DOE Bioenergy Technologies Office (BETO)
2021 Project Peer Review

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

Award: DE-EE0008254
WBS: 3.1.1.002

Jim Dooley, Ph.D., PE
Chris Lanning, PE

forestconcepts™

Auburn, Washington

Hojae Yi, Ph.D.
Virendra Puri, Ph.D.

PennState

State College, Pennsylvania

Jeff Caldwell,
Ralph Coates, Ph.D.

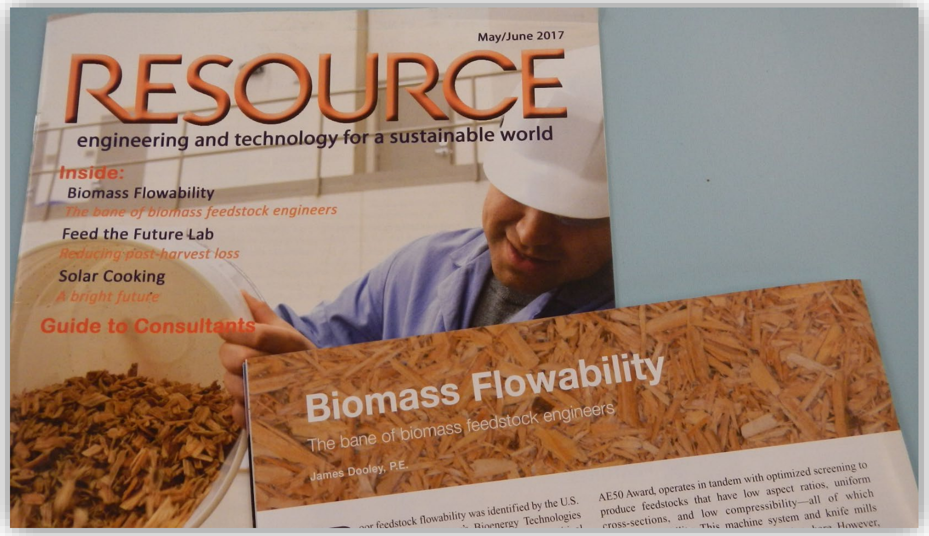
Amaron Energy

Salt Lake City, Utah

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



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.
- Project focus is to enable feedstock handling equipment and systems engineers to more reliably design and apply bulk handling equipment
  - Laboratory Test Devices
  - Laboratory Protocols
  - Models and Simulation Tools

New tools for the toolbox of feedstock handling equipment engineers

Project Overview
Objectives from SOPO

Modeling 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 to other IBR projects.**

Project Overview
Biomass Materials

Material selection reflects common feedstocks with a wide size range

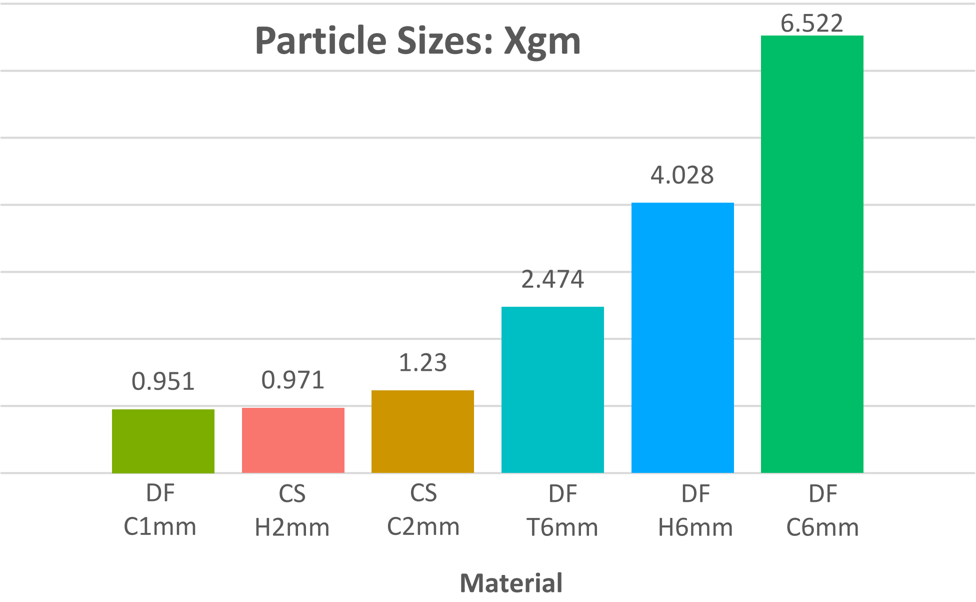
Woody Biomass (Douglas fir)

- 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

“Cat Fur” biomass must be milled into a more flowable format ….



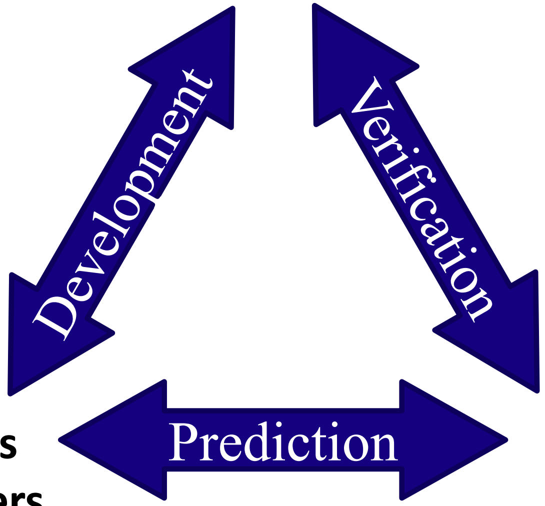
1 - Management

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 – Management
Stakeholder Engagement

- 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
- 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

1 – Management
Risks and Mitigation

Process Step	Risk Description	Severity (High/ Med/Low)	Mitigation Response	Planned Action Date	Active/ Closed
Task 2 Design and Construction of CTT					
	Design and assembly of CTT takes longer than expected	Med	Focus on most critical features	4/25/19	Closed Fully Operational
	New CTT measurement does not match PSU CTT measurement	Med	Adjust sample loading procedure	5/15/2019	Closed Experimental Data
Task 3 Implement computational model					
	Models work for all unit operations	Med	Identify which operations are applicable	6/31/2020	Closed BP2 Go/No-Go

2 - Approach

Ties to FOA and BETO Goals

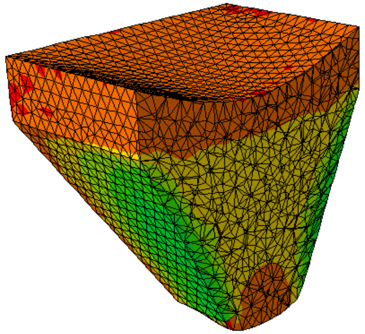
- **IBR FOA Topic 4**
  - Characterize flowability parameters across range of moisture and temperature
  - Need for dynamic, novel, real-time analytical models for design of biomass feeding systems.

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

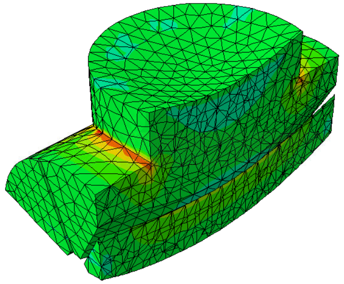
- **Problems We are Addressing**
  - There were no consistently reliable tools available to measure the bulk flow properties needed to implement reliable biomass material models
  - Our focus on new lab devices will fill a big hole in the need for tools to quantify mechanical properties of biomass materials.
    - 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.

2 – Approach
Innovations

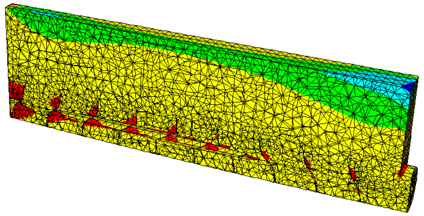
- New Cubical Triaxial Tester scaled for biomass feedstocks and with internal heating and drainage capabilities
- New gas pycnometer to obtain specific particle density
- Implementation of bulk flow modeling with simulation/animation of flow



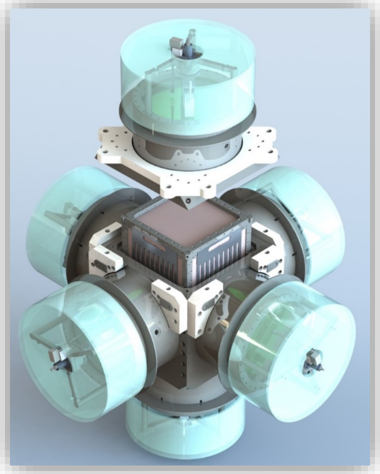
Hopper

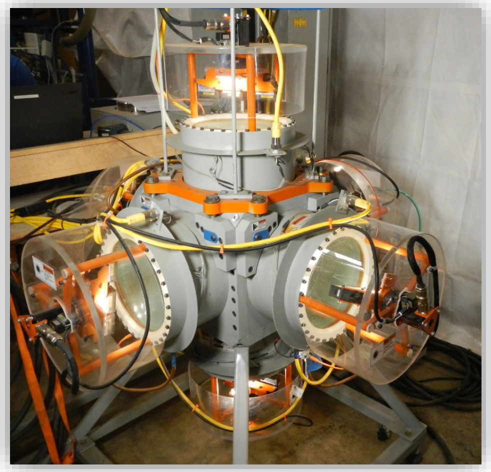


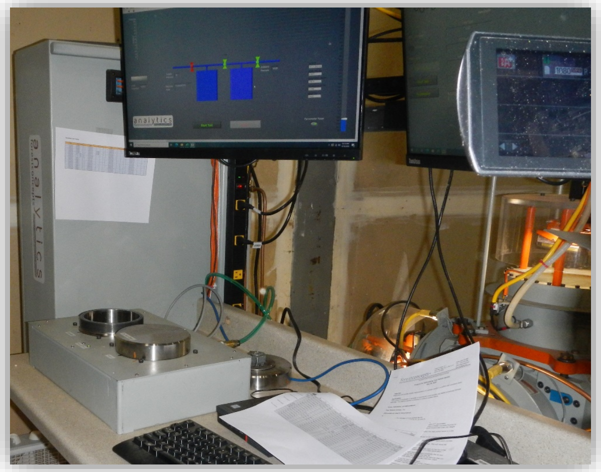
Rotary Valve



Screw Conveyor







2 – Approach
Success Factors & Challenges

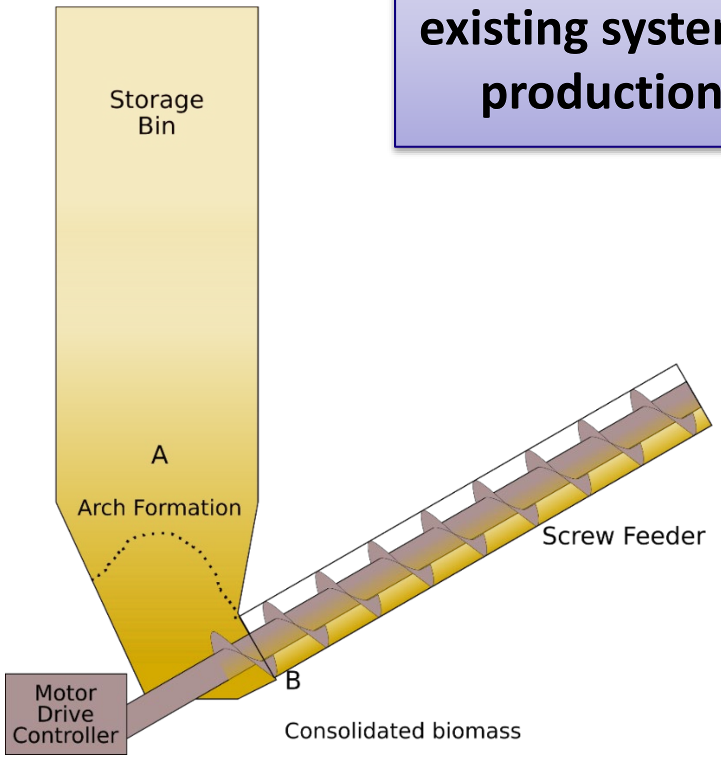
- **Success Factors**
  - ☑ – New equipment and protocols that work well
  - ☑ – Output of models and simulations correlate with experimental results
  - ☑ – Engineers and other IBR project participants find new/improved tools useful

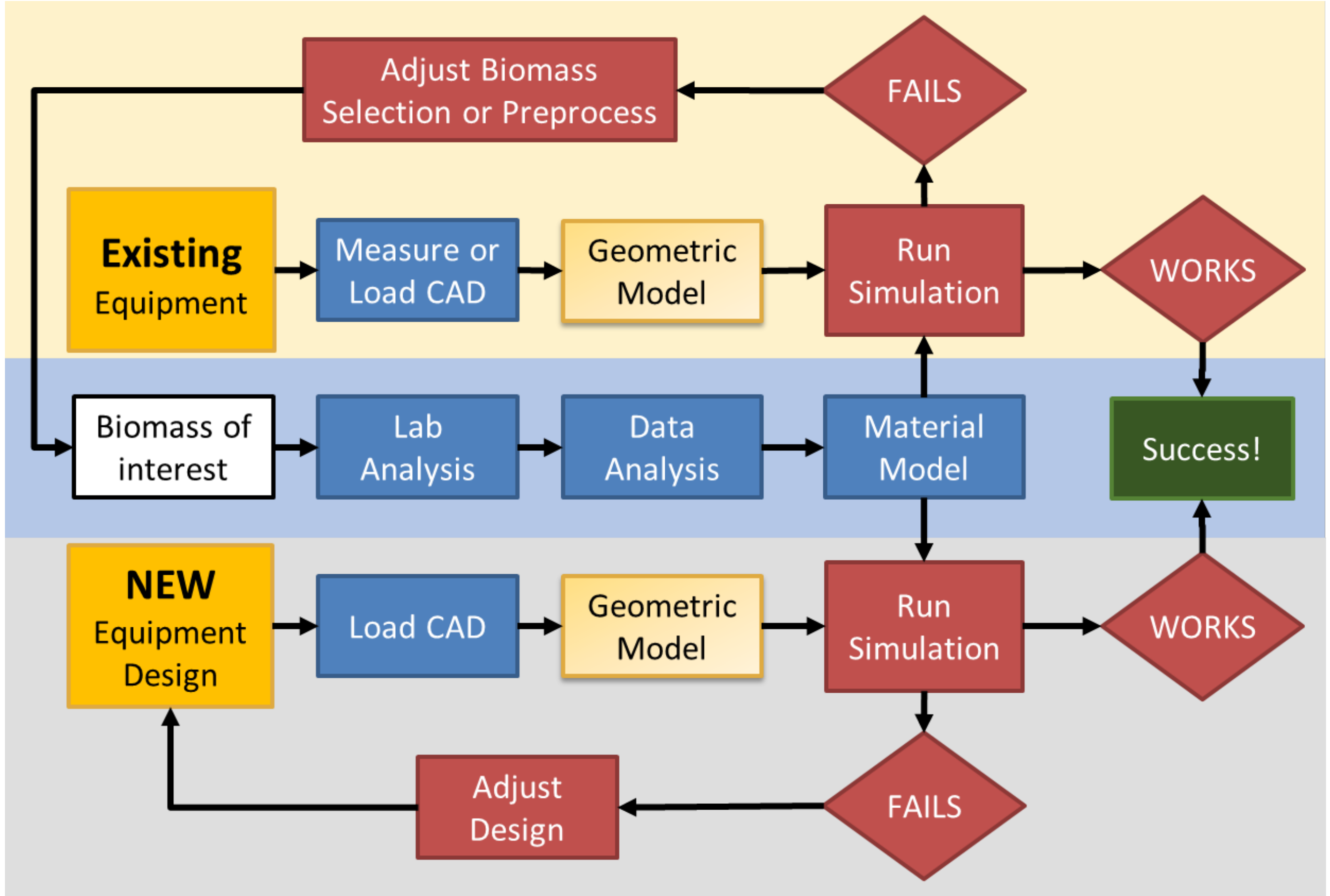
- **Key Challenges**
  - ☑ – Engineering a bulk biomass material behavior measurement device with scale/size and functional capability for biomass feedstock
  - ☑ – Methods development to prepare uniform samples having high moisture and elevated temperature
  - ☐ – To broadly introduce new and improved 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

3 – Impact

Practitioners

Lab and modeling tools directly impact new and existing system feedstock production facilities





3 – Impact
Industry and Research

The bioenergy industry will be better off because:

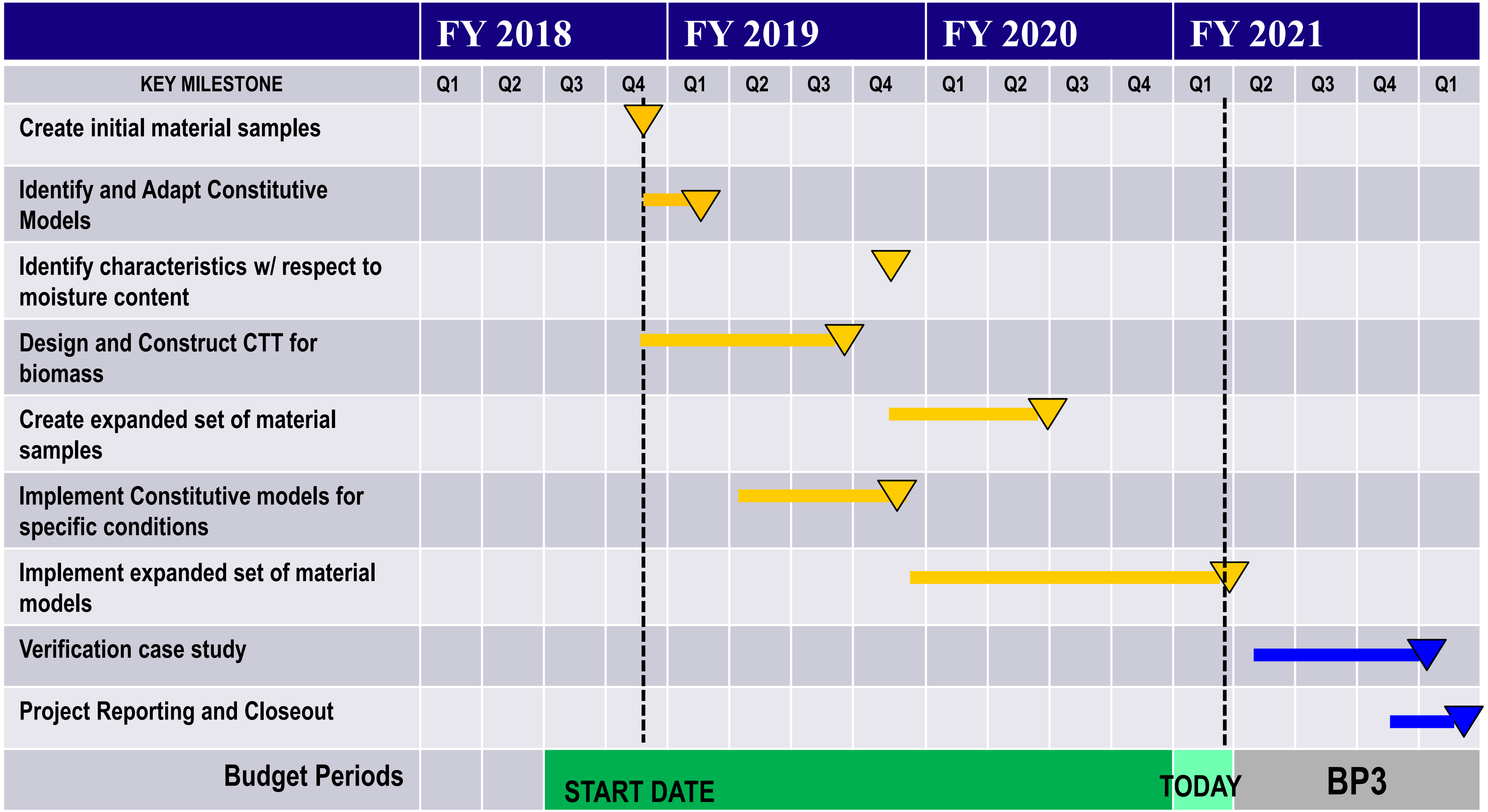
- There will be fewer high visibility failures due to feedstock handling issues
- Facilities are less likely to be affected by inevitable variance in feedstock bulk properties
- Facilities will be better able to predict potential handling issues with new feedstock materials
- Biorefinery EPCs can better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

Market Transformation / Commercialization:

- New lab equipment will be commercially produced and sold through existing channels
  - At least five potential licensees
- 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 will be 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 will increase awareness of new methods and devices

4 – Progress & Outcomes

Project Timeline



– Scheduled
– Active
– Completed
– Delays
▼ Major Milestone

4 – Progress & Outcomes
New Laboratory Devices

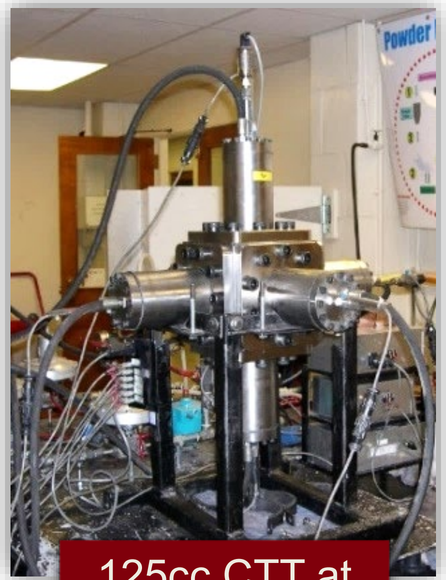
New lab devices to overcome the limitations of existing laboratory methods and equipment related to flowability measurements

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


125cc CTT at PSU

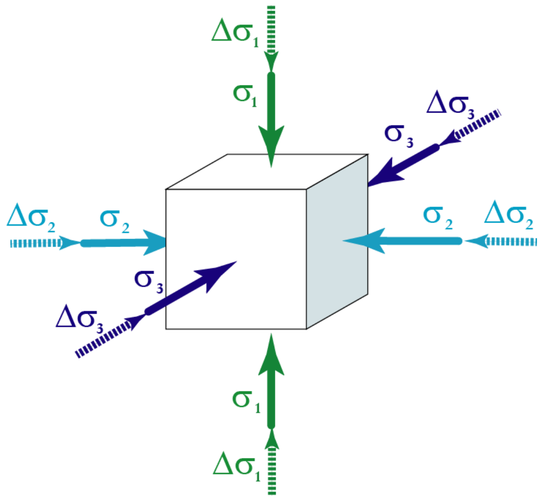
Gas Pycnometer for Biomass Scale Materials

- 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

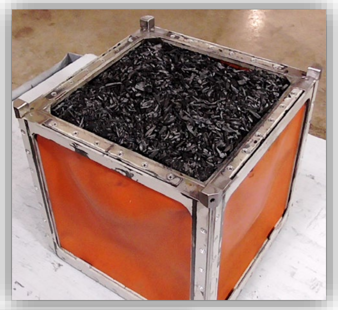
4 – Progress & Outcomes
New Laboratory Devices

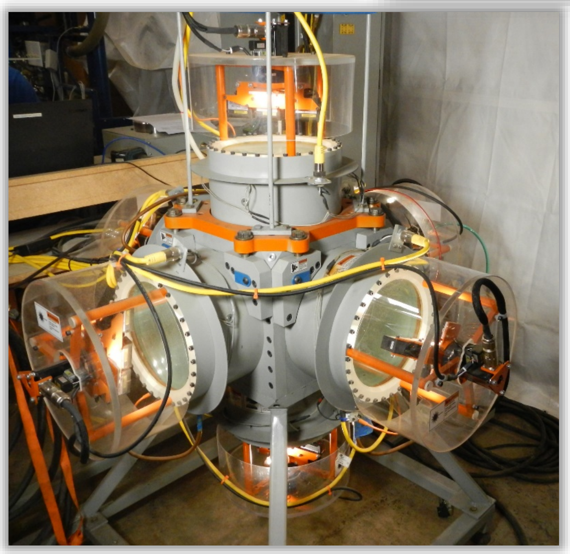
CTT for Biomass Scale Materials

Hydrostatic Triaxial Compression (HTC) Test

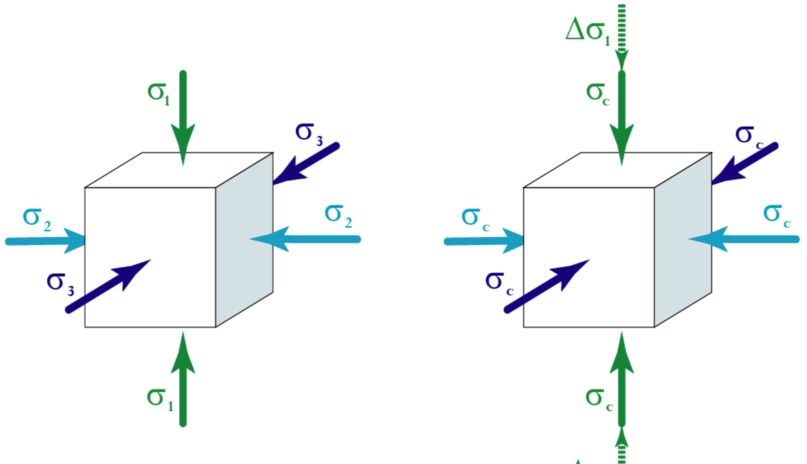


15,625cc CTT for biomass

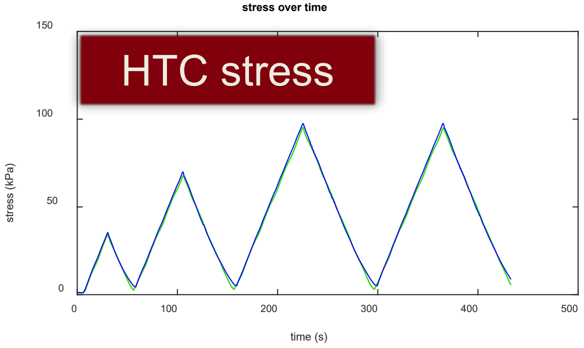


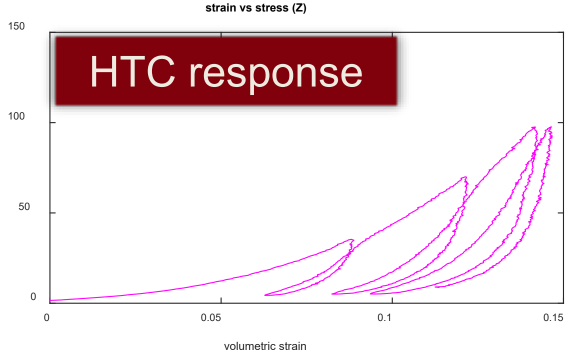


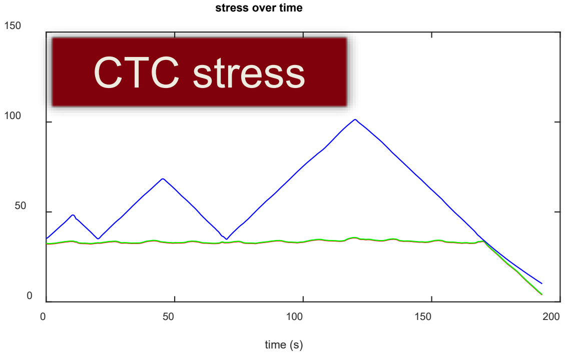
Conventional Triaxial Compression (CTC) Test

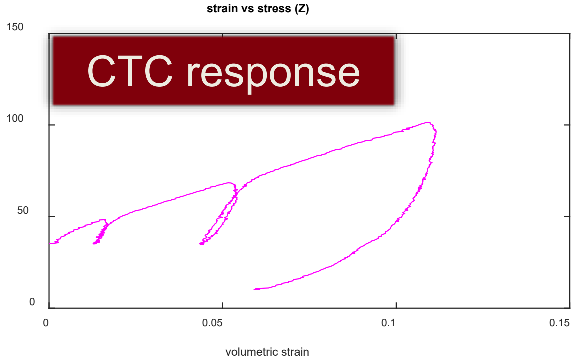


$\sigma_1 = \sigma_2 = \sigma_3 = \sigma_{confining}$



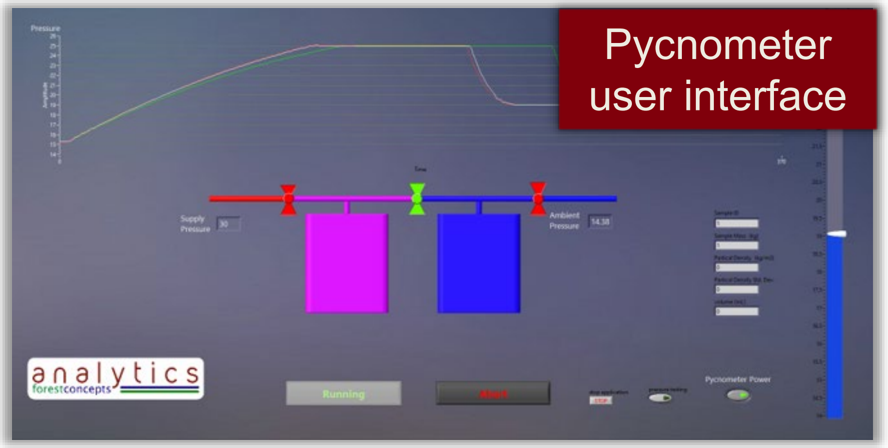






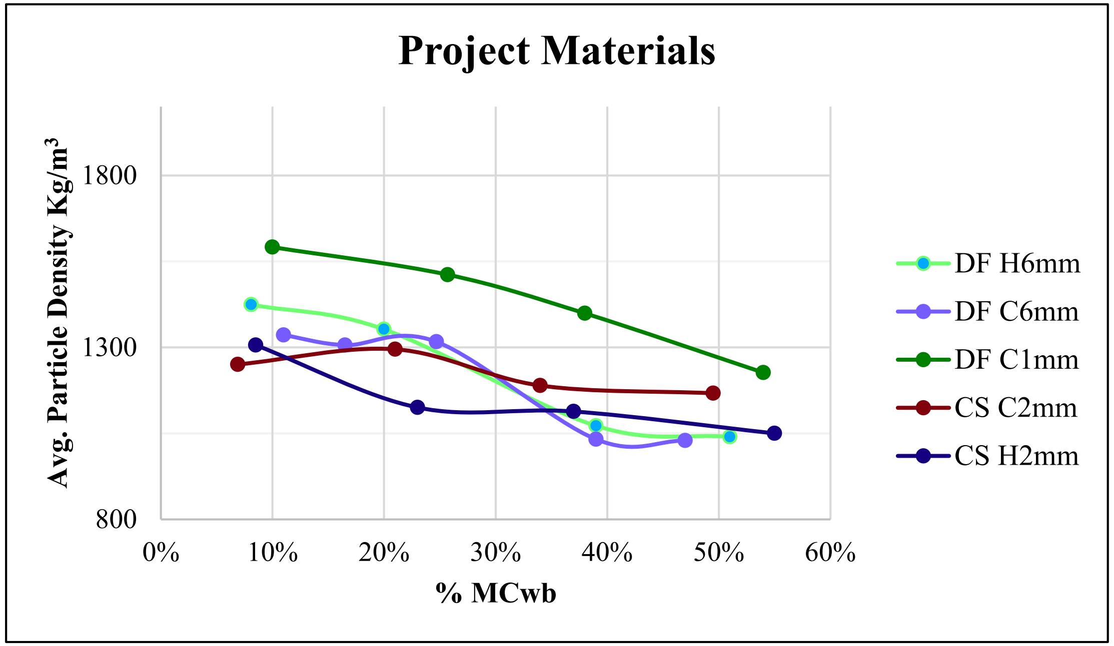
4 – Progress & Outcomes
New Laboratory Devices

Gas Pycnometer for Biomass Scale Materials



Pycnometer user interface

1300cc Pycnometer



Data flowchart

- CTT, Pycnometer, etc. → Stage 1: Reduction MATLAB® (FC)
- Stage 1: Reduction MATLAB® (FC) → Data Repository (PSU); → Stage 2: Extraction Python, R-Statistic (PSU)
- Stage 2: Extraction Python, R-Statistic (PSU) → Data Repository (PSU); → Stage 3: Application CAD, FEM (PSU)
- Stage 3: Application CAD, FEM (PSU) → Data Repository (PSU)

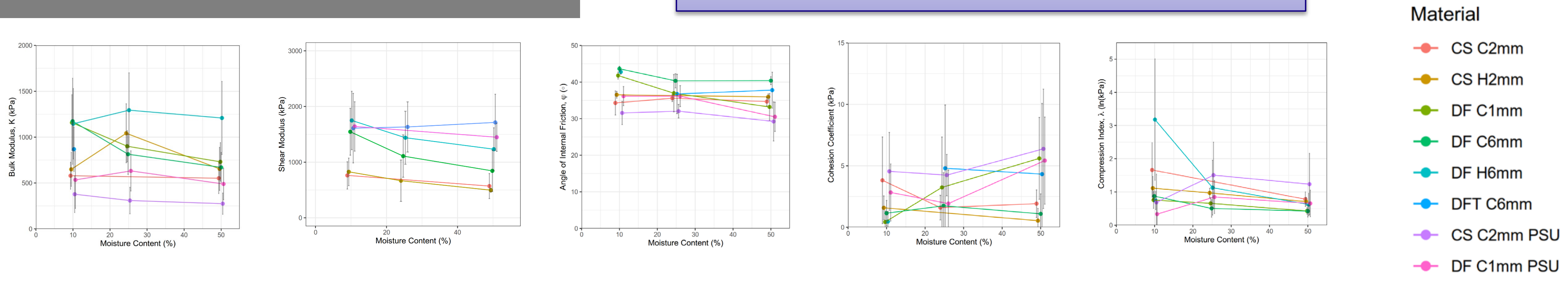
4 – Progress & Outcomes
Properties to Measure

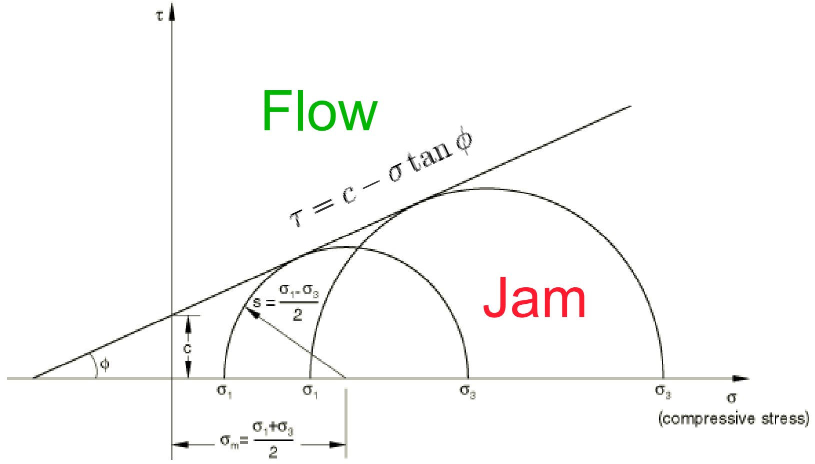
The parameters for all 3 models can be determined from a single series of HTC and CTC tests

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)

4 – Progress & Outcomes
Model Parameters

Results available in 9 publications to date, many more to come.



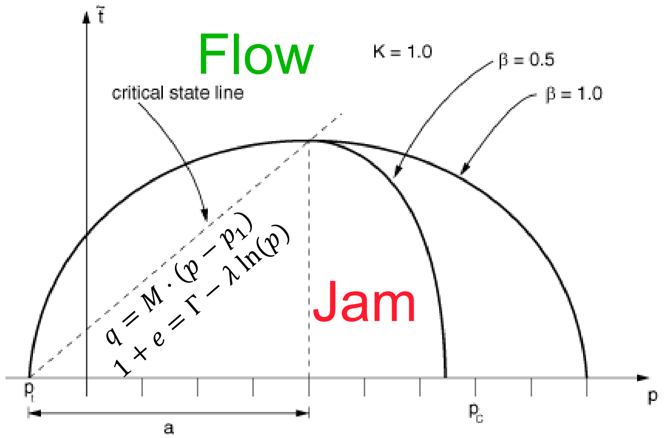


Mohr-Coulomb

- CTC
- Similar to Jenike procedure

Drucker-Prager/Cap

- HTC, CTC
- Robust, 3D



Modified Cam-Clay

- HTC, CTC
- Robust Alternative, 3D

4 – Progress & Outcomes
Experience and Status

- Number of Runs on New CTT
  - Conventional: > 190
  - Hydrostatic: > 70
- 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
    - Membrane set cost ~ $40/set

Lessons Learned

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

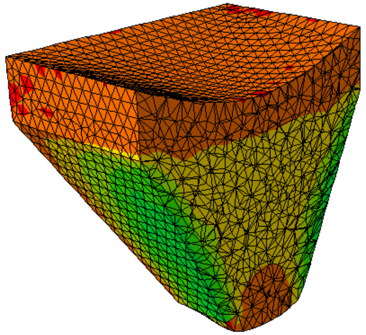
Key Takeaways

- Cubical triaxial 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
- The variation in properties of biomaterials is large, which has been expected

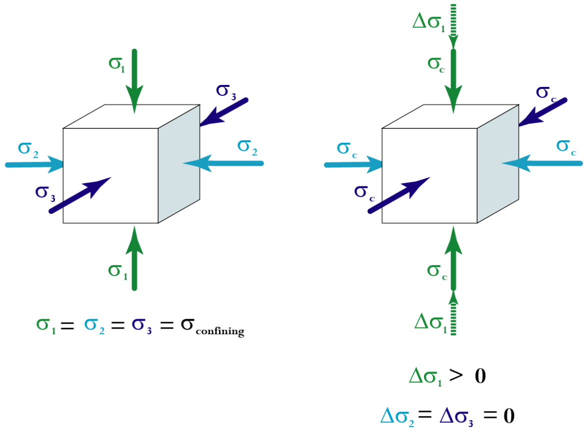
Summary

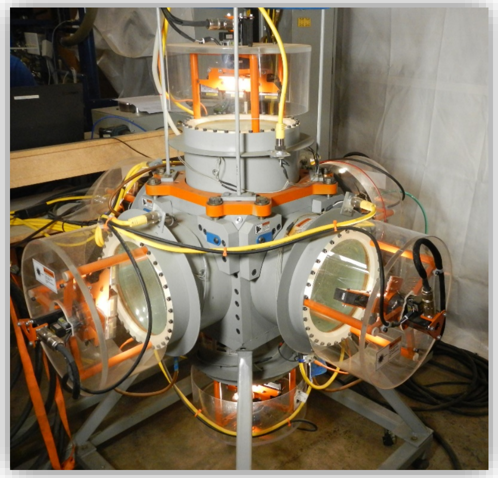
- New lab devices design, built, and commissioned
- More than 250 runs to-date on CTT
- Models developed and implemented
- Multiple publications, presentations, webinars
- Tightly connected to INL and Purdue project teams

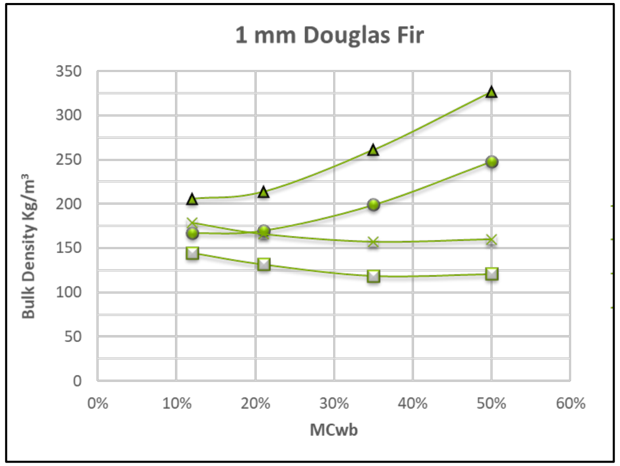
New Tools Work!



Hopper







Quad Chart

Timeline

- Project start date June 1, 2018
- Project End Date: December 31, 2021
- Percent complete: 80%

Budget

	FY 20 Costs (10/01/2019 – 9/30/2020)	Total Award
DOE Funded	938K	1,300K
Forest Concepts Cost Share	156K	211K
PSU Cost Share	79K	115K

Project Goals

- Measure physical and mechanical properties as function of moisture and temperature
- Develop and implement flowability models
- Design, build, and commission new laboratory devices and protocols

End of Project Milestones

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

Funding Mechanism

FOA - DE-FOA-0001689

Integrated Biorefinery Optimization (2018)

Topic: 4: Analytic modeling of solid materials

IBR Project
Control Number: 1689-1534
Award Number: DE-EE0008254

Thank You

Chris Lanning, PE	Hojae Yi, Ph.D.	Jeff Caldwell,
Jim Dooley, Ph.D., PE	Virendra Puri, Ph.D.	Ralph Coates, Ph.D.
forestconcepts™	PennState	Amaron Energy
Auburn, Washington	State College, Pennsylvania	Salt Lake City, Utah

Additional Slides

3 – Impact
Publications To Date

1. Lanning et. al. (2020) Feedstock Flowability Measurement and Modeling Using Bulk Material Properties. Presented at TCS 2020
2. Dooley et. al. (2020) Overview of DOE Flowability Measurements and Modeling Project. ASABE paper 200080 Lanning and Yi et. al. (2020) Design of a Biomass Scale Cubical Triaxial Tester. ASABE paper 2000078
3. Yi et. al. (2020) Effects of Moisture on the Fundamental Mechanical Properties of Biomass Flow Models. ASABE Poster number 2000060
4. Yi et. al. (2020) Finite Element Modeling of Biomass Hopper Flow. ASABE paper 2000059.
5. Yi et. al. (2020) Biomass Flow Mechanical Properties Characterizations. ASABE paper 2000058
6. 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
7. 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
8. Yi et. al. (2019). Computational modeling of continuum scale constitutive equations to improve biomass feedstock material handling and conveying systems. ASABE paper number 19000929
9. 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