2015 DOE Bioenergy Technologies Office (BETO) Project Peer Review

WBS 2.5.4.405 - Catalytic Upgrading of Thermochemical Intermediates to Hydrocarbons

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Bio-Oil Technology Area Review

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

Goals and Objectives

Objective: Demonstrate an advanced biofuels technology that integrates a catalytic biomass pyrolysis step and a hydroprocessing step to produce infrastructure compatible biofuels.

Technical goals are to:

1) optimize the catalytic biomass pyrolysis process (1 ton/day) to achieve high degree of deoxygenation, while maximizing the bio-crude production
2) improve bio-crude thermal stability
3) evaluate the impact of bio-crude quality in the hydroprocessing step
4) minimize hydrogen demand of the integrated process
5) maximize biofuels yields.

Quad Chart Overview

Timeline

- Conditional award date: 9/22/2011
- Contract award date: 8/16/2012
- Project kick-off: 11/6/2012
- ~60% complete
- Project end date: 9/30/2015

Barriers Addressed

- Tt-F. Deconstruction of Biomass to Form Bio-Oil Intermediates
- Tt-J. Catalytic Upgrading of Bio-Oil Intermediates to Fuels and Chemicals
- Tt-S. Petroleum Refinery Integration of Bio-Oil Intermediates

Partners

- RTI – project lead, CFP technology development, Engineering Design and Scale-up, project management
- Haldor Topsøe A/S (HTAS) - Hydroprocessing Development and Process Modeling

High impact feedstock providers

- Idaho National Laboratory
- Local NC wood products suppliers

	Total Costs FY 10 –FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date)
DOE Funded		$433,965	$1,180,943	$2,735,020
Project Cost Share				
RTI		$105,021	$46,366	-$151,387
HTAS		$119,343	$121,422	$759,234
State of NC			$100,000	

1 – Project Overview

Feedstocks
Woody biomass
Switchgrass
Corn Stover

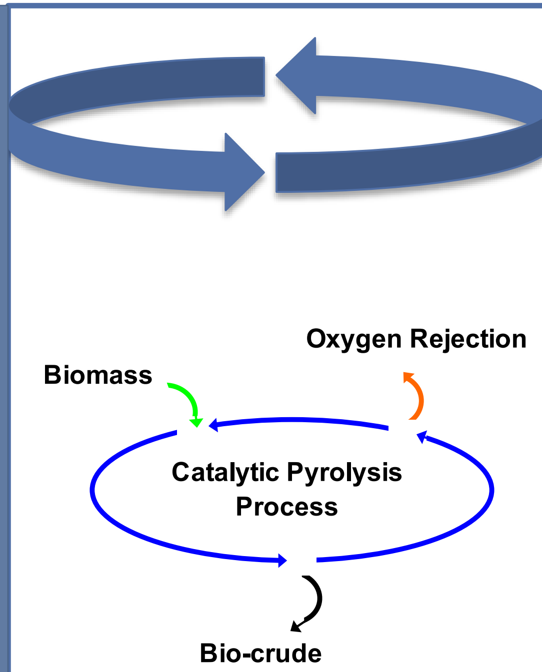
→ **Conversion Technology**
Catalytic Biomass Pyrolysis

→ **Upgrading Technology**
Hydroprocessing

→ **Advanced Biofuels**
Diesel (F-76)
Jet Fuel (JP-5, JP-8)

RTI Catalytic Biomass Pyrolysis Process based on a Multi-functional Catalyst ……

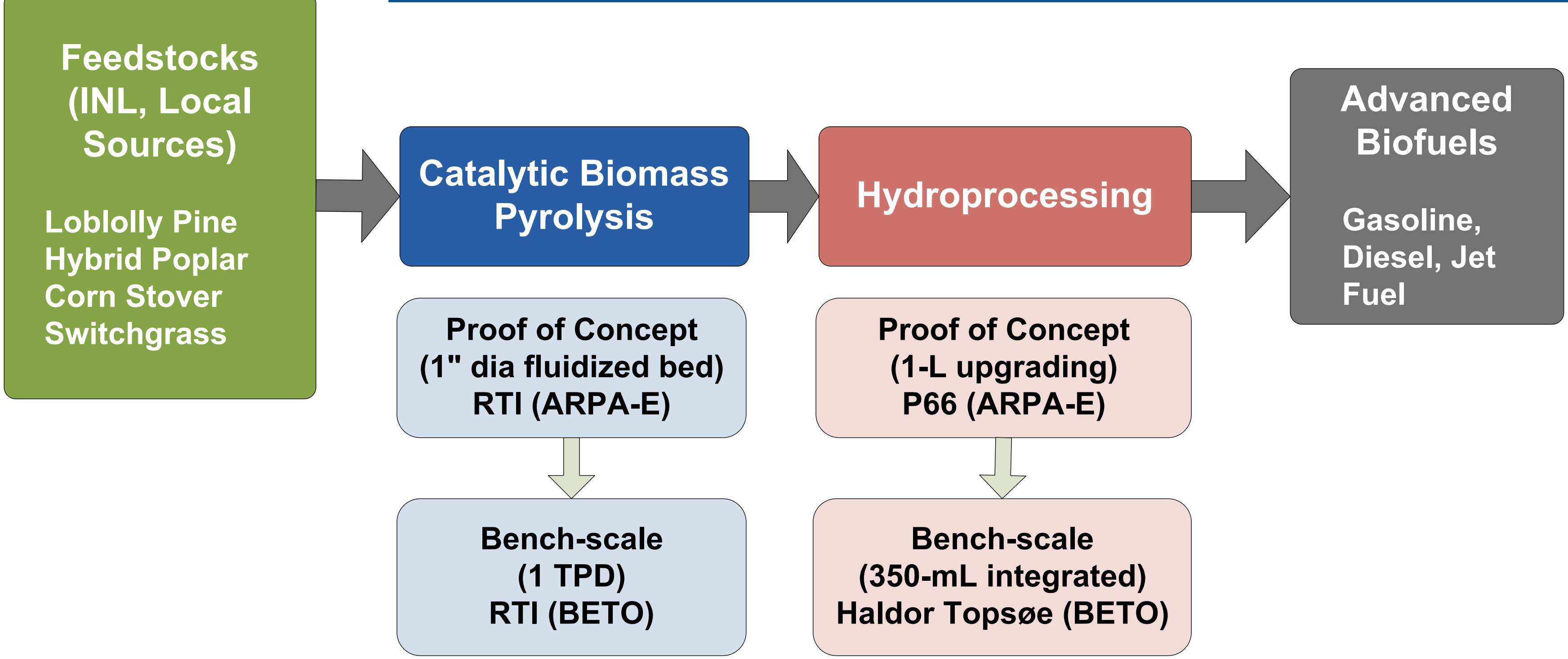
- Multi-functional catalyst to maximize carbon efficiency, remove oxygen, and control bio-crude properties
- High attrition resistance



…..in a Fluidizable form for use in a single loop Transport Reactor

- Continuous catalyst reaction and regeneration
- System can be operated auto-thermally with heat of regeneration
- "Bio-crude" intermediate that can be processed with existing refining technology

2 - Technical Approach



Critical Success Factors:

- Scale-up RTI's catalytic biomass pyrolysis process
- Integrate a hydroprocessing unit and develop bio-crude upgrading strategies
- Demonstrate the long-term operation and performance of the bio-crude production and upgrading
- Update techno-economics and life-cycle assessment to validate cost competitiveness for advanced biofuel production

2 – Management Approach

Task 1.0: Pilot-scale Catalytic Biomass Pyrolysis (RTI, INL)

Key Milestones: Complete 1TPD unit commissioning; prepare, deliver, and characterize feedstocks for pilot plant, bio-crude production

Task 2.0: Hydroprocessing Evaluation and Optimization (Haldor Topsoe)

Key Milestones: Develop upgrading strategy for RTI bio-crude samples; Develop optimized process conditions for bio-crude upgrading; Bio-crude/refinery intermediate co-processing

Task 3.0: Hydroprocessing Reactor Design and Fabrication for Integrated Process Development (RTI, Haldor Topsoe)

***Go/NoGo Decision Point** – Technical review of hydroprocessing unit design and cost analysis prior to start of fabrication. (April 2014)*

***Go/NoGo Decision Point** – Commissioning hydroprocessing unit. (March 2015)*

Task 4.0: Integrated Bio-crude Upgrading and Process Operation (RTI)

Key Milestones: Complete up to 1000 hours of upgrading with loblolly pine bio-crude, 500 hours of upgrading with hybrid poplar bio-crude, and 500 hours of upgrading with switchgrass bio-crude.

Task 5.0: Process Modeling and Refinery Integration (RTI, Haldor Topsoe)

Key Milestones: 2000 TPD Integrated Process Design and Economics; Economic analysis of the technical feasibility of co-processing bio-crude and hydrocarbon intermediate streams

Task 6.0: Project Management and Reporting (RTI)

Detailed project plan with quarterly milestones and deliverables and annual Go/NoGo decision points (See Gantt Chart and Milestone Tables in Additional Information)

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3 – Technical Accomplishments/Progress/Results

Feedstock Preparation and Characterization

- Loblolly Pine (NABC and local source)
- 5 tons Hybrid Poplar delivered to RTI from INL
- 5 tons switchgrass awaiting additional preparation before delivery
- Proximate and ultimate analysis
- Ash and chemical analyses (carbohydrate and lignin compositions)

1 TPD Catalytic Biomass Pyrolysis Unit Commissioning and Operation

- Catalyst circulation under hot conditions
- Steady biomass feeding at a minimum of 100 lbs/hr
- Quench system modifications for improved collection efficiency
- Steady-state catalytic biomass pyrolysis for 10+ hours
- Bio-crude yields from laboratory-scale experiments achieved in 1TPD system

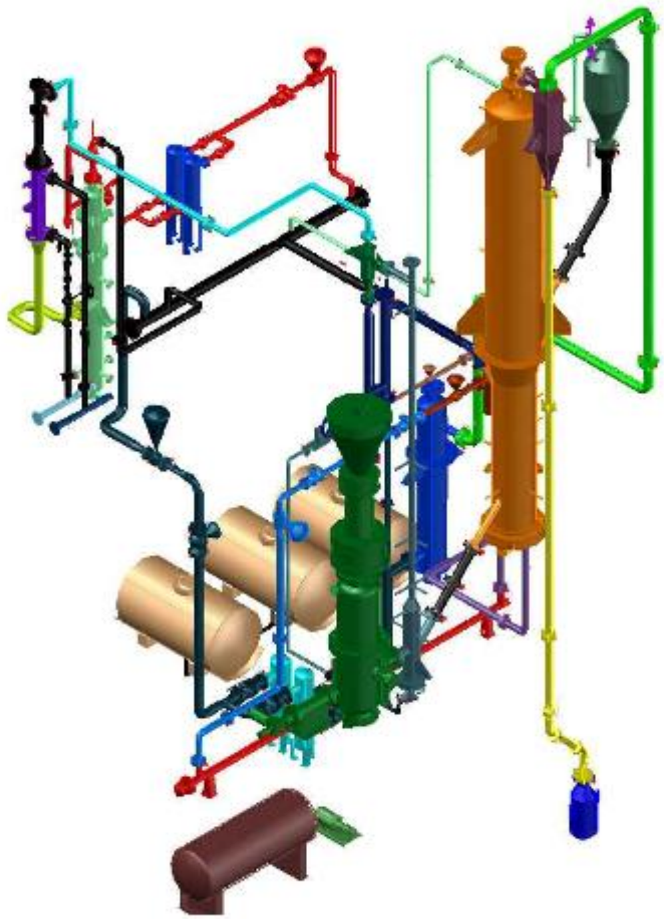
Hydroprocessing Evaluation and Optimization

- Bio-crude sample analysis complete and ongoing
- Developed strategy for upgrading RTI bio-crude samples (catalyst selection and initial process conditions)
- Evaluating strategies for co-processing bio-crude/refinery intermediate blends

Hydroprocessing Reactor Unit for Integrated Process Development

- Design, fabrication, and installation of hydroprocessing unit at RTI complete
- Commissioning and baseline testing underway

1 TPD Catalytic Biomass Pyrolysis Unit



Critical Success Factors:

- Demonstrate RTI's catalytic biomass pyrolysis process at pilot-scale with a biomass feed rate of 100 lb/hr
    - Bio-crude with less than 20 wt% oxygen
    - At least 50% energy recovery
    - Mass closure at least 90%
- Understand the effect of operating parameters on product yields and quality
    - – Pyrolysis temperature (350-500 ºC)
    - – Residence time (0.5-1.0 s)
    - – Regenerator temperature (500-700 ºC)
    - – Catalyst circulation rate (500 – 2000 lb/hr)
    - – Biomass Feedrate (50 – 200 lb/hr)
    - – Type of biomass

Design based on single-loop transport reactor system

- Catalyst undergoes continuous reaction and regeneration
- System can be operated autothermally with heat of regeneration (and char combustion) carried over by the catalyst to the reaction zone

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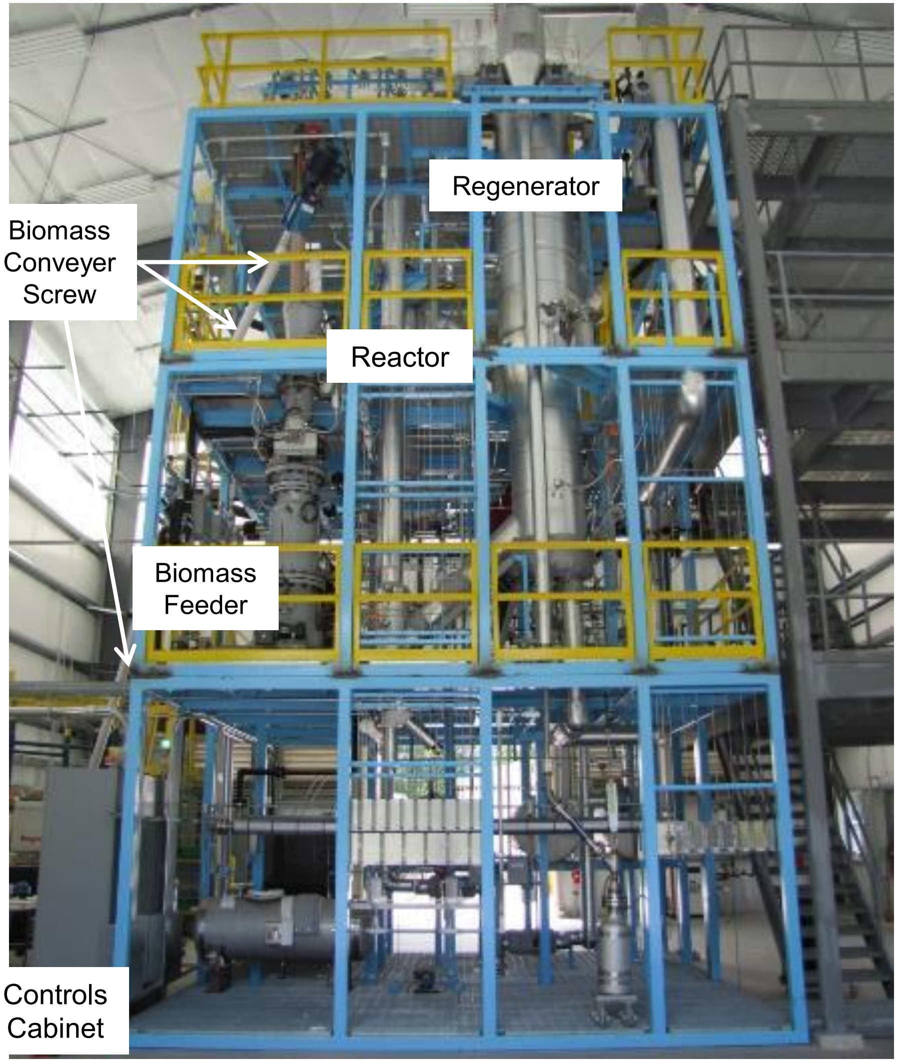
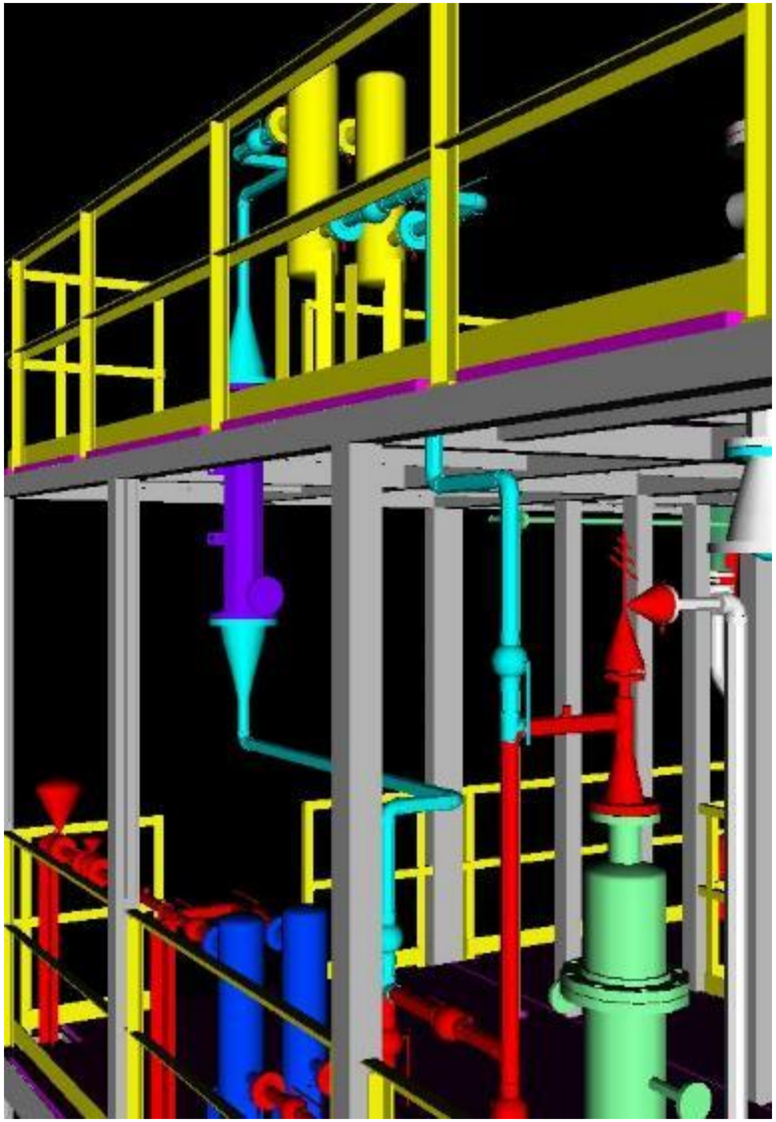
RTI's 1 TPD Catalytic Biomass Pyrolysis Unit

Front View



Back View

Quench System Design and Modifications



Initial design included spray quench into heat exchanger

- Issue: solids build on HX inlet and fouling of HX

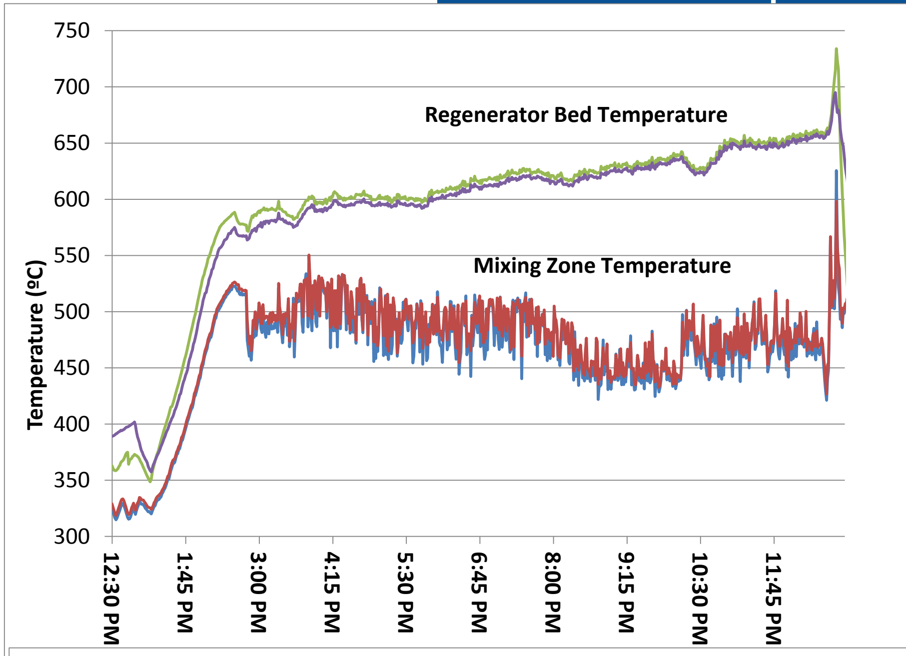
Replaced heat exchanger with water cooled 3" pipe upstream of gas/liquid separator

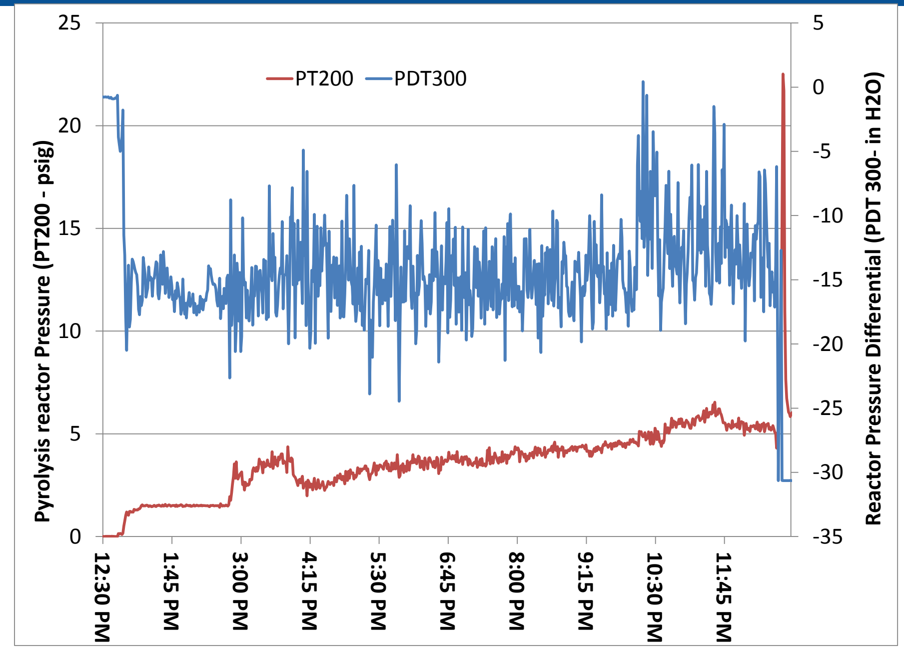
- Issue: poor heat transfer so pyrolysis gas was too hot causing inefficient product collection

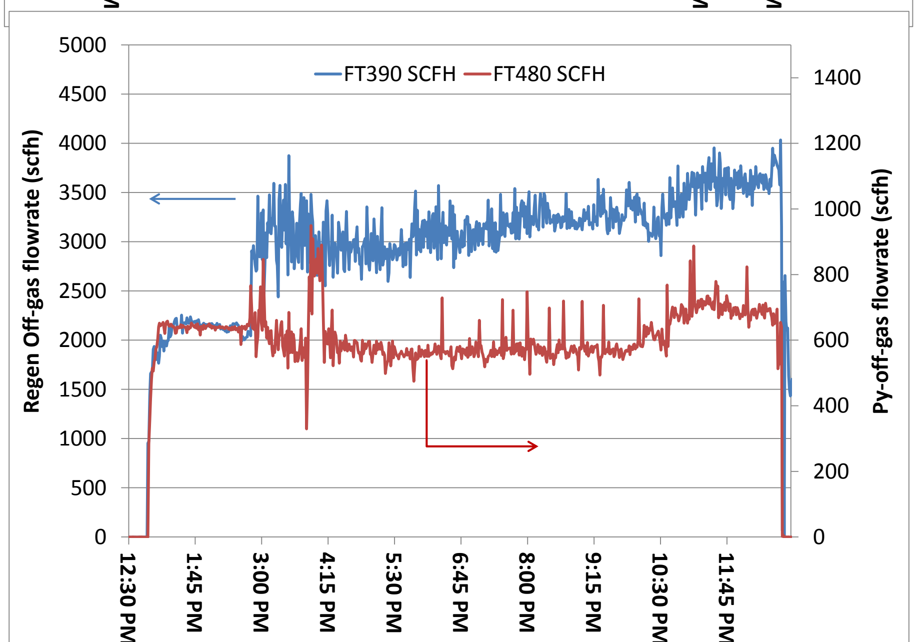
Re-install heat exchanger with an additional pair of coalescing filters downstream of separator

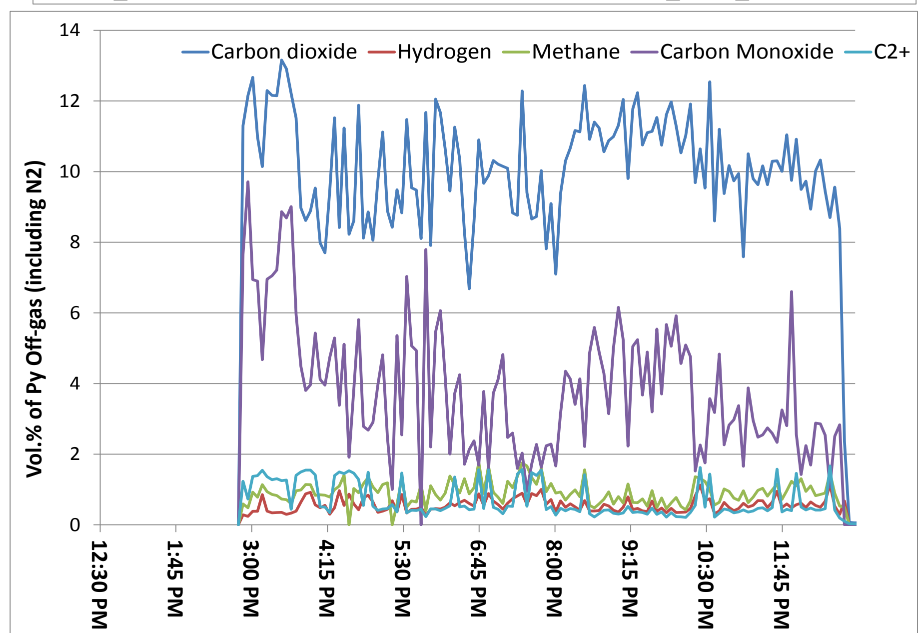
- Improved collection efficiency
  - Heavy fraction collected at outlet of gas/liquid separator
  - Light fraction and water collected downstream of the heat exchanger
  - Aqueous phase collected in storage tanks

Pilot Plant Operations









Catalytic Biomass Pyrolysis Material Balances

Comparison between lab- and pilot-scale catalytic biomass pyrolysis

Feedstock
- Loblolly pine sawdust
(17 lb/ft^3 at ~10 wt% moisture)

Catalyst - RTI-A10A

Pyrolysis Temperature
- Initial – 500C
- Average – 482C

Regenerator Temperature: 575-650C

1120 lbs (509 kg) of pine fed in 9.75 hours

	1" Fluid-Bed Reactor	1 TPD Unit Operation
Carbon Balance (wt. %)		
Organic Liquid Product	24.2	10
Aqueous Liquid Product	4.3	17†
Pyrolysis Gases	17.6	7
Char & Regeneration Off-Gas	51.3	49
Total	97.4	85.2
Bio-crude Composition		
C (wt%.dry basis)	76.7	70.7
H (wt%, dry basis)	7.1	6.4
O (wt%, dry basis)	16.1	22

† Higher than expected due to water quench

Summary of Technology Status

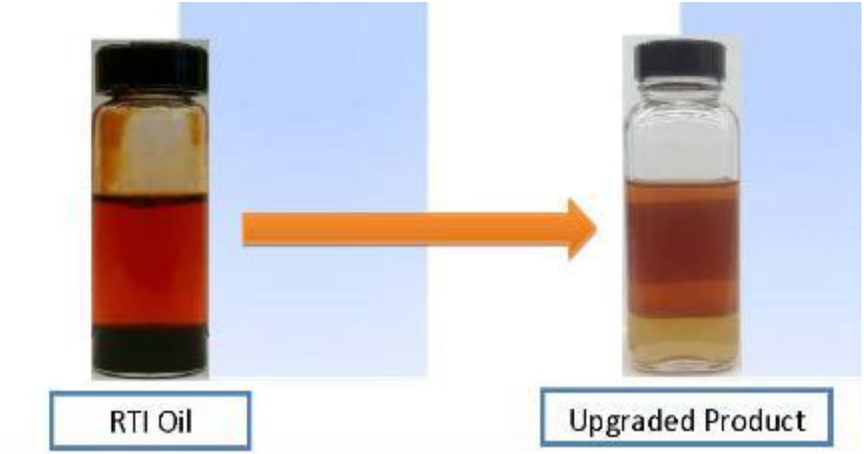
Previous Work

- ❑ Catalyst development included model compound screening and bench-top (~ 1 g/hr) biomass conversion
- ❑ Catalytic biomass pyrolysis in a 1”-dia fluidized bed reactor
- ❑ 20 wt% oxygen content with 42% energy recovery

Progress Since Last Review

- ❑ 1 TPD unit operational for more than 18 months
  - 3 catalysts tested – FCC, RTI-A9, and RTI-A10A
  - 4 feedstocks attempted – loblolly pine, hybrid poplar, corn stover, hardwood pellets
  - Over 8000 lbs of biomass fed in the past 18 months
  - 10 hours of steady-state operation achieved without upset in July 2014
  - 50-gal of loblolly pine bio-crude produced for upgrading
  - Yields in 1” FBR achieved in 1 TPD pilot plant

Hydroprocessing Evaluation and Optimization



Proof-of-Principle (ARPA-E)

- Bio-crude can be upgraded to hydrocarbons
- Product is mainly in gasoline range
- Product is rich in cyclic alkanes and monoaromatics

Hydroprocessing reactions:

- Decarbonylation
- Decarboxylation
- Hydrodeoxygenation (HDO)

Competing reactions:

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$
$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

Key process variables to determine

- H_2 consumption
- product yields
- catalyst inhibition
- reactant gas composition
- CO, CO_2, and CH_4 content in the hydroprocessing reactor
- heat balance

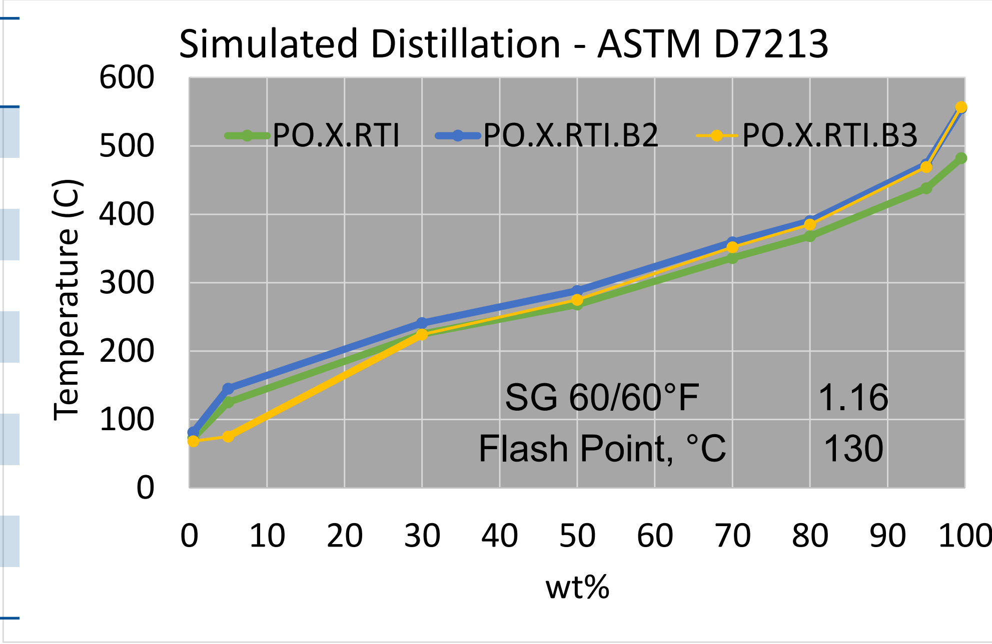
Hydroprocessing at Haldor Topsøe A/S

Haldor Topsøe A/S is leading expert in hydroprocessing

- 50 test units with over 90 reactors available for R&D
- Expertise in pilot testing and scale-up
- Three different configurations available to simulate commercial units
- Known deviations between pilot and commercial units (fractionation, S in naphtha, etc.)
- Reliable tests:
  - High reproducibility between two pilot units
  - Results close to performance in commercial units

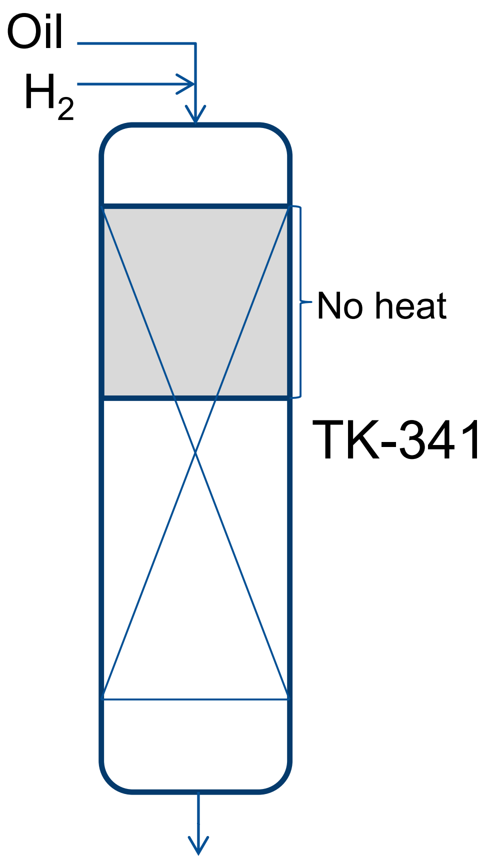
Bio-crude Analysis

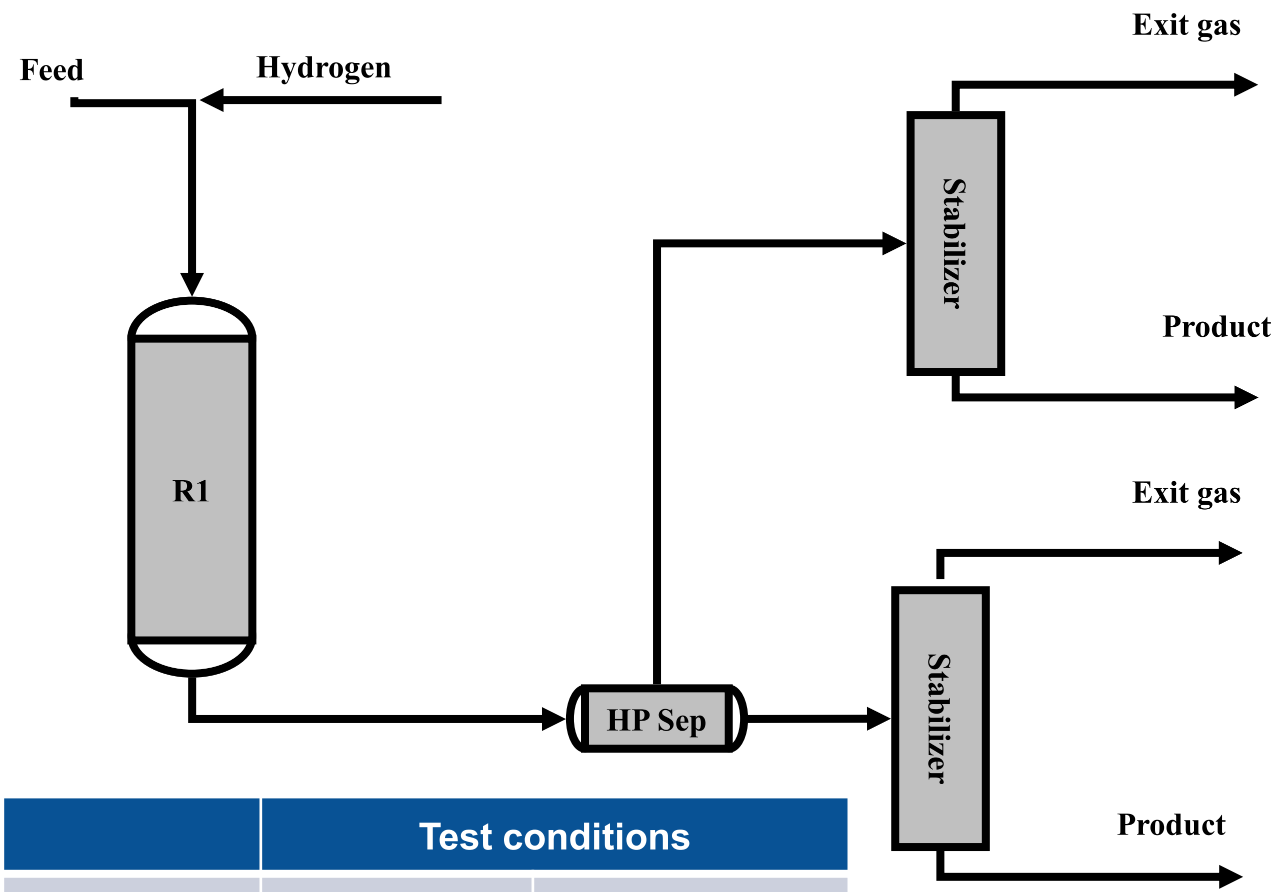
	PO.X.RTI	PO.X.RTI.B2	PO.X.RTI.B3
C, wt% (dry)	75	75	70
H, wt% (dry)	6	8	7
O, %wt (dry)	19	17	24
S, wt ppm	576	55	278
N, wt ppm	1390	1390	1700
Si, wt ppm	25	9.5	7.9
Na, wt ppm	16.3	38.3	16.5
K, wt ppm	8.3	5.9	3.2
Ca, wt ppm	23.5	17	9
P, wt ppm	8.5	1.1	1.4



Combined sample (PO.X.RTI.B3) that consists of 8 liters PO.X.RTI and 40 liters PO.X.RTI.B2

Bio-crude Upgrading

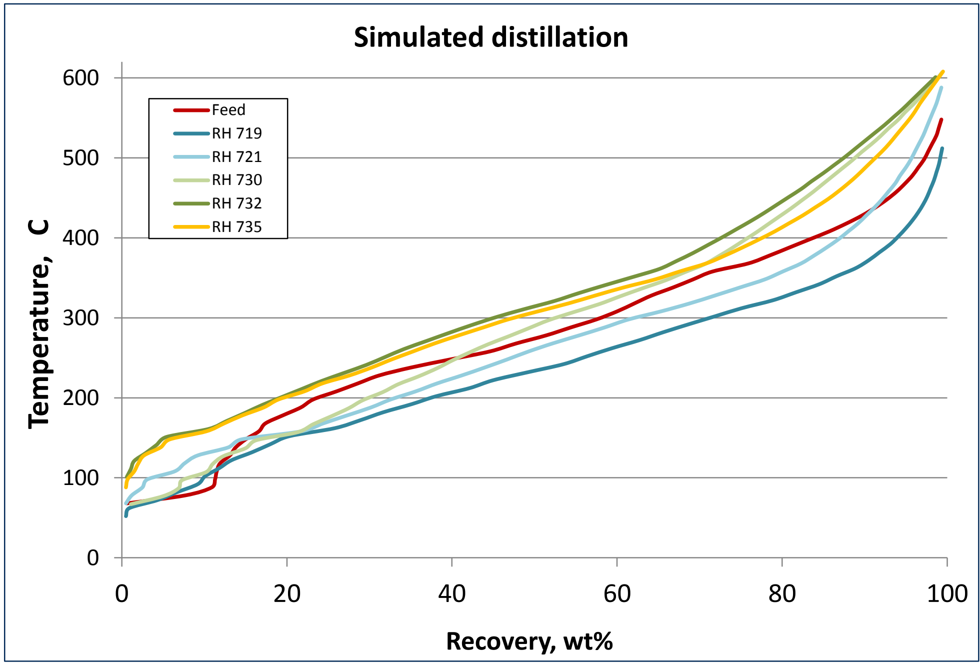




	Test conditions	
Temperature	350 – 375 °C	660 – 705 °F
LHSV	0.5 1/h	0.5 1/h
Pressure	100 barg	1450 psig
H_2/oil	2000 Nl/l	11870 SCF/BBL

Preliminary Bio-crude Upgrading Results

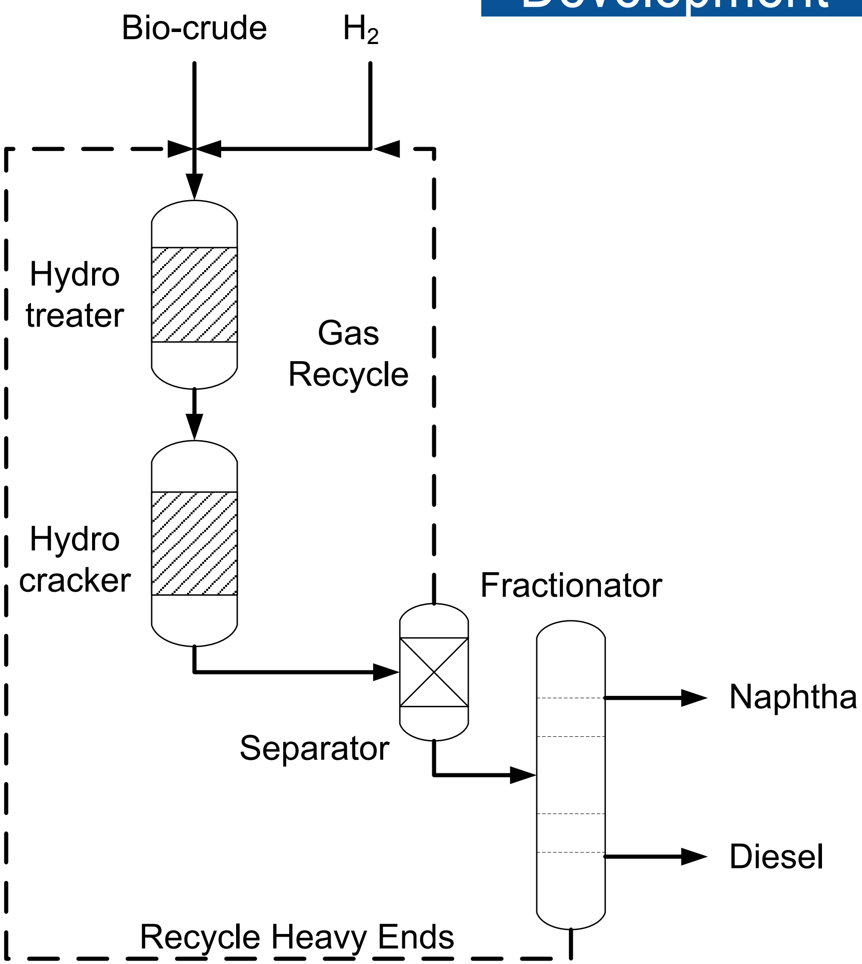
	FEED	PRODUCT				
Run Hour		719	721	730	732	735
Temp, °C		350	350	365	365	375
S, wt%	0.03					
N, wt ppm	1700					
H, wt%	7	11.6	12.2	11.1	10.6	10.8
O, wt%	24					
C, wt%	70					
SG 60/60°F	1.16	0.905	0.898	0.947	0.952	0.997
CCI 4337	16	29	33	27	26	22
Aromatics						
Mono	-	--	--	21.9	25.7	21.7
Di	-	--	--	4.7	5.7	5.5
Tri	-	--	--	15.4	19.6	16.0



- Analysis can't be performed (Sample won't dissolve)

-- Not enough sample

Hydroprocessing Reactor Unit for Integrated Process Development



Conceptual Process Flow Diagram for Bio-crude Hydroprocessing (Recycle streams to be validated)

Hydroprocessing reactor with a high-pressure separator (HPS) followed by a low-pressure stabilizer (LPS) for removal of gases and other non-condensed light hydrocarbons

Design Basis

- Reactor volume - 350 ml
- Catalyst volume - 20 to 100 ml of catalyst
- Liquid hourly space velocity - 0.5 to 1.0
- Flow rates - 10 to 100 ml/h
- N_2 is used as the stripping agent
- H_2/bio-crude ratio will depend on the H_2 consumption that will be adjusted as needed.

Process Development Hydroprocessing Unit

UNIT OPERATIONS

- Oil feed system including pumps and flow control
- Gas feed system
- Reactor system
- Separator system
- Gas and liquid sampling system

Design temperature: 450C
Max. operating temperature: 430C
Design pressure: 3000 psig
Max. operating pressure: 2500 psig

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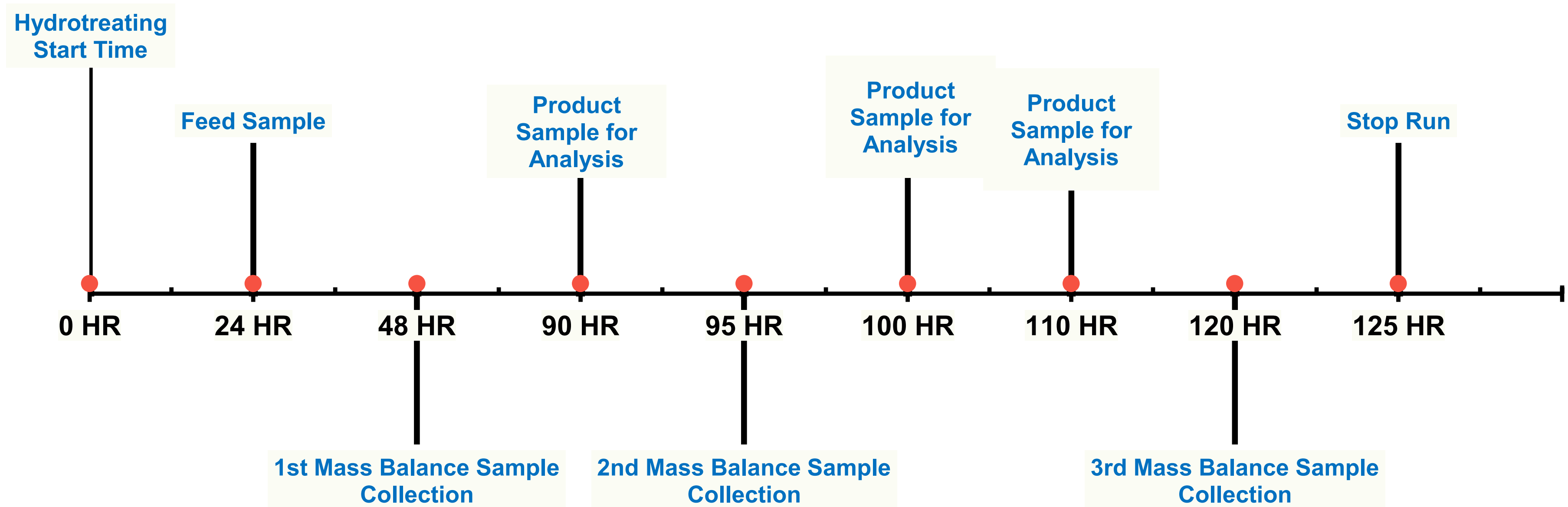
1st VGO Baseline Experiment (125 Hours)



VGO

HDT Product

4 - Relevance

BETO MYPP: The strategic goal of Thermochemical Conversion R&D is to develop commercially viable technologies for converting biomass into energy-dense, fungible, finished liquid fuels, such as renewable gasoline, jet, and diesel, as well as biochemicals and biopower.

Applicable Thermochemical Conversion Process Steps*:*

- *Deconstruction to Form Bio-Oil Intermediates*
- *Bio-Oil Intermediate Stabilization and Upgrading*

Performance Milestones for Thermochemical Pathways

- By 2017, achieve an nth plant modeled conversion cost of $2.50/GGE via a thermochemical pathway. This contributes to a minimum gasoline and diesel blendstock fuel selling price of $3.50/GGE in 2011 dollars.
- By 2017, validate the R&D performance goal of $2.50/GGE nth plant modeled conversion cost and thus the Office's performance goal of $3.00/GGE MFSP by performing integrated operations using on-specification feedstock via a thermochemical pathway that produces gasoline and diesel blendstock fuels.

5 - Future Work

1TPD Pilot Plant Operation

- Improve operational experience to achieve long-term steady-state operation (at least 100 hours continuous)
- Evaluate aqueous phase recycling for quench to reduce fresh water consumption
- Test at least 3 different feedstocks and produce quantities for upgrading tests

Bio-crude Upgrading

- Validate bio-crude upgrading to gasoline and diesel range hydrocarbons
- Determine biofuel yields, carbon efficiency, and product split (gasoline/diesel/naphtha)
- Shakedown and operate hydrotreating Unit at RTI
- Optimize catalyst formulation and process conditions to maximize biofuel yield
- Long-term upgrading (1000 hours) to determine upgrading catalyst stability and lifetime

Techno-economic Analysis

- Updated process models and economics incorporating pilot plant and upgrading data

Summary

Directly supports BETO Thermochemical Conversion R&D Objectives
- Pilot-scale bio-crude production
- Bio-crude stabilization and upgrading

Building on successful proof-of-concept (ARPA-E project)
- Proof-of-principle biomass catalytic fast pyrolysis and bio-crude upgrading
- Catalyst development and scale-up
- Design, installation, and commissioning of 1 TPD catalytic biomass pyrolysis unit

Leveraging extensive refining expertise at Haldor Topsøe A/S
- Integrated work plan for bio-crude upgrading
- Catalyst selection and process optimization
- Experimental results scale to commercial systems

Project success
- Long term bio-crude production and upgrading
- Technology at a process development unit (PDU) status by the end of the project
- Updated techno-economic analysis with commercially-relevant experimental data

Acknowldegments

BETO Project Officer: Liz Moore

Idaho National Laboratory

- Tyler Westover

RTI Contributors

- David C. Dayton (PI)
- John Carpenter
- Jonathan Peters
- Gary Howe
- Atish Kataria
- David Barbee
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- Michael Carpenter
- Kaige Wang
- Nandita Akunuri

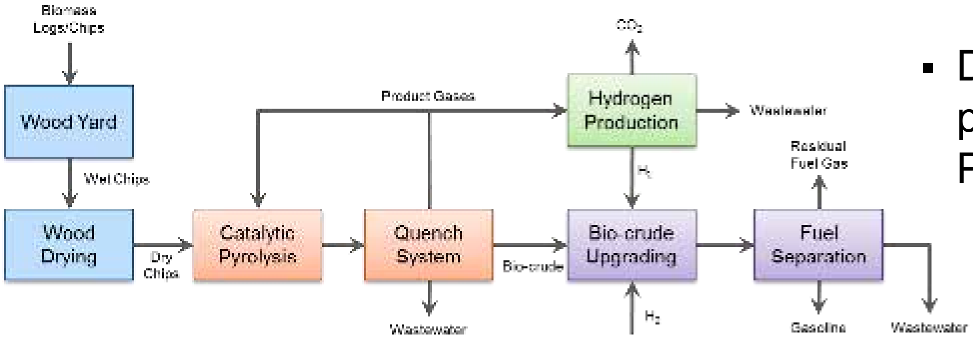
Haldor Topsoe

- Kim Knudsen
- Glen Hytoft
- Jostein Gabrielsen
- Nadia Luciw Ammitzboll
- Jeppe Kristensen

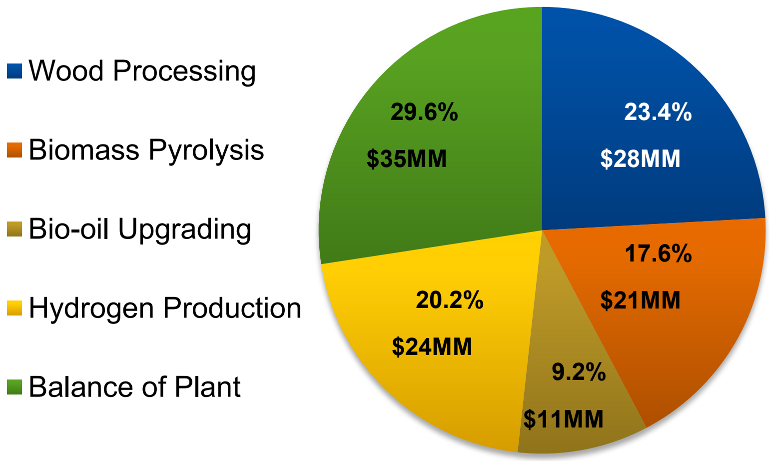
Additional Information

- Publications/Patents/Awards – none
- Presentations
- D.C. Dayton, "Catalytic Biomass Pyrolysis in a 1 ton/day Pilot Plant." Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, Denver, CO, 2-5 September 2014.
- J.C. Carpenter, D.C. Dayton, and J. Gabrielsen, "Hydroprocessing of Catalytic Fast Pyrolysis Bio-crude." Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, Denver, CO, 2-5 September 2014.
- D.C. Dayton, "Catalytic Biomass Pyrolysis Technology Development for Advanced Biofuels." Oral Presentation, TCBiomass 2013 September 3-6, 2013 Chicago, IL.
- M. Von Holle, "Small Scale Catalyst Testing with Biomass for Advanced Biofuels Technology Development." Poster Presentation, TCBiomass 2013 September 3-6, 2013 Chicago, IL.
- J. Carpenter, "Low Oxygen-Content Bio-Crude via Single Step Hydropyrolysis." Poster Presentation, TCBiomass 2013 September 3-6, 2013 Chicago, IL.
- J. Hlebak, "Experimental Capabilities at RTI International to Support R&D for Direct Biomass Liquefaction Pathways." Poster Presentation, TCBiomass 2013 September 3-6, 2013 Chicago, IL.
- J. Peters, "Deoxygenation Chemistry of Bio-oil Model Compounds with Selected Catalysts." Poster Presentation, TCBiomass 2013 September 3-6, 2013 Chicago, IL.

Techno-economic Analysis Summary



Equipment Cost By Area



- Detailed techno-economic analysis was performed for a 2000 TPD Catalytic Fast Pyrolysis Processes
  - Developed preliminary process flow diagrams and heat and material balances
  - Generated sized equipment list
  - Generated utility summary
  - Developed capital cost estimate
  - Developed O&M costs
  - Generated Pro Forma to predict pre-tax IRR
  - Performed risk analysis to identify the areas of uncertainty
- Analysis indicate attractive IRR potential
  - Gasoline selling price & yield are main drivers
  - ~$400 MM CAPEX
  - < $3/gal cost of production

Responses to Previous Reviewers' Comments

Please evaluate the degree to which:

- The project performers have made progress in reaching their objectives based on their project management plan.
- The project performers have met their objectives in achieving milestones and overcoming technical barriers.
- New project performers have identified viable plans to accomplish their objectives.

Reviewer Comments

Allowing for late start, reasonable progress to date, although it's hard to tell how much of the work was done under the ARPA-e grant and how much under this one. Looks like a lot of the work was part of the ARPA-e project. Unfortunate that sub-contracts are still under negotiation 1 yr. & 8 months after the award date; these should have been agreed in principle at the time of the application and finalized long before now.

System installed last month; making progress; however, some issues not addressed before scale up, little concerning.

Limited progress due to kickoff in late 2012. Major effort is underway.

Significant progress has been made. The 1 TPD CFP FCC-type reactor has been designed, built and delivered and was installed in April and will be commissioned in June. Most of the larger-scale industry-based collaborations, including this one, experienced delays in getting contracts in place. In this case, the delay is longer than usual, and is now at 20+ months without technical progress. In some ways, this may be ok since the larger-scale pyrolysis unit is just being installed. However, the significant delay needs to be closely monitored.

Presenter Response

Delays associated with award negotiation and subcontract were typical of other DOE/BETO awards we have recevied in the recent past. The cost share requirement prohibits us from aggressively starting the project work plan until all contractual issues are resolved since it puts RTI at financial risk, but we do maintain the core project team and align our efforts to complete early project deliverables once negotiations are complete. In this case, the delays will result in more efficient sample production for the hydrotreating studies becuase the 1 TPD pilot plant installation is complete and smaller scale laboratory reactors do not need to be used. As previously mentioned, the subcontract is now in place and fully executed.

Responses to Previous Reviewers' Comments

1) Please evaluate the degree to which:

- The project performers have implemented technically sound research, development, and deployment approaches and have demonstrated the results needed to meet their targets.
- The project performers have identified a project management plan that includes well-defined milestones and adequate methods for addressing potential risks.

Reviewer Comments:

Project selected 8/11 but not started until 11/12; not sure who's at fault for that, but what a waste! Strong R&D plan; involvement of Haldor-Topsoe and two reputable feedstock providers is useful; refining & marketing partner would have been nice to have. Very useful to have a 2000 tpd design package as part of the deliverables! Overall, a comprehensive study of process & catalysis for pyrolysis and hydroprocessing, including modelling & design. 1 tpd system is just now mechanically complete - not yet started up Based on a cat. pyrol. process they developed under an ARPA-e grant. Hydroprocessing will be part of H-T scope

August 2012 money awarded; Pilot scale processing at RTI with help from Haldor Topsoe; Need to integrate fp with hydrotreating; milestone based technical approach

Appears to be a sophisticated development effort involving knowledgable organizations. This process integrates in-situ CFP with HDO in a 1 TPD in-situ CFP followed by HDO in a smaller unit. This project intends to design, build, operate and model an integrated CFP/HDO unit and utilizes a milestone based approach.

This project leverages ARPA-E experience and Haldor Tospoe's engineering design experience.

Overall, the approach seems to be solid, well-planned and capable of commercial success.

The overall project approach is very good, and excellent partners are involved. Goals are clear

Presenter Response:

We want to thank the reviewers for their diligent and insightful comments regarding our project. As a general comment, we have completed negotiations with our partner and now have a fully executed subcontract with Haldor Topsoe. With the startup and commissioning of the 1 TPD pilot plant, we will be generating numerous samples for upgrading studies and executing the project plan.

Responses to Previous Reviewers' Comments

Please evaluate the degree to which:

The project contributes to meeting the goals of the specific technology area and of the Bioenergy Technologies Office, as identified in the Office's November 2012 Update of the Multi-Year Program Plan.

The objectives of the project have relevance for the bioenergy industry and project performers have considered commercial applications for the expected outputs of the project.

Reviewer Comments

Highly relevant to the BETO Program goals. By decoupling a potentially superior 1st stage of pyrolysis with fuel finishing by hydrotreating offsite, the performers have a concept that could be the core of a commercially viable technology.

Relevant, but didn't show how well you are meeting that relevance

A good parallel development effort that complements DOE and NL research and research goals.

Nothing really novel here but could be successful and move things forward if >1000 hrs of operation achieved

Highly relevant if successful -- could greatly shorten the time to successful catalytic pyrolysis. BETO should consider how, if successful, this project could serve as a validation of the pyrolysis pathway, thus reducing the need for resources for otherwise duplicative efforts.

Presenter Response

Our experimental capabilities and facilities used in this project directly support the in situ bio-oil pathway defined by BETO for producing cost-competitive advanced biofuels for $3/gallon. With minimal modification, we could also adapt our 1 TPD system to evaluate the ex situ bio-oil pathway as well.

Responses to Previous Reviewers' Comments

Please evaluated the degree to which:

- The project performers have identified critical factors (including technical, market, and business) that will impact the potential technical and commercial success of the project.
- The project performers have presented adequate plans to recognize, address, and overcome the top two to three challenges (technical and non-technical) that need to be overcome for achieving successful project results.
- Successful completion of the project will advance the state of technology and impact the viability of commercial bioenergy applications.

Reviewer Comments

Good, comprehensive, but somewhat generic.

Not sure you operated reliably on small scale, so not sure you will be successful at larger scale

No preliminary TEA results

Demo fast pyro. Demo 1000 hr hydroprocessing operation. Study and meet product quality goals.

The critical performance metrics/barriers are well defined and understood.

Technical and generic factors listed are good; the critical management factor of getting an agreement with partner in place is not mentioned

Presenter Response

Comprehensive catalyst development and laboratory-scale (1" diameter fluid bed reactor) catalytic biomass fast pyrolysis experiments with > 95% mass balance and product stream analyses were completed in our ARPA-E project. The results from this previous work provided the basis for the design of the 1 TPD pilot unit. We have preliminary TEA results from the ARPA-E project that suggest our CFP process is cost competitive and could achieve the $3/gallon BETO target but it includes generic assumptions about the upgrading step. These assumptions will be updated based on the hydrotreating studies and a revised TEA will be developed within this project. Technical barriers and metrics not already identified will be addressed as the project progresses.

Responses to Previous Reviewers' Comments

Please evaluate the degree to which:

- The project performers have outlined adequate plans for future work, including key milestones and go/no go decision points.
- The project performers have addressed how they plan to deal with upcoming decision points and any remaining issues.

Reviewer Comments

Reasonably detailed plan. Most of the project still lies ahead. Gantt chart was not presented and is only marginally legible in the slide deck; this should have been part of the presentation, and the progress that was made under the ARPA-e grant could have been summarized in many fewer slides.

Lots to do in order to complete project

Project is just kicking off, so future work is the bulk of the project involving pilot plant operations to generate volumes of bio-oils and treated products.

Future work appears to be well planned with ample schedule time.

The entire project is yet to be started, but the plan seems reasonable assuming it gets started.

Presenter Response

Now that the contractual negotiations are complete, we will aggressively execute the project plan. The Gantt chart presented as supplemental information has been approved by our DOE Project Officer as submitted with our Annual Operating Plan. Progress will be updated on a quarterly basis and plans will be revised in consult with DOE as needed.

Responses to Previous Reviewers' Comments

Please comment on the degree to which the project coordinates with other institutions and projects to provide additional benefits to both BETO and the industry. Please provide suggestions on additional opportunities for encouraging further coordination.

Reviewer Comments

Good group of collaborators but for the absence of a refining & marketing partner. Such a partner will have to be engaged eventually, but otherwise there is a reasonable team for tech transfer.

No publications listed.

This project has many partners/participants including RTI, haldor topsoe, ADM (corn stover), and the Biofuels center of NC (woody biomass), which together seem capable of advancing the SOT.

Good potential for tech transfer if successful

Presenter Response

We have just completed a Joint Development Agreement with Haldor Topsoe as part of our commercialization strategy. Haldor Topsøe is uniquely qualified as a market leader in the field of heterogeneous catalysis to assess the commercial viability of hydroprocessing bio-crude intermediates. Their catalysts and technologies are supplied to the refining industry and they have developed process technologies and catalysts for virtually all areas of hydroprocessing. Their worldwide market share in hydroprocessing catalysts is more than 20%. In high severity applications such as ULSD production and FCC pretreatment and hydrocracking, they have shares of 20 to 40%. We have had interest in our technology from refiners (we are working with Phillips66 in our ARPAE project) but they are not partners in this particular project. As we develop more understanding and demonstrate the technical feasibility of upgrading our bio-crude intermediate there may be additional opportunties for strategic partnerships. A goal of this project is to advanced the commercial potential of our catalytic biomass pyrolysis technology and as soon as we secure our intellectual property we will begin publishing the results of our work.

Responses to Previous Reviewers' Comments

Please provide an overall assessment of the project based on the above criteria. Please note that these comments will be featured in the Final Peer Review Report.

Reviewer Comments

Solid project with real commercial potential. Delayed start means that work has only begun, so much of the potential remains just that for now.

Had some issues with glossing over getting certain things done before scaling up.

Problematic that RTI does not having contract yet with Topsoe

Appears to be a well thought out and well executed process and catalyst development effort. This is a project that may provide some good results/data. There is nothing novel in the configuration but, if successful, could be commercialized as multiple small units located near the biomass source producing either drop in fuels or a stable, low oxygen, low TAN bio-oil that can be pipelined to a central processing facility.

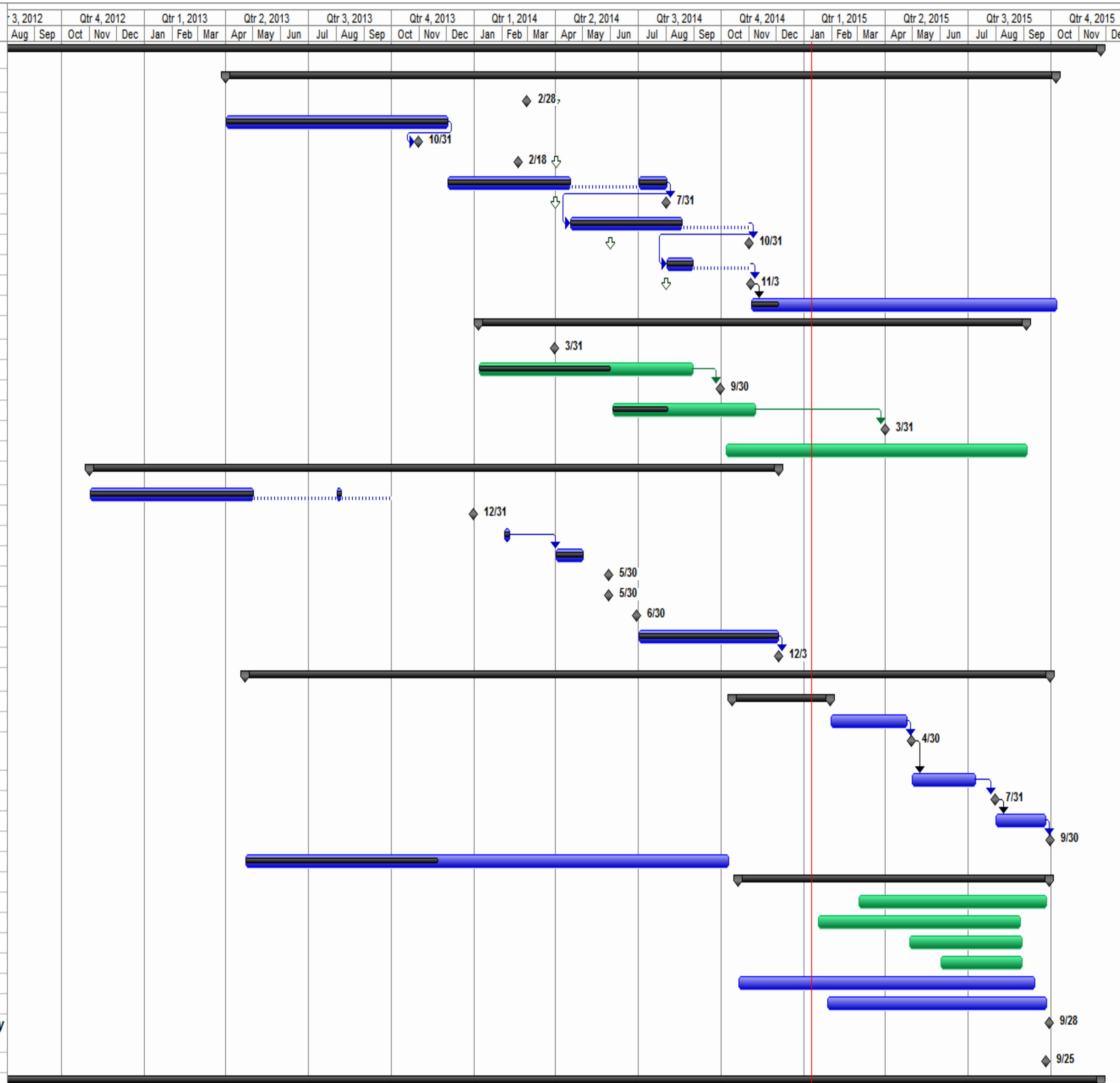
This makes the process more flexible and improves the probability of commercial success.

While the significant delay in project start-up is troubling, the project may ultimately benefit since larger scale equipment will now be in place. The larger-scale equipment will provide more realistic data for the proposed effort.

Presenter Response

Since the Peer Review Meeting, our subcontract with Haldor Topsoe has been signed and fully executed and the 1 TPD pilot plant commissioning has begun. The design of the catalytic biomass pyrolysis reactor system may be quite familiar; however, the novel catalyst developed for this process has the potential to improve the yield of low oxygen content bio-crude that is more easily upgraded than other bio-oil intermediates. We intend to optimize process conditions in the CFP step to maximize bio-crude yields while also investigating the impact of the bio-crude composition in the hydrotreating step to maximize biofuel yield. The integration of the biomass conversion and upgrading steps in a single experimental facility allows us to validate process conditions that maximize process yields and carbon efficiency while minimizing hydrogen demand. The results from this project will provide the technical and economic data required for scale-up and commercialization to produce cost-competitive advanced biofuels for $3/gallon.

ID	Task Name
1	**Thermochemical Upgrading Project Plan**
2	**Task 1: Pilot-scale Catalytic Biomass Pyrolysis**
3	**M1.1 Milestone: 3 feedstocks characterization**
4	Process development and startup
5	**M1.2 Milestone: 1 TPD Commissioning Complete**
6	**D1.1.1 Prepare and deliver biomass feedstock**
7	Produce 25 gal of pine bio-crude
8	**D1.2.1 Deliverable: 25 gal of pine bio-crude**
9	Produce 25 gal of hybrid poplar bio-crude
10	**D1.2.2 Deliverable: 25 gal of poplar bio-crude**
11	**Produce 25 gal of corn stover bio-crude**
12	**D1.2.3 Deliverable: 25 gal of corn stover bio-crude**
13	Additional bio-crude production
14	**Task 2: Hydroprocessing Evaluation and Optimization**
15	**M2.1 Develop upgrading strategy for RTI bio-crude**
16	Biocrude hydrotreating (catalyst/process - T, P, SV, etc.)
17	**M2.2 Hydroprocessing conditions for 3 bio-crude samples**
18	Bio-crude/refinery intermediate blends
19	**M2.3Technical evaluation of bio-crude/refinery intermediate blends**
20	Hydroprocessing modeling
21	**Task 3: Hydroprocessing Reactor Design and Fabrication**
22	Catalytic pyrolysis reactor design and fabrication
23	**D3.1.1 Hydroprocessing Unit design basis**
24	Complete Hydroprocessing unit design package
25	***Process hazard analysis***
26	**M3.1 Hydroprocessing Unit Design**
27	**D3.2.1 Design Safety Review**
28	**GN3.1 Technical Review and Cost analysis**
29	Hydrotreater Reactor Fabrication
30	**D3.3.1 Integrated System Delivery**
31	**Task 4: Integrated Process Operation**
32	**Hydrotreating Reactor**
34	Wood catalytic pyrolysis (1000 hours total) on blends
35	**M4.1 Complete 1000 hours integrated operation with woody feedstock**
36	Switchgrass catalytic pyrolysis (500 hours) on blends
37	**M4.2 Complete 500 hours integrated operation with switchgrass**
38	Corn stover catalytic pyrolysis (500 hours) on blends
39	**M4.3 Complete 500 hours integrated operation with corn stover**
40	Catalyst Characterization and Sample Analysis
41	Task 5:Process Modeling and Refinery Integration
42	Insertion point determination
43	Blending ratios and other considerations
44	Finished product quality and specifications
45	Integrated hydroprocessing modeling
46	Techno-economic analysis
47	Life cycle assessment (GHG reductions, etc.)
48	***Refinery integration options for catalytic biomass pyrolysis technology***
49	***Design package for a 2000 tpd integrated process for TEA and LCA***
50	Task 6: Project Management



Task 1 Milestones and Deliverables

Task #	Task or Subtask	Milestone Number*	Milestone Description	Milestone Verification Process (What, How, Who, Where)	Date (Month)
1	Pilot-scale Catalytic Biomass Pyrolysis	M1.1	Detailed characterization of 3 high impact biomass feedstocks	INL to provide detailed physical and chemical analyses of hybrid poplar and switchgrass. RTI to provide detailed physical and chemical characterization of loblolly pine feedstock. Analyses to include: particle size distribution, density, moisture content, proximate and ultimate analyses, and ash composition.	2/2014 (29)
1	Pilot-scale Catalytic Biomass Pyrolysis	M1.2	Complete 1TPD unit commissioning	Demonstrate 1000 lb/hr catalyst circulation under hot conditions, steady biomass feeding at a minimum of 100 lbs/hr, and steady-state catalytic biomass pyrolysis for a minimum of 4 hours.	8/2013 (23)
1.1	Feedstock Preparation	D1.1.1	Prepare and deliver biomass feedstock	INL to prepare 5 tons of 0.5" top size (minimum) hybrid poplar and switchgrass material with less than 20% moisture content and deliver to RTI	3/2014 (30)
1.1	Feedstock Preparation	D1.1.2	Prepare and deliver feedstock	INL to prepare an additional 5-10 tons of 0.5" top size (minimum) hybrid poplar and switchgrass material with less than 20% moisture content to be delivered in Year 3.	3/2015 (42)
1.2	Pilot-scale Operation for Bio-crude Production	D1.2.1	Loblolly pine bio-crude production	RTI to produce at least 25 gallons of loblolly pine bio-crude with less than 20 wt% oxygen in the 1TPD unit for upgrading studies in Task 2.0.	3/2014 (30)
1.2	Pilot-scale Operation for Bio-crude Production	D1.2.2	Hybrid poplar bio-crude production	RTI to produce at least 25 gallons of hybrid poplar bio-crude with less than 20 wt% oxygen in the 1TPD unit for upgrading studies in Task 2.0.	5/2014 (32)
1.2	Pilot-scale Operation for Bio-crude Production	D1.2.3	Switchgrass bio-crude production	RTI to produce at least 25 gallons of switchgrass bio-crude with less than 20 wt% oxygen in the 1TPD unit for upgrading studies in Task 2.0.	6/2014 (33)

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Task 2: Milestones and Deliverables

Task #	Task or Subtask	Milestone Number*	Milestone Description	Milestone Verification Process (What, How, Who, Where)	Date (Month)
2	Hydroprocessing Evaluation and Optimization	M2.1	Develop upgrading strategy for RTI bio-crude samples	Haldor Topsøe to select hydroprocessing catalysts and identify process conditions (T, P, P_{H2}) for bio-crude upgrading	6/2014 (33)
2	Hydroprocessing Evaluation and Optimization	M2.2	Develop optimized process conditions for bio-crude upgrading	Optimize bio-crude upgrading conditions based on long-term hydroprocessing of bio-crude samples from at least 3 different feedstocks.	9/2014 (36)
2	Hydroprocessing Evaluation and Optimization	M2.3	Bio-crude/refinery intermediate co-processing	Technical evaluation of strategies for co-processing	3/2015 (42)

Task 3: Milestones and Deliverables

Task #	Task or Subtask	Milestone Number	Milestone Description	Milestone Verification Process (What, How, Who, Where)	Date (Month)
3	Hydroprocessing Reactor Design and Fabrication for Integrated Process Development	GN3.1	Technical Review and Cost Analysis of Hydroprocessing Unit	RTI and DOE/BETO review design and cost of hydroprocessing unit prior to fabrication	4/2014 (31)
3.1	Hydroprocessing Unit Design	D3.1.1	Hydroprocessing unit design basis	RTI and Haldor Topsoe to complete PFD, HMB, and preliminary P&ID's for dual-reactor hydroprocessing unit	12/2013 (27)
3.2	Process Hazard Analysis	D3.2.1	Design Safety Review	Conduct a Design Safety Review meeting overseen by an independent consultant including members of the design team (RTI, Haldor Topsoe, and consultant) and operating staff (RTI)	3/2014 (30)
3.3	Fabrication and Installation	D3.3.1	Hydroprocessing Unit Delivery and Installation	Vendor/engineering design partner to complete fabrication of hydroprocessing unit for delivery and installation at RTI.	11/2014 (38)
3.3	Hydroprocessing Unit Commissioning	GN3.2	Commissioning and initial operation of hydroprocessing unit	RTI, with technical support from Haldor Topsoe, will commission the new hydroprocessing unit by demonstrating 8 hours of biocrude upgrading	3/2015 (42)

Task 4: Milestones and Deliverables

Task #	Task or Subtask	Milestone Number*	Milestone Description	Milestone Verification Process (What, How, Who, Where)	Date (Month)
4	Integrated Bio-crude Upgrading and Process Operation	M4.1	Loblolly pine bio-crude upgrading	RTI to complete up to 1000 hours of upgrading with loblolly pine bio-crude. Document optimized process parameters for the unit operations in the integrated catalytic biomass pyrolysis/hydroprocessing process and determine biofuel yields and quality.	6/2015 (45)
4	Integration Bio-crude Upgrading and Process Operation	M4.2	Hybrid poplar bio-crude upgrading	RTI to complete up to 500 hours of upgrading with hybrid poplar bio-crude. Document optimized process parameters for the unit operations in the integrated catalytic biomass pyrolysis/hydroprocessing process and determine biofuel yields and quality.	7/2015 (46)
4	Integration Bio-crude Upgrading and Process Operation	M4.3	Switchgrass bio-crude upgrading	RTI to complete up to 500 hours of upgrading with switchgrass bio-crude. Document optimized process parameters for the unit operations in the integrated catalytic biomass pyrolysis/hydroprocessing process and determine biofuel yields and quality.	8/2015 (47)

Task 5: Milestones and Deliverables

Task #	Task or Subtask	Milestone Number*	Milestone Description	Milestone Verification Process (What, How, Who, Where)	Date (Month)
5	Process Modelling and Refinery Integration	M5.1	2000 TPD Integrated Process Design and Economics	RTI and Haldor Topsoe to develop a design package for a 2000 tpd integrated catalytic biomass pyrolysis/hydroprocessing process based on experimental results.	9/2015 (48)
5	Process Modelling and Refinery Integration	M5.2	Economic analysis of the technical feasibility of co-processing bio-crude and hydrocarbon intermediate streams to define refinery integration options for catalytic biomass pyrolysis technology	Based on experimental results and hydroprocessing model development, Haldor Topsoe will determine the economic feasibility of options for integrating bio-crude upgrading in a variety of refinery unit operations	8/2015 (47)