OAK RIDGE National Laboratory

DOE Bioenergy Technologies Office (BETO)
2019 Project Peer Review

3.5.5.1 Evaluation of Bio-oils for Use in Marine Engines

March 7, 2019

Advanced Development and Optimization: Analysis and Modeling

Mike Kass
Oak Ridge National Laboratory

Project Sponsor: The Bioenergy Technology Office of the U.S. Department of Energy

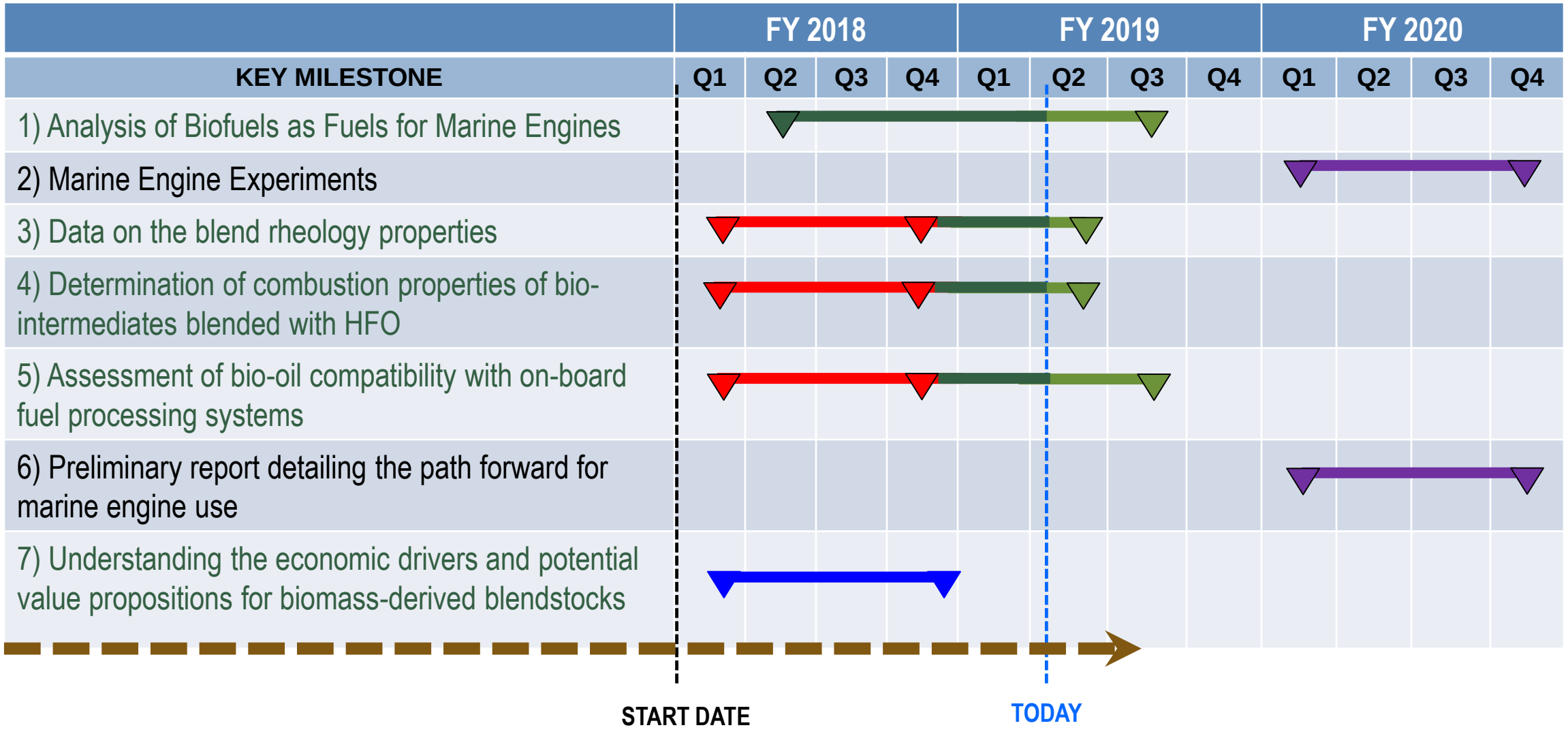
U.S. DEPARTMENT OF ENERGY

Goal Statement

- **Goal: Determine the technical feasibility of using biofuels, especially bio-oils for marine engine use. Feasibility determined by compatibility, emissions reduction & efficiency improvement**
  - Addresses Barrier ADO-H by assessing the compatibility of bio-intermediates and determining system modifications needed to utilize these fuels with marine engines & fuel systems
  - Addresses Barrier At-D, by identifying a new market opportunities for bio-intermediates
- **Relevance: Bio-oil and biocrude offer a potentially economically competitive fuel for marine engines powered using low-quality heavy fuel oil (HFO)***
  - Pathway towards reduction of sulfur and particulate emissions
  - Potential path towards improved efficiency (reduced CO_2 emissions)
- **Tangible Outcomes: Understand the efficacy of biofuels in marine transport**
  - Determine impact on fuel handling systems
  - Determine impact of mixing bio-oil with HFO
  - Identify technical needs associated with bio-oil use as fuel

* HFO is a heavy residuum fuel derived from the non-distillate fraction of crude oil

Key Milestones



Delay at start due to delays in obtaining HFO

Project Budget Table

	Original Project Cost (Estimated)			Project Spending and Balance		Final Project Costs
Budget Periods	**DOE Funding**	**Project Team Cost Shared Funding**	**Contingency**	**Spending to Date**	**Remaining Balance**	**What funding is needed to complete the project**
BP1 – FY2018	**$200k**	N/A	N/A	$120k	$80k (carryover)	N/A
Biofuel analysis for marine applications	$100k	N/A	N/A	$80k	$20k (carryover)	N/A
Determination of blend properties	$100k	N/A	N/A	$40k	$60k (carryover)	N/A
BP2 – FY2019	**$480k***	N/A	N/A	**$70k**	**$410k**	**$400k**
Biofuel analysis for marine applications (c/o)	$20k	N/A	N/A	$10k	$10k	N/A
Determination of blend properties (c/o)	$60k	N/A	N/A	$50k	$10k	N/A
Combustion properties	$120k	N/A	N/A	$10k	$110k	N/A
Bio-intermediate compatibility	$200k	N/A	N/A	$0	$200k	N/A
Preliminary report	$80k	N/A	N/A	$0	$80k	N/A

*includes $80k carryover from prior budget period
*received $285k in BP2 to-date

Quad Chart Overview

Timeline

- Project start date: Oct. 1, 2017
- Project end date: Sept. 30, 2020
- Percent complete: 25

Budget

	Total Costs Pre FY 17	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date
DOE Funded	N/A	N/A	$200k	$800k
Project Cost Share (Comp.)*	N/A	N/A	N/A	N/A

Barriers

Barriers addressed

- Pm-A. Strategy and Goals
- At-D. Identifying New Market Opportunities for Bioenergy and Bioproducts
- ADO-H. Materials Compatibility, and Equipment Design and Optimization

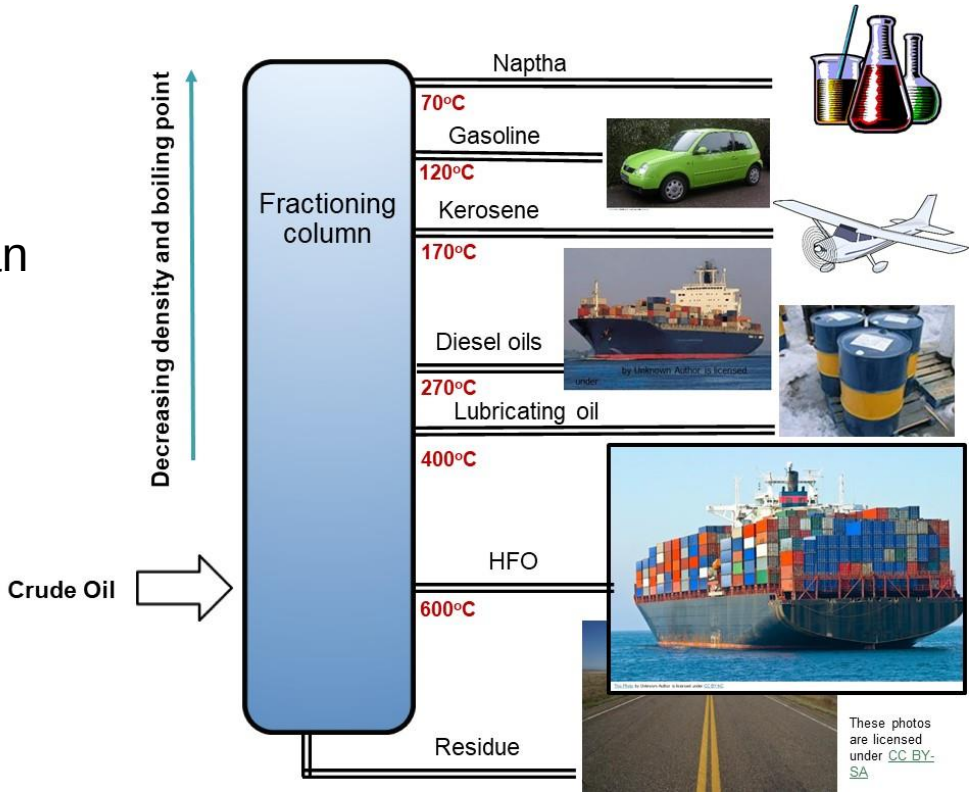
Partners

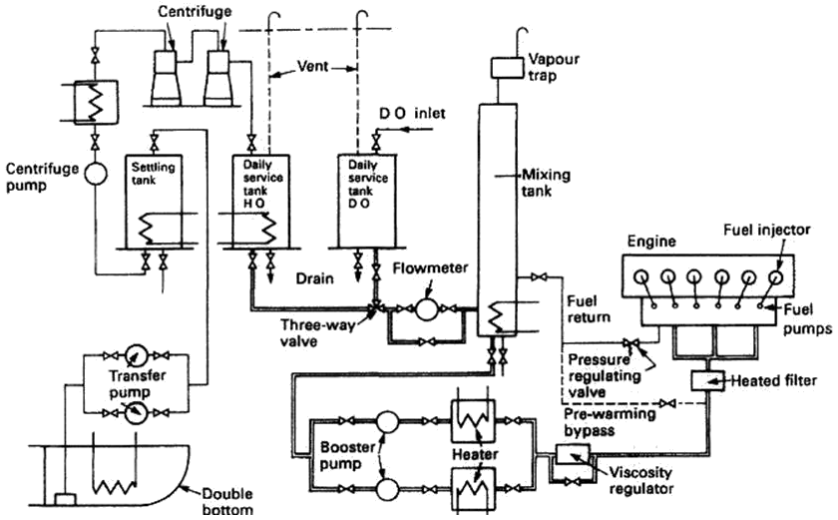
Partners

- Complementary activities at NREL/PNNL/ANL
- NREL (25%)
- Other interactions/collaborations
  - Maritime Administration (DOT)
  - ExxonMobil
  - Goodfuels

Project Overview: Background

- Over 90% of all goods are shipped via marine vessels fueled with high sulfur (3.5 wt.%) heavy residual fuel oil (HFO)
  - 40,000 ships burn ~87 billion gallons of fuel/year (higher than aviation and on-road combined)
  - Largest source of global anthropogenic sulfur emissions worldwide and black carbon in the arctic
  - Important contributor to worldwide CO_2 emissions (~2%)
- In addition to sulfur, HFO also contains significant water and solids
- HFO is also highly viscous and must be heated to temperatures exceeding 90°C to achieve proper flow characteristics
- On-board processing requires:
  - Heaters: maintain flow
  - Separator: remove water & sludge
  - Holding tanks
  - Filters
- In spite of the added hardware & energy costs, HFO is most economical fuel





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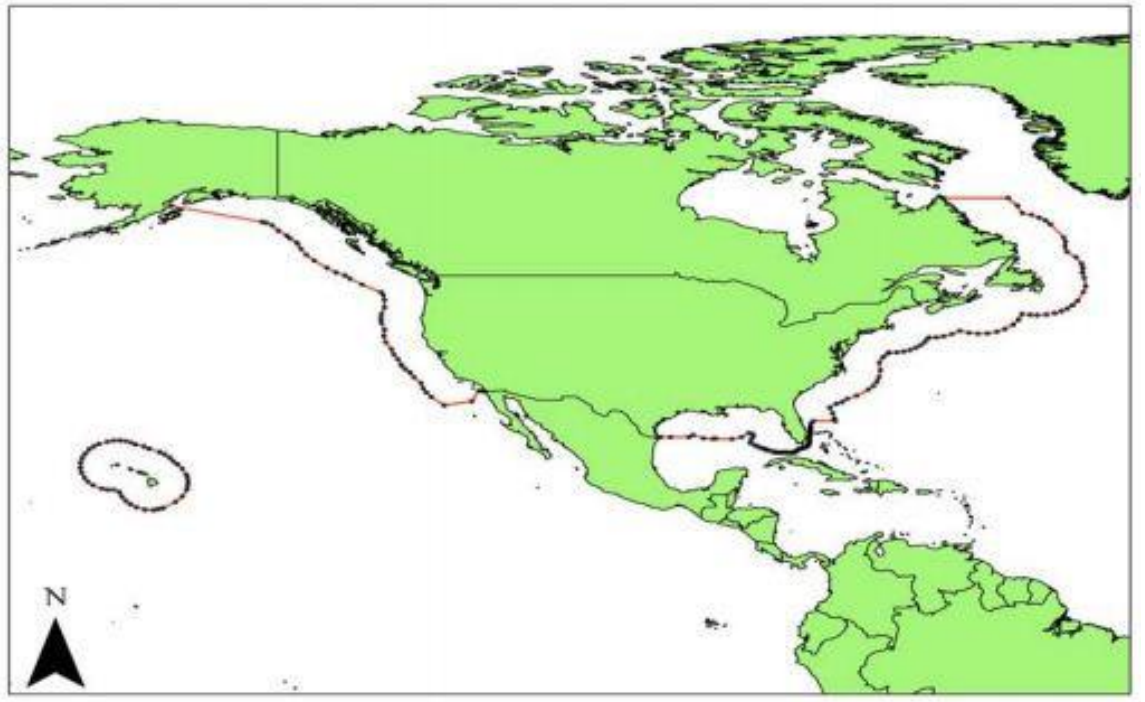
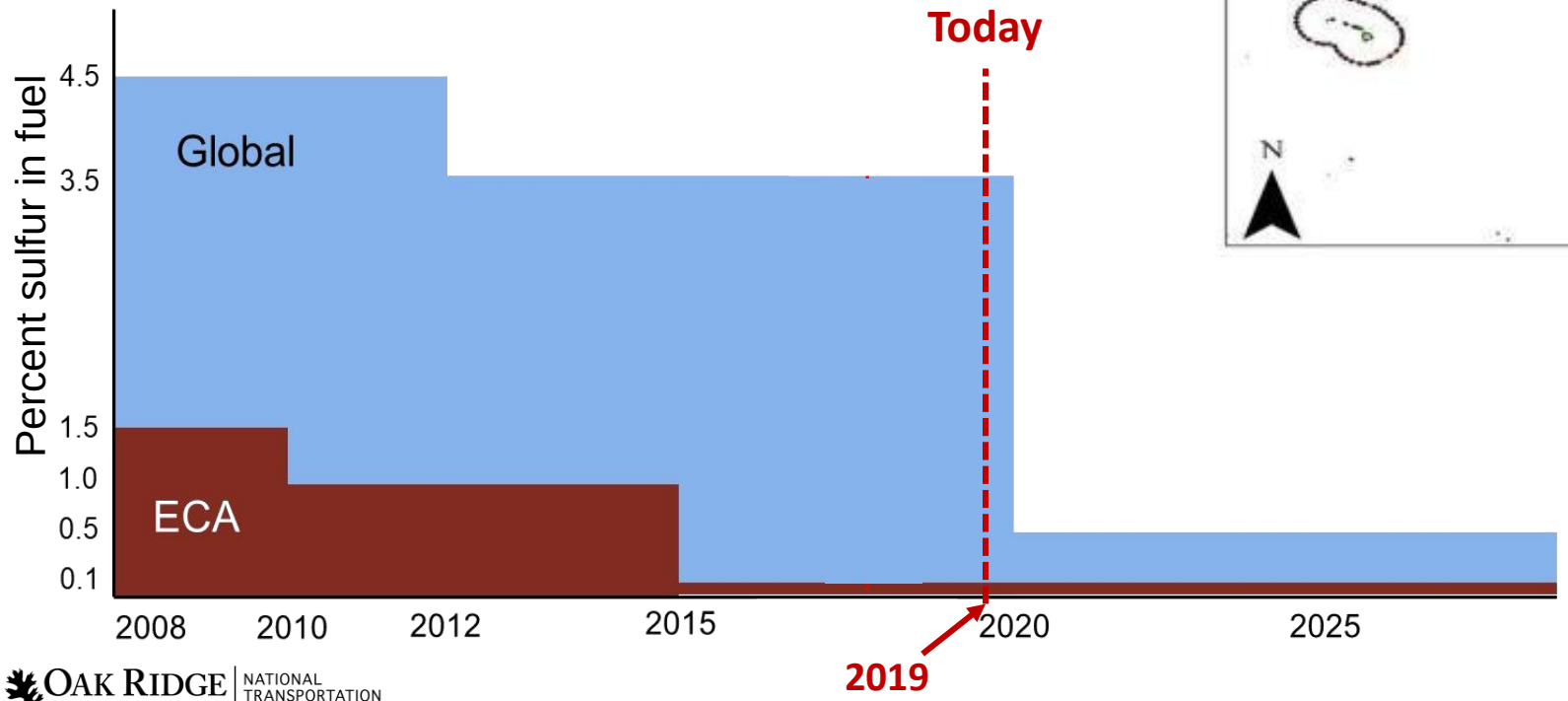
Project Overview: Background (continued): Sulfur emissions from marine vessels are being regulated globally and in coastal zones known as Emission Control Areas (ECAs)

- IMO is regulating the fuel sulfur content from 3.5 to 0.5 wt.% starting in 2020
- Reductions in CO_2 and NOx are underway
- Particulate matter emissions regulations forthcoming



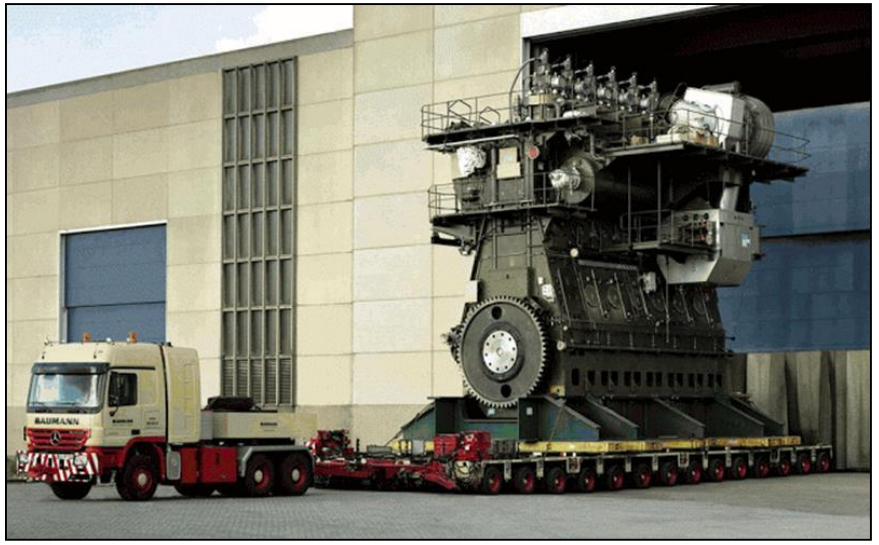


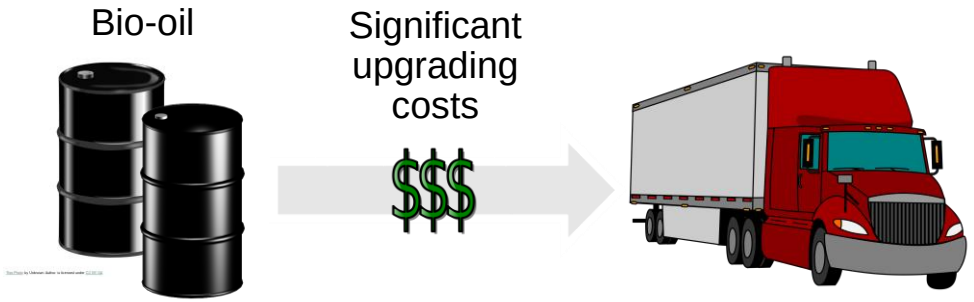
Sulfur reductions are being met by:

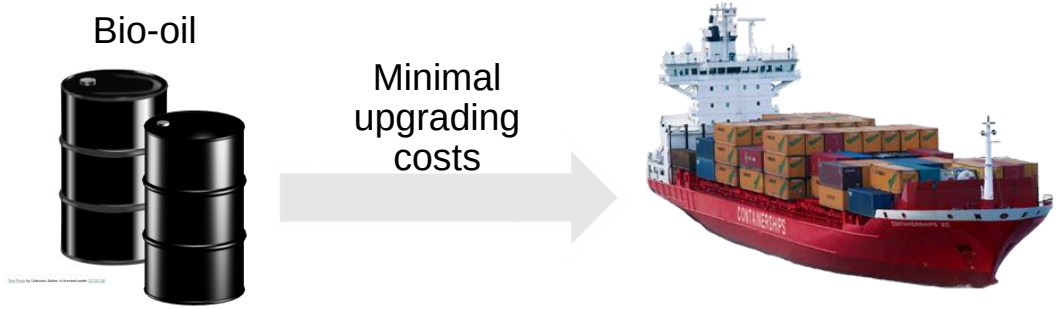
- Reducing sulfur content of HFO
- Switching to low sulfur fuel (currently done in ECAs)
- Emission control technologies

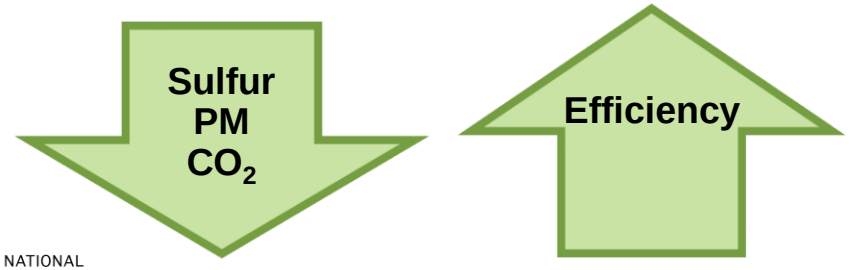
Project Overview: Context. Biofuels are an attractive option since they are inherently low in sulfur and provide lifecycle greenhouse gas benefits

- Marine engines are designed to burn low-grade residuum, which has high water and solids (similar to bio-oils & biocrudes)
- Bio-oils and biocrudes are expensive to upgrade to be miscible with distillates (diesel, etc.), but have drop-in potential with HFO
- Compliance will raise operating costs such that biofuels may offer an economic alternative
- In addition to reduced sulfur emissions, biofuels have much lower viscosity, which, if blended with HFO, would be expected to lower heating costs thereby increasing overall system efficiency







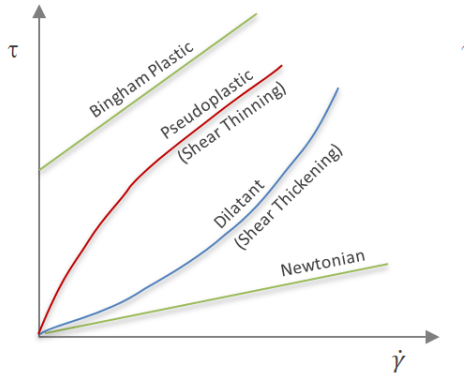


Project Overview: High-level Objectives and Plans

- **Objectives**
  - Determine the compatibility of bio-intermediates with HFO
  - Assess the feasibility of bio-intermediates with marine engines and fuel systems
  - Identify fuel properties and systems to facilitate bio-intermediates as a marine fuel
- **Key Planned Activities for FY19**
  - Measure and assess the flow (rheological) properties of bio-intermediate/HFO blends
  - Determine combustion properties of HFO and bio-intermediates
- **Differences Between Plans & Progress**
  - Unexpected difficulties/delays in HFO procurement have subsequently delayed experimental start by several quarterly periods
- **Potential Showstopper**
  - Heavy polymerization of bio-intermediates may preclude use as blend with HFO
- **Available Resources**
  - HFO
  - ExxonMobil research engine

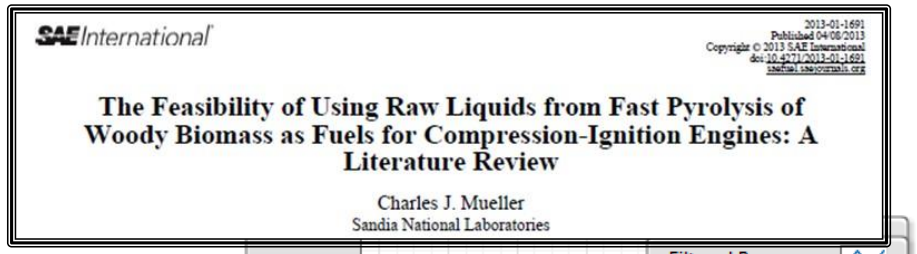
Project Overview: Specific Project Goals

- Survey literature and engine data to assess the performance of bio-oils and their blends with HFO in existing engines
- Determine the rheological (flow and transport) properties of bio-oils with HFO as a function of temperature
  - Viscosity
  - Lubricity
  - Polymerization
- Based on rheology study, determine the efficacy of bio-oil with on-board fuel processing systems
  - Polymerization
  - Separation
  - Temperature requirements
- Conduct engine & fuel handling experiments



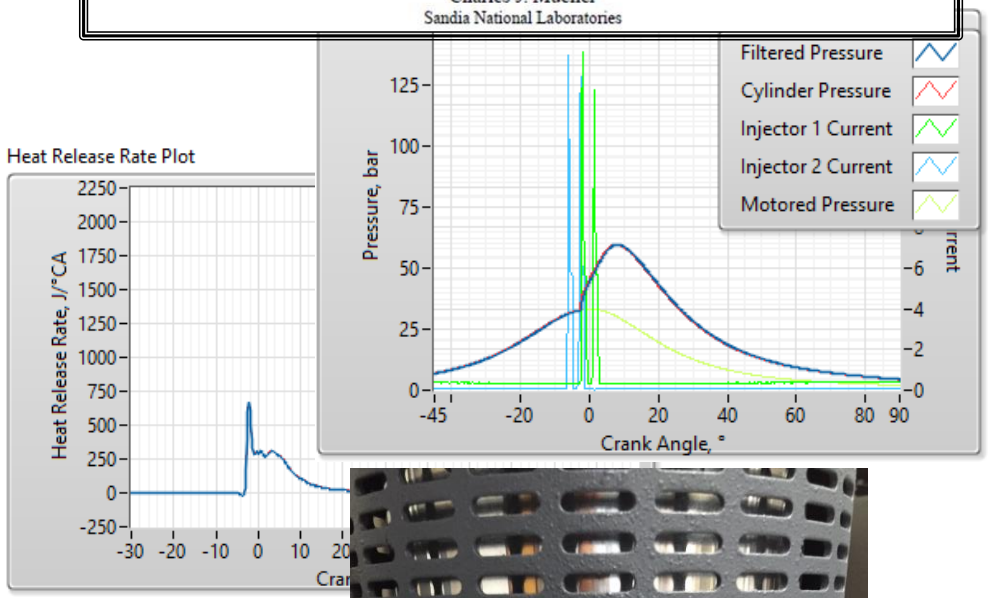
Approach (technical)

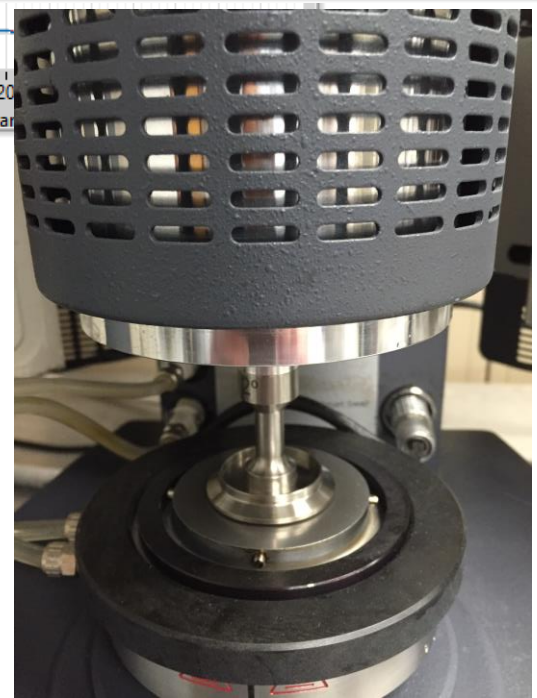
- **Understanding bio-oil use with engine performance**
  - Reviewing relevant literature on engine studies. Note that there is a limited body of literature on this topic
  - Utilizing established modeling/simulation techniques. Input will include the known combustion properties of bio-oils and the combustion behavior of 4-stroke and crosshead engines
- **Measuring bio-oil properties relevant to its miscibility with HFO and subsequent flow**
  - Miscibility (solubility) determination
  - Viscosity measurement as a function of temperature (in the relevant temperature ranges)
  - Static measurements at elevated temperature to assess polymerization effects
- Using the information gained from the rheology study, the efficacy of the ship-borne fuel systems to handle bio-oils will be determined


SAE International

The Feasibility of Using Raw Liquids from Fast Pyrolysis of Woody Biomass as Fuels for Compression-Ignition Engines: A Literature Review

Charles J. Mueller
Sandia National Laboratories



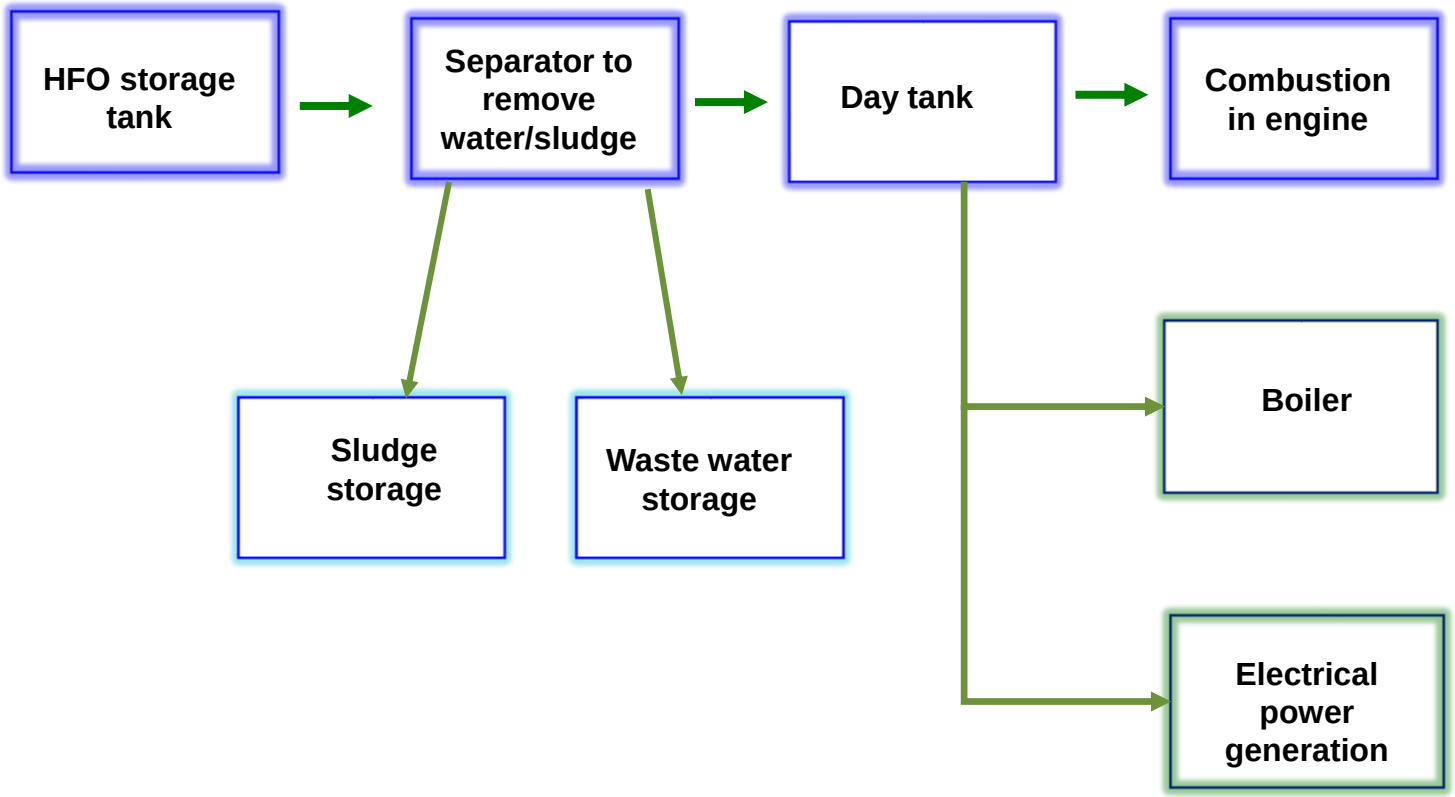


Approach (technical)

- **Potential challenges**
  - Lack of available information
  - Excessive polymerization
  - Lack of suitable quantities of biofuels for evaluation
  - Removal of retained water
- **Critical success factors (technical, market, business)**
  - Reduced blend viscosities
  - Efficient combustion with lowered PM formation
  - Cost effectiveness
  - Compatibility with existing infrastructure

Milestone	Status
1. Elucidation of flow properties of HFO blended with bio-oil	Underway, anticipate completion in Q2
2. Data compilation on combustion properties	Completed survey Data analysis underway
3. Fuel system compatibility	To begin at the conclusion of Milestone 2
4. Feasibility report	To begin at the conclusion of Milestone 3

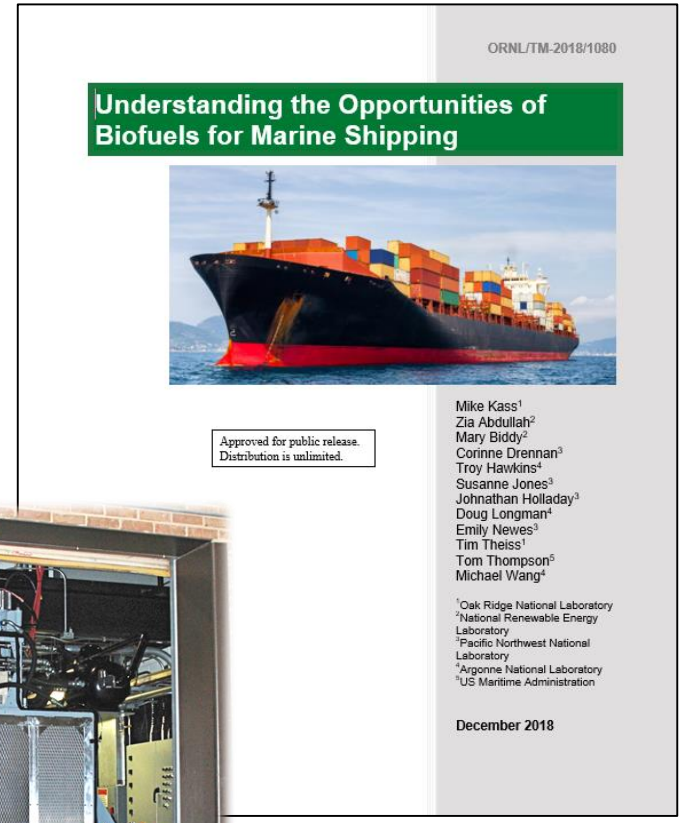
Process Operations Block Diagram for HFO Processing & Use On-board Ships



All of these systems are heated to maintain proper flow characteristics

Approach (Management)

- Working with DOE, DOT and colleagues at NREL, PNNL & ANL to gain stakeholder input and economic assessment
  - Bi-weekly telecoms with staff from other National Labs, DOE and DOT have led to recently published whitepaper highlighting opportunities for biofuels as a marine fuel
  - Organizing workshop on Marine Biofuels
- Leveraging effort with ExxonMobil research facilities at ORNL
  - Single cylinder crosshead research engine
  - Fuel handling system (tanks, separators, filters, heaters, etc.)
  - HFO
- Bio-oils provided by colleagues at NREL & industry
- Close integration with ORNL compatibility team evaluating bio-oil compatibility with materials
- Communicating results through technical publications, conference presentations and visits to sites of interested parties


ORNL/TM-2018/1080

Understanding the Opportunities of Biofuels for Marine Shipping

Approved for public release.
Distribution is unlimited.

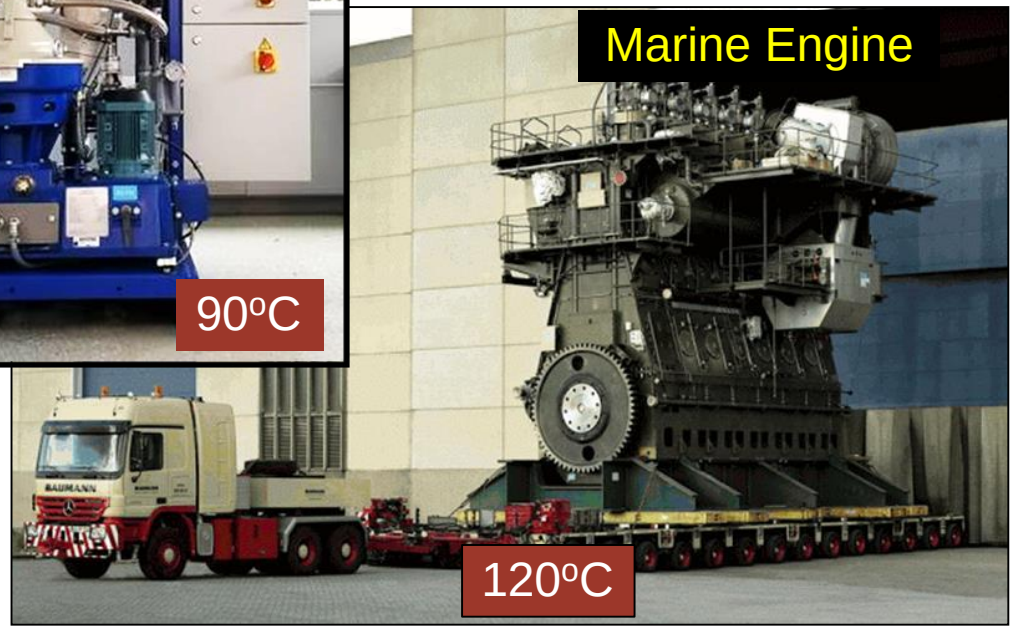
Mike Kass[1]
Zia Abdullah[2]
Mary Biddy[2]
Corinne Drennan[3]
Troy Hawkins[4]
Susanne Jones[3]
Johnathan Holladay[3]
Doug Longman[4]
Emily Newes[3]
Tim Theiss[1]
Tom Thompson[5]
Michael Wang[4]

[1]Oak Ridge National Laboratory
[2]National Renewable Energy Laboratory
[3]Pacific Northwest National Laboratory
[4]Argonne National Laboratory
[5]US Maritime Administration

December 2018

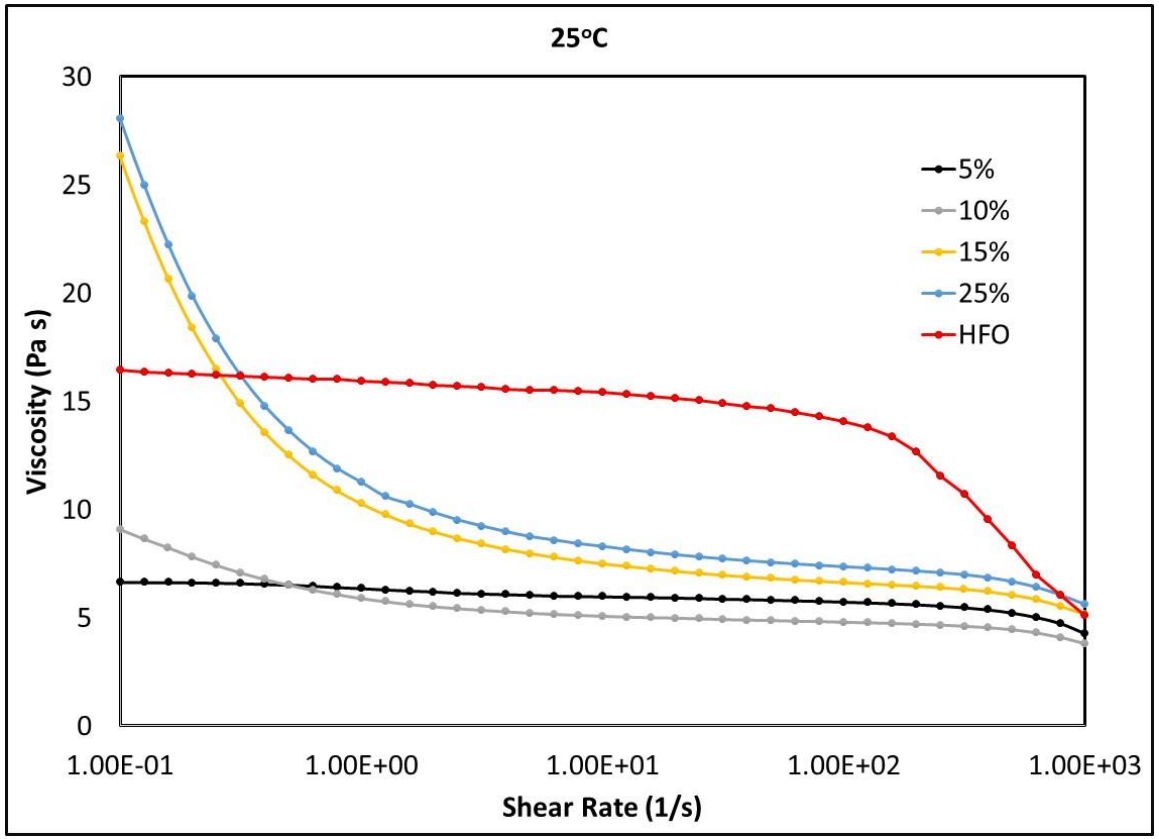
Technical Accomplishments/ Progress/Results

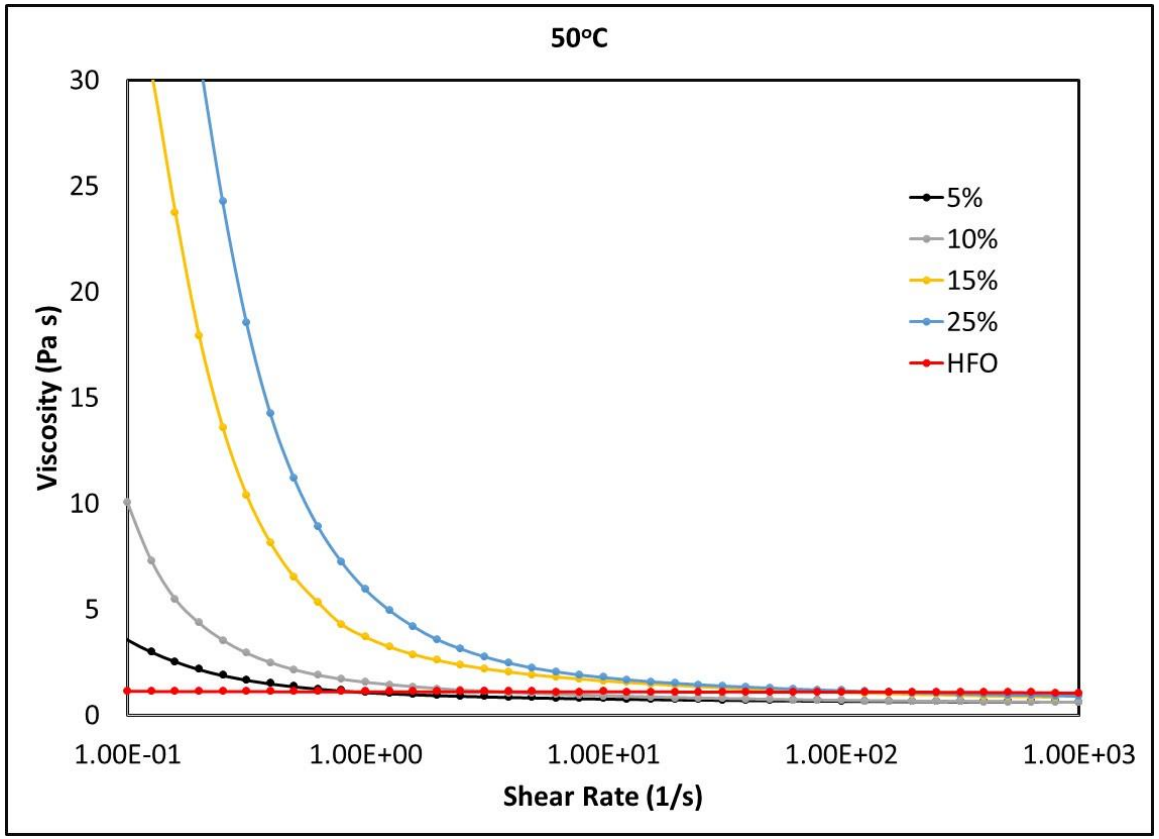
- Begun assembling combustion literature
- Confirmed bio-oil miscibility or blend uniformity with HFO ✓ Critical finding
- Completed viscosity study evaluating fast pyrolysis-derived bio-oil (pine feedstock)
  - Evaluated blends of 5, 10, 15, 25% bio-oil in HFO
  - Conducted viscosity measurements at:
    - 25°C
    - 50°C
    - 90°C
    - 120°C



Technical Accomplishments/ Progress/Results

✓ Critical Finding: The addition of small levels of bio-oil (5-10%) dramatically lowers the viscosity of HFO at low temperatures





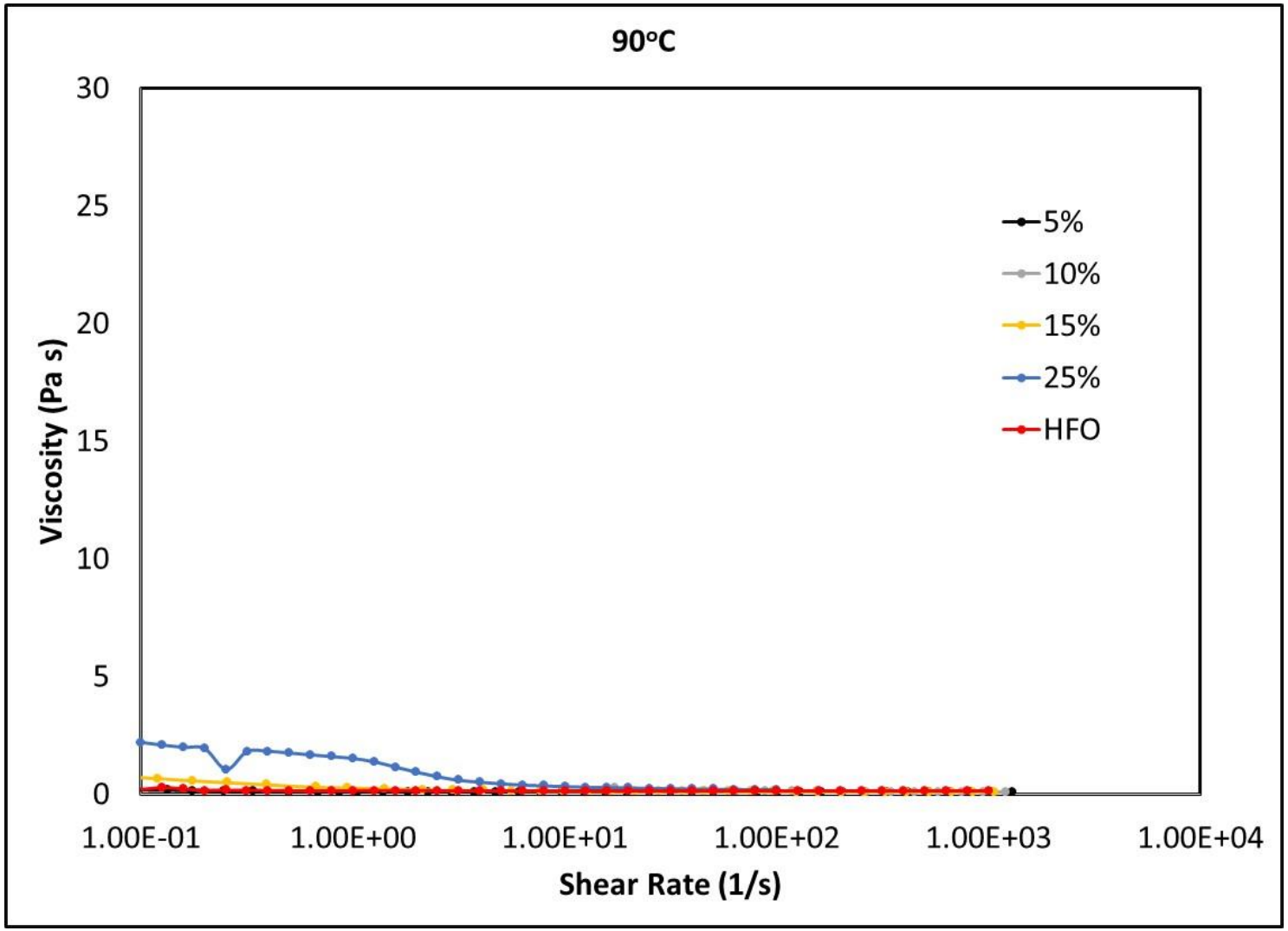
✓ **Implications:**

1. No added energy cost associated with bio-oil additions to HFO processing/handling systems
2. Storage tanks require less heat and pumping energy to maintain equivalent viscosity or flow properties

Technical Accomplishments/ Progress/Results (continued)

Observations at higher temperatures:

- Viscosities of bio-oil blends exhibit similar viscosity characteristics as HFO
- 25% blends showing viscosity increase at low shear rates
- Testing apparatus gave incoherent results at 120°C and higher



Relevance

Improving Efficiency and Emissions of Marine Vessels by Enabling Use of Bio-intermediates as a Marine Fuel

- Directly supports BETO mission:

  "develop and transform our renewable biomass resources into commercially viable, high-performance biofuels"

- This project fills a critical need for Identifying New Market Opportunities for Bioenergy/ Bioproducts:

  Biofuels can potentially offer performance advantages relative to other technology options, and they can also provide unique solutions in certain sectors that have limited energy alternatives, such as aviation and marine

- Bio-oil has properties favorable as a HFO replacement

Future Work

Key Milestones

- Determine impact on engine performance
- Complete rheology study for low blend levels
  - Determine if polymerization is a concern
  - Evaluate water separation
- Evaluate higher blend levels
- Assess the impact of bio-oil use in existing infrastructure and necessary upgrades

Remaining Budget (~$410k) is sufficient

Go/No-Go Decision Point (6/30/2019)

Property	Status
Miscible with HFO	**Confirmed**
Viscosity match with HFO	**Confirmed**
Polymerization	**Not yet detected. Additional studies underway**
Water separation	To be evaluated in upcoming months
Material compatibility	To be assessed

Summary

- **Overview:** Goal is to determine the technical feasibility of using biofuels, especially bio-oils for marine engine use. Feasibility is to be determined by compatibility, emissions reduction & efficiency improvement
- **Approach:** combines leveraging complementary efforts with industry and other national labs Key determinants are:
  - Economic feasibility
  - Engine and handling properties
  - Bio-oil compatibility with HFO and system hardware
- **Technical Accomplishments/Progress/Results**
  - Bio-oil miscible with HFO
  - Bio-oil additions improve flow/handling properties of HFO
- **Relevance:** This effort directly supports BETO's overarching commercial viability mission while providing a unique solution to addressing the limited energy options of the marine sector
- **Future work:** Activities include 1) examining the compatibility of bio-oil blends with fuel system architecture, 2) understanding engine performance, 3) assessing economic viability

Additional Slides

Responses to Previous Reviewers' Comments

N/A. Since this effort is a relatively new project, it has not been previously reviewed

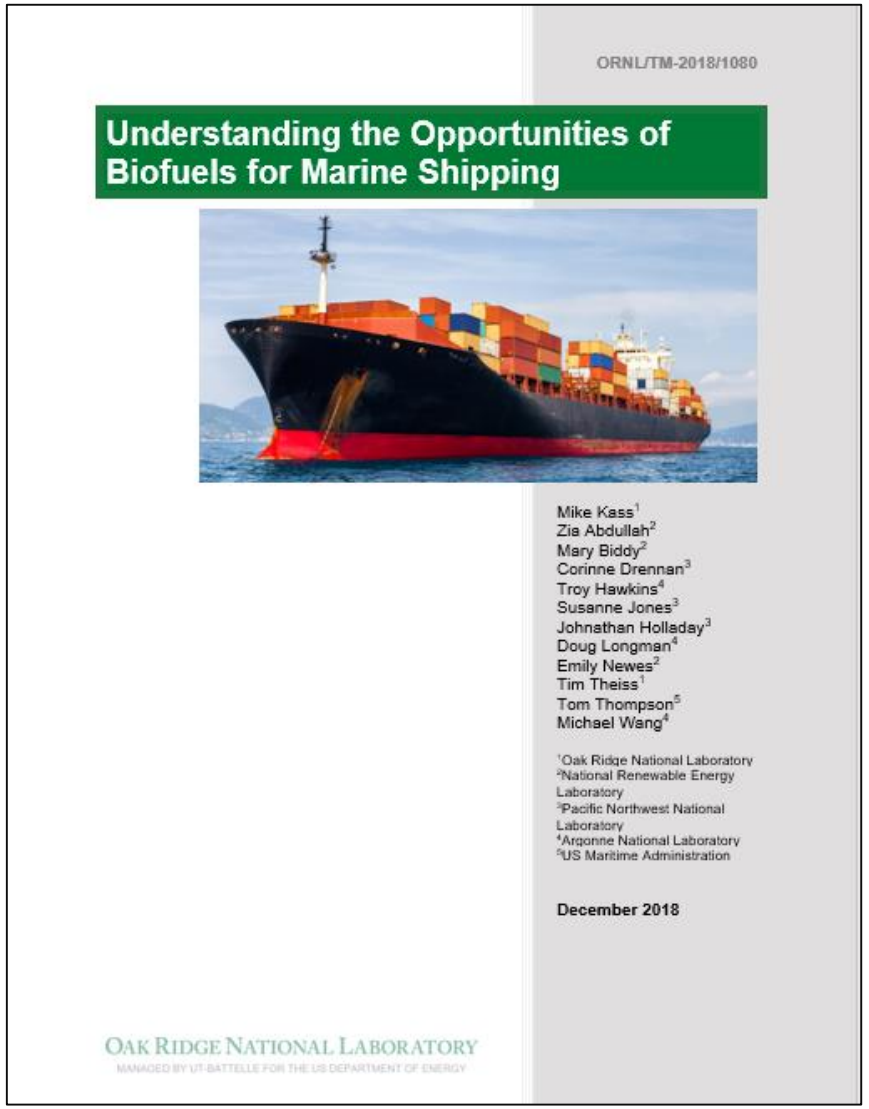
Publications, Patents, Presentations, Awards, and Commercialization

Publications

1. Kass et al., “Understanding the Opportunities of Biofuels for Marine Shipping” ORNL/TM-2018/1080. December 2018. https://info.ornl.gov/sites/publications/Files/Pub120597.pdf

Invention Disclosure

1. Invention Disclosure ID# : 201904312, "Bio-intermediates as Viscosity Reduction Agents for Residual Fuels and Oils“ Kass, Connatser, Armstrong & Lewis



Project Scope Change Table

Scope Changes	Date	Logic / Reasoning	Approval / Rejection Date
BP1- FY2018	N/A	No change in scope	N/A
BP2- FY2019	N/A	No change in scope	N/A

Risk Registry Table

	Risk Identified			Mitigation Strategy		Current Status
Risk ID	**Process Step**	**Risk Description**	**Severity (High/ Med/Low)**	**Mitigation Response**	**Planned Action Date**	**Active/ Closed**
Limited data availability						
1	N/A	Cetane and vaporization rate are important parameters for assessing combustion performance. Some biofuels, especially bio-intermediates have not been fully characterized for combustion performance	Medium	Currently consulting with combustion property measurement expertise at Southwest Research Institute. Looking at alternative methods to measure cetane number.	3/31/2019	Active