IEA Bioenergy
Task 34

Direct Thermochemical Liquefaction

IEA Bioenergy Task 34

Proceedings of
Biomass Liquefaction Workshop

November 30, 2017

CanmetENERGY-Ottawa, Ottawa, Canada

IEA Bioenergy

Task 34

Direct Thermochemical Liquefaction

Biomass Liquefaction Workshop – November 30, 2017

CanmetENERGY-Ottawa, 1 Haanel Drive, Ottawa – Building #1

0900	**Introductions and Welcome**
	CanmetENERGY-Ottawa Overview
	Dean Haslip, CanmetENERGY-Ottawa
0915	**IEA Country Reports:**
	Alan Zacher, USA
	Ferran de Miguel Mercader, New Zealand
	Bert van de Beld, Netherlands
	Magnus Marklund, Sweden
	Kristin Onarheim, Finland
	Axel Funke, Germany
1115	**Ensyn: RFO Experience and New Projects Update**
	Dave Boulard, Ensyn Technologies Inc
1145	**Introduction to Energy Services Acquisition Program and Biomass Pilots**
	Mike Burke, Public Services and Procurement Canada
1215	Lunch
1300	**ABRI-Tech Inc: Update on New Projects**
	Peter Fransham, ABRI-Tech Inc
1330	**Hydrothermal Liquefaction of Algae and Low Quality Feedstocks**
	Devinder Singh, National Research Council Canada
1400	**Pyrolysis Process and Product Research at Memorial University**
	Kelly Anne Hawboldt, Memorial University

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Direct Thermochemical Liquefaction

1430 **Making Use of Abundant Low Quality Residuals through Thermochemical Liquefaction**

Ben Bronson, Dillon Mazzerole, Murlidhar Gupta,

Fernando Preto, CanmetENERGY-Ottawa

1530 **Ontario's New Regulations and Guidelines to Promote Biomass Heating**

Steven Law, Ontario MOECC

1600 **Pyrolysis Oil Blends As An Alternative Fuel For Diesel Engines And Gas Turbines**

Ashwani Kumar, Sean Yun and W. Stuart Neill, National Research Council Canada

16:30 **Discussion**

Natural Resources Canada / Ressources naturelles Canada

CanmetENERGY-Ottawa Overview

Dean Haslip, Director General

CanmetENERGY
Leadership in ecoInnovation

Canada

CanmetENERGY-Ottawa…

CanmetENERGY-Ottawa leads the development of energy S&T solutions for the environmental and economic benefit of Canadians

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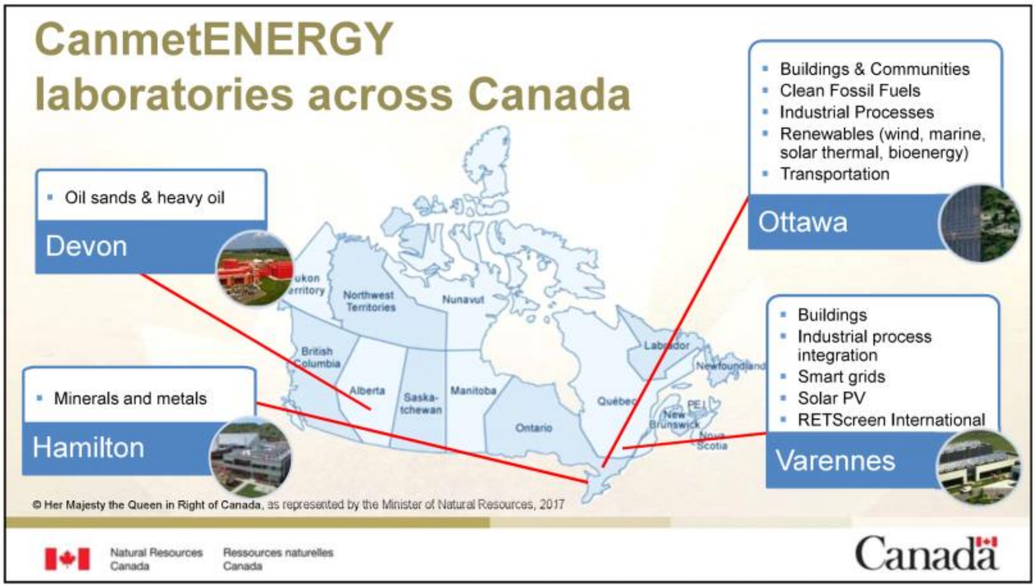
CanmetENERGY
laboratories across Canada
Oil sands & heavy oil
Devon
Minerals and metals
Hamilton
Buildings & Communities
Clean Fossil Fuels
Industrial Processes
Renewables (wind, marine, solar thermal, bioenergy)
Transportation
Ottawa
Buildings
Industrial process integration
Smart grids
Solar PV
RETScreen International
Varennes
Northwest Territories
Nunavut
British Columbia
Alberta
Saska-tchewan
Manitoba
Ontario
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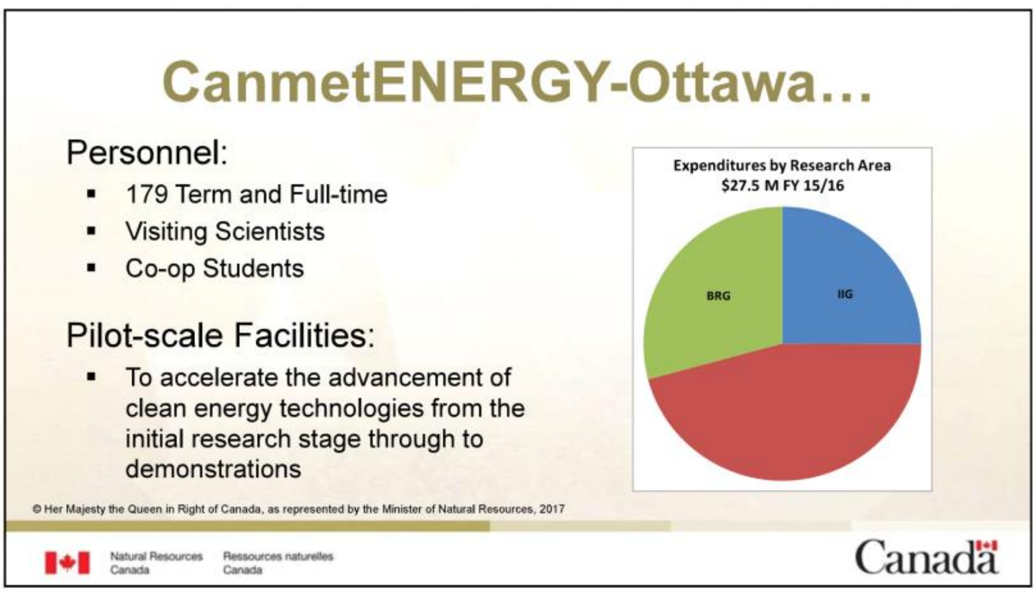
CanmetENERGY-Ottawa…
Personnel:
179 Term and Full-time
Visiting Scientists
Co-op Students
Pilot-scale Facilities:
To accelerate the advancement of clean energy technologies from the initial research stage through to demonstrations
Expenditures by Research Area
$27.5 M FY 15/16
BRG
IIG
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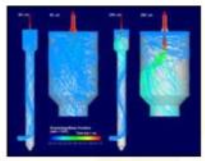
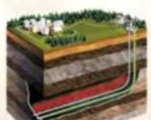
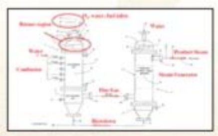
CanmetENERGY-Ottawa leads the development of energy S&T solutions…

… in Clean Fossil Fuels

- Carbon Capture and Storage
- Fluidized Bed Combustion
- Direct Contact Steam Generation
- Gasification
- Shale Gas







CanmetENERGY-Ottawa leads the development of energy S&T solutions…

… in Renewables

- Solar Thermal
- Wind Technology for Cold Climates
- Marine & Hydrokinetic
- Bioenergy/ Biofuels

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CanmetENERGY-Ottawa leads the development of energy S&T solutions…

…in Energy End-Use

- Built environment
  - Energy Efficient Buildings
  - Advanced Mechanical systems
  - Integration of Renewables
- Industry
  - Iron and Steel
  - Pulp and Paper
  - Transformative Technologies
- Transportation
  - Electric Vehicles
  - Alternative Fuels

CanmetENERGY-Ottawa leads the development of energy S&T solutions…

… through longstanding R&D collaborations with:

- Academia
- Industry and Associations
- Other Canadian Government Departments and Organizations
- Foreign Governments, Industry and International Organizations

CanmetENERGY-Ottawa leads the development of energy S&T solutions…

…for the environmental and economic benefit of Canadians.

Direct Contact Steam Generation – Development Program for In-situ Oil Sands Production

CanmetENERGY-Ottawa has developed a technology that reduces the production cost and carbon intensity of extracting in-situ oil in the oil sands. More specifically, it reduces greenhouse gas emissions by 33–70% and water consumption by 50–100%.

…for the environmental and economic benefit of Canadians.

50 year collaboration with CCRA

This year marks 50 years of collaboration with the Canadian Carbonization Research Association (CCRA). This long-standing collaboration has enhanced the sustainability, environmental and economic viability of Canada's metallurgical coal industry by demonstrating the suitability of Canadian coals for producing high-quality metallurgical coke.

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…for the environmental and economic benefit of Canadians.

Rapidly Deployable Northern House

This prototype is a less expensive and more energy-efficient option for housing in rural, remote and northern regions of Canada and throughout the world, than traditional approaches. The pre-fabricated structure can be assembled in days with limited skills and minimal tools. It also uses green fuel sources such as a wood pellet boiler for space and water heating.

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…for the environmental and economic benefit of Canadians.

Biofuels used for transportation applications

CanmetENERGY-Ottawa is working with industry to convert woody biomass derived feedstocks to liquid biofuels for transportation applications.

…for the environmental and economic benefit of Canadians.

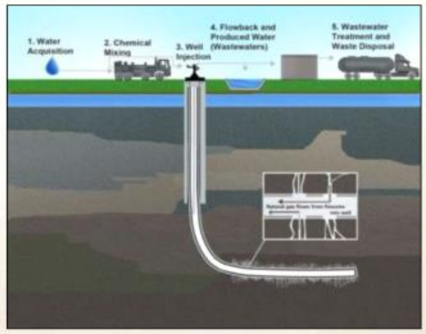
High Pressure Oxy-Fuel Combustion (HiPrOx)

CanmetENERGY-Ottawa is working with international collaborators (US DOE, Gas Technology Institute) to develop and test high-efficiency carbon capture HiPrOx technologies for power generation.

…for the environmental and economic benefit of Canadians.

Shale Gas Laboratory

CanmetENERGY's Sub-Surface Environment group provides expertise in petrophysics, geochemistry, geomechanics and high pressure testing due to its capabilities in the Shale Gas Laboratory where research into improving unconventional enhanced oil recovery (EOR) technologies, compressed energy storage and wellbore integrity is conducted.



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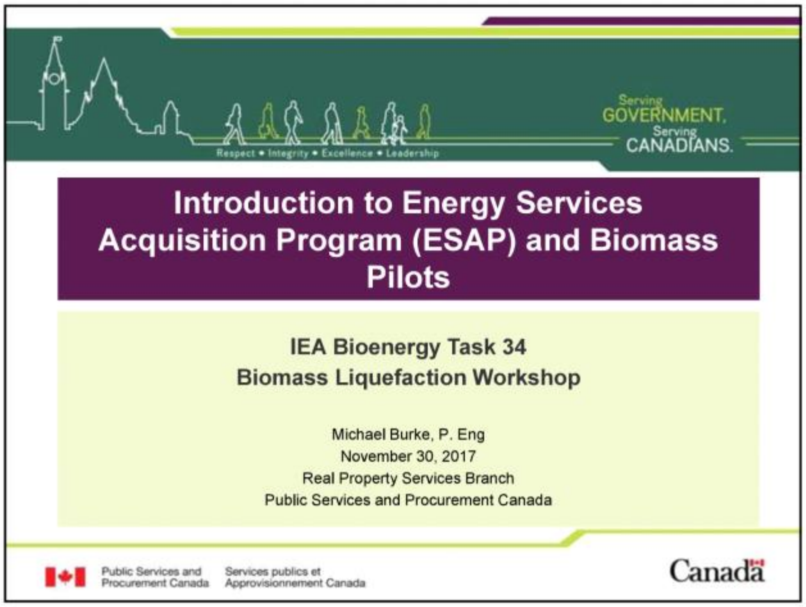
Serving GOVERNMENT, Serving CANADIANS.
Respect • Integrity • Excellence • Leadership
Introduction to Energy Services Acquisition Program (ESAP) and Biomass Pilots
IEA Bioenergy Task 34
Biomass Liquefaction Workshop
Michael Burke, P. Eng
November 30, 2017
Real Property Services Branch
Public Services and Procurement Canada
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8 - 9 Financial Commitment
10 - 11 GHG Reductions – Stage 1
12 - 14 Delivery Model
15 - 20 Vision for Stage 2
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Program Overview

The **Energy Services Acquisition Program (ESAP)** is modernizing the District Energy System (DES) which provides heating services to over 80 buildings and cooling services to 67 buildings in the National Capital Region (>1.6M m^2 of floor space), accommodating 55,000+ occupants

There are **two stages** to ESAP:

- Stage 1: DES Modernization
- Stage 2: Deeper Greening

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ESAP Objectives

1. Improve the Government of Canada's environmental performance
2. Reduce costs of building heating and cooling operations
3. Increase safety and reliability of heating and cooling operations
4. Leverage private sector's innovation, capacity and expertise
5. Promote growth of the DES throughout the NCR
6. Design Cliff CHCP to be an architectural landmark
7. Integrate an education platform as part of the system's transformation and operation

Example – Education at Hydro-Québec

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Supporting Government Priorities

The ESAP program will help the Government of Canada to meet the following commitments:

- **Paris Agreement** committing Canada to reducing GHG emissions by 30% by 2030;
- **Federal Sustainable Development Strategy** and **Greening Government** committing to lead by example by greening government operations and reducing emissions in government buildings and fleets by 40% by 2030 at the latest; and
- **Pan-Canadian Framework on Clean Growth and Climate Change** committing to move toward smart and sustainable buildings that use less energy and open the way for using renewable energy sources

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ESAP Has Two Stages

Stage 1 – DES Modernization

- Convert to industry-standard low temperature hot water technology (LTHW)
- Switch from steam to electric chillers
- Implement Smart Buildings data analysis to improve efficiency
- Test new carbon neutral fuels for deeper greening - pilot projects, feasibility studies

Stage 2 – Deeper Greening

- Convert base load to carbon neutral fuels – achieve **low carbon government**
- Increase the number of government buildings connected to the DES
- Expand and share carbon neutral energy with non-federal buildings in the community

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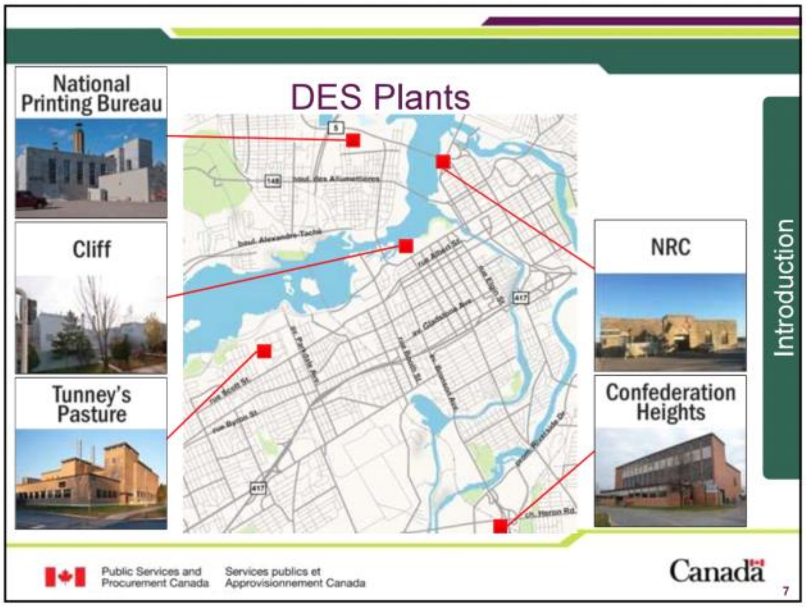
DES Plants
National Printing Bureau
Cliff
Tunney's Pasture
NRC
Confederation Heights
Introduction
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Opportunity
Stage 1 will:
• Reduce GHG emissions by over 60% of the 2005 emissions baseline.
• Generate savings estimated at $750 million over 40 years.
• Meet a government commitment to eliminate use of ozone-depleting substances.
Inside Cliff heating and cooling plant
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Financial Commitment in 2016

- Budget 2016 committed new funding to ESAP to:
  - upgrade the aging DES to use more efficient technologies (**Stage 1**); and
  - explore using renewable sources of energy (start of **Stage 2**)
- A Treasury Board (TB) Submission was approved in December 2016

Cliff heating and cooling plant

Financial Commitment

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TB Submission Approval

December 2016

- TB approved **Stage 1** – Project Approval for the modernization of the heating and cooling DES in the NCR, at a total estimated cost of $3.1B (including HST)
- TB also provided access to $250M in funding for:
  - The ESAP Team work necessary to get to contract award ($60M); and
  - The first four years of Building Conversion and Smart Buildings / Plants work ($190M)

Confederation Heights heating and cooling plant

Financial Commitment

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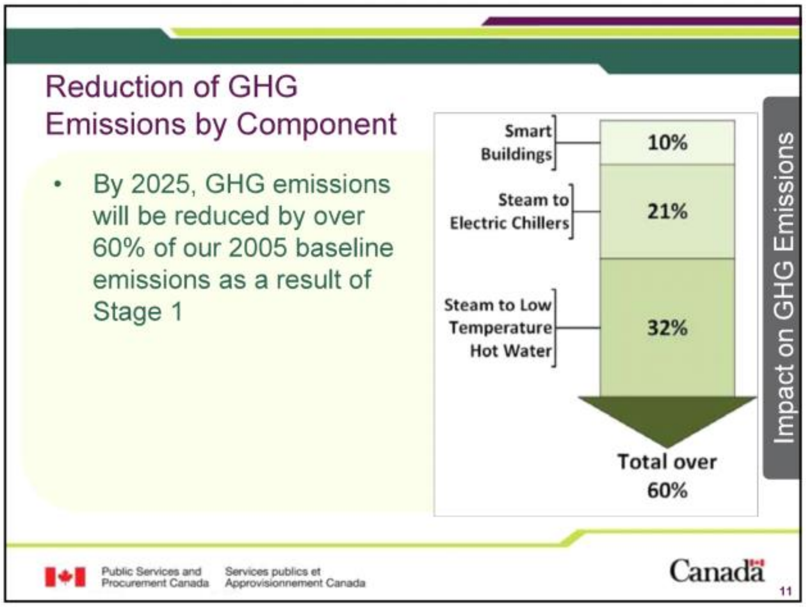
Reduction of GHG Emissions by Component
By 2025, GHG emissions will be reduced by over 60% of our 2005 baseline emissions as a result of Stage 1
Smart Buildings
10%
Steam to Electric Chillers
21%
Steam to Low Temperature Hot Water
32%
Total over 60%
Impact on GHG Emissions
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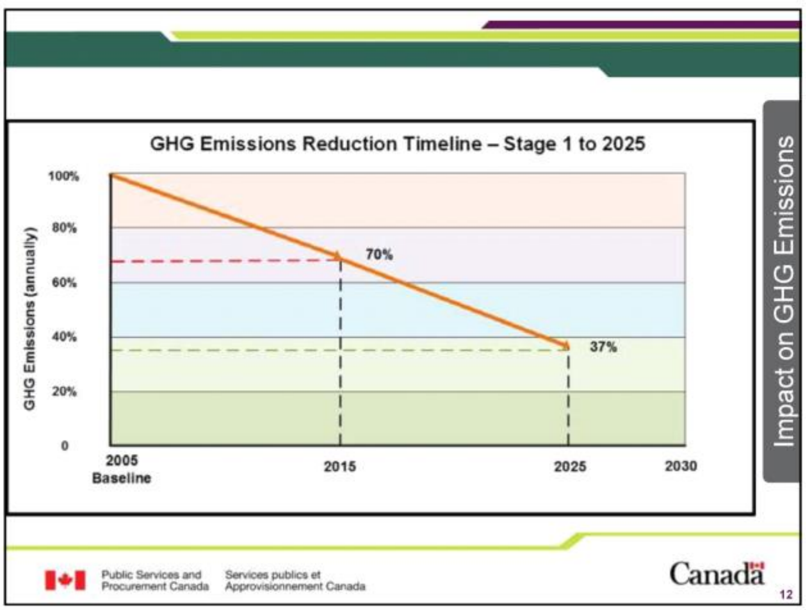
GHG Emissions Reduction Timeline – Stage 1 to 2025
GHG Emissions (annually)
100%
80%
60%
40%
20%
0
70%
37%
2005 Baseline
2015
2025
2030
Impact on GHG Emissions
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The Delivery Model

- For DES Modernization (Stage 1), it is a single Design-Build-Finance-Operating-Maintenance (DBFOM) contract
  - It is a P3 project agreement with a duration of 35+ years
  - **DB** = design build – this phase will take five years
  - **f** = finance of the construction phase for a seven year term
  - **OM** = operations and maintenance – 2020 to 2055
- For Smart Buildings/Plants, it is an Memorandum of Understanding (MOU) with National Research Council (NRC)
- For Building Conversion, it is several Design-Bid-Build (DBB) contracts
- For two Biomass Pilot Projects, it is a MOU with NRC and Natural Resources Canada (NRCan)

Delivery Model

P3 Procurement Process

It is comprised of two principal stages:

Request for Qualifications (RFQ)

- Evaluates consortia based on experience in designing, constructing, short term financing, operating, and maintaining a project of similar size and complexity
- Selects the top three Qualified Respondents that will be invited to participate as Proponents in the Request for Proposals (RFP)

Request for Proposal (RFP)

- Sets out the conditions and specifications required to undertake the Project
- Invites proponents to submit binding technical and financial proposals
- Results in the selection of the successful Proponent and signature of the Project Agreement

Delivery Model

P3 Procurement Process Timeline

Activity	Date
RFQ Issued (RFP developed to 70%)	August 2017
RFQ Closed	November 2017
RFQ Short List Approved	January 2018
RFP Issued	February 2018
RFP Technical Submission	October 2018
RFP Financial Submission	January 2019
RFP Evaluation Completed, Preferred Proponent Identified	January 2019
Contract Award	April/May 2019

Delivery Model

Exciting Models are an Inspiration for ESAP

New models are emerging across the world for heating and cooling – ESAP will be a model for others once completed

Innovative design for incineration plant in Copenhagen, Denmark

The Optic Cloak
Greenwich Peninsula Energy Infrastructure (London, UK)

Vision for Stage 2

Vision for Stage 2

The vision for Stage 2 consists of two components:

1. Switch from natural gas to carbon neutral fuels for base load; and
2. Expand the system gradually to grow from 80 to 600 buildings

Place du Portage Complex – a target for system expansion

Vision for Stage 2

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What is Biomass?

- In **Stage 2** we will move to carbon neutral fuels, including biomass
- There are several types of biomass:
  - Hog fuel;
  - Wood chips;
  - Regular wood pellets;
  - Torrefied wood pellets; and
  - Bio-oil (renewable fuel oil) made from wood by-products

Tomasz and Pierre checking out biomass samples in Thunder Bay

Stage 2

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Biomass Pilot Projects

- The first step of **Stage 2** is to assess the feasibility of various carbon neutral fuels
- In 2017–18, ESAP will be testing two fuel sources:
  - Wood chip, and
  - Bio-oil (renewable fuel oil) made from wood by-products
- The goal will be to better understand the benefits and costs of use

Biomass samples that are being considered for testing at Confederation Heights Plant

Vision for Stage 2

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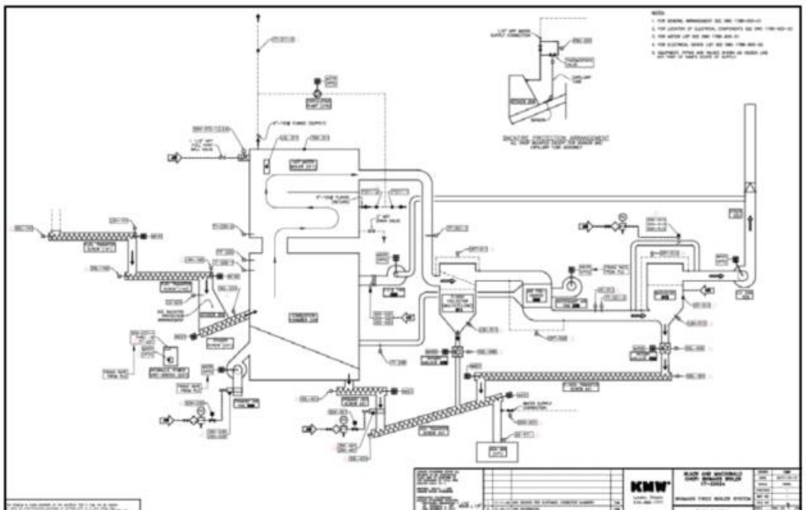

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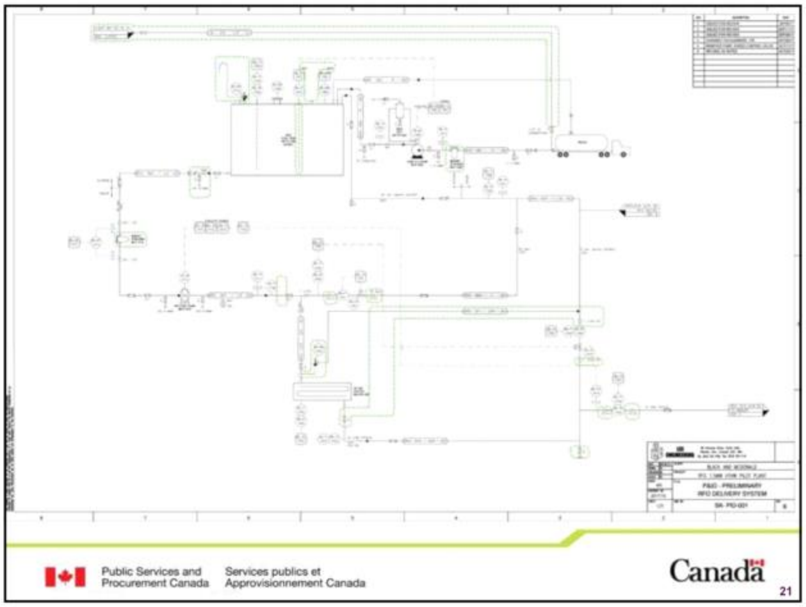
P&ID - PRELIMINARY
RFO DELIVERY SYSTEM
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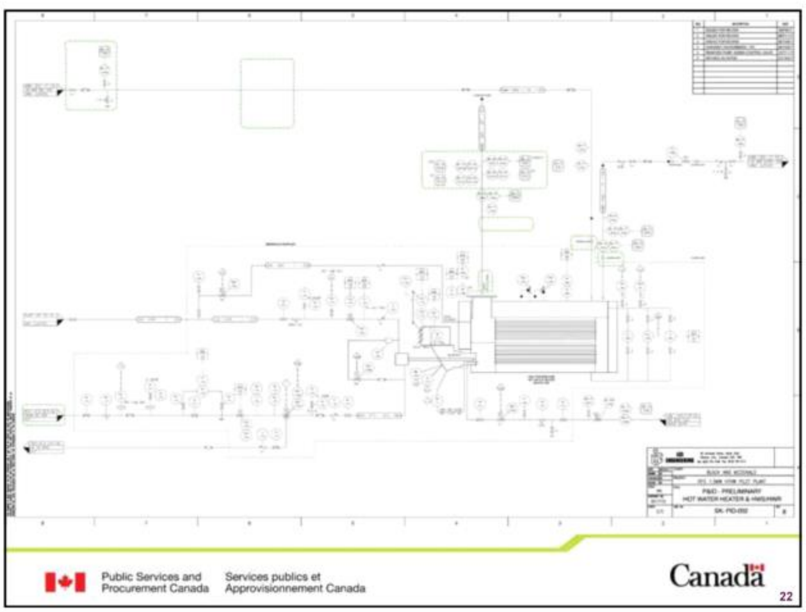
P&ID - PRELIMINARY
HOT WATER HEATER & HWS/HWR
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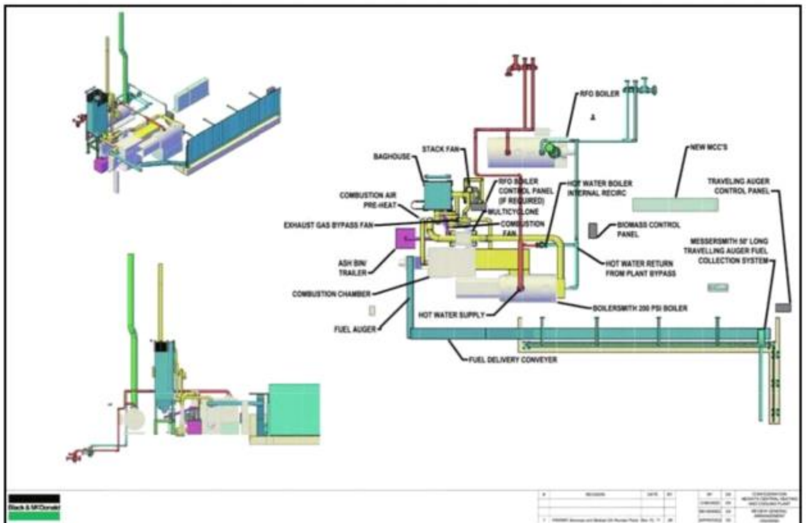
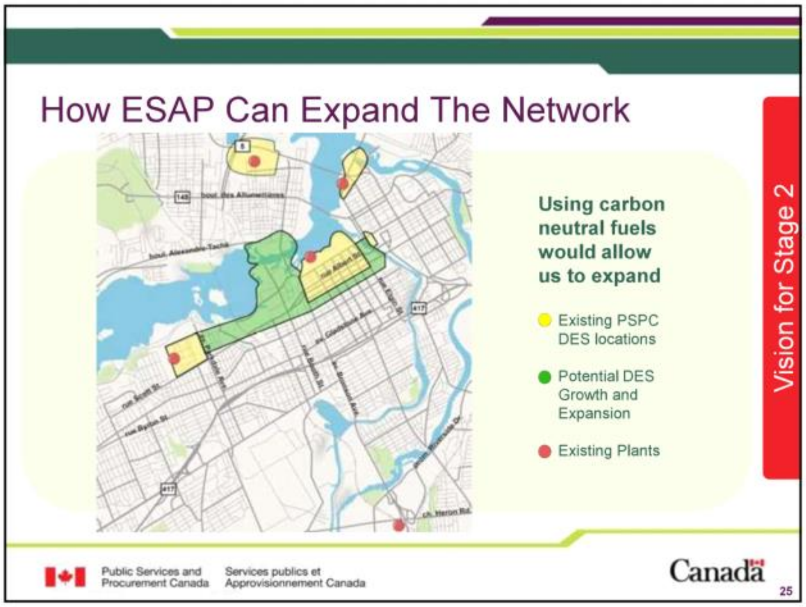


Biomass Pilot Projects

- 2 X 1.5 MWth Pilot plants operational in spring 2018
- At full load will consume approx 0.57 tonnes/hr of wood chips and 380 litres/hr of RFO.
- Evaluating trade-offs in wood chip cost and quality against equipment cost and operation
- Feasibility will be affected by RFO/ wood chip price vs fossil fuel pricing, carbon tax impact and ongoing commitment to climate change mitigation
- Possibility of a 40 MWth biomass plant for base load after 2025


How ESAP Can Expand The Network
Using carbon neutral fuels would allow us to expand
Existing PSPC DES locations
Potential DES Growth and Expansion
Existing Plants
Vision for Stage 2
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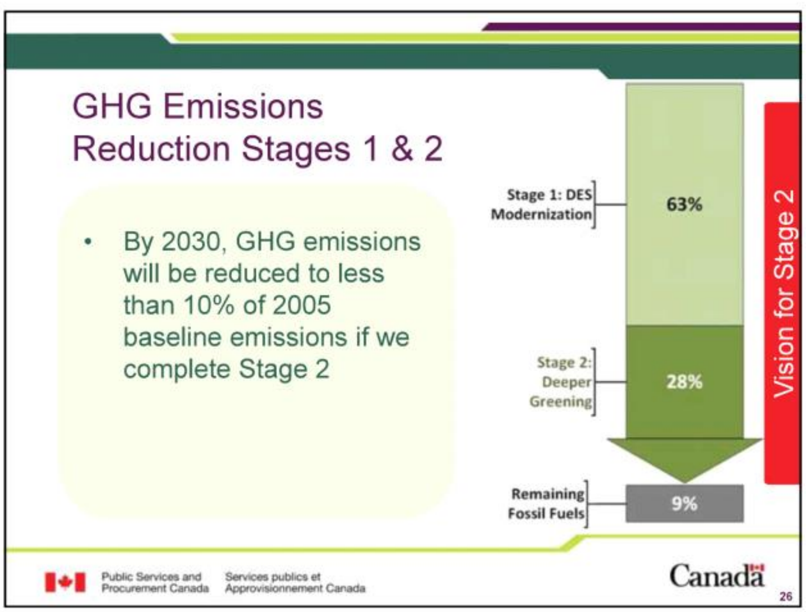
GHG Emissions Reduction Stages 1 & 2
• By 2030, GHG emissions will be reduced to less than 10% of 2005 baseline emissions if we complete Stage 2
Stage 1: DES Modernization
63%
Stage 2: Deeper Greening
28%
Remaining Fossil Fuels
9%
Vision for Stage 2
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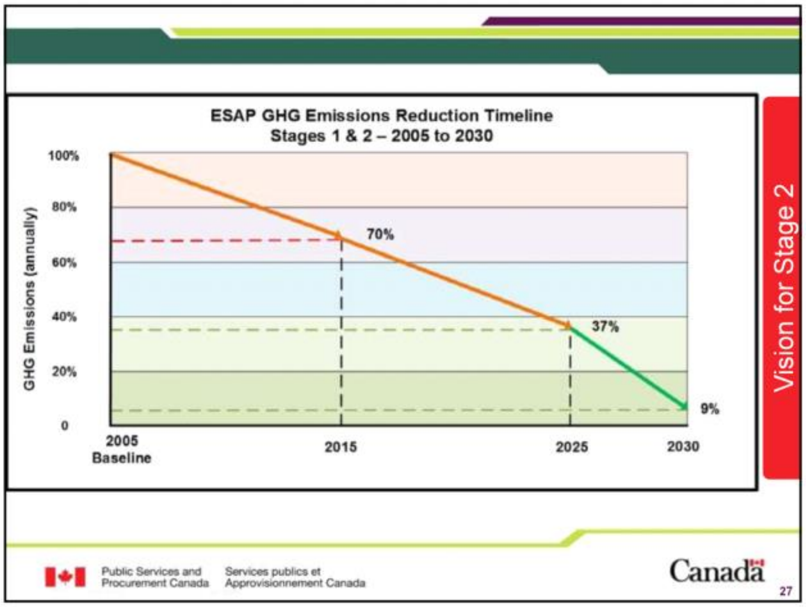
ESAP GHG Emissions Reduction Timeline
Stages 1 & 2 – 2005 to 2030
GHG Emissions (annually)
100%
80%
60%
40%
20%
0
70%
37%
9%
2005
Baseline
2015
2025
2030
Vision for Stage 2
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Thank you.
Chilled Water Plant in Paris
Michael Burke
Energy Services Acquisition Program
Public Services and Procurement Canada
Michael.burke@pwgsc.gc.ca
ESAP PASE
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PYROLYSIS PROJECT UPDATE

T34 Liquifacton Workshop
Bells Corners Complex

Peter Fransham, PhD
ABRI-Tech Inc.

November 30, 2017

The Team

- ABRI Tech is part of the Leggett Group
  - Forestry company with logging and sawmill operations in Namur, Quebec
  - In continuous operation since 1932
  - Current management is 3rd generation
- Memorial University
  - Collaboration on a variety of pyrolysis related subject
  - Ideal industry/academic relationship where we both benefit from the other's expertise

ABRI-Tech Auger Pyrolysis

- Three modules: dryer, reactor, and condenser
- Unique chain flail dryer simultaneously grinds and dries
- Auger reactor with steel shot heat carrier
- There is no fluidizing gas or transport gas to heat and cool
- Parasitic loss by keeping elevation changes to a minimum
- Combination direct and indirect condensing system

Shot/Biomass Mixing

- Pyrolysis is all about energy transfer from a carrier to the biomass
- We use temperature as a measure, but really we want energy transfer
- Steel shot is dense and has a high thermal conductivity
- Biomass is rapidly incorporated into the shot.
- Optimal biooil yield between 450C and 475C for most biomass

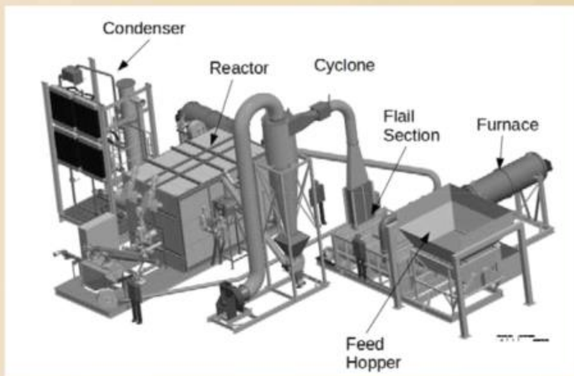
Shot/Biomass Blending

- See video

Biooil Properties

- 65% biooil yield is easily reached and could be better with better condensation – ESP or other techniques
- Meets lower range of ASTM standards – char content is too high with current design
- Distillation test was perfomed on a recent sample and did not polymerize and distilled up to 475C when only 2% was left
- Memorial University has an indepth study of distillation underway

3D Drawing



50 DTPD Parent Plant

Parent Update

- First scale up of the current design
- We are in the commissioning stage
- Identified technical issue that have been fixed
  - Undersized blower for dryer – dryer will not operate at full capacity
  - Excessive char carryover into condenser – plugging of tube and shell heat exchanger

Prototype Solutions 1TPD

- We have a 40 kg/hr pilot plant in Namur for testing solutions
-

Status

- A polishing cyclone was added between the reactor and the condenser.
- Results so far are positive
- Additional instrumentation added to dryer for better control of air flows.
- Commissioning is progressing

Russian Project

- Customer is 1000 strong engineering firm specializing in energy related projects
- End user is an oil company wanting to make transportation fuels from abundant forest residuals
- Modular and transportable are key requirements
- Biooil to be shipped to refinery for processing
- NCG and biochar to be used for heat

Timeline

- March 2017 Visit to Canada by Russian Engineers
- June 2017 Contract documents signed
- July 2017 Kick off meeting and modifications to deliverables.
- October 14 – November 10 Completion of design package in Kazan and Moscow
- Plant to be built in Russia
- Target date for comissioning – late 2018

Upgrading Biooil

- ABRI-Tech has only limited knowledge of their upgrading technology
- Based on FCC
- Testing in pilot scale FCC facility using BTG biooil has been successful and produced the right mix of hydrocarbons
- Technology is different from UOP/Ensyn and separate patents will be filed.

Wrap up Comments

- Payment according to contract terms was received after a short delay by Canada looking for violations of infractions
- Russian engineers are first class and a joy to work with
- Given the talent, probability of success is high
- Management is decisive – no waffling on issues

Questions/Comments

- Thank you

NRC·CNRC

Hydrothermal Liquefaction of Algae and Low Quality Feedstocks

Devinder Singh
Nov 30, 2017
T34 Biomass Liquefaction Workshop

National Research Council Canada Conseil national de recherches Canada

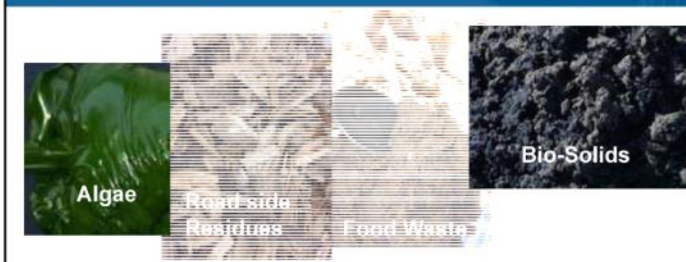
Canada

Overview

- Introduction
- Hydrothermal Liquefaction (HTL) of various algae species and low quality feedstocks in batch reactor and plug flow reactor.
- Conversion of HTL Water Organics
- Process for recovery and recycle of nutrients from HTL Water
- Thermal Upgrading and co-processing of bio-crude with bitumen
- Summary

NRC·CNRC

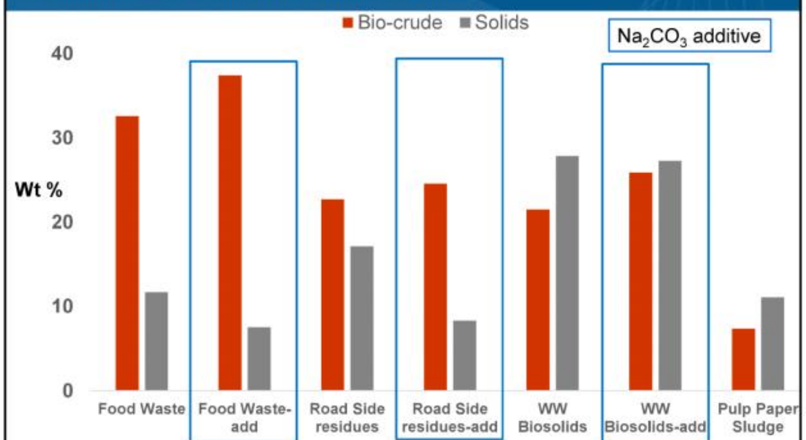
Hydrothermal Liquefaction



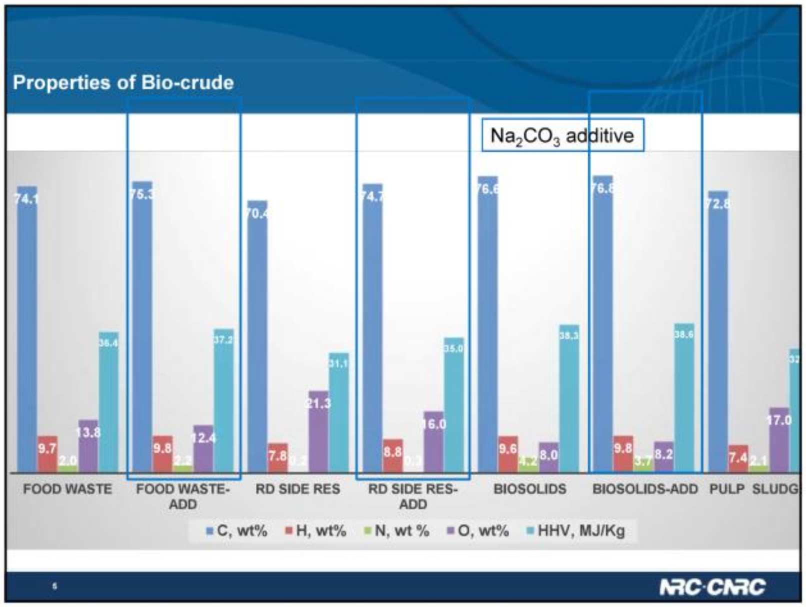
- Wet, low quality feedstocks like food wastes, biomass slurries, algae
- Typical conditions: ~350 C, up to 30 min, ~ 2900-3000 psi
- Produces high quality bio-crude and aqueous phase

3 NRC·CNRC

Batch Reactor Yields of Bio-crude and Solids

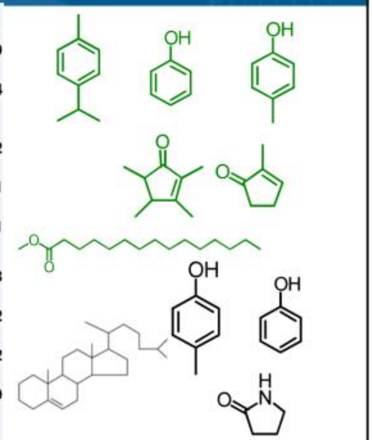


4 NRC·CNRC



Major species from GC-MS: Food Waste, WW Bio-solids

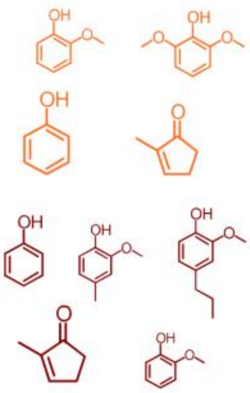
Food Waste		Bio Solids	
Cymene	9.8	Cholest-4-ene	6.9
Phenol, 4-methyl-	3.5	Cholest-3-ene, (5.alpha.)-	5.4
2-Cyclopenten-1-one, 2,3,4-trimethyl-	3.1	Phenol, 4-methyl-	5.2
2-Cyclopenten-1-one, 2-methyl-	2.4	Cholest-3-ene, (5.beta.)-	4.1
2-Cyclopenten-1-one, 3-ethyl-	2.1	Cholest-7-ene, (5.alpha.)-	4.1
1-Ethyl-2-pyrrolidinone	1.8	Cholest-2-ene	3.8
Hexadecanoic acid, methyl ester	1.5	Phenol	3.2
8-Octadecenoic acid, methyl ester	1.5	Cholest-5-ene	3.2
1H-Indole, 2,3-dimethyl-	1.4	2-Pyrrolidinone	2.9
9-Octadecenoic acid (Z)-, methyl ester	1.3	4.alpha.-Methylcholest-7-en-3-one	2.3



6 NRC·CNRC

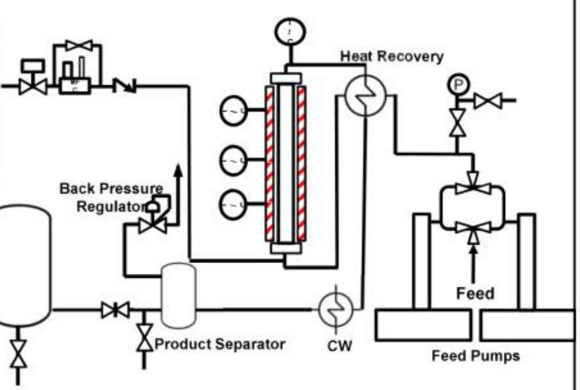
Major species from GC-MS: Road Side Residue, Pulp sludge

Road Side Residues		Pulp Sludge	
Phenol, 2-methoxy-	8.7	Phenol, 2-methoxy-	11.8
Phenol, 2,6-dimethoxy-	8.6	Phenol, 2-methoxy-4-methyl-	6.0
Phenol	5.2	Phenol, 4-ethyl-2-methoxy-	4.6
Phenol, 2-methoxy-4-methyl-	3.8	Phenol	3.2
Phenol, 4-methyl-	3.5	Phenol, 4-methyl-	3.0
2H-Pyran-2-one, 3-acetyl-4-hydroxy-6-methyl-	3.4	Phenol, 2-methoxy-4-propyl-	2.7
2-Cyclopenten-1-one, 2-methyl-	3.2	2-Cyclopenten-1-one, 2-methyl-	2.1
Phenol, 4-ethyl-2-methoxy-	2.9	1H-Indole, 2,3-dimethyl-	1.5
Phenol, 3-[(trimethylsilyl)oxy]-	2.2	Phenol, 4-ethyl-	1.5
Phenol, 4-ethyl-	2.0	Phenol, 2-methoxy-4-methyl-	1.5



7 NRC·CNRC

Hydrothermal Liquefaction Plug Flow Reactor



8 NRC·CNRC

Algal-crude yields and properties

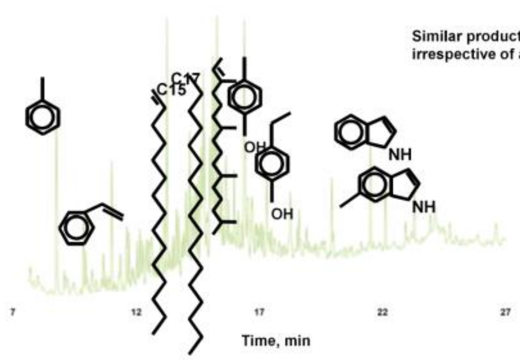
	Nannochloropisis CCMP525 (Marine)	Chlorella sp.	Chlorella vulgaris NRC's Ketch Harbor Facility	Chlorella sorokiniana NRC's Ketch Harbor Facility
Dry wt, %	18	20	20	17
Feed, L/h	1.2	1.0	1.0	1.2
C, wt %	**69.1 ± 0.3**	**75.1± 0.6**	**74.4 ± 0.1**	**73.7 ± 0.1**
H	**10.7 ± 0.1**	**10.7 ± 0.2**	**11.4 ± 0.3**	**12.0 ± 0.1**
N	**4.6 ± 0.1**	**6.2 ± 0.1**	**4.6 ± 0.4**	**3.8 ± 0.01**
S	**0.69 ± 0.1**	**1.1 ± 0.1**	**0.64± 0.1**	**0.7± 0.01**
O	**14.7 ± 0.11**	**6.7 ± 0.5**	**8.8 ± 0.30**	**9.3 ± 0.12**
HHV, MJ/Kg	**36.0 ± 0.42**	**39.6**	**40.0 ± 0.35**	**40.52 ± 0.11**
Ash, wt %	**0.44**	**0.24**	**0.2**	**0.36**
Algal-crude yields, wt %	**40.4**	**40.7**	**43**	**39**

9

NRC·CNRC

Algal-crude product profiles: GC-MS

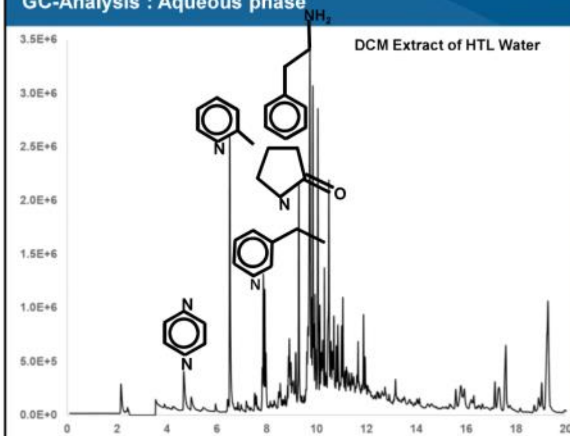
Similar product profiles were observed irrespective of algae species



10

NRC·CNRC

GC-Analysis : Aqueous phase



Pyridine, 2-methyl-
Pyridine, 3-methyl-
Pyrazine, methyl-
2,5-Pyrrolidinedione, 1-ethyl-
Pyrazine
2-Pyrrolidinone, 1-methyl-
Pyrazine, ethyl-
2-Cyclopenten-1-one, 2-methyl-
2-Cyclopenten-1-one, 3-methyl-
Cyclopentanone, 2-methyl-
Pyrrolidine, 1-acetyl-
Pyrazine, 2-ethyl-6-methyl-
Pyrazine, 2,3-dimethyl-
Pyridine, 3-methyl-
1,4-Benzenediamine, N,N'-diethyl-
Benzeneethanamine
Pyrazine, 2,6-dimethyl-

11

NRC·CNRC

Nutrients

- Nitrogen and Phosphorous requirements are a potential barrier to the scalability of algae based biofuels.
- Production of ammonia by Haber-Bosch process is energy intensive.
- Phosphate is a non-renewable resource

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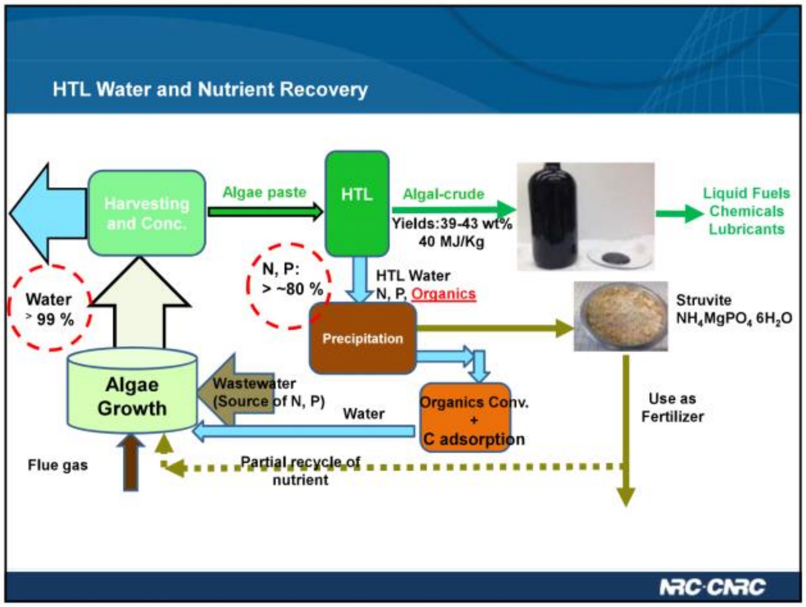
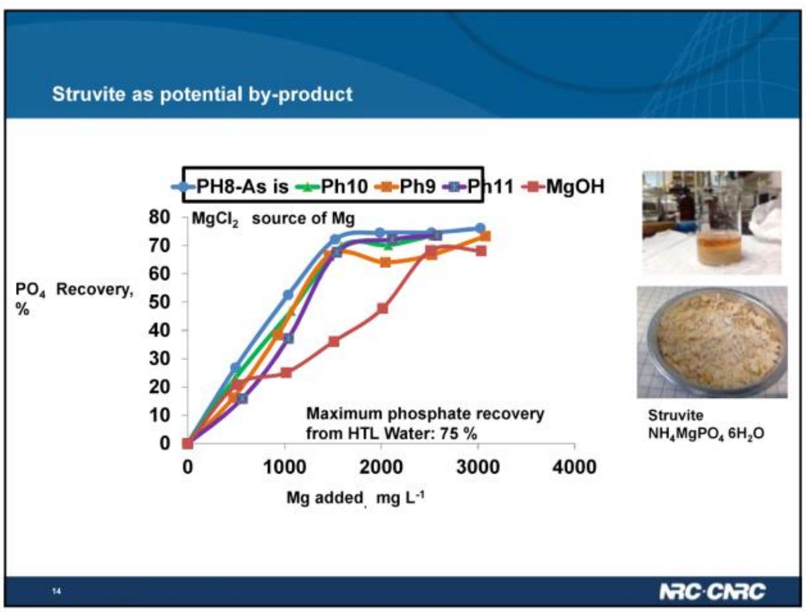
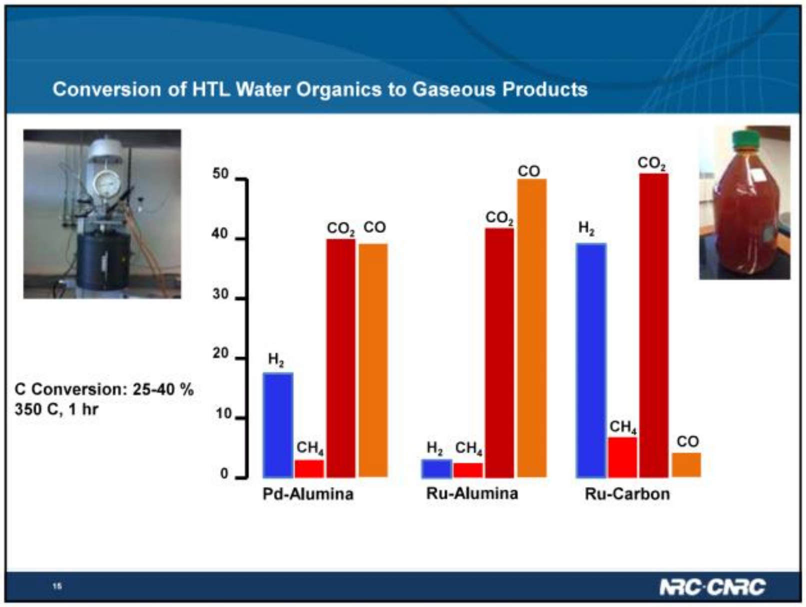
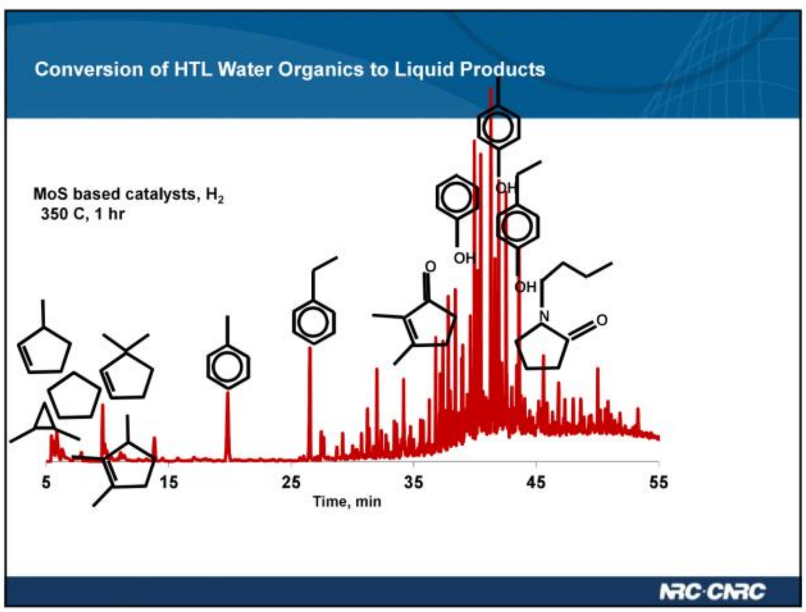
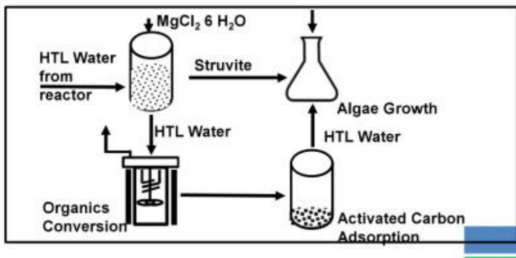
NRC·CNRC


HTL Water and Nutrient Recovery
Harvesting and Conc.
Algae paste
HTL
Algal-crude
Yields:39-43 wt%
40 MJ/Kg
Liquid Fuels
Chemicals
Lubricants
N, P:
> ~80 %
HTL Water
N, P, Organics
Water
> 99 %
Precipitation
Struvite
NH_4MgPO_4 $6H_2O$
Algae Growth
Wastewater (Source of N, P)
Water
Organics Conv. + C adsorption
Use as Fertilizer
Flue gas
Partial recycle of nutrient
NRC·CNRC


Struvite as potential by-product
PH8-As is
Ph10
Ph9
Ph11
MgOH
$MgCl_2$ source of Mg
PO_4 Recovery, %
80
70
60
50
40
30
20
10
0
1000
2000
3000
4000
Mg added, mg L^{-1}
Maximum phosphate recovery from HTL Water: 75 %
Struvite
NH_4MgPO_4 $6H_2O$
14
NRC·CNRC


Conversion of HTL Water Organics to Gaseous Products
C Conversion: 25-40 %
350 C, 1 hr
50
40
30
20
10
0
H2
CH4
CO2
CO
Pd-Alumina
Ru-Alumina
Ru-Carbon
15
NRC·CNRC


Conversion of HTL Water Organics to Liquid Products
MoS based catalysts, H2
350 C, 1 hr
O
OH
N
5
15
25
35
45
55
Time, min
NRC·CNRC



	Biomass, mg/L
WW	751
WW-Struvite	590
WW-Struvite-0.8%HTL	660
WW-Struvite-0.4% HTL	910
WW-Struvite-0.2% HTL	600

- increase in biomass concentrations with HTLW
- Inhibition significantly reduced

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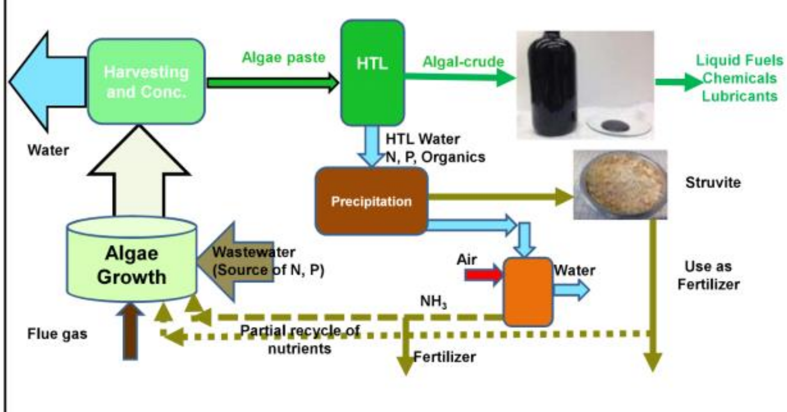
NRC·CNRC

Another approach: decoupling nutrient recycle from HTL Water



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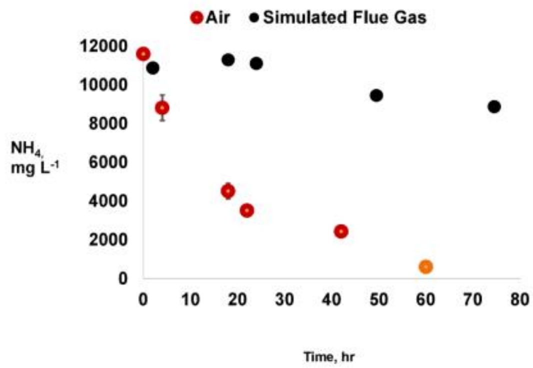
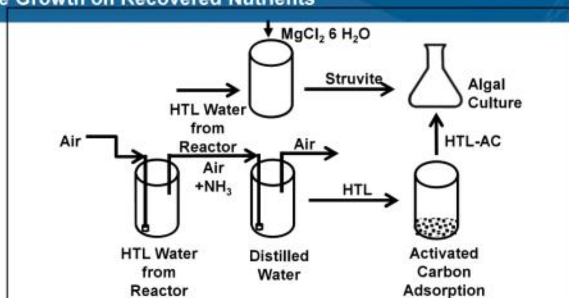
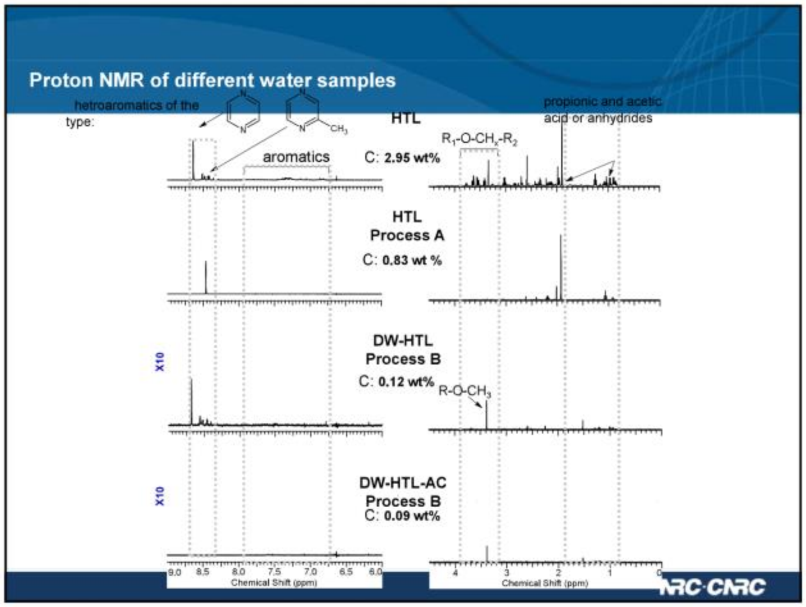
Decoupling nutrient recycle from HTL Water

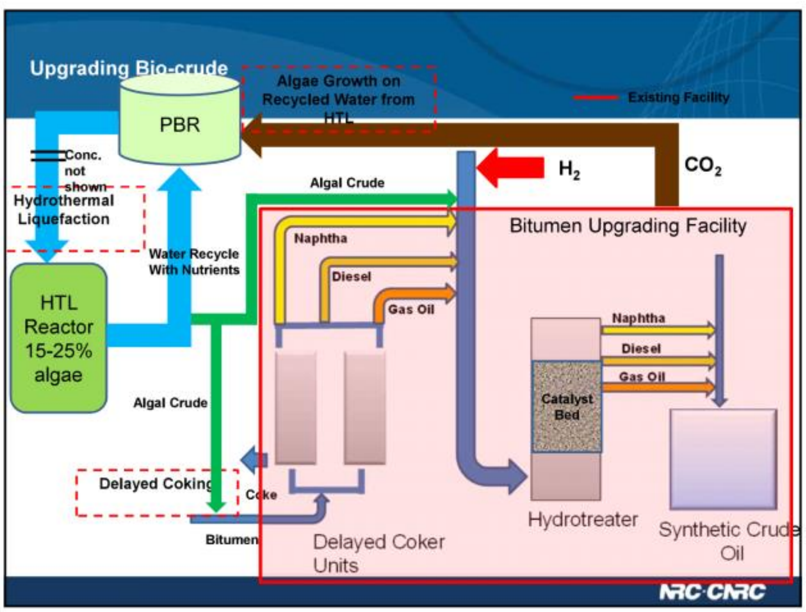


Algae Growth on Recovered Nutrients



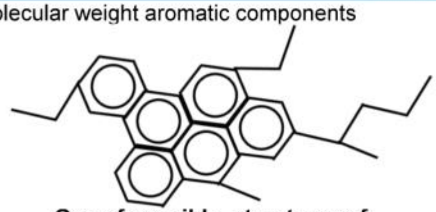
Growth Media	Apparent N Removal (%)	Apparent P Removal (%)	Specific Growth Rate (d^{-1})	Final Biomass Yield (g dw L^{-1})
DW-HTL	44 ± 5.8	-20.4 ± 11.1	0.73 ± 0.12	0.03 ± 0.02
DW-HTL-AC	> 99	68.3 ± 5.7	1.15 ± 0.09	0.95 ± 0.05
Modified Bold's Basal	63.2 ± 31.1	6.4 ± 5.0	1.24 ± 0.04	0.91 ± 0.27


Proton NMR of different water samples
hetroaromatics of the type:
HTL
C: 2.95 wt%
aromatics
R1-O-CH2-R2
propionic and acetic acid or anhydrides
HTL
Process A
C: 0.83 wt %
DW-HTL
Process B
C: 0.12 wt%
R-O-CH3
X10
DW-HTL-AC
Process B
C: 0.09 wt%
X10
Chemical Shift (ppm)
Chemical Shift (ppm)
NRC·CNRC


Upgrading Bio-crude
PBR
Algae Growth on Recycled Water from HTL
Existing Facility
CO2
H2
Conc. not shown
Hydrothermal Liquefaction
Algal Crude
Water Recycle With Nutrients
HTL Reactor 15-25% algae
Bitumen Upgrading Facility
Naphtha
Diesel
Gas Oil
Catalyst Bed
Algal Crude
Delayed Coking
Coke
Bitumen
Delayed Coker Units
Hydrotreater
Synthetic Crude Oil
NRC·CNRC

Asphaltenes

High molecular weight aromatic components



One of possible structures of asphaltenes in crude

Problems in processing and refining:

- Precipitate
- Coke formation
- Increased catalyst poisoning

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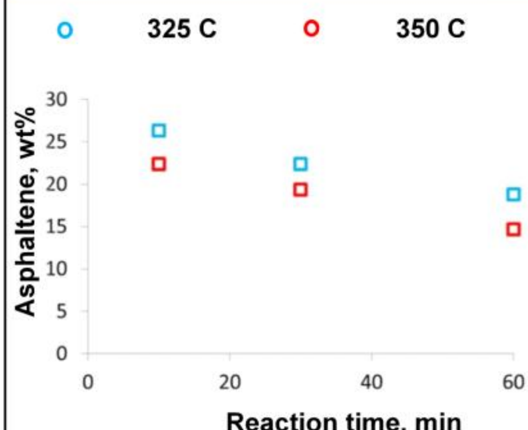
Asphaltenes in bio-crude



Asphaltenes from algal bio-crude

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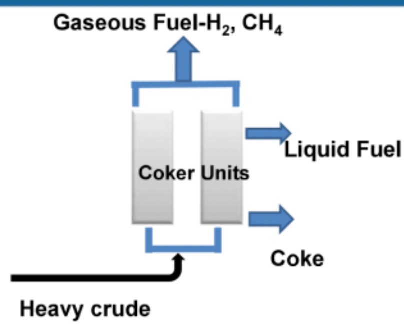
NRC·CNRC

Delayed Coking

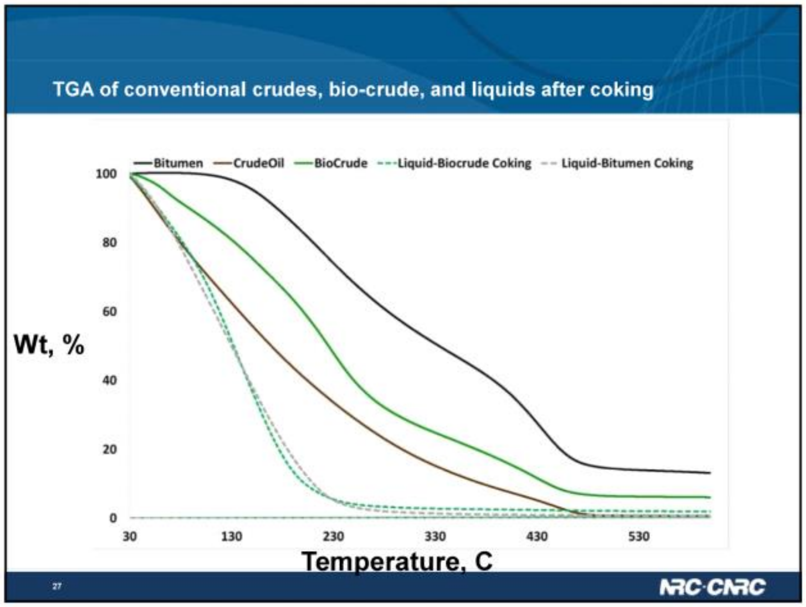


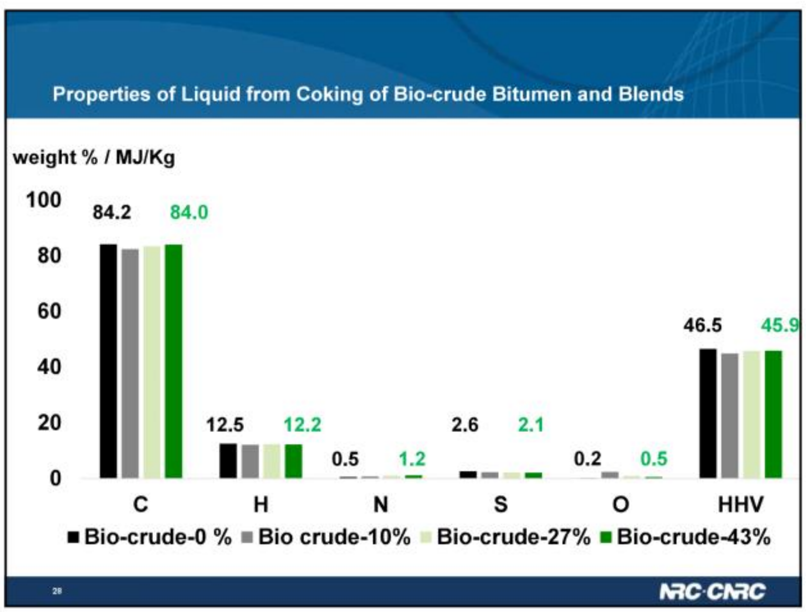
- Produces lighter oil, coke, and light gases
- Minimizes hydrogen consumption
- Reduce heteroatoms before catalytic upgrading
- Impurities would end up in coke

NRC·CNRC

Liquid Yields of Coking Bitumen and bio-crude blends

26 NRC·CNRC


TGA of conventional crudes, bio-crude, and liquids after coking
Bitumen
CrudeOil
BioCrude
Liquid-Biocrude Coking
Liquid-Bitumen Coking
100
80
60
40
20
0
Wt, %
30
130
230
330
430
530
Temperature, C
27
NRC·CNRC


Properties of Liquid from Coking of Bio-crude Bitumen and Blends
weight % / MJ/Kg
100
80
60
40
20
0
84.2
84.0
12.5
12.2
0.5
1.2
2.6
2.1
0.2
0.5
46.5
45.9
C
H
N
S
O
HHV
Bio-crude-0 %
Bio crude-10%
Bio-crude-27%
Bio-crude-43%
28
NRC·CNRC

Conclusions and Future Work

- Low quality biomass feedstocks- bio-crude:7-37 wt%, 35-39 MJ/kg HHV.
- Various species of marine and freshwater algae strains showed similar yields, properties and product composition.
- Nutrient recycle process that would minimize collapse and increase biomass yields using nutrients recovered from HTL water was developed.
- Upgrading of bio-crude and bitumen blends produced similar liquid yields and HHV.
- Evaluate best thermochemical routes for different low quality biomass feedstocks.
- Valorization of the aqueous phase from low quality biomass feedstocks.

29 NRC·CNRC

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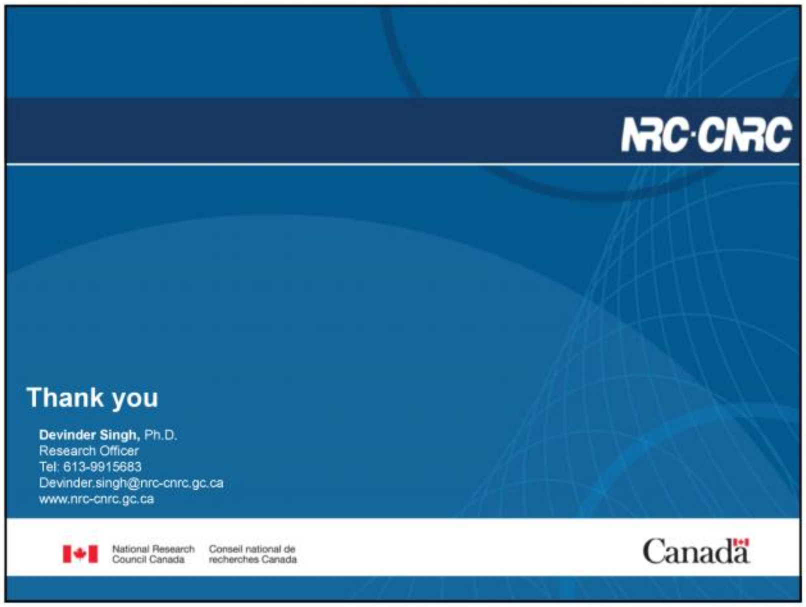
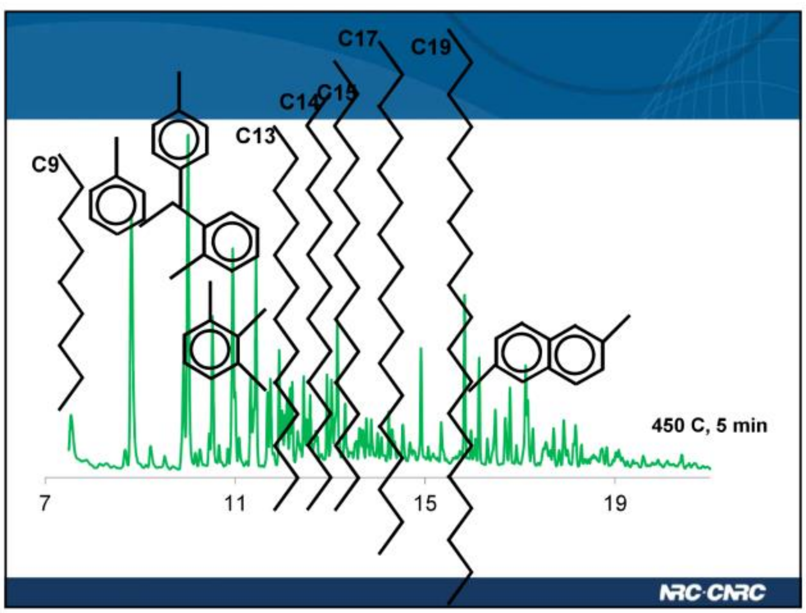
OERD's EIP Program
NRC's Algal Carbon Conversion Flagship Program

30 NRC·CNRC


NRC·CNRC
Thank you
Devinder Singh, Ph.D.
Research Officer
Tel: 613-9915683
Devinder.singh@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca
National Research Council Canada
Conseil national de recherches Canada
Canada


C17
C19
C14
C15
C13
C9
450 C, 5 min
7
11
15
19
NRC·CNRC

Pyrolysis research in forestry biofuels and bioproducts at Memorial University, Cape Breton University, and UNB

Team

Process Engineering: Kelly Hawboldt (Professor), Yan Zhang (Professor) Sadegh Papari, Anke Krutof, Tobias Bruekner, Hannieh Bamdad Mechanical Engineering (UNB) Dr. Muhammad Afzal Director, Bioenergy Bioproducts Research Lab (BBRL)

Chemistry: Bob Helleur (Professor), Stephanie MacQuarrie (Professor-CBU) Shofuir Rahman (post-doc)

Peter Fransham (Collaborator, ABRI-Tech Inc.)

NEWFOUNDLAND & LABRADOR, CANADA
WWW.MUN.CA

Remote/rural challenges/opportunities

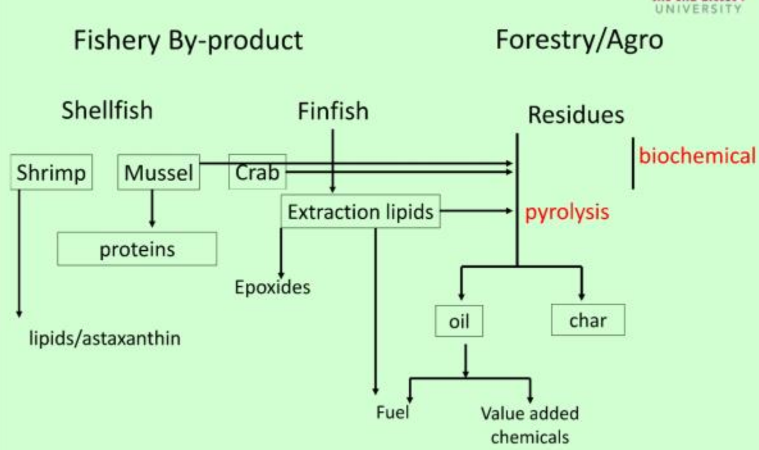
- Feasibility of any biomass processing whether it be to biofuels, biochemicals, or biomaterials driven by
  - location of feedstock,
  - state of feedstock,
  - available infrastructure,
  - distance to market, and
  - regional needs.
- Remote/rural operators (forestry, fisheries, mining) have a number of challenges when managing waste/residues:
  - Treatment/storage/disposal costs are high State of residues/waste (high moisture and cross contamination)
  - Transport of residues/wastes high in moisture is costly
  - Limited infrastructure on-site to process/treat waste

Research Focus

- In the short term may not be economically feasible or environmentally sustainable to transport biomass "as is" for processing

  → develop/modify pretreatment (e.g. densification) processes and APPROPRIATE conversion systems to produce products from biomass for transport or regional use

- The overarching objective behind this research is to develop and optimize bioproducts production (from pretreatment to end product) based on above factor and TRANLSLATE to industry.



Feedstock Properties

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- Characterized feedstocks – forestry and fishery residues
  - Sawmill residues – sawdust, shavings, chips, bark
  - Corner Brook Pulp and Paper – hog fuel, bark, residues

Annual generation of residues from CBPPL and current uses

Waste source	BDT/y	Current method of disposal
Fuel bark	97, 500	100% Hogfuel
Black bark	29, 000	Landfilled
Effluent treatment sludge	32, 500	100% Hogfuel
Boiler ash	15, 000	Landfilled

BDT – Bone dry tonnes

Total amount of residues generated and stockpiled on mill yards (green t/y)

Mill #s	Residues Generated (green t/y)					Stockpiled Residue (green t/y)			
	sawdust	bark	shavings	Slabs	chips	sawdust	bark	shavings	slabs
1	268	0	36	791	0	268	0	36	791
1	3,949	12,342	5,600	0	0	0	4,320	0	0
1	202	0	84	0	719	0	0	0	0
2	857	1,456	796	609	0	0	0	0	0
1	4,361	2,851	3,224	0	0	0	0	0	0
2	344	213	215	1,338	0	243	213	189	1,271
2	191	0	111	654	0	147	0	109	0
	10,172	16,861	10,067	3,392	719	657	4,532	334	2,062

Pyrolysis of forestry residues

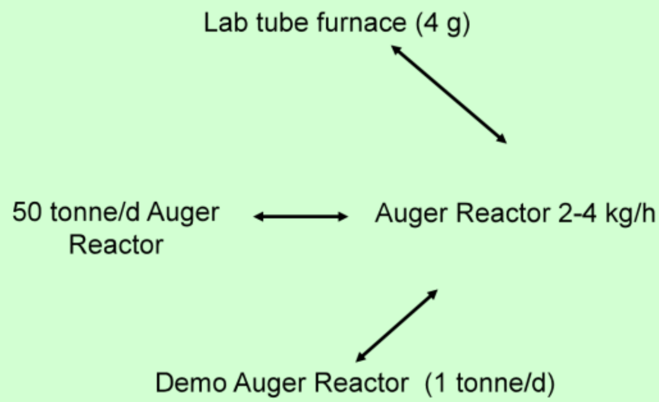
MEMORIAL UNIVERSITY

Mode	Conditions	Wt% Liquid	Char	Gas
Fast	~500°C, hot vapour residence time ~1-10 s	50-75	12-22	13-23
Intermediate	~500°C, hot vapour residence time ~10-30 s	50	25	25
Slow (Torrefaction)	~240-300°C solids residence time ~30 mins		75-85	15-25
Slow (Carbonisation)	~400°C, vapour residence time hrs → days	30	35	35
Gasification	~800°C	5	10	85

Lab → Pilot → large scale

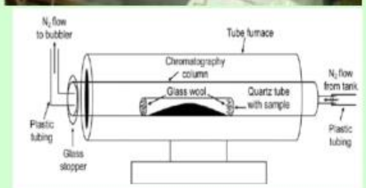
Lab → Pilot → large scale

3

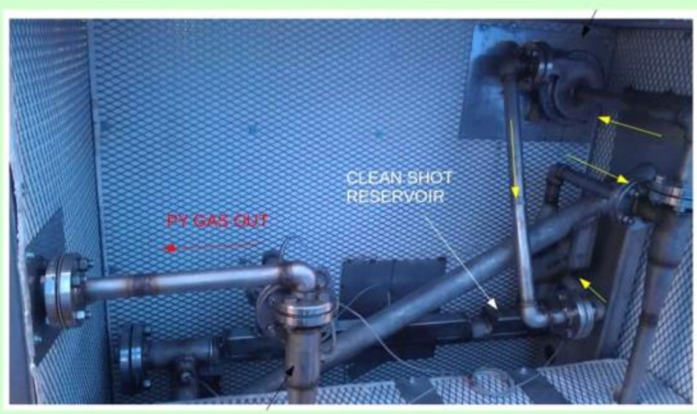


- Pyrolysis has many entrance points into biofuel/biorefinery process:
  1. Produce low grade fuels for heating oil and marine vessel fuel
  2. Pre-treatment step to densify materials and generate intermediate products for further refining.
  3. Integrated process in biorefinery.
- Research Areas
  - bio-oil and bio-char quality and production cost as a function of feedstock and pyrolysis technology;
  - Auger modeling and experiments (lab→50 tonne/d);
  - **solutions towards Fast and Slow Pyrolysis use as a techno-economically viable process as a function of feedstock, location, and market**

Tube lab scale reactor (batch unit)

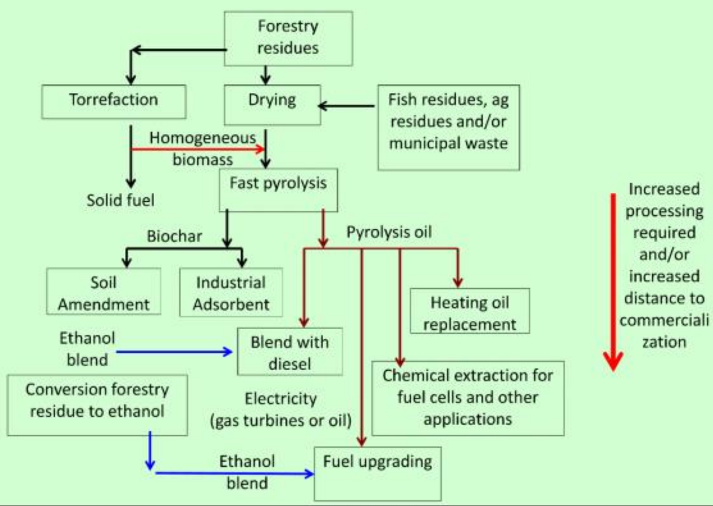


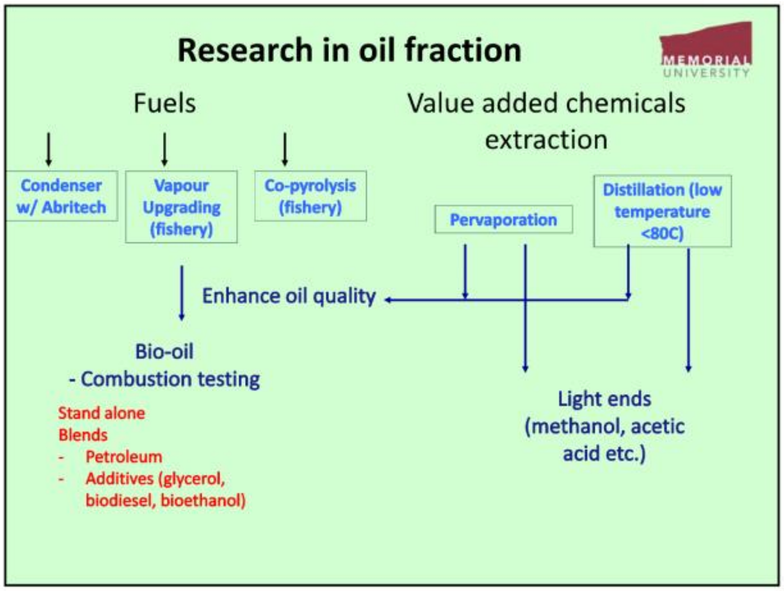
Auger pyrolysis reactor (2-4 kg/h)

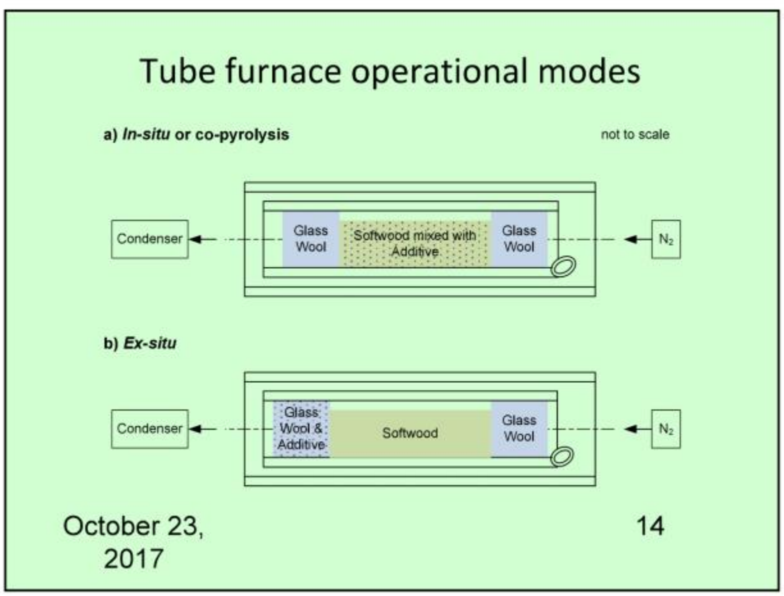


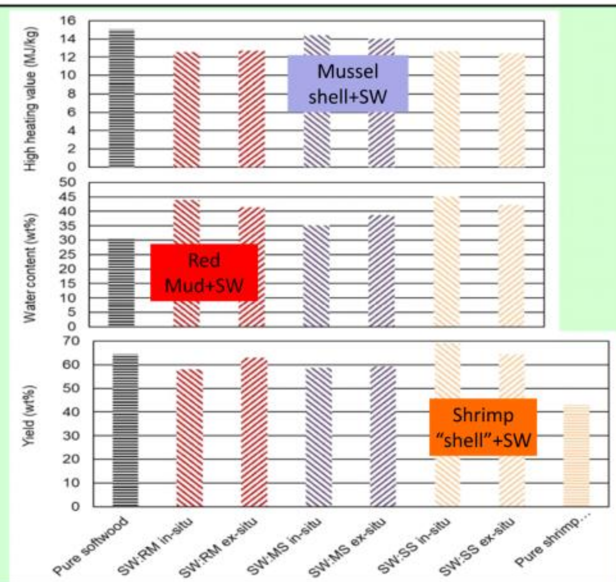
Slow pyrolysis (1 tonne/d CBU)

Pyrolysis Biorefinery Overview




Research in oil fraction
MEMORIAL UNIVERSITY
Fuels
Value added chemicals extraction
Condenser w/ Abritech
Vapour Upgrading (fishery)
Co-pyrolysis (fishery)
Pervaporation
Distillation (low temperature <80C)
Enhance oil quality
Bio-oil
- Combustion testing
Stand alone
Blends
- Petroleum
- Additives (glycerol, biodiesel, bioethanol)
Light ends (methanol, acetic acid etc.)

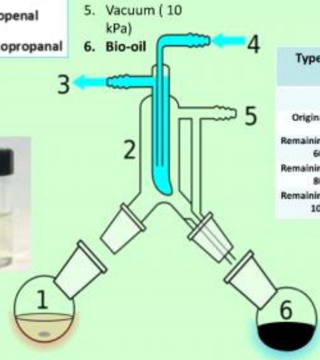

Tube furnace operational modes
a) In-situ or co-pyrolysis
not to scale
Condenser
Glass Wool
Softwood mixed with Additive
Glass Wool
N2
b) Ex-situ
Condenser
Glass Wool & Additive
Softwood
Glass Wool
N2
October 23, 2017
14



Vacuum Distillation of bio-oil to upgrade the oil and isolate chemicals

- Acetic acid
- Acetol
- Methanol
- Gylcolaldehyde
- 2-Propenal
- 2-Oxopropanal

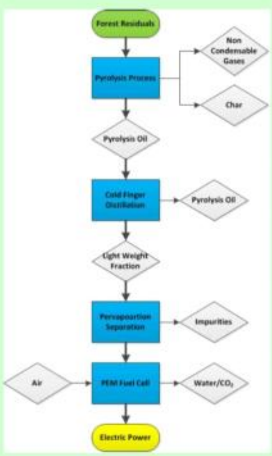
1. **Distillate fraction**
2. Cold finger
3. Cold water outlet
4. Cold water inlet
5. Vacuum (10 kPa)
6. **Bio-oil**

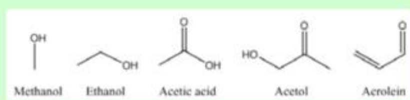


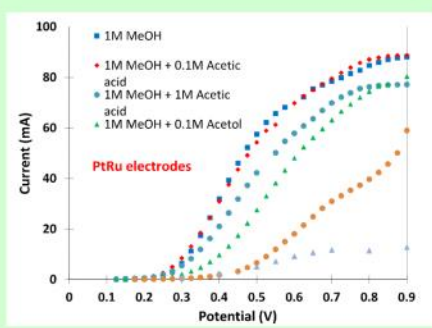
Type of oil	Water content (%)		Acetic acid (%)		HHV (kJ/g)		TAN	
	SW	Bark	SW	Bark	SW	Bark	SW	Bark
Original bio-oil	33.7	49.2	15.1	13.6	13.6	8.3	85.2	69.3
Remaining bio-oil at 60 °C	28.6	35.1	13.9	10.8	15.5	10.6	79.7	64.5
Remaining bio-oil at 80 °C	21.9	26.5	11.2	8.1	17.4	15.6	66.9	60.1
Remaining bio-oil at 100 °C	14.9	19.4	9.1	6.7	21.3	20.4	63.5	49.6

Type of oil	Water content (%)		Acetic acid (%)		HHV (kJ/g)		TAN	
	SW	Bark	SW	Bark	SW	Bark	SW	Bark
Original bio-oil	33.7	49.2	15.1	13.6	13.6	8.3	85.2	69.3
Remaining bio-oil at 60 °C	28.6	35.1	13.9	10.8	15.5	10.6	79.7	64.5
Remaining bio-oil at 80 °C	21.9	26.5	11.2	8.1	17.4	15.6	66.9	60.1
Remaining bio-oil at 100 °C	14.9	19.4	9.1	6.7	21.3	20.4	63.5	49.6

Fuel cell and biofuels (Dr. P. Pickup)



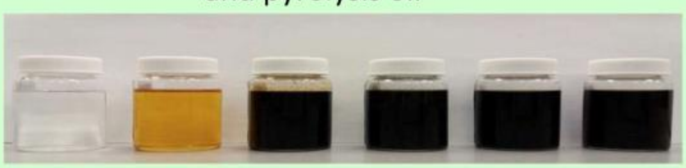




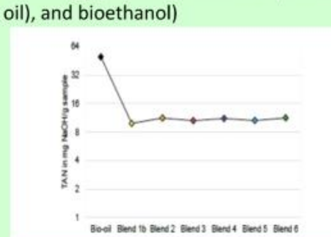
Preliminary work on blends of waste fish oil and pyrolysis oil

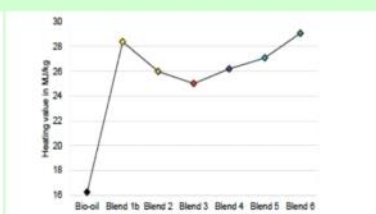
Property	Fish oil	80:20[a]	50:50[a]	20:50[a]	Pyrol. oil	50:50:10[b]
Pyrolysis oil fraction, wt%	0.0	24.3	51.8	83.6	100.0	47.6
Density at 15 °C, kg/m³	923.1	976.8	1043.9	1139.6	1185.0	1024.3
Kinematic viscosity at 40 °C, mm²/s	31.50	30.07	29.28	15.70	11.62	23.52
Activation energy, J/mol	27352.6	30245.9	47886.1	40295.0	36461.0	38219.5
Flow behavior index at 20 °C	0.99	0.96	0.81	0.96	0.91	0.65
Flow behavior index at 40 °C	0.99	0.93	0.90	0.92	0.94	0.92
Flow behavior index at 60 °C	0.99	0.92	0.88	0.92	0.95	0.93
Calorific value, MJ/kg	39.48	33.95	27.91	21.12	16.38	39.48
Calorific value, MJ/L	36.23	32.93	28.96	23.89	19.30	36.22
pH	4[c]	3.67[d]	3.30[d]	2.86[d]	2.64	
Water content, wt%	0.05[c]	7.4[d]	15.7[d]	25.3[d]	30.3	
Solid content, wt%	0[c]	0.73[d]	1.55[d]	2.51[d]	3.0	
< 200 °C, wt%	0.23	11.83	31.36	45.03	57.47	
200-600 °C, wt%	99.42	85.78	62.65	43.57	28.85	
Carbon, wt%	0.23	2.15	5.61	10.95	12.94	
Ash content, wt%	0.117[e]	0.244[e]	0.382[e]	0.455[f]	0.741[f]	
Melting peak 1, °C	−19.8	−20.7	−20.5	−21.3	−19.5	
Melting onset 1, °C	−26.4	−28.1	−31.3	−31.7	−30.5	
Melting peak 2, °C	−7.5	−7.2	−7.2			
Melting onset 2, °C	−10.5	−10.0	−9.6			
Freezing peak, °C	−11.8	−14.0	−14.4	−13.9		
Freezing onset, °C	−8.7	−9.3	−10.2	−10.3		

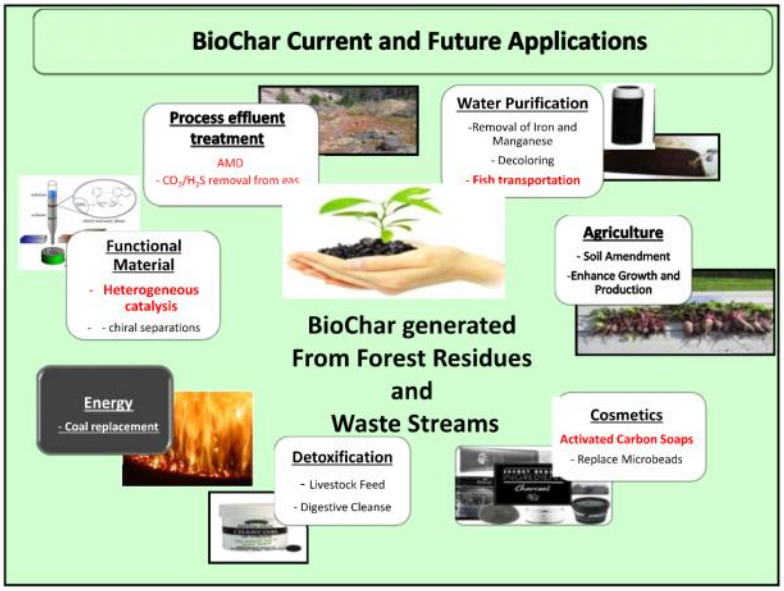
Preliminary work on blends of additives and pyrolysis oil



Blending glycerol and biodiesel (derived from transesterification waste fish oil), and bioethanol)







Bio-char as a fuel

Sample	HHV [kJ/g] Mobile torrefaction unit	Literature Value [kJ/g]
Fresh Sawdust	18. 27± 0.44	18.5[1] 18.6[2]
Sawdust (290-300° C) Aug 8	23.575± 1.61	22.6[2], 23.3[4]
Sawdust (290-300° C) Aug 7	23.36	
Fresh Bark	----	19.5[3] 19.71[5]
Bark (290-300° C) Aug 22	23.48± 1.2	24.6[3] 22.78[5]
Bark (290-300° C) Aug 8	22.08	

[1] D. A. Granados et al. 2014 – Micro-furnace, [2] J. H. Peng et al. 2013 – Tubular furnace –spruce, pine and fir sawdust - [3] bark pine , [4] H. Li et al. 2012 – Fluidized bed, [5] N. Doassans et al. –40kg/h pilot unit -pine bark -2014

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BioChar in soil and cosmetics - MUN and CBU

Soils

- Reduce soil acidity
- Increase soil moisture, water retention, soil structure
- Increase numbers of and stimulates beneficial soil microbes
- Increase productivity and crop yields
- Reduced leaching of nitrogen into ground water therefore reduce fertiliser use

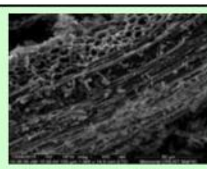
Cosmetics

- Replaces activated carbon in soaps → company developed at CBU

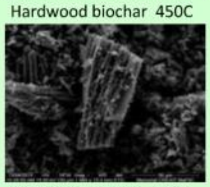
Radishes from char enriched soil

Salmon hydrosolate

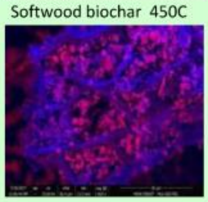
Hydrosolate+char



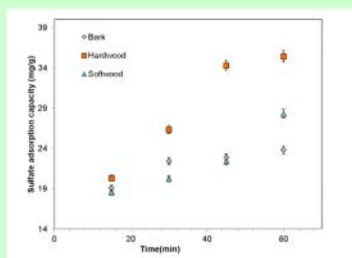
Hardwood biochar 450C



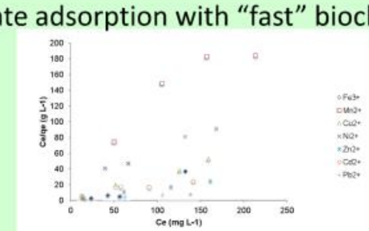
Softwood biochar 450C



Softwood+mussel shell biochar 450C



Sulfate adsorption with “fast” biochar



Metals adsorption with “slow” biochar

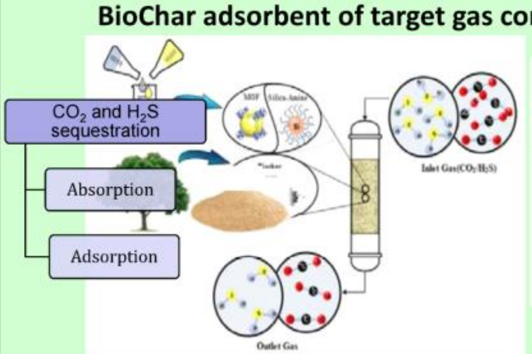
Collaboration with Grenfell (lead-Dr. Doreen Churchill and Dr. Mano Krishnapillai)

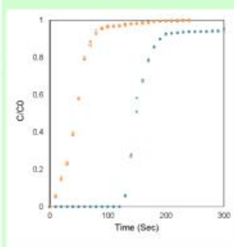
- Wood ash+biochar as soil amendment
  - Ash produced at mill and high mineral content makes possible soil additive
  - Metals in ash limit diversion options
- Ability of biochar to "fix" and metals present in wood ash

Fly and boiler ash from NB P and P

Element	HBP	MAP-1	MAP-2	MAP-3
	mg/kg	mg/kg	mg/kg	mg/kg
Ca	153,767	139,244	127,822	145,550
V	281.99	82.92	84.72	66.86
Cr	51.47	69.48	82.61	68.52
Fe	17,767	30,297	36,355	26,194
Mn	6,952	8,449	6,931	8,556
Co	10.83	8.80	10.83	9.54
Ni	212.26	57.66	57.29	52.42
Cu	203.40	94.40	90.30	83.00
Zn	7,129	342.13	149.03	55.03
Al	12,526	28,130	41,958	103,905
Mg	61,689	42,450	41,408	10,152
Ti	777	2,047	2,685	1,748
As	31.76	4.04	2.18	1.61
Mo	27.45	6.07	4.49	5.21
Se	9.22	<RL	0.45	2.24
Pb	293.08	16.61	5.69	1.60
Hg	<RL	0.06	0.17	<RL
Cd	72.37	2.67	0.78	<RL
Ag	3.50	0.53	0.47	0.47
Si	131,000	47,400	127,000	90,700
P	56,000	12,600	-	19,100
Na	18,000	600	12,500	7,500
K	36,000	6,500	145,000	13,300

BioChar adsorbent of target gas contaminants





CO_2 adsorption capacities (mmol/g)

		Total inlet flow rate (ml/min)	
		60	200
Mass of Adsorbent (g)	1	3.12	2.97
	2	3.40	3.23

- Collaboration with UNB
  - UNB focus on microwave pyrolysis and densification
    - Producing oil and char – working comparing chars and analyzing oils
- Database of chars
  - Determine "best" chars for specified application
  - CBU functionalizing for better adsorbent properties
    - Developing catalysts
    - cosmetics

Ongoing/future focus

- Overall objective is creation of new markets through product/process research and development
- Identify valuable by-products in residues from forestry, fisheries and mining through characterization
  - Determines best pre-treatment processes
- Develop feedstock handling/storage methods to minimize product degradation and identify optimum points in process to extract by-products

Ongoing/future focus

MEMORIAL UNIVERSITY

- Develop innovative processes to extract value-added products that are environmentally sustainable and economically feasible
  - Develop both small (plant) and large scale systems (central processing facility)
- Refine/Develop bio-based fuels/chemicals for application in domestic, commercial, and industrial markets
  - Within this integrate with other resources

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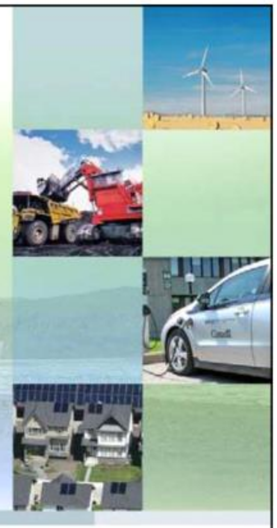
Making Use of Abundant Low Quality Residuals through Thermochemical Conversion

Ben Bronson, Dillon Mazerolle, Murlidhar Gupta and Fernando Preto

IEA Bioenergy, Task 34 (Direct Thermochemical Liquefaction), Technical Workshop. November 30th, 2017: Ottawa, ON

CanmetENERGY
Leadership in ecoInnovation



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About CanmetENERGY

- CanmetENERGY is a science and technology branch of Natural Resources Canada and operates three labs across Canada with over 450 scientists, engineers and technicians
- CanmetENERGY-Ottawa's mission is to lead the development of energy S&T solutions for the environmental and economic benefit of Canadians

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Objectives

- Generate public data on conversion performance <u>low quality residues</u> and resulting liquid properties
- Explore and document issues and / or opportunities for these residues

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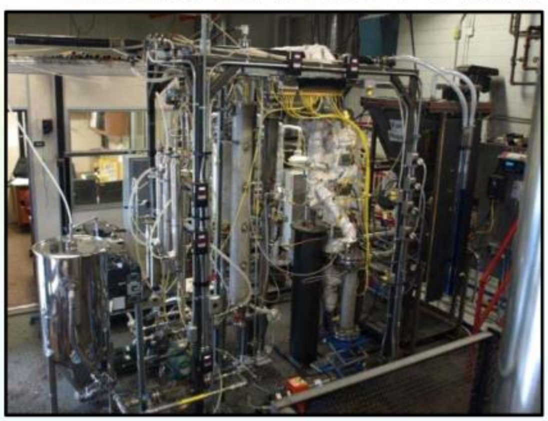
$4x10^6$ km^2 forested land
$140x10^6$ $m^3.a^{-1}$ annual cut

CanmetENERGY Fluid Bed Pyrolyzer



- 5 – 10 kg/h biomass feed rate
- 1 – 2 second vapour residence time
- Electrically heated
- 2 cyclones in series for char removal
- Condensation via quench with immiscible hydrocarbon
- "5 micron*" filters installed on bio-oil recovery

*nominal rating. Subsequent product testing has shown this not to be an absolute rating

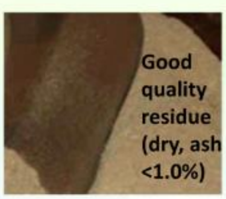
Catalytic Upgrading of Biomass-Derived Intermediates

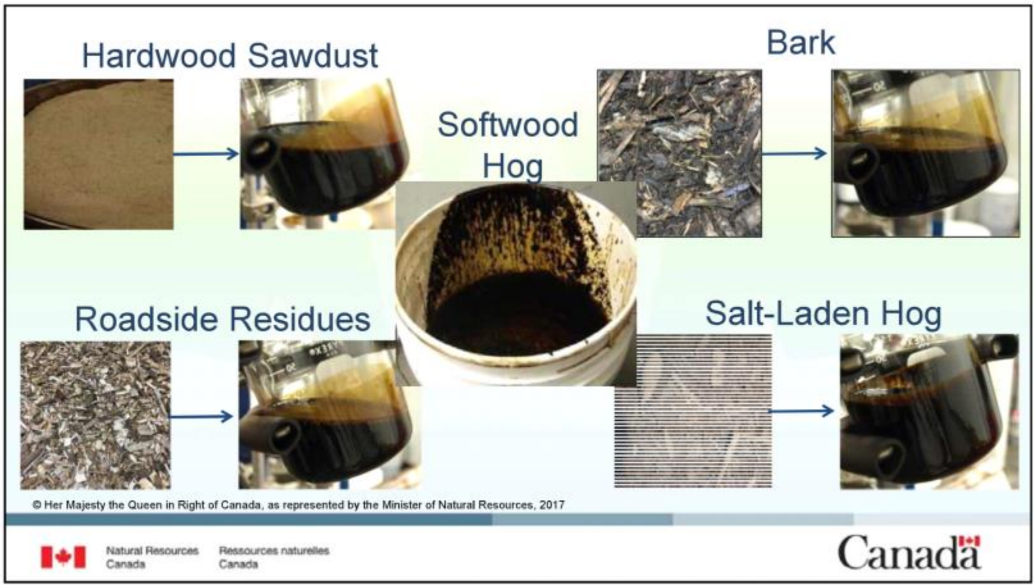
- Catalytic hydrotreating of pyrolysis bio-oils for application in production of transportation fuels such as jet fuel/diesel fuel
- Upgrading of bio-crudes produced from hydrothermal liquefaction of algae in collaboration with NRC
- Conversion of lignin-derived intermediates to drop-in liquid biofuels
- In-process vapour upgrading integrated with CE-O fluidized bed fast pyrolysis reactor


20-120 mL Continuous Reactor System


1-3 kg/h Process Development Unit

Low quality feedstocks




Hardwood Sawdust
Bark
Softwood Hog
Roadside Residues
Salt-Laden Hog
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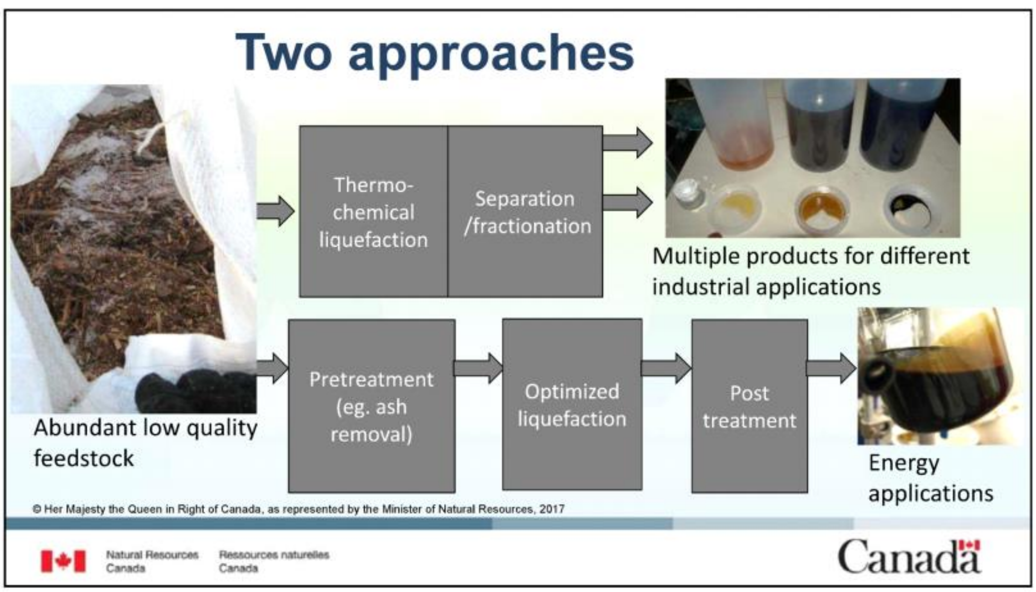
Two approaches
Thermo-chemical liquefaction
Separation /fractionation
Multiple products for different industrial applications
Pretreatment (eg. ash removal)
Optimized liquefaction
Post treatment
Abundant low quality feedstock
Energy applications
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Multi-Stream Approach

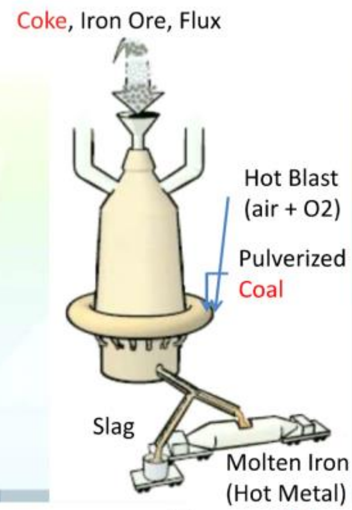
- Properties, consistency and behaviour of separated liquid products from low quality materials
- Viable separation (or direct fractionation) approaches
- Identification of opportunity markets and requirements of those markets
- Equipment operation on untreated, low quality residues
- Generation of suitable quantities of separated liquid products to test in end-use applications

Uniform Biofuel Approach

- Solids, ash, and uniformity of product liquids are significantly impacted by feedstock quality. Viable treatment pathways required.
- Lack of publically available data on appropriate treatment approaches
- Treatment costs ($/L). Is it worth it?
- Fuel property requirements for heating applications established. Fuel property requirements for engine and turbine applications?

Solid Products

- Evaluating industrial applications of different pyrolysis streams
- Iron & steel is a major opportunity
- Steel Industry emitted ~14.6 MT GHG in 2013, concentrated in one region (Ont.)
- Major C-sources: Coke and pulverized coal
- Metallurgical coke demands specific properties (low K & P, hot strength, reactivity).



Solids and Tars for Steelmaking

- Char for Pulverized Coal Injection (PCI) Steel Blast Furnace
  - Challenges: high ash loading from residuals feedstocks
- "Organic" phases for binders
  - The tarry phase from fast pyrolysis of low quality residues showing promise to fabricate briquettes for coking of coal and biochar mixes

Multi-Stream Approach: Novel Ablative Centrifuge Pyrolysis System

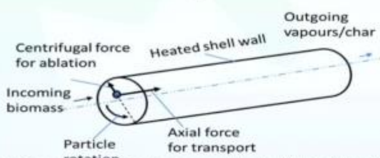
Additional credits: Andy McFarlan and Leslie Nguyen

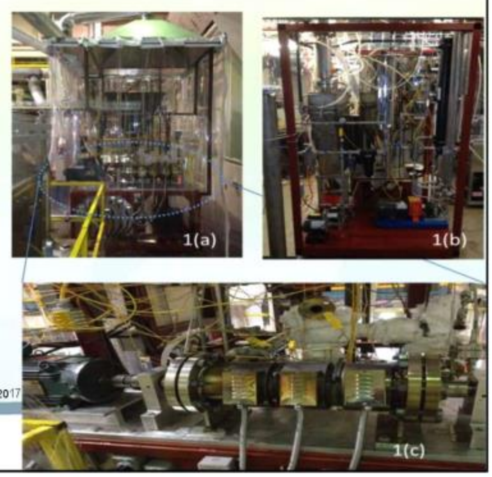
Design Objectives

- Low carrier gas volume.
- Capability to handle low quality biomass
  - with lower requirements for size reduction
  - better suited for distributed pyrolysis?
- Flexibility to operate with variable regimes e.g. slow as well fast pyrolysis.

Pilot scale ablative pyrolysis unit

Innovative rotor design provides continuous centrifugal force for ablation of biomass particles against a cylindrical heated surface and axial force for downstream transport.





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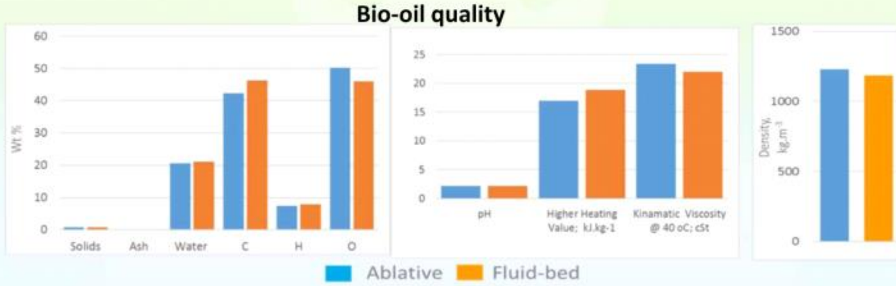
Comparative performance

- Initial tests completed using baseline high quality residue (low ash hardwood sawdust from flooring manufacture)

Bio-oil quality



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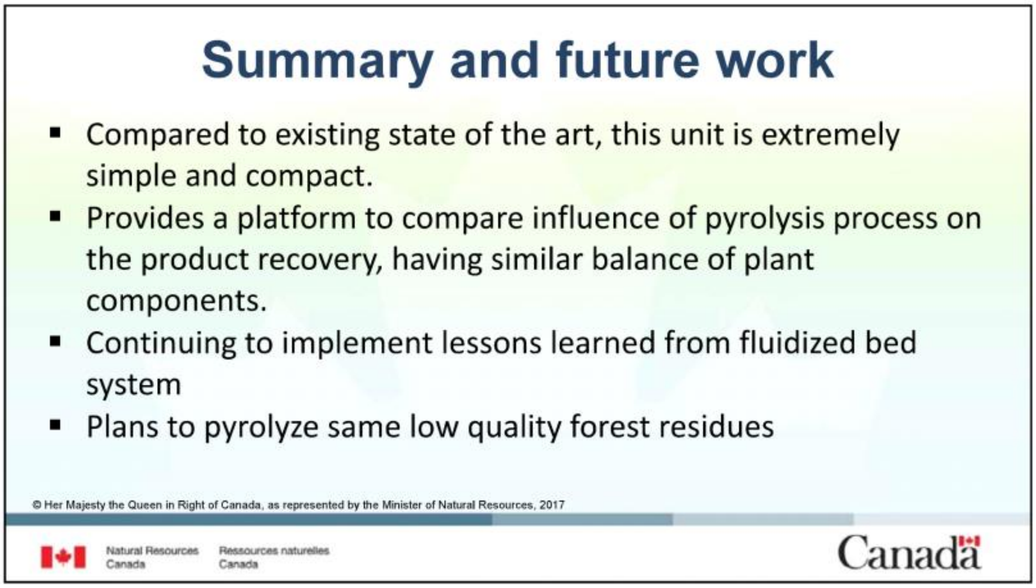
Summary and future work
Compared to existing state of the art, this unit is extremely simple and compact.
Provides a platform to compare influence of pyrolysis process on the product recovery, having similar balance of plant components.
Continuing to implement lessons learned from fluidized bed system
Plans to pyrolyze same low quality forest residues
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Multi-Stream Approach: Condensation Issues
Additional credits: Ben King, Evan Shuparski
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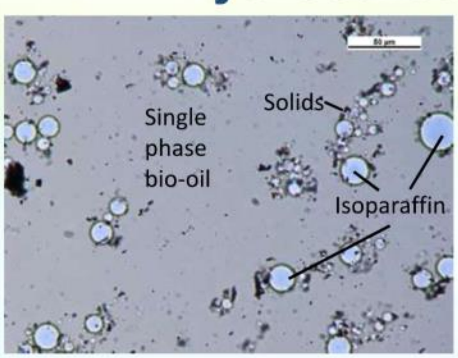
Challenges with "immiscible" hydrocarbon quench fluid

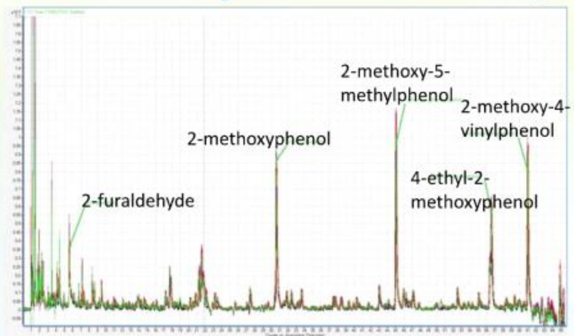
- Emulsification of the hydrocarbon fluid in the product bio-oil
- Dissolution of bio-oil components in the quench fluid
- Separation difficulties with low quality residues

Transitional samples between bark bio-oil and isoparaffin – No clear interface found

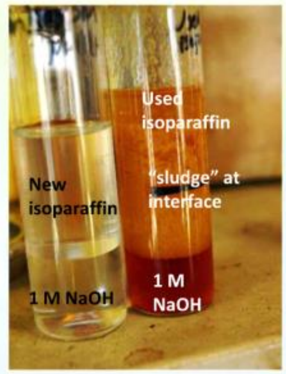
Challenges with "immiscible" hydrocarbon quench fluid



Challenges with "immiscible" hydrocarbon quench fluid

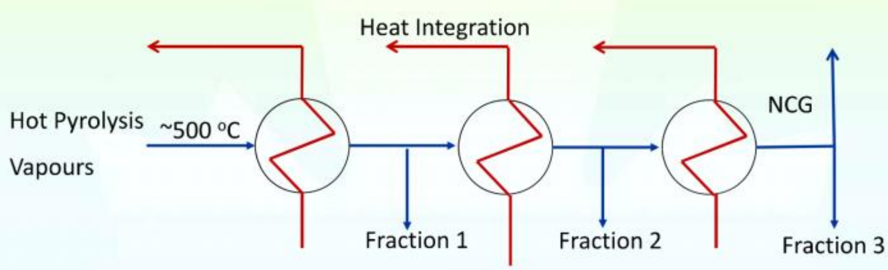


Used isoparaffin with subtract from new isoparaffin



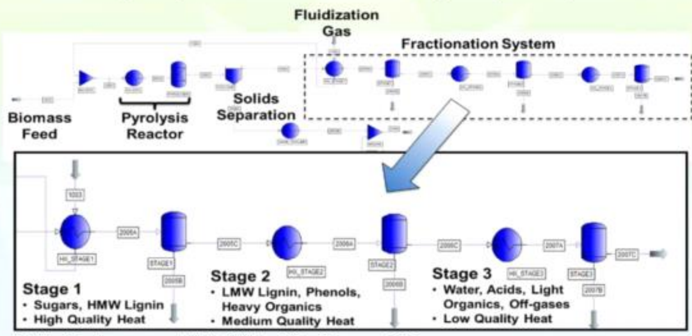
Re-design of Condensation

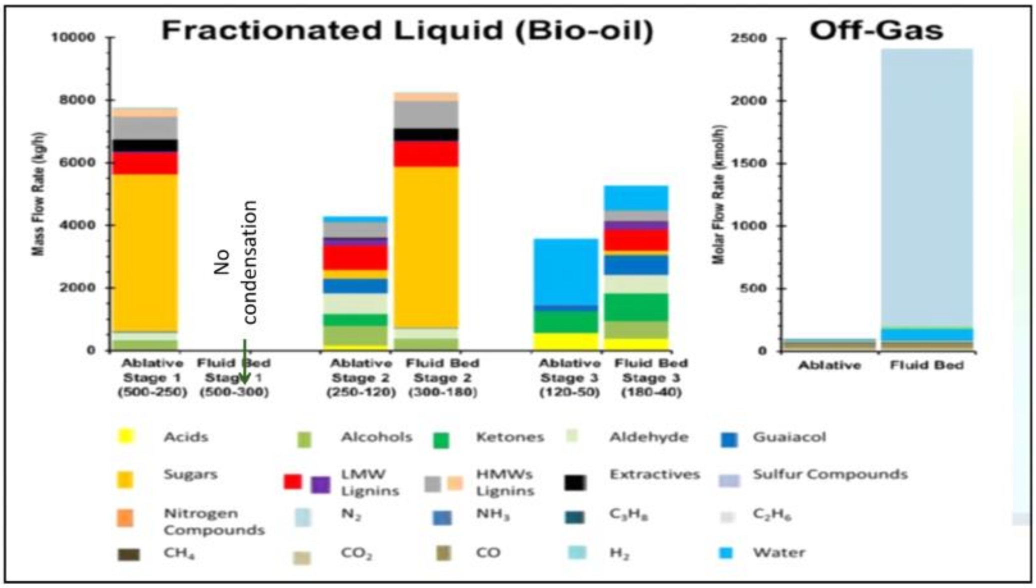
- Thermal quench with heat recovery
- Chemical quench to stabilize the product streams.



Pro/2 process model

- Fluid Bed Pyrolysis and Ablative Pyrolysis System





Summary and future work

- The simplified assumption of an "immiscible" quench fluid has led to operational challenges. Caution needs to be applied in translating experimental systems to commercial scale systems using recycled bio-oil quench.
- Increased dilution gas significantly suppresses dew points
- Judicious selection of condenser temperatures facilitates early isolation of sugars and lignin promising better stability of products.
- Working towards experimental evaluation of condenser configurations and selection of quench fluids

Uniform Biofuel: Addressing solids content through filtration

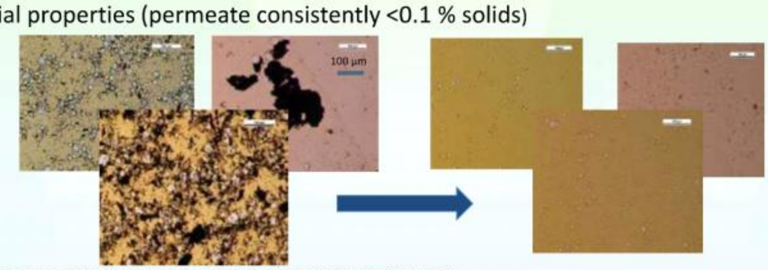
Filtration approaches

- Hot vapour filtration – technically challenging, some data on performance in literature, reduction in liquid yield
- "Simple" filtration approach taken at experimental scale work for experimental purposes – Not transferable to commercial scale
- Biggest issue with filtering pyrolysis oil – large fouling resistances requiring high pressure or frequent operational cycling and / or filter material replacement. Cross-flow approaches with thin membranes may alleviate issues.

Membrane Microfiltration – Solids Content

- Targets: Grade D ASTM D7544-12 < 0.25%, CEN 16900 Grade B <0.5%, Wärtsilä suggested for diesels <1.0% with >90% below 25 µm.

Results: Solids content of the permeate with 5 µm membrane is similar regardless of feed material properties (permeate consistently <0.1 % solids)

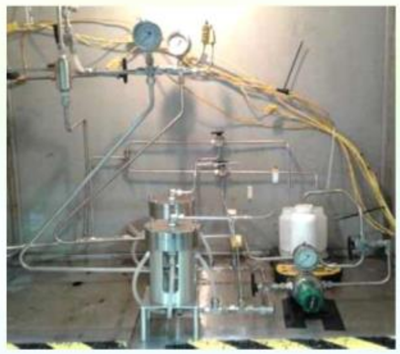


Membrane Microfiltration

- Technique is clearly suitable of meeting solid content targets

Next steps:

- Scale up production to process full batches of bio-oil produced at CE-O (>10L)
- Increase membrane productivity / reduce fouling
- Achieve long duration, steady operation



Membrane Fouling

Uniform Biofuel: Removing feedstock ash by sieving and acid washing

Ash Removal

- One of most significant issues with low quality residues is higher ash content. This leads to:
  - Higher solids and ash in bio-oil
  - Phase stability issues (non-uniform bio-oil)
- One approach is to remove ash components from feedstocks prior to conversion
  - Sieving (removes "contamination" ash from collection practices)
  - Acid washing (removes ash inherent to the biomass)

Sieving

Removes fine particles which tend to have higher ash content (soil, brittle constituent materials)

Feedstock Description	Bulk ash content	Ash in coarse fraction	Ash in fines fraction
Sawmill bark, poplar, eastern Canada	6.4%	4.7%	7.3%
Hog Fuel, softwood, western Canada	11.8%	4.1%	52.5%
Harvest residues, birch & maple, eastern Canada	2.8%	1.6%	5.4%

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Impact of sieving

	Softwood Hog Fuel		Hardwood Roadside Residue	
Parameter	Original	Sieved	Original[1]	Sieved[2]
Feedstock recovery	100%	83%	100%	68%
Ash in feedstock	11.8%	4.1%	2.8%	1.6%
Char yield (DAF)	20.8%	19.4%	14.5%	14.1%
Gas yield (DAF)	13.8%	13.0%	11.5%	10.9%
Bio-oil uniformity	obvious multiphase	obvious multiphase	visually uniform, non-uniform in 7-day settling test	visually uniform, non-uniform in 7-day settling test
Solids in bio-oil	0.79%[3]	0.74%[3]	0.51%	0.53%
Ash in bio-oil	0.38%[3]	0.30%[3]	0.13%	0.13%

1 - Average of 3 trials

2 - Average of 2 trials

3 - Weighted average result from the two analyzed phases

- 480°C, ~1 s vapour residence time
- Observed very little impact of ash removal by sieving

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Acid washing

- 0.1 M HNO_3, Western Canada Softwood Hog

	Original	Sieving	Acid Washing
mg / kg feedstock db		% removed	% removed
Aluminum	2471	60%	57%
Calcium	25038	57%	86%
Iron	2063	61%	53%
Magnesium	11471	54%	94%
Phosphorus	6144	40%	95%
Potassium	2206	11%	88%
Silicon	11140	56%	56%
Sodium	1478	69%	96%
Sulfur	1765	46%	92%

Impact of acid washing

Original Feedstock
Obvious multiphase
DAF yield – Char: 20.8% Gas: 13.8%
Bio-oil – water: 35.7% solids: 0.79% ash: 0.38%

Acid Washed Feedstock
Uniform*
DAF yield – Char: 14.6% Gas: 8.8%
Bio-oil – water: 17.7% solids: 0.39% ash: 0.07%

*Passes at 5% RD on water in 7-day settling test

Summary and future work

- Sieving – led to significant reduction in feedstock ash content but showed significant material losses and had minimal impact on yields and bio-oil properties
- Acid washing – substantially improved removal of bioactive minerals such as K, Ca, and P. Generated higher yields of single phase bio-oil with reduced solids and ash content
- Future work: evaluate feasibility of large scale acid washing on forestry residues

Uniform Biofuel: Combustion of bio-oil

Current Bio-oil Combustion Objectives

- Addressing the question of whether or not achieved bio-oil properties are suitable for end-use in combustion equipment
- Substantial experience over the past two decades at scales up to 200 kg/h. Need for smaller scale (commercial) capacity (lower bio-oil volume requirements & lower costs = more tests)
- Platform to generate data on fuel-N conversion to NOx, PM emissions and other key emission factors for combustion and generate understanding between burner design or bio-oil properties and combustion performance

Bio-oil-fired Furnace

- Converted waste-oil furnace for bio-oil firing
- 150 – 200 MJ/h capacity (close to our production capability)
- Air-assisted atomization. Fuel pre-heating

Initial experience at small scale

- Off-the-shelf the system operated for a handful of tests with bio-oil / furnace oil emulsions
- As expected, issues encountered while trying to move towards pure bio-oil
- Flash point is a significant issue for bio-oil solvents to help incremental approach to firing 100% bio-oil. Initial work limited to a maximum of 10% dilution with volatile alcohol due to flash point.

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Identification of a suitable high-flash solvent

- Integrated with work on bio-oil uniformity
- Mostly using low flash point solvents (<40 deg. C)
- Good success recently achieved using glycol ethers for cleaning bio-oil
- Need for something non-toxic and relatively easy to get

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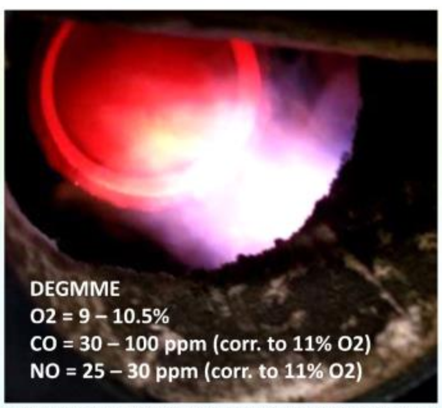
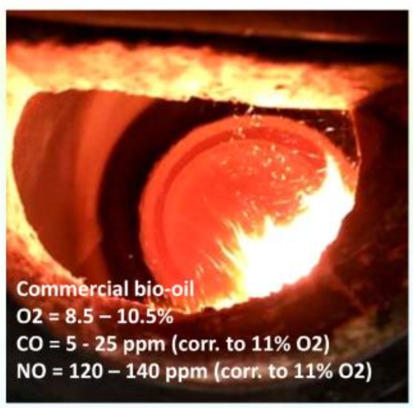
Modifications for combustion testing

- Required to modify entire fuel delivery system up to the (but not including) the nozzle
- Pressure regulators, fuel solenoids, pre-heating strategy, pump, etc...
- Selection of Diethylene Glycol Monomethyl Ether (DEGMME) as flush solvent / secondary fuel for the furnace

Combustion on solvent and bio-oil





Summary and future work

- Combustion testing proceeding successfully on 100% bio-oil
- Emissions and flame monitoring being established
- Continued improvement to instrumentation and data logging
- Immediate plans are to validate the stability of operation
- Need to move towards bio-oils with different properties

Thank you

- Benjamin.Bronson@Canada.ca
- Dillon.Mazerolle@Canada.ca
- Murlidhar.Gupta@Canada.ca
- Fernando.Preto@Canada.ca

Ontario

Ontario's New Regulations and Guidelines to Promote Biomass Heating

Steven Law, P. Eng.

IEA Bioenergy Task 34 - Direct Thermochemical Liquefaction: Biomass Liquefaction Workshop

November 30, 2017

Agenda

- Introduction
- Environmental Protection Act
- Ontario Regulation 524/98
- Ontario Regulation 1/17
- Ontario Regulation 419/05
- Guideline A-13
- Guideline A-14
- Air Emission EASR Limits and Other Requirements
- More Information

Introduction

- Through the government's 2015 Fall Economic Statement, the MOECC committed to improving the Environmental Compliance Approval (ECA) process by:
  - Reducing, for the fall of 2017, the amount of MOECC time taken to review air and noise ECA applications by at least 50 per cent
  - Implementing a one-year service standard for higher-risk ECA applications received after 2017
- A new Environmental Activity and Sector Registry (EASR) Regulation was developed for facilities with air emissions that are not considered high risk or complex in support of the ministry's on-going efforts to implement a risk-based approach to environmental approvals

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Ontario

Introduction

- New air quality guidelines are available in Ontario that differentiate between large wood-fired combustors (LWFC) and small wood-fired combustors (SWFC)
- Under certain circumstances, SWFC may be registered under the EASR program or may even be exempt entirely from the EASR and ECA programs
- Several factors need to be assessed to determine which program applies, such as the NAICS code of the facility, the heat input and output capacity of the combustion system, the certification status of the combustion system and the characteristics of the wood fuel

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Ontario

Environmental Protection Act

- In Ontario, subsection 9(1) of the Environmental Protection Act (EPA) generally prohibits the discharge of air emissions from any source except in accordance with an ECA
- Exceptions to this requirement are listed under subsection 9(3) for sources that do not require an approval and subsection 9(4) for activities that are prescribed for the purposes of the EASR as described here:

https://www.ontario.ca/laws/statute/90e19#BK11

5 Ontario

Environmental Protection Act

- Ontario Regulation 524/98 (updated on February 3, 2017) sets out exemptions from the approval requirement in 9(1) of the Act (e.g., SWFC with a maximum heat output of up to 50 kW and masonry fireplaces constructed on-site) can be found here:

https://www.ontario.ca/laws/regulation/980524

- Ontario Regulation 1/17 (effective January 31, 2017) prescribes many activities with air emissions which must be registered in the EASR can be found here:

https://www.ontario.ca/laws/regulation/r17001

6 Ontario

Ontario Regulation 419/05

- Whether applying for an ECA or registering under EASR, a facility must develop a program-specific Emission Summary and Dispersion Modelling (ESDM) report to ensure that the concentration of each air contaminant emitted from the facility is below the relevant point of impingement limit and is not likely to cause an adverse effect
- Ontario Regulation 419/05 regulates local air quality and is the primary governing regulation for local air quality in Ontario which can be found here:

https://www.ontario.ca/laws/regulation/050419

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Ontario

Guideline A-13

- Guideline for the Control of Air Emissions from Large Wood-Fired Combustors (LWFC) with a Heat Input Capacity of 3 Megawatts or Greater (≥ 3 MW) which was first published in January 2015 can be found here:

https://www.ontario.ca/page/control-air-emissions-large-wood-fired-combustors

- Guidance varies depending on status of LWFC, including whether it is considered “existing”, “significantly modified” or “new”
- This Guideline is considered by the Director in determining ECA applications relating to LWFC

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Ontario

Guideline A-14

- Guideline for the Control of Air Emissions from Small Wood-Fired Combustors (SWFC) with a Heat Input Capacity of Less than 3 Megawatts (< 3 MW) was first published on January 31, 2017
- Facilities with SWFC that do not meet the eligibility requirements for EASR (O. Reg. 1/17) are required to submit an application for an ECA
- Guideline A-14 is considered by the Director in determining ECA applications and can be found here:

https://www.ontario.ca/page/controlling-air-emissions-small-wood-fired-combustors

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Ontario

Wood Fuel Parameters

- Wood Fuel Specifications: new and reassessed SWFC
- Wood Pellets: ISO 17225-2 (Type A1, A2 or B) or PFI (premium or standard grade)
- Wood Chips: moisture content of 50% or less and ISO 17225-4 (Type A1, A2, B1 or B2)
- For wood chips, 50% or less moisture content expectation will begin on Jan. 31, 2017, but ISO specification will not begin until Jan. 31, 2027
- Wood Briquettes: ISO 17225-3 (Type A1, A2 or B)
- See Guideline A-14 Appendix F for Natural Resources Canada bulletins on ISO wood fuel standards

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Ontario

Guideline A-14

- There are two options in the Guideline – follow "certified" rules based on the European Standard EN 303-5 (2012) with some extra provisions (similar to EASR) or otherwise follow rules for "uncertified" SWFC
- Reference to use Guideline A-13 where Guideline A-14 is not applicable to the SWFC (e.g., the SWFC uses a wood fuel that is not set out in Guideline A-14)
- Expectations for "new", "reassessed" and "existing" SWFC based on the January 31, 2017 transition date as described in Guideline A-14
  - Note: expectations can be considered "best practices" and implemented voluntarily where not required

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Ontario

Guideline A-14

- Generally, source testing will be required for any SWFC that receives an ECA using Guideline A-14 as this is within the Director's discretion
- Generally, continuous emission monitoring for carbon monoxide and oxygen in the flue gas will be required for any "uncertified" SWFC
- The rationale document used to support the development of Guideline A-14 contains technical and jurisdictional information and can be found here:

http://www.downloads.ene.gov.on.ca/envision/env_reg/er/documents/2016/012-7760%20rationale.pdf

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Ontario

EASR O. Reg. 1/17

- Ontario Regulation 1/17 "Registrations under Part II.2 of the Act – Activities Requiring Assessment of Air Emissions" came into force on January 31, 2017
- Prescribed activities are set out in section 2 and the prescribed activities are required to register in the EASR (specific NAICS codes and all renewable energy electricity projects cannot register)
- Accompanying document "Environmental Activity and Sector Registry – Limits and Other Requirements"

https://www.ontario.ca/page/environmental-activity-and-sector-registry-limits-and-other-requirements-activities-air-emissions

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Requirements for Prescribed Activities

- SWFC with a nominal heat output capacity of greater than 50 kW and a heat input capacity of less than 3 MW that were installed on or after January 31, 2017 and uses wood fuel as specified in Chapter 5 must be registered in the EASR
- Prior to registration, the following must be prepared:
  - EASR ESDM report and report supplement - supplement needs to include a combustion equipment statement for SWFC
  - Noise report and odour screening report
  - If applicable, BMPP for fugitive dust, BMPP for odour and an Odour Control Report
- Reports/plans/statements must be signed and sealed by a licensed engineering practitioner (LEP)
- In stack testing may be required by the Director

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Ontario

Refer to Chapters 1 & 5!

- Emission limits
- Wood-fuel specifications
- Automated wood fuel feed system
- Wood fuel management plan
- Design criteria
- Operational parameters and measurement methods for monitoring operational parameters
- Installation test
- Routine inspections or remote connection
- Annual performance assessment
- Record-keeping

Design Criteria = EN 303-5 (2012)

- Must meet the requirements of EN 303-5 (2012) at nominal (100%) and partial (30%) load heat output capacity (can be above 500 kW), subject to:
    - Designed to meet Class 5 for thermal efficiency and carbon monoxide
    - Designed to meet at least one of Class 3, 4 or 5 for particulate matter, taking into account any air pollution control equipment (APCE) specified by the manufacturer (Class 3 requires extra APCE)
- Design criteria must be confirmed by an independent person that meets EN ISO/IEC 17025 lab standard

More Information

- The Ministry has created guidance material to help support the implementation of the EASR including the User Guide. These materials are available here: https://www.ontario.ca/page/environmental-activity-and-sector-registry
- For more information on how to register an eligible facility please call 416-314-8001 or 1-800-461-6290 or email EAASIBGen@ontario.ca
- The Ministry's Access Environment web page allows the public to search for registered activities and sectors: http://www.accessenvironment.ene.gov.on.ca/AEWeb/ae/GoSearch.action?search=basic&lang=en

17 Ontario

Questions

Contact Information:

Steven Law, P. Eng.
Renewable Energy Engineer
Ministry of the Environment and Climate Change
Standards Development Branch
Technology Standards Section
40 St. Clair Avenue West, 7th Floor
Toronto, Ontario M4V 1M2
Tel. 416-327-6436
Email: Steven.Law@ontario.ca

18 Ontario

NRC·CNRC

Pyrolysis oil blends as alternate fuel for diesel engines and turbines

Ashwani Kumar , Sean Yun and Stuart Neill
IEA Bioenergy Task 34, Biomass Liquefaction Workshop
November 30, 2017

National Research Council Canada | Conseil national de recherches Canada

Canada

Objectives

- Demonstrate the feasibility of utilizing pyrolysis oil (PO) blends in diesel engines and turbines
- Optimize the combustion and emissions performance of a diesel generator utilizing PO blends
- Characterize PO-blend sprays for turbine applications

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Fuel properties

- Investigated binary mixtures with alcohols
  - ➢stable blends with desirable physical properties
- Also looked at tertiary blends with petroleum diesel
  - ➢only limited compositions were stable
- Measured the physical properties of PO blends e.g. density, viscosity and lubricity
- Used cetane improver additive (CIA) to improve the auto-ignition behaviour of the selected alcohol-PO-CIA fuel blends

Diesel generator and test procedure

- 8 kW diesel generator with Kubota D1105 engine (3 cylinder, 1.1 liter, IDI, 24:1 CR, 1800 rpm)
- CARB and EPA certified Tier 4
- Fuel switching strategy to avoid PO blend contact with diesel fuel

Test Procedure

- Warm up engine on diesel fuel
- Switch to alcohol blend for 5 minutes to remove hydrocarbons
- Run engine on the PO blend
- Reverse fuel order was followed to remove PO blend

Composition of fuel blends selected for tests

Blends	Alcohol	Pyrolysis Oil	Cetane Improver	Lubricity Improver
	Percentage by Volume			
Ethanol	89.9	0	10	0.1
Ethanol – PO	59.9	30	10	0.1
Butanol	89.9	0	10	0.1
Butanol - PO	59.9	30	10	0.1

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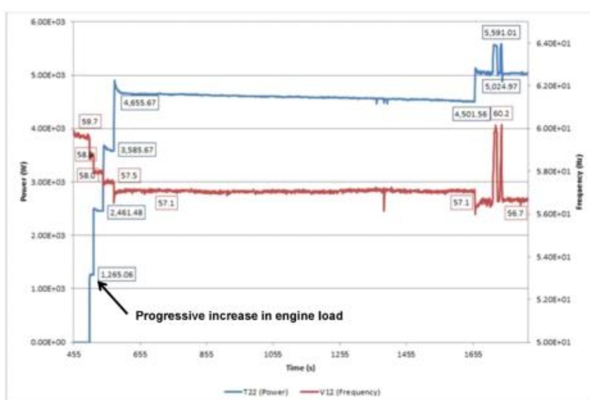
Experiment: Ethanol-CIA blend



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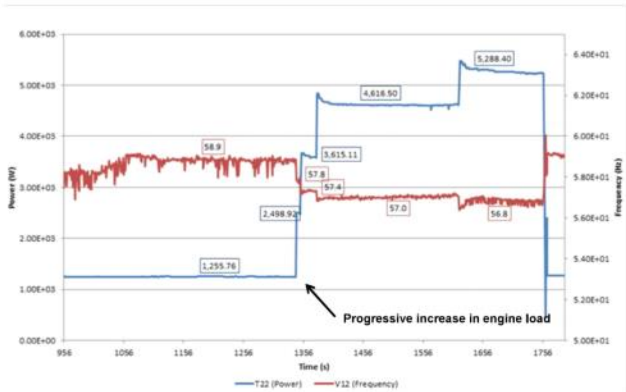
Experiment: Ethanol-PO-CIA blend



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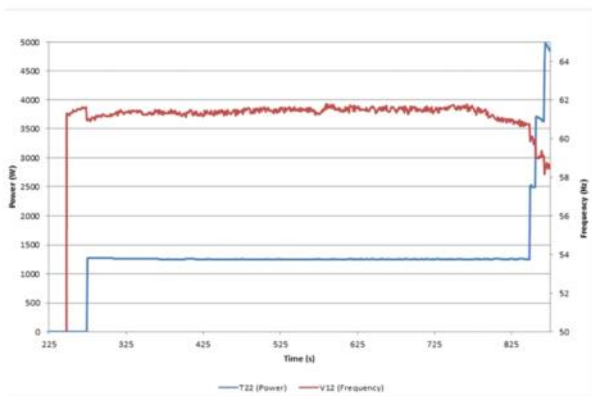
Experiment: Butanol-CIA blend



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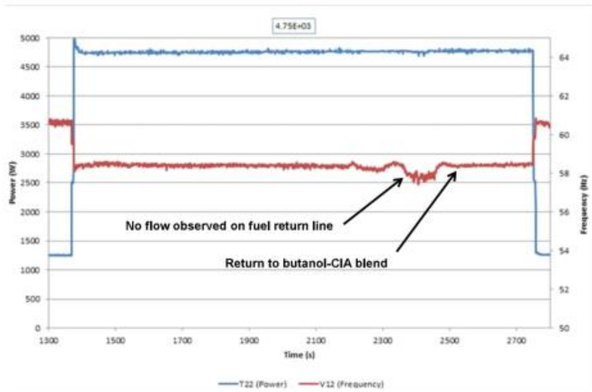
Experiment: Butanol-PO-CIA blend



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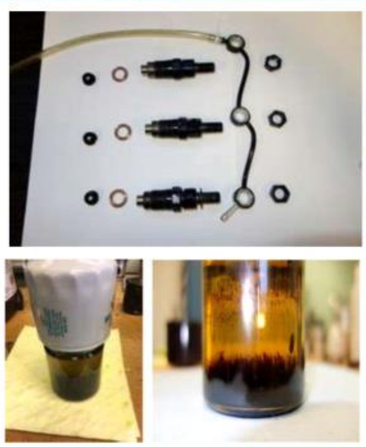
Fuel filter collected quantities of aged pyrolysis oil



- The return fuel is exposed to relatively high temperatures in this engine as it is used to cool the fuel injectors
- The fuel in the return line darkened as the butanol-PO-CIA test progressed
- After the test, a large quantity of solid material was collected in the engine fuel filter
- The engine will be modified to provide a separate fuel injector cooling loop so that the PO blends will not be heated in the return line

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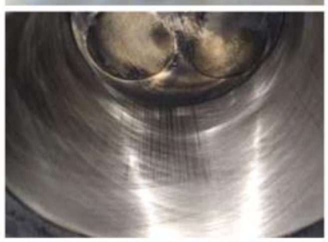
Observations



- Engine was unable to start a few days after the butanol-PO-CIA experiment as the fuel pump had seized in stop position
- Significant scoring observed on all three cylinder walls where the fuel jet from the pre-chamber is directed
- The engine pre-chambers were clean, but the main combustion chamber had carbon build-up
- All fuel injection system components are being inspected, disassembled and cleaned in an ultrasonic bath

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Conclusions and next steps - diesel engine

- A small diesel generator has been successfully operated for 15 minutes each on ethanol-PO-CIA and butanol-PO-CIA blends at up to 60% of the rated peak load
- A large quantity of solid material was collected in the fuel filter after the butanol-PO-CIA experiment, which is believed to be caused by PO aging in the fuel return line
- A new fuel injector cooling loop is being implemented to avoid having the fuel return line used for cooling the fuel injectors
- Significant scoring was observed on the cylinder walls where the fuel jet from the pre-chamber is directed
- Next step is to instrument the diesel engine to measure the combustion and emissions performance of selected PO blends

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Spray Performance Evaluation for Turbines

Pyrolysis Oil Properties

- ***Half of heating***
- ***Very High Viscosity***
- ***Higher density***
- ***Highly polar, containing 35~40% oxygen (dry basis)***
- ***Not soluble in mineral oils or bio-oils***
- ***Acidic and contains particles***
- ***Polymerise when heated***

Gas Turbines
- ***Relatively fuel-flexible***
- ***Can generate power on both large and small scales***
- ***Possibility for small CHP in remoted communities where diesel is expensive***

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Alternative Fuel for Industrial G/T - Pyrolysis Oil

Previous Studies on test rig or engine reveals the issues in using pure pyrolysis oil as is:

- *Blending the pyrolysis oil with other fuels, pre-heating and start-up with other fuels*
- *CO emissions*
- *Flame stabilities*
- *Fuel deposits in the hot sections*

What we think:
- ***Poor combustion performance can be attributed to its physical and chemical properties. But, also related to the spray performance (longer evaporation time, high viscosity)***
- ***Investigate the spray performance and try to improve it***
- ***Lead to improvement in combustion performance***

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Spray Test Matrix

Two Set of Spray Performance Test

- *Change of pyrolysis oils*
  - *Five Pyrolysis oils from different feedstock/ producers*
  - *Each has different properties*
  - *Evaluate the impact of fuel properties (viscosity)*
- *Change of atomizers*
  - *Different Atomization Mechanism*
  - *Pressure Swirl/ Air blast atomizer*
  - *Evaluate the impact of atomization mechanism*

Important Guidelines to oil producers

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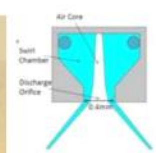
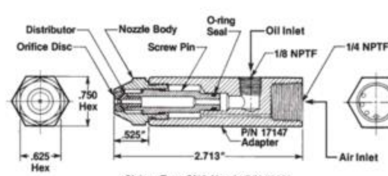
Atomizers

- *Pressure Swirl Type Atomizer:*

  In-house designed atomizer for research project



- *Air Blast Atomizer*
  Commercially Available Air Blast Atomizer (Delavan, P/N 30609)



Siphon Type SNA Nozzle P/N 30609

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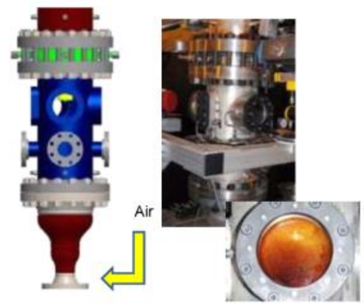
- ***Major Modification and Commissioning of the spray test facility***
  - Added additional air line for supplying atomization air
  - Changed the window design to keep windows clean from fuel mist -> wider spray angle, windows get easily dirty
  - Changed main air supply system: from push to sucking
- ***Set-up laser based diagnostics***
- ***Performed the spray test for various pyrolysis oils***



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Laser Based Diagnostics

Point Measurement

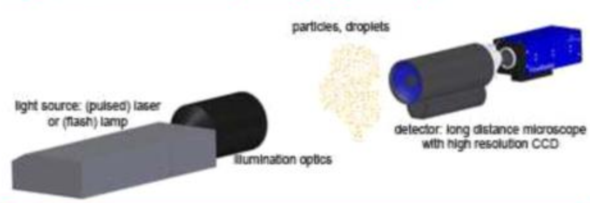
- **Phase Doppler Particle Analyzer**

Line of Sight Measurement

- **Malvern Laser Diffraction Method (Malvern)**

Other Imaging Technique

- **Long Distance Microscopic Imaging Technique**



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Spray Test Conditions

- ***Pyrolysis oils for the spray performance test***
  - 5 different batches of pyrolysis oils
  - ***No pretreatment and/or blending were not made for spray test***
  - Detailed physical properties were available
  - Fuel temperatures up to ~60˚C
  - Two different locations and various air/liquid ratios

- ***Detailed Measurements were made using***
  - Long distance Microscopic Imaging Technique
  - Malvern laser diffraction method

	C	H	N	O by diff	Water	Ash	Viscosity @ 25°C	Viscosity @ 40°C	Viscosity @ 60°C	pH	Density @ 20°C	Gross Calorific Value	HHV	Solids content
	mass fraction	mass fraction	mass fraction	mass fraction	mass fraction	mass fraction	cSt	cSt	cSt		kg/m³	cal/g	MJ/kg	mass fraction
JAN2016 shipment														
Ext A (>2 yr old bio-oil)	41.1%	7.78%	0.16%	50.8%	27.7%	0.154%	227.2	65.1	24.36	2.79	1217	3927	16.4	0.03%
CE-HWS-1 (0-2 years old)	49.9%	8.44%	<0.15%	41.1%	21.7%	0.580%	212.6	70.32	18.58	3.18	1215	4329	18.1	1.62%
CE-HWS-2 (0-2 years old)	46.5%	8.20%	<0.15%	44.6%	21.2%	0.740%	173.2	55.03	13.2	3.28	1224	4264	17.9	1.55%
JUN2016 Shipment														
Ext B (new bio-oil)	43.2%	7.52%	<0.15%	49.3%	24.4%	0.01%	94.85	34.83	12.32	2.28	1211	4178	17.5	0.06%
CE-HWS-3	42.6%	7.7%	<0.15%	49.6%	24.0%	0.07%	34.16	14.21	6.07	2.58	1184	4415	18.5	0.43%

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Result:
Pressure Swirl Atomizer

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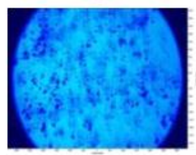
Spray Test W/T a Pressure Swirl Atomizer

Pressure Swirl Atomizer

- ***Pyrolysis oils from two different sources (CE-HWS-2, Industry)***
- ***Laser Based Diagnostics***
  - ✓ *Malvern Laser Diffraction Particle Sizer*
  - ✓ *Long Distance Microscopic Imaging Technique*
- ***Performing spray test of pyrolysis oil blends for various test conditions***
  - ✓ *Poor Atomization Quality*
  - ✓ *Measured only for pyrolysis oil blend (ethanol 30%)*

30% ethanol
T_f=40C



30% ethanol
T_f=70C
7 mm below

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Result:
Air Blast Atomizer

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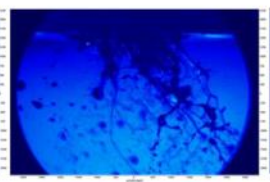
Test Results – Long Distance Microscopic Imaging

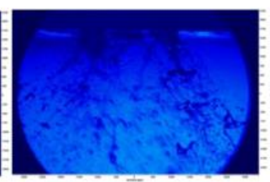
Shadow graphy Images

- Fuel: CE-HWS-3, fuel flow rate: 4 lb/min
- Reveals microscopic details of fuel break-up process

Atomization Air: 10 l/min
T_f=22 ˚C



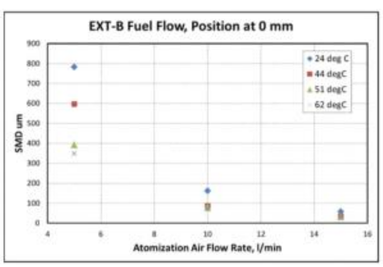
Atomization Air: 10 l/min
T_f=60 ˚C

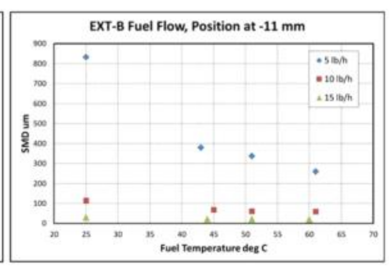


Atomization Air: 15 l/min
T_f=60 ˚C

NRC·CNRC

Test Results - Malvern



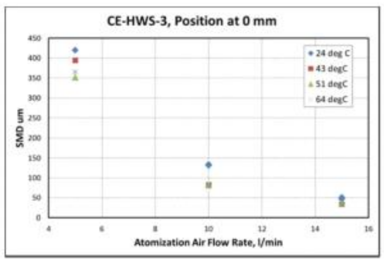


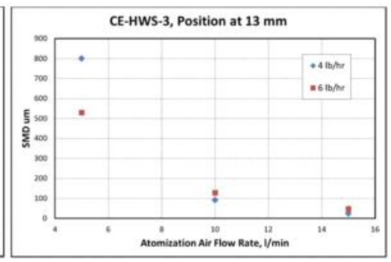
Summary

- Fuel: Ext-B, Flow rate: 4 lb/min
- As atomization air increases, SMD decreases significantly
- As temperature increases, SMD decreases

NRC·CNRC

Test Results - Malvern





Summary

- Fuel: CE-HWS-3, fuel flow rate: 4 lb/min
- Same trend as previous slide
- Fuel flow rates does not show significant effect above a certain atomization air flow rates

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Conclusions and Future Work

Spray performance test completed and the results shows that

- Air blast atomizer performs better than pressure swirl atomizer
- For air blast atomizer, atomization air flow rate plays significant roles in reducing SMD
- Once atomization air flow is sufficient, fuel temperature effect is secondary
- ***A selection of properly designed atomizer reduces the impact of initial physical properties, which requires upgrade***
- The result is promising in using pyrolysis oil to use gas turbines (at least for CE-HWS-3 and Ext-B)

Future Work

- Performs more spray test with other fuels
- Design optimization for fuel nozzles will be required
- Detailed correlation between spray and combustion test result will be crucial

NRC·CNRC

Team Members

- Andrzej Nicalek
- Michel Charbonneau
- Brian Galeote
- Simon Lafrance
- David Stevenson
- Kevin Austin
- Alexis Tanner

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Thank you

Dr. Ashwani Kumar
Research Officer
Tel: 613-998-0498
Ashwani.Kumar@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca

National Research Council Canada Conseil national de recherches Canada Canada