NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) 2017 Project Peer Review

# Integration & Scale-Up (WBS 2.4.1.301) Thermochemical Capital Equipment (WBS 2.4.1.302)

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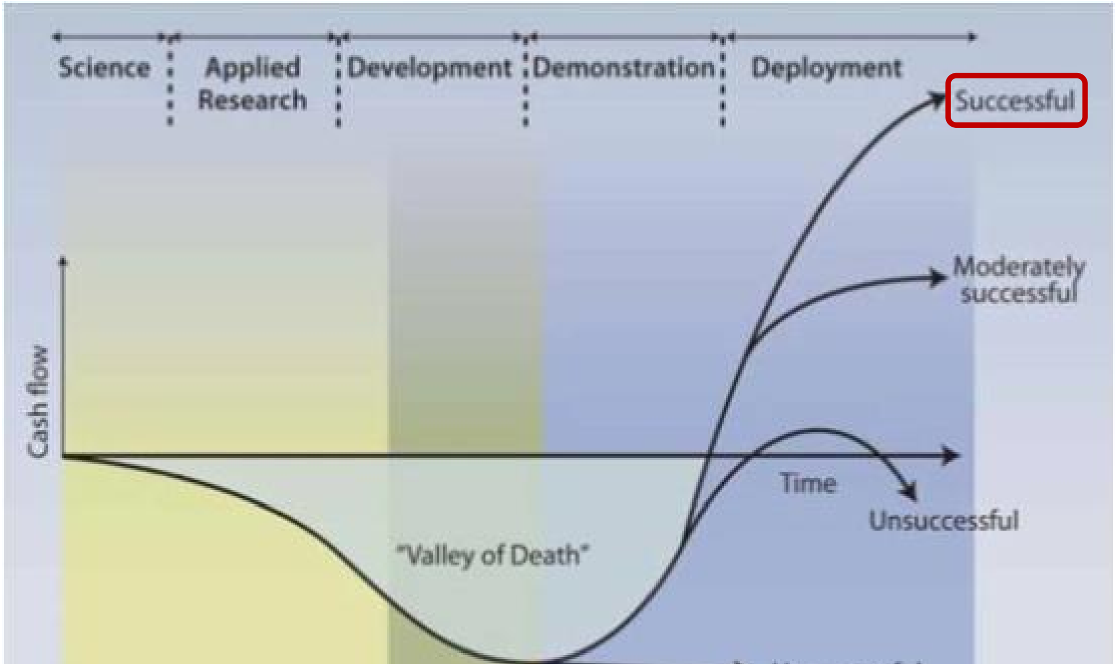
This presentation does not contain any proprietary, confidential, or otherwise restricted information

# Goal Statement

**Reduce the cost and risk of industrial scale-up to enable commercialization of thermochemical biomass conversion technologies.**

- **Verify performance** of unit operations, engineering designs, feedstocks, catalysts, and other thermochemical technologies at the pilot scale by operating the system at steady-state for extended period of time.
- Identify and **develop engineering solutions** to overcome scale-up effects, improve operations, and reduce cost.
- **Provide pilot scale data** for technoeconomic analysis (TEA) and reactor models.



California Energy Commission

# Quad Chart Overview

## Timeline

Project start: 2014

Project end: 2017

Percent complete: 83%

Type: On-going project

## Barriers

- Tt-K. Bio-Oil Pathways Process Integration
  - Integration of feedstock, conversion, and bio-oil upgrading technologies
- Tt-H. Bio-Oil Intermediate Stabilization and Vapor Cleanup
  - Design and operation of pilot-scale ex-situ catalytic fast pyrolysis process

## Budget

| | Total Costs FY 12 – FY 14 | FY 15 Costs | FY 16 Costs | Total Planned Funding FY 17-Project End Date |
|---|---|---|---|---|
| DOE Funded Task | $6.6M | $2.1M | $2.5M | $2.5M |
| DOE Funded Capital | $3M | - | - | $4.4M |

## Partners

- Collaborations with:
  - PNNL 2.3.1.407 Hydroprocessing of pyrolysis oils
  - PNNL/NREL 2.1.0.301-302 Thermochemical Platform Analysis
  - ORNL 2.4.2.301 Materials Degradation In Biomass-Derived Oils
  - INL 2.2.1.301 Feedstock Interface
  - NREL/PNNL/ANL/ORNL/INL 2.5.1.301-305 CCPC

# TCPDU Benefits to Industry and Research

## Reduces cost and risk to industry

- Pilot plants are expensive to build, maintain, and operate.
- Ability to identify and solve technical barriers necessary for commercialization.

## Collaboration with BETO tasks

- Understanding of bench-scale research efforts and technoeconomics improve design & operation.
- Design constraints and operational data from TCPDU provided to other tasks to guide research.

## Flexibility

- Capable of multiple thermochemical pathways:
  - Fast pyrolysis
  - Ex-situ catalytic fast pyrolysis
  - Indirect liquefaction
- Complements in-situ capabilities of other BETO funded pilot plants.
- Highly instrumented.
- Adapt unit operations to accommodate changing pathways.
- Industrial partners can connect equipment to test proprietary technologies.

## Dedicated pilot plant team

- Trained operators reduce downtime and increase safety.
- Continuous improvement of process through knowledge of plant.

# TCPDU Proven Pilot-Scale Capabilities

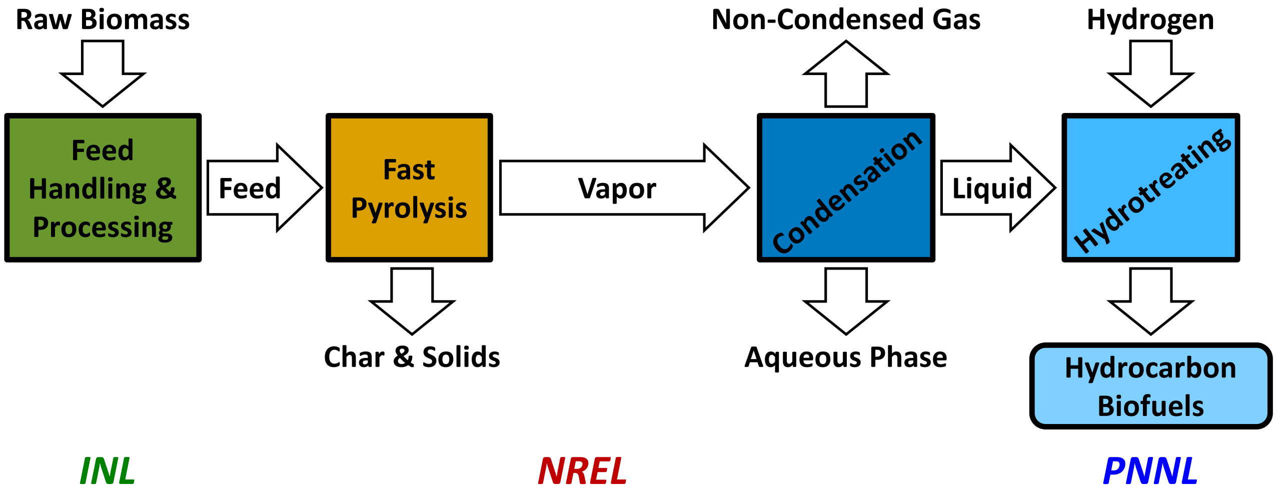
## History of TCPDU and it's contributions to industry and BETO:

- Late 1990s: First pilot-scale reactor installed
- 2008: Produced > 100 gal of pyrolysis oil for a DOE FOA
- 2010: Pyrolysis oil produced for CRADA with Petrobras
- 2010-11: Constructed Hot Gas Filter and tested on pyrolysis oil[1]
- 2012: BETO pathway verifications for mixed alcohols:
  - DOW CRADA: 120 hours
  - BETO demonstration[2]: 150 hours
- 2013: Provided syngas for Lanzatech CRADA upgrading technology
- FY13 & FY14 upgrades provided:
  - Improved mass balances
  - Reduction in operational problems, downtime, and maintenance
  - Enhanced safety

1. Baldwin, R.M.; Feik, C.J., **2013** "Bio-oil Stabilization and Upgrading by Hot Gas Filtration" *Energy Fuels*, 27, p. 3224.
2. Bain, R.L.; Magrini-Bair, K.A.; Hensley, J.E.; Jablonski, W.S.; Smith, K.M; Gaston, K.R., & Yung, M.M., **2014** "Pilot Scale Production of Mixed Alcohol from Wood" *IECR*, 53, p. 2204.

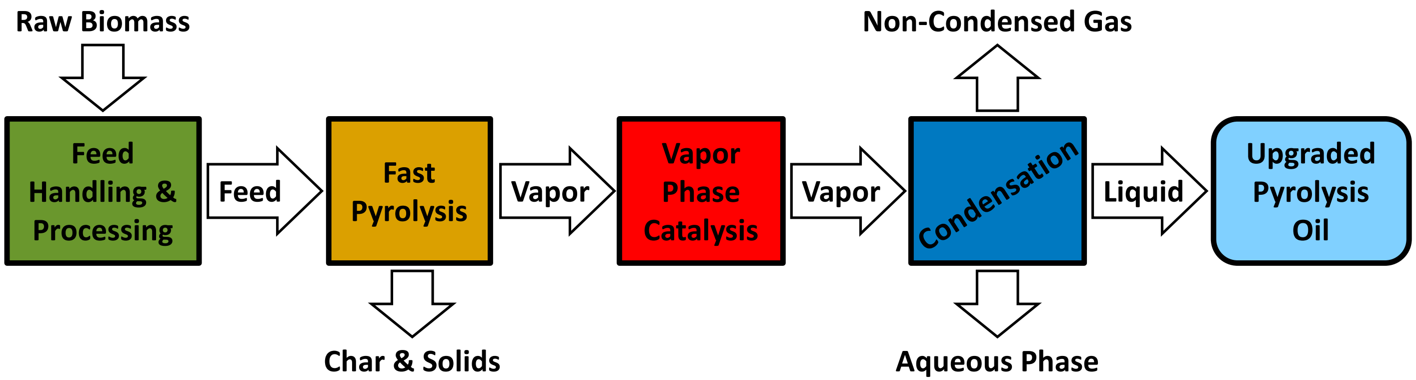
# 1 – Project Overview
# Parallel Efforts for Pilot-Scale Pyrolysis Pathways

## Fast Pyrolysis and Hydrotreating (FP)




**FY17 Goal:**
Pilot-scale verification of pathway from feedstock to fuel meeting BETO FY17 cost targets.

## Ex-situ Catalytic Fast Pyrolysis (CFP)

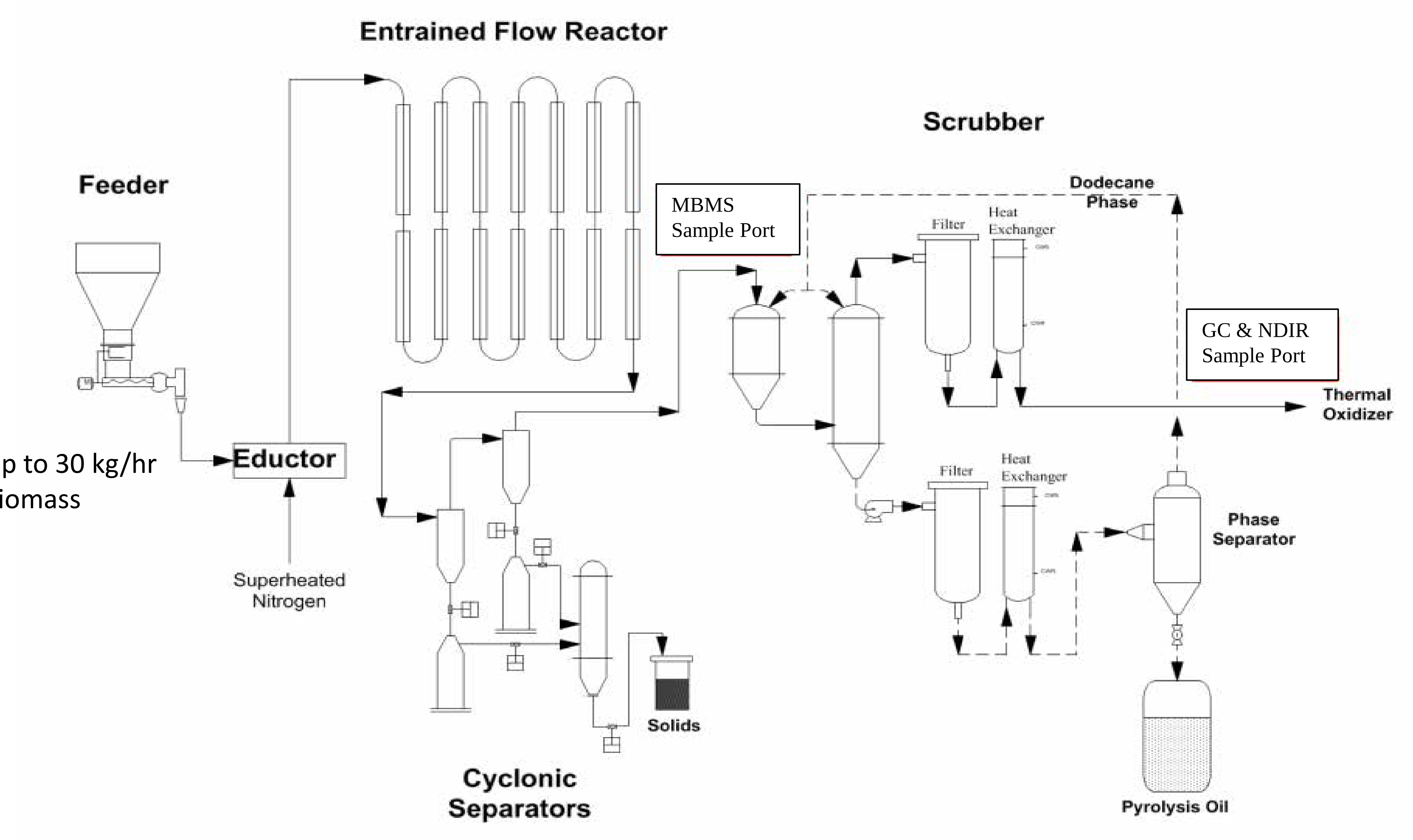



**FY18 Goal:**
Demonstrate pilot-scale capability to produce upgraded oils equivalent to bench-scale.

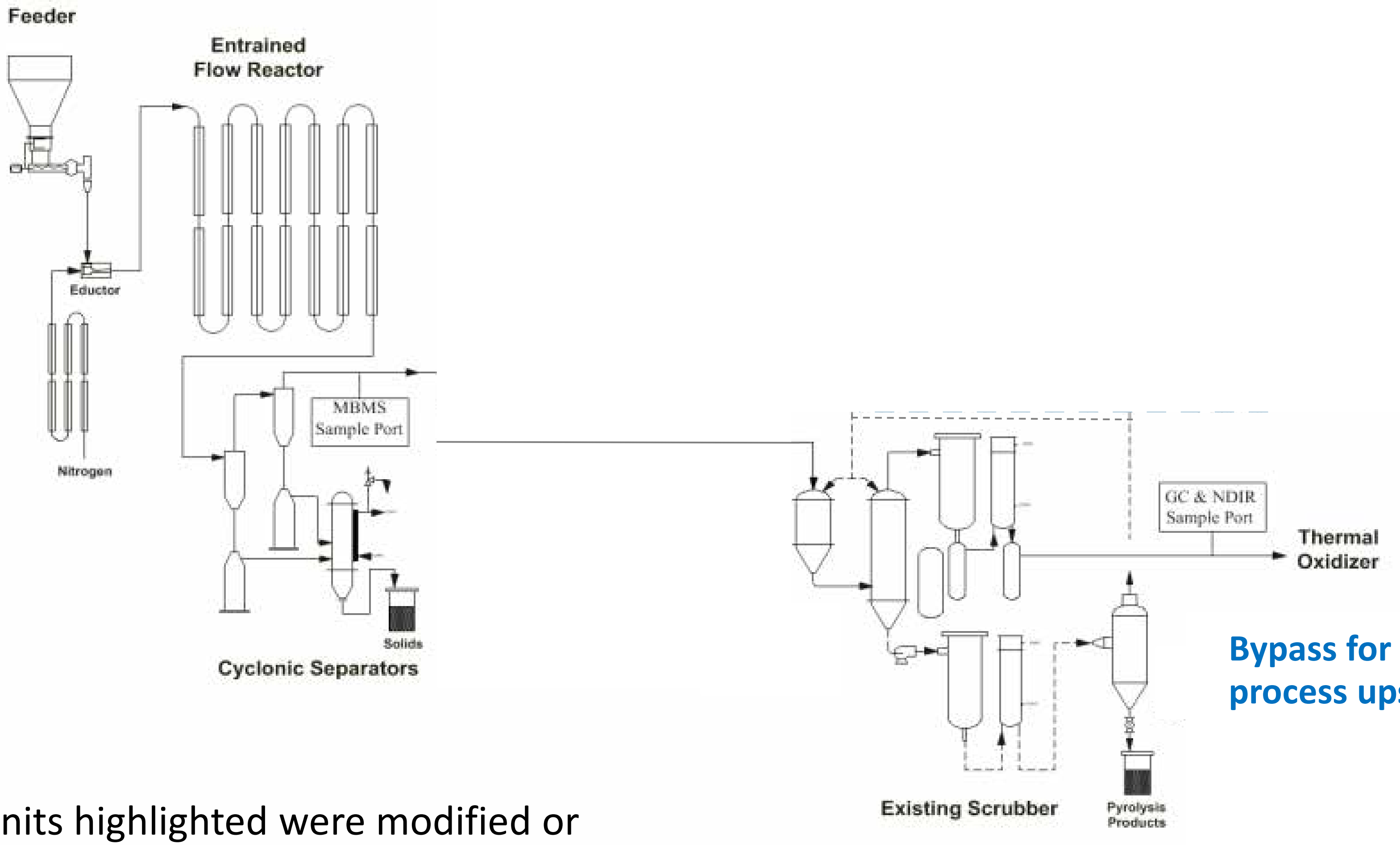
**FY22 Goal:**
Pilot-scale verification of pathway from feedstock to fuel meeting BETO FY22 cost targets.

# TCPDU Fast Pyrolysis Flow Diagram

Up to 30 kg/hr biomass



# TCPDU Ex-situ CFP Flow Diagram

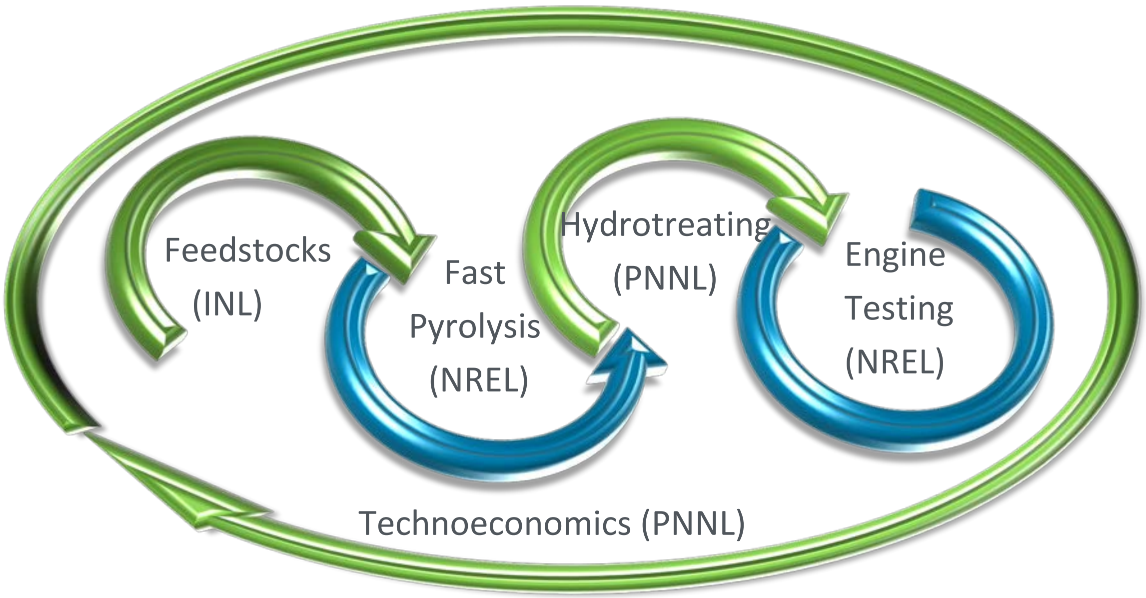



**Bypass for startup and process upsets**

Units highlighted were modified or created for use in ex-situ CFP

# 1 – Technical Approach: 2017 Fast Pyrolysis Verification
## Enable Achievement of BETO 2017 Performance Goal

**5 major components of the verification:**




**BETO FY17 Performance Goal:**

*"Validate at a pilot scale at least one technology pathway for hydrocarbon biofuel production at a mature modeled price of $3/GGE with GHG emissions reduction of 50% or more compared to petroleum fuel."* - BETO MYPP 2016

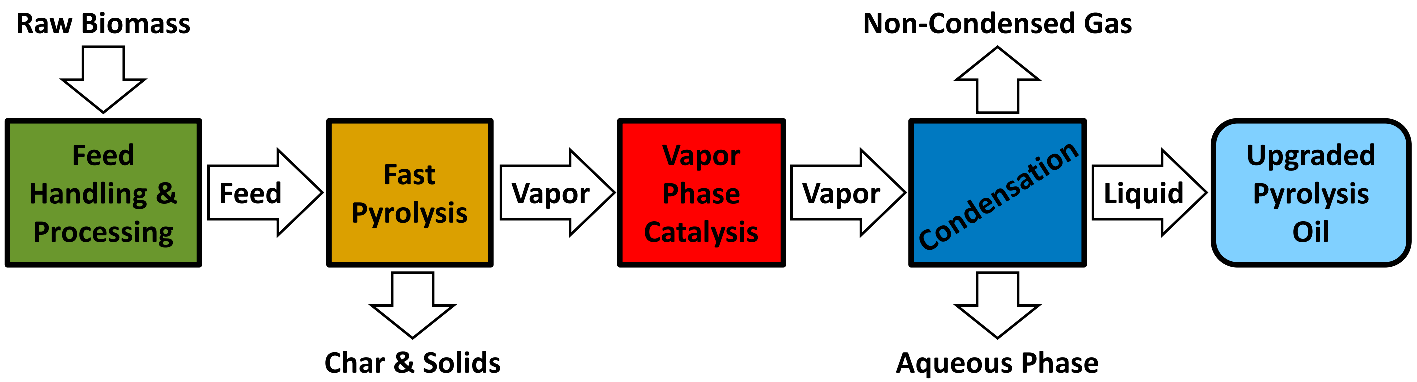
**Critical Success Factors:**

- **Product yields and oil properties meeting design case targets and hydrotreating specifications.**
- Sufficient fast pyrolysis oil produced for engine testing of final biofuels.
- Steady-state operation without upsets and consistent mass balances (>95%) and oil properties throughout run.

**Challenges:**

- **Multi-lab coordination** with several material transfers for FY17 verification. Mitigated by frequent communication with the tasks at the other national labs.
- Feedstocks previously untested in TCPDU. Mitigated by conducting small runs in TCPDU with verification feedstocks.

# 1 – Technical Approach: Ex-Situ Catalytic Fast Pyrolysis
# Enable Achievement of BETO 2022 Performance Goal




**BETO 2022 Performance Goal:**

*"By 2022, validate hydrocarbon biofuels production from at least two additional technology pathways at pilot or demonstration scale"* -BETO MYPP 2016

**Critical Success Factors:**

**Demonstrate TCPDU ex-situ CFP capability:**

- Meets design specifications and catalyst requirements.
- Can be controllably operated at specified conditions continuously for min. 8 hours.
- Product yield and properties comparable to bench-scale.

**Challenges:**

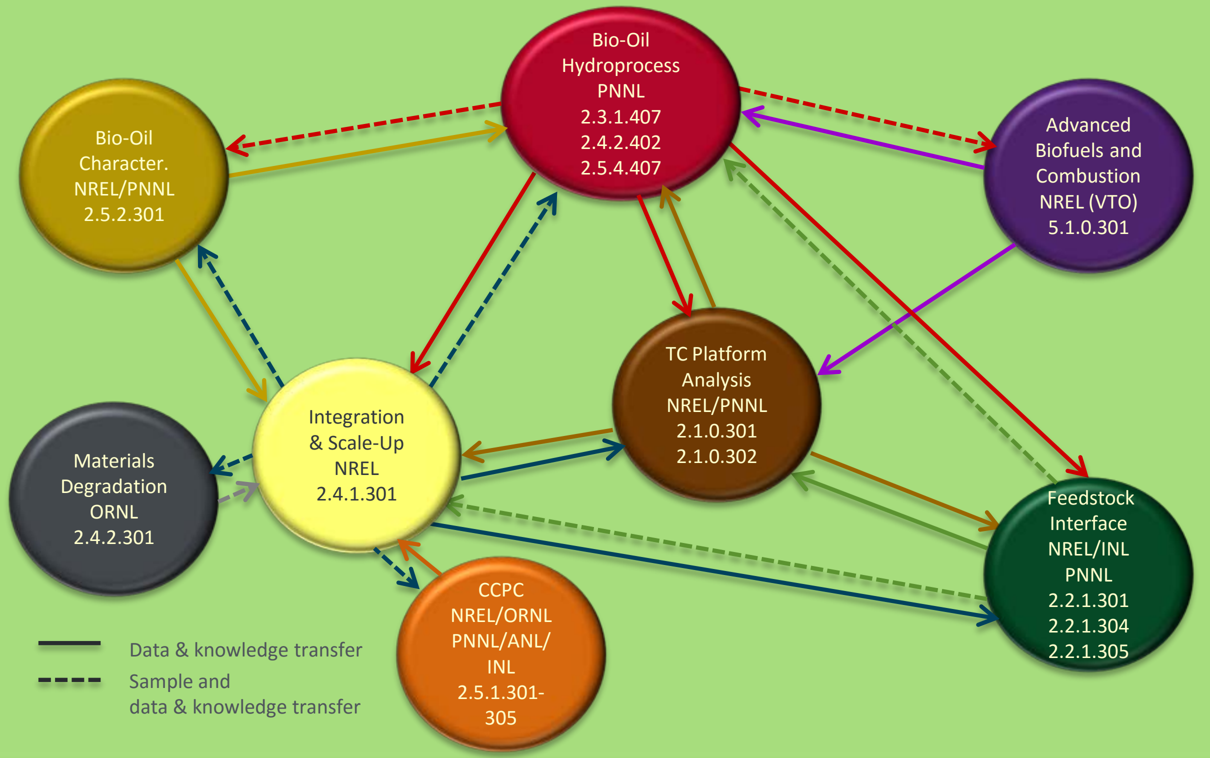
- **Design of new unit operations prior to catalyst down-selection.** Mitigated by working with ChemCatBio to define design criteria and designed large operational range as possible.
- Maintaining existing TCPDU capabilities. Mitigated by working with PSRI to redesign R-cubed for ex-situ CFP and syngas reforming.

# 2 – Management Approach

**Management approach tailored to specific work effort and parties involved to monitor progress and mitigate potential risks early.**

## Fast Pyrolysis Verification:

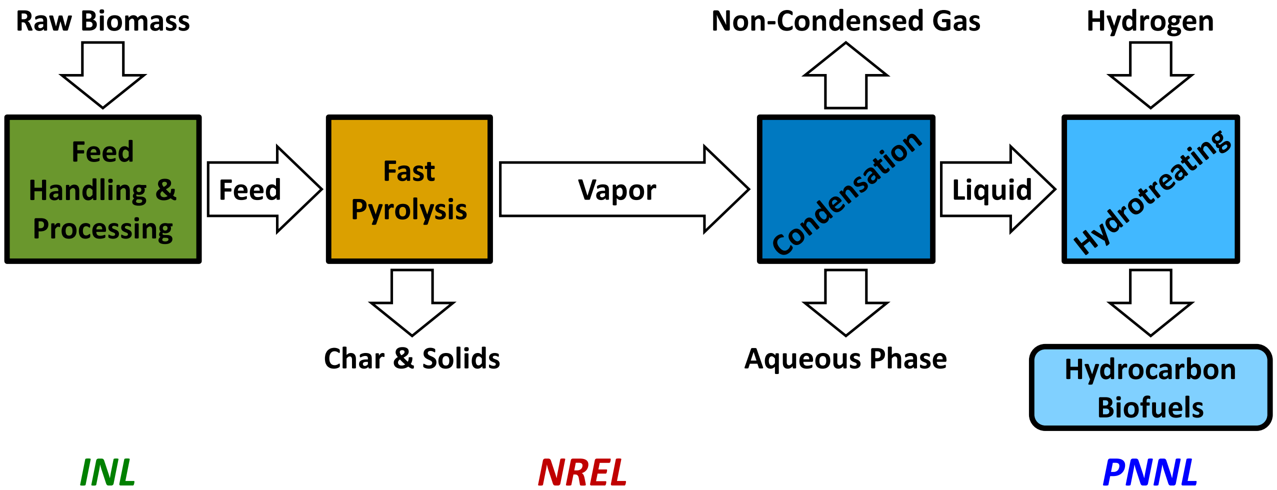
- Project plan for entire verification effort developed and updated regularly.
- **Bi-weekly conference calls with NREL, PNNL, INL, and BETO.**
- Logistics of sample transfers defined in advance.



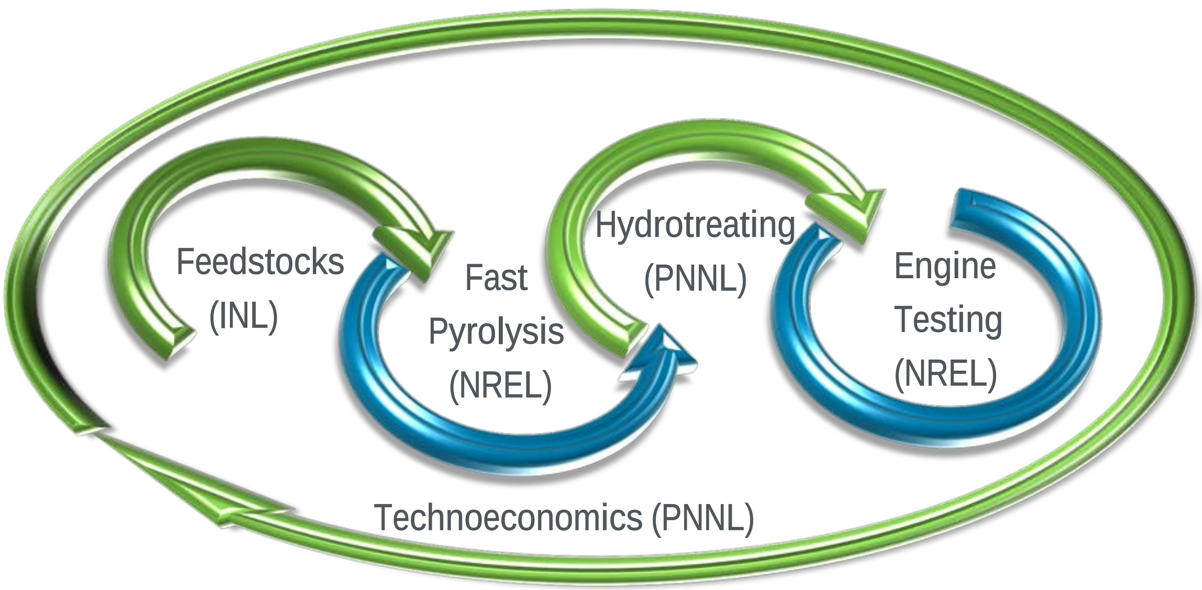

## Ex-Situ CFP Verification:

- ChemCatBio provided design input.
- Final reactor and catalyst specifications provided back to ChemCatBio.
- Safety review prior to fabrication.
- Knowledge transfer meetings with ChemCatBio including DCR team.
- Weekly updates from subcontractors.
- **Fabrication inspections by NREL engineers prior to delivery of units.**
- Site acceptance test after delivery.

# Achieved Design Case Targets for Fast Pyrolysis Oils




**FY17 Goal:**
Pilot-scale verification of pathway from feedstock to fuel meeting BETO FY17 cost targets.



# 3 - Technical Accomplishments: Fast Pyrolysis Verification
## Risks Reduced by Identifying and Resolving Issues Early

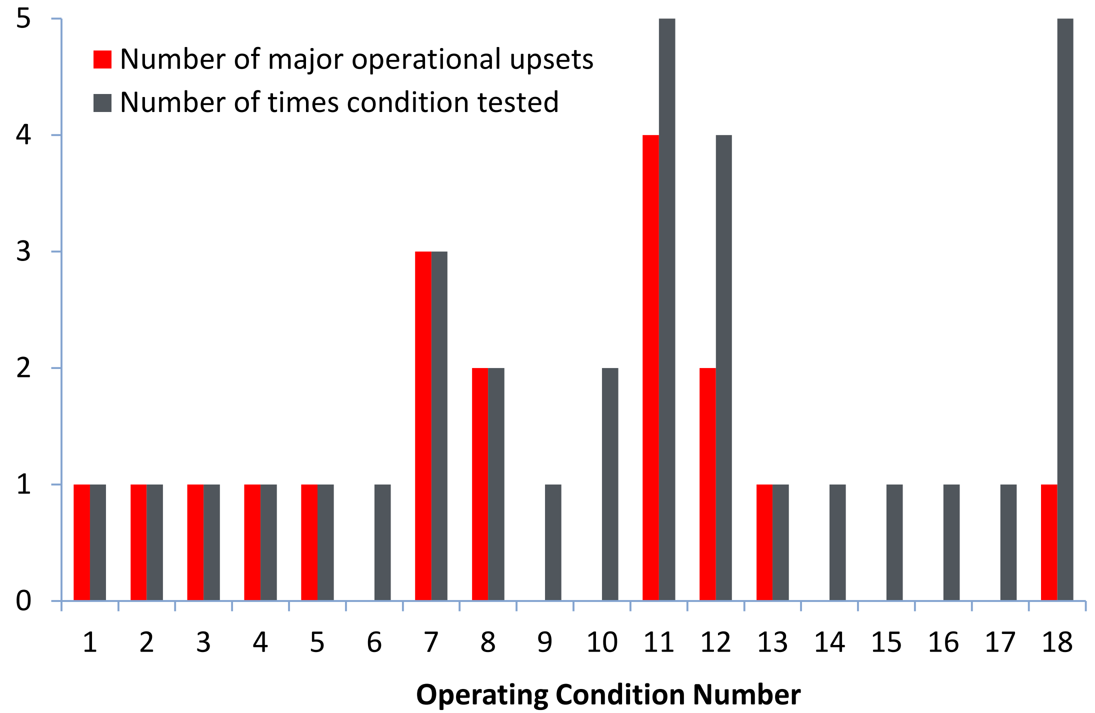
Background: During initial operation of feedstock and operating condition tests in TCPDU, char bridged in the cyclones, leading to shutdowns and intensive maintenance.

Approach: Designed experiments to test various hypothesis. Tested over 30 operating conditions using online MBMS and char characterizations to evaluate cause of bridging.

Results:

- Primary cause was **under-pyrolyzing.**
- Secondary cause was **char particle size and shape** coupled with current cyclone design.
- Longer residence times, increased valve temperatures, and increased transfer line size resolved bridging.
- **No bridging issues since implementing solutions.**

**Lesson Learned:**
Conducting early initial full scale tests at verification conditions allows for the **discovery and mitigation of potential risks** in advance of verification.



# 3 - Technical Accomplishments: Fast Pyrolysis Verification
# Confirmed Verification Targets Achievable at Pilot-Scale

Goal: Confirm operability, yield and oil properties for potential verification feedstocks.

Results:

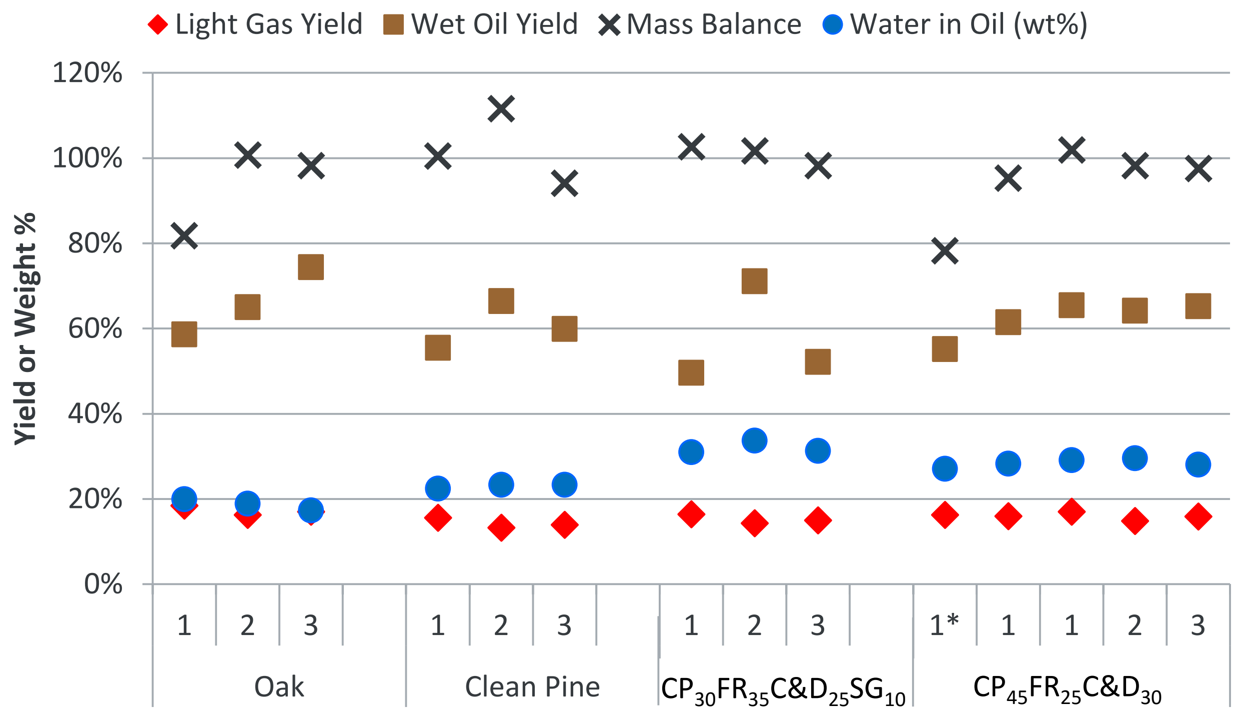
- Produced 12 different fast pyrolysis oil samples from 4 feedstocks, each at 3 conditions.
- Oil properties repeatable for a given feedstock and operating condition.
- Greater differences between feedstocks than operating conditions.
- Oil yield increases as scrubber equilibrates.

**Lesson Learned:**

Scrubber requires ~8 hrs to equilibrate in order to achieve consistent oil yields.

**Verification Selections:**

- Made jointly with NREL, PNNL, INL, & BETO
- Feedstock: Clean Pine and $CP_{30}acFR_{60}HP_{10}$
- Operating Condition: 500°C, t- 3 seconds




CP = Clean Pine, FR = Forestry Residues, SG = Switch Grass, C&D = Construction & Demolition Waste, HP = Hybrid Poplar, acFR = Air Classified Forestry Residues

* Strainer complications in scrubber resulted in reduced oil yield.

Condition 1: 500°C, t 4 sec. Condition 2: 480°C, t 4 sec.

Condition 3: 500°C, t 3 sec.

# 3 - Technical Accomplishments: Fast Pyrolysis Verification
## Achieved Targets for Clean Pine Baseline Verification Run

**Operated for ~100 hrs (~1500 kg total clean pine fed) with no significant operational issues and achieved design case targets.**

- Over 200 gallons fast pyrolysis oil shipped to PNNL for hydrotreating.
- Oil samples provided to support efforts of other tasks.
- Data used to prove economic viability of bio-crude co-processing in refinery operations.

| Fast pyrolysis products (wt% of dry biomass) | | | | |
|---|---|---|---|---|
| | TCPDU | StDev | Norm[1] | Design Case[2,3] |
| Total liquid after filtration (wt %) | 66.7 | 2.9 | 69.5 | 73 |
| Dry organic fraction (wt%) | 57.5 | 2.7 | **60.0** | **62** |
| Char (wt%) | 13.4 | 1.4 | 13.9 | 12 |
| Gas (wt%) | 16.7 | 0.3 | 17.4 | 12 |
| Mass balance | 96.0 | 3.3 | 100 | 100 |
| Carbon Balance | 96.9 | 2.1 | | 100 |

[1] TCPDU verification values normalized to 100% mass balance.

[2] Design case assumes ~3 wt% product loss during cold filtration.

[3] Jones, Susanne B., et al. "Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels." (2013)

| Fast Pyrolysis Oil Analysis | | | |
|---|---|---|---|
| | TCPDU | StDev | Design Case[3] |
| Ash (wt%, dry basis) | < 0.05 | | - |
| C (wt%, DAF) | 55.4 | 0.5 | 56.61 |
| H (wt%, DAF) | 6.8 | 0.2 | 6.61 |
| N (wt%, DAF) | 0.10 | 0.01 | 0.0081 |
| O (wt%, DAF) | 37.7 | 0.5 | 36.77 |
| Water (wt%) | 21.9 | 0.6 | 26.50 |
| TAN (mg KOH/g) | 67.2 | 3.8 | - |
| Carbonyl (mol/kg) | 5.68 | 0.18 | - |
| Density (wet basis) | 1.19 | 0.04 | 1.21 |
| HHV (Btu/lb, wet basis) | 7,618 | 88 | 7,266 |

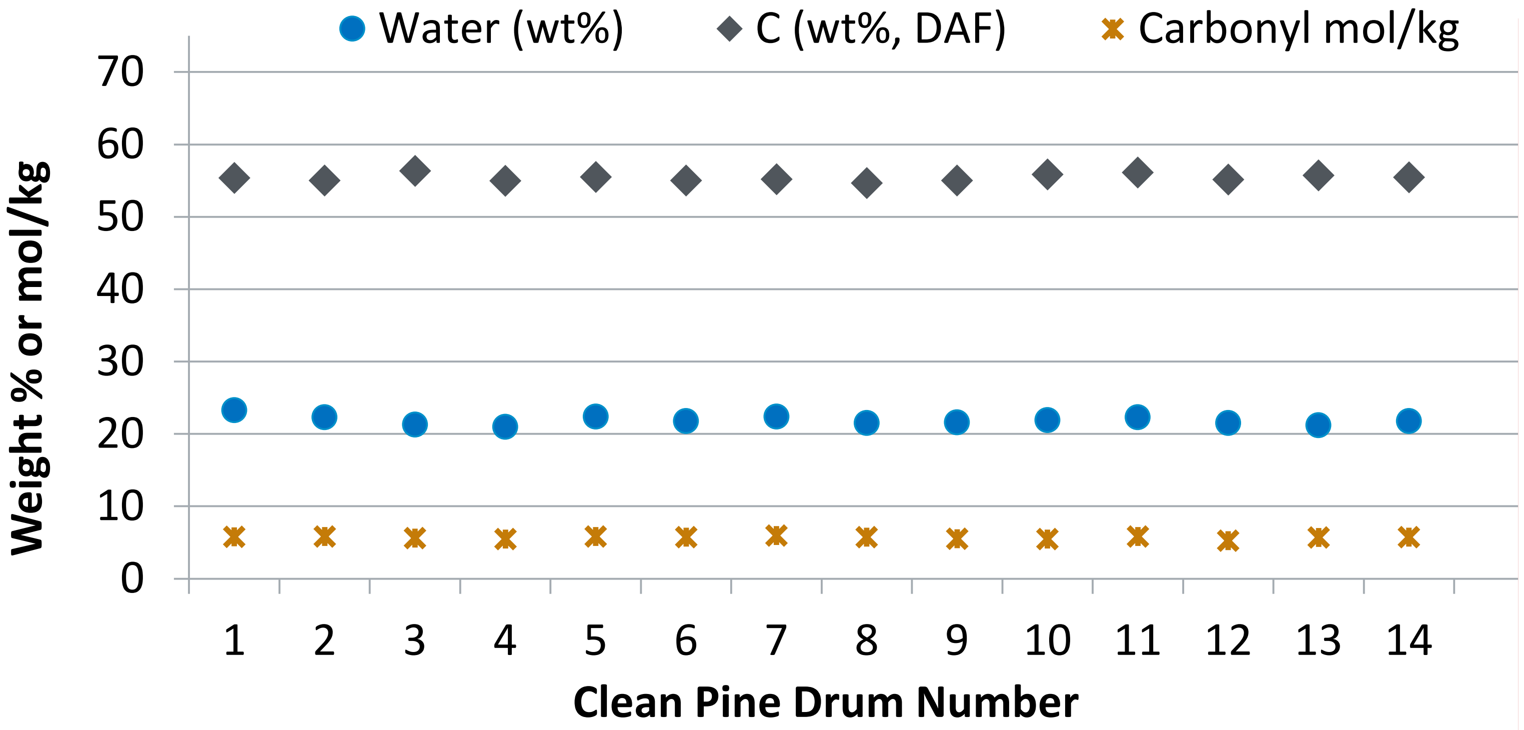
DAF = Dry ash free
TAN = Total acid number
HHV = High heating value

# 3 - Technical Accomplishments: Fast Pyrolysis Verification
## Clean Pine Oil Properties Consistent Throughout Verification Run

**Clean pine oil properties consistent throughout verification run.**

Goal: Confirm operability, yield and oil properties for verification feedstock and components.

**Blend feedstock yield and oil properties similar to clean pine.**
**No operability issues.**




Clean pine drum volume = 15 gallons. DAF = Dry and Ash Free

CP = Clean Pine, acFR = air classified Forestry Residues, HP = Hybrid Poplar, B3 = $CP_{30}acFR_{60}HP_{10}$

# 3 - Technical Accomplishments: Fast Pyrolysis Verification

# Initial Results Promising For Blended Feedstock FP Verification

**Operated for ~100 hrs (~1500 kg total $CP_{30}acFR_{60}HP_{10}$ fed) with no significant operational issues and initial data close to design case targets.**

- Over 200 gallons fast pyrolysis oil shipped to PNNL for hydrotreating.
- Over 15 gallons provided to ORNL for corrosion testing.
- Oil samples provided to support efforts of other tasks.

| Fast pyrolysis products (wt% of dry biomass) | | | | | |
|---|---|---|---|---|---|
| | Blend[1] | Norm[2] | Clean Pine | Norm[2] | Design Case[3] |
| Total liquid after filtration (wt%) | 65.3 | 68.0 | 66.7 | 69.5 | 73 |
| Dry organic fraction (wt%) | 54.9 | 57.3 | 57.5 | 60.0 | 62 |
| Char (wt%) | 13.9 | 14.5 | 13.4 | 13.9 | 12 |
| Gas (wt%) | 16.7 | 17.4 | 16.7 | 17.4 | 12 |
| Mass balance | 95.9 | 100 | 96.0 | 100 | 100 |

[1] Preliminary results based on one mass balance period and one oil sample. Blend: $CP_{30}acFR_{60}HP_{10}$

[2] TCPDU verification values normalized to 100% mass balance.

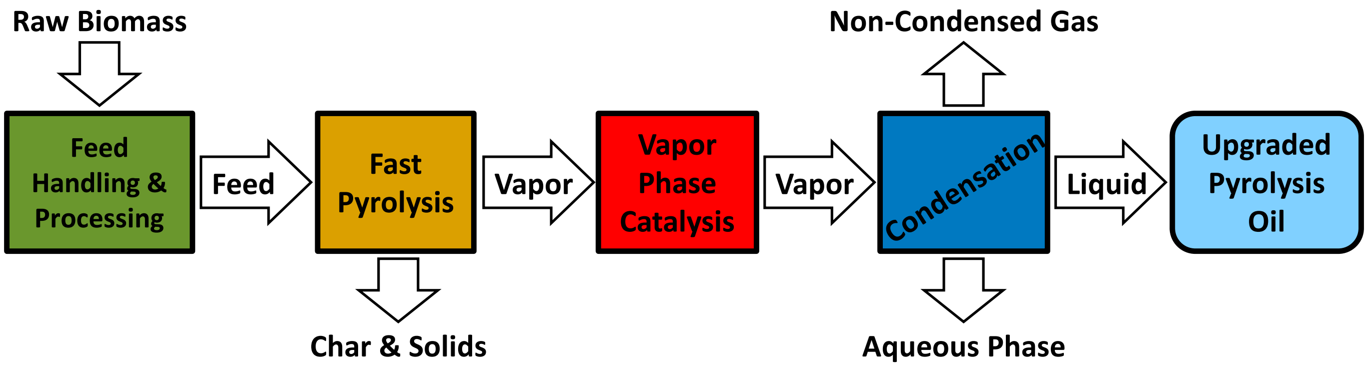
[3] Design case assumes ~3 wt% product loss during cold filtration.

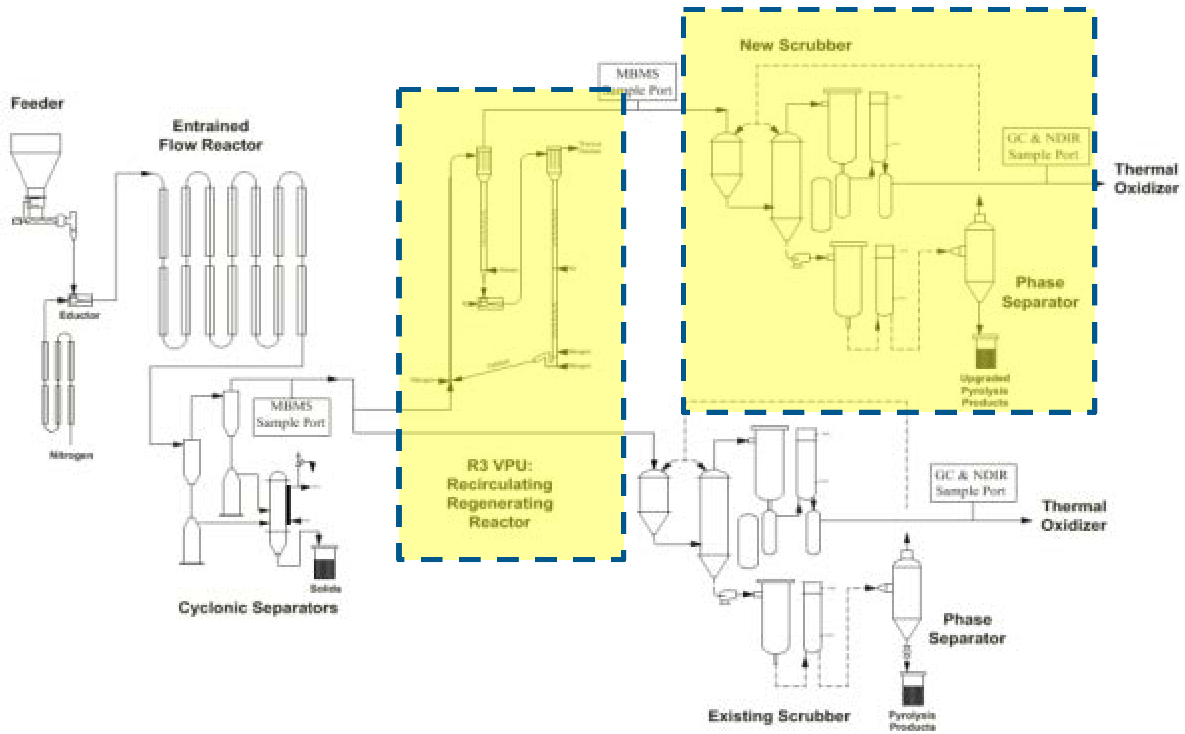
| Fast Pyrolysis Oil Analysis | | | |
|---|---|---|---|
| | Blend[1] | Clean Pine | Design Case |
| Ash (wt%, dry basis) | <0.05 | < 0.05 | - |
| C (wt%, DAF) | 56.5 | 55.4 | 56.61 |
| H (wt%, DAF) | 6.2 | 6.8 | 6.61 |
| N (wt%, DAF) | 0.10 | 0.10 | 0.0081 |
| O (wt%, DAF) | 37.2 | 37.7 | 36.77 |
| Water (wt%) | 21.8 | 21.9 | 26.50 |
| TAN (mg KOH/g) | 66.9 | 67.2 | - |
| Carbonyl (mol/kg) | 5.76 | 5.68 | - |
| HHV (Btu/lb, wet basis) | 7,745 | 7,618 | 7,266 |

DAF = Dry ash free
TAN = Total acid number
HHV = High heating value

# 3 – Technical Accomplishments: FY22 Ex-Situ CFP Verification

## Fabricated & Installed Ex-Situ CFP Unit Operations



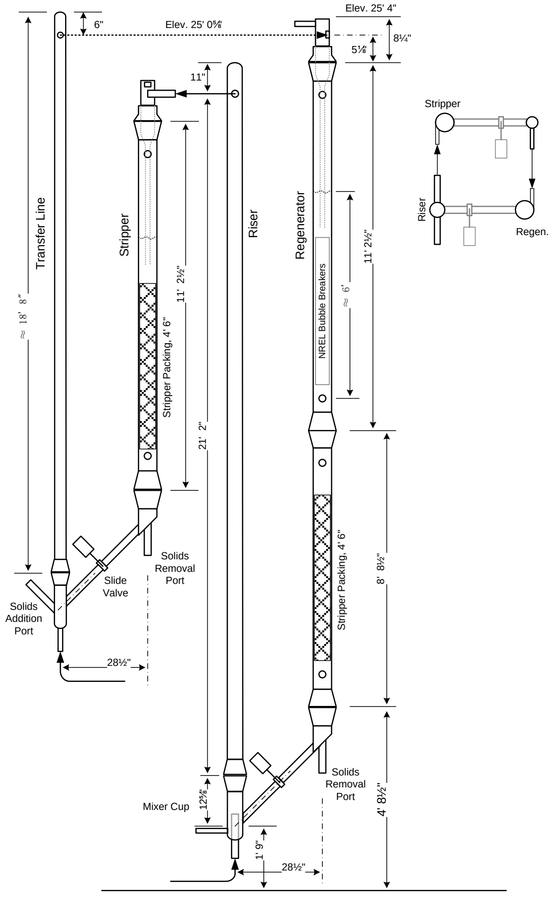




**FY15-17 Goal:**
Design, fabricate, and install ex-situ CFP capabilities into TCPDU.

**FY18 Goal:**
Demonstrate pilot-scale capability to produce upgraded oils equivalent to bench-scale.

**FY22 Goal:**
Pilot-scale verification of pathway from feedstock to fuel meeting BETO FY22 cost targets.

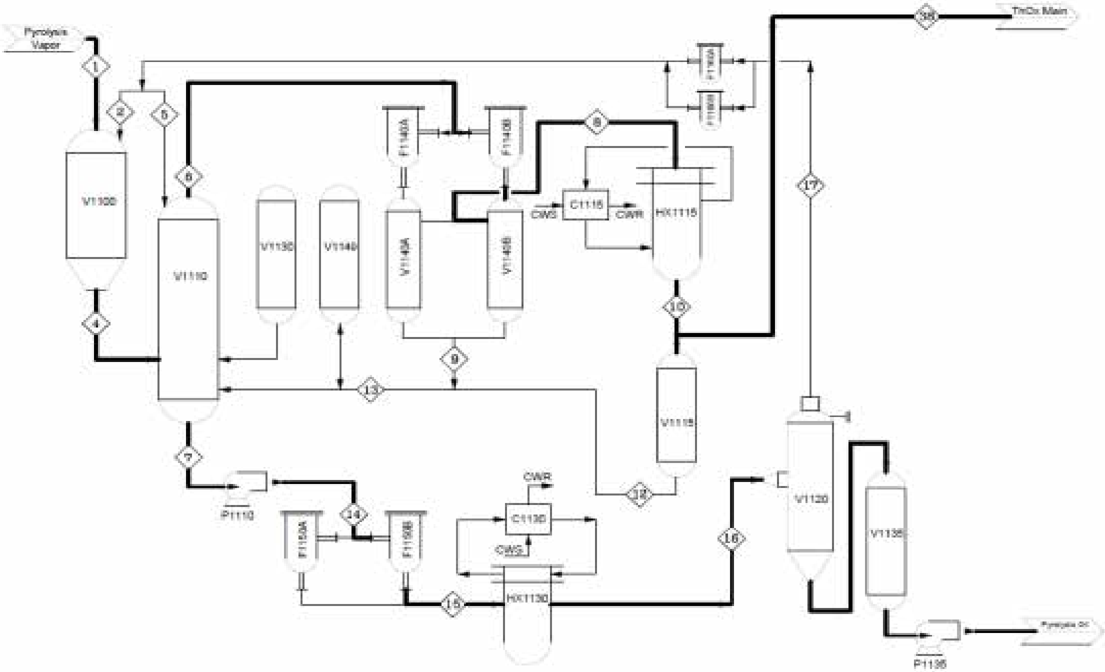
# 3 - Technical Accomplishments: FY22 Ex-situ CFP Verification
## Ex-situ CFP Reactor Installed




- Modified existing reactor for ex-situ CFP & reforming capabilities.
- **Worked with Particulate Solids Research, Inc.**, experts in solids flow, on design and Springs Fabrication for fabrication.
- Changes based on learnings from 2012 demonstration and input from ChemCatBio tasks.
- Design parameters defined with ChemCatBio tasks:
  - Usable for modified HZSM-5 catalyst (70 – 80 µm, 900 g/L density)
  - Solids loading range of 0.5 to 3 $mass_{catalyst} : mass_{py\ vapor}$ ratio
  - Controllable solids flow
  - Minimize attrition and solids carry-over
  - Steam stripping and air regeneration of catalyst
- **CCPC modeling of reactor** to provide commissioning guidance.

# 3 - Technical Accomplishments FY22 Ex-situ CFP Verification
## Ex-situ CFP Condensation Train Installed

- Worked with Process Engineering Associates for design, and Zeton for fabrication.
- 5 separation methods evaluated including distillation and centrifugation.
- Key design elements:
  - Safe collection of carcinogenic products, such as benzene.
  - Ability to use variety of scrubbing fluids.
  - **Reduced operational risks** by existing separation method.
  - **Improve design** for easier operation and maintenance based on lessons learned from existing system.



# 4 - Relevance

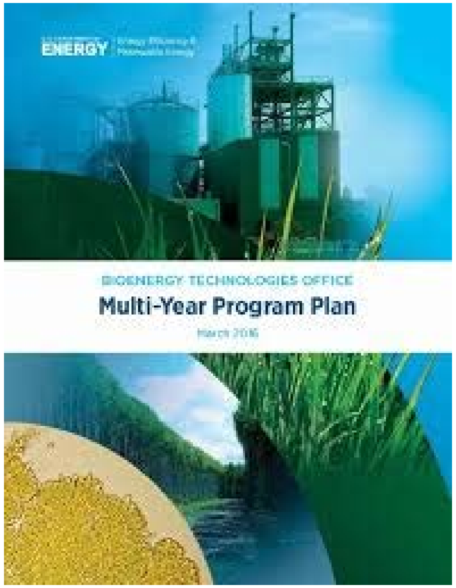
**Instrumental in demonstrating the commercial viability of thermochemical pathways.**

**Reduces cost and risk to industry:**

- Development of necessary engineering designs to overcome issues associated scaled operations. Examples:
  - Method to effectively heat-trace process lines.
  - Passivation method for biochar for safe post-production handling.
  - Inert vacuum for use with oxygen sensitive materials.
- Determining operational boundaries.
- Pilot-scale evaluation of proprietary technologies.

**Addresses BETO's strategic goal for thermochemical conversion:**

- Maintains & operates a BETO core capability for Technology Demonstration & Market Transfer.
- Provides large quantity of products to further bench-scale efforts such as corrosion testing, and oil characterization method development.
- Fills data gaps for analysis, including operation uncertainties.
- Pilot-scale integration of technologies.



# Conduct ASTM & Engine Testing on Verification Bio-Fuel (FY17-FY18)

**Demonstrate that biofuels produced from the fast pyrolysis pathway can be blended and utilized in internal combustion engines.**

Collaborate with Co-Optima to conduct ASTM and engine testing of gasoline and diesel fractions received from PNNL hydrotreating of verification fast pyrolysis oils.

| Test | Information Obtained / Use |
|---|---|
| Initial ASTM tests | Octane, cetane, distillation<br>Used to determine blending strategy |
| Full ASTM tests | ASTM specification properties and detailed characterization |
| Diesel engine | Tail pipe emissions, CO, NOx, fuel economy, transient Functional Threshold Power (FTP) cycles |
| Gasoline single cylinder | Fine particle mass & number emissions, knock limit, efficiency measurement |
| Gasoline full engine | Cold start, chassis dyno FTP cycle, efficiency |

No more than 20% biofuel blend with fossil fuel will be used for engine tests.

# 5 – Future Work
# Commission Ex-Situ CFP and Improve Pyrolysis Run-Time

**Demonstrate pilot-scale capability to produce ex-situ CFP oils equivalent to bench-scale.**

- Receive safety approval to begin ex-situ CFP operations. (FY17)
- Initial commissioning of ex-situ CFP operations. (FY18)
- Understand effect of process conditions on operation of reactor and catalyst flow. (FY18)
- Demonstrate that TCPDU ex-situ CFP products equivalent to small scale systems. (FY18)
- Joint Go/No-Go decision on additional upgrades for FY22 ex-situ CFP verification. (FY18)

**Increase pyrolysis run-time by reducing product deposition at scrubber inlet.**

- Develop multiple scrubber inlet designs aimed at maintaining pyrolysis product vapor until contact with scrubbing fluid. (FY18-FY19)
- Install and test designs to determine optimum to reduce deposition at scrubber inlet, maintenance, and increasing operational run-time. (FY19)

# Summary

**This project provides industry with technical expertise necessary to overcome scale-up challenges and bridge the valley of death.**

**TCPDU verifications are the culmination of several years worth of bench-scale and engineering efforts. They achieve BETO goals and support industrial commercialization of thermochemical technologies.**

**Fast pyrolysis oil production completed for FY17 verification. Clean pine met targets.**

| Fast pyrolysis products (wt% of dry biomass) | | | | | |
|---|---|---|---|---|---|
| | Blend[1] | Norm[2] | Clean Pine | Norm[2] | Design Case[3] |
| Total liquid after filtration (wt%) | 65.3 | 68.0 | 66.7 | 69.5 | 73 |
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| Mass balance | 95.9 | 100 | 96.0 | 100 | 100 |

[1] Preliminary results based on one mass balance period and one oil sample. Blend: $CP_{30}acFR_{60}HP_{10}$

[2] TCPDU verification values normalized to 100% mass balance.

[3] Design case assumes ~3 wt% product loss during cold filtration.

**On-track for successful FY22 ex-situ CFP verification.**

# Acknowledgements

- Thermochemical Process R&D Section:
  - Tim Dunning
  - Katie Gaston
  - Chris Golubieski
  - Ray Hansen
  - Matt Oliver
  - Marc Pomeroy
  - Kristin Smith

- Many collaborators

**DOE BETO**

# Thank You!

www.nrel.gov

NATIONAL RENEWABLE ENERGY LABORATORY

# Glossary of Terms

| | |
|---|---|
| **acFR** | Air Classified Forestry Residues |
| **ASTM** | American Society for Testing and Materials - an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services |
| **AOP** | Annual Operating Plan |
| **ANL** | Argonne National Laboratory |
| **BETO** | Bioenegy Technology Office |
| **B3** | Blend 3 |
| **CFP** | Catalytic Fast Pyrolysis |
| **CP** | Clean Pine |
| **CCPC** | Consortium for Computational Physics and Chemistry |
| **C&D** | Construction & Demolition Waste |
| **CRADA** | Cooperative Research and Development Agreement |
| **DCR** | Davidson Circulating Reactor – mini-pilot scale system at NREL for ex-situ CFP studies |
| **DOE** | Department of Energy |
| **DAF** | Dry Ash Free |
| **FP** | Fast Pyrolysis |
| **Q** | Fiscal Quarter |
| **FY** | Fiscal Year |
| **FR** | Forestry Residues |
| **FOA** | Funding Opportunity Announcement |
| **GGE** | Gallons of Gasoline Equivalent |
| **GC** | Gas Chromatograph |
| **GHG** | Green House Gas |
| **HHV** | High Heating Value |
| **HGF** | Hot gas filter |

| | |
|---|---|
| **HP** | Hybrid Poplar |
| **HZSM-5** | Zeolite Socony Mobil–5 |
| **INL** | Idaho National Lab |
| **MBMS** | Molecular Beam Mass Spectrometer |
| **MYPP** | Multi-Year Program Plan |
| **NREL** | National Renewable Energy Laboratory |
| **NDIR** | Nondispersive Infrared Detector |
| **ORNL** | Oakridge National Laboratory |
| **PNNL** | Pacific Northwest National Laboratory |
| **PFD** | Process flow diagram |
| **R&D** | Research and Development |
| **R-Cubed** | Recirculating Riser Reactor |
| **StDev.** | Standard Deviation |
| **SOT** | State of Technology, always relative to an indicated date |
| **SG** | Switch Grass |
| **TEA** | Technoeconomic Analysis - includes a process design and associated economics based on economic assumptions in BETO-sponsored design reports |
| **TC** | Thermochemical |
| **TCPDU** | Thermochemical Process Development Unit – a pilot scale system used for demonstration of thermochemical pathways |
| **TAN** | Total Acid Number |
| **VPU** | Vapor Phase Upgrading (ex-situ CFP) |
| **VTO** | Vehicle Transportation Office |
| **WBS** | Work Breakdown Structure |

# Response to 2013 Reviewer comments

Comment – "Big project, lots of scope, not sure if it can be completed on time and within budget for the scope promised."

You are correct that the project scope and schedule is ambitious. We have risk mitigation plans to alleviate any potential issues that may arise.

Comment – "Establishing state-of-the-art steady-state conversion capabilities at the national labs is important. However, BETO may realize more value from the investment by utilizing that equipment and expertise to some evolving issues rather than duplicate results which have already been largely obtained by BETO-funded industry projects."

The TCPDU system provides the pilot scale capability within the national lab system. This allows DOE the ability to test catalysts and other technologies developed within the national labs at the pilot scale. Additionally, we can produce large volumes of product which are required by other tasks and other labs for their efforts and can be difficult for them to source from industry.

Comment – "The project team needs a core capability to demonstrate fast pyrolysis and ex-situ pyrolysis. Getting quality data is the key-material balanced weight in and out and C, H, O in and out of all major reactors. Is there overlap between the DOE funded unit at RTI with this one at NREL? And what about the DCR unit at PNNL?"

We have online capabilities (MBMS, GCs, NDIR) before and after each reactor system. We are continuing our efforts to improve the mass and atomic balances of the system, for example we are evaluating total carbon analyzers to use in the system. The RTI pilot plant is capable of in-situ pyrolysis. The TCPDU system has the capability for fast pyrolysis and ex-situ pyrolysis. It provides DOE with added capabilities. The DCR system is a smaller reactor for ex-situ pyrolysis. The TCPDU provides DOE with a larger scale system (~10x) to that of the DCR.

Comment – "The project will be successful if the facility is fully utilized by the program so that the facility is kept busy to justify the capital involved."

Though we are currently focused on the 2017 demonstration, there are future plans for the pilot plant. Due to the flexibility of the TCPDU, we expect it to be used for the demonstration of additional pathways.

# Publications, Patents, & Presentations (FY15 – current)

Michael D. Kass et. al., "Compatibility Assessment of Fuel System Elastomers with Bio-oil and Diesel Fuel" Energy & Fuels 30 (2016): 6486-6494, doi: 10.1021/acs.energyfuels.6b01138

Kathrine Gaston and Esther Wilcox "Comparison of Entrained-Flow & Fluidized-Bed Reactors for Production of Fast Pyrolysis Oils" Paper presented at the Thermochemical Biomass biannual meeting, Chicago, Illinois, September, 2015.

Marc Pomeroy, "Method for Hot Real-Time Sampling of Biomass-Derived Pyrolysis Vapors" Paper presented at the American Institute for Chemical Engineers Spring Meeting, Houston, Texas, April, 2016.

Katherine Gaston, "Comparison of Entrained-Flow and Fluidized-Bed Reactors for Production of Fast Pyrolysis Oils" Paper presented at the American Institute for Chemical Engineers Spring Meeting, Houston, Texas, April, 2016.

Kristin Smith and Esther Wilcox, "Method of Biochar Passivation Using Low Percent Oxygen" Paper presented at the American Institute for Chemical Engineers Spring Meeting, Houston, Texas, April, 2016.

Marc Pomeroy, "Method for Hot Real-Time analysis of Pyrolysis Vapors" Paper presented at the European Biomass Conference & Exhibition, Amsterdam, Netherlands, June, 2016.

Marc Pomeroy et. al., "Method of Biochar Passivation Using Low Percent Oxygen" Paper presented at the European Biomass Conference & Exhibition, Amsterdam, Netherlands, June, 2016.

Marc Pomeroy, "Mass Spectrometer Capabilities at NREL" Paper presented at the Gas Analysis Workshop, Amsterdam, Netherlands, June, 2016.

Marc Pomeroy, "MBMS Application in Gasification and Pyrolysis" Paper presented at the Gas Analysis Workshop, Rome, Italy, June, 2016.

Esther Wilcox and Katherine Gaston, "Impact of feedstock, temperature, and residence time on pyrolysis products produced at pilot-scale" Paper presented at the Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, Chapel Hill, North Carolina, October, 2016.

Katherine Gaston, "Pilot-Scale Pyrolysis: investigating and solving operational problems from running a new feedstock" Paper presented at the Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, Chapel Hill, North Carolina, October, 2016.

Esther Wilcox and Kristin Smith, "Effect of feedstock, temperature and residence time on pilot-scale pyrolysis products" Paper presented at the Emerging Energy Technologies Summit and Exhibition, Melbourne, Australia, December, 2016.

Esther Wilcox, "From concept to pilot-scale demonstration: Thermochemical biomass conversion research at the National Renewable Energy Laboratory" Paper presented at the Emerging Energy Technologies Summit and Exhibition, Melbourne, Australia, December, 2016.

Marc Pomeroy, "Method for Hot Real-Time Analysis of Pyrolysis Vapors at Pilot Scale" Paper presented at the Emerging Energy Technologies Summit and Exhibition, Melbourne, Australia, December, 2016.

Patent Record of Invention: "Spark-less vacuum cleaner for pyrophoric material"