DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Improved biomass feedstock materials handling and feeding engineering data sets, design methods, and modeling/simulation tools

April 4, 2023
Systems Development and Integration

Award: DE-EE0008254
WBS: 3.1.1.002

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Presenter: Chris Lanning, PE
forestconcepts™
Auburn, Washington

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Presentation Format

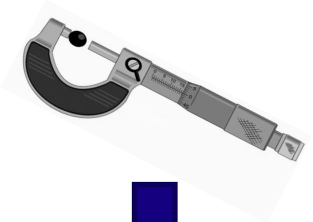
- Talking points are abbreviated from text and figures on slides

Key point in purple boxes

Project Overview

Focus on Tools & Methods

- Forest Concepts is the leading US private company producing biomass feedstocks for academia, labs, start-ups and early-stage biofuels producers
- Forest Concepts has been operating a pilot processing plant since 2005.
- Forest Concepts operates a biomass characterization lab that now includes both physical and bulk mechanical properties.
- Our project goal is to provide the laboratory tools and biomass mechanical properties data sets that enable feedstock handling equipment and systems engineers to more reliably design and apply bulk handling equipment
- Our team and others are under this BETO FOA are developing models and simulation tools
  - Our research and data fill gaps in the data sets they need for a wide range of biomass materials



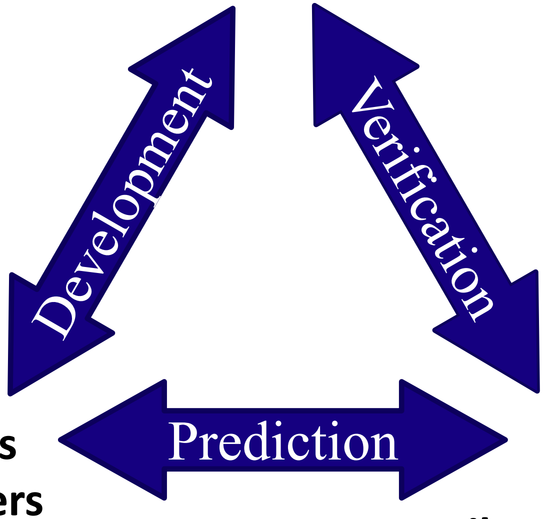
How can we accurately simulate biomass feedstock materials in handling equipment?

1 - Approach
Team and Coordination

- **Project Administration Team**
  - Forest Concepts
    - Jim Dooley, PI
    - Chris Lanning, Project manager
    - Mike Perry, Business manager
  - Penn State
    - Verindra Puri, past PI (retired)
    - Hojae Yi, Project manager, current PI
- **Coordination**
  - Frequent communication among all team members
  - Regular webinars with DOE
  - Systematic project tracking and budgeting by Forest Concepts

Each task has a designated leader and execution team

- **Lab Protocols & Equip**
- **Biomass Production**
- **Biomass Testing**
- **Application of Tools**



- **Model Design**
- **Data Analysis**
- **Simulations**
- **Teaching methods to design engineers**

- **Pilot-scale verification**

1 – Approach
Stakeholder Engagement

Project team is engaged with industry needs and in collaboration with several DOE projects

- Frequent communication with Purdue and INL teams
  - Dooley is member of Purdue team
  - Conducted limited special CTT runs for them in BP2
  - Modified BP3 to increase support to other teams using new CTT device
- Extended project to support DE-EE0008936 “Characterization of Mechanical Biomass Particle-Particle and Particle-Wall Interactions”
- Mined literature and materials handing directories to build list of 75+ stakeholders in 18 countries
  - Sent email project introduction, offered webinars, and solicited feedback
  - Resulted in spike in web traffic to FC website
- Prepared and posted videos, papers, and project overview to website
- Prepared and delivered webinars upon request
  - Engaged with questions to identify interests and data needs
- Have been awarded ASABE AE50 innovation award for 2023

1 – Approach
Objectives from SOPO

Models based on BULK flow physics and behavior

Objective 1. Identify and **adapt a continuum constitutive model** capable of describing key bulk biomass behaviors that hinder reliable and efficient conveying

Objective 2. Design and **develop test device**(s) and **laboratory protocols** that reliably characterize and quantify biomass feedstock's physical and mechanical properties

Objective 3. **Implementation of the adapted constitutive model** in the form of a computational model

Objective 4. **Verify and Validate computational model** in the context of feedstock handling equipment regularly used by Forest Concepts

Objective 5. **Document** all aspects of the project

Objective 6. Provide data and material properties **support this and other IBR projects.**

1 – Approach
Biomass Materials

Material selection reflects common feedstocks with a wide size and moisture content range

Woody Biomass (Douglas fir)

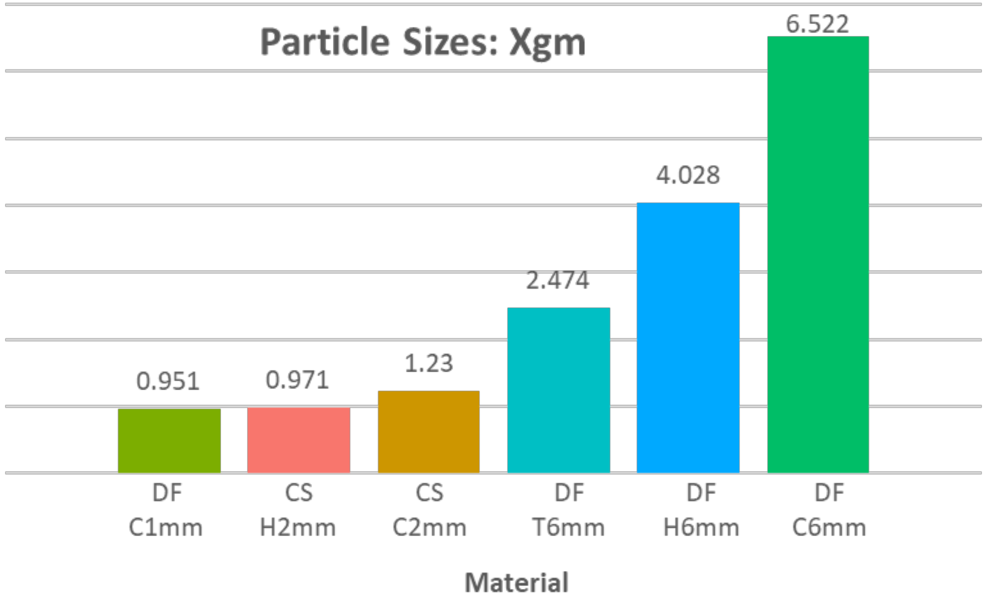
- 1 mm rotary sheared and screened
- 6 mm rotary sheared and screened
- 6 mm rotary sheared and screened pyrolysis biochar
- 6 mm hammermilled and screened

Corn Stover (INL/Iowa Sourced)

- 2mm rotary sheared and screened
  - NOTE: Same material as used by Purdue IBR (Ladisch)
- 2 mm hammermilled and screened

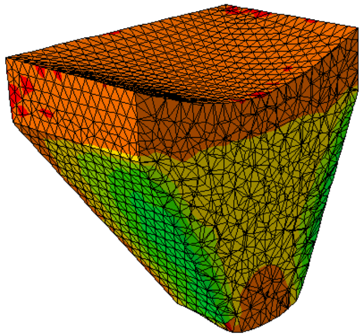
Additional materials include full size wood chips in response to past review suggestions



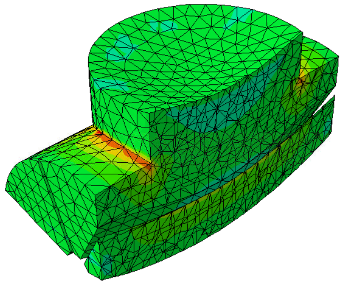


1 – Approach
Innovations

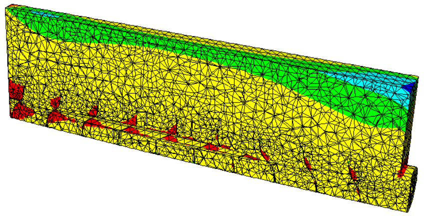
- New Cubical Triaxial Tester scaled for biomass feedstocks and with internal heating and drainage capabilities
- New gas pycnometer to obtain specific particle density
- Implementation of bulk flow modeling with simulation/animation of flow



Hopper



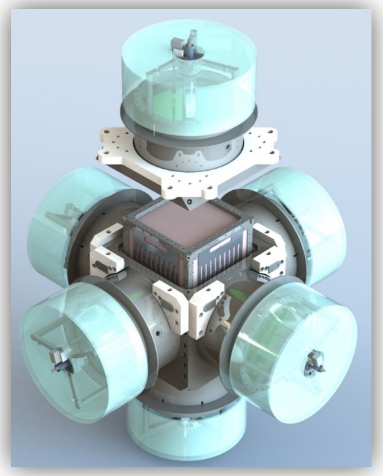
Rotary Valve

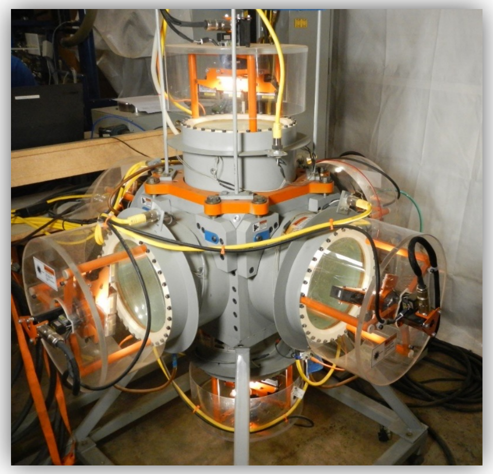


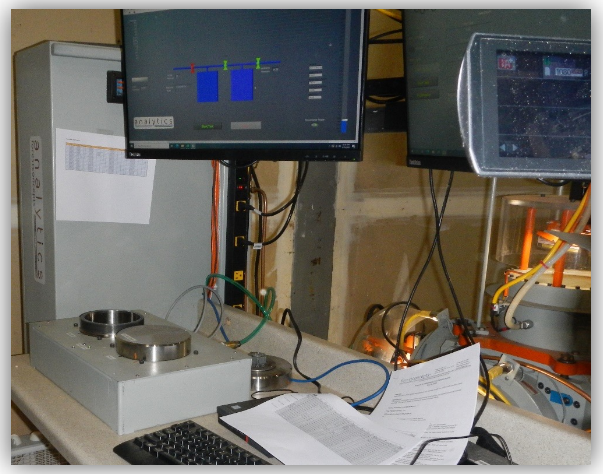
Screw Conveyor

2 new biomass-scale test devices

3 adapted modeling techniques







1 – Approach
Ties to FOA and BETO Goals

- **Ft-E** Feedstock Quality
- **Ft-J** Operational Reliability
- **At-B** Analytical Tools and Capabilities for System-Level Analysis
- And others

- **IBR FOA Topic 4**
  - Characterize flowability parameters across range of moisture and temperature
  - Need for dynamic, novel, real-time analytical models for design of biomass feeding systems.

Directly addresses FOA topic 4 and several BETO goals

- **Problems We are Addressing**
  - <u>There were no consistently reliable tools available</u> to measure the bulk flow properties needed to implement reliable biomass material models
  - Our focus on new lab devices has filled a big hole in the need for tools to quantify mechanical properties of biomass materials.
    - Previously existing flowability measurement lab devices for powders are not scaled for biomass materials
    - Previously existing flowability measurement lab devices cannot test across the needed range of temperatures experienced during biomass feedstock handling
  - Of the available bulk materials flow models, it was not apparent which model was appropriate to use with different biomass formats.

1 – Approach
Success Factors & Challenges

Risks were managed and Key Challenges overcome

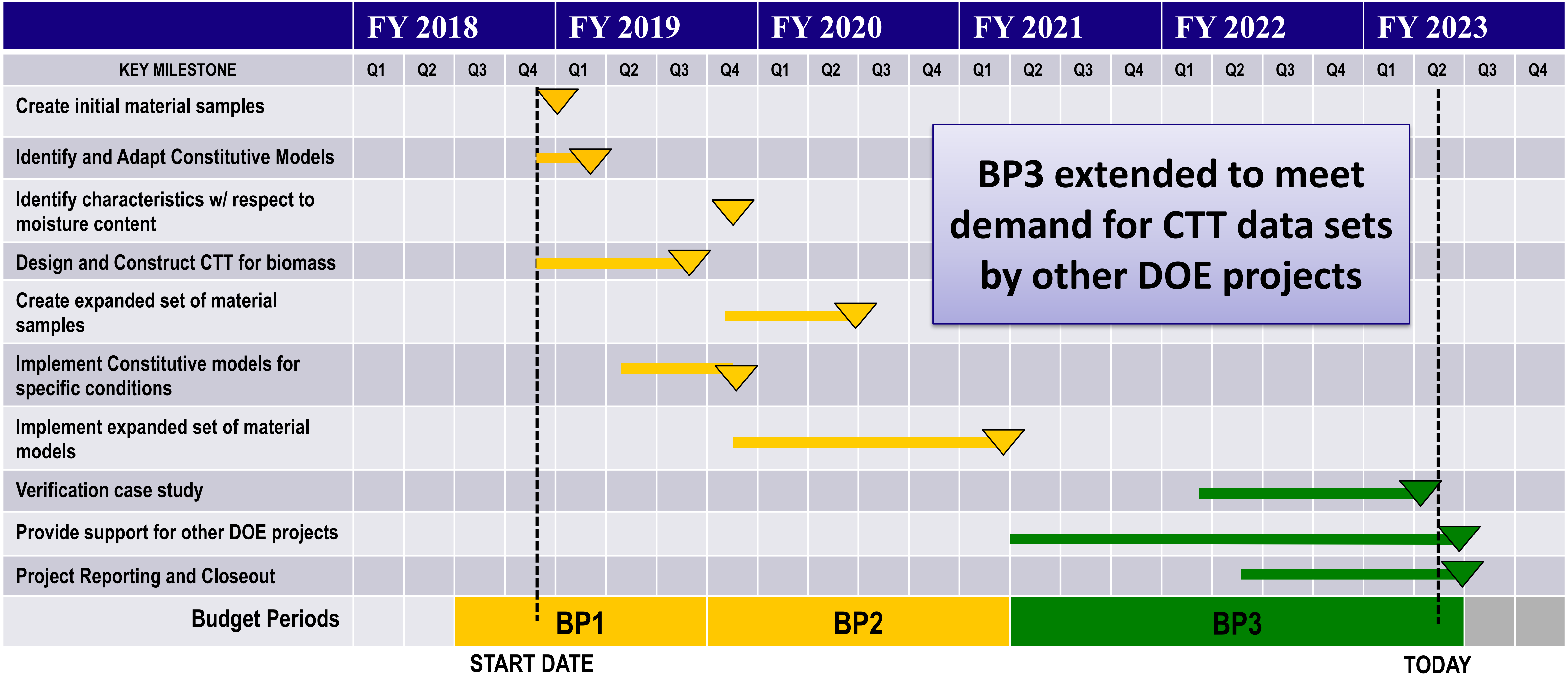
- **Success Factors**
  - ☑ – New equipment and protocols that work well
  - ☑ – Output of models and simulations correlate with experimental results
  - ☑ – Engineers and other IBR project participants find new/improved tools useful

- **Key Challenges**
  - ☑ – Engineering a bulk biomass material behavior measurement device with scale/size and functional capability for biomass feedstock
  - ☑ – Methods development to prepare uniform samples having high moisture and elevated temperature
  - ☑ – To broadly introduce new and improved design tools across all engineering disciplines engaged in feedstock handling design
    - Forest concepts has experience with webinars, trade magazine stories, professional consulting services, and commercialization of DOE funded technologies

- Active
- Completed
- ▼ Major Milestone

2 – Progress & Outcomes

Project Timeline



2 – Progress & Outcomes
New Laboratory Devices

New lab devices to overcome the limitations of existing laboratory methods and equipment related to flowability measurements

Previously existing Bulk Property Measurement Tools

- Cylindrical Shear Tester for soils is confounded by rigid walls & assumes uniform material (not anisotropic).
- Jenike Shear Tester only measures in one confined plane

Cubical Triaxial Tester (CTT)

- Truer measure of material behavior without confounding effect of die-wall friction
- Measurement of the pressures and displacements in three orthogonal directions
- Previously existing CTTs (soils devices, etc.) not suitable for most biomass
- New CTT is scaled and optimized for biomass material

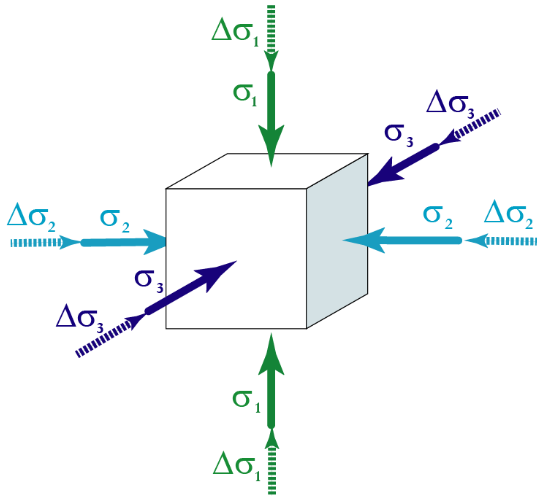
Gas Pycnometer for Biomass Scale Materials

- Air as pressure medium (enables broad use in industry)
- A large sample chamber enables evaluation of 30mm wood chips, etc.
- Automated measurement sequence integrated with CTT workstation and data collection to linked dataset

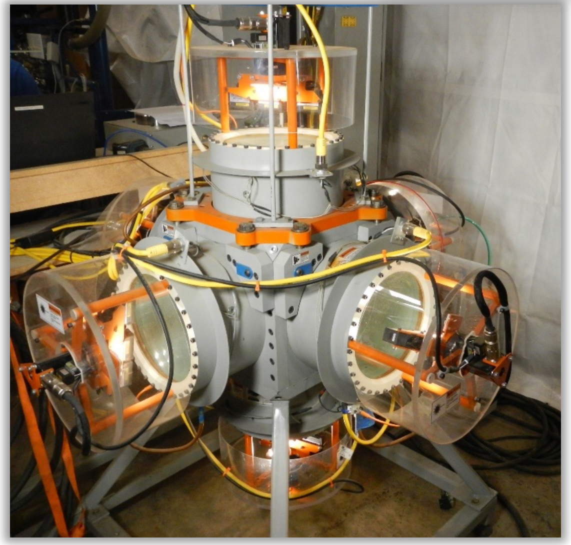
2 – Progress & Outcomes
New Laboratory Devices

CTT for Biomass Scale Materials

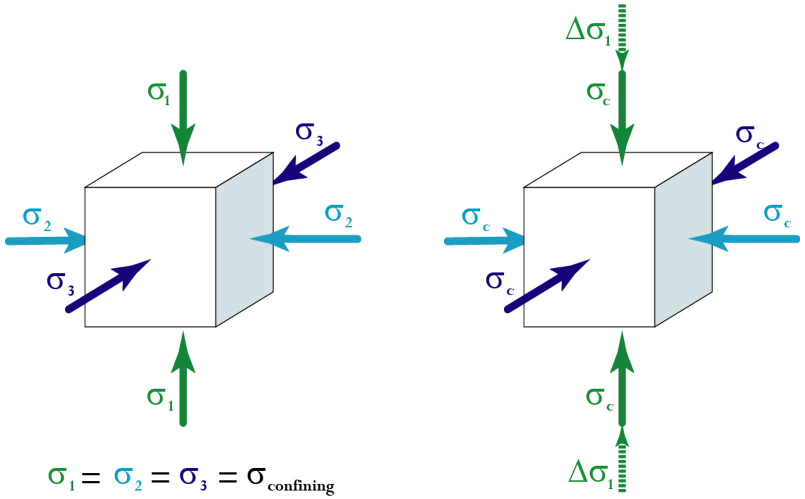
Hydrostatic Triaxial Compression (HTC) Test

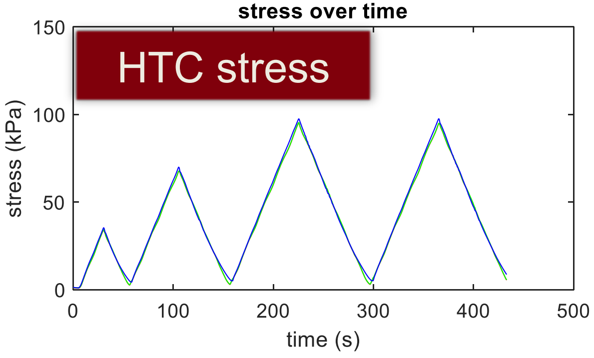


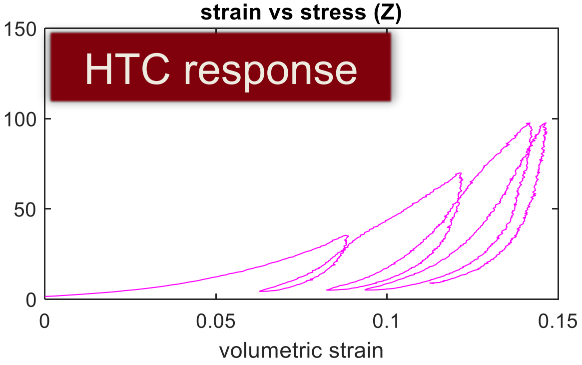
15,625cc CTT for biomass

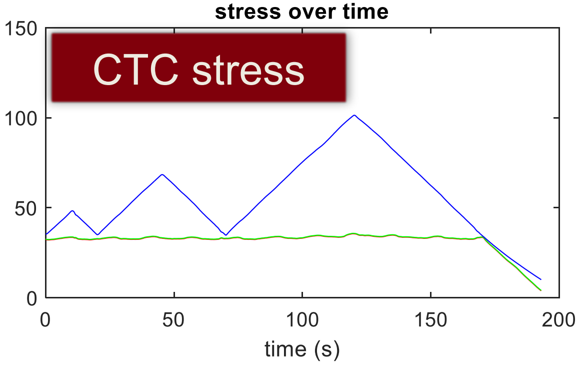


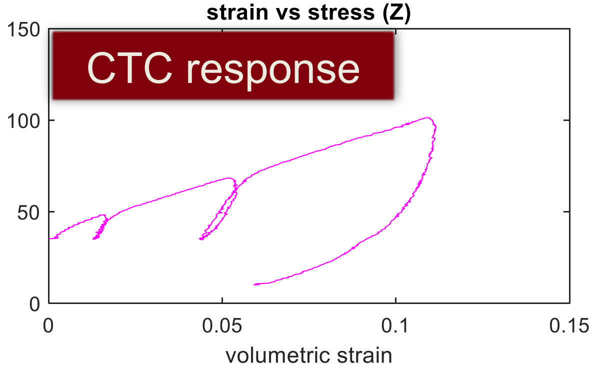
Conventional Triaxial Compression (CTC) Test





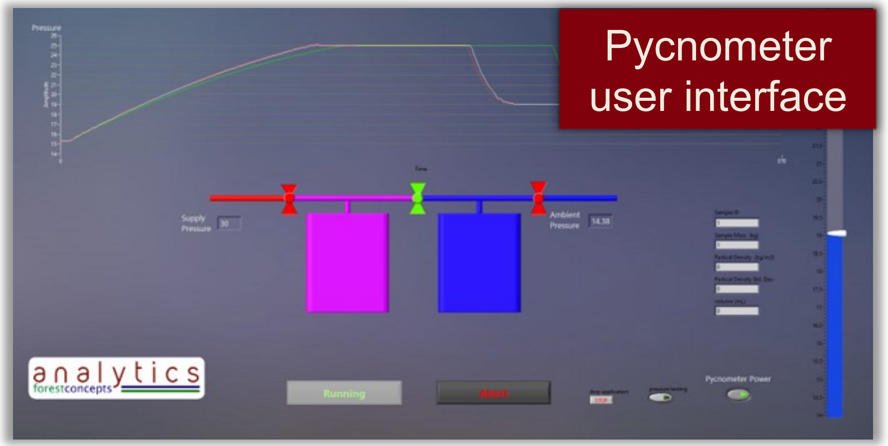






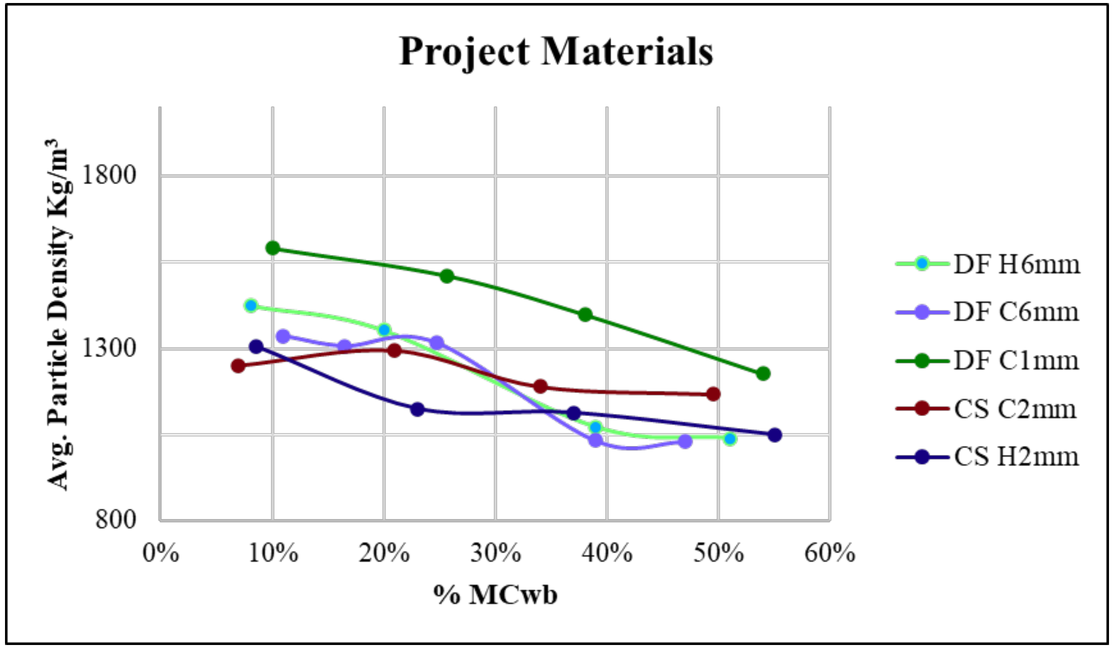
2 – Progress & Outcomes
New Laboratory Devices

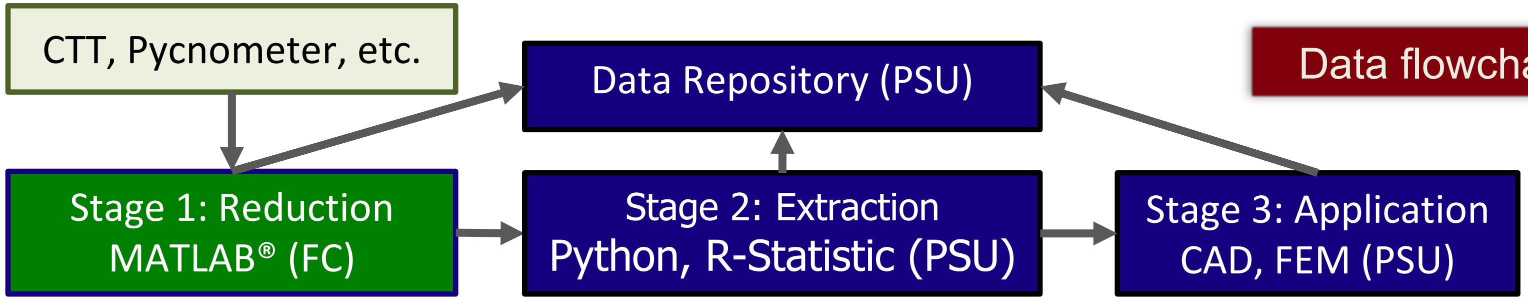
Gas Pycnometer for Biomass Scale Materials



Pycnometer user interface

1300cc Pycnometer





Data flowchart

2 – Progress & Outcomes
Properties to Measure

Constitutive Biomass Flow Model	Model Parameters from Hydrostatic Compression Triaxial Tests	Model Parameters from Conventional Compression Triaxial Tests
Mohr-Coulomb model	NONE	C (Coefficient of Cohesion) ϕ (Angle of Internal Friction)
Drucker-Prager/Cap model	p_c (Hydrostatic Yield Stress) $\varepsilon_{vol}^{plastic}$ (Corresponding Volumetric Plastic Strain)	d (Coefficient of Cohesion on $j_1 - \sqrt{j_2}$ plane) β (Angle of friction on $j_1 - \sqrt{j_2}$ plane) R (Cap eccentricity parameter) $\varepsilon_{vol,0}^{initial}$ (initial cap yield surface position) α (Transition surface radius parameter) K (tensile/compression yield stress ratio)
modified-Cam/Clay model	K (Bulk modulus) λ (Compression index) p_c (Hydrostatic Yield Stress) $\varepsilon_{vol}^{plastic}$ (Corresponding Volumetric Plastic Strain)	M (Critical State Slope) $\varepsilon_{vol,0}^{plastic}$ (initial plastic volumetric strain) β (tensile/compression yield coefficient), K (tensile/compression yield stress ratio)

DEM simulations	Contact bond parameters are often obtained by performing a small-scale simulation of the experiments and fitting. CTT can provide full strain-strain tensor values for various stress paths, making DEM calibration more robust and accurate.

The parameters for all 3 models can be determined from a single series of HTC and CTC tests

2 – Progress & Outcomes
Properties to Measured

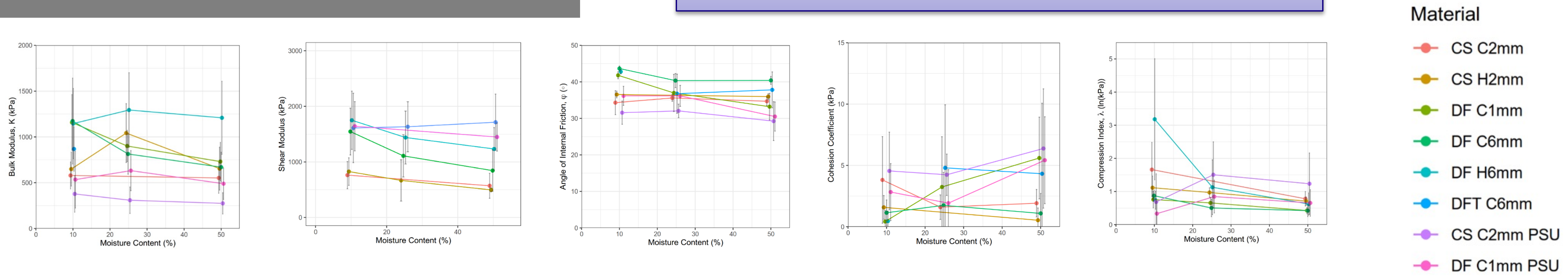
A series of HTC and CTC test results are reduced to a set of model parameters

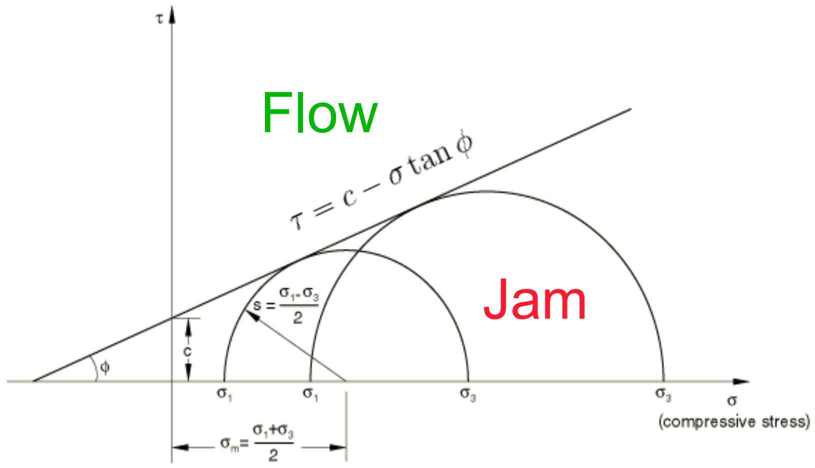
			Drucker-Prager/Cap							
Description	%wb	Temperature	*ε1*	*pc (kPa)*	*d (kPa)*	*β (degree)*	*R (approximated)*	*ε2*	α (assumed)	*K (assumed)*
CS C2mm	10	Ambient	0.01	1.0	6.9	8.7	0.020	0.01	1.0	1.0
CS C2mm	10	75 C	0.01	1.0	0.5	16.8	0.001	0.01	1.0	1.0
CS C2mm	25	Ambient	0.01	1.0	3.0	11.5	0.030	0.01	1.0	1.0
CS C2mm	50	Ambient	0.01	1.0	3.4	10.1	0.001	0.01	1.0	1.0

Beyond the project, we are implementing a CTT sample chamber modification to enable direct measurement of *α* and *κ*

2 – Progress & Outcomes
Model Parameters

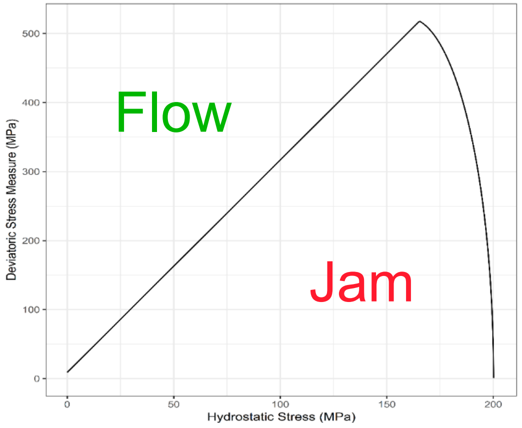
Properties vary as function of material and moisture content





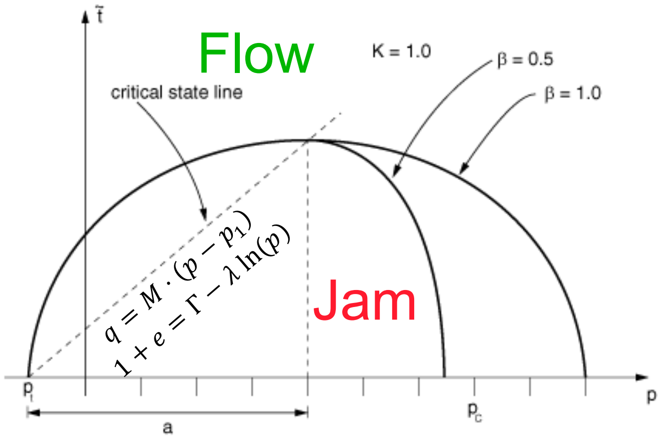
Mohr-Coulomb

- CTC
- Similar to Jenike procedure



Drucker-Prager/Cap

- HTC, CTC
- Robust, 3D

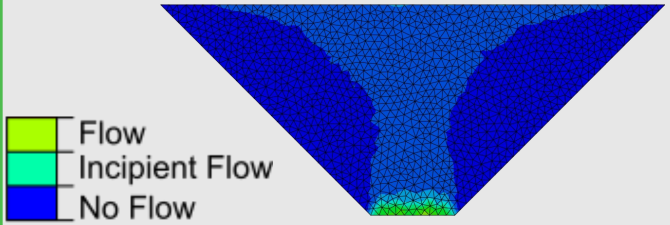


Modified Cam-Clay

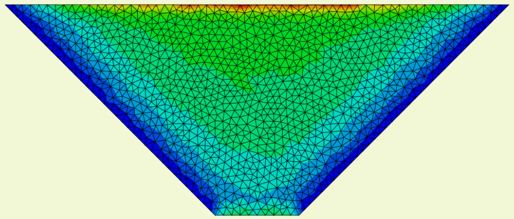
- HTC, CTC
- Robust Alternative, 3D

Simulation strategy is scalable

Lab scale



Drucker-Prager/Cap Model
Corn Stover 2mm



Drucker-Prager/Cap Model
Douglas Fir 1mm

Pilot scale

2 – Progress & Outcomes
Experience and Status

- Number of Runs on New CTT
  - Various stress profiles: > 900
- Run Time by Test type
  - All test profiles: ~ 10 minutes
  - High Temperature: +2 hrs. pre-heating
    - Multiple runs possible once heated
- Membrane Life
  - Highly dependent on specific material
  - Approximately 30 tests per membrane set
- **Project objectives have been met**

For the first time, quantification of flowability properties is possible

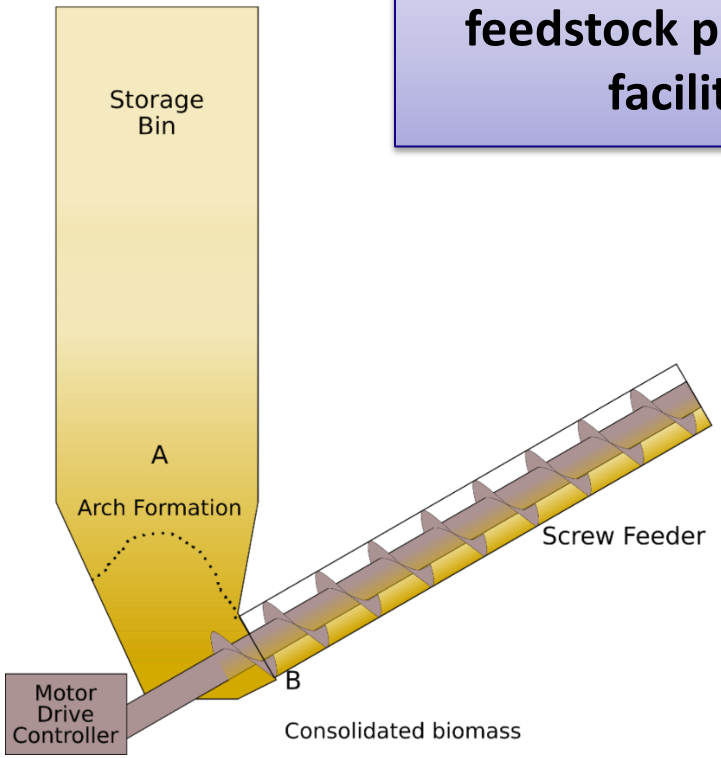
Lessons Learned

- Testing samples at high temperature (>75 C) and high moisture is not practical nor relevant to atmospheric pressure flowability modeling
- Biomass scale CTT is proving to be a valuable and efficient laboratory device

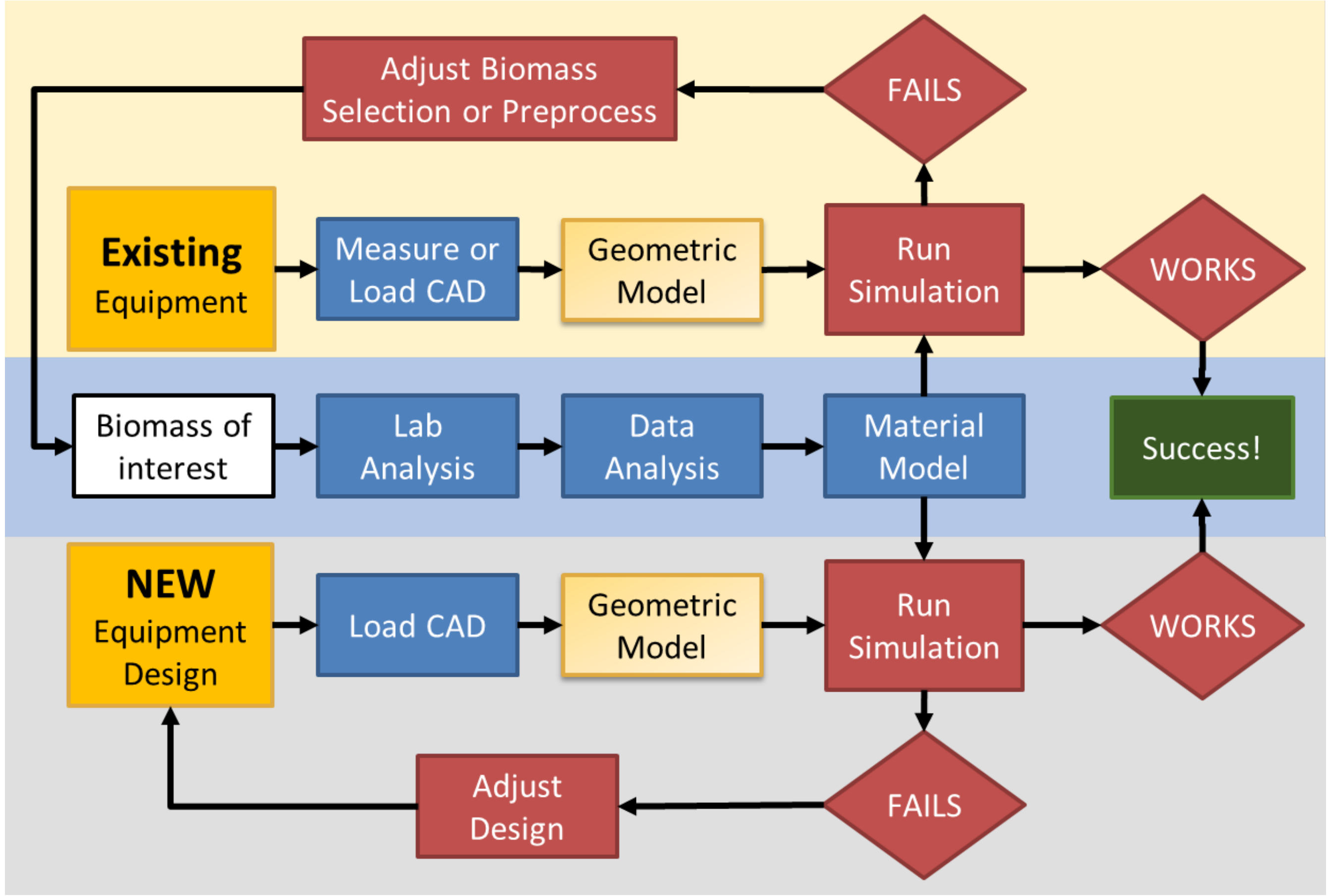
Key Takeaways

- CTT tests apply pressures and measure corresponding strains in the principal directions
- Parameters of all three models are determined with the same underlying data sets
- Moisture influences from material to material cannot be generalized
- Response to moisture and temperature are non-linear
- Response to moisture is far more important than response to temperatures up to 75 C
- **The variation in properties of biomaterials is large, which has been expected**

3 – Impact



New tools broadly impact new and existing biomass feedstock production facilities



3 – Impact
Industry and Research

The bioenergy industry will be better off because:

- There will be fewer high visibility failures due to feedstock handling issues
- Facilities are less likely to be affected by inevitable variance in feedstock bulk properties
- Facilities will be better able to predict potential handling issues with new feedstock materials
- Biorefinery EPCs can better define the range of applicability for feedstock handling equipment and systems

Results are available in 14 publications to date with many more to come.

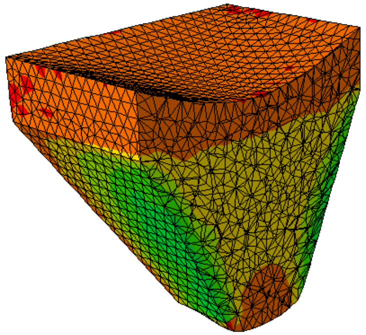
Market Transformation / Commercialization:

- New lab equipment will be commercially produced and sold through existing channels
  - At least five potential licensees
  - System already in demand to support outside research
    - 6 additional materials fully characterized for others to date
- New protocols will be converted to draft Standards and enter national / ISO processes
  - Jim Dooley on ISO TC238 and US ASABE standards committees
- Models and simulation tools in made into practitioner-level products
- Workshops, webinars, CPD courses, conference papers, etc. will be used to train engineers from relevant disciplines (ASME, AIChE, ASABE, …)
- Trade and professional magazine articles have increased awareness of new methods and devices: 14 conference papers published with multiple journal and magazine articles in process.

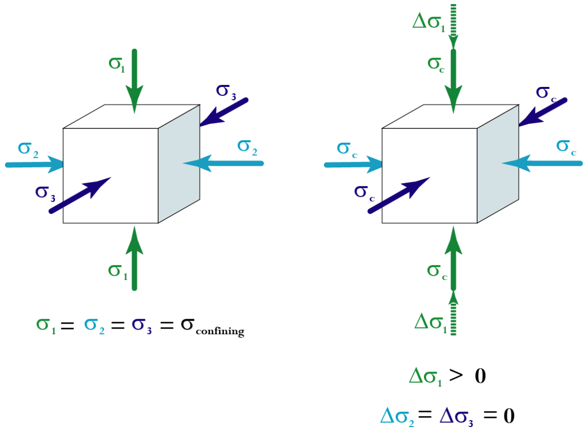
Summary

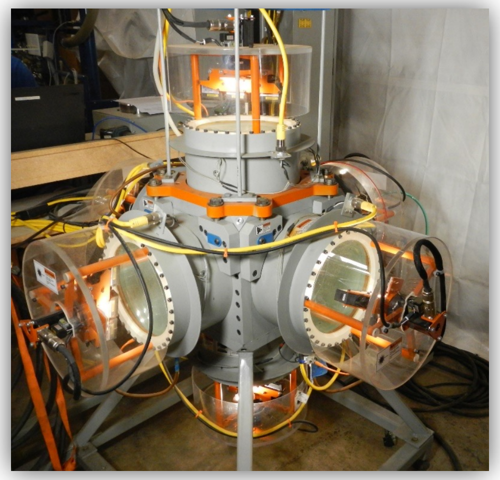
- New lab devices design, built, and commissioned
- More than 900 runs to-date on CTT, robust
- Models developed and implemented
- Multiple publications, presentations, webinars
- Tightly connected to INL and Purdue project teams

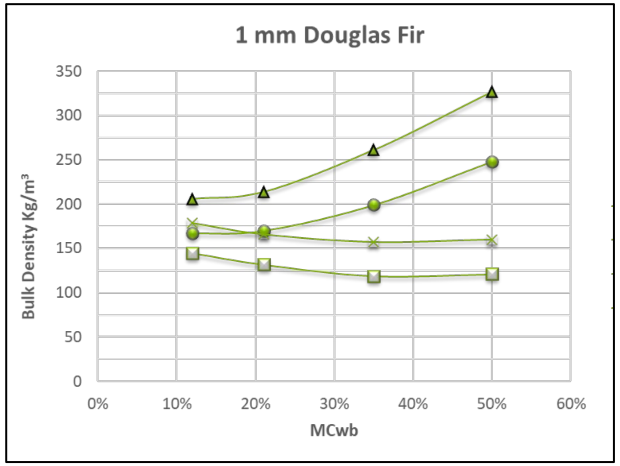
New Tools Work!



Hopper







Quad Chart

Timeline

- Project start date June 1, 2018
- Project End Date: April 30, 2023

Budget

	FY 22 Costs (10/01/2021 – 9/30/2022)	Total Award
DOE Funded	268K	1,479K
Cost Share	45K	370K

Project Goal

Minimize feedstock handling equipment failures through the creation of new laboratory devices and protocols to measure physical and mechanical properties as function of moisture and temperature, enabling development and implementation of better flowability models

End of Project Milestones

- Laboratory protocols of biomass feedstock characterization
- Novel test device for feedstock characterization
- A verified computational modeling and simulation framework

TRL

Start: 3

End: 5

Project Partners

Lead: Forest Concepts, LLC

Sub: The Pennsylvania State University

Funding Mechanism

FOA - DE-FOA-0001689

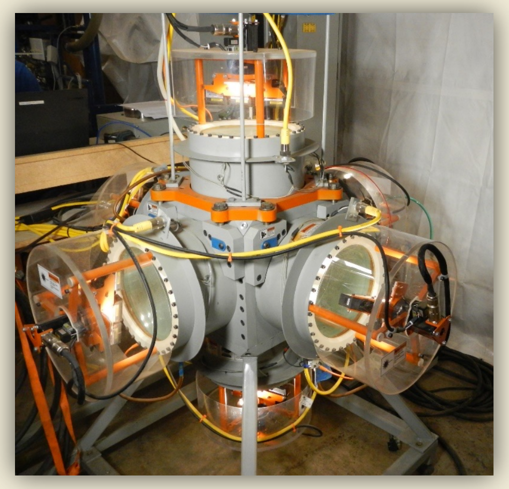
Integrated Biorefinery Optimization (2018)

Topic: 4: Analytic modeling of solid materials

IBR Project

Award Number: DE-EE0008254
WBS: 3.1.1.002

Thank You



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Virendra Puri, Ph.D.

PennState

State College, Pennsylvania

Additional Slides

Publications To Date

1. Lanning et. al. (2022) Presentation: ASABE (2200549) Evaluation of Hopper flow prediction based cubical triaxial tester data and FEM modeling
2. Yi et. al. (2022) Presentation: ASABE (2200765) Finite Element modeling of post-incipient biomass flow from a gravity hopper.
3. Yi et. al. (2022) Determination of Fundamental Mechanical Properties of Biomass using the Cubical Triaxial Tester to Model Biomass Flow
4. Presentation of cumulative project accomplishments to 2021 BETO Peer Review.
5. Lanning et. al. (2020) Feedstock Flowability Measurement and Modeling Using Bulk Material. Thermal and Catalytic Sciences Symposium 2020 presentation.
6. Dooley et. al. (2020) Overview of DOE Flowability Measurements and Modeling Project. ASABE paper 200080
7. Lanning and Yi et. al. (2020) Design of a Biomass Scale Cubical Triaxial Tester. ASABE paper 2000078
8. Yi et. al. (2020) Effects of Moisture on the Fundamental Mechanical Properties of Biomass Flow Models. ASABE Poster number 2000060
9. Yi et. al. (2020) Finite Element Modeling of Biomass Hopper Flow. ASABE paper 2000059.
10. Yi et. al. (2020) Biomass Flow Mechanical Properties Characterizations. ASABE paper 2000058
11. Yi, H., V. M. Puri, C. J. Lanning, and J. H. Dooley (2019). Determination of Fundamental Mechanical Properties and Modeling the Flow Behavior of Biomass Feedstocks using the Cubical Triaxial Tester, ASABE Annual International Meeting, Boston, MA, July 7-10, Paper Number: 1901409
12. Yi et. al. (2019). Computational modeling of continuum scale constitutive equations to improve biomass feedstock material handling and conveying systems. ASABE paper number 19000929
13. Yi, H., V. M. Puri, C. J. Lanning, and J. H. Dooley (2018). Computational modeling of continuum scale constitutive equations to improve biomass feedstock material handling and conveying systems. ASABE Annual International Meeting, Detroit, MI, July 29 - August 1, Paper Number: 1800867
14. Yi et. al. (2018). Computational modeling of continuum scale constitutive equations to improve biomass feedstock material handling and conveying systems. ASABE paper number 1800867.

Materials

Woody Biomass

Corn Stover

Terms and Acronyms

- ADO – Advanced Development and Optimization program of BETO
- BETO – Bioenergy Technologies Office
- CTT – Cubical Triaxial Tester – new laboratory device for measuring mechanical properties
- DOE – U.S. Department of Energy
- EPC – Engineering, Procurement, and Construction firms
- FC – Forest Concepts
- FOA – Funding Opportunity Announcement – request for proposals
- IBR – Integrated Biorefinery
- INL – Idaho National Laboratory, Bioenergy Research Unit
- PI – Principal Investigator
- PM – Project Manager
- PSU – Pennsylvania State University

Comments from Previous Reviews

Past Peer Review concern: The diameter of biomass selected did not reflect the full-size range used in industry (up to 50mm). It is not clear why the project limited itself to the 6mm biomass size. Many gasification projects utilize chips up to 50mm. Although Forest Concepts is working with the FCIC group, it isn't clear if there was knowledge sharing between FCIC and this project despite it being a goal of this project. Unclear what features or attributes of biomass were not covered by existing lab protocols or test devices at the start of this project. i.e. It is not clear whether the bulk flow properties of powders apply to biomass or whether these properties have proven to be insufficient to characterize biomass flow. Project is validating their model at multiple facilities and comparing the results and methods used for validation. This is an excellent approach. Would be good to coordinate testing limits with others in BETO to ensure the temperature range is relevant to all upfront pieces of equipment. There is a concern that 150C is not high enough for screw feeders or other pieces of equipment connected to high temperature reactors. Really well explained on why the new equipment was selected, how its used and what it can provide. Unclear whether there have been failures in industry that they can point to the incorrect measurement of these parameters Appreciate that risk management was shared. Project appears to be task orientated towards resolving risks and challenges in this project. Collaboration with ATSM or other protocol developing bodies not a part of this project. If the methods used are an improvement, than these methods can and should become a part of a new testing standard.

Response: The project team thanks the review panel for their time and thoughtful comments. The focus of our proposal and project is to enable the use of existing bulk flow models by quantifying biomass mechanical and physical properties across a range of temperatures and pressures typical of feedstock handling systems. Unfortunately, existing powder and soil property testers are not scaled for use with comminuted biomass feedstocks ranging from particle sizes of 1-30mm and having the high elasticity and plasticity of biomaterials. Thus, we focused our efforts on the laboratory devices and protocols to characterize milled-biomass mechanical properties needed for simulations and models. Known bulk flow models were used to validate the utility of the measured properties with typical feedstock material handling equipment. Other projects funded this same FOA are more focused on model development and simulation of flow within conversion facilities.

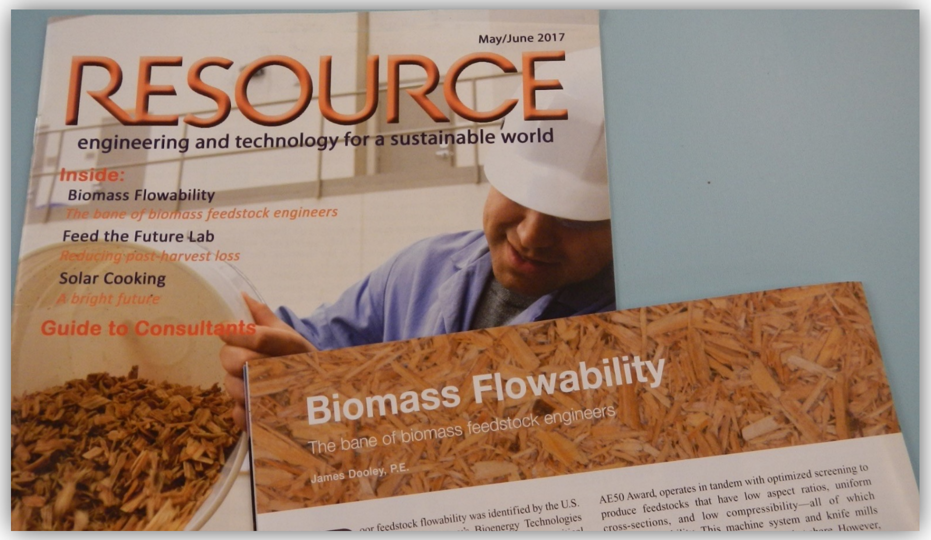
We developed a cubical triaxial tester (CTT) to measure stresses and strains in three orthogonal directions in order to overcome a shear cell limitation of only measuring in one confined plane. The CTT was scaled to work with the full range of common biomass feedstock materials, including fuel chips. The materials chosen for this project are the preferred species and particle sizes for ongoing biochemical and thermochemical research funded by DOE BETO. Their use leverages prior datasets and provides direct comparison to modeling efforts by the Purdue IBR project. The project team fully expects to evaluate a wider range of particle shapes, sizes, and species, once this proof-of-concept work is complete.

The existing CTT device and model development are currently focused on moderate temperature (<150C), and moderate pressure (<350kPa) flow regimes typical of feedstock handling systems.

The Forest Concepts prototype CTT is a first-of-of kind device never-before used with biomass feedstocks. Data gathered from more than 250 test runs is proving the efficacy of the device to produce bulk material parameters needed for flow modeling. The Market Transformation Plan anticipates that market prototypes and commercial versions will be appropriately specified and scaled based on Voice of the Customer and Appreciative Design methods into a family of products that meet the needs of various sectors of the emerging bioeconomy.

Context

- On a scale of marbles to matted cat fur
  ... shredded biomass flows like cat fur!
- Current flow modeling and simulation tools are not good enough to reliably design biomass equipment
- Current biomass lab methods and equipment are inadequate to measure coefficients used in flowability models
- PI Jim Dooley wrote cover story in ***Resource*** describing flowability issue and work going on around world



How can we better model biomass feedstock material handling?

2 – Progress & Outcomes
Model Parameters

Verification of material properties and adapted models

Hopper Wall Angle	Comparison	Corn Stover 2mm Mass Flow Rate (kg/sec) @ MC			Douglas Fir 1mm Mass Flow Rate (kg/sec) @ MC		
		10 %	25%	50%	6%	25%	50%
45°	Experiment	0.8 ±0.1	0.3±0.1	0.3±0.1	2.7±0.5	2.5±0.3	2.7±0.2
	Simulation	0.9	0.3	0.3	2.3	2.1	3.1
	Difference	+13%	0%	0%	-15%	-16%	+15%
60°	Experiment	0.9±0.2	0.5±0.1	0.6±0.1	3.5±0.1	3.0±0.1	4.4±0.3
	Simulation	0.9	0.5	0.5	3.4	3.1	4.4
	difference	0%	0%	-17%	-3%	3%	0%