Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

2015 DOE Bioenergy Technologies Office (BETO) Project Peer Review

1.3.4.101 Thermochemical Interface

PNNL-SA-109025

DATE MARCH 24, 2015

TECHNOLOGY AREA REVIEW: ALGAE

DAN ANDERSON
DOUG ELLIOTT, ANDY SCHMIDT, KARL ALBRECHT, JON MAGNUSON

PACIFIC NORTHWEST NATIONAL LABORATORY

Goal Statement

Develop emerging technologies and data at the conversion interface of algal biofuels production focused on hydrothermal liquefaction (HTL)

- Initial focus wrap-up of NAABB (HTL processing, cultivation modeling and strain development tools)
- Current focus advanced HTL processing methods, process integration and scale-up

❑ Alignment with Goals of Algal Feedstocks R&D Technology Area

- ***Priority Technology Pathway***
- ***Whole algae hydrothermal liquefaction and upgrading***

Quad Chart Overview

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Timeline

- Project Start: 2/1/2013
- Project Finish: 9/30/2017
- Percent complete: 34%

Budget

	Total Costs FY 10 – FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	$0	$602,371	$1,117,336	$3,300,000
Project Cost Share (Comp.)*	NA	NA	NA	NA

Barriers

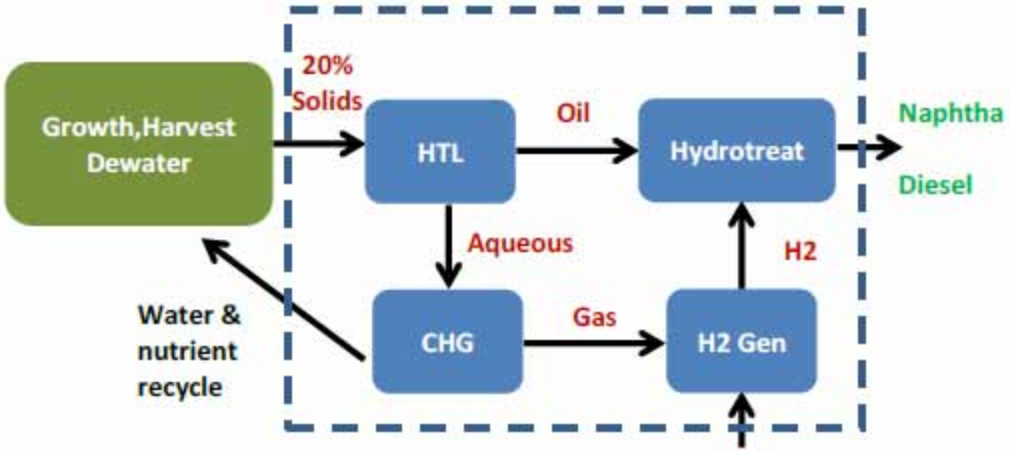
- AFt-H. Overall Integration and Scale-Up
- AFt-I. Algal Feedstock Preprocessing
- Aft-J. Resource Recapture and Recycle
- Tt-J. Catalytic Upgrading of Bio-Oil Intermediates to Fuels and Chemicals

Partners

- Other interactions/collaborations
  - National Alliance for Biofuels and Bio-products (NAABB)
  - ANL, NREL, PNNL - Algae Harmonization task
  - LANL, PNNL, NREL- Algal Biotechnology Hub
  - Sapphire, Bioprocess Algae
  - Regional Algal Feedstock Testbed (RAFT)
  - Genifuel
  - Pall Corporation- Separations

1 - Project Overview
Algae HTL Process (AHTL)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



Catalytic Hydrothermal Gasification (CHG)

AHTL processes wet algal biomass to finished fuels
AHTL enables nutrient recycle

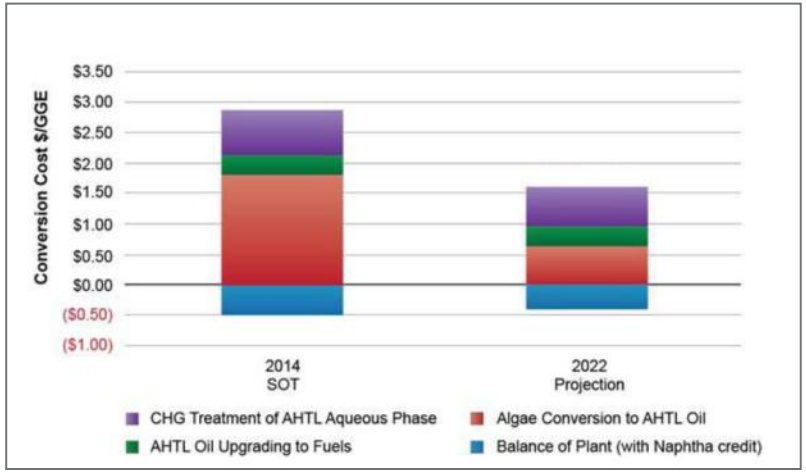

Wet Algae


Algae HTL Oil

Component	Weight %
Lipid content of whole algae	33%
Bio-oil from HTL as % algae AFDW	64%
% of algae carbon in HTL oil	69%

HTL results in high carbon yield to fuel

Thermochemical Interface Project focused on advanced HTL processing methods to reduce conversion cost, improve sustainability and enable scale-up.



HTL accounts for **~75% of conversion cost**

1 - Project Overview (cont.)

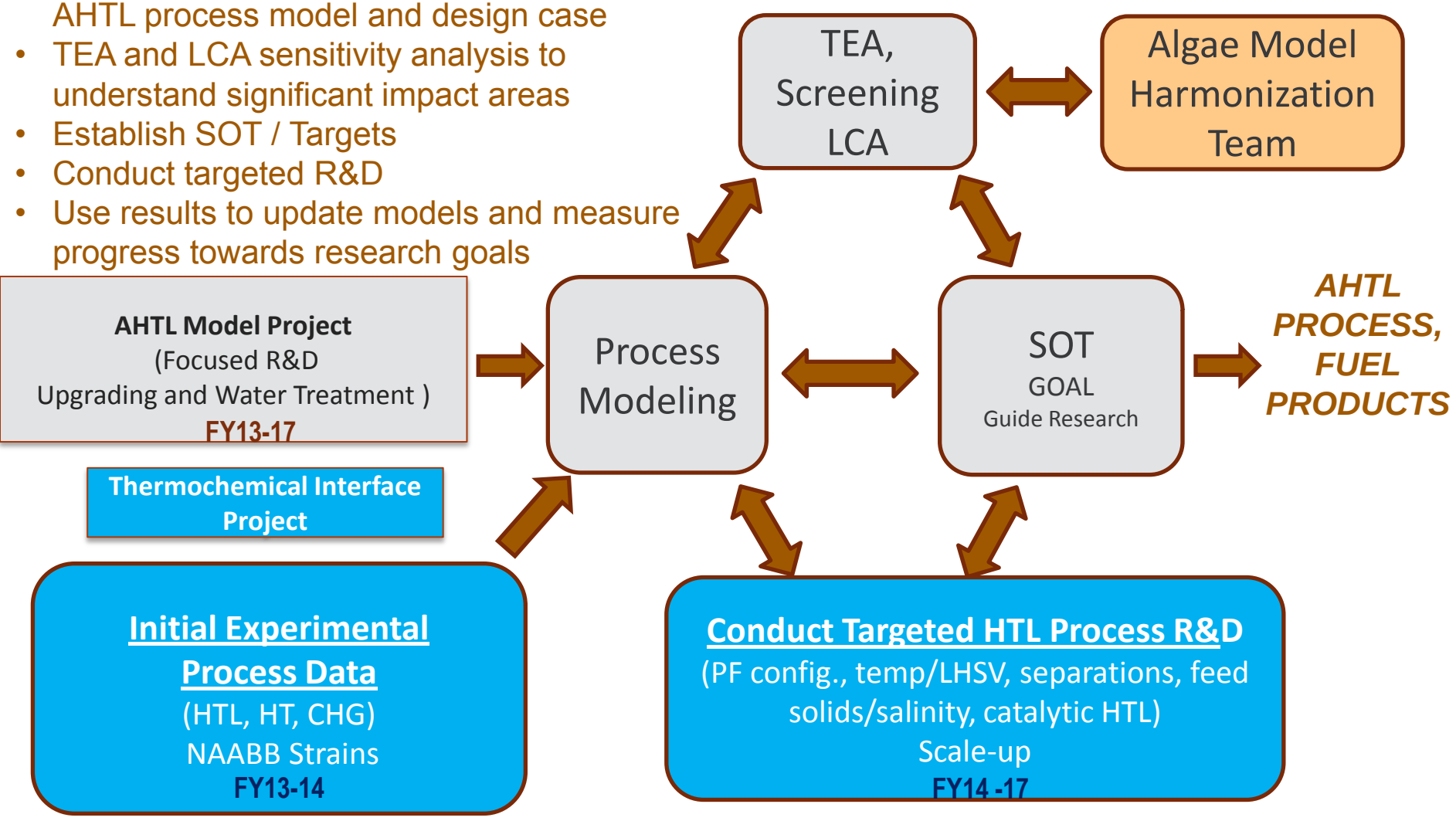
- FY13 project focused on completing NAABB data sets and analysis
  - HTL processing NAABB strains
  - Cultivation modeling and analysis
- FY14 project focus shifted to developing advanced HTL processing methods and strain development tools for NAABB production strain
  - HTL plug flow reactor, feed concentration/salinity, process parameters, separations, catalytic HTL
  - Transformation methods and stress gene targets for winter production strain *Scenedesmus sp.*
- FY15 project focus on HTL process development, scale-up and integration
  - Variable algal feedstocks, HTL plug flow reactor, process parameters, enhanced oil/water separations
  - HTL nutrient recycle for algal cultivation
  - Scoping and design of a modular /engineering- scale HTL skid with capability for a range of biomass feedstocks

2 – Approach (Technical)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Technical Approach

- Use experimental process data to build AHTL process model and design case
- TEA and LCA sensitivity analysis to understand significant impact areas
- Establish SOT / Targets
- Conduct targeted R&D
- Use results to update models and measure progress towards research goals



2 – Approach (Management)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- ***Critical Success Factors***
  - *Decreasing HTL conversion costs*
    - *Plug flow, processing efficiency, biocrude yield and quality*
  - *Demonstrating AHTL process integration*
  - *Validation of fuel products*

- ***Top Potential Challenges***
  - *HTL process capital and operation costs*
  - *Strategies to mitigate process turndown (seasonal productivity effects)*

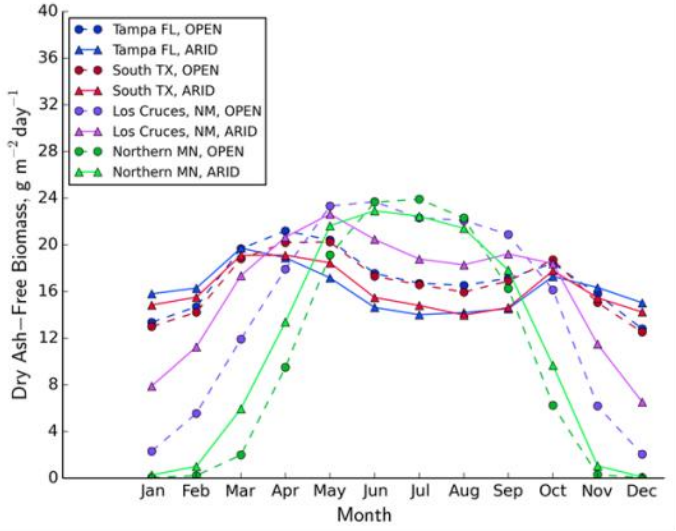
- ***PM Approach***
  - *Regular Milestones (1/Quarter) and Deliverables, Data Input for AHTL Model and Validation of SOT Technical Targets*
  - *Go/No Go decision point based on MYPP 2016 decision point*
    - ***(select integrated approaches for high-yield algal biofuel intermediates)***
  - *Regular meetings with BETO*
  - *Management and integration of supporting projects and partners*

3-Technical Accomplishments / Progress / Results

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Completed NAABB cultivation modeling and analysis

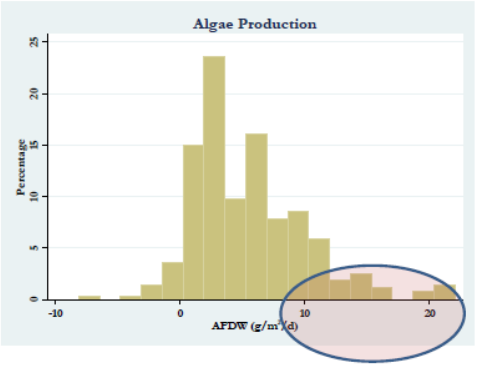
- Adapted the Biomass Assessment Tool (BAT) to predict increased annual biomass productivity related to a cultivation method (ARID) with thermal management.



- Completed analysis of cultivation variables important for achieving high prooductivity
  - Data from 5 sites and 3 years (565 observations)
  - Conducted by New Mexico State University

Empirical Estimation of Production

Average yields are too low to be economically or environmentally viable.
However, the distribution of the data tells another story…



The right-tail of the data shows much higher productivity than the average for the dataset (approx. 18% > 10 g/m2/d).

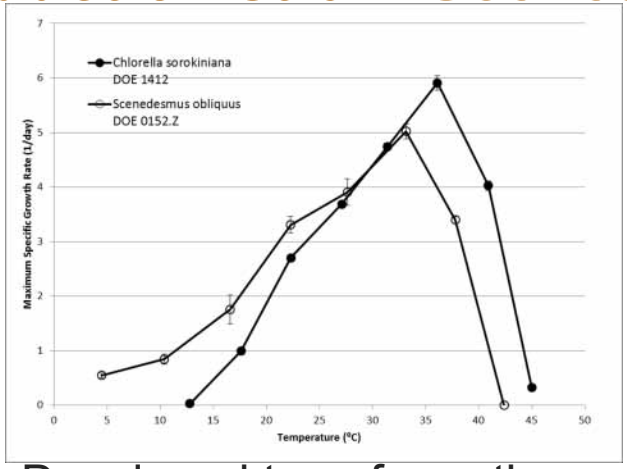
Indicating that culture-crashes; measurement error; and experimental design are lowering the overall productivity in our sample.

Embedded within our data are sets of observations that show productivity between 10-20 g/m2/day. This is a viable productivity rate for most processes.

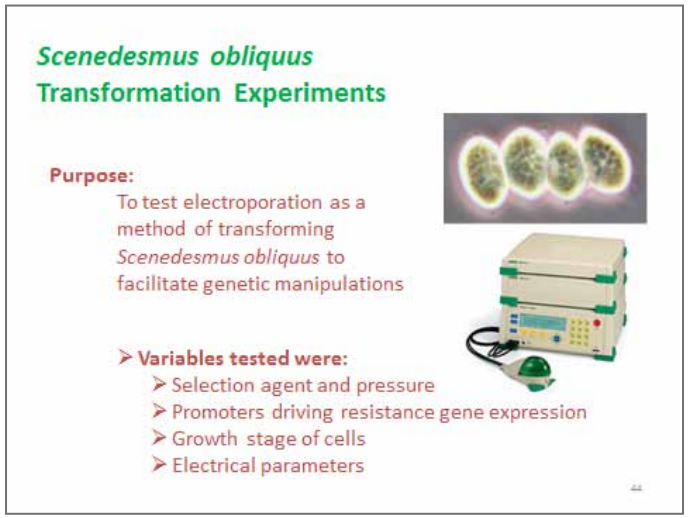
Supports Algal Feedstock Development

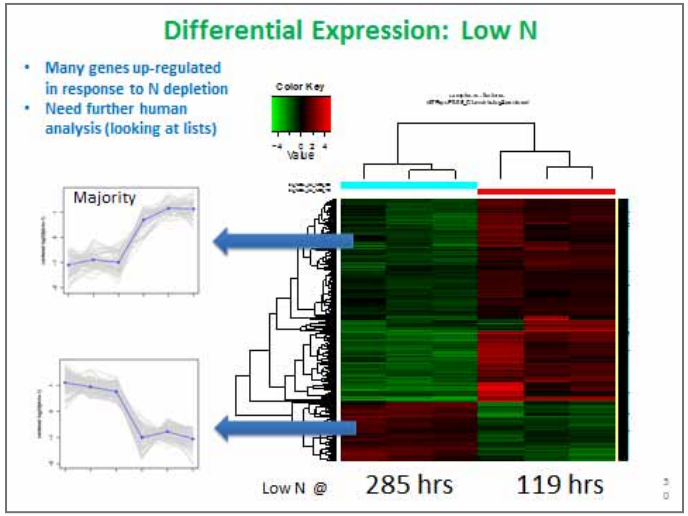
3-Technical Accomplishments / Progress / Results (cont'd)

Genetic Tools Developed for Improving NAABB winter production strain *Scenedesmus obliquus*



- Developed transformation methods for winter production strain *Scenedesmus obliquus*
- Completed transcriptional analysis identifying gene targets associated with stress (N/Salinity) for improving strain productivity



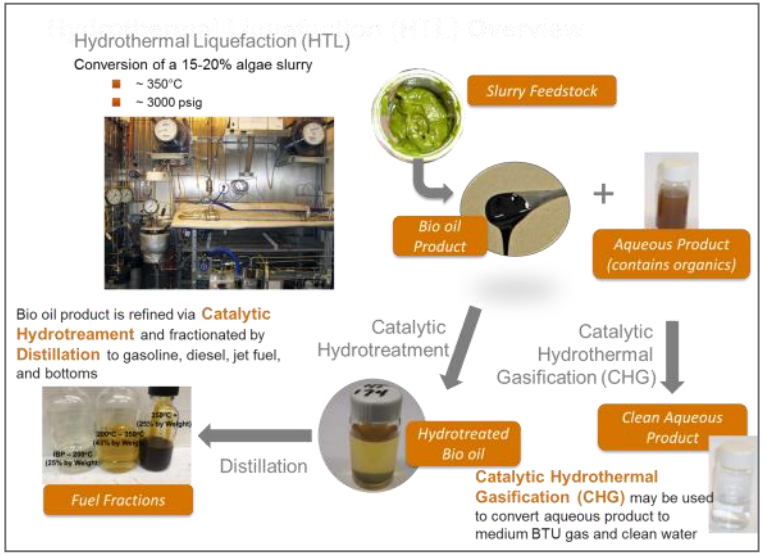


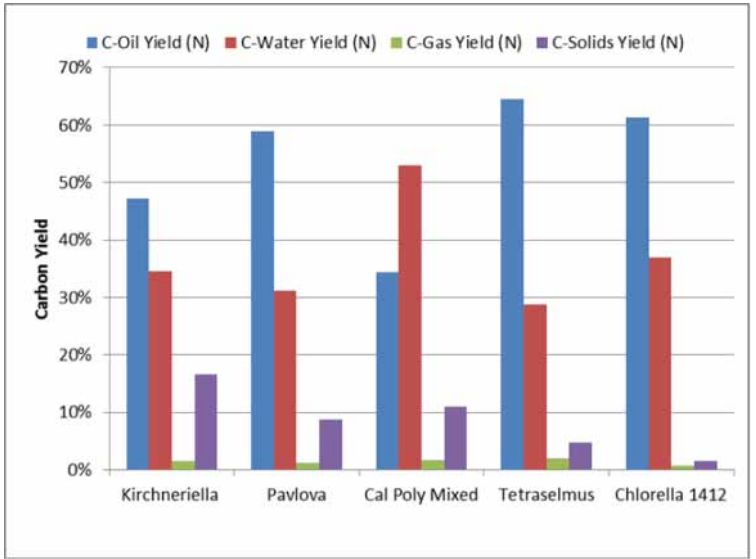
Supports Algae Biotechnology HUB concept established in FY15 between LANL, PNNL and NREL for developing tools for strain improvements

3-Technical Accomplishments / Progress / Results (cont'd)

AHTL Processing Completed for Five Strains

- Completed continuous HTL (CSTR/PF) processing for four additional strains (NAABB)
  - *Chlorella 1412 (freshwater)*
  - *Tetraselmis (seawater)*
  - *Kirchneriella sp. (freshwater)*
  - *Pavlova sp. (seawater)*
  - *Cal Poly (WWT mixed culture)*
- Completed CHG processing of the aqueous phase
- Completed upgrading of the biocrudes to fuels**
- Provided critical process data to inform AHTL process model, TEA and LCA, and SOT





**Kirchniella sp* not processed due to emulsion

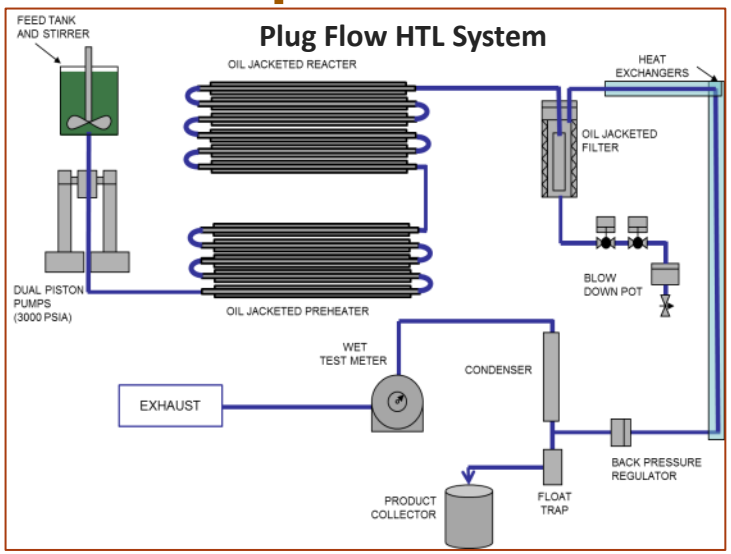
3-Technical Accomplishments / Progress / Results (cont'd)

Advanced HTL Processing Methods Developed

- ✓ Demonstrated 8% increase in biocrude yield by increased salinity/solids content in algal feedstock **(Reduced CapEx/OpEx)**
- ✓ Developed clean-up methods that improve biocrude quality resulting in improved hydrotreating catalyst lifetime. **(Reduced OpEx, Biocrude Quality)**
- ✓ Developed novel product separation method for continuous processing **(Reduced CapEx/OpEx)**
- Demonstrated continuous pure plug flow HTL operations with product collection were successfully demonstrated with high yield. **(Reduced Capex)**
- Completed initial catalytic HTL testing showing modest improvements to bio-oil quality, but no improvements yield.

(MAJOR MILESTONE FY14)

✓ Demonstrated at least **two** new advanced HTL processing methods that improve **yield**, **separation** and/or **biocrude quality**.



Biocrude /aqueous product separation during continuous product collection. **Invention Report**

3-Technical Accomplishments / Progress / Results (cont'd)

Technology Transfer - HTL Processing/Upgrading Assistance provided to BETO IBRs and Industry

- Completed continuous HTL processing for Sapphire productions strain
- Completed continuous HTL, HT processing and fuel characterization for Bioprocess Algae (BPA)
- Assisted Genifuel and Reliance, in design/start-up 1 metric ton/day HTL/CHG pilot system for algal feedstocks
  - **2015 FLC Award**

FLC NATIONAL AWARDS

- Assisting Algenol and Reliance in process development and scale-up of HTL processing (Work for Others Contracts)

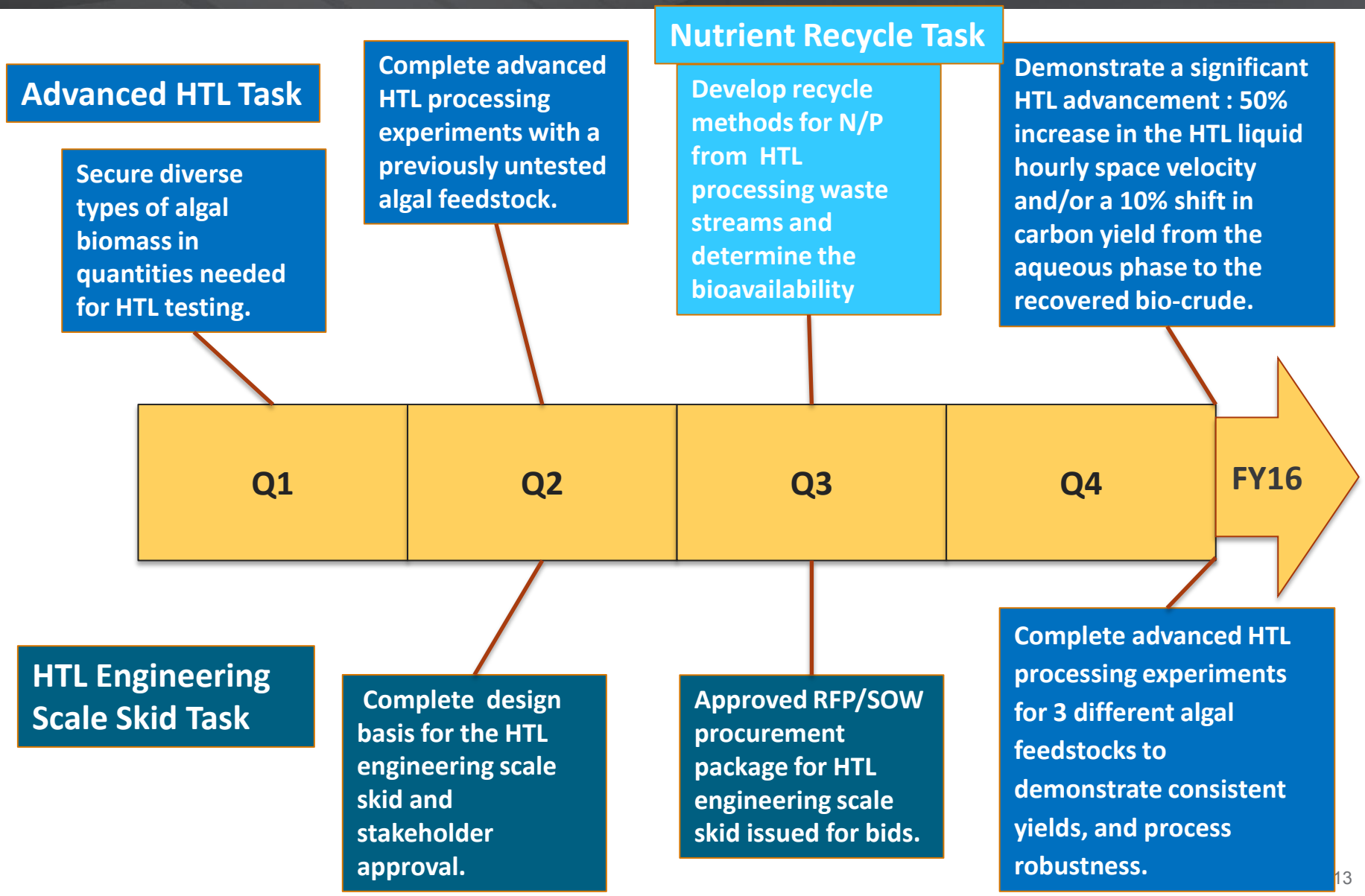
BPA Low Lipid ~20%

BPA High Lipid ~60%

Genifuel HTL Pilot

3 – Technical Accomplishments/ Progress/Results (FY 15 Milestones)

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



3-Technical Accomplishments / Progress / Results (cont'd)

Important technical accomplishments HTL Engineering Scale Skid Procurement

- Completed functional design criteria and preliminary design basis
- Completed preliminary hazards analysis
- Completed acquisition strategy
- RFP/SOW under development
- Planning for installation and start-up in Q2 FY16
- Capital funds from Thermochemical Program

4 - Relevance

- **Targeted R&D focused on BETO primary technology pathway**
  - AHTL pathway technical needs and cost targets identified
  - Developing new enabling technology for the AHTL pathway
- **Project has resulted new IP**
- **Project is supporting technology transfer**
  - 2015 FLC Award
  - Multiple collaborations with industrial partners and BETO IBRs
- **Project is leveraging synergies with Thermochemical Platform**
  - HTL process development
  - Acquisition of engineering scale HTL skid designed for multiple feedstocks
- **Project has already contributed to 7 publications and 12 invited presentations**

5 – Future Work FY16-17

- Procurement and testing of a modular /engineering scale HTL skid at PNNL will completed.
- Validation of advanced HTL processing methods at engineering scale will be conducted.
- Critical data will be provided to update AHTL Model and SOT
- Working with BETO's commercial partners we will support process integration and generate large fuel samples that can be used to meet fuel specifications
- Integrations of key elements of the AHTL process (nutrient recycle, water treatment, and upgrading processes) will be completed in collaboration with related projects
- Go/No-Go will be structured around meeting specific technical and cost targets associated with MYPP Decision Point in FY16

Summary

- **Relevance:** Project directly contributes to meeting the goals and objectives of the Algae Conversion Technology Area (AHTL Pathway)
- **Approach:** Conduct HTL process development and scale-up base on AHTL modeling and SOT technical and cost targets
- **Technical Accomplishments:** The project leveraged and completed up key NAABB data sets, developed advanced HTL process technologies, and provided data for AHTL model and SOT
- **Future Work:** The project will conduct targeted research in FY15-17 based on SOT targets to significantly reduce HTL conversion cost, validate at engineering and enable commercialization
- **Success Factors and Challenges**: The critical success factors and challenges for the project have been identified and are being addressed
- **Technology Transfer**: The project is actively supporting technology transfer to industry through collaborations, IP development and licensing, publications and presentations. Received FLC Award in 2015

Additional Slides

Publications, Patents, Presentations and Awards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Publications

Elliott DC, TR Hart, AJ Schmidt, GG Neuenschwander, LJ Rotness, MV Olarte, AH Zacher, KO Albrecht, RT Hallen, and JE Holladay. 2013. "Process Development for Hydrothermal Liquefaction of Algae Feedstocks in a Continuous-Flow Reactor." Algal Research 2(4):445-454.

Elliott, D.C.; Biller, P.; Ross, A.B.; Schmidt, A.J.; Jones, S.B. 2014. "Hydrothermal liquefaction of biomass: Developments from batch to continuous process" invited submission to Special Issue: Thermo-chemical conversion, Bioresource Techno 178 147–156, web publication date: October 13, 2014, DOI: 10.1016/j.biortech.2014.09.132.

Zhu Y, KO Albrecht, DC Elliott, RT Hallen, and SB Jones. 2013. "Development of Hydrothermal Liquefaction and Upgrading Technologies for Lipid-Extracted Algae Conversion to Liquid Fuels." Algal Research 2(4):455-464. doi: 10.1016/j.algal.2013.07.003. logy.

Venteris ER, R Skaggs, MS Wigmosta, and AM Coleman. 2014. "A National-Scale Comparison of Resource and Nutrient Demands for Algae-Based Biofuel Production by Lipid Extraction and Hydrothermal Liquefaction." Biomass & Bioenergy 64:276-290. doi: 10.1016/j.biombioe.2014.02.001.

Jones SB, Y Zhu, DB Anderson, RT Hallen, DC Elliott, AJ Schmidt, KO Albrecht, TR Hart, MG Butcher, C Drennan, LJ Snowden-Swan, R Davis, and C Kinchin. 2014. Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading . PNNL-23227, Pacific Northwest National Laboratory, Richland, WA. (AHTL design report).

Publications, Patents, Presentations and Awards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Publications

Jones SB, Y Zhu, LJ Snowden-Swan, DB Anderson, RT Hallen, AJ Schmidt, KO Albrecht, DC Elliott. 2014. Whole Algae Hydrothermal Liquefaction: 2014 State of Technology. PNNL-23867, Pacific Northwest National Laboratory, Richland, WA. (AHTL 2014 SOT).

S Archambault, CMS Downes, W Van Voorhies, CA Erickson, P Lammers. 2014 "Nannochloropsis sp. algae for use as biofuel: Analyzing a translog production function using data from multiple sites in the southwestern United States" Algal Research 6, 124-131.

Presentations

Albrecht KO, RT Hallen, DC Elliott, GG Neuenschwander, MV Olarte, LJ Rotness, S-J Lee, T Schaub, and B Dungan. 2013. Conversion and Catalytic Upgrading of Algal-Derived Lipids and Bio-Oil to Hydrocarbon Fuels. Presented by Karl O. Albrecht at the SEDP First Year Poster Session, May 22, 2013, Richland, WA.

Anderson DB, RT Hallen, SB Jones, DC Elliott, and KO Albrecht. 2013. 9.3.2.1 Whole Algae Liquefaction Model Development. Presented by Dan Anderson (Invited Speaker) at DOE Bioenergy Technologies Office (BETO) Project Peer Review , May 22, 2013, Alexandria, VA.

Elliott, Doug, Rich Hallen, Karl Albrecht, Andy Schmidt, Todd Hart, Gary Neuenschwander, Mariefel Olarte, L.J. Rotness, and Gary Maupin. "Conversion of Algal Biomass to Liquid Fuels by Hydrothermal Processing in Continuous-Flow Reactors." Presented by Doug Elliott at tcbiomass2013, Chicago, Illinois, September 2013.

Holladay JE, and KO Albrecht. 2013. Hydrothermal Processing of Algae. Presented by Karl Albrecht (Invited Speaker) at 3rd International Conference on Algal Biomass, Biofuels and Bioproducts, June 17, 2013, Toronto, Canada.

Skaggs R, AM Coleman, ER Venteris, and MS Wigmosta. 2013. Collaborative: Algae-Based Biofuels Integrated Assessment Framework Development, Evaluation and Demonstration. Presented by Richard Skaggs (Invited Speaker) at 2013 DOE Bioenergy Technologies Office (BETO) Project Peer Review, May 23, 2013, Alexandria, VA.

Publications, Patents, Presentations and Awards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Presentations

Venteris ER, R Skaggs, MS Wigmosta, and AM Coleman. 2013. A National-Scale Comparison of Resource and Nutrient Demands for Algae-Based Biofuel Production by Lipid Extraction and Hydrothermal Liquefaction. Presented by Erik R Venteris (Invited Speaker) at SEDP Poster Session, May 22, 2013, Richland, WA.

Albrecht KO, JE Holladay, and DC Elliott. 2014. "Advanced Biofuel and Biochemical Production at Pacific Northwest National Laboratory." Presented by Karl O Albrecht (Invited Speaker) at Bioenergy at CSU Seminar, Ft. Collins, CO on December 3, 2014. PNNL-SA-106969.

Elliott, D.C., "Conversion of Algal Biomass to Liquid Fuels by Hydrothermal Processing in Continuous-Flow Reactors." Joint Engineering and Science Seminar, Washington State University/Tri-Cities, Richland, Washington, March 28, 2014.

Elliott, D.C., "Conversion of Algal Biomass to Liquid Fuels by Hydrothermal Processing in Continuous-Flow Reactors." Portland Section meeting, American Chemical Society, Reed College, Portland, Oregon, April 10, 2014.

Elliott, D.C., "Conversion of Algal Biomass to Liquid Fuels by Hydrothermal Processing in Continuous-Flow Reactors." Southern California section meeting, American Institute of Chemical Engineers, Anaheim, California, April 15, 2014.

Holladay JE. 2014. Liquefaction Technologies for Producing Biocrude for Jet, Diesel and Gasoline. Presented by John Holladay (Invited Speaker) at Northwest Wood-based Biofuels and Products, April 29, 2014, Seattle, WA.

Holladay JE. 2013. Technical and Economic Aspects for Hydrothermal Liquefaction of Algae. Presented by John Holladay (Invited Speaker) at Algae Biomass Summit, October 2, 2013, Orlando, FL.

Venteris ER, R Skaggs, MS Wigmosta, and AM Coleman. 2013. A National-Scale Comparison of Resource and Nutrient Demands for Algae Based Biofuel Production by Lipid Extraction and Hydrothermal Liquefaction. Presented by Erik R. Venteris at Algae Biomass Summit, October 1, 2013, Orlando, FL.

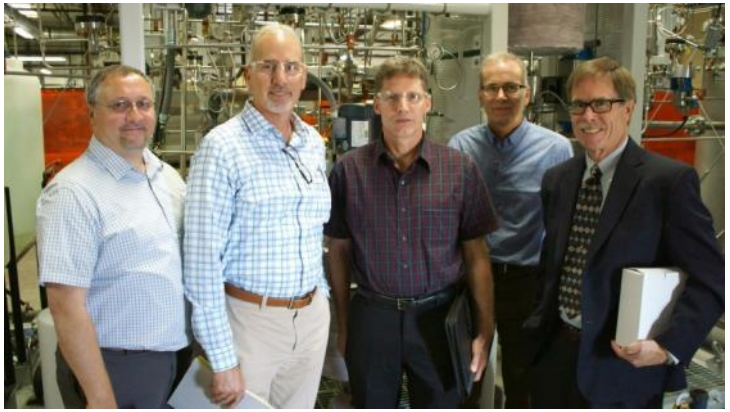
Publications, Patents, Presentations and Awards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Hydrothermal processing technology developed at PNNL supported by NAABB and Conversion Interface Project is being used in BETO IBRs and privately funded efforts.

NAABB cost share provided funding for engineering plans and construction a 1 tonne/day demonstration system for HTL and CHG processing for algal biomass.

FLC NATIONAL AWARDS



2015 Federal Laboratory Consortium (FLC) Excellence in Technology Transfer Award. “Renewable Fuel from Algae” to PNNL and Genifuel