulk format early in the bulk-format logistics. <u>It is possible to perform an economic analysis using the reduced flowability of tub ground material in the bulk system, though it is not recommended. Essentially reduced flowability of the wider particle size distributions would add costs per dry ton.</u> …Bins were not recommended for commercial scale due to required numbers and costs. <u>(The bulk system is somewhat defined with the forage harvester – how does one harvest for tub grinder without baling for input into a tub grinder?)</u>

Response to 2013 Review comments

- Overall Impressions:
  - Comment: “This project addressed the complete logistics system from the field to the conversion plant. This is a wider scope than the high-tonnage logistics programs, and it seems to have a broader set of lessons learned. The project group should be complimented for taking on such a large scope of study. The study on handling of the chopped biomass is a significant addition to the knowledge base. Differences identified between the size reduction techniques are a unique addition to the knowledge base. This project added great value in terms of experiences with material handling systems. BETO needs to continue this type of project.”
  - Response: Thank you. The broad supply chain was prioritized to best reflect the actual supply chain from field to BCF. Examining and testing the complete supply chain, especially as it nears the BCF by considering biomass processing, such as size reduction, was found to be important.

Response to 2013 Review comments

- Overall Impressions:
  - Comment: (Summarized)“This project evaluated loose bulk handling of switchgrass. …Downstream materials storage and handling was done at demonstration-scale to commercial-scale specifications, including full permitting and operational details (e.g. dust collection). ...Tub-ground material had a wider particle size distribution than the field-chopped material, which dramatically reduced flowability. …The critical barrier to commercialization of this uniform format system appears to be a mobile stacker/reclaimer system with a low cost, but durable, membrane cover for moisture protection. Developing strategies to engage commercial partners with that challenge is an essential next step. This was a first-of-kind demonstration of the depot concept with uniform formatting and loose handling of biomass. Such systems have been recommended by theoretical analysis at INL, but had not previously been demonstrated at field scale. It is very encouraging to see the potential, as well as to advance the practical understanding of the challenges. A clear understanding of the challenges and barriers to this approach now sets the stage for further scale-up and commercialization..”
  - Response: Further scale-up and commercialization with a mobile stacker reclaimer is the next logical step in developing a system that can be scaled to the high tonnage requirements of a BCF. The impact of a simple parameter such as particle size distribution impacts selection of harvesters and handling capacity.

Response to 2013 Review comments

- Overall Impressions:
  - Comment: “This project mobilized a wide range of resources to apply to the problem. It generated some novel solutions and evaluated them with the resources available.”
- Response: Thank you.

Response to 2013 Review comments

- Overall Impressions:
  - Comment: “Very nice project that should be an example to other feedstock/logistics system.”
  - Response: Thank you.

Publications, Presentations, and Commercialization

- Womac, A.R., M.D. Groothuis, C. Dye, S.W. Jackson, and K. Tiller. 2015. Reclaim and flow performance of bulk switchgrass in automated handling and storage facility. Applied Engineering in Agriculture (in press).
- Womac, A.R., M.D. Groothuis, C. Dye, S. Jackson, and K. Tiller. 2014. Automated handling and storage of switchgrass in bulk format. Editors: G.S. Murthy, M. Wilkins, and M. Tumbleson. In 2014 S-1041 Science and Engineering for a Biobased Industry and Economy Poster Symposium Abstracts, Southern Regional Research Center, USDA-ARS, Aug 4-5, 2014. http://nimss.umd.edu/homepages/home.cfm?trackID=9057.
- Womac, A.R., W.E. Hart, V. Bitra. 2014. Forage equipment performance in high-yielding switchgrass. *Forage Focus*, Midwest Forage Association, St. Paul, MN. Pp 8-9.
- Bitra, V.S.P., A.R. Womac, B.J. Wesley, and K.V. Reddy. 2013. Bio-energy status in India. 47th Annual Convention of Indian Society of Agricultural Engineers & International Symposium on Bio Energy-Challenges and Opportunities, Jan. 28-30, 2013, Rajendranagar, Hyderabad, India.
- Womac, A.R. 2014. Biomass supply logistics using bulk-format systems – switchgrass versus corn cobs . Training of national representatives of Agricultural Extension personnel. Sombor, Serbia, Aug 19, 2014.
- Womac, A.R. 2014. Biofuels developments in the U.S. – A brief summary. Address at celebration of Agricultural Extension-USAID facilities grand opening, Sombor, Serbia, Aug 18, 2014.
- Womac, A.R. 2014. Biofuel feedstock logistics –lessons learned from research on systems-wide supply chains. 2014 NIRS Consortium Annual Meeting, February 12, 2014, Knoxville, Tennessee