2017 U.S. Department of Energy Bioenergy Technologies Office Project Peer Review

Thermochemical Feedstock Interface

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Goal Statement

**GOAL:** To enable a commercially viable biomass conversion value chain by evaluating the impacts of low-cost feedstocks, blends, and preprocessing approaches on the economics of thermochemical (TC) biofuels processes.

**Outcomes:**
- **Reduced risk** to biorefineries
- Biofuel **cost sensitivity** to feedstock composition
- In-feed **specifications**
- Compatibility of feedstocks with conversion technologies.

**Relevance:** This project provides insight to biorefineries regarding the financial viability of processing and conversion approaches with respect to feedstock choice, enabling the development of more flexible and market-responsive technologies.
Project Quad Chart Overview

Timeline
• Start: October 2015
• End: September 2018
• 50% complete

Barriers:
• Ft-E. “Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance”
• Ct-A. “Feedstock Variability.”

This project quantifies the impacts of feedstock physical and chemical characteristics on conversion performance.

Budget

<table>
<thead>
<tr>
<th>DOE Funded</th>
<th>FY 16 Costs</th>
<th>Total Planned Funding (FY 17-18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NREL</td>
<td>$1,014K</td>
<td>$2,000K</td>
</tr>
<tr>
<td>INL</td>
<td>$983K</td>
<td>$1730K</td>
</tr>
<tr>
<td>PNNL</td>
<td>$600K</td>
<td>$1200K</td>
</tr>
</tbody>
</table>

Partners
• NREL (40%)—Pyrolysis, catalytic pyrolysis, gasification/synthesis, feedstock screening, product analysis, modeling
• INL (35%)—Feedstock characterization, screening, handling, logistics, modeling
• PNNL (25%)—Bio-oil upgrading, fuel product analysis, modeling
• CCPC—Reactor modelling/optimization
• C3Bio—Lignin-modified poplars
• MIT/BP—Pyrolysis/Gasification modeling.
1 – Project Overview

*Feedstock is a dominant cost driver*

- **Feedstock $**
- **Feed handling**
- **Process conditions**
- **Yield/Quality**
- **Contaminants**

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**Bio-Oil**

**Vapor**

**Syngas**

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**Catalyst development**

**Process conditions**

**H₂ consumption**

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**TEA¹**

**Balance of plant**

**MFSP² $**

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¹techno-economic analyses

²minimum fuel selling price
1 – Project Overview

- Joint NREL/INL/PNNL Project
- Feedstock variability = risk (cost, composition, format)
- Impacts of blending are largely unknown
- Need to test commercially-relevant feedstocks at a process-relevant scale for meaningful models

Near-Term Objective: Determine feedstock blend properties required to meet BETO cost targets – $84/dry ton, $2.53/gasoline gallon equivalent (GGE) for fast pyrolysis (FP) + hydrotreating (HT) (2017), $2.96/GGE for catalytic FP (2018).

Long-Term Objective: Develop a feedstock/process co-optimization tool for regional blends matched to specific TC conversion technologies (feed composition + process conditions → fuel yields).
2 – Management Approach

Coordination, Communication, Feedback

- Designated leads at each lab, technology area contacts
- Joint Merit Review, AOP’s, Milestones, Go/No-Go’s (GNG)
- Open sharing of feedstocks, products, characterization and conversion data (bar coded)
- Monthly team meetings, annual site visits
- Dissemination of results—annual joint publication, public Webinar (Apr. 2016), conferences

Related BETO Projects: Feedstock Development, Core Conversion, Scale-Up
2 – Technical Approach

Technical and Economic Metrics

- Meet delivered feedstock cost target (<$84/dry ton for blend)
- Meet conversion yield/cost targets (0.27 $g_{fuel}/g_{biomass}$, $2.53/GGE$ for HT)
- Industrially-relevant (e.g. available at 800,000 tons/year)
- Meet sustainability targets (50% greenhouse gas reduction vs. fossil fuels)
- Variation in feedstock composition for robust predictive conversion models

FY16 Mid-Project GNG: Choose blend for FY17 FP+HT verification
FY17 Annual Milestone: Develop composition-based model to predict FP+HT yields
FY18 Objective: Validate model; determine acceptable feedstock properties
### Critical Success Factors

- **Demonstrate** technical targets met with low-cost feedstocks (Go/No-Go)
- **Quantify** process and MFSP sensitivity to feedstock
- **Enable** industry use of low-cost feedstocks and blends

### Challenges

- Many feedstocks and conversion technologies (variability, scaling)
- Extreme complexity of intermediates (e.g. bio-oil)
3 – Technical Accomplishment: Go/No-Go

**Goal:** Identify feedstock blend for the fast pyrolysis + hydrotreating FY17 Verification that meets all selection criteria.

**BETO Performance Goal:** “By 2017, validate at a pilot scale at least one technology pathway for hydrocarbon biofuel production…”

**Bench-Scale “Field-to-Fleet” Tests:**

- **INL:** Feedstock recommendations, processing (1000 kg), delivery, characterization, model development
- **NREL:** Bench-scale (10 kg) pyrolysis oil production, mass balances, product characterization
- **PNNL:** Bench-scale (1 L) hydrotreating to fuel blendstock, mass balances, product characterization
- **2014:** Baseline materials (pine, hybrid poplar, tulip poplar, switchgrass, corn stover, 2 blends)
- **2015:** Blends, replicates, linearity, OSB, pinion/juniper
- **2016:** Forest residues (FR), construction & demolition waste, air-classified FR, “least-cost” blends, miscanthus

Biomass-to-fuel yields range from 0.16-0.27 g\textsubscript{fuel}/g\textsubscript{biomass}.

- Pine, ac-Forest Residues, and Miscanthus all close to design case

- Need to evaluate *entire process* from feedstock to final products
Blends Behave Linearly

- Tested several blends (yield vs. % switchgrass shown)
- For FP+HT, blended feedstocks behave as the weighted sum of the components
- Conversion performance of new blends can be predicted based on yields of components
3 – Technical Accomplishment: GNG Met

**Blend Reduces Projected MFSP by $0.24/GGE**

Feedstock **cost** + process **yield** data + **linearity** of blends → optimal blend

“**Blend 3**” = 60% air-classified forest residues, 30% clean pine, 10% hybrid poplar

- Yields similar to clean pine and 2013 Jones et al. design case (pulpwood)
- Represents MFSP reduction of 7% over clean pine ($0.24/GGE)

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**“Blend 3” meets all selection criteria**

![Graph showing hydrocarbon product yield](image)

<table>
<thead>
<tr>
<th></th>
<th>Design Case</th>
<th>Pine</th>
<th>acFR</th>
<th>Hybrid Poplar</th>
<th>&quot;Blend 3&quot; expected</th>
<th>&quot;Blend 3&quot; measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon Product Yield (B_fuel/B_biomass)</td>
<td>0.273</td>
<td>0.259</td>
<td>0.274</td>
<td>0.249</td>
<td>0.267</td>
<td>0.284</td>
</tr>
</tbody>
</table>
Developed Composition-Based Model

Goal: Model the impact of feedstock on thermochemical conversion processes

Enable predictive capabilities for biorefinery TEA with respect to feedstock composition to improve TEA projections (with Analysis Tasks, 2.1.0.301-2)

- Developed predictive model for fast pyrolysis oil yield
- Predictors are volatile matter, lignin, and K+Na (>90% correlation)
- Hydrotreating performance is not predicted
- Enables selection of blends optimized for cost and performance

4 – Relevance

Ensuring a robust biomass conversion value chain...

• **Provides the link** between feedstock and conversion research and development (R&D) that is critical to “ensuring a fully integrated supply chain from field to fuel”

• **Addresses the R&D need** to understand “how feedstock variability and characteristics affect overall conversion performance”

We are quantifying the impacts of feedstock physical and chemical characteristics on conversion performance

Supports BETO FY17 Performance Goals:

- “…supply and logistics systems that can deliver feedstock to the conversion reactor throat at required conversion process in-feed specifications, at or below $84/dry ton…”

- “…deliver feedstocks and complete verification operations at pilot scale…”
4 – Relevance

This project provides insight into the cost trade-offs of processing and conversion approaches with respect to feedstock choice, enabling the development of more flexible and market-responsive technologies.

Targeted industry outcomes:

- Feedstocks and conversion are **co-optimized** (matched) to maximize process robustness and minimize MFSP
- Market-responsive biorefineries are enabled with **flexibility** to meet shifting market conditions (feedstock price, end product value)
5 – Future Work

**Shifting to other processes:**

- **Catalytic fast pyrolysis (CFP)**
  - Product yields, catalyst lifetime vs. feedstock, aerosols, feed cleanup vs. hot filtration
  - FY18 CFP verification blend

- **Hydrothermal liquefaction (HTL)**
  - Field-to-fuel tests using same feedstocks
  - Product yields vs. feedstock
  - Potential 1-step upgrading

- **Gasification (IDL)**
  - Inorganic byproducts, bed interactions, loading on syngas cleanup systems/catalysts
  - FY17 IDL verification blend
5 – Future Work

- Other predictive models
- Scaling
- Integrate into TEA and Biomass Scenario models
- Develop feedstock/process optimization tool:
  - (Feed Composition + Process Conditions → Fuel Yields)
- Support formation of FCIC:
  - Near-term industrial impact
  - Feeding, handling, “flowability”
  - Grading, specifications
Summary

• **Problem:** Understanding how low-cost feedstocks and **blends** impact conversion is key to reducing biofuel costs and ensuring **compatibility**

• **Approach:** **Testing** commercially-relevant feedstocks, blends, preprocessing at relevant scales and developing feedstock/conversion predictive **models**

• **Results:**
  - Feedstock **impacts** almost every part of the process: bio-oil yield & composition, fuel blendstock yield & composition, and $/GGE (**40% variation** in conversion cost)
  - Go/No-Go: Selected blend for FP+HT **verification** that meets cost and yield criteria (ac-FR\textsubscript{60} CP\textsubscript{30} HP\textsubscript{10})
  - Developed composition-based **model** to predict fast pyrolysis oil yield

• **Future:** Yield models for **other processes** and a feedstock/process **optimization tool** for market-responsive biorefineries
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*Project leads at respective labs

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Additional Peer Review Slides
Responses to 2015 Review Comments

1. Please evaluate the degree to which the project performers have communicated the projects history, the context in which the project fits into the portfolio, and its high level objectives.

Reviewer comments: (a) There is not a clear delineation between what is being done in this project and what is being done in the INL Feedstock Interface project. (b) The work in this project is closely related to the INL TC Feedstock Interface project. To avoid the perception of overlap and duplication of effort, DOE may want to combine these projects into a single, integrated project.

Response: Although reviewed separately this year, the Feedstock Interface projects at INL, NREL, and PNNL are very closely coordinated. Research plans are harmonized during each planning cycle, and results are shared between labs throughout the year and are used to develop the next year’s plans. This ensures that we make effective use of each Lab’s unique facilities and expertise while preventing duplication of efforts. Moving forward, the three projects will be formally reviewed as one for the purposes of the Merit Review process and likely for future Peer Reviews.

2. Please evaluate the degree to which (1) the project performers have made progress in reaching their objectives based on their project management plan, and (2) the project performers have described their most important accomplishments in achieving milestones, reaching technical targets, and overcoming technical barriers, (3) the project performers have clearly described the progress since the period of the last review.

Reviewer comments: Starting to develop large data base of products and upgrading, and accelerate this by rapid screening. But need to make sure that upgrading data is of sufficiently high quality.

Response: The current practice is to take samples from the “steady state” portion of each upgrading experiment (defined as the period when density of the oil is constant), analyze them separately, and then determine standard deviations within each run. Reported values are averages from these tests. Future upgrading experiments will include replicates of selected feedstocks to determine variability and the level of experimental error within the hydrotreatment process itself.

Reviewer comments: (a) Overall, the technical direction, results, and analysis make sense and were well presented. The ash influence, and means of at least quantifying it, really should be addressed - ash in switch grass is quite large and forms ash-oxides that "glass" onto the reactor walls and catalysts, but it's not as sever a problem from other biomass sources. (b) Suggest that future work highlight impact of the multitude of ash and ash-oxide constituents, and the type of ash glassing that occurs as a function of temperature in the 750-900 degC range.
Response: It is recognized that high-ash feedstocks can be problematic. In the case of gasification, we have observed this agglomeration/glassing with herbaceous feedstocks under certain process conditions. We will use this information to guide future experiments and to suggest feedstock formulations for the FY17 validation. Glass formation and bed slagging could certainly be an issue during gasification of high-ash feedstocks, especially those high in potassium. This, along with overall process efficiency, will likely limit the amount of herbaceous biomass in the blend proposed for the demonstration and the bed material used (e.g. olivine instead of silica sand to prevent bed agglomeration). In the proposed IDL design case, in addition to using olivine as a bed material, a small amount of MgO is added to sequester potassium and prevent glassing.

3. Please provide an overall assessment of the project based on the above criteria.

Reviewer comments: Relating feedstock properties to performance is a key and how to economically blend different feedstocks. Need to make final connection with producing a quality fuel. Quality data is key here--tightly material balanced results.

Response: Several quality indicators are assessed for the hydrocarbon fuel blendstocks produced in this project, such as simulated distillation, water content, total acid number, CHNS/O, viscosity, density, inorganic content, and heating value. Additionally, efforts are underway in Analysis projects to develop advanced biofuels blending models to estimate the value of biomass-derived blendstocks to refineries. We will coordinate with these projects to ensure the fuel quality data are relevant.


Presentations


Backup Slides
**Bench-Scale Feedstock Testing**

**NREL 2FBR Fast Pyrolysis Reactor**
- Feed rate: 0.5 kg/h
- Reactor: 5.0 cm ID
- T = 500 °C
- P = 1 atm.

**PNNL 40 mL Hydrotreating Reactor**
- Feed rate = 48 mL/h
- T = 220 °C/400 °C
- Reactor = 1.3 cm ID
- P = 1550 psi
Supply-cost curves for some key feedstocks (BT2)

2017 design case ($84/ton, 2014$)

Carpenter, Westover, Jablonski, Czernik, Green Chem., 2014, 16, 384, adapted from BT2
Armor of blending (e.g. wood)

- ~315 million tons projected available in 2022
- Projections depend upon assumptions;
  - EPA estimated that 164 million tons of C&D waste were generated in the U.S. in 2003 (EPA, 2011; Paper in Support of Final Rulemaking: Identification of Nonhazardous Secondary Materials That Are Solid Waste)

Woody feedstock supply as functions of projected average cost
- Combining woody feedstocks in blend accesses all 315 million tons for average cost of $85/dry ton ($2011).
- Blending feedstocks increases supply while reducing costs and risks
Formulated feedstocks

Move toward formulated feedstocks...to mitigate variability, reduce/stabilize cost
- commoditize feedstocks for biofuels production
- establish composition-based specifications (precedence for this is coal and animal feed industries)

Example blend *(from Jones, et al design report)*:

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Reactor Throat Feedstock Cost ($/dry ton)$^2$</th>
<th>Formulation Fraction (%)</th>
<th>% Ash Delivered to Throat of Conversion Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp</td>
<td>99.38</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>Logging Residues$^1$</td>
<td>74.83</td>
<td>35</td>
<td>1.5</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>80.54</td>
<td>10</td>
<td>2.8</td>
</tr>
<tr>
<td>C&amp;D Wastes</td>
<td>63.77</td>
<td>25</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Formulation Totals</strong></td>
<td><strong>80.00</strong></td>
<td><strong>100</strong></td>
<td><strong>1.1</strong></td>
</tr>
</tbody>
</table>

$^1$ residues do not include costs for harvest and collection; they are moved to landing while attached to the merchantable portion of the tree (for example, timber or pulpwood)

$^2$ includes ash mitigation

How will the process tolerate different feedstocks? Biomass resource development and process optimization need to be closely-coupled!
Verification blend

Key feedstock compositional properties and preliminary availability and cost (2014$) of blend components near Piedmont, SC. (Note 1: all properties are similar, except K+Na content. Note 2: these estimates have changed based upon BY16 data

<table>
<thead>
<tr>
<th>Blend 3</th>
<th>CP</th>
<th>acFR</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM</td>
<td>82.0</td>
<td>83.7</td>
<td>81.8</td>
</tr>
<tr>
<td>Ash</td>
<td>0.65</td>
<td>0.65</td>
<td>0.61</td>
</tr>
<tr>
<td>C</td>
<td>51.1</td>
<td>51.4</td>
<td>51.3</td>
</tr>
<tr>
<td>HHV</td>
<td>8982</td>
<td>9026</td>
<td>9020</td>
</tr>
<tr>
<td>Lignin</td>
<td>28.3</td>
<td>28.1</td>
<td>29.5</td>
</tr>
<tr>
<td>K+Na</td>
<td>1703</td>
<td>779</td>
<td>3430</td>
</tr>
<tr>
<td>Grower pay</td>
<td>23.30</td>
<td>22.0</td>
<td>14.20</td>
</tr>
<tr>
<td>Harvest/ collection</td>
<td>9.60</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Field prep</td>
<td>20.65</td>
<td>10.75</td>
<td>10.75+1.5</td>
</tr>
<tr>
<td>Transport etc.</td>
<td>13.95</td>
<td>13.95</td>
<td>13.95</td>
</tr>
<tr>
<td>In-plant receiving, prep, etc.</td>
<td>31.38</td>
<td>31.38</td>
<td>31.38</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$84.77</td>
<td>98.88</td>
<td>70.78</td>
</tr>
</tbody>
</table>

Production and Quality Assurance

• ≈ 4,000 kg of clean pine prepared at INL shipped to NREL (processed in NREL’s TCPDU in Q1)
• 30 barrel bags of blend 3 prepared (≈104 kg each for 3,100 kg total)
• 5 bags selected at intervals for intra-bag variability sampling (2 kg sampled from top and bottom of each bag for analysis)
• 5 separate bags selected for inter-bag variability sampling (contents of entire bag uniformly split for analysis)
• 25 of the 30 bags shipped to NREL for processing with TCPDU (inter-bag variability testing still in progress).
Ash Removal: Air Classification Alone

Equipment: Model #16 Air Classifier by Key Technology (Walla Wall, WA)

Process costs for air classification at 22.68 dt/hr of wood chips. Assumptions match BETO fast pyrolysis design report (Jones, et al., PNNL-23053; November 2013).

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Usage</th>
<th>Unit cost</th>
<th>Cost ($/dt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other fixed costs</td>
<td>100%</td>
<td>$55,000/yr</td>
<td>0.34</td>
</tr>
<tr>
<td>Total capital investment</td>
<td>100%</td>
<td>$1,124,000</td>
<td>0.21</td>
</tr>
<tr>
<td>Salaries</td>
<td>62%</td>
<td>$52,700/yr</td>
<td>0.18</td>
</tr>
<tr>
<td>Electricity for blowers</td>
<td>2@15 HP</td>
<td>$0.10/kWh</td>
<td>0.10</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>0.83</td>
</tr>
</tbody>
</table>

Effectiveness and costs of air classifying logging residue wood chips at 22.68 dt/hr. Cost associated with yield loss is assumed to be $20/dt of lost organic material.

<table>
<thead>
<tr>
<th>Fan VFD</th>
<th>Total mass (%)</th>
<th>Organic loss (%)</th>
<th>Organic loss (dt)</th>
<th>Yield loss cost ($/dt*)</th>
<th>AAEMS+P removal (%)</th>
<th>Total cost ($/dt*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>6.7%</td>
<td>6.3%</td>
<td>1.42</td>
<td>$1.34</td>
<td>42%</td>
<td>$2.17</td>
</tr>
<tr>
<td>12 Hz</td>
<td>9.1%</td>
<td>8.7%</td>
<td>1.97</td>
<td>$1.90</td>
<td>49%</td>
<td>$2.73</td>
</tr>
</tbody>
</table>

New Resources

Figure ES.4 | Combined potential supplies from forestry, wastes, and agricultural resources, base case, 2040°

Model Development

Pure feedstocks (10)
1. Clean pine (CP) (5x)
2. Hybrid poplar (HP)
3. Tulip poplar (TP)
4. Piñon/juniper (PJ)
5. Oriented strand board (OSB)
6. Corn stover (CS)
7. Switchgrass (SG)
8. Construction & demolition waste (C&D-0.5mm)
9. Air classified forest residues (acFR-0.5mm)
10. Miscanthus (MS-0.5mm)
   • CP-0.5mm
   • SG-450 °C

Material were ground to 2 mm and temperature of pyrolysis reactor was 500 °C, except as noted

Blends (8)
1. CP₂HP₁
2. CP₁TP₁SG₁ (2x)
3. CP₈SOB₂
4. CP₇OSB₂SG₁
5. CP₄OSB₂SG₄
6. CP₃₀acFR₆₀HP₁₀⁻⁰.₅mm
7. CP₄₅FR₂₅C&D₃₀⁻⁰.₅mm
8. CP₃₀FR₃₅C&D₂₅SG₁₀⁻⁰.₅mm

Response variables
• Dry, ash-free pyrolysis oil yield
• Ash-free pyrolysis char yield
• Dry hydrotreating oil yield

Independent tests (pure feedstocks): 10
Effective replicates: 13
Predictor variables: 22
• Ultimate (C, H, N, S, O, HHV, LLV)
• Proximate (Volatiles, Fixed C, Ash)
• Ash speciation (Al, Ca, K, Mg, Na, S, Si)
• Composition (H₂O Ext, Protein, Arabinan, Glucan, Lignin)
Herbaceous and woody energy

Figure 4.5 | Production of herbaceous and woody energy crops under ≤$40, ≤$60, and ≤$80 offered farmgate prices under a base-case (1%) scenario for select years.

Figure ES.5 | Potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside in 2040 (base case)
Figure ES.6 | Combined potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside for select years (base case) \textsuperscript{11}
2016

Figure 2-23: Cost projection breakdown for the fast pyrolysis design case

Based on the 2013 design case for fast pyrolysis, Figure 2-23 shows that a total potential cost reduction of 75% can be achieved between 2009 and 2017 with improvements in all four R&D areas shown in the legend.
## Project timeline:

<table>
<thead>
<tr>
<th>SOT</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17 Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulpwood ($120/ton)</strong></td>
<td><strong>Plan &gt;</strong> Test 8 baseline feedstocks, preliminary conversion model</td>
<td><strong>Test 10 blends, propose 1-3 blends for demo, validate model</strong></td>
<td><strong>Validate yield model with 1-3 blends, optimize conversion</strong></td>
<td><strong>Demonstration with blended feedstock ($80/ton)</strong></td>
</tr>
<tr>
<td><strong>Materials used &gt;</strong> Pine, poplar, corn stover, switchgrass, two blends</td>
<td>Combinations of pine, poplar, log. res., switchgrass, MSW</td>
<td>1-3 blends (per FY15 results)</td>
<td>1 blend for optimized conversion conditions</td>
<td></td>
</tr>
<tr>
<td><strong>Carbon eff. (% feed carbon)</strong> FP wood: 58-60% HT wood: ?</td>
<td></td>
<td></td>
<td>FP blend: 69% HT blend: 47%</td>
<td></td>
</tr>
<tr>
<td><strong>Example spec: Total ash &lt; 1%</strong> Propose &gt; 1%, but limit specific elements (N, S, K, P, etc.)</td>
<td>Set initial chemical and physical specifications</td>
<td>Finalize specifications for demonstration</td>
<td>Update specifications as needed</td>
<td></td>
</tr>
</tbody>
</table>