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DLA Contracting Services
700 Robbins Avenue
Philadelphia, PA 19111

Submitted to:

COTR: Jose.Maniwang@dla.mil
ACO: valarie.woodbury@navy.mil
CO: angela.mattox@dla.mil

Submitted by:

PI: Pendse@maine.edu

Name of the preparer of the report:

Dr. Hemant Pendse, Principal Investigator
Director, Forest Bioproducts Research Institute

Telephone Number: 207-581-2290
E-mail : pendse@maine.edu

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FINAL REPORT

Woody Biomass Conversion to JP-8 Fuels

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Section II - Executive Summary:

Woody Biomass Conversion to JP-8 Fuels

This University of Maine (UMaine) Wood to Jet Fuel project has demonstrated technical and economic feasibility of producing jet fuel from renewable lignocellulosic biomass. Specific opportunities that would allow adaptation or repurposing of existing wood processing infrastructure (Kraft pulp mills, in particular) to produce jet fuel and diesel from low-cost woody biomass have been identified. The specific feedstock focus in this study was on forest residues available as low-grade wood, often used for direct combustion in wood-fired industrial boilers for their heating value, and not as a source of wood fiber.

The wood to jet fuel pathway investigated in this project consists of two steps. In step one, the five- and six-carbon complex sugars in wood are converted to a liquid intermediate consisting of a mixture of Furfural, Levulinic Acid, and Formic Acid. *Furfural* is recovered as a co-product, and a mixture of Calcium Levulinate and Calcium Formate salts is prepared for further processing using Calcium Oxide for neutralization. In step two, the Calcium Levulinate–Formate mixture is subjected to the patented Thermal DeOxygenation (TDO) process to obtain synthetic crude called *TDO Oil*. Solid char from the TDO reactor is burned to provide process energy, while allowing Calcium Oxide recycle. Synthetic crude TDO Oil is hydroprocessed to reduce its naphthalenes content, and then fractionated to obtain various boiling point cuts. Approximately 40% of the hydroprocessed TDO oil is in the JP-8 range, and 60% is in the F-76 range

In this project a floor-scale 50 L TDO reactor was developed for production of TDO oil starting with a 13 kg mixture of dry Levulinate and Formate salts in a single batch. One liter sample of 180 to 250 °C boiling point cut of hydroprocessed TDO Oil was tested at the Air Force Research Laboratory (AFRL) in Ohio to assess its suitability as a JP-8 drop in or blend. The AFRL tests confirmed that the jet fuel sample derived from TDO oil is primarily naphthenic, with the density which is "out of spec" at ~0.85 g per mL and the measured heat of combustion at 42.5 MJ/kg which is a bit below the spec limit of 42.8. However, it just means the fuel would have to be blended with conventional jet (or one of the low density alternative jet fuels). The freeze point is found to be less than -70 °C, and low temperature (-20 °C) viscosity is found to be 7.6 cSt which is below the limit of 8 cSt.

A detailed material balance analysis predicts that the overall mass yield of TDO oil is approximately 20% on complex six-carbon sugar mass in the biomass feed. Preliminary techno-economic analysis of a 2,000 dry tonne per day wood processing plant shows EBITDA of \$125 million. A compelling business case can be made for a continuous pilot-scale validation, using a variety of cellulosic feedstocks (including forest residues) for one barrel per day TDO oil production and its hydroprocessing.

Section III – Project Deliverables and Accomplishments:

UMaine's Wood-to Jet Fuel program had been focused on the Integrated Forest BioRefinery (IFBR) framework shown in Figure 1 and eight subsystems are listed in Table 1.

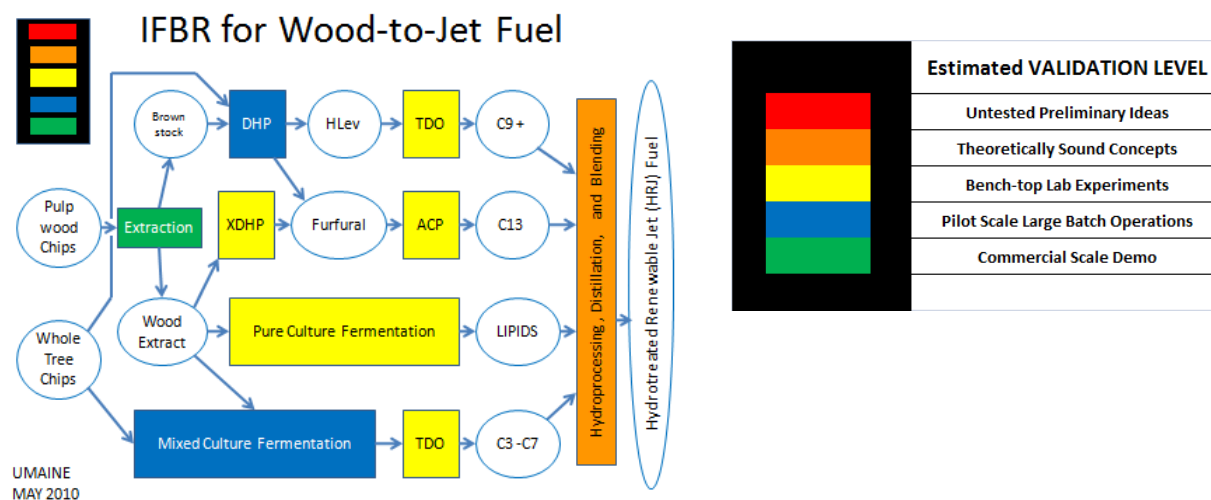


Figure 1: Early Concept of Integrated Forest BioRefinery for Wood to Jet Fuel

Table 1. List of Subsystems of UMaine Framework of IFBR for Wood to Jet Fuels

SUB 1	Extraction and extract conditioning if needed
SUB 2	DHP: Dehydration Process for Cellulose to Levulinic Acid (HLev) Conversion
SUB 3	XDHP: Dehydration Process for Xylan to Furfural Conversion
SUB 4	Pure Culture Fermentation of Conditioned Extract or Brownstock to Lipids
SUB 5	Mixed Culture Fermentation of Mixed-sugars in Raw extract to Mixed Acids
SUB 6	TDO: Thermal Deoxygenation of Carboxylate Salts
SUB 7	ACP: Aldol Condensation Process for Furfural to Tridecane Conversion
SUB 8	Hydroprocessing, Distillation & Blending
Wood Handling, On-site Steam, Power & Hydrogen Generation, and other co-products recovery processes not shown for convenience of simplification of graphical illustration.	

Specific project deliverables which were accomplished are given below.

Subsystem Assessment: Deliverable 1:

A Technology readiness level analysis for each subsystem, shows that the conversion pathways included here, in general depend on the conversion of complex sugar portion of biomass feed, and not lignin and ash portions. Furthermore, pulpwood, pulpwood extracts or brownstock do not make suitable candidates for low-cost feedstock for jet fuel production. Only forest residues, including logging residues consisting of tops and branches or pre-commercial thinnings and whole tree chips make suitable candidates for prices under \$40 per green ton. Two key parameters related to biomass composition are:

- (1) total mass fraction of five and six carbon complex sugars of dry biomass (which ranges from 60% to 65% for common lignocellulosics), and
- (2) the ratio of five carbon complex sugars to six carbon complex sugars (which ranges from 13% to 72%).

Figure 2 below compares biomass composition parameters of several feedstocks in triangular coordinates.

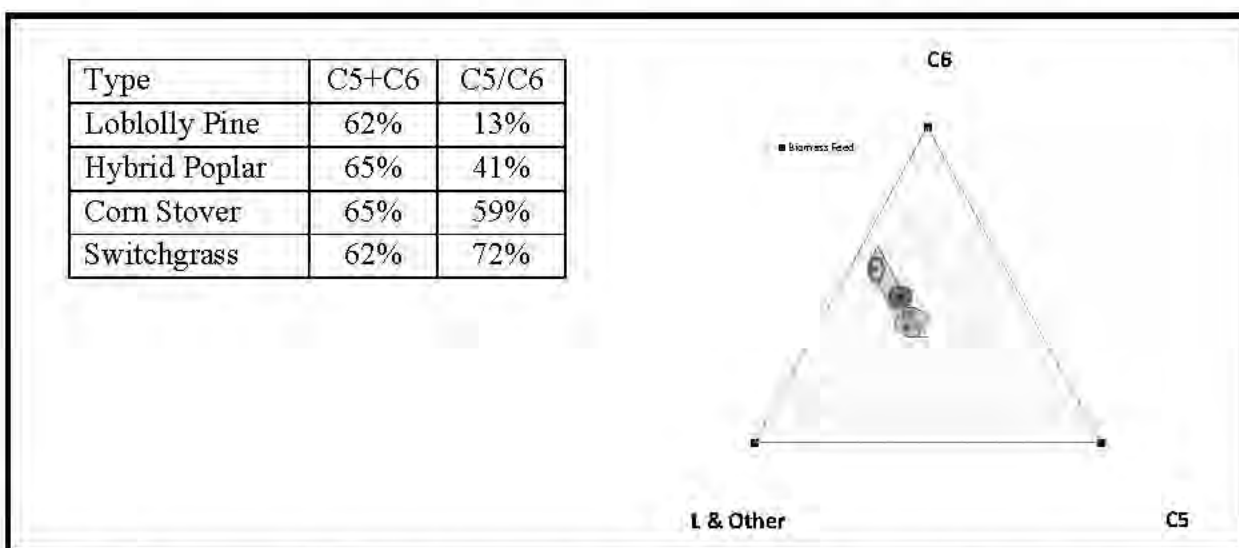
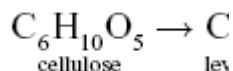


Figure 2: Biomass composition in terms of six-carbon complex sugars, five-carbon complex sugars, and remainder lignin & other matter

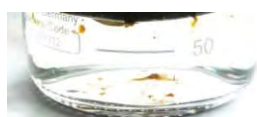
Direct conversion of complex sugars is preferable avoiding the need for producing clean simple sugars through controlled hydrolysis, and detoxification in a particular case of fermentation. Hydrolysis and dehydration of biomass complex sugars (Subsystems 2 & 3) has been demonstrated on a one ton per day pilot plant producing a stoichiometric mixture of levulinic and

formic acids, using several cellulosic feedstocks. Five-carbon complex sugars (e.g. xylan) yield furfural. This pilot plant facility is currently located in Old Town, Maine.



Thermal deoxygenation (Subsystem 6: TDO of carboxylate salts) was selected as an area of high impact risk reduction within the scope of the current project. Particular emphasis was put on mixtures of calcium levulinate and formate.

Using a mixture of calcium levulinate and formate in 1:1 molar ratio, TDO oil is produced in high yield and can be easily separated from other products such as water and char. In addition, the oil has a neutral pH, high energy density, low viscosity and hydrogen to carbon ratio of ~1.3. The extent of deoxygenation during TDO decreases the downstream hydrotreating required to produce a drop-in transportation fuel. Furthermore, this process does not use a catalyst, making it tolerant to trace impurities that could poison or foul precious metal catalysts.



Experimental research for targeted risk reduction: Deliverable 2:

Key experiments were conducted to produce sufficient quantities of TDO oil for independent testing, fractionation, and hydroprocessing. A floor-scale 50 L TDO reactor (See Figure 3) was developed for production of TDO oil starting with a 13 kg mixture of dry Levulinate and Formate salts in a single batch. Earlier experiments were limited to a Parr 300 mL batch reactor. These bench-scale experiments had already shown (Case et al. 2012) that 1:1 molar ratio of formate to levulinate gives highest oil yield with a higher heating value (HHV) in excess of 40 MJ/kg, with viscosity at 23 C of 20 cP. This raw TDO oil is known to be stable, highly deoxygenated, and also known to phase-separate from water. The TDO oil has a neutral pH with TAN of about 1.5 mg KOH per g of oil. Raw TDO oil (as well as hydroprocessed TDO oil) was fractionated using a BR 9400 ASTM Distillation set up (See Figure 4).¹

¹ **P.A. Case**, A.R.P. van Heiningen and M.C. Wheeler, "Liquid hydrocarbon fuels from cellulosic feedstocks via thermal deoxygenation of levulinic acid and formic acid salt mixtures," Green Chem. 14 (1), 85 – 89 (2012).

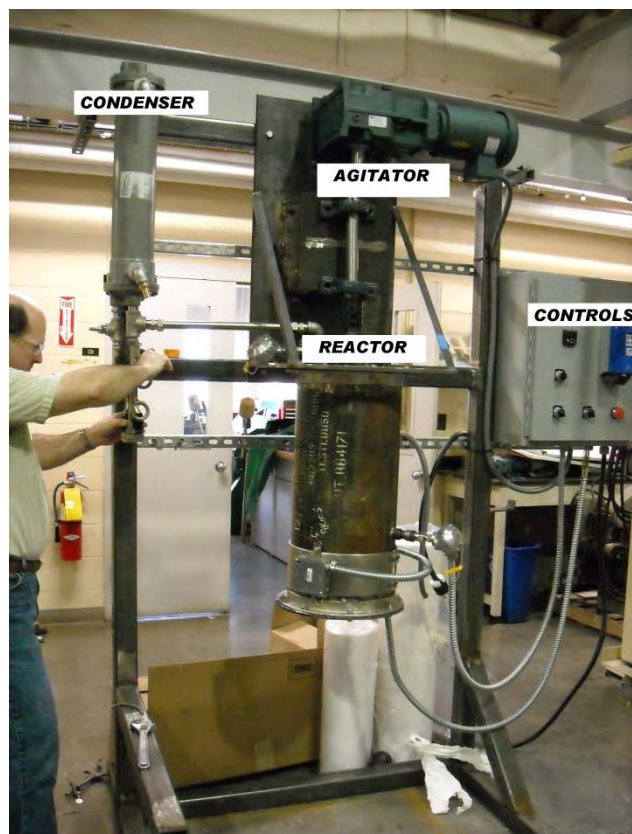


Figure 3: Floor-scale TDO reactor



Figure 4: ASTM Distillation system

Raw TDO Oils

Several batches of raw TDO oil were prepared. Raw TDO oil was fractionated to obtain so-called gasoline, JP-8, F-76, and Fuel Oil cuts for further analysis. The raw TDO oils were characterized for fuel and material properties according to ASTM methods. The oxygen by GC Low Ox method was found to be less than 1% by mass. The oils were found to have low total acid number less than 1.4 mg KOH/g oil, and a consistent boiling point distribution according to high temperature simulated distillation (ASTM 7169) shown in Figure 5.

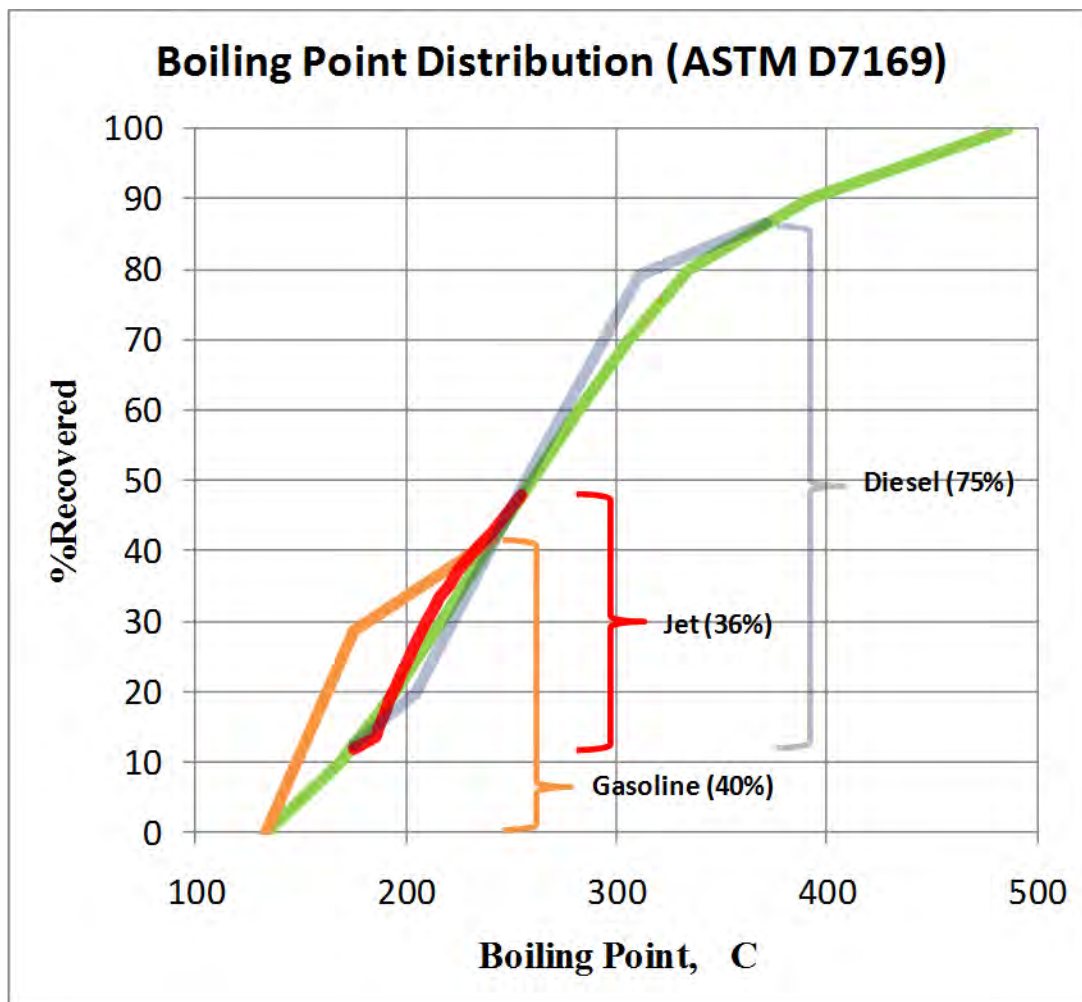


Figure 5: Boiling point distribution data for raw TDO oil with gasoline, jet and diesel cut fractions

The gasoline-cuts (sub-200 °C) of raw TDO oil consist primarily of aromatic and olefin compounds, (as shown in Figure 6) with a calculated octane rating of 82, which offers high potential as a gasoline blendstock.

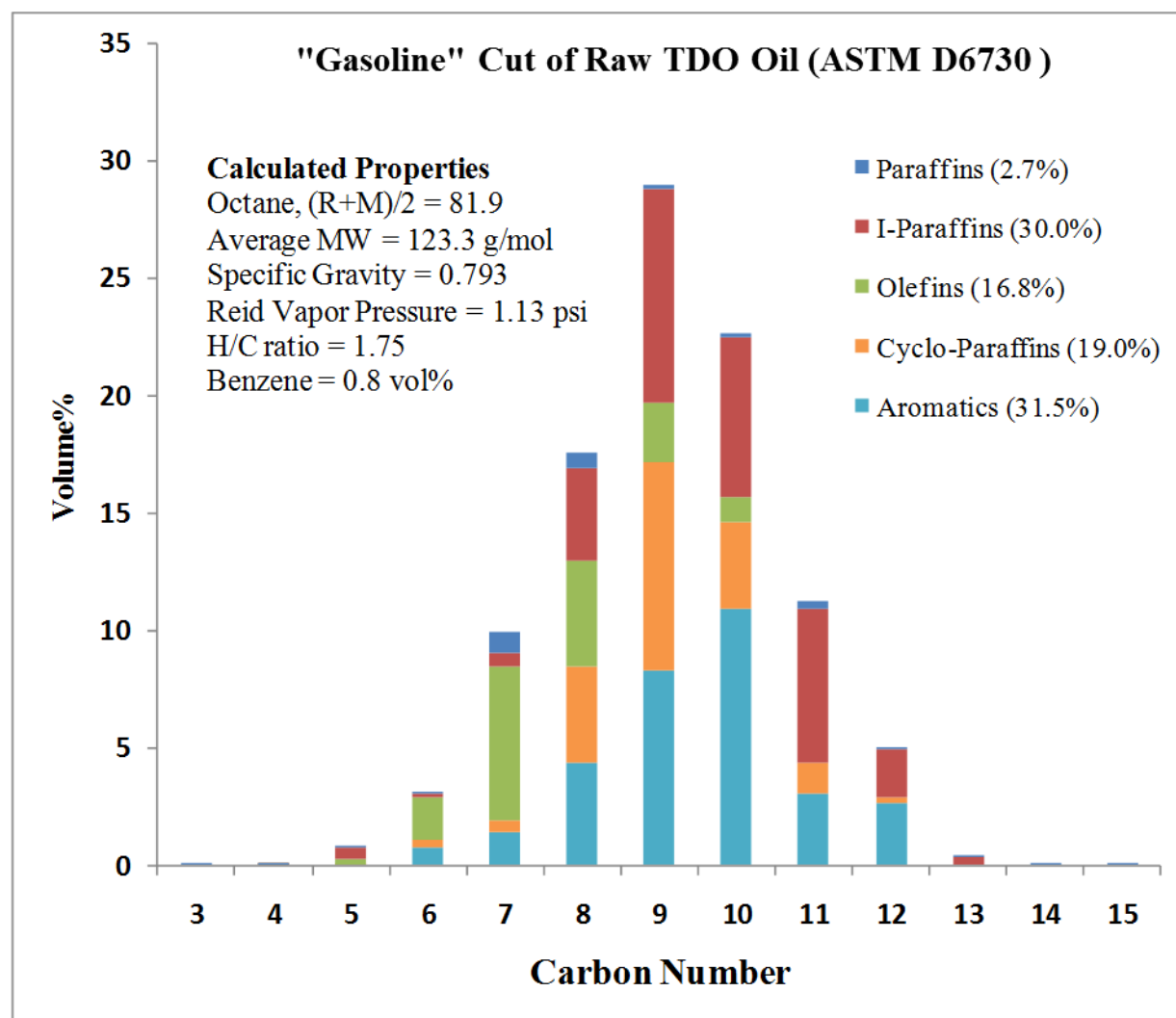


Figure 6: Carbon number distribution and other test data for UMaine gasoline sample

Atmospheric residue cut (boiling point greater than 325 °C) of raw TDO oil was tested for Intermediate Fuel Oil (IFO) specifications. It compared well with IFO-180 as shown in the table below.

Table 2: UMaine residue oil test data

ASTM Fuel Specifications		IFO-180		IFO-180	TDO
Characteristic	Units	Specification		Field Sample	Crude Residual
Relative Density		991	Max.	0.9772	1.073
Carbon Residue	Wt %	20	Max.	12	6.9
Sediment	Wt %	0.1	Max.	0	0
Pour Point	°C	30	Max.	0	12
Ash Content	Wt %	0.15	Max.	0.018	0.05
Kinematic Viscosity @ 50°C	mm ² /S	180	Max.	188.4	115.8

Hydroprocessed TDO Oils

In a recent campaign, over three-months in duration, approximately 20 liters of raw TDO oil was produced for a variety of hydroprocessing experiments. Hydroprocessing of whole raw TDO oil was done using two different commercial catalysts in a bench-scale 0.5 inch trickle bed reactor. We were able to completely deoxygenate the oil and increase the hydrogen content from about 8.5 wt% to as much as 13.5wt%. The higher hydrogen content was achieved during the first few days on stream, and was accompanied by significant cracking of the feed. The product was initially clear (similar to a technical white oil), but became slightly dark over about 3 days at which time the conversion stabilized. The hydrogen content of the hydroprocessed TDO oil was then approximately 12.25%. The optimum conditions for 10 g of catalyst in the reactor were hydrogen pressures greater than about 750 psig, hydrogen flow rate of 0.3 g-H₂/g-feed, weight hourly space velocity WHSV=0.18 and reactor temperature of 325°C.

Hydroprocessing of whole raw TDO oil was scaled up by a factor of 10 in the floor-scale 1.0 inch trickle bed reactor at the FBRI Technology Research Center. It was attempted, but it wasn't possible to operate the larger reactor with catalyst powder. Therefore, a method was developed to pelletize the more effective catalyst. The optimum conditions for the larger reactor were the same except the hydrogen flow rate was 0.09 g-H₂/g-feed, and the temperature was 300°C. The hydroprocessing was operating continuously for 695 hours (30 days) with essentially no change

in the hydrogen content of the product after catalyst stabilization. After the catalyst stabilized, the yield was $\geq 95\%$ on a mass basis.

Several atmospheric/vacuum distillations have been completed on the hydroprocessed TDO oil. One was up to 450°C for detailed characterization, and two were up to 325°C for F-76 characterization. The TBP curves of the hydroprocessed and raw TDO oils are presented in Figure 7. Approximately 40% of the hydrotreated TDO oil mass is in the JP-8 ($180\text{--}250^{\circ}\text{C}$), and 60% is in the F-76 ($150\text{--}325^{\circ}\text{C}$) boiling point range, respectively.

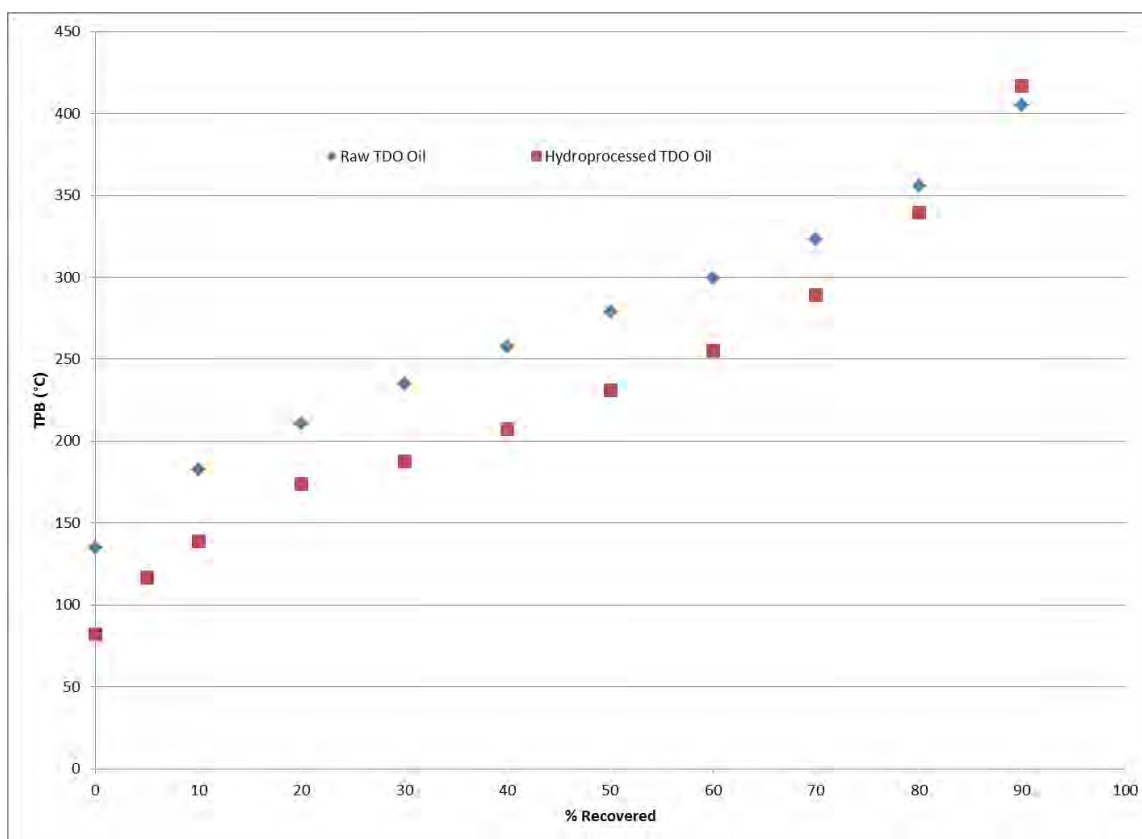


Figure 7. True boiling point curve of hydroprocessed TDO oil. Compared to raw TDO oil

We collected fractions in 25°C cuts up to 450°C for detailed characterization. Samples of the individual cuts encompassing $150\text{--}275^{\circ}\text{C}$ were sent to SGS for aromatic and naphthalene analysis to determine their suitability as a JP-8 drop in or blend stock. The average naphthalene was $<0.6\%$ and the average aromatics were $<9.9\%$ with the largest quantity of both being in the $225\text{--}275^{\circ}\text{C}$ range.

Hydroprocessed TDO oil fractions in the JP-8 ($180\text{--}250^{\circ}\text{C}$) and in the F-76 ($150\text{--}325^{\circ}\text{C}$) boiling point ranges were sent to SGS to test their suitability as drop-in or blend stock.

Test data for these two samples is given below in Tables 3 and 4

Table 3: UMaine F-76 sample test data

Test data on 180 to 250 °C boiling point cut of hydroprocessed TDO Oil		
Specification	MIL-DTL-8133H	Measured
Total acid number (mgKOH/g)	<0.015	0.002
Aromatics (vol%)	<25	11.7
Napthalene (vol%)	<3.0	0.12
Sulfur (mass%)	<0.30	<0.100
Flash point (°C)	>38	67.5
Density (kg/m ³)	0.775-0.840	0.8745
Freezing point (°C)	<-47	<-60
Viscosity (mm ² /s)	<8	7.373
Net Heat of Comb (MJ/kg)	>42.8	42.638
Hydrogen Content (wt%)	>13.4	12.88
Smoke point (mm)	>25.0	26
Copper Strip Corrosion	<No. 1	1a
Existent gum (mg/100mL)	<7.0	<1
Water reaction interface rating	>1b	1

Table 4: UMaine JP-8 sample test data

Test data on 150 to 325 °C boiling point cut of hydroprocessed TDO Oil		
Specification	MIL-DTL-16884M	Measured
Demulsification (minutes)	<10	5
Density (kg/m ³)	<876	889.8
Cloud point (°C)	<-1	<-60
Flash point (°C)	>60	64.5
Viscosity (mm ² /s)	1.7-4.3	2.268
Acid Number (mg KOH/g)	<0.3	0.02
Ash (wt%)	<0.005	0
Carbon Residue (wt% max)	<0.2 (D524)	0.16
Hydrogen Content (wt%)	>12.5	12.7
Cetane Index	>43	26.3
Lubricity (micrometers)	<460	490

Overall process material and energy balances: Deliverable 3:

The complete conversion process to produce TDO oil from woody biomass was modeled in ASPEN, and a detailed stream table was produced. This model was used as basis for the techno-economic analysis done by AMEC personnel.

Process modeling and economics: Deliverable 4:

The woody biomass feedstock specified for this project mimics low-grade wood currently used at Maine biomass power plants:

- ☐ Forest-derived biomass fuel chips (from logging and land clearing operations)
- ☐ Chip size - maximum size – 2.5 inches in any direction
- ☐ Maximum percent oversize – 10% by volume, with a maximum size of 6"
- ☐ Maximum fines (<+ 1/32"): 10%
- ☐ Expected moisture content (as delivered): 40% to 55%

This feedstock specification is intended to set the wood used at these facilities apart from facilities that currently utilize pulpwood in the production of pulp and paper. Such feedstock comes from forest residues associated with logging and pre-commercial thinning operations.

Thermal deoxygenation, TDO), is a transformative technology invented UMaine. Researchers here have demonstrated production of stable, wood-derived, energy dense liquid hydrocarbons, requiring neither precious metal catalysts nor added hydrogen. The TDO process produces hydrophobic oil that could be used directly as heating oil, blended into off-road fuels or further hydroprocessed for jet fuel (JP-8) and Navy diesel (F-76) uses. Figure 8 depicts a simple process flow diagram of the overall process used in the techno-economic analysis.

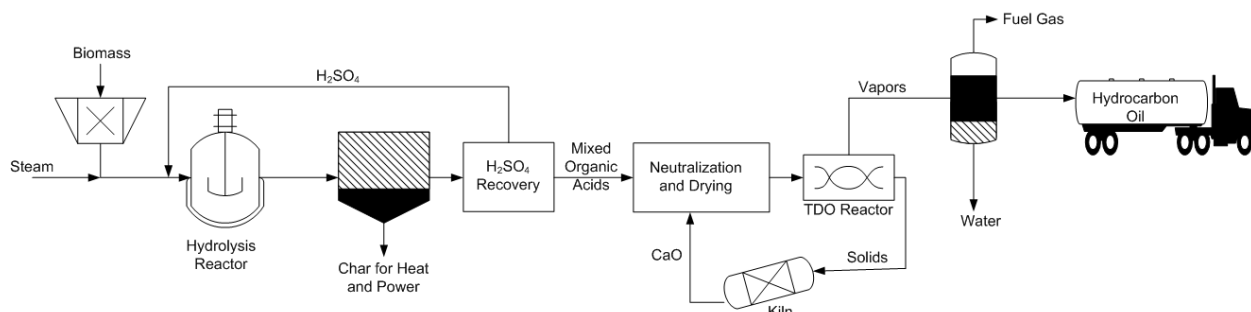


Figure 8: Process flow showing major inorganic recycle loops for the method of producing high energy density oils from lignocellulosic biomass, involving a TDO reactor to process intermediate salt mixture

A detailed process flow diagram which includes raw materials, products, and various recycle streams for recovery of sulfuric acid, calcium oxide, and water was developed. Pro forma for a facility to process 2,000 dry tonnes per day of biomass is shown Table 5. The pro forma utilized

data from various sources to estimate input costs of items such as feedstock and other raw materials, utilities, and labor. A pro forma was developed to determine the net income and also to determine the breakeven price for the furfural co-product.

AMEC used the level of detail considered to be Front End Loading (FEL) level 1, equivalent to a DOE Class 5, Concept Screening Estimate with an anticipated level of accuracy range of -20% to -50% (lower range) and +30% to +100% (higher range). This estimate is based on AMEC in-house data, including previous AMEC estimates and vendor budgetary pricing. AMEC analysis shows that the process is economically justified at current costs of feedstocks and feed chemicals and selling prices of TDO oil, furfural, and fuel gas. Capital costs can dramatically reduce the economic viability and future investigations need to concentrate on reducing capital requirements. At current selling prices of the commodities, the rate of return is found to be sufficient to justify the investment.

The pro forma is based on the following key assumptions:

1. Char resulting from acid hydrolysis and dehydration (Biofine Char) receives credit for its heating value.
2. Co-product furfural produces revenue on the market.
3. Fuel gas receives heating value credit
4. Raw TDO oil is priced at WTI crude price.

Based on a review of readily available secondary data sources and project-specific information regarding environmental matters, several issues were identified. Most critically, decisions will need to be made with respect to air emissions controls as well as wastewater and biosolids disposal. Options appear to be available to reduce the consumption of fossil fuels (such as the combustion of biosolids). The facility could be subject to major source air permitting depending on the outcome of judicial decisions regarding GHG emissions from biomass use. The facility may otherwise be able to avoid major source air permitting, but that will require BACT-level emissions controls for PM, VOC, SO₂, and NO_x.

Co-locating with a Kraft Pulp Mill allows the use of existing equipment for some of the process steps such as the lime kiln, air pollution control systems such as HVLC, liquor evaporators, recovery cycle and wood handling. Potential capital cost reduction/savings would be on the order of 10%.

Table 5: Pro Forma supplied by AMEC**PROFIT & LOSS PROFORMA**

PROJECT NO.	173724	
CUSTOMER:	UNIVERSITY OF MAINE	DATE: 11/22/2013
Operating Rate	2000 Tonne/Day Feed (Dry)	
SUBJECT:	COSTS FOR BIOFUELS FROM CELLULOSIC MATERIALS	PREPARED BY: Carl Marsano

ITEM	2000 Tonne/Day	Ton/Day	UNIT COST	UNIT	Daily Revenue (COST)	Yearly Production (350 Days/Year	YEARLY REVENUE (COST)	
REVENUE STREAMS								
FURFURAL	247.00		\$753.15	TONNE	\$186,029	86,450	\$65,110,093	BREAKEVEN SELLING PRICE
FURFURAL	247.00		\$1,250.00	TONNE	\$308,750		\$108,062,500	INTERNET WEBSITE & AMEC DATA
TDO	196.00	216.19	\$106.48	BARREL	\$158,828	522,068	\$55,589,846	WTI CRUDE (827 KG/M^3)
CHAR							\$0	BURN IN KILN - NET ZERO
BIOFINE CHAR	786.00	866.96	\$52.50	TON	\$78,310	522,068	\$27,408,593	25% MOISTURE CONTENT, BURN IN BIOMASS BOILER
FUEL GAS	24.03	26.49	\$7.50	Dth	\$8,516	9,271	\$2,980,577	METHANE - 21433 BTU/LB
TOTAL REVENUE							\$194,041,516	

							\$151,089,109	BREAKEVEN
OPERATING COST STREAMS								
FEEDSTOCK (BIOMASS)	3,674.00	4,049.89	(\$35.00)	GREEN TON	(\$141,746)	1,417,462	(\$49,611,174)	AMEC DATA - 50% MOISTURE
NATURAL GAS			(\$7.50)	Dth				INCLUDED IN STEAM
STEAM	1,108.50	1,221.91	(\$12.00)	MILLION BTU	(\$14,663)	427,669	(\$5,132,031)	AMEC DATA
ELECTRICITY	453.20	499.57	(\$0.06)	kWH	(\$5,395)	174,849	(\$1,888,365)	p. 198 Peters & Timmerhaus, 1980, Used Acetic Acid, 180 kWH per ton produced
SULFURIC ACID	6.64	7.33	(\$200.00)	TON	(\$1,465)	2,565	(\$512,907)	
WATER	0.00	0.00	(\$130.00)	100,000 GALLONS	\$0	0	\$0	
QUICK LIME	16.92	18.67	(\$200.00)	TON	(\$3,734)	6,535	(\$1,306,985)	For Sulfate & NPE Purge
WASTEWATER	3,582.50	3,953.29	(\$130.00)	100,000 GALLONS	(\$1,232)	1,383,651	(\$431,354)	
LABOR		40.00	(\$65,000.00)	/ PERSON YEAR			(\$2,600,000)	p. 196 Peters & Timmerhaus, 1980, 40 personnel, \$25.00/HR PLUS BENEFITS
TOTAL							(\$61,482,816)	
GROSS MARGIN							\$132,558,700	
							\$89,606,292	BREAKEVEN

INSURANCE							(\$250,000)	Allowance
MANAGEMENT							(\$500,000)	Allowance
PROPERTY TAXES	United States Average Industrial Rate		1.473%				(\$6,749,286)	Lincoln Institute of Land Policy, 50-State Property Tax Comparison Study, April, 2011 Minnesota Taxpayers Association
TOTAL							(\$7,499,286)	
EBITDA							\$125,059,414	
							\$82,107,006	BREAKEVEN
DEPRECIATION							(\$45,820,000)	10 YEAR STRAIGHT LINE
INTEREST			\$458,200, 000	TOTAL COST			(\$36,287,006)	@5% FOR 20 YEARS
Net Income							\$42,952,407	
							\$0	BREAKEVEN

Potential site assessment: Deliverable 5:

Possible site locations (Figure 6) were identified for a medium-scale processing facility requiring about a one million green ton per year biomass supply chain. In general, pulp mill infrastructure on the host site would offer capital cost savings based on available wood-yard and steam and power capacity, as well as possible lime kiln synergy. Old Town Fuel & Fiber facility would be a potential candidate site with the owners declared interest in jet fuel production.



Figure 9: Suggested potential locations for wood to jet fuel production

It is important to note that the locations above are based upon the physical availability of forest residues as a feedstock supply. There may be limitations on the ability of a facility to secure the necessary volume (e.g., landowner attitudes or pre-existing fiber supply agreements) that impact availability at the project level; such limitations would need to be evaluated on a case-by-case basis.

Plans for pilot demonstration: Deliverable 6:

Key areas requiring further study are identified below:

1. The TDO process needs to be studied in continuous processing mode to understand material handling issues and to obtain design data for scale-up,
2. TDO char handling and preparation of calcium carbonate feed for possible processing in lime kilns at host pulp mill needs to be validated,
3. Hydroprocessing of TDO oil needs to be optimized to make drop-in JP-8 or F-76 fuels.
4. Laboratory testing of levulinic and formic acid extraction using furfural is needed.

Pilot demonstration plans need to wait until a strategy for getting ASTM qualification for hydroprocessed TDO oil is fully developed and prospective fuel producer has been identified. Prospective alternative jet fuel producers often engage with the Commercial Aviation Alternative Fuels Initiative® (CAAFI®), ASTM International, and the Coordinating Research Council (CRC) regarding the qualification of new production pathways. ASTM D4054 User's Guide produced by CAAFI® states:

“The Test Program is comprised of four tiers as shown in Figure 3. Tier 1 consists of the Fuel Specification Properties. Tier 2 includes the Fit-For Purpose (FFP) Properties. Tier 3 is comprised of Component Tests. Tier 4 consists of Engine Tests. Samples of both the neat synthetic blending component and the blended jet fuel will be required for evaluation. Most of the testing except for compositional and trace materials analyses are performed with the blended jet fuel. Fuel volumes that may be required are up to 10 gallons (38 liters) for the Specification Tests; 10 to 100 gallons for the FFP tests; 250 to 10,000 gallons (950 to 38,000 liters) for the Component and Rig Tests; and up to 225,000 gallons (852,000 liters) for the engine test. The aforementioned are rough estimates because the extent of required FFP tests is dependent upon the fuel chemistry and results of the Specification tests. Actual quantities could be higher or lower.”

This project has successfully produced several liters of jet fuel cuts from hydroprocessed TDO oil using reagent-grade calcium levulinate and formate salt mixtures. Earlier studies involving biomass-derived levulinic acid (Eaton et al. 2013)² to produce such intermediates have shown consistent TDO oil quality, when compared to reagent-grade comparable mixtures. Fuel specification property data obtained on limited jet fuel samples tested in this project are very encouraging. Thermal deoxygenation is demonstrated to be a robust conversion pathway for the production of crude hydrocarbons from biomass. Kerosene-cuts of hydroprocessed TDO oil are found to give JP-8 blend stocks.

² **S.J. Eaton**, S.H. Beis, B.G. Bunting, S.W. Fitzpatrick, G.P. van Walsum, H.P. Pendse, and M.C. Wheeler, “Characterization and Combustion of Crude Thermal Deoxygenation Oils Derived From Hydrolyzed Woody Biomass,” *Energy & Fuels*, 27 (9), 5246-5252 (2013)

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Related Publications resulting from this project:

S.J. Eaton, S.H. Beis, B.G. Bunting, S.W. Fitzpatrick, G.P. van Walsum, H.P. Pendse, and M.C. Wheeler, "Characterization and Combustion of Crude Thermal Deoxygenation Oils Derived From Hydrolyzed Woody Biomass," **Energy & Fuels**, 27 (9), 5246-5252 (2013).

Relevant Patent Issued based on work prior to July 6, 2011.

U.S. Patent 8,362,306 B2 (January 29, 2013) "Energy densification of biomass-derived organic acids", M. C. Wheeler, G.P. Van Walsum, T.J. Schwartz, and A.R.P. van Heiningen.

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