Technical evaluation of REG Bio-Residual Oil
REG biorefinery capacity

**Crude Feedstock Capable**
- Albert Lea, MN
- Danville, IL
- Emden, Germany
- Geismar, LA
- Madison, WI
- Mason City, IA
- New Boston, TX
- Newton, IA
- Oeding, Germany
- Seneca, IL

**Refined Feedstock Capable**
- Grays Harbor, WA
- Houston, TX
- Ralston, IA

**Biomass-Based Diesel Plants**
- 13
- 502 MMGY

**Nameplate Capacity**

Source: REG Analysis
REG Bio-Residual Oil is a co-product of biodiesel production

- In 2016 REG produced more than 400 million gallons of biodiesel
- 10 million gallons of REG Bio-Residual Oil is produced annually, at the following locations:
  - REG Albert Lea (MN)
  - REG Mason City (IA)
  - REG Newton (IA)
  - REG Danville (IL)
100% renewable replacement to petroleum fuel oils

• REG Bio-Residual Oil is produced from recycled fats and oils:
  – used cooking oil – byproduct of the restaurant industry
  – inedible corn oil – byproduct of corn ethanol production
  – animal fats – byproduct of meat production

• REG Bio-Residual Oil has the lowest carbon intensity of any commercially available liquid fuel
Can be produced in two grades: S50 and S500

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>S50 BRO</th>
<th>S500 BRO</th>
<th>No. 6 Fuel Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 100 °F [lb/gal]</td>
<td>7.6</td>
<td>7.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Viscosity @ 100 °F [cSt]</td>
<td>40</td>
<td>450</td>
<td>1,000</td>
</tr>
<tr>
<td>Sulfur [ppm]</td>
<td>35</td>
<td>250</td>
<td>8,000</td>
</tr>
<tr>
<td>Nitrogen [ppm]</td>
<td>300</td>
<td>600</td>
<td>5,000</td>
</tr>
<tr>
<td>Ash [wt%]</td>
<td>0.04</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Karl Fischer Moisture [wt%]</td>
<td>0.1</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Ultimate Analysis [wt%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>79</td>
<td>80</td>
<td>86</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>11</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>Oxygen</td>
<td>10</td>
<td>8</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

Data represents typical values
REG Bio-Residual Oil has comparable energy density to conventional fuels
REG Bio-Residual Oil’s viscosity allows easy handling at moderate temperatures.

Temperature-Viscosity Relationship

- **S50 BRO**
- **S500 BRO**
REG Bio-Residual oil is a low-cost liquid fuel alternative

REG Bio-Residual Oil qualifies for RINs when burned for human comfort and RECs when burned for power generation

Source: REG Analysis and EIA
3 combustion trials have been conducted at Brookhaven National Labs

- Tested on 3 different platforms
  - Quartz combustion chamber
  - Residential boiler
  - 1.5 MMBTU boiler (pictured)

- Tom Butcher, PhD with the Energy Conversion Group at Brookhaven National Lab led the testing programs
Trial #1: Residential boiler trial

• Carlin pressure atomized residential burner
• 0.5-1 gal/hr flow rate
• Feed lines preheated to 200 °F
• Emissions analysis
  – Particulate matter emissions analyzed with a Wöhler SM500
  – Smoke number analyzed per D2156
  – CO, NOx analyzed with a Testo 350
Brookhaven National Lab residential burner test configuration

S50 Bio-Residual Oil
No. 6 Fuel Oil
S500 Bio-Residual Oil

Heat Traced Feed Lines
Stack Emissions
Combustion Conditions

Source: REG Analysis and EIA
Residential boiler emissions data

Emissions data generated from a residential fuel oil burner. All fuels were preheated to 200 °F.
Trial #2: Brookhaven National Lab flame visualization test configuration

- S50 Bio-Residual Oil
- No. 2 Fuel Oil
- S500 Bio-Residual Oil
- Heat-traced Feed Lines
- Flame Visualization Quartz Chamber

Source: REG Analysis and EIA
Quartz chamber flame visualization

REG Bio-Residual oil exhibits excellent characteristic flame behavior:

• Flame retention – flame front at the burner outlet indicates suitable volatility for initial combustion

• Flame stability – stable flame indicates fuel homogeneity and atomization at the nozzle

Source: REG Analysis and EIA
Trial #3: Industrial boiler trial

- Carlin pressure-atomized burner
- 6-8 gal/hr flow rate
- 1.5 MMBTU/hr heating rate
- Dry-back firetube boiler
- Feed lines were preheated to 200 °F
- Emissions analysis was the same as residential boiler trial

Source: REG Analysis and EIA
Industrial boiler emissions data

Emissions data generated from a residential fuel oil burner. All fuels were preheated to 200 °F.

Placeholder for actual data, currently under review

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Bio-Residual Oil is lipids-based

<table>
<thead>
<tr>
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<th>S500 BRO</th>
<th>S50 BRO</th>
<th>No. 6 FO†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatics [wt%]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>34</td>
</tr>
<tr>
<td>Polar Aromatics [wt%]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>30</td>
</tr>
<tr>
<td>Asphaltenes [wt%]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>15</td>
</tr>
</tbody>
</table>

• Aromatics and asphaltenes contribute to particulate matter (PM) emissions
• BRO is produced from lipids and does not contain any aromatics or asphaltenes

Negligible nickel and vanadium is a significant benefit for local air quality

<table>
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<th>S500 BRO</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Nickel [ppm]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>89</td>
</tr>
<tr>
<td>Vanadium [ppm]</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>73</td>
</tr>
</tbody>
</table>

• Nickel and vanadium are present at significant quantities in petroleum fuel oils
• Fine particle nickel and vanadium, and with PM$_{2.5}$ have been linked to increased mortality rates in New York City‡
• BRO has negligible nickel and vanadium and significantly reduced PM emissions compared to petroleum residual fuels

REG Bio-Residual Oil is a sustainable replacements for petroleum fuel oils

- S50 BRO is suitable as a drop-in fuel for both light- and heavy-oil burners
- S500 BRO is suitable as a drop-in for heavy-fuel burners
- Test conditions on a light-fuel oil burner were 200 °F injection temperature and 150 – 300 psig injection pressure
Acknowledgements

This work was funded by the Renewable Energy Group

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Special thanks to the Energy Conversion Group at Brookhaven National Lab

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