DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

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

Award: DE-EE0008254

March 7, 2019
Advanced Development & Optimization Review

PI: Dr. James Dooley
Forest Concepts, LLC

Presenter: Chris Lanning, Project Manager

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

forestconcepts™ Amaron Energy

1-Project Overview

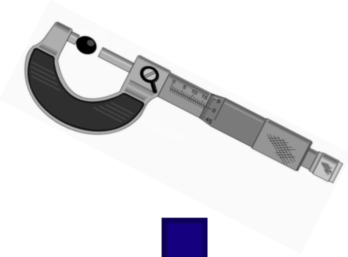
- History
  - Forest Concepts has been dealing with biomass flowability issues since 2005
  - DOE Workshops
    - Dec 2011 conversion technologies workshop identified plugging and flowability as major issues. (Jim Dooley participated)
    - Oct 2016 biorefinery optimization workshop reaffirmed plugging and flowability as major issue (Chris Lanning participated)
  - IBR FOA Topic 4
    - Need for dynamic, novel, real-time analytical models for design of biomass feeding systems.
- Context
  - Forest Concepts put together a small team with Penn State University Particulate Materials Center (50 years experience with biomaterials) and Amaron Energy (developer of a truly mobile fast pyrolysis systems for use with forest residuals, pinyon-juniper forest restoration debris, and other woody biomass)
    - Forest Concepts brings design engineering, lab protocols, lab and process equipment, and feedstocks
    - Penn State brings modeling and simulation, unique lab equipment, strong scientific methods
    - Amaron Energy brings an operating fast pyrolysis system with appropriate infeed and outfeed systems
      - Forest concepts has extensive experience producing feedstock for Amaron to reduce plugging and feeding issues.
- Resource Status
  - Project started June 1, 2018, Still in BP 1. On budget and on track.

1-Overview
Why Forest Concepts

A technology company that lives with flowability challenges every day!

- Toll-processing plant
- Design, build, sell feedstock preprocessing equipment
  - Strong equipment engineering capability
- Excellent modeling, simulation, and research team
- Competent project and program managers
- Strong relationships with labs and universities

1-Overview
Goal Statement



- Enable feedstock handling equipment and systems engineers to more reliably design and apply equipment that has a low incidence of plugging or variable flow under a wide range of operating conditions.
  - Through new and biomass-specific tools and data sets, including characterization equipment, laboratory protocols, and modeling and simulation software.
- The expected outcome will be reduced risk of operational failures at new and existing biorefineries.

Creating tools to add the toolbox of feedstock handling equipment engineers

1-Overview
High-Level Objectives

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

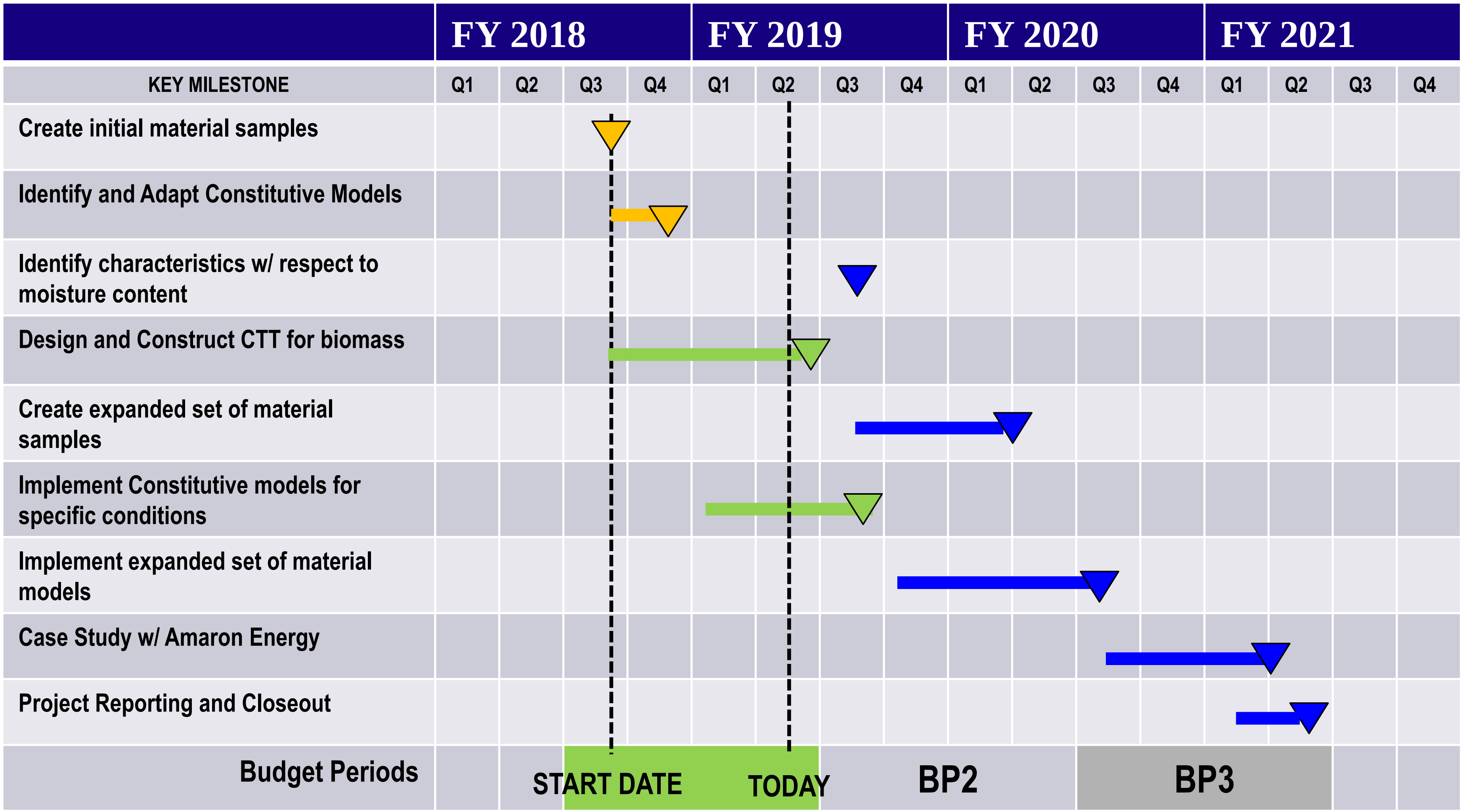
Objective 3. **Implementation of the adapted constitutive model** in the form of a computational model

Objective 4. **Verify and Validate computational model** in the context of an existing fast pyrolysis system including hopper, auger conveyor, rotary airlocks, and char auger

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

1-Overview
Key Milestones

– Scheduled – Completed
– Active – Delays
▼ Major Milestone



1-Overview
Project Budget

	Original Project Cost (Estimated)		Project Spending and Balance (Dec 31, 2018)	
Budget Periods	**DOE Funding**	**Project Team Cost Shared Funding**	**Spending to Date**	**Remaining Balance**
BP1	**$532,535**	**$133,174**	**$320,527**	**$345,182**
Design and Build CTT				
Setup modeling system	$162, 260	$40,591		
BP2	**$459,875**	**$115,053**	**$0**	**$574,928**
Use CTT				
Validate Modeling in unit steps				
BP3	**$486,623**	**$112,151**	**$0**	**$608,774**
Comprehensive Case Study				

1-Overview Quad Chart

Timeline

- Project start date June 1, 2018
- Project End Date: May 31, 2021
- Percent complete: 25%

Barriers

- **Ft-E** Feedstock Quality: Monitoring and Impact on Preprocessing and Conversion Performance
- **Ft-J** Operational Reliability
- **ADO-A** 3,4 Process Integration
- **AT-B** Analytical Tools

Budget

	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date
DOE Funded	0	178K	1,300K
Forest Concepts Share	0	31K	211K
PSU Share	0	14K	115K

Partners

- Sub-recipient
  - Penn State University
- Vendor
  - Amaron Energy
- Non-funded collaborators
  - INL
  - Purdue University

Amaron Energy

2-Approach, Management

- Project administration team
  - Forest Concepts
    - Jim Dooley, Principal investigator
    - Chris Lanning, Project manager
    - Mike Perry, Business manager
    - Tom Broderick, Intellectual property
  - Penn State
    - Verindra Puri, Principal investigator
    - Hojae Yi, Project manager
- Coordination
  - Frequent communication among team members and collaborators
  - Monthly webinar with DOE
  - Systematic project tracking and budgeting by Forest Concepts
  - Long term file storage using PSU ScholarSphere

2-Approach Task Leaders

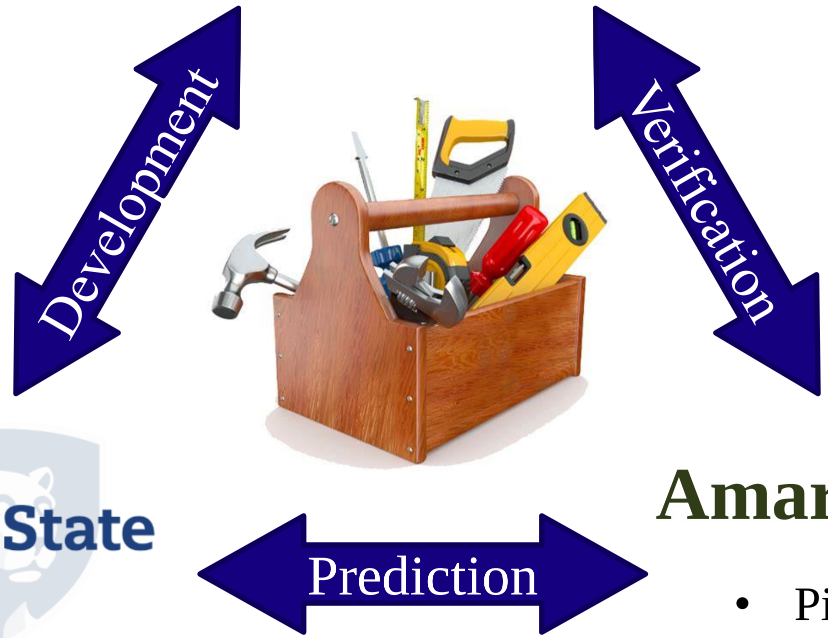
Each task has a designated leader and a cross-collaborator support team

- Project Execution team and responsibilities
  - Task Area 1: Adapt a continuum constitutive model
    - Hojae Yi, Task leader
    - Forest Concepts: Chris Lanning, James Slosson, Jordan Whitt, Shawn Baugher
  - Task Area 2: Design and develop test device(s) and laboratory protocols
    - Chris Lanning, Task Leader
    - Forest Concepts: Jim Dooley, James Slosson, Jordan Whitt, Shawn Baugher, Matt Wamsley, Dave Lanning
    - Penn State: Verindra Puri, Hojae Yi
  - Task Area 3: Implementation of the adapted models
    - Hojae Yi, Task Leader
    - Forest Concepts: Chris Lanning, Jordan Whitt
  - Task Area 4: Verify and Validate computational model
    - Chris Lanning, Task Leader
    - Forest Concepts: James Slosson, Jordan Whitt, Matt Wamsley, Jason Perry, Dave Lanning
    - Penn State: Hojae Yi, Verindra Puri
    - Amaron Energy: Ralph Coates, Jeff Caldwell
  - Task Area 5: Document all aspects of the project
    - Jim Dooley, Task Leader
    - Everybody

2-Approach
Close Collaboration

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

forestconcepts™



PennState

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

Amaron Energy

- Pilot-scale verification host
- Industry perspective

2-Approach
Major milestones and Go/No-go Points

Milestone Summary Table

Milestone Type	Milestone Number	Milestone Description	Milestone Verification Process	Anticipated Month	Anticipated Quarter
Budget Period 1					
Go/No-Go Decision Point	Go/No-Go # 1	Demonstrate applicability of adapted constitutive models	Simulation predicts within 20% the mass flow rate of incipient flow and mass flow rate of biomass	12	4
Budget Period 2					
Go/No-Go Decision Point	Go/No-Go # 2	Simulate selected biomass flow through infeed/outfeed system	Simulation completes without programmatic errors (code errors) or physical law violations (i.e. calculation of negative energy)	25	8
End of Project					
End of Project	Deliverable # 1	Laboratory protocols of biomass feedstock characterization pertaining to the design and operation of continuous biomass feeding systems	A collection of protocols is prepared as a package for feedstock analysis	36	12
End of Project	Deliverable # 2	Novel test device for feedstock characterization	All test devices required for feedstock characterization prepared for post project application	36	12
End of Project	Deliverable # 3	A comprehensive project report including TEA	Final project report submitted to EERE	36	12

Milestone Summary Table

Recipient Name: Forest Concepts, LLC

Project Title: Improved biomassfeedstock materials handling and feeding engineering data sets, design methods, and modeling/simulation tools

Task Number	Task or Subtask Title	Milestone Type	Milestone Number	Milestone Description	Milestone Verification Process	Anticipated Month	Anticipated Quarter
Verify reasonableness of project objectives							
0	Host virtual meeting with all project members and DOE staff	Milestone	0	Presentation delivered to DOE and review panel with all project members participating in a thorough technical overview presentation	Presentation delivered and feedback incorporated in work plans	1	1
Build appropriately sized lab device and preliminary model implementation							
1B	Identification and adaption of a continuum constitutive model	Milestone	1B	Finished mathematical description of continuum model(s) describing mechanical flow based on biomass physical and mechanical properties	Documentation of model is sent to lead organization	3	1
2A	Characterization of initial biomass feedstocks' mechanical properties	Milestone	2A.1	Complete characterization of initial biomass material PHYSICAL properties	All physical characterization protocols have been finished	6	2
2A	Characterization of initial biomass feedstocks' mechanical properties	Milestone	2A.2	Complete characterization of initial biomass material MECHANICAL properties	All mechanical characterization protocols have been finished	8	3
2B	Design and construction of re-scaled test device	Milestone	2B	Construction of scaled up cubical triaxial tester complete	When tester is able to produce raw data	11	4
		Go/No-Go Decision Point	Go/No-Go # 1	Demonstrate applicability of adapted constitutive models	Simulation predicts within 20% the mass flow rate of incipient flow and mass flow rate of biomass	12	4
Test lab device and complete model implementation							
3B	Implementation of additional material models	Milestone	3B.1	Complete implementation of comprehensive material models	When characterization data is fully populated into computer code	16	6
2D	Create additional biomass material	Milestone	2D	Process all material and complete characterization	All project materials produced and characterized	20	7
3B	Implementation of additional material models	Milestone	3B.2	Implement geometric models	When geometric model parameters are entered into computer code	22	8
		Go/No-Go Decision Point	Go/No-Go # 2	Simulate selected biomass flow through infeed/outfeed system	Simulation completes without programmatic errors (code errors) or physical law violations (i.e. calculation of negative energy)	25	8
Verification case study of predictive model							
4B	Verify Simulation Results	Milestone	4B.1	Verification case study biomass material produced, dried, and shipped.	Materials for study in-transit to case study site	26	9
4B	Verify Simulation Results	Milestone	4B.2a	Verification case study biomass pyrolyzed, biomass flow rate, and equipment energy data collected	Verification physical processing and data collection complete	28	10
4B	Verify Simulation Results	Milestone	4B.2b	Analysis of case study data complete and ready for TEA	All raw sensor data converted to units of natural language	31	11
		End of Project	Deliverable # 1	Laboratory protocols of biomass feedstock characterization pertaining to the design and operation of continuous biomass feeding systems	A collection of protocols is prepared as a package for feedstock analysis	36	12
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Regular milestones track progress

2-Approach, Technical

- Success Factors
  - New equipment and protocols that work well across the range of biomass materials to facilitate reliable quantification of biomass bulk flow properties
  - Output of models and simulations correlate with experimental results
  - Forest Concepts' and Amaron's design engineers find new/improved tools useful for real-time machine design feedback during design work
- Key Challenges
  - Engineering a bulk biomass material behavior measurement device with scale/size and functional capability for biomass feedstock materials (existing soil mechanics devices and shear cells do not produce adequate output)
  - 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-Progress/Results

Task: Identify and mitigate limitations of existing laboratory methods and equipment related to flowability measurements

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
- PSU (Puri) has refined system and analysis for more than 30 years
  - Existing CTT is too small (125cc) for most biomass
  - Major part of this project is to scale up device to accommodate biomass (15,625cc) rather than powders in existing devices
- A project output will be designs for commercial versions to be distributed by lab equipment firms

Other 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

3-Progress/Result
CTT Specifications

Functional

- 250mm Cubic sample holder
  - Established by experiment
- 0.001 to 2MPa (290psi)
  - Ranges from atmospheric hoppers to plug screw feeders
- 0.5% to saturated moisture
- Ambient to 150C temperature

Technical

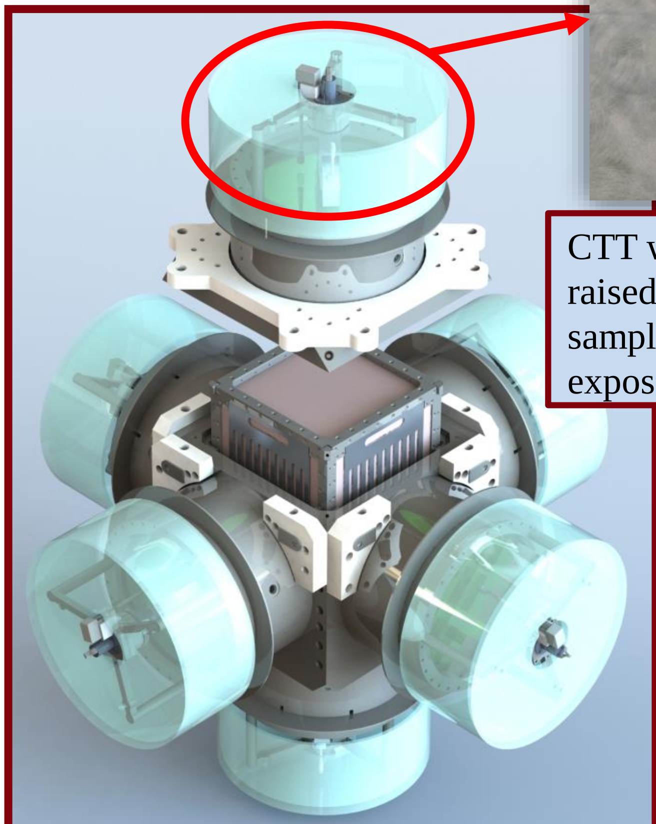
- Deformation Resolution
  - 0.1% linear strain (2mm)
- Membrane surface mapping
  - Minimum 9 points/face
  - Existing small CTTs use 1 point/face
- Membrane strain allowable
  - Minimum +/- 120mm from neutral plane
- Pressure resolution
  - Control +/- 0.6 kPa
  - Sense +/- 0.3 kPa
- Sampling frequency $\geq$ 1 Hz

Task Results

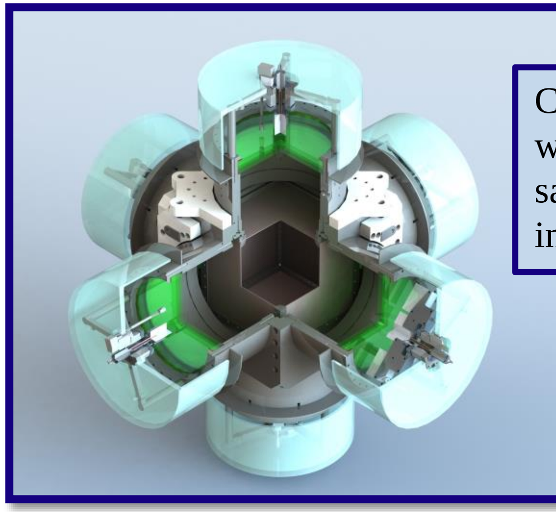
3-Progress/Result
CTT Design/Fab

Task Results implementation on track to reach Milestone 2B.4 “Construction of Scaled up CTT Complete” by end of May 2019

CTT design and engineering completed in SolidWorks® and components purchased or being manufactured



CTT with lid raised and sample holder exposed

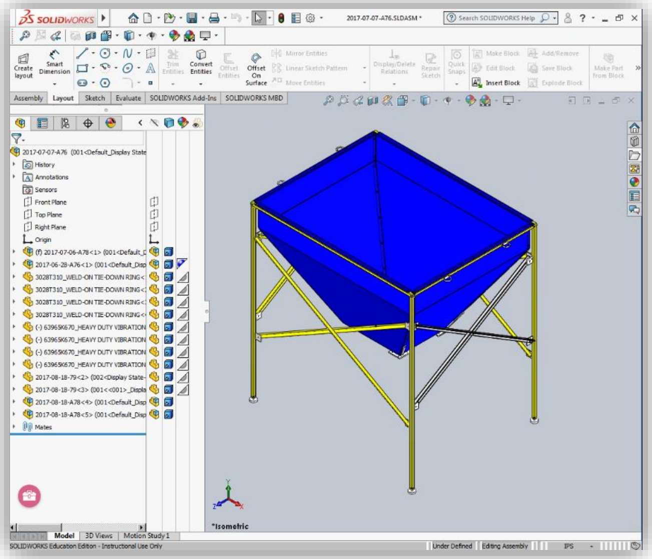


Cutaway of CTT with lid and sample chamber in place for test.

CTT User Interface

3-Progress/Results Modeling

Task: Modeling existing feedstock handling equipment



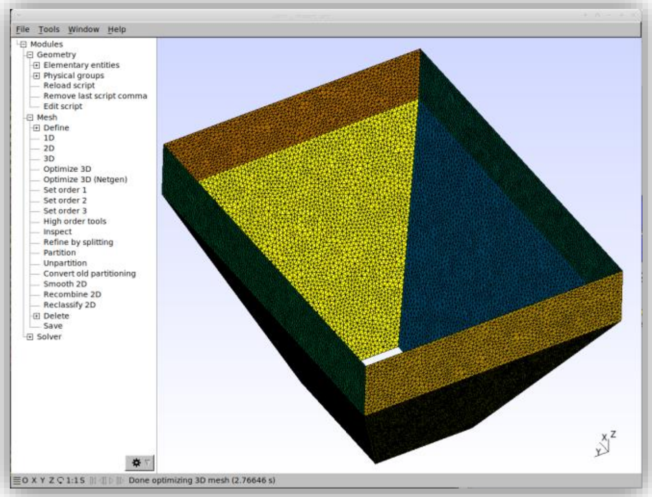
Milestones Reached:

- **1B Mathematical description…**

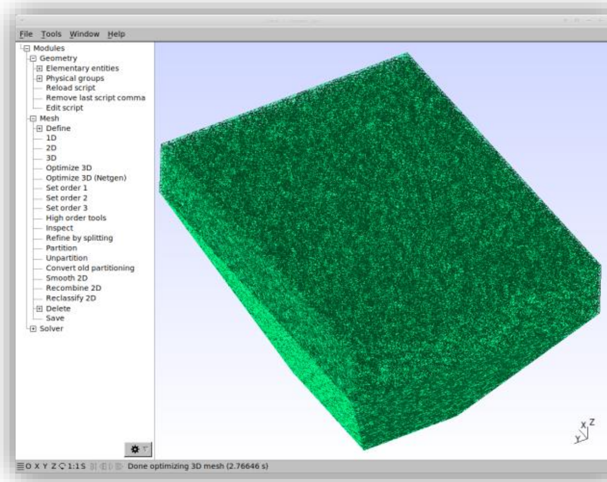
  of a continuum model describing mechanical flow and rheological behavior in continuous biomass feeding systems based on biomass feedstock's physical and mechanical properties.

- **2A.1 Initial biomass material physical…**

  properties of particle size distribution, true (particle) density, bulk density, tapped density, quantified as a function of moisture content ranging from 5% to 60% wet basis at ambient temperature.



From the existing hopper design of Forest Concepts facility (top), meshes for hopper wall (left), and loaded biomass (right) have been created



4-Relevance

Link to 2019 MYP

De-risk bioenergy production technologies through validated proof of performance at the pilot scale and to remove any additional barriers to commercialization.

- Ft-E Feedstock Quality: Monitoring and Impact on Preprocessing and Conversion Performance
  - Available data and information are extremely limited to identify the key physical and mechanical quality characteristics of feedstocks, and their impacts on feeding and preprocessing performance
- Ft-J Operational Reliability
  - Fundamental R&D is needed to identify the key feedstock quality factors affecting operational reliability
- ADO-A 3,4 Process Integration
  - Understanding process integration is essential to 3) generate predictive engineering models to guide process optimization and scale-up efforts and develop process control methodologies, and (4) devise equipment design parameters and operational considerations to improve reliability of operations and increase on-stream performance of equipment.
- At-B Analytical Tools and Capabilities for System-Level Analysis
  - High-quality analytical tools and models are needed to better understand bioenergy supply chain systems, linkages, and dependencies.
- And others

4-Relevance

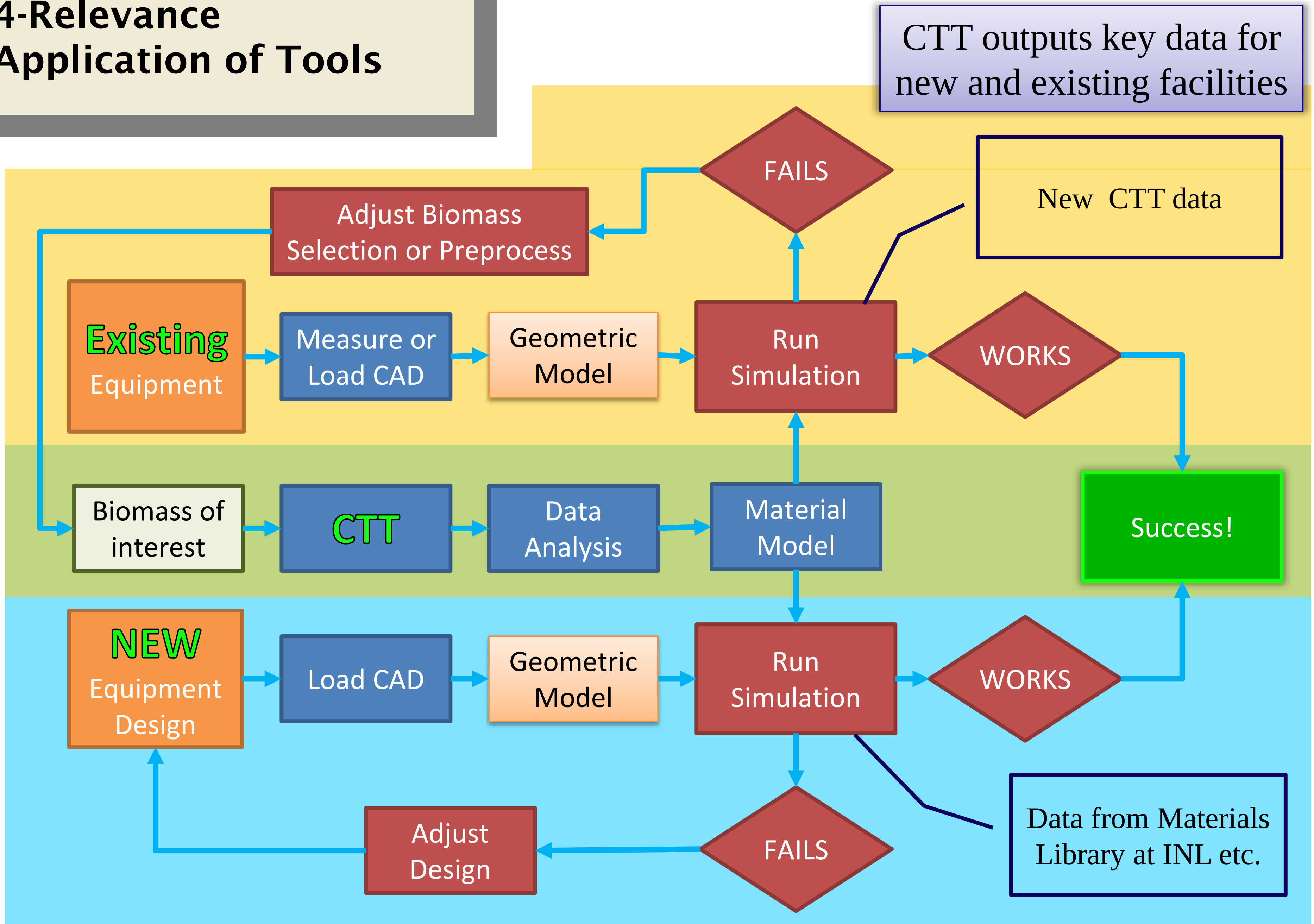
The bioenergy industry will be better off because:

- 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
- Libraries of biomass property data will be encouraged to be in INL library and/or KDF
- 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-Relevance
Application of Tools



5-Future Work

- Work plan specifies tasks with at least 1 project milestone each quarter
- Each Budget Period has at least 1 Go/No-Go measurable decision point
- The remaining budget is sufficient to complete the work

SPENT Through: Dec 31, 2018			
	Cost Share	Federal	Project
FC	$60,112	$226,105	$270,325
PSU	$3,992	$14,655	$25,201
TOTAL	64,104	$256,423	$320,527

5-Future Work
Go/No-Go BP 1

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Go/No-Go Decision Point 1:

We will **demonstrate the applicability of adapted constitutive models for bulk biomass feedstock handling** by modeling, simulation, and validation testing of the initial biomass feedstocks (Task 1A) and physical mechanism described in Task 4A. The Go-ahead decision will be given if the simulation accurately predicts (+/- 20%) the behavior of incipient flow and mass flow rate through the simple mechanism at 5, 25, and 50% moisture content, and two side slope angles for both initial biomass feedstocks.

5-Future Work
Go/No-Go BP 2

Milestone Summary Table					
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Go/No-Go Decision Point 2:

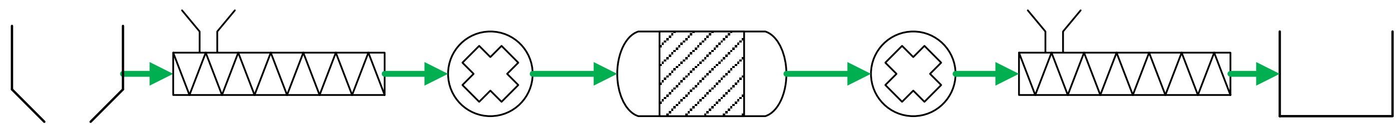
We will be able to **simulate how the selected biomass materials flow through a complete infeed system** including a hopper, auger, and a rotary airlock, modeled after Amaron Energy's existing biorefinery infeed equipment.

- The Go-ahead decision will be given when the simulations are able to complete without programmatic errors (code failures), or give physically impossible results (i.e. mass is created).
- Determination of the accuracy of the simulations is left to budget period 3

5-Future Work
Case study

Verification **CASE STUDY**
With **Amaron Energy**

Hopper	Auger	Airlock	Reactor	Airlock	Auger	Bin
Woody	Woody	Woody	Conversion	Biochar	Biochar	Biochar



Bridging	Mass flow, Power	Bridging		Bridging	Mass flow, Power	

First predict, then measure

5-Future Work
BP 3 Deliverables

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Deliverable 1: Laboratory protocols of biomass feedstock characterizations for design and operation of robust and reliable continuous biomass feeding system of an integrated biorefinery that can handle variety of biomass feedstocks. These lab protocols produce the coefficients needed by the computation model.

Deliverable 2: Novel test equipment for the purpose of characterization of the mechanical properties of biomass feedstocks at different environmental conditions including moisture content, pressure up to 350kPa and elevated temperature up to 150C.

Deliverable 3: A comprehensive **project report**.

Summary

- Overview
  - We're developing better design tools and biomass characterization methods for feedstock handling systems
  - Our audience includes engineers at equipment manufactures, EPC consultants, system integrators, and operating biorefineries
- Approach
  - Create biomass scale laboratory equipment (CTT)
  - Treat feedstock as a bulk material
- Progress/Results
  - A biomass-scale material properties measurement device is under construction
  - Modeling framework is nearly complete
- Relevance
  - We will enable engineers to design new systems that are less prone to failure and predict performance of existing systems with new feedstock materials.
- Future work
  - 75% of the project lies ahead

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

Additional Slides
Risks

Risk Identified			Mitigation Strategy		Current Status
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	Active
	New CTT measurement does not match PSU CTT measurement	Med	Adjust sample loading procedure	5/15/2019	Active
Task 3 Implement computational model					
	Models work for all unit operations	Med	Identify which operations are applicable	6/31/2020	Active

- Objectives of Modeling Efforts
  - Two biomass handling systems, i.e., auger conveyor and hopper, will be modeled.
  - Bulk biomass flow will be modeled with continuum scale constitutive models, namely elasto-plasticity models.
  - Drucker-Prager (DP) and Modified Cam-Clay (MCC) models will be adapted and compared.

Additional Slides

How?

- Analytical modeling of common biomass handling equipment.
- Analytical modeling of milled wood chip and corn stover biomass feedstocks
  - Development of lab methods and equipment for improved and accurate flowability properties and model coefficients
- Verifying models with existing Forest Concepts equipment using all proposed materials
- Verify tool set with material subset case study at Amaron Energy fast pyrolysis plant in Salt Lake City, UT

Additional Slides

Sophisticated Tools

Simple Tools

- Material Test Device(s)
- Material Characterization Protocols
- Engineering Software Tools
  - Fed by:
    - Material data measured according to protocols
    - Geometric and dynamic data of material handling system
  - Outputs critical design data
    - Drive Power required
    - Material flow rate
    - Hopper/chute angle
    - Etc.

Additional Slides

- On a scale of marbles to matted cat fur

  ... Most 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.
- “Cat Fur” biomass must be processed into a flowable format

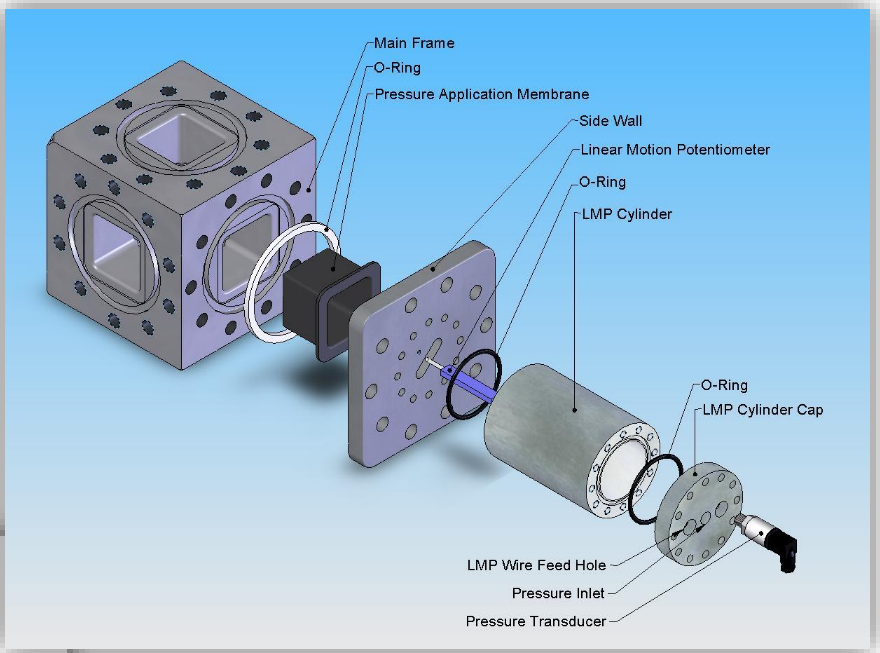
Additional Slides
The Flowability Problem

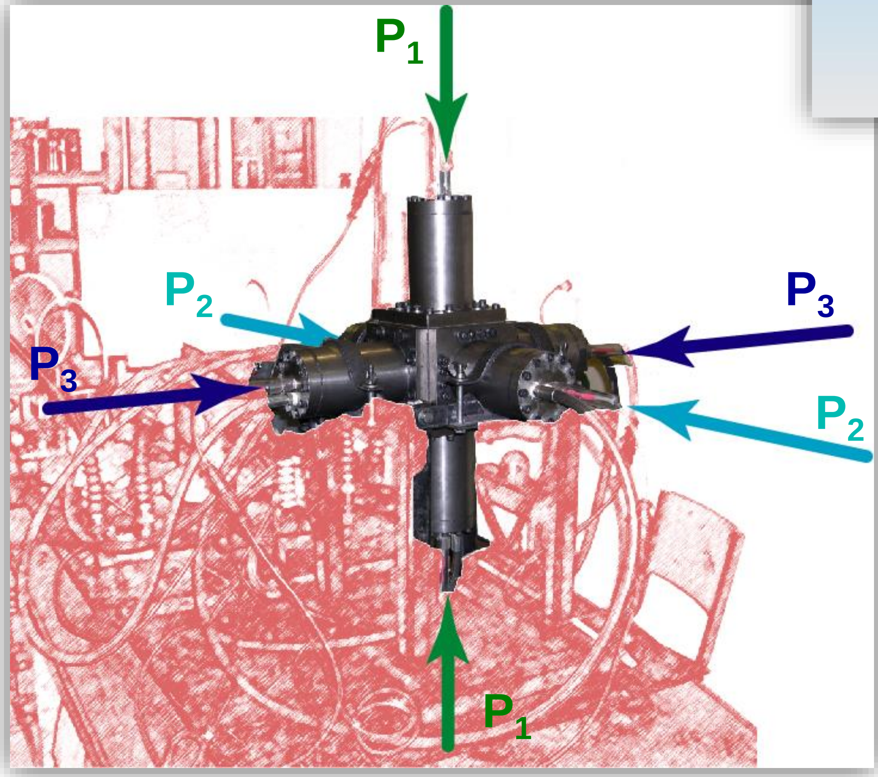
Woody Biomass

and Corn Stove

Additional Slides
Existing CTT at PSU

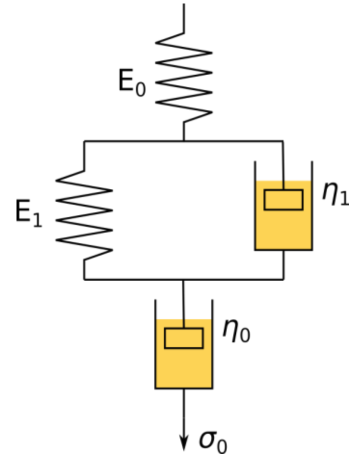
- 50mm maximum axial strain
- Single point displacement on each cube face
- 50 mm chamber





- Independent pressure control in three principal directions
- Measurement of the pressures and displacements in three orthogonal directions
- Measure of material behavior without confounding effect of die-wall friction direction

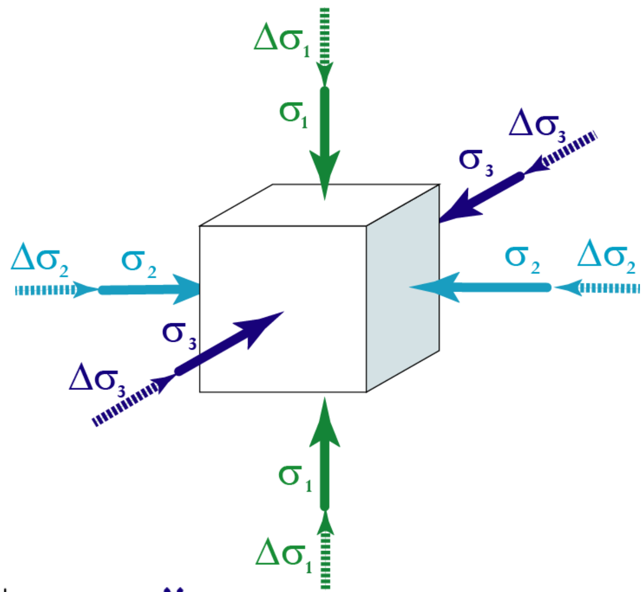
Additional Slides
CTT Testing types

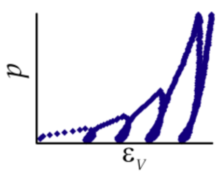


Key issues include initiation and continuation of biomass flow.

Two types of tests are used to capture the non-linear aspects of biomass physical properties

Hydrostatic Triaxial Compression (HTC) Test

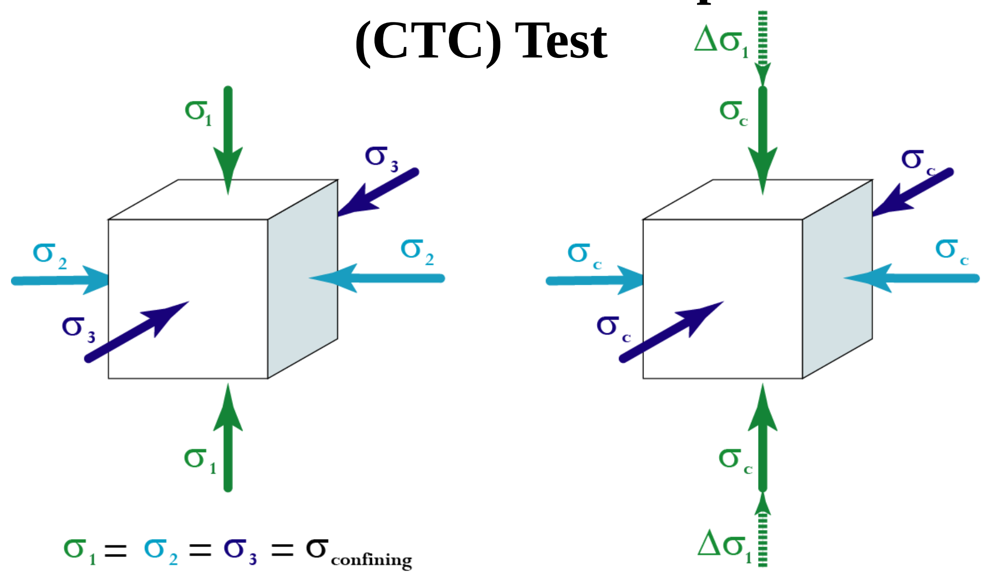




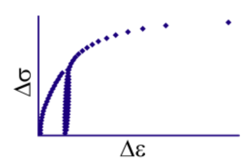
$\sigma_1 = \sigma_2 = \sigma_3$

$\Delta\sigma_1 = \Delta\sigma_2 = \Delta\sigma_3$

Conventional Triaxial Compression (CTC) Test



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



$\Delta\sigma_1 > 0$

$\Delta\sigma_2 = \Delta\sigma_3 = 0$

- Flow of bulk biomass can be described with stress state.
  - For example, when bulk biomass is at higher deviator (shear, q) stress state under a pressure (hydrostatic stress, p), then it is beyond a critical state and considered flowing.

$$q = M \cdot p \qquad (1)$$

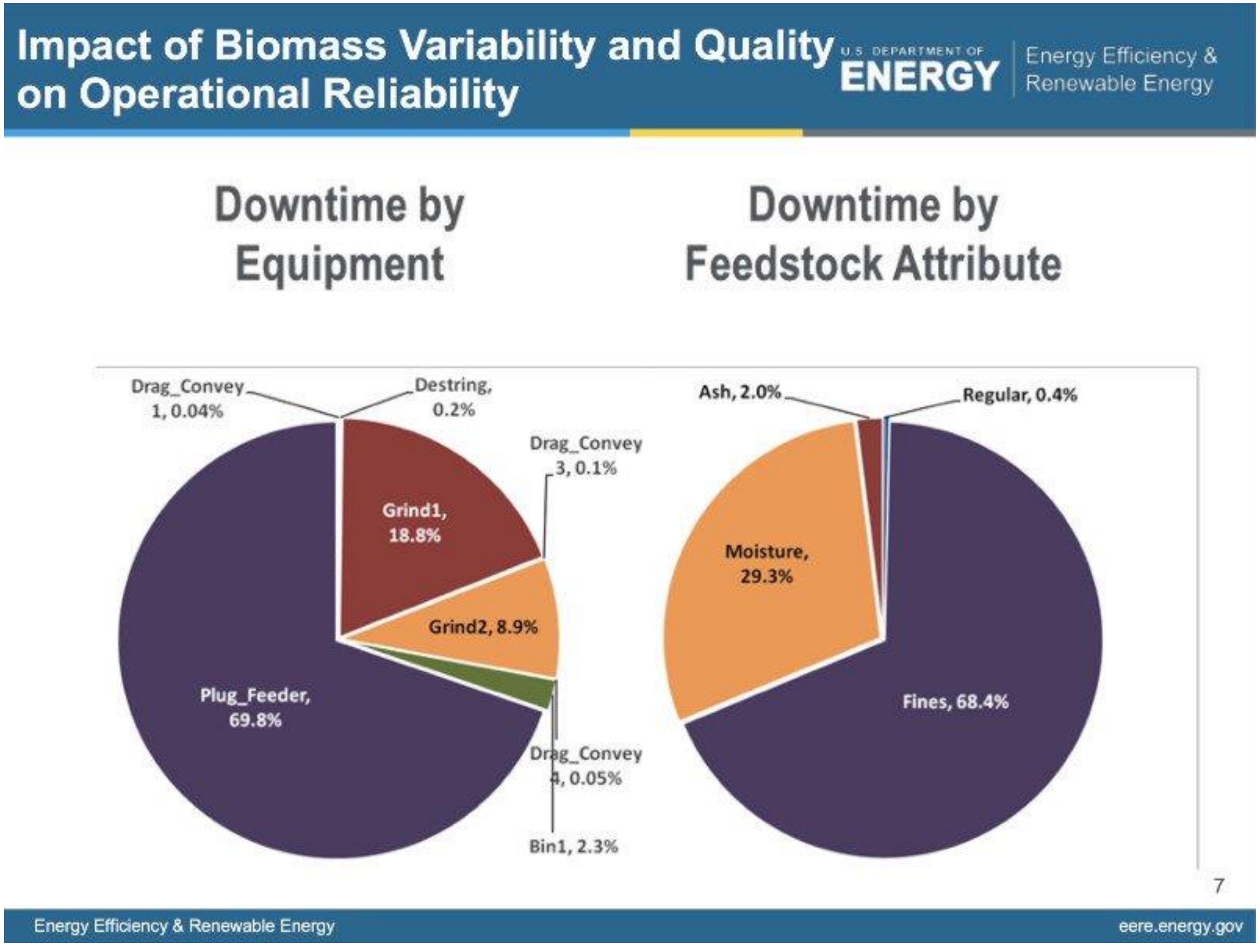
$$\Gamma = \kappa + \lambda \cdot \ln p \qquad (2)$$

where M, κ , and λ are material properties.

- These material properties can be determined using a cubical triaxial tester, with which bulk biomass' three dimensional deformation under a specific stress paths are measured.
- Drucker-Prager (DP) and Modified Cam-Clay (MCC) models will be adapted and compared.

Successful implementation relies on characterization of properties with minimal confounding effects of rigid walls.

Additional Slides
Relevance



Additional Slides
Relevance