5th ICCT Workshop on Marine Black Carbon Emissions

Bio-Oil use in Marine Engines

John Storey, Mike Kass, Tim Theiss, Brian Kaul, and Eric Nafziger

Oak Ridge National Laboratory

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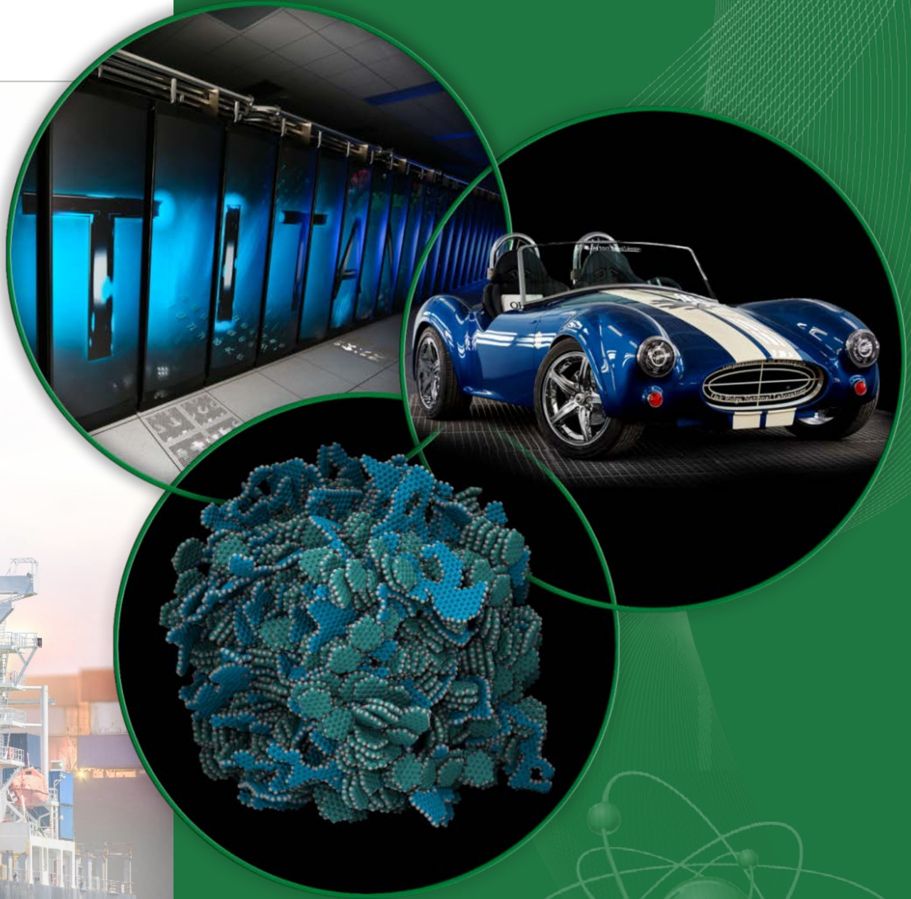
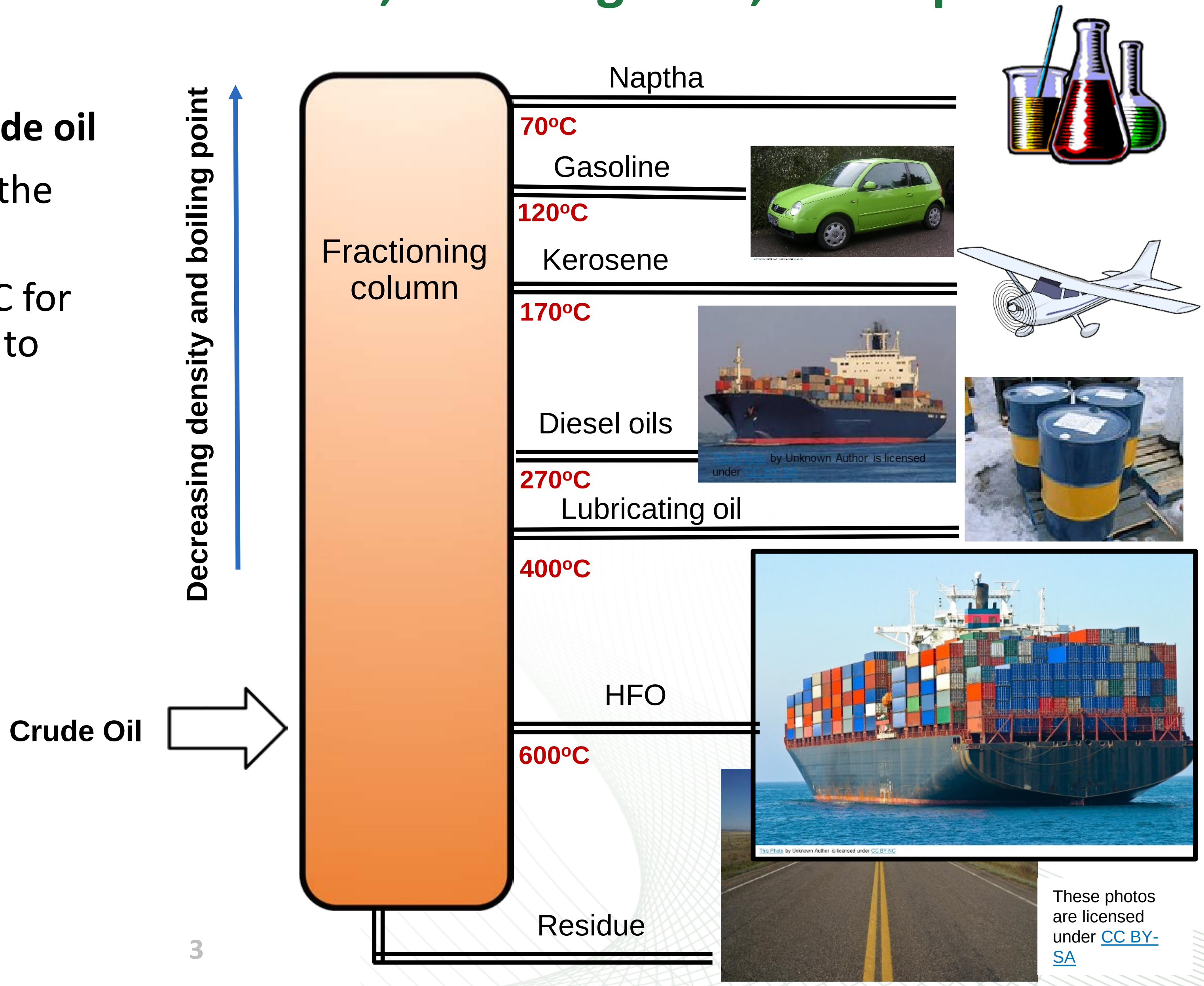


Use of Bio-Oil in Marine Engines

Over 75% of fuel used to operate marine cargo vessels is Heavy Fuel Oil (HFO), other fuels include medium distillate oil, marine gas oil, and liquid natural gas.

- **HFO is the lowest fraction removed from crude oil**
  - Viscosity at room temperature is roughly the same as molasses
  - Fuel has to be heated to around 90-120 °C for proper flow and run through a centrifuge to remove solids and water

  - **HFO contains up to 3.5% sulfur**



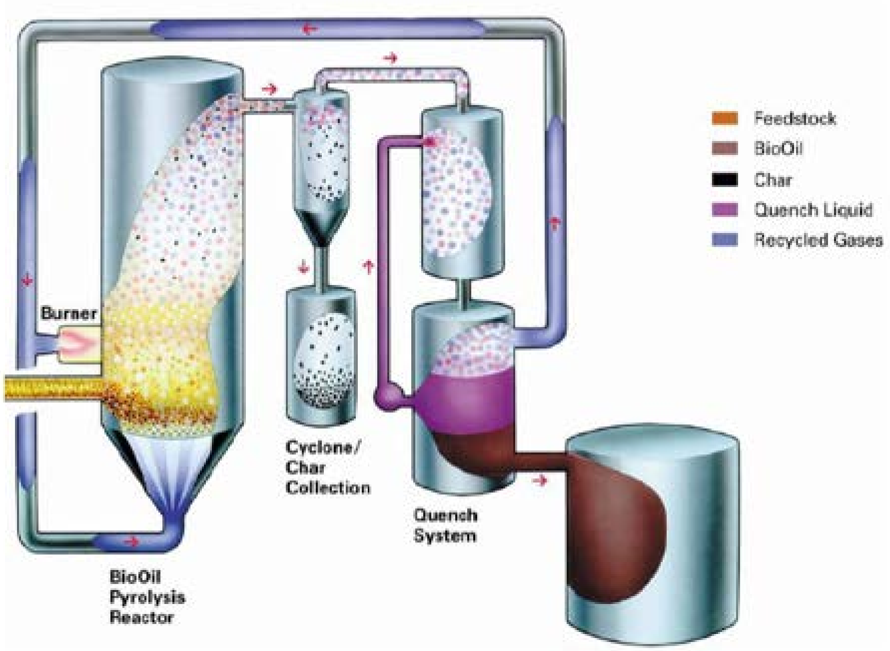
Bio-Oil: What is this stuff?

- Bio-Oil is made by pyrolysis of lignocellulosic biomass (plant material)
- Typically 30-40% oxygen
- Hydrophilic – lots of water and acidic components
- Will typically polymerize on its own if not “upgraded”
- Will not mix with distillate fuel unless upgraded

Property	Pyrolysis Oil	Diesel
Density at 20°C, g/cc	1.2	0.85
Viscosity at 20°C, cStoke	13	2.5
Lower heating value, MJ,kg	17.5	42.9
Ash, wt.%	0.13	<0.01
Water content, wt.%	20.5	0.1
Oxygen content, wt.%	42.5	0.9

Fast pyrolysis is an efficient pathway to lignocellulosic liquid fuels

A Fast Pyrolysis Process (Dynamotive)



- Whole biomass
- Temperature: 450 °C
- Pressure: 1 atm
- Residence time: 1-2 s
- Atmosphere: inert
- High yield in liquids (bio-oils)
- Inexpensive
- Viable as small scale operation
- Bio-oils are highly acidic

Bio-oil composition	
C (wt%)	40.1
H (wt%)	7.6
O (wt%)	52.1
Moisture (wt%)	23.9

ORNL Project: Evaluation of Bio-oils for Use in Marine Engines

Goal: Evaluate bio-oils as substitutes/blends for HFO

Motivation:

- Bio-oils low in sulfur, high in oxygen.
- Dilute 3.5% sulfur HFO
- Oxygenated fuels typically reduce PM in diesel application
- Bio-oils need upgrading to become “drop in” fuels
- Bio-oil upgrading (catalytic, hydrogen addition) very expensive

ORNL Project: Evaluation of Bio-oils for Use in Marine Engines

Steps:

1. Measure fuel properties of pyrolysis oil-HFO blends - *ongoing*
    - Pre-separator stability (HFO is typically heated) – does it polymerize in situ?
        - Viscosity, density measurements as a function of time, temperature
    - Post-separator: How effective is the separator at water, particulate removal? Does bio-oil "carry" water past the separator? (May or may not be a problem)
    - What is the cetane of different blends?
2. Operate in marine engine – *Summer 2020*

3. Emissions measurement – *Summer 2020*

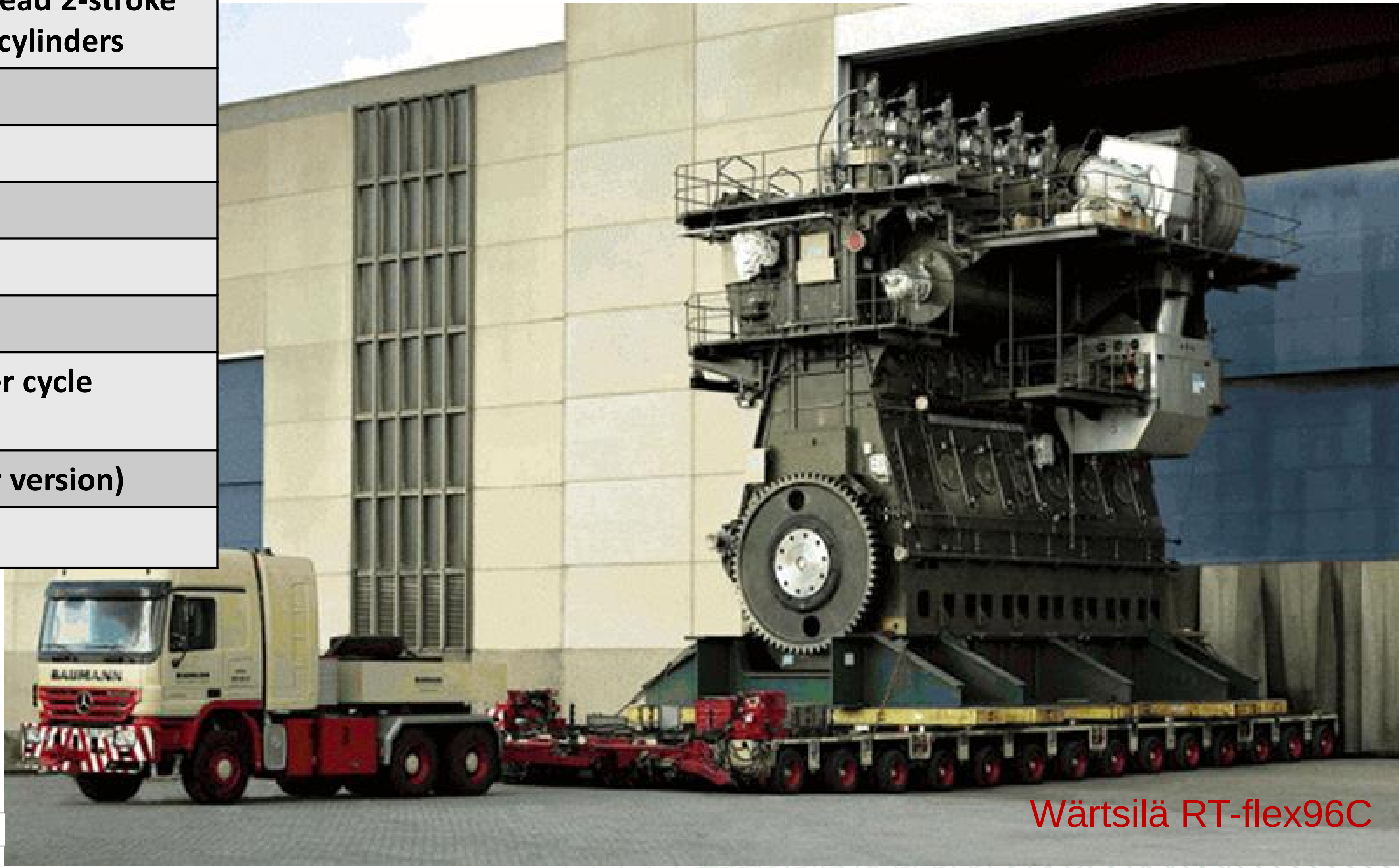
ORNL Marine Engine Facility

Oak Ridge National Laboratory

Big ships require big engines. Two noteworthy features are their high efficiencies (50%) and that they are directly coupled to the propeller.

Configuration	Turbocharged crosshead 2-stroke inline diesel, 6 to 14 cylinders
Bore	0.96m (3.14 ft)
Stroke	2.5m (8.4 ft)
Speed	22 – 102 RPM
BMEP	1.96MPa @ full load
Power	5720 kW/cylinder
Fuel consumption	160 g per cylinder per cycle (up to 250 tons/day)
Crankshaft weight	300 tons (14 cylinder version)
Piston weight	5.5 tons

Photo taken from Pinterest



Primary Engine Companies:

- MAN Diesel & Turbo
- Wartsila

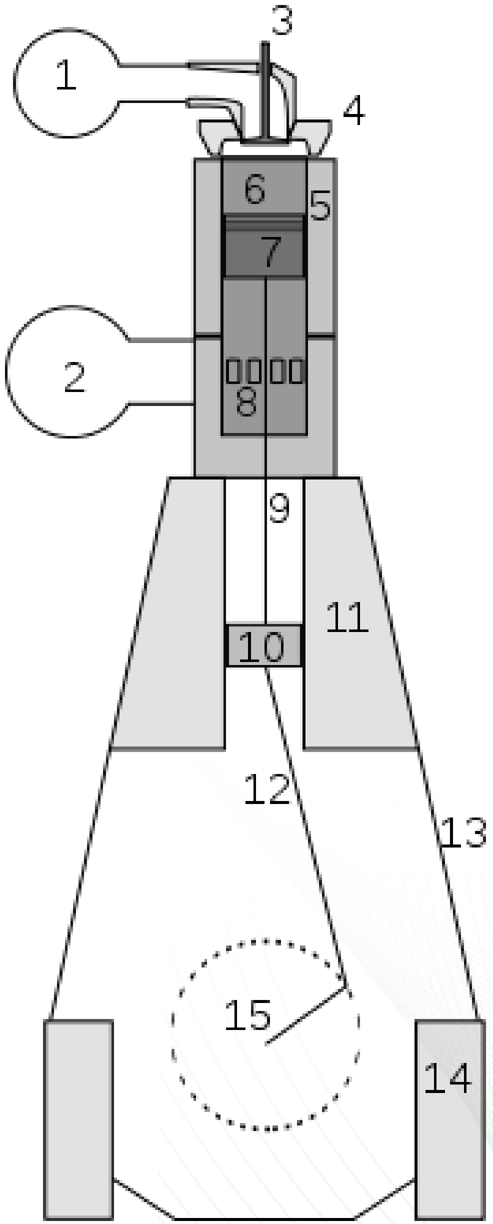
Long stroke. Very long stroke.

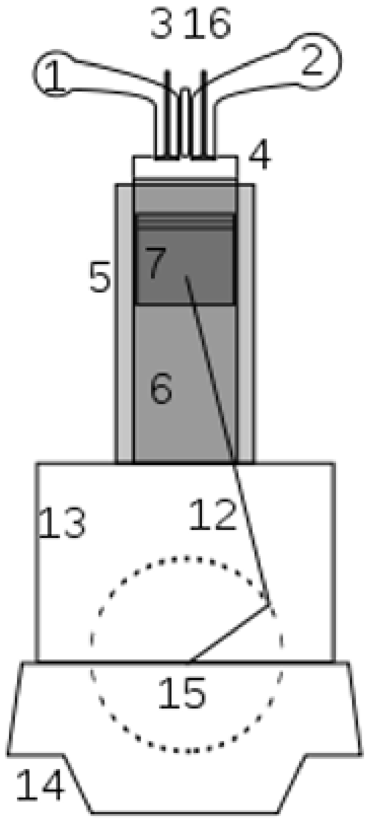
- Bore/stroke ratio
  - Square (1:1)
  - Oversquare (1.x:1)
  - Undersquare (0.x:1)
- Marine…the extreme "stroker" motor
  - Bore/stroke ratios of 3:1 or 4:1
  - Extremely high torque

"more torque = more better"

Crosshead vs Trunk Piston

- Trunk piston engine
  - Power piston connected directly to the crankshaft by means of a connecting rod
  - Horizontal pin (wrist pin) used for piston-rod interface
- Crosshead engine
  - Connecting rod connects the crankshaft to a “crosshead”…a non-compression piston that slides up and down in a liner
  - A piston rod is a rigid member connecting the crosshead piston to the power piston





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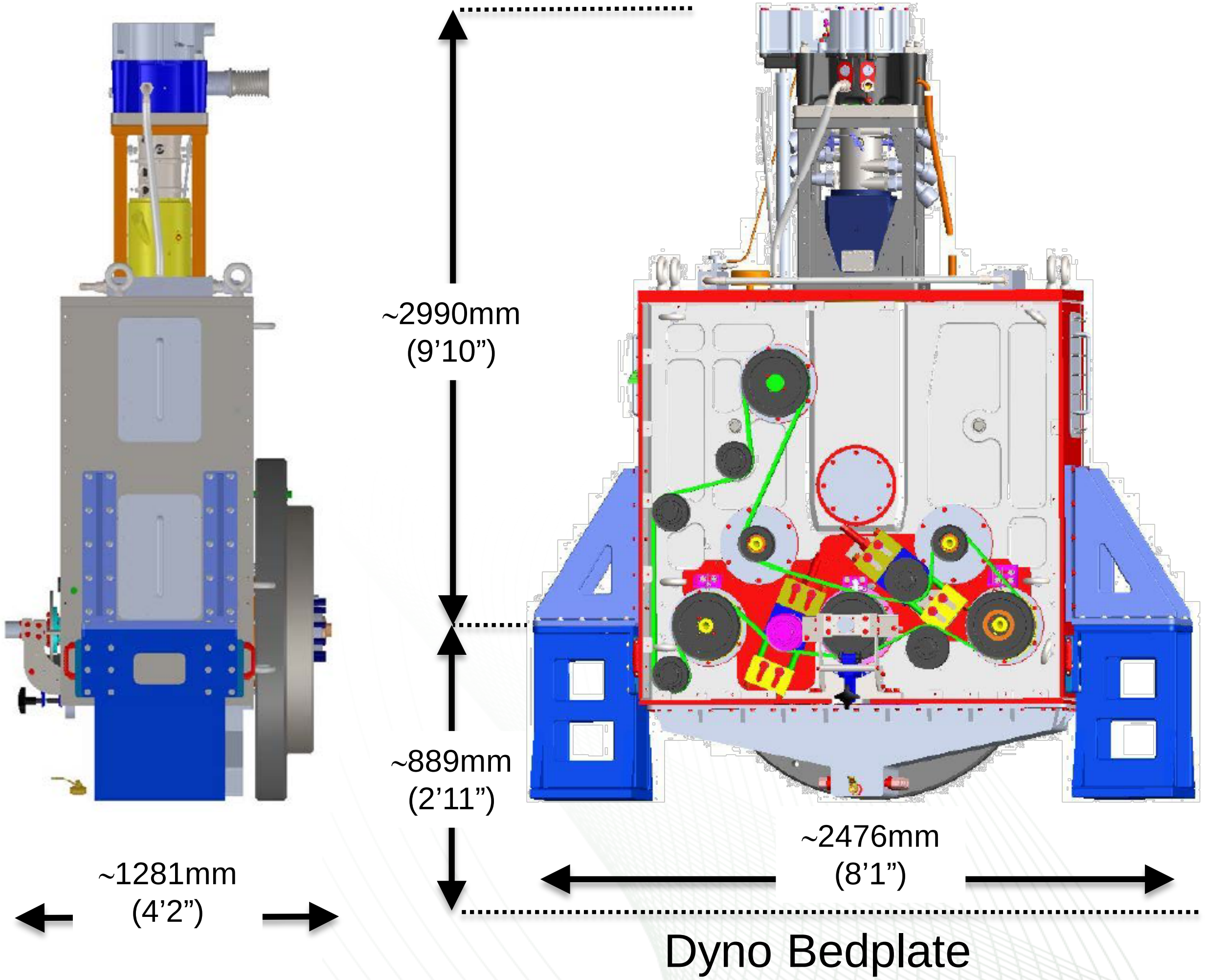
ExxonMobil selected ORNL and Mahle as key partners in the development of new marine lubricants.

- ORNL now operates the only down-scaled single-cylinder crosshead engine (Mahle) in the world
- 1/10th scale
- Stands ~12 feet tall
- Weighs ~16,000 pounds
- Future Opportunities:
  - CO_2 Regulations
  - PM emissions
  - Bio-oil blends

Bore = 108mm
Stroke = 432mm
Disp = 4L

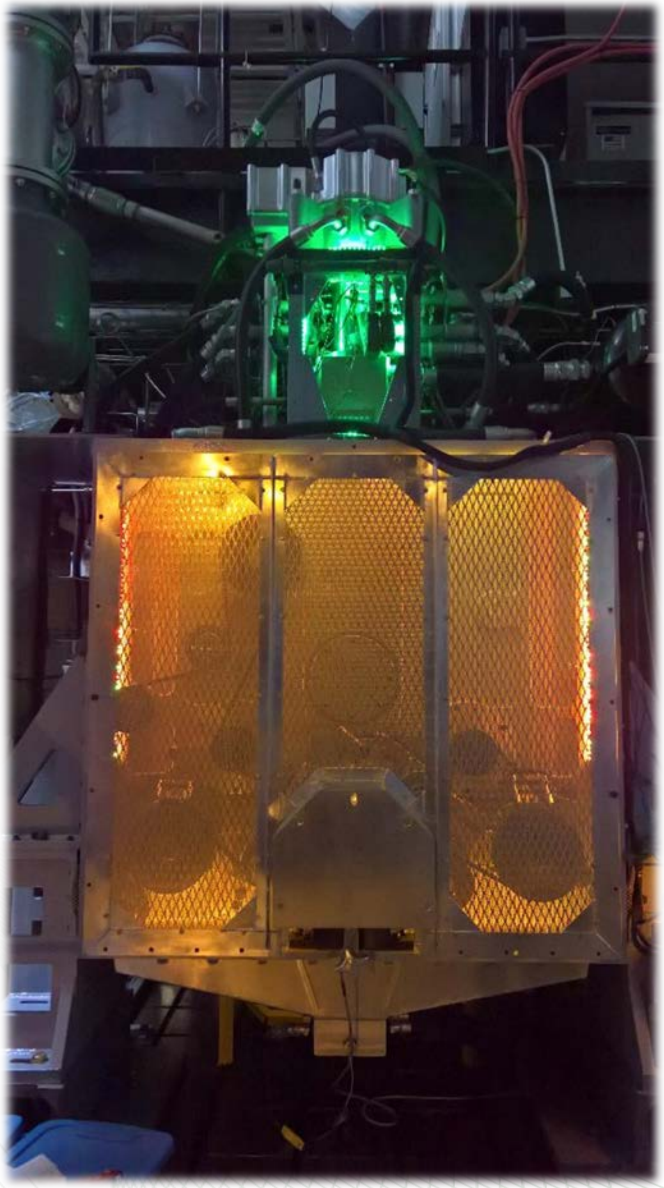


A scaled-down approach – Why do it?

- Economics
  - Previous full-scale test engine had become too costly to operate
- Perform detailed analysis on deposit and wear

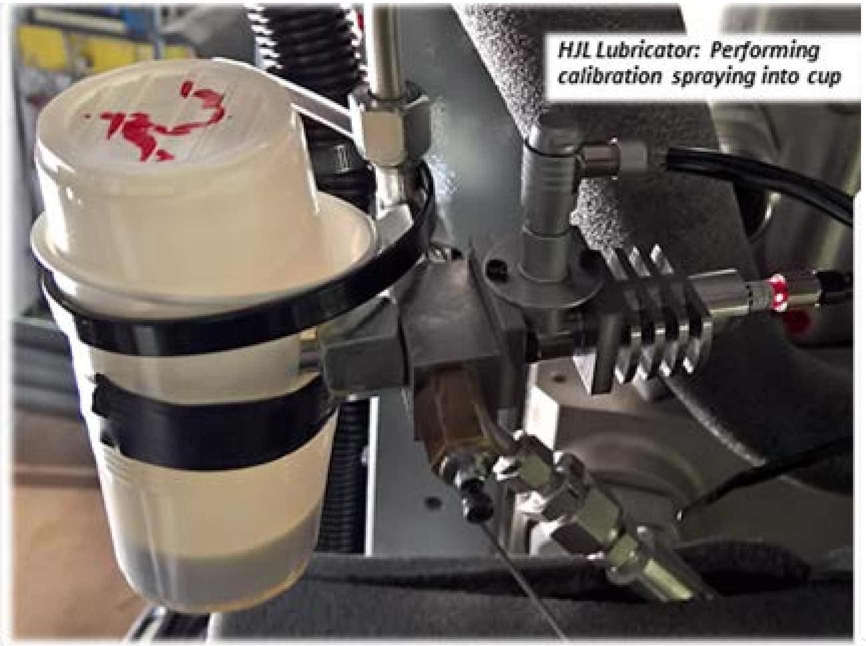
A scaled-down approach – How do we do it?

- Engine designed to match mean piston speed
  - As size scales down, speed scales up
  - 520 rpm ≈ 100 rpm
- Replicated 2-stroke uniflow scavenged design
- Further single cylinder engine considerations
  - Simulated boost with variable speed compressor
  - Pulse damping tanks
  - Balancing
    - Primary and secondary
    - 3,000 lb flywheel!!

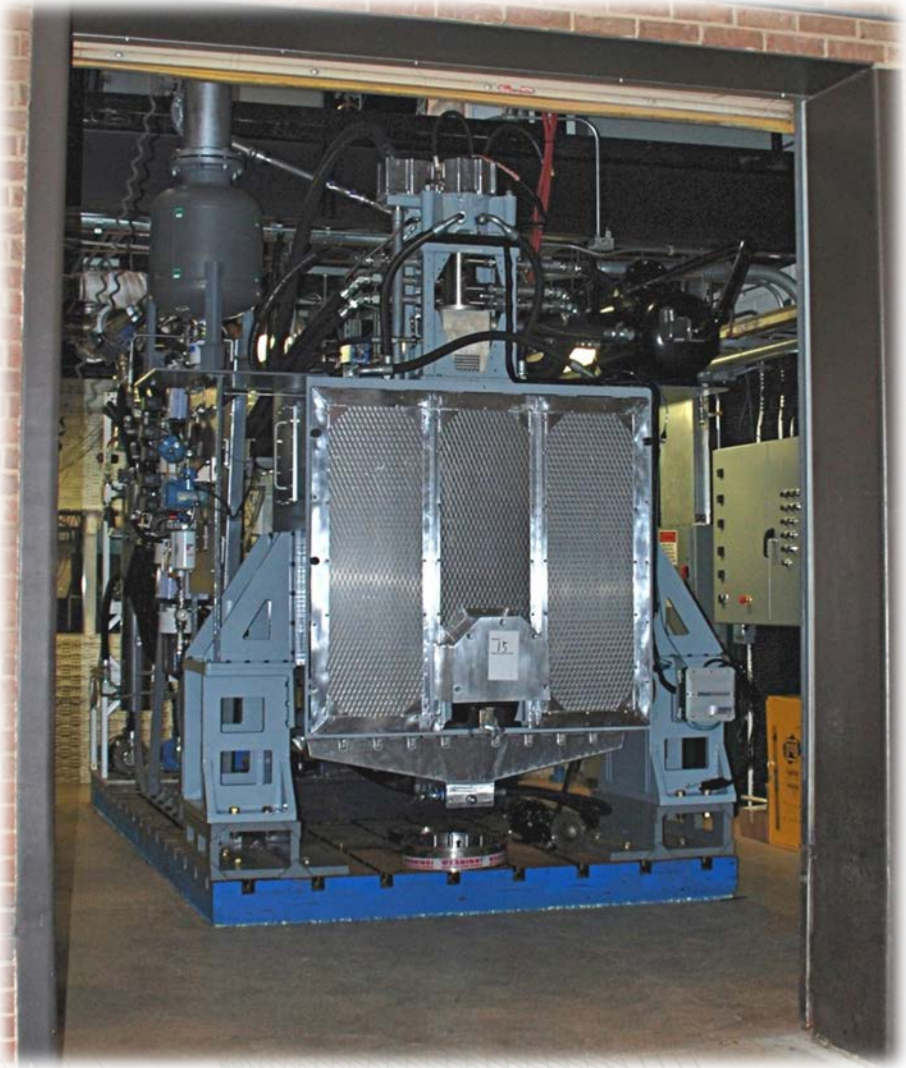


A scaled-down approach – How do we do it?

- Deposit and wear studies require careful matching of liner temperature
  - 4 distinct cooling zones used to set temperature profile
- Lubricators located every 90° around cylinder liner for timed lubrication of piston rings



Installing the Engine



So, how much horse-power does this thing make?

- ~ 100 hp and 1,000 ft-lbs torque

More torque than a Powerstroke

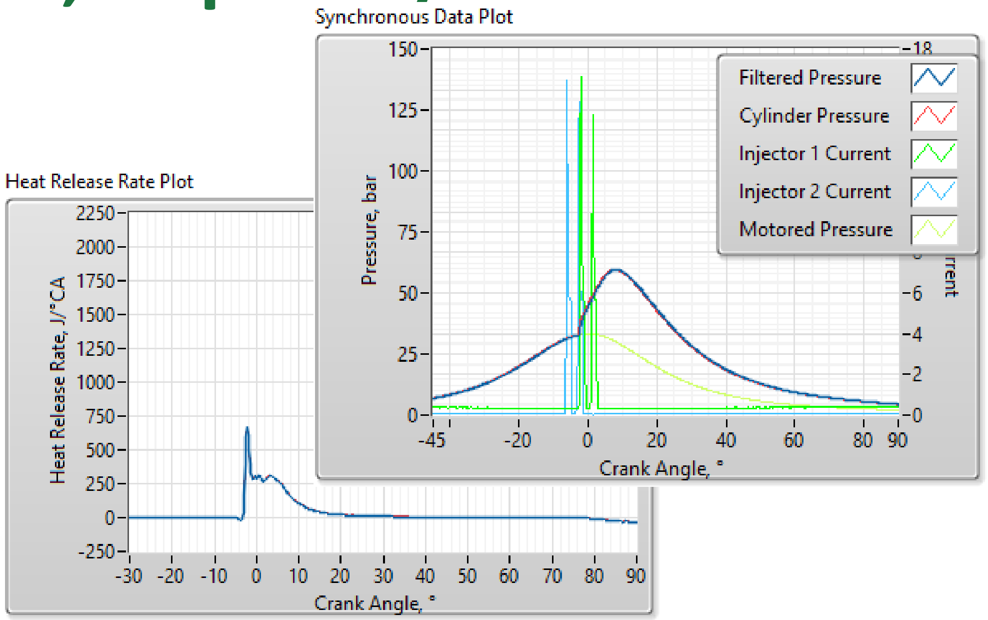
More torque than a Duramax

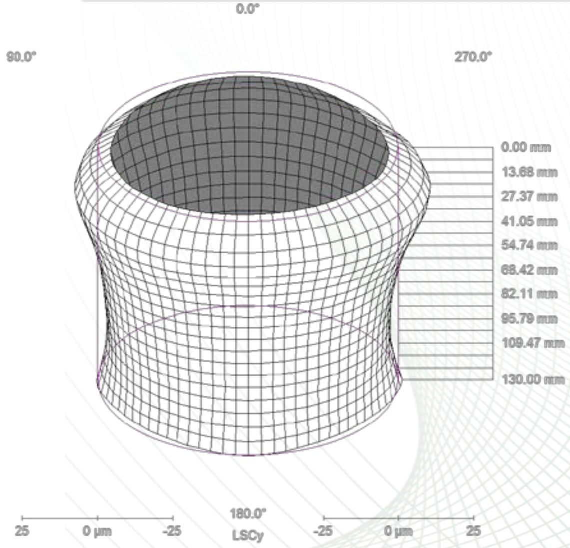
More torque than a Cummins

That's not horsing around!!

Research Goal: Determine Impact of Lubricants on Engine Efficiency and Durability (Wear, Corrosion, Deposits)

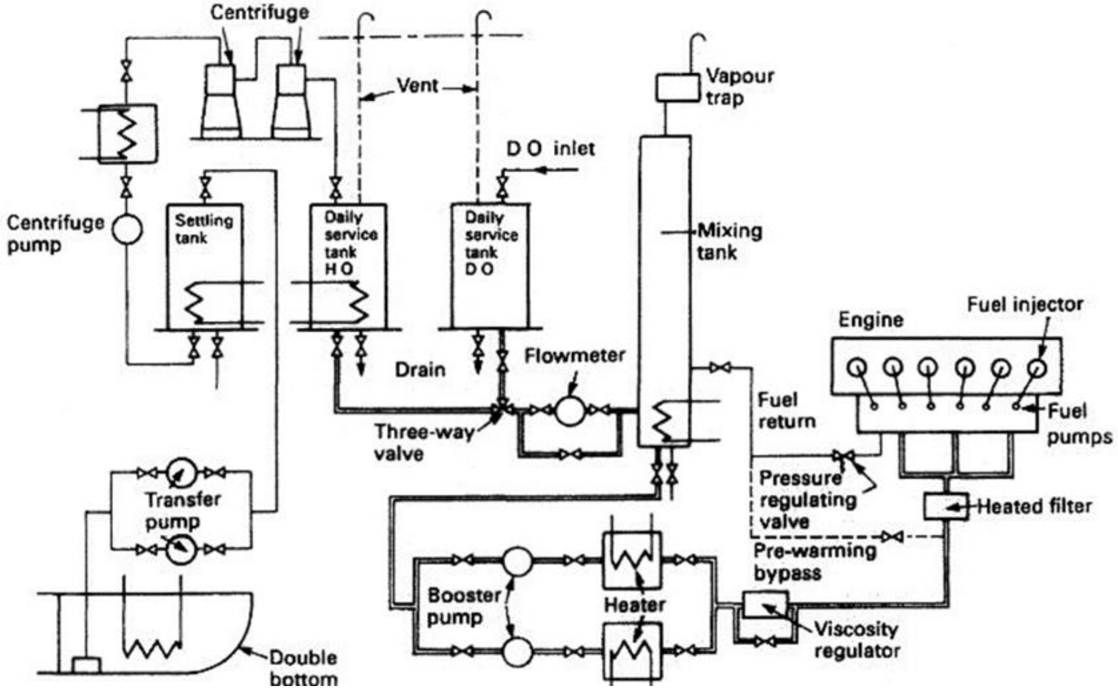
- Engine instrumentation (online data acquisition)
  - Cylinder P (measured every 0.2°CA)
  - Intake & exhaust P & T
  - Exhaust emissions
  - P, T, flow rate of all coolant & oil flows
  - Brake torque
  - Piston T (telemetry) & liner T
- Wear instrumentation (offline inspection)
  - Incometer (liner profile)
  - XRF (scrapedown oil metal content)
  - Surface replicas (for microscopy)

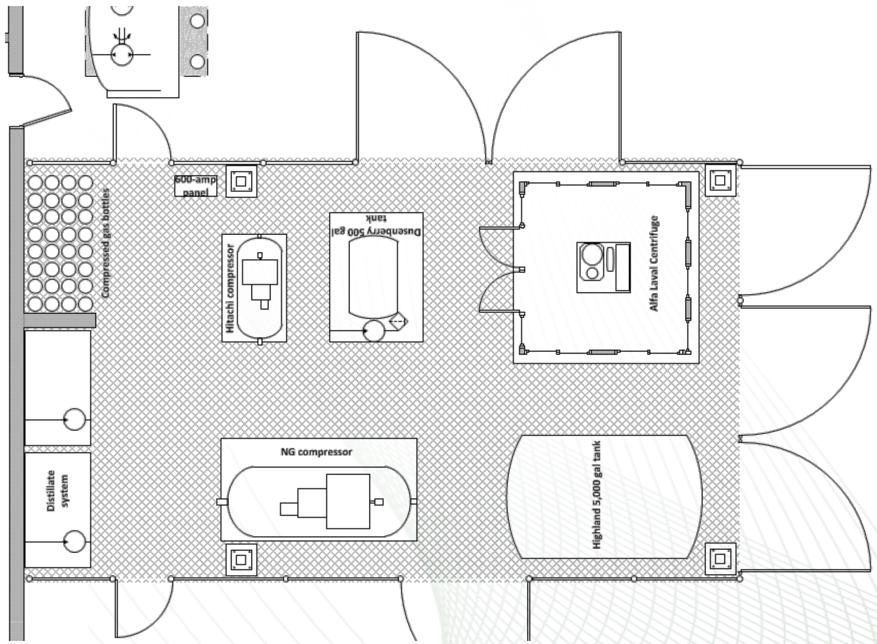




HFO system design

The systems and processes needed to condition the fuel are complex





What does the engine run on now? Future research?

- Active experiments running on distillate (#2 diesel fuel)
- Currently installing processing systems to allow operation on HFO
- Sample ports available for PM emissions
  - Extensive PM measurement capabilities at ORNL
  - PM mass, size, number, bulk composition
  - Real time soot carbon (AVL smokemeter, micro soot sensor)
  - Chemical composition of PM and semi-volatiles by GC-MS, LC-MS, ICP-MS
- Bio-oil/HFO blends in future if fuel passes stability tests

Questions?

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