FINAL REPORT

COMBUSTION TESTING OF A BIO-DIESEL FUEL OIL BLEND IN RESIDENTIAL OIL BURNING EQUIPMENT

Prepared for:

MASSACHUSETTS OILHEAT COUNCIL & NATIONAL OILHEAT RESEARCH ALLIANCE

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1. Acknowledgements

The work summarized in this report is a collaborative effort between the National Oilheat Research Alliance (NORA), the Massachusetts Oilheat Council (MOC), the New England Fuel Institute (NEFI), Advanced Fuel Solutions, Inc., the Energy Research Center, Inc., the service managers who participated in this oilheat equipment testing program, and others who supplied valuable input and guidance.

NORA supplied the funding that was required to support the engineering and technical services, the test equipment, and other supplies that were required for this project.

Michael Ferrante, President of the Massachusetts Oilheat Council, was responsible for conceiving of the project, procuring the funding that was needed, and supplying overall project direction and management.

Jack Sullivan of NEFI supplied the facilities and support personnel for conducting the tests, while NEFI's Michael Markarian provided on-site management of the project that included testing a range of oil fired boilers and furnaces that are included in the NEFI training facility.

Paul Nazzaro of Advanced Fuel Solutions, Inc., supplied the Bio-diesel test fuels and assistance with project planning and review of test results, and Edmund Burke of Dennis K. Burke, Inc., supplied the low sulfur diesel fuel.

The work of Tony Ruffo and Dave Bessette, two highly experienced oil heat service managers, is gratefully acknowledged. They conducted the combustion testing of all the oil heat equipment that was included in this project, and supplied valuable insight into the operation of oil heat systems and the potential advantages offered by bio-diesel fuel blends. They were critical to the successful and timely completion of this project.

We thankfully acknowledge the discussions and technical input, including review of data and interim and draft reports, by Ray Albrecht of the New York State Energy Research and Development Authority, and Tom Butcher, Roger McDonald, and CR Krishna who are research engineers at Brookhaven National Laboratory.

2. Executive Summary

Biodiesel fuel blends have been shown to lower air emissions in residential and small commercial oil heating equipment. The purpose of this study is to evaluate the combustion performance of a blend of 20% soy-based biodiesel fuel combined with 80% low sulfur (0.05%) highway diesel compared to conventional home heating oil. Tests were conducted at the New England Fuel Institute Training facility using a range of conventional oil powered boilers and furnaces over a range of fuel firing rates and excess combustion air settings.

Key observations and findings of these combustion tests include:

- Nitrogen Oxide emissions are frequently reduced by about 20% by using the biodiesel/low sulfur blend.
- Combustion stability with the biodiesel blend is very good as indicated by low levels of carbon monoxide that are similar to the conventional fuel oil.
- Sulfur Oxide emissions are reduced by 83 percent by using the biodiesel blend.
- Smoke numbers are lower with the biodiesel blend than the home heating oil when the same burner air setting is used.
- Fuel oil and combustion odors are improved by using the biodiesel /low sulfur oil blend compared to home heating oil based on these preliminary tests.

This combustion test project demonstrated that very good combustion performance is produced by the biodiesel fuel blend in the conventional residential oil heating equipment that was tested. No significant changes in carbon monoxide levels (incomplete combustion) were observed. The reduction of air emissions with the biodiesel blend is substantial, producing much lower environmental impacts. This includes reductions in sulfur oxides (83%), nitrogen oxide (20%), carbon dioxide (20%), and particulate matter. Most of the sulfur oxide reduction is produced by using the low sulfur highway fuel. Preliminary analyses indicate that the 20% soy-based biodiesel/low sulfur diesel blend has an environmental cost that is better than natural gas when gas leakage during transmission, storage, and distribution are included. This transforms home heating oil into a premium fuel with very favorable environmental impacts.

Other benefits include improved odor characteristics, and domestic production of part of the fuel supply from soy bean farms.

The next steps needed to further evaluate biodiesel fuels include:

1. Combustion testing for a range of biodiesel blends to optimize performance and costs
2. Tests of cold-flow characteristics
3. Test of biodiesel fuels with ultra-low (0.0015 %) fuel oil
4. Long-term tests of boiler fouling rates with biodiesel fuels
5. Field tests and demonstrations of biodiesel blends.

3.0 Introduction

Bio-diesel fuels and blends of bio-diesel and distillate heating oils have been shown to reduce air emissions and offer other advantages compared to conventional heating oil. Recent combustion tests by Brookhaven National Laboratory indicate that blends of heating oil and bio-diesel fuel can lower nitrogen oxide emissions from residential oil burners by 10 percent to 20 percent when compared to conventional distillate fuel oil. In addition, sulfur oxides and greenhouse gas emissions are also substantially lowered. Tests completed to date often have been limited to a single burner-boiler or burner-furnace unit.

The purpose of this test project was to perform combustion tests on biodiesel and normal fuel oils in a range of residential oil boilers, furnaces, and combustion chamber configurations, and to analyze combustion performance for various operating conditions. The objective was to identify potential benefits in combustion performance and lowered air pollutant emissions, while noting any combustion problems caused by using biodiesel fuel oil. The primary focus of this initial study was on the combustion performance of biodiesel fuels compared to conventional fuel oil.

The test fuel primarily used for these tests was 80% low sulfur diesel fuel (0.05% by weight sulfur) with 20% soy-based biodiesel fuel. Conventional home heating oil (#2 distillate oil) was tested for comparison purposes. Limited testing was also completed using the conventional home heating oil blended with 20% soy-based biodiesel fuel. All combustion tests were performed at the NEFI training center in Watertown Massachusetts. The NEFI facility has a wide range of burners, boilers, and furnaces that are used for training oilheat service technicians. A sampling of these units was included in this initial testing program. Each burner-boiler and burner-furnace unit that was selected was evaluated at 3 or 4 firing rates, and at 3 or 4 excess combustion air settings to evaluate a range of operations. Combustion measurements that were completed include: flue gas smoke, carbon dioxide, oxygen, carbon monoxide, draft, and nitrogen oxide emissions.

Attachment A is a table that summarizes the tests that were completed as part of this project.

4. Methodology

This combustion test project was designed to compare the performance and emissions of biodiesel fuel blend with conventional heating oil in residential boilers and furnaces. Heating equipment to be tested was located in the New England Fuel Institute training facility in Watertown, Massachusetts and included a range of oil burners, furnace, and boilers including older and new equipment in a wide range of designs.

The test program covered a sample of these heating units, and each was tested over a range of fuel firing rates and for a range of burner air settings. A layout for the preliminary schedule of testing follows.

TEST PLAN MOC/NORA BIODIESEL PROJECT - PART I

NEFI UNIT #	FUEL	NOZZLE (gph)	NOZZLE (actual)	EXCESS AIR SETTING Tr SMK	TR-1%CO2	8-9% CO2	#1 SMK
1	Biodies	0.5					
	Biodies	0.85					
	Biodies	1.1					
1	#2 0il	0.5					
	#2 0il	0.85					
	#2 0il	1.1					
22	Biodies	0.5					
	Biodies	0.85					
	Biodies	1.1					
22	#2 0il	0.5					
	#2 0il	0.85					
	#2 0il	1.1					
10	Biodies	0.5					
	Biodies	0.85					
	Biodies	1.1					
10	#2 0il	0.5					
	#2 0il	0.85					
	#2 0il	1.1					

The following equipment was selected for testing.

Unit #1: Small-commercial Steam Boiler, steel construction
Flame Retention Oil Burner
2.5 gallon per hour fuel nozzle

Unit #8: Older Residential Hot Water Boiler, cast-iron construction
Flame Retention Oil Burner
0.75 gallon per hour fuel nozzle

Unit #10: Compact, Residential Hot Water Boiler, steel construction
Flame Retention Oil Burner
0.75 gallon per hour fuel nozzle

Unit #13: Older Residential Warm Air Furnace, steel construction
Flame Retention Oil Burner
0.65 gallon per hour fuel nozzle

Unit #22: Residential Hot Water Boiler, cast-iron construction
Flame Retention Oil Burner
0.75 gallon per hour fuel nozzle

Unit #23: Residential Hot Water Boiler, cast-iron construction
Flame Retention Oil Burner
0.75 gallon per hour fuel nozzle

Test Instruments

Test instruments for performing combustion testing and flue gas analysis that were used for this project included the following.

Testo 300 M - Commercial & Industrial Combustion Analyzer with printer that measures: Oxygen (O_2), Carbon Monoxide (CO), Nitric Oxide (NO), Nitrogen Oxides (NO_x), Flue temperature, and draft.

Testo 325-i - individual gas analyzer for measuring sulfur dioxide (SO_2) content of the flue gases.

Fuels tested

The biodiesel fuel that was evaluated was a blend of 20% soy-based biodiesel combined with 80% low sulfur highway diesel, which is referred to as the biodiesel or biodiesel blend in this report.

A second fuel was conventional number 2 distillate home heating oil that is used at the NEFI training facility.

A limited number of tests were conducted on a third fuel. This is a 20% soy-based biodiesel fuel combined with 80% number 2 home heating oil that is available at the NEFI facility.

Test Procedures

The biodiesel fuel was pre-mixed and supplied in a 55 gallon drum. It was introduced to the test boilers and furnace by using a 2 gallon plastic fuel contained and a flexible hose to the inlet of the oil burner. The conventional home heating oil was piped to the heating equipment with copper tubes and valves.

At the start of the test, the biodiesel fuel supply was connected to the heating unit to be tested. A fuel nozzle was installed and the fuel pressure was measured and adjusted as needed. The burner air shutter was adjusted to supply a range of burner excess air levels and corresponding flue oxygen percentages. Combustion test data were measured and recorded for each excess air setting. The biodiesel fuel was disconnected and the piping to the conventional home heating oil was reconnected. Combustion tests were then completed for the same nozzle at similar excess air setting.

These procedures were continued for a range of fuel nozzle sizes and/or oil pressures, and for the six different heating units that were part of this test project. The data combustion collected was then entered into a specially designed EXCEL spreadsheet for analysis and plotting. Some of the plots that were generated are shown in Attachment B.

5. Test Results and Analysis

Attachment A is a Table which summarizes key information about the various boilers and furnaces that were tested using the a blend of 20% soy-based biodiesel fuel combined with 80% low sulfur (0.05%) highway diesel, and conventional home heating oil. Detailed test results for the heating equipment included in this project are contained in **Attachment B**. Combustion tests that were completed included measurement of the following flue gas constituents.

- Nitric Oxide (NO) and Total Nitrogen Oxides (NOx)
- Sulfur Dioxide
- Carbon Monoxide
- Smoke Number, and
- Flue Gas Temperature

Each of these combustion test factors will be discussed for all the equipment that was tested, and engineering analyses will be presented and discussed. Specific references will be made to the test data contained in Attachment B.

a. Reduced Nitrogen Oxide Emissions with Biodiesel Blends

A significant reduction in Nitrogen Oxide (NOx) emissions was observed in many cases when the conventional home heating oil was replaced with the low sulfur highway diesel blended with 20% biodiesel fuel. Typical reductions in NO emissions of about 20 parts per million or about 20% were observed. A brief discussion follows for each of the warm air furnaces and boilers that were tested. **Appendix B** shows Nitric Oxide NO emissions for each test unit corrected for 3 percent oxygen in the flue gas as a function of excess air setting.

Comparisons of Nitric Oxide (NO) emissions for the standard home heating oil and Low sulfur Fuel Oil blended with 20 percent soy-based biodiesel are presented in Attachments B-1a, B-2a, B-3a, B-4a, B-5a, B-6a, B-7a, B-8a, B-9a, B-10a, B-12a, B-13a, B-14a, B-15a, B-16a, and B-17a. Attachment A supplied details on each test including type of heating equipment and fuel firing rate.

Attachment B-1a shows the test results for unit #13 which is a warm air furnace with a firing rate of 0.75 gallons per hour (gph). For this conventional warm air furnaces, the Nitric Oxide (NO) emissions decrease by approximately 20 parts per million when the conventional heating oil is replaced by at 20% biodiesel blended with 80% highway diesel. This reduction was observed over the entire range of burner excess air settings that were evaluated. It is observed that the NO levels increase to a maximum value when the flue gas oxygen level reaches about 5 percent. At this air setting, the low sulfur diesel/ bio-diesel blend produces about 95 parts per million (ppm) of NO while the conventional home heating oil produces about 115 ppm. This is a significant reduction in emissions.

Attachment B-2a is for the same warm air furnace fired at 0.65 gph, and shows a similar reduction in NO emissions for the biodiesel blend. However, **Attachment B-3a** is for the same furnace fired at 0.5 gph, and the observed NO reductions are slightly lower at about 15 ppm.

Attachment B-4a is for test unit # 22 which is a hot water boiler fired at 0.85 gph and the peak NO emissions again occur when the burner air supply is adjusted to produce approximately 5 percent oxygen in the flue gas. The reduction in NO levels in the flue gas for the biodiesel fuel is 15 to 20 ppm, or about 15 to 20 percent. The rapid decrease in NO as the flue oxygen percent goes below 5 percent is coincident with rapid increases in carbon monoxide production. See Attachment B-4b. This is observed for other heating units also, and is expected as there is less oxygen available in the combustion gases to combine with nitrogen to form NO.

Attachment B-5a shows NO for test results for the same hot water boiler fired at 0.65 gph. In this case, the peak NO occurs at 6 or 7 percent flue oxygen levels. The reduction in NO levels by the biodiesel blend is about 20 ppm or about 20 percent, which is similar to the other tests.

Attachment B-6a shows NO results for test unit #8 which is another hot water boiler fired at 0.75 gph. In this case, the peak NO occurs at 7 or 8 percent flue oxygen levels. The reduction in NO levels by the biodiesel blend is about 13 to 17 ppm at the peak levels or about 20 percent, which is similar to the other tests. The rapid decrease in Nitric Oxide (NO) to the right of the peak occurs as carbon monoxide levels in the flue gas begin to rise, as discussed earlier.

Attachment B-7a shows NO emissions for test unit #23 which another hot water boiler fired at 0.75 gph, and also show how increasing oil pressure (increasing fuel delivery rate) affects Nitrogen oxide emissions. In this case, the peak NO occurs at different percent flue oxygen levels. The biodiesel fuel blend peaks at about 9 percent flue oxygen, the standard fuel oil peaks at about 8 percent flue oxygen, and the higher flow oil peaks at about 7 percent flue oxygen. The biodiesel peak NO emissions are about 17 ppm less than the standard home heating oil, or about 20 percent. The higher oil pressure increases NO emissions by about 10 ppm, which is consistent with a higher volumetric heat release rate in the combustion chamber, higher combustion temperatures, and higher thermal NOx.

Attachment B-8a shows NO measurements for test Unit #10, another hot water boiler, fired at 0.75 gph with a refractory lined and higher temperature combustion chamber. This design reduces the rate of heat loss from the combustion gases, produces higher peak combustion temperatures, and higher thermal NOx levels. The NO levels in this boiler were higher than any of the other heating units that were tested. The reduction in NO for the biodiesel fuel blend is much lower than in the other boiler and furnace tests. There appears to be no reduction at the point where the standard home heating oil hits its peak at about 7 percent flue oxygen. Small increases in NO production of about 10 ppm are observed for the biodiesel fuel on either side of the peak.

Attachment B-9a shows NO measurements for test Unit #10, the boiler with high combustion temperatures, fired at 0.85 gph. In this case the NO emissions for the biodiesel and standard fuel or virtually the same, with levels approaching 150 ppm. It appears that the high thermal NOx generated by the higher temperature combustion process in this boiler overcomes any benefit produced by lower fuel Nitrogen in the biodiesel blend.

Attachment B-10a shows NO measurements for test Unit #10 fired at 0.99 gph produced by increasing the oil pressure to the fuel nozzle. In this case, a reduction of about 15 ppm in NO levels is observed for the biodiesel blend at the point of peak emissions for the standard home heating oil.

Attachment B-11a presents the results of tests of the low sulfur diesel/ biodiesel blend for unit #10 with a 0.65 gph fuel nozzle operated at 100, 150, and 200 psig pressure. Similar NO levels are produced at the various fuel flow rates, producing a reasonably continuous curve over the entire range of flue oxygen. The drop off in NO levels at the right side and left side of the curve is consistent with elevated carbon monoxide emission as shown in Attachment B-11b.

Attachment B-12a shows NO measurements for test Unit #10 fired at 0.58 gph using a 0.5 gph nozzle at 130 psig. In this case, Nitric Oxide (NO) levels are similar for the biodiesel blend and the standard home heating oil at 10 percent flue gas oxygen. The biodiesel blend produces between 12 ppm to 18 ppm less NO than the standard heating oil at higher oxygen levels.

Attachment B-13a shows NO measurements for test Unit #10 fired at 0.62 gph using a 0.5 gph nozzle at 150 psig. NO levels for the biodiesel blend and the standard home heating oil have different fuel oxygen levels, but the trends indicate lower emissions for the biodiesel fuel.

Attachment B-14a shows NO measurements for test Unit #10 fired at 0.70 gph using a 0.5 gph nozzle at 200 psig. NO levels for the biodiesel blend and the standard home heating oil are similar, with higher emissions for the biodiesel blend for the lower flue gas oxygen tests. However, the carbon monoxide levels for the standard home heating oil tests are elevated at about 250 ppm, which tends to suppress the NO levels as observed for other tests.

Attachment B-15a shows NO measurements for test Unit #1, a small commercial steam boiler fired at **2.5 gph** using a 2.5 gph nozzle at 100ig. The

NO tests recorded are for different flue oxygen contents, so these tests cannot be directly compared.

Attachment B-16a shows NO measurements for test Unit #1 fired at **3.1 gph** using a 2.5 gph nozzle at 150 psig. The NO emission produced by the biodiesel blend is approximately 20 ppm lower than for the standard home heating oil.

Attachment B-17a shows NO measurements for test Unit #1 fired at **3.5 gph** using a 2.5 gph nozzle at 200 psig. The NO emissions produced by the biodiesel blend are approximately 20 ppm lower than for the standard home heating oil over the entire range of flue oxygen percentages that were tested.

Attachment B-18a is for test unit # 22 which using a 20% biodiesel and 80% conventional #2 heating oil blend . The reduction in NO levels in the flue gas for the biodiesel blend compared to #2 heating oil varies from about 4 ppm to 8 ppm, for an average of about 6 percent.   This reduction in NO emissions is less that reduction using the blend containing biodiesel with the low sulfur diesel (see Attachment B-4a. These tests shown in B-18a were at a slightly lower firing rate of 0.75 gph.

Tests on the various furnaces and boilers completed to date clearly show a substantial reduction of Nitric Oxide (NO) emissions in many cases on the order of 20 ppm by using the biodiesel fuel blends. Only one heating unit which contains a fully refractory lined combustion chamber showed lower NO reductions. In this case, the total Nitrogen Oxide levels were very high as a result of high thermal NOx produced by the elevated combustion chambers.

b. Carbon Monoxide Emissions with Biodiesel Blends

In general, similar carbon monoxide (CO) emissions were produced by the biodiesel/low sulfur blend and the conventional home heating oil. The total emission rates and changes in CO emissions as a function of flue oxygen content were also similar for the two fuels that were tested.   A brief discussion follows for each of the warm air furnaces and boilers that were tested. **Appendix B** shows carbon Monoxide emissions for each heating unit that was tested. Carbon Monoxide (CO) is an important measure because it indicates of how completely the fuel is burned. Elevated CO levels indicate incomplete combustion.

Comparisons of Carbon Monoxide emissions for the standard home heating oil and Low sulfur Fuel Oil blended with 20 percent soy-based biodiesel are presented in Attachments B-1b, B-2b, B-3b, B-4b, B-5b, B-6b, B-7b, B-8b, B-9b, B-10b, B-12b, B-13b, B-14b, B-15b, B-16b, and B-17b. Attachment A supplies details on each test including type of heating equipment and fuel firing rate.

Attachment B-1b shows the test results for unit #13 - a warm air furnace with a firing rate of 0.75 gallons per hour. The Carbon Monoxide emission profiles are virtually the same for both fuels for the entire range of flue oxygen percentages that were tested. The minimum levels are the same and occur for burner air settings that are between 4% and 9% flue oxygen, and the CO levels begin to rise for both fuels when the flue oxygen percent falls below 4 percent. This suggests that combustion stability is similar for the biodiesel/low sulfur blend and the standard home heating oil.

Attachment B-2b for test unit#13 fired at 0.65 gph shows similar CO emissions for the biodiesel blend and standard home heating oil. As the burner excess air is lowered below 4% flue oxygen, the CO levels for the biodiesel blend increase, while CO levels do not increase for the standard home heating oil until flue oxygen contents approach 2 percent.

Attachment B-3b for test unit #13 fired at 0.50 gph shows very similar CO emissions for the two fuels over the entire range of burner air adjustments that were tested.

Attachment B-4b for test unit #22 fired at 0.85 gph shows very similar CO emissions for the two fuels. The CO emissions begin to rise rapidly for the biodiesel blend when the burner air is adjusted to produce about 4 percent flue oxygen. The CO emissions begin to rise rapidly for the standard home heating oil when flue oxygen is above 3 percent.

Attachment B-5b for test unit #22 fired at 0.65 gph shows slightly higher CO emissions for the biodiesel blend from 5% to 8% flue oxygen settings. The CO emissions begin to rise rapidly for the biodiesel blend when the burner air is adjusted to produce about 4-1/2 percent flue oxygen.

Attachment B-6b for test unit #8 fired at 0.75 gph shows very similar CO emissions for the biodiesel blend from 6% to 10% flue oxygen settings. In this case the CO levels rise as excess combustion air increases, and flame temperatures cool down due to very high levels of excess air. The rate of rise in CO emissions for the two fuels is very similar, suggesting that combustion stability is the same for the two fuels.

Attachment B-7b for test unit #23 fired at 0.75 gph for the biodiesel and standard home heating oil, and at 160 psig (0.95 gph) for the standard heating oil. The CO profiles are virtually identical for the biodiesel blend and home heating oil fired at 0.75 gph. However, when the oil pressure is increased and the fuel flow rate rises to approximately 0.95 gph, the point where Carbon monoxide rates increase drops from about 7.5% to 6.5 percent flue oxygen percent. This can be attributed to smaller fuel droplet sizes and better fuel air mixing within the burner at the higher oil pressure and higher fuel flow rates.

Attachment B-8b for test unit #10 fired at 0.75 gph shows much higher carbon monoxide emission rates for the standard home heating oil compared to the biodiesel blend over the entire range of burner excess air adjustments from 6 to 10 percent flue gas oxygen. Biodiesel emissions are below 10 ppm for the entire range of tests, while CO emissions range from 156 ppm to 345 ppm for the standard heating oil. In this case, the biodiesel fuel produces more complete combustion.

Attachment B-9b for test unit #10 fired at 0.85 gph (a 0.75 gph fuel nozzle at 130 psig) shows much higher carbon monoxide emission rates for the standard home heating oil compared to the biodiesel blend over the entire range of burner excess air adjustments from 3-1/2 to 8-1/2 percent flue gas oxygen. Biodiesel emissions are below 10 ppm for the entire range of tests, while CO emissions range from 124 ppm to 144 ppm for the standard heating oil. As before, the biodiesel fuel produces more complete combustion in this boiler.

Attachment B-10b for test unit #10 fired at 0.85 gph (a 0.75 gph fuel nozzle at 175 psig) again shows higher carbon monoxide emission rates for the standard home heating oil. Biodiesel emissions are below 10 ppm when the flue oxygen content is above 2 percent, while CO emissions range from 113 ppm to 124 ppm over the range for the standard heating oil. The general shape of the CO curve is similar for the two fuels.

Attachment B-11b for test unit #10 fired at 0.65, 0.80, and 0.92 gph with the biodiesel blend only. This shows the entire range of CO emission for burner air setting that produce from 3 percent to 12 percent flue oxygen contents. This is the classic "U-shaped" carbon monoxide curve that shows a large increase from incomplete combustion as the excess air is reduced. On the right side of the curve, excess air levels increase and the flame temperature drops causing the chemical reaction rates to decrease. This also causes elevated carbon monoxide production rates.

Attachment B-12b for test unit #10 fired at 0.58 gph again shows higher carbon monoxide emission rates for the standard home heating oil.

Attachment B-14b for test unit #10 fired at 0.70 gph again shows much higher carbon monoxide emission rates for the standard home heating oil. The biodiesel is below 50 ppm while the standard home heating oil is near 250 ppm.

Attachment B-15b, B-16b, and B-17b for test unit #1 fired with a 2.5 gph nozzle shows very low carbon monoxide emission rates for both the biodiesel and standard home heating oil.   B-17b shows that as excess burner air is reduced, the CO levels for the tow fuels increase in a similar way, with the biodiesel emissions increasing before the standard home heating oil.

Attachment B-18b shows the results of tests for unit #22 using a 20% biodiesel and 80% conventional #2 heating oil blend compared to the performance of conventional #2 fuel oil. As in the other tests, the carbon monoxide versus excess air profiles are very similar.

c. Other Test Observations and Discussions

The Sulfur Dioxide (SO_2) content of the flue gas was measured as part of the emissions testing using a Testo 325I single gas instrument. The SO2 emissions are directly related to the sulfur content of the fuel oil or fuel oil blend. Tests on heating unit #10 produced sulfur dioxide emissions in the flue gas that averaged 90 parts per million and corrected for 3 percent excess air when tested with the conventional home heating oil. When the same boiler was operated with the blend of 20% soy-based biodiesel fuel combined with 80% low sulfur (0.05%) highway diesel, the SO_2 emissions fell to 15 parts per million. Based on these measured sulfur dioxide levels, and using information published by Industrial Combustion, the fuel sulfur contents for the two heating fuels were calculated to be 0.17 percent by weight for the conventional home heating oil, and 0.028 percent for the biodiesel / low sulfur diesel blend.

The flue gas temperatures were measured during the combustion tests, and no significant differences were observed for the two fuels that were tested. Attachment B-1c shows typical results.

One important observation during testing was the change in smoke number for the two fuels that may exist when the burner air setting is not changed. Attachment B-4c shows Smoke Number versus burner Air Shutter Setting for test unit #22. When the burner is set for a zero smoke with the biodiesel fuel, the smoke increased to a number 3 when the standard home heating oil was used without readjusting the burner air setting. A similar change in smoke numbers was observed for test unit #23 shown in Attachment B-7c. This means that burner adjustment should be checked whenever a burner is switched from a biodiesel blend to conventional heating oil.

One additional observation during combustion testing was the improvement in fuel and combustion odors offered by the biodiesel/low sulfur oil blend when compared to conventional home heating oil. The people working on this test project felt that the biodiesel fuel has a less objectionable odor in its unburned form. In addition, at times when the combustion gas escaped from the boiler or furnace being tested, the biodiesel fuel had a more favorable odor. In fact, the odor was found to much less intense and be pleasant smelling. Aroma testing was not a part of this test project. This is an area that needs further evaluation and quantitative testing.

5. Conclusions and Recommendations

This preliminary testing program has demonstrated that the biodiesel blend consisting of 20 percent soy-based biodiesel and 80 percent low sulfur highway diesel fuel produces improved emissions and very good overall combustion characteristics. Air emissions of several key pollutants are lowered substantially. In addition, excellent combustion performance was observed for the biodiesel blend in a range of conventional oil heating boilers and furnaces.

Air Emissions Improvements

Nitrogen Oxide emissions were lowered by approximately 20 percent for many of the conventional home heating units that were tested when compared to emissions from conventional home heating oil. This is a substantial reduction that moves home heating oil into a very elite group of low emitting fuels. It substantially reduces the difference in nitrogen oxide emissions from residential oil and gas burning equipment. In fact, this reduction is on the same order as the levels mandated in the mid-1990s by state departments of environmental protection of 25 to 30 percent for commercial and industrial boilers.

Sulfur Oxides emissions are reduced by as much as 80 percent or more which is another important benefit produced by the biodiesel fuel blended with low sulfur highway diesel. The sulfur in the fuel is converted directly to Sulfur Dioxide (SO_2) when it burns which is a primary air pollutant controlled by the USEPA that contributes to acid rain. Conventional home heating oil has historically contained on the order of 0.25 percent sulfur by weight. By using the highway diesel fuel at 0.05 percent sulfur, sulfur oxide emissions can be reduced by 80 percent. The soy-based biodiesel contain very low sulfur, which can lower sulfur oxide emission even more. Sulfur Dioxide (SO2) emissions were reduced from approximately 90 ppm for the conventional home heating oil to 15 ppm for the biodiesel /low sulfur blend during the test project. This is an 83 percent reduction in sulfur oxide emissions which is expected based on typical fuel sulfur contents.

One other important environmental benefit is the reduction in carbon dioxide emissions which is a greenhouse gas that is believed to contribute to global warming. The biodiesel fuel is regenerated by growing more soy plants. This process absorbs carbon dioxide from the air. The effect of using a biomass fuel is a reduction in carbon dioxide emissions proportional to the percentage of biodiesel that is consumed. Therefore, using a 20 percent biodiesel fuel blend can lower effective carbon dioxide emissions by 20 percent. Research indicates that when process efficiency of about 80% is included, the net greenhouse gas reduction is 16 percent. This substantially reduces the difference in greenhouse gas emissions between home heating oil and natural gas.

These reductions in nitrogen oxide, sulfur oxide, and greenhouse gas (carbon dioxide) emissions by using the biodiesel fuel blend have a very significant environmental benefit for home heating oil. It virtually eliminates any remaining environmental advantage that can be claimed by natural gas powered heating equipment. From an environmental perspective, the blend of 20% soy-based biodiesel fuel combined with 80% low sulfur (0.05%) highway diesel that was tested is a premium fuel that has extremely low air emissions. Initial calculations show that the environmental impacts and costs of the biodiesel / low sulfur diesel blend is even lower than natural gas when leakage rates during gas storage, transmission, and distribution are included. This can be verified by further analyses and evaluation of environmental emissions and costs for the two fuels.

Favorable Combustion Performance and Characteristics with Biodiesel Fuels

The combustion tests completed to date indicate very good combustion performance of the biodiesel /low sulfur fuel oil blend when used to power residential oil heating equipment. Carbon Monoxide is an indicator of the completeness of combustion and the relative stability of the burner. When the biodiesel blend was used, it produced carbon monoxide emission rates as a function of burner air adjustment that were very similar to conventional home heating oil. The same "U-shaped" curve that is observed for home heating oil was also observed for the biodiesel blend. In several tests, carbon monoxide emissions began to rise slightly sooner than as the burner excess air was lowered. However, in other cases (unit #10, for example) the carbon monoxide levels were much lower for the biodiesel blend than for the conventional heating oil over the entire range of burner air adjustments.

In general, carbon monoxide levels were very similar for the two fuels, and the shape of the CO versus Flue Oxygen Percent (excess combustion air) were very similar. This suggests very good combustion stability for the residential oil burners when they were operated with the biodiesel blend for the range of tests completed to date.

Other Benefits: less odor, home-grown fuel

Reduction of objectionable odors is another potential benefit based on the preliminary qualitative assessments completed as part of this project. All the observers of these tests agreed that the biodiesel /low sulfur diesel blend produce better-smelling combustion products than the conventional home heating oil. Initial observations are that the odor produced by the low sulfur biodiesel is less intense and has a better, more fragrant odor. Quantitative testing is needed to substantiate and measure this preliminary finding, but this could be an important advantage for the biodiesel and low sulfur fuel blends.

Another favorable attribute of the soy-based biodiesel fuel is that it is a home-grown agricultural product that can be blended with distillates from domestic and foreign sources. In terms of overall domestic energy needs, it is important to be able to use energy sources from within the US as part of the energy mix. This is especially important to augment fuel supplies during unusually cold winter months or during times of fuel supply interruption.

NEXT STEPS

This preliminary evaluation of biodiesel fuel blends focused solely on the combustion performance of a single 20 percent biodiesel blend in home heating equipment. Follow-up activities that are recommended include the following.

1. **Evaluate combustion performance and emissions reductions benefits for a range of biodiesel blends and for varying fuel sulfur contents** of the fuel into which the biodiesel product is blended. This is needed to optimize performance improvement for various combinations of biodiesel and petroleum blends which may result from government actions which may include subsidies or tax credits.

2. **Test the cold-flow characteristics of biodiesel fuels and biodiesel fuel blends** for a range of temperatures to simulate the effect of storage in above-ground outdoor fuel storage tanks. Specifically, evaluate pour point, cloud point, and filter plug points to assure compatibility in colder climates.

3. **Test the interactive effect of biodiesel when combined with ultra-low sulfur** (0.0015 percent or 15 ppm sulfur) fuel oil. Some combustion problems have been observed with the ultra-low oil including damage to flame tubes caused by unexpected chemical reactions. The impact of using biodiesel blends with the ultra-low fuel oil needs to be evaluated.

4. **Long-term tests of reductions in boiler and furnace fouling rates** with the biodiesel and low sulfur biodiesel fuel blends needs to be evaluated similar to the work completed at Brookhaven National Laboratory for the low sulfur (0.05%) fuel oil. This is important to fully evaluate potential service cost savings by extending the intervals between vacuum cleanings.

5. **Field Studies of biodiesel blends are needed** to further test and demonstrate the advantages of these fuels in actual home heating installations. Field testing is now on-going in New York State and Rhode Island. Work similar to the low sulfur heating oil demonstration of by the New York State Energy Research and Development Authority (NYSERDA) is recommended. This is important for quantifying the benefits and identifying any problems that may arise related to using the biodiesel blends.

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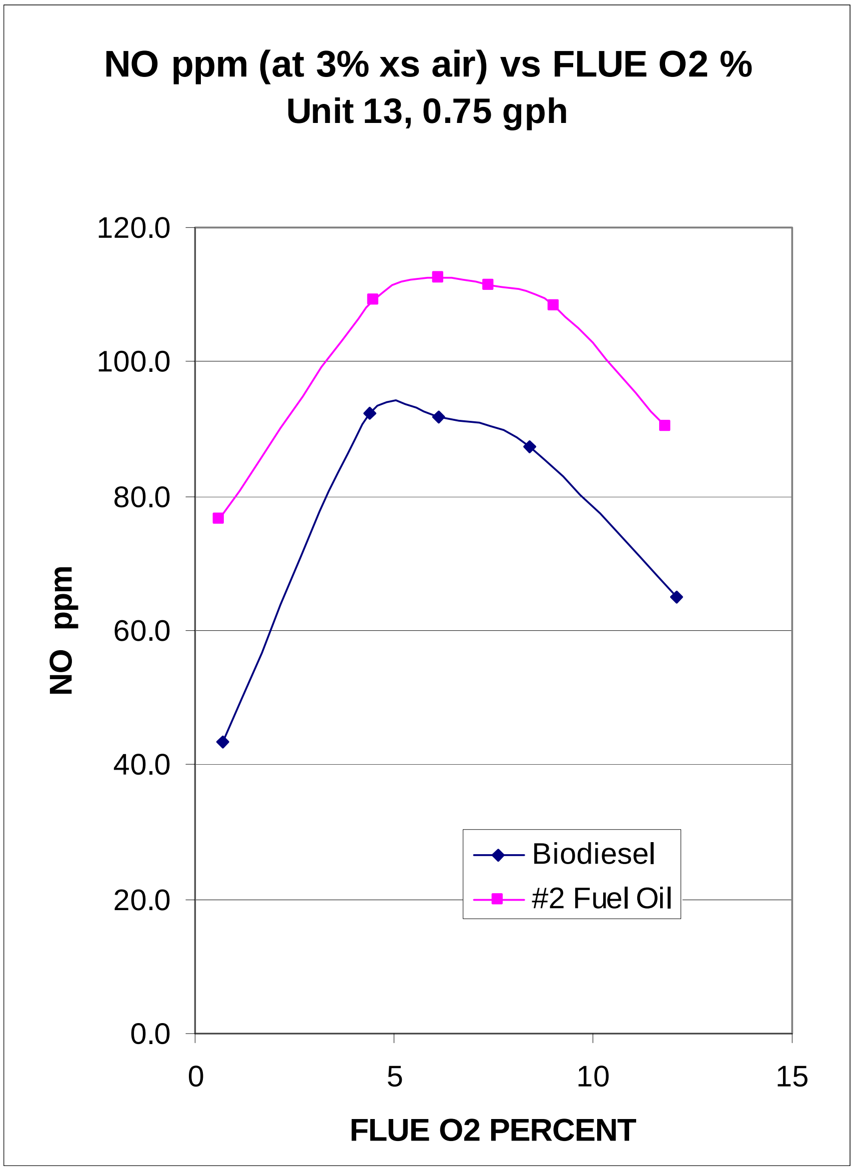
Attachment A - Summary of Tests Completed

NORA / MOC BIODIESEL BLEND TESTS AT NEFI

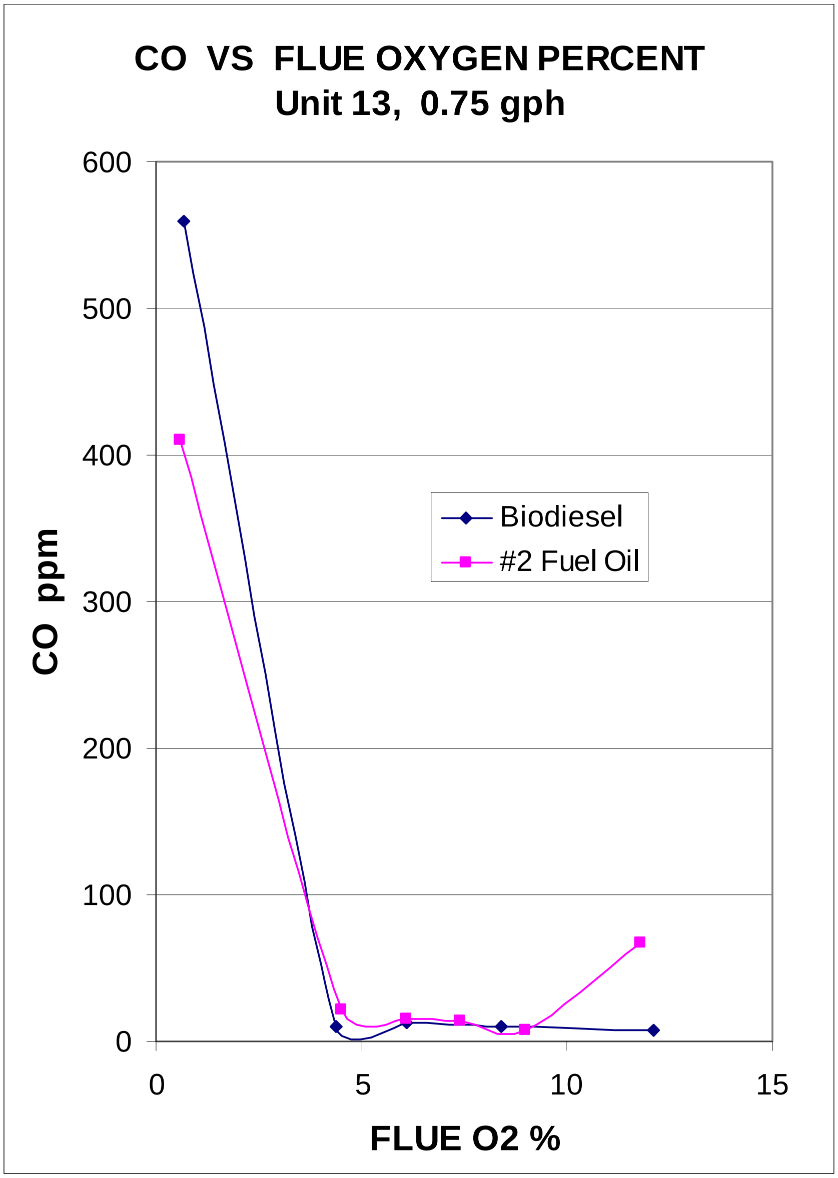
REF	NEFI Unit No.	Unit Type	Fuel Nozzle Gph	Pressure psig	Flow Rate gph	Fuels Tested Biodiesel	Fuel Oil
B-1	**13**	WAF	0.75	100	0.75	20% Bio/LSF	#2 oil
B-2	**13**	WAF	0.65	100	0.65	20% Bio/LSF	#2 oil
B-3	**13**	WAF	0.50	100	0.50	20% Bio/LSF	#2 oil
B-4	**22**	HWB	0.85	100	0.85	20% Bio/LSF	#2 oil
B-5	**22**	HWB	0.65	100	0.65	20% Bio/LSF	#2 oil
B-6	**8**	HWB	0.65	100	0.65	20% Bio/LSF	#2 oil
B-7	**23**	HWB	0.75	100 / 160	0.75 / 0.95	20% Bio/LSF	#2 oil
B-8	**10**	HWB	0.75	100	0.75	20% Bio/LSF	#2 oil
B-9	**10**	HWB	0.75	130	0.85	20% Bio/LSF	#2 oil
B-10	**10**	HWB	0.75	175	0.99	20% Bio/LSF	#2 oil
B-11	**10**	HWB	0.65	100/150/200	0.65	20% Bio/LSF	#2 oil
B-12	**10**	HWB	0.50	130	0.58	20% Bio/LSF	#2 oil
B-13	**10**	HWB	0.50	150	0.62	20% Bio/LSF	#2 oil
B-14	**10**	HWB	0.50	200	0.70	20% Bio/LSF	#2 oil
B-15	**1**	StB	2.50	100	2.50	20% Bio/LSF	#2 oil
B-16	**1**	StB	2.50	150	3.10	20% Bio/LSF	#2 oil
B-17	**1**	StB	2.50	200	3.50	20% Bio/LSF	#2 oil
B-18	**22**	HWB	0.75	100	0.75	20% Bio/ #2 oil	#2 oil

NOTES: WAF: Warm Air Furnace; HWB: Hot Water Boiler
StB: Steam Boiler; Bio: Soy-based Biodiesel fuel
LSF: low sulfur (0.05%) Home Heating Oil

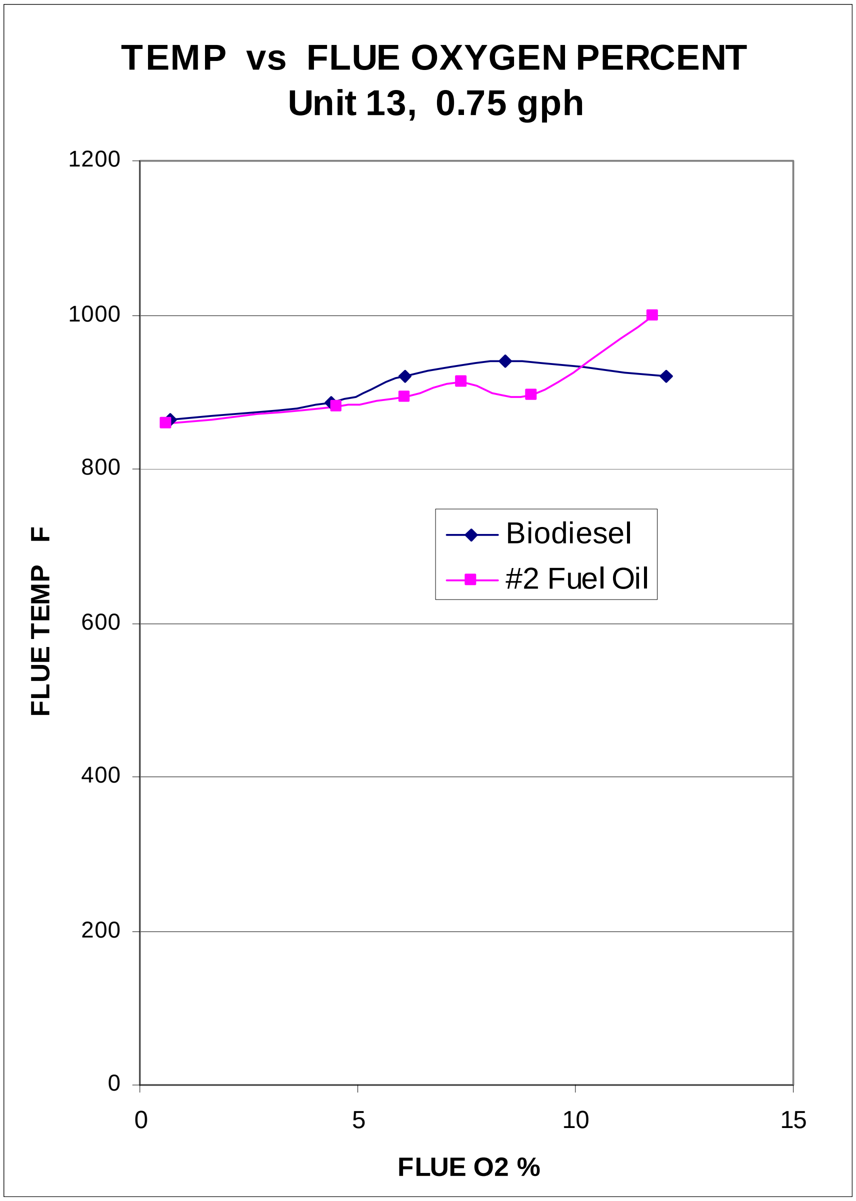
Attachment B-1a: Test Unit #13, 0.75 gph



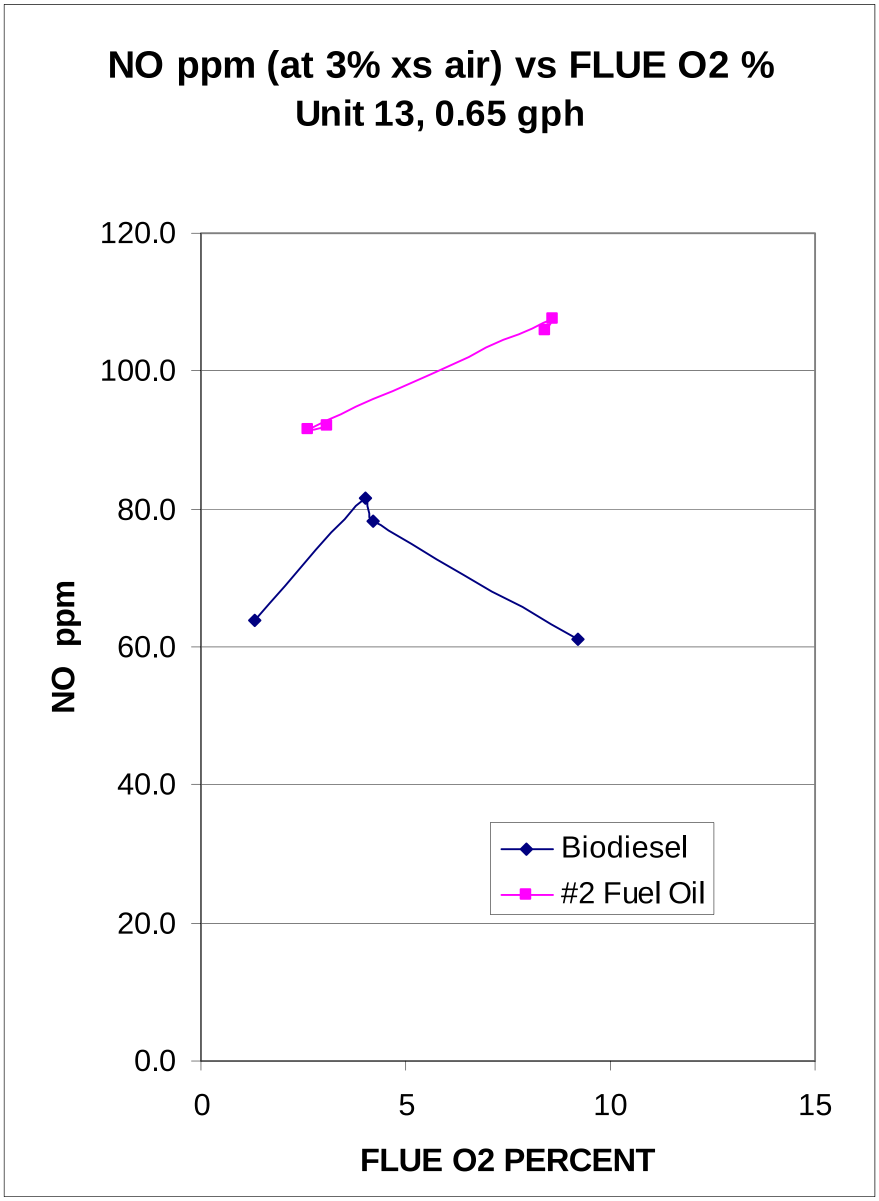
Attachment B-1b: Test Unit #13



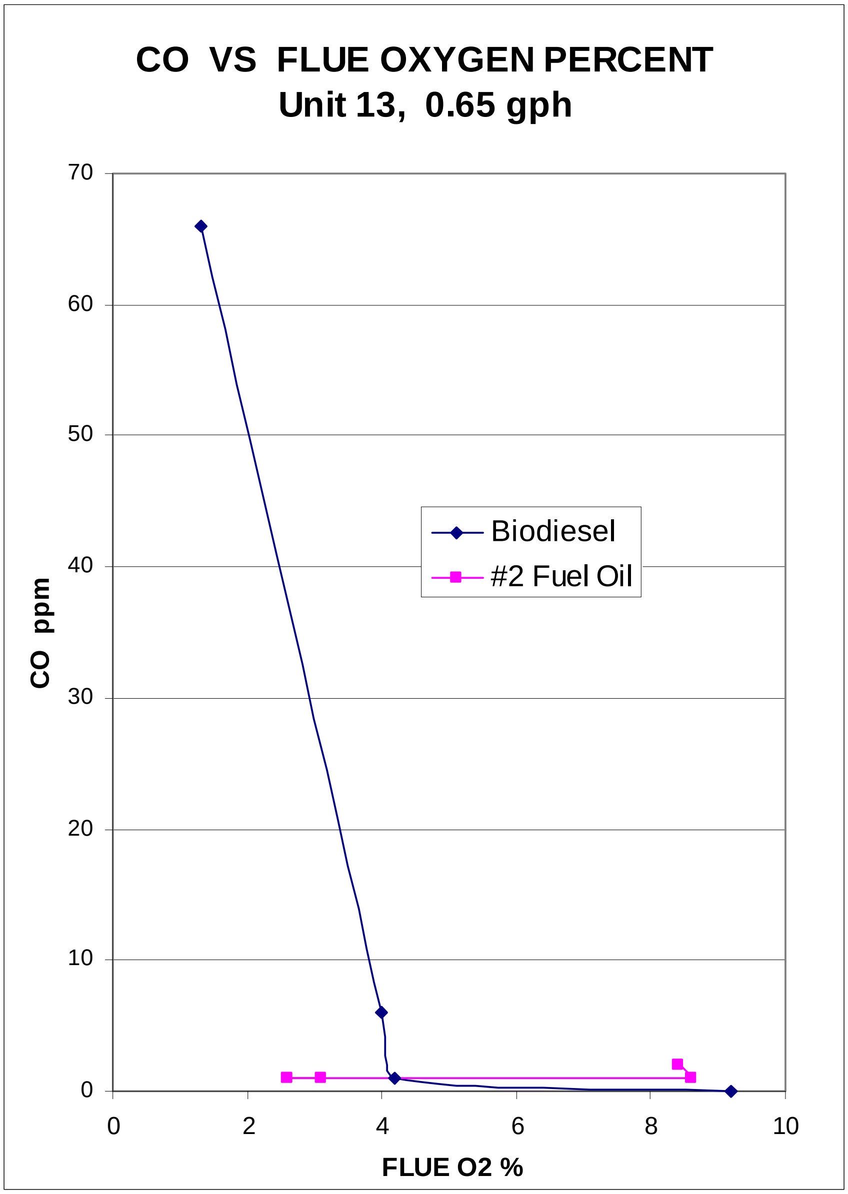
Attachment B-1c: Test Unit #13



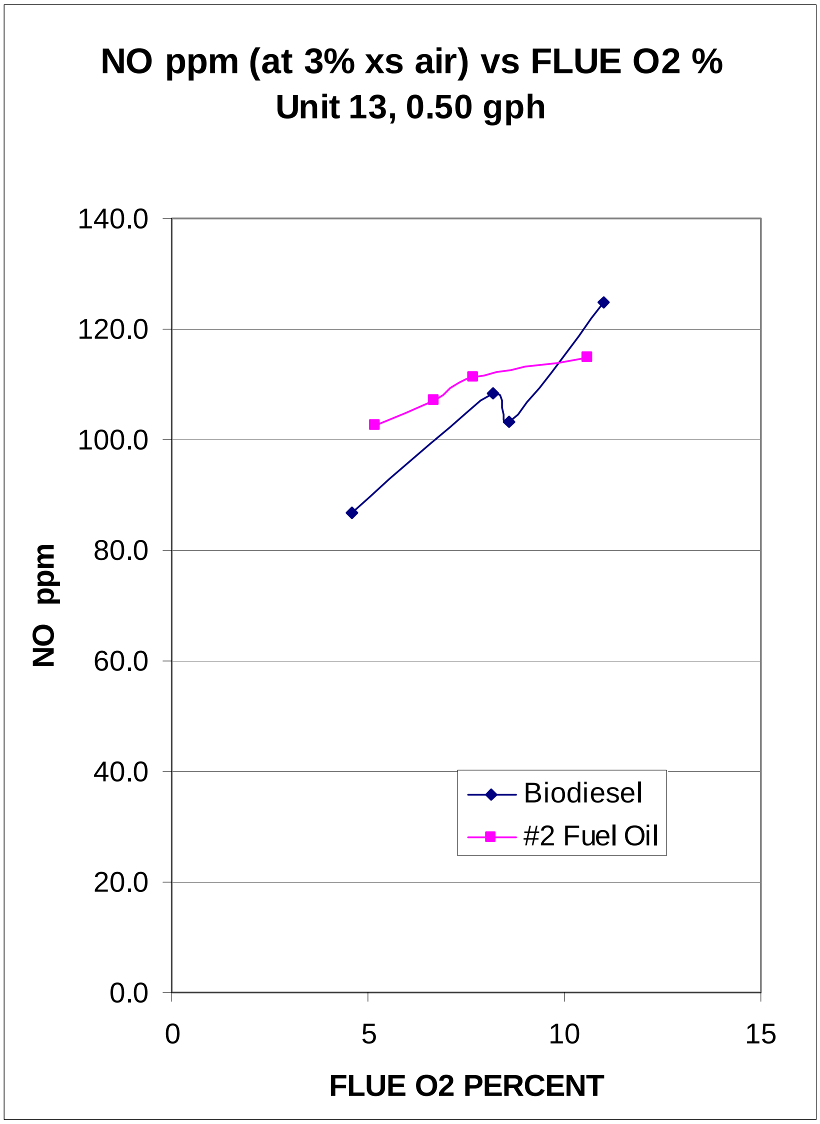
Attachment B-2a: Test Unit #13, 0.65 gph



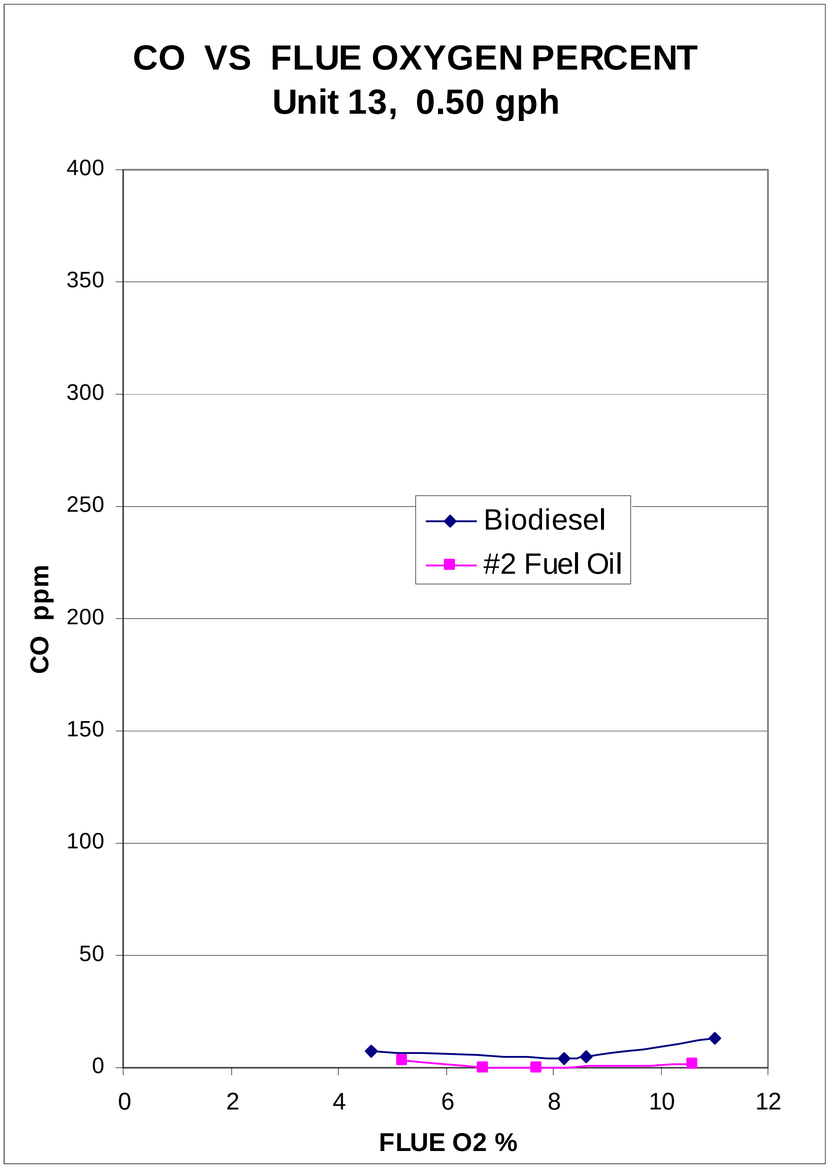
Attachment B-2b: Test Unit #13



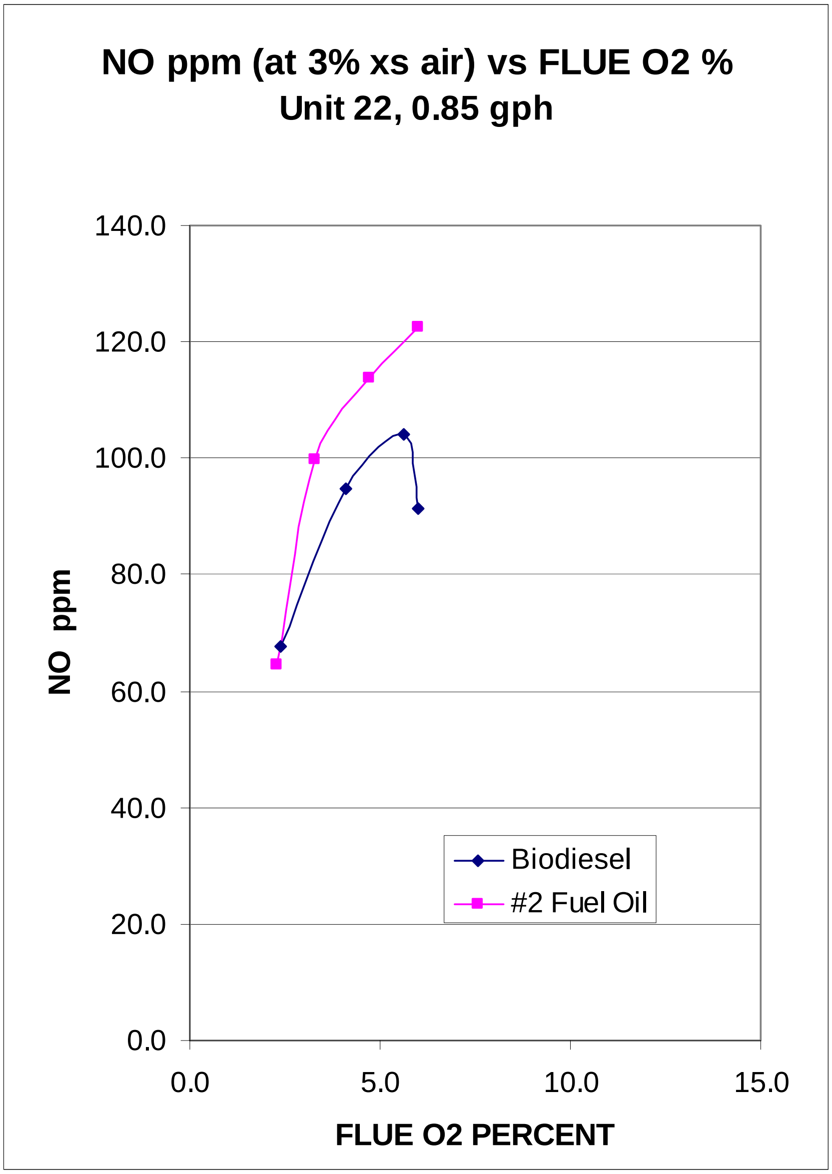
Attachment B-3a: Test Unit #13, 0.50 gph



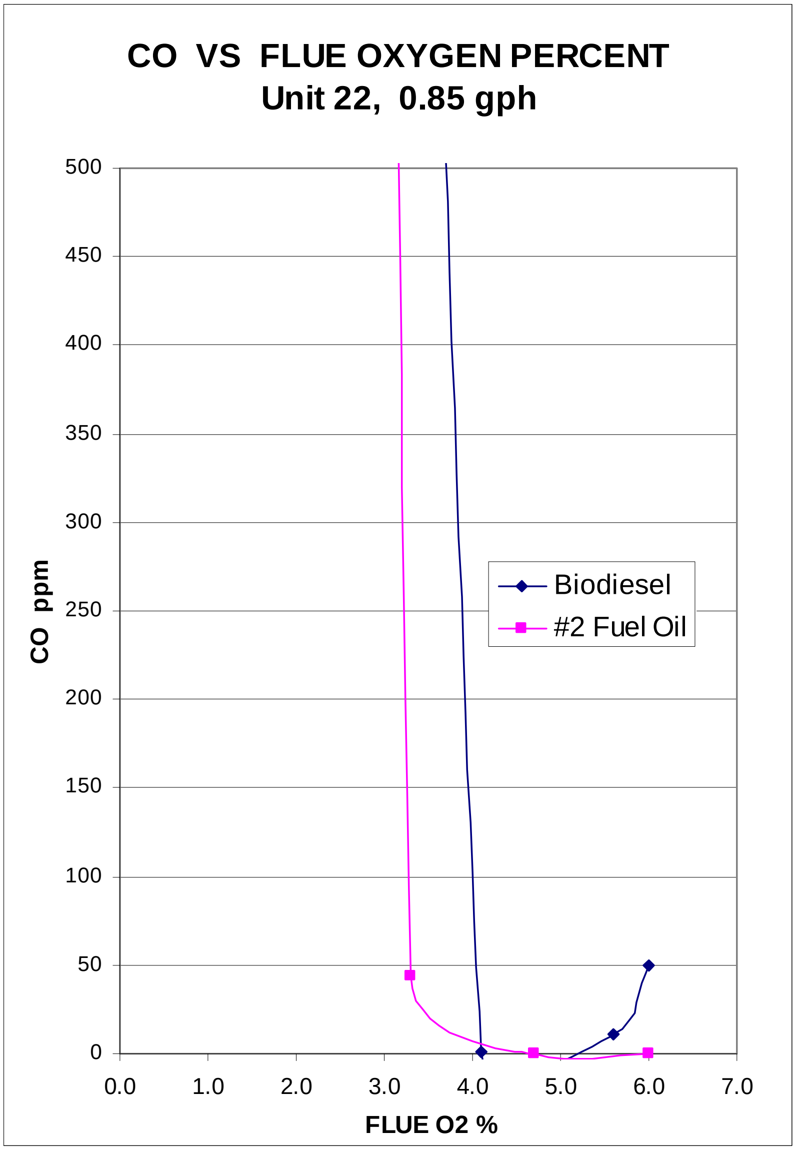
Attachment B-3b: Test Unit #13, 0.50 gph



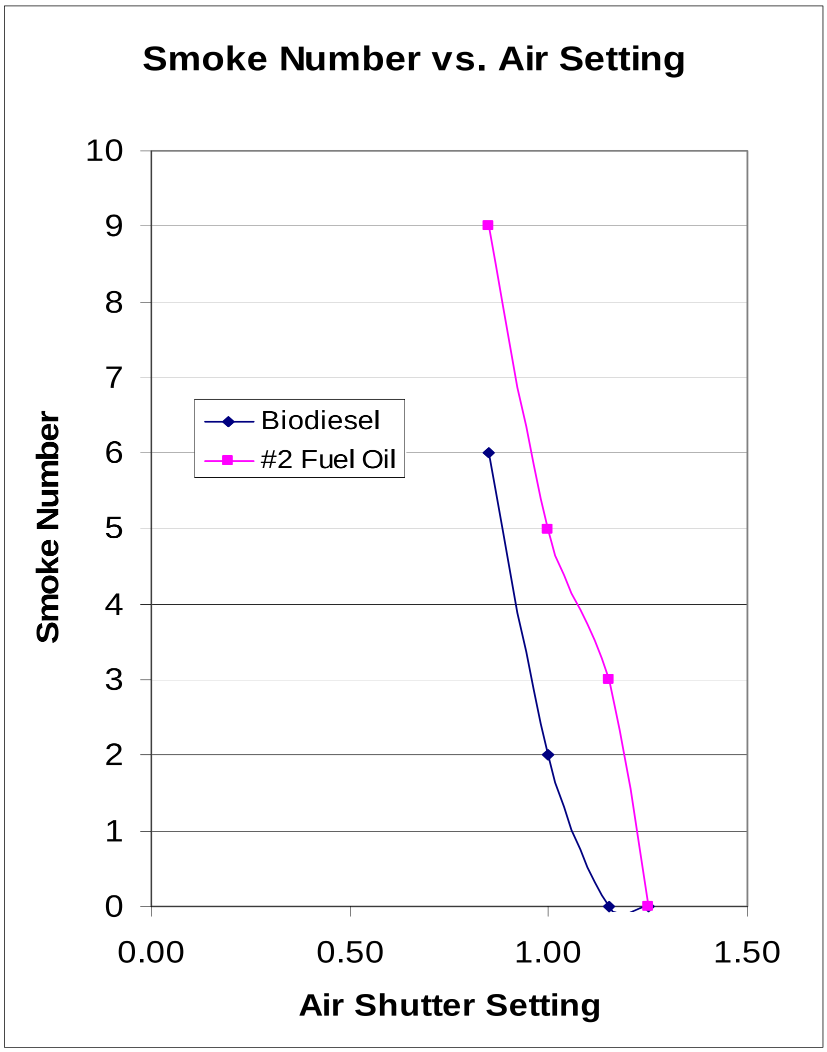
Attachment B-4a: Test Unit #22, 0.85 gph



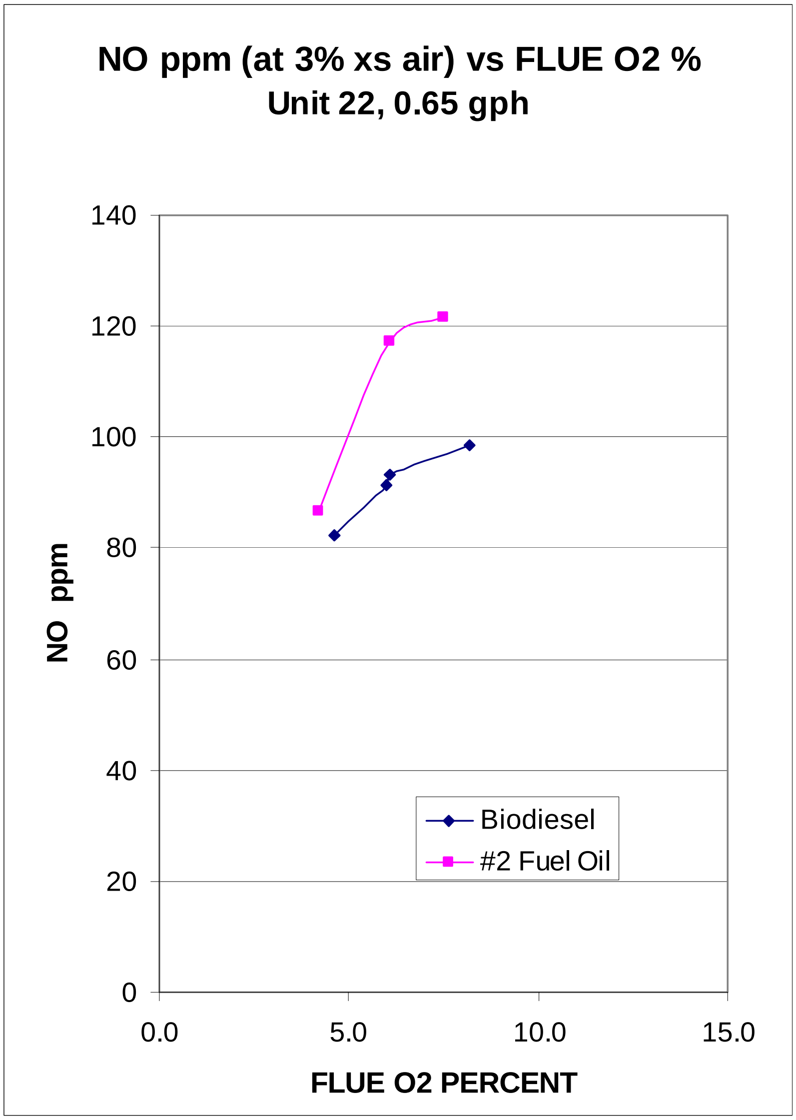
Attachment B-4b: Test Unit #22, 0.85 gph



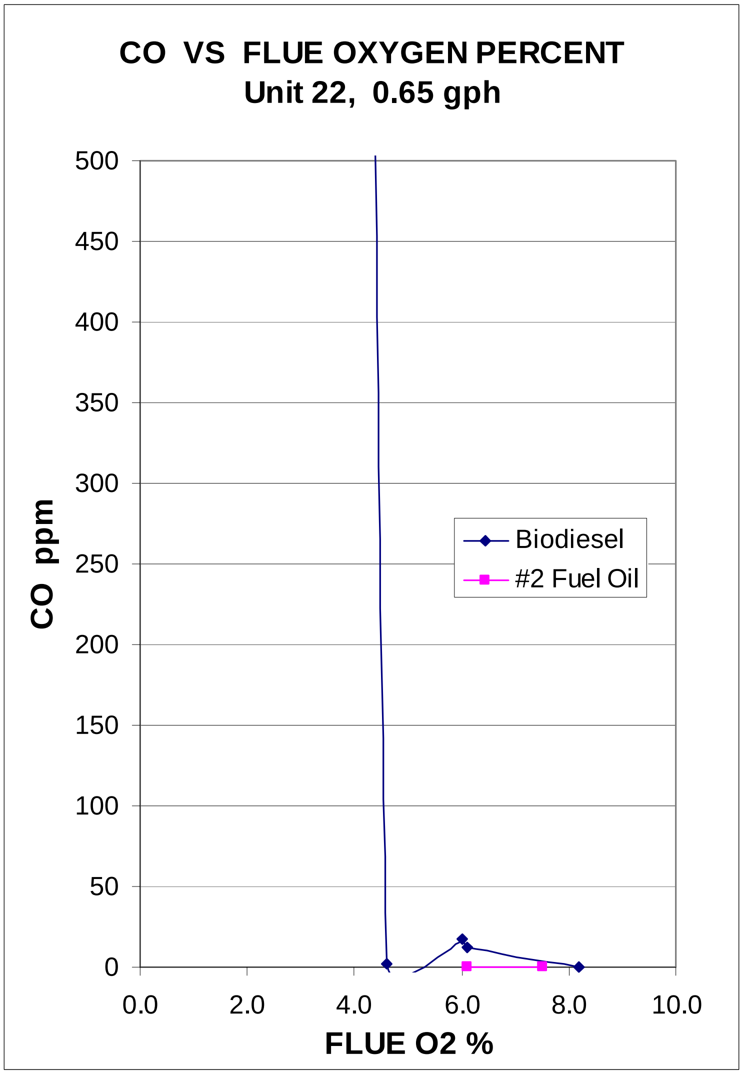
Attachment B-4c: Test Unit #22, 0.85 gph



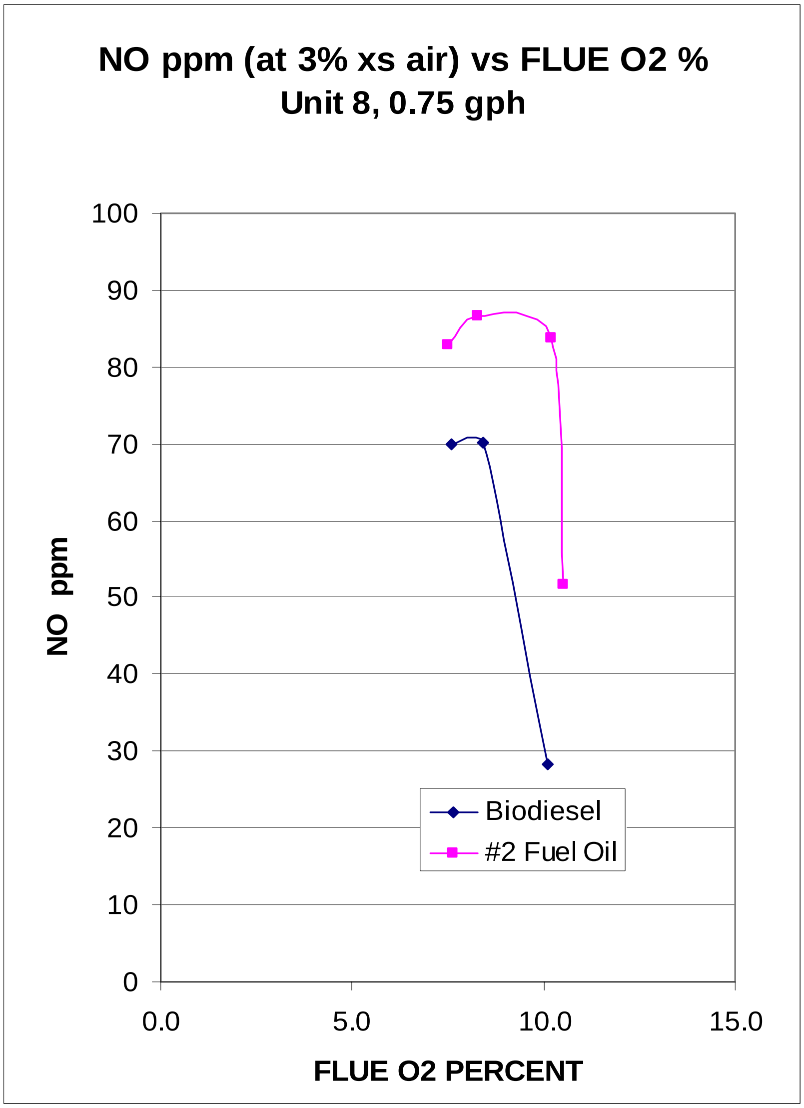
Attachment B-5a: Test Unit #22, 0.65 gph



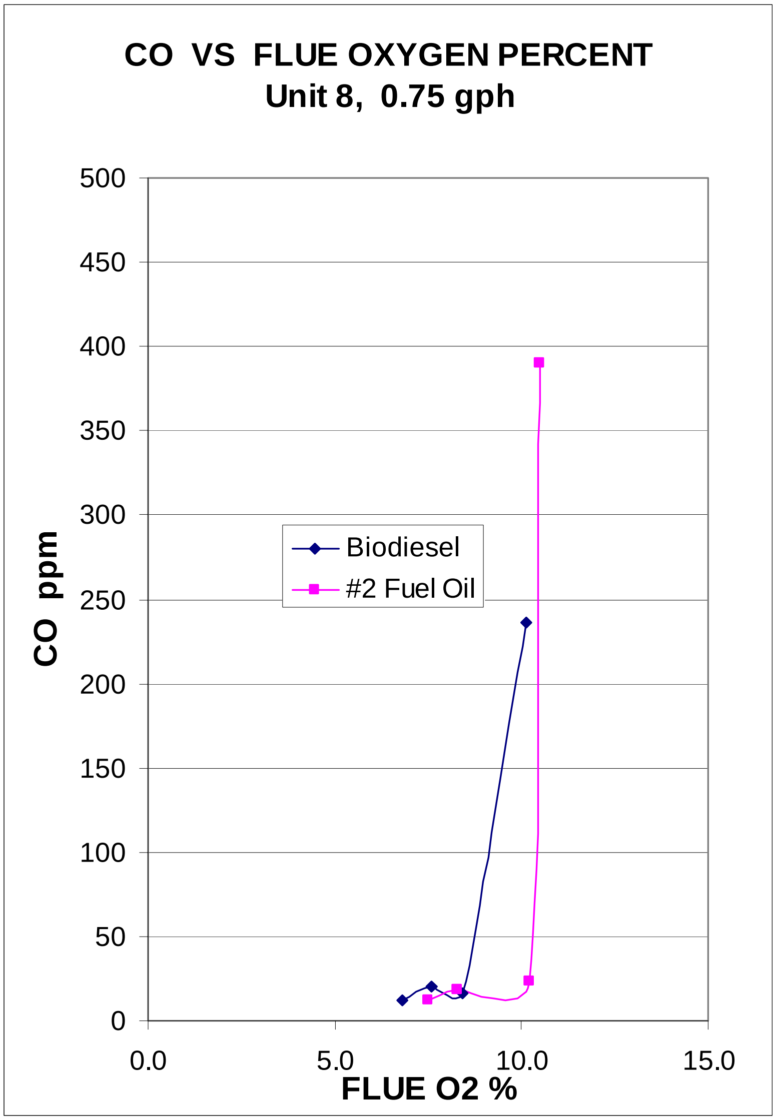
Attachment B-5b: Test Unit #22, 0.65 gph



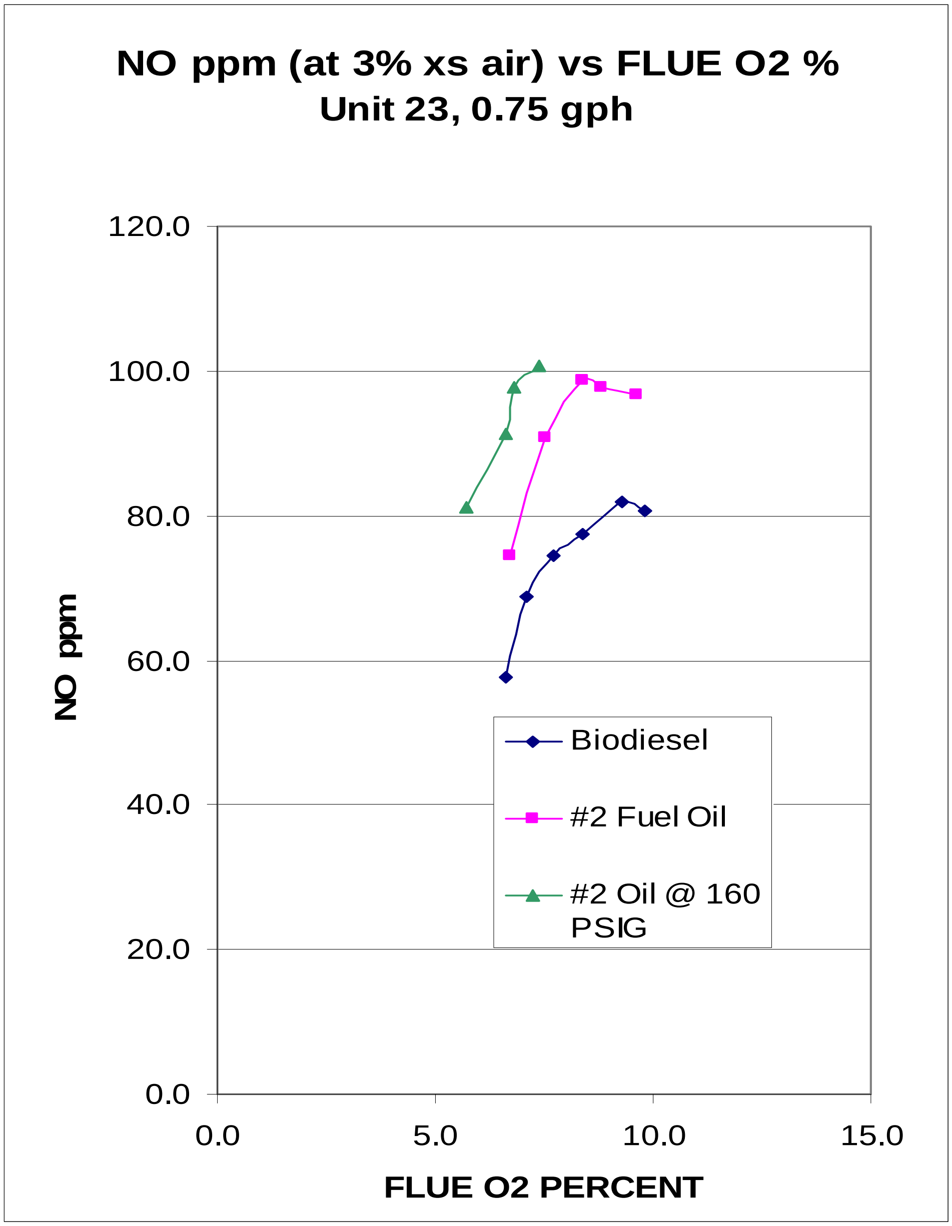
Attachment B-6a: Test Unit #8, 0.65 gph



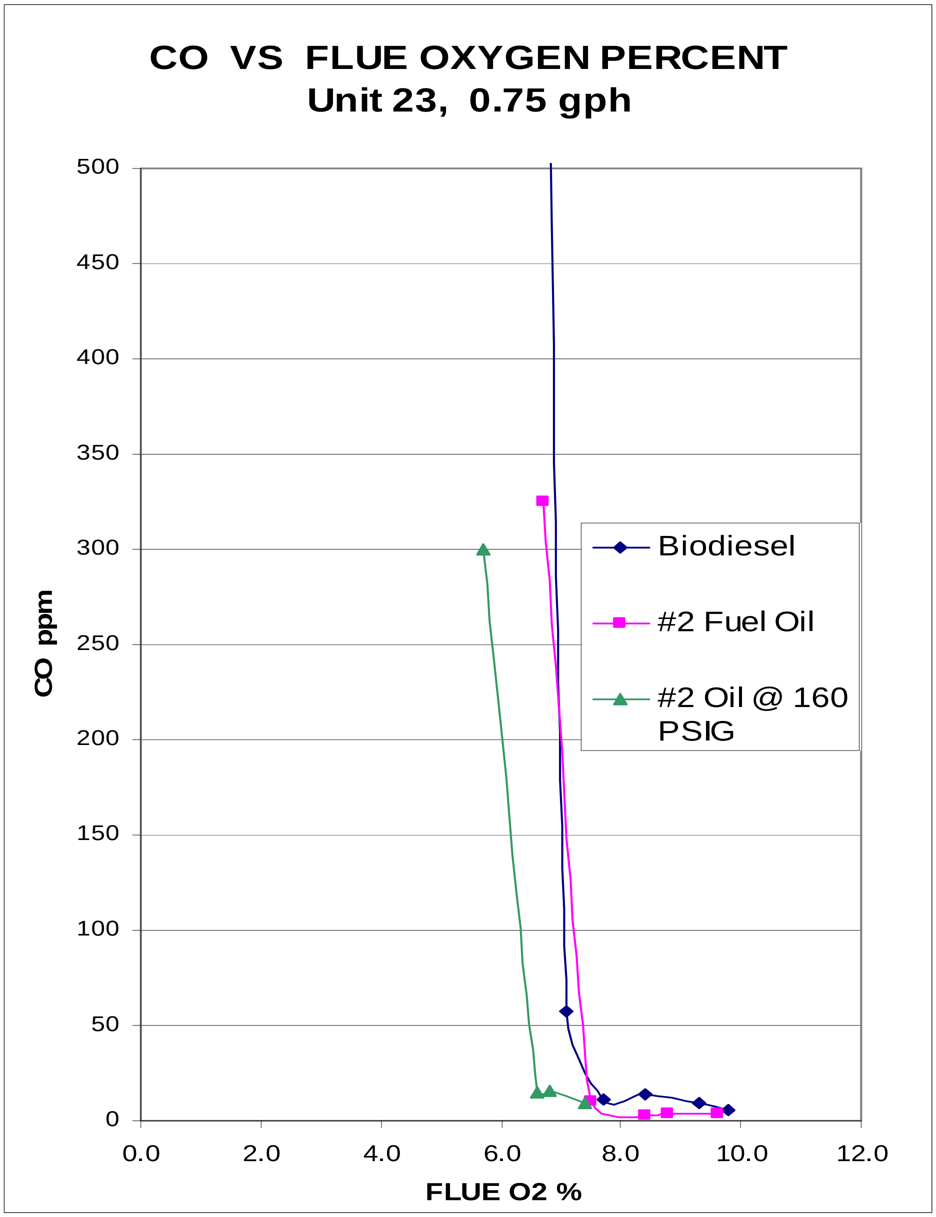
Attachment B-6b: Test Unit #8, 0.65 gph



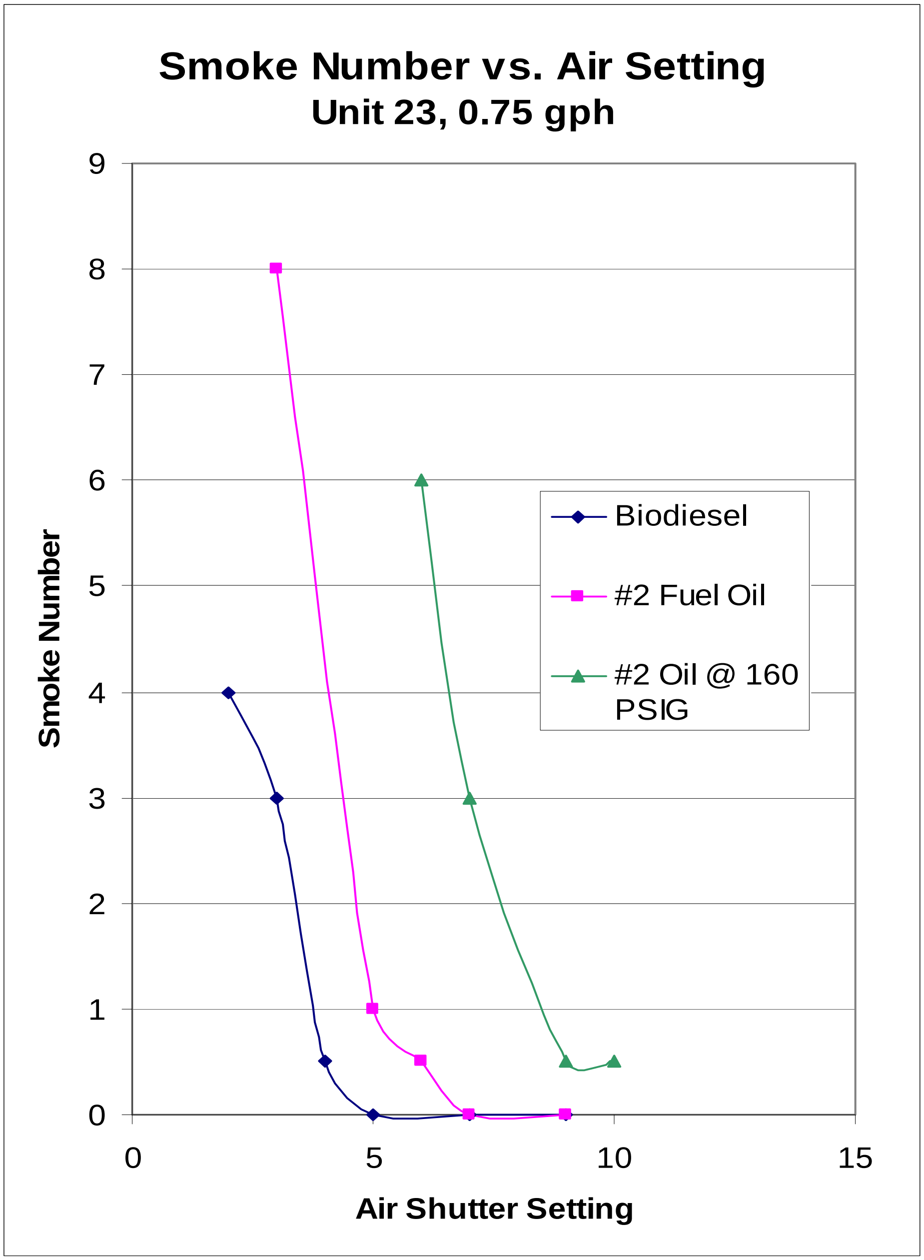
Attachment B-7a: Test Unit #23, 0.75 gph



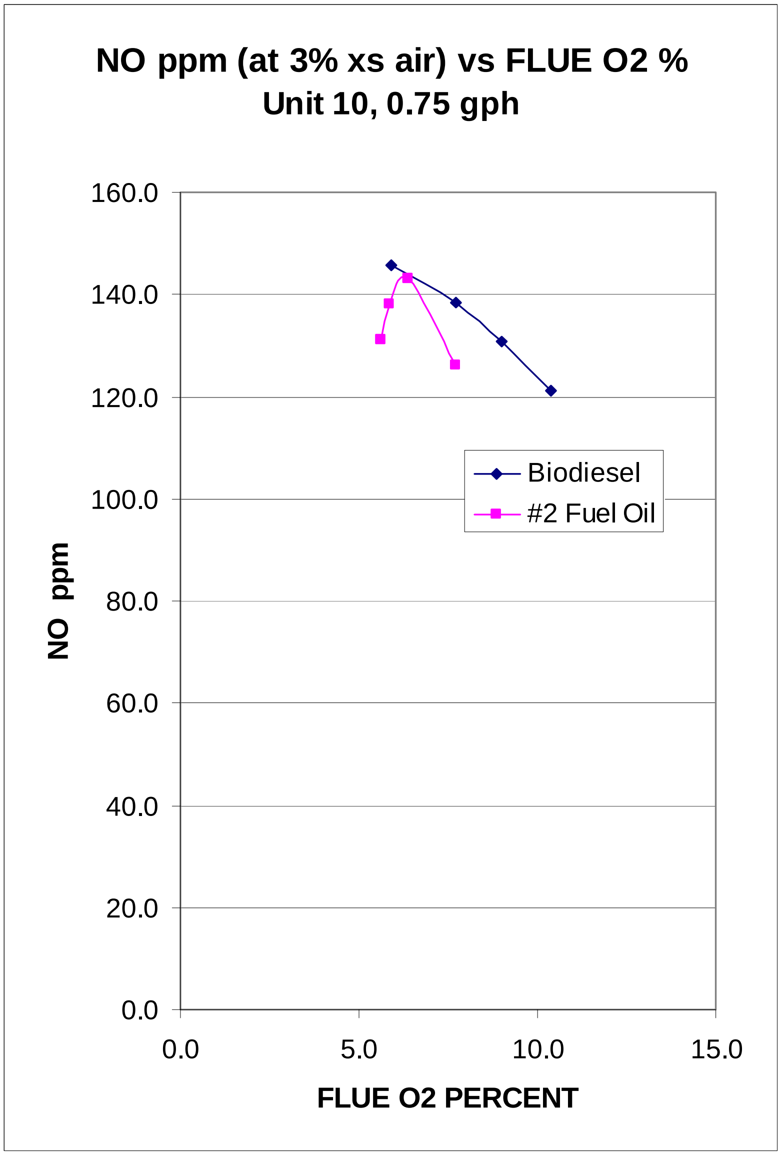
Attachment B-7b: Test Unit #23, 0.75 gph



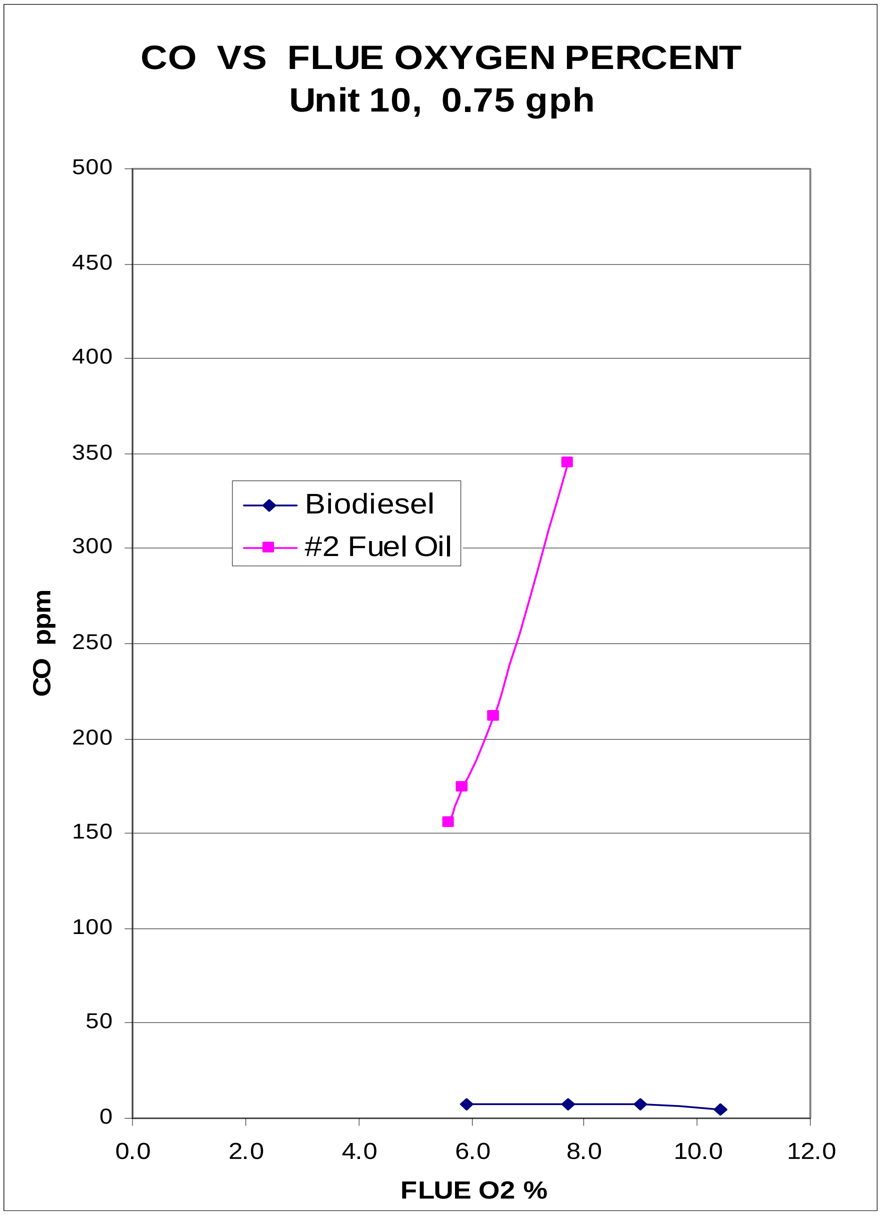
Attachment B-7c: Test Unit #23, 0.75 gph



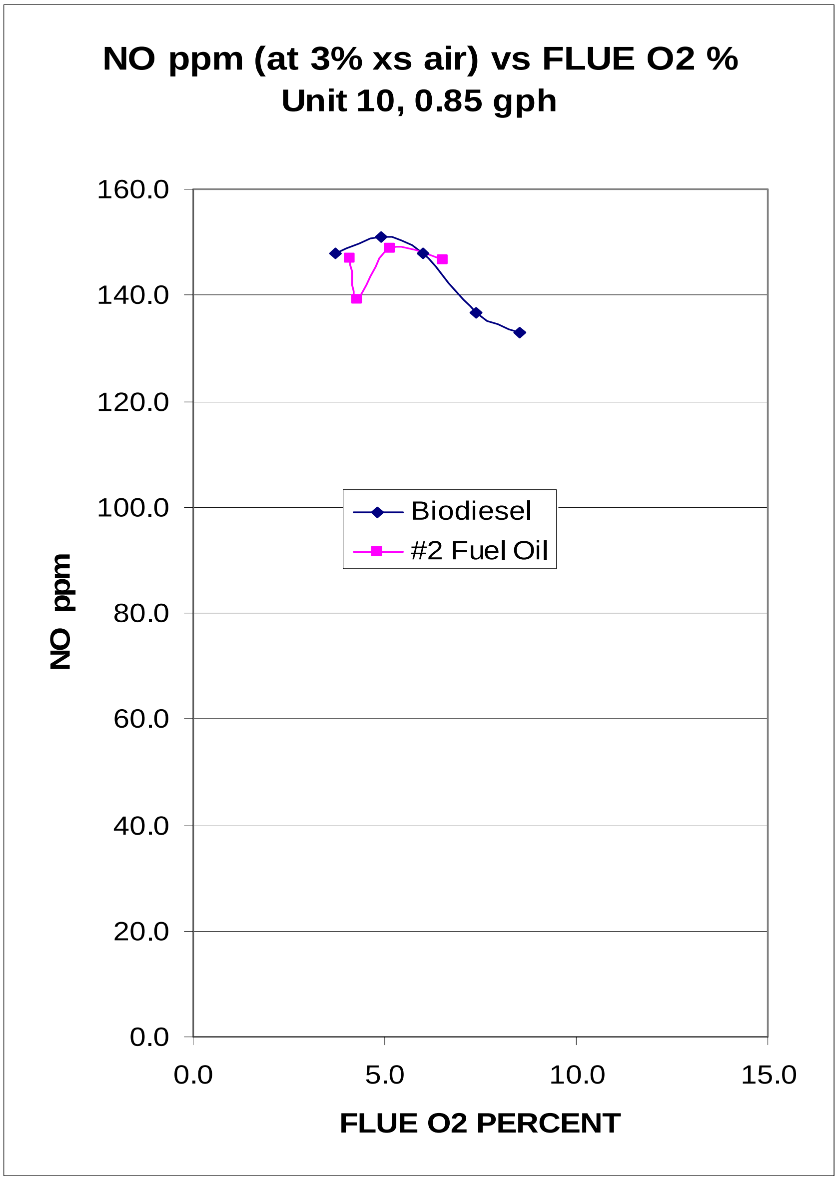
Attachment B-8a: Test Unit #10, 0.75 gph



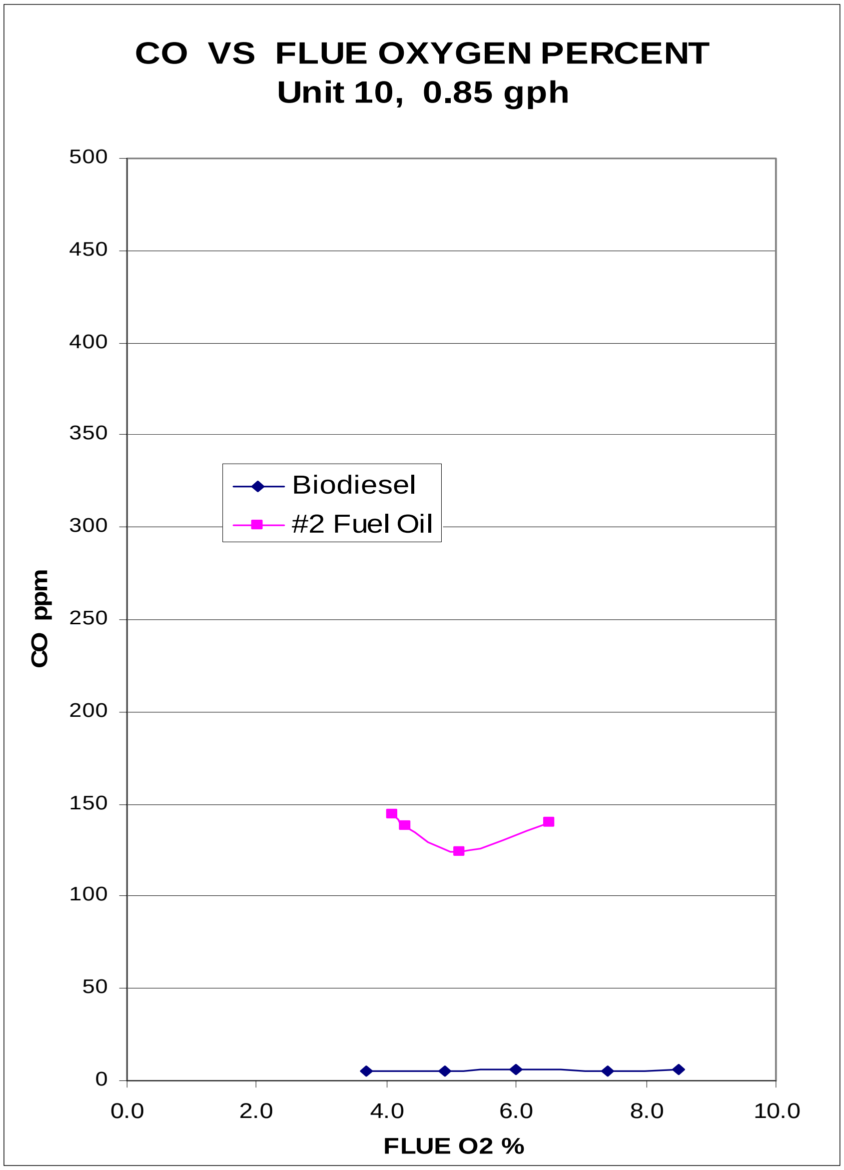
Attachment B-8b: Test Unit #10, 0.75 gph



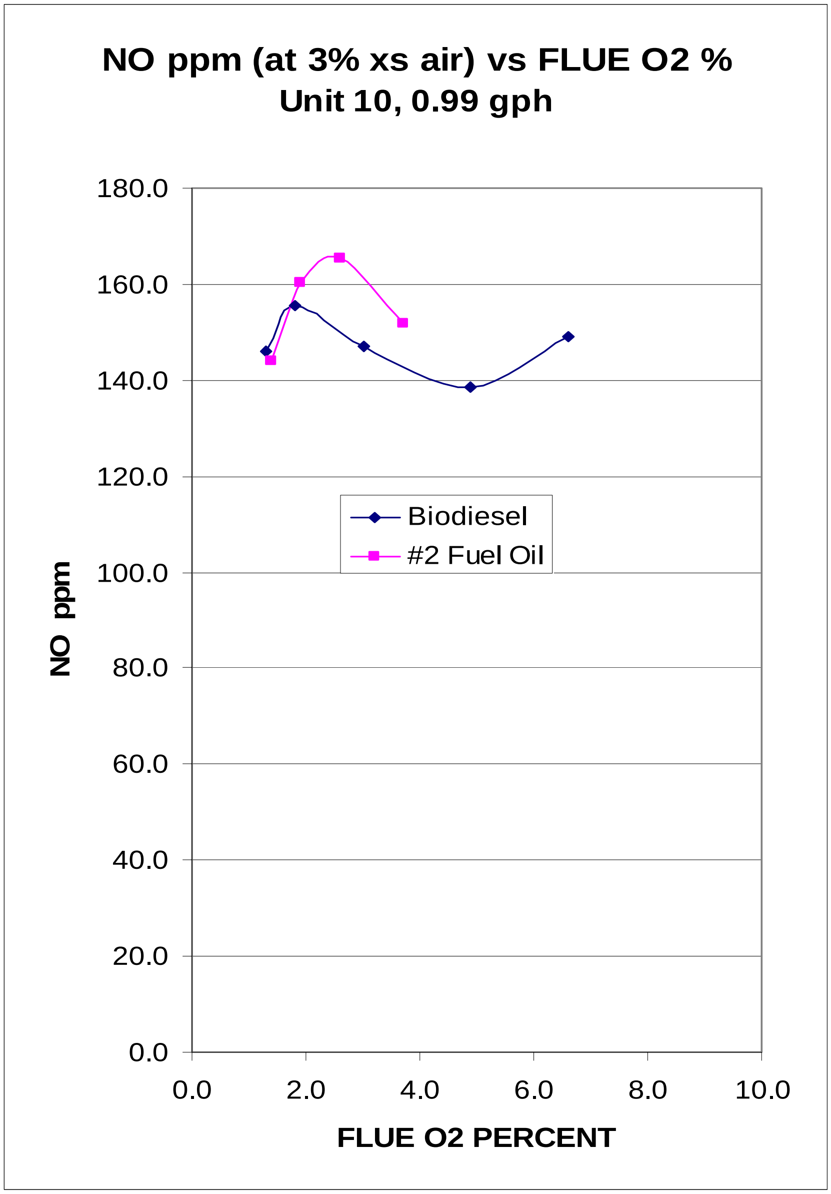
Attachment B-9a: Test Unit #10, 0.75 gph Nozzle at 130 psig



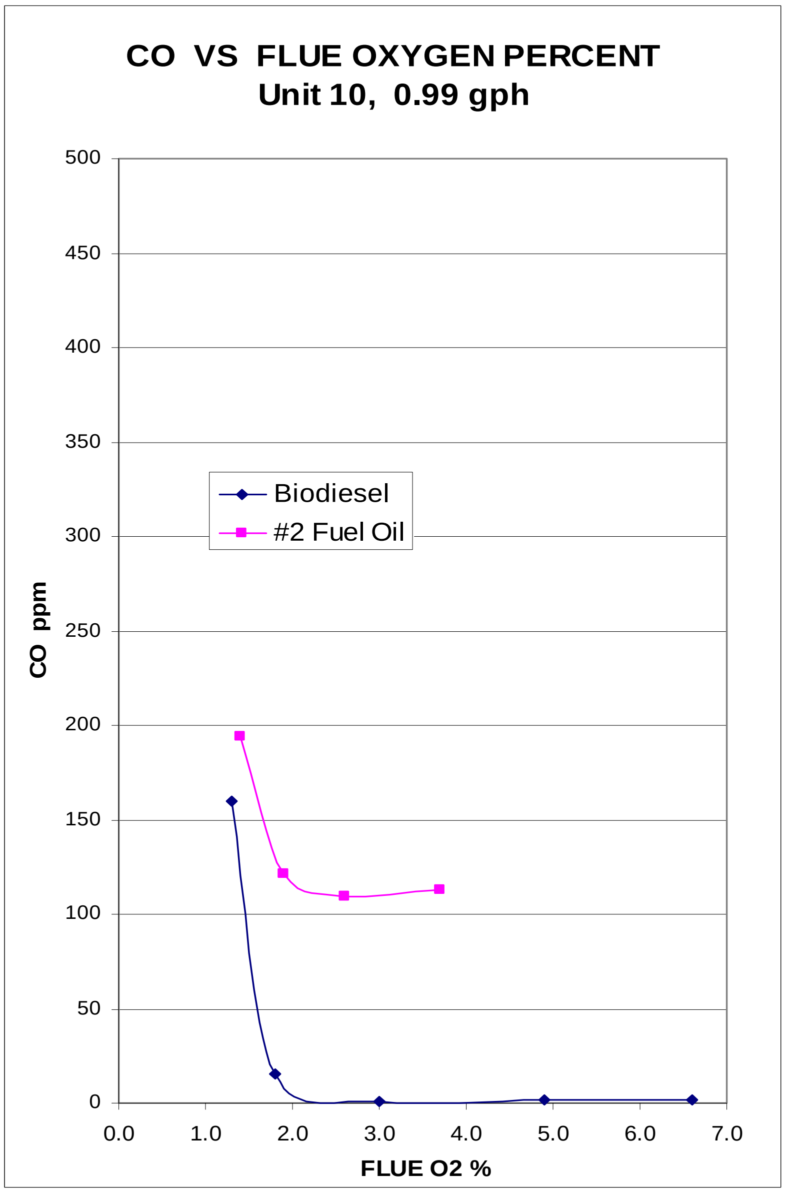
Attachment B-9b: Test Unit #10, 0.75 gph Nozzle at 130 psig



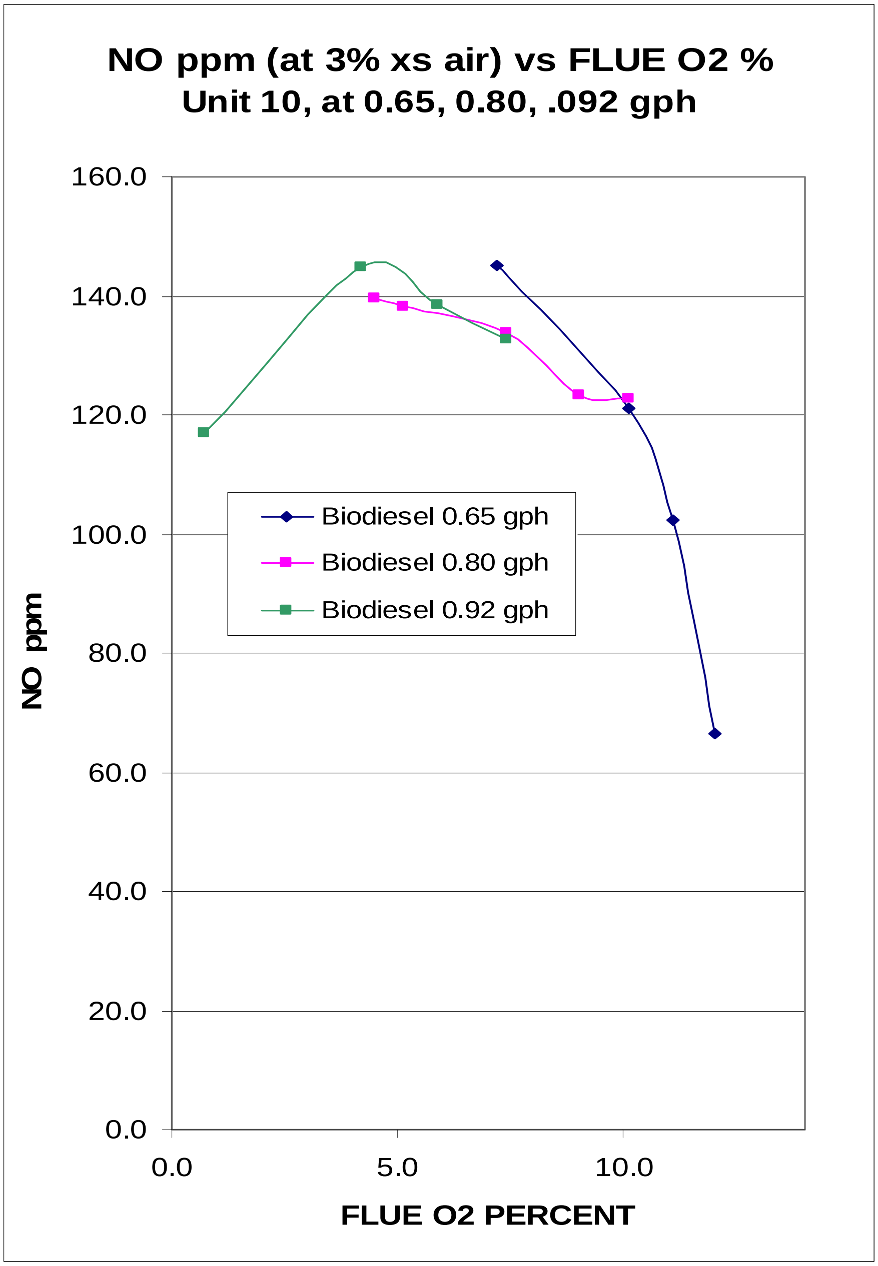
Attachment B-10a: Test Unit #10, 0.75 gph Nozzle at 175 psig



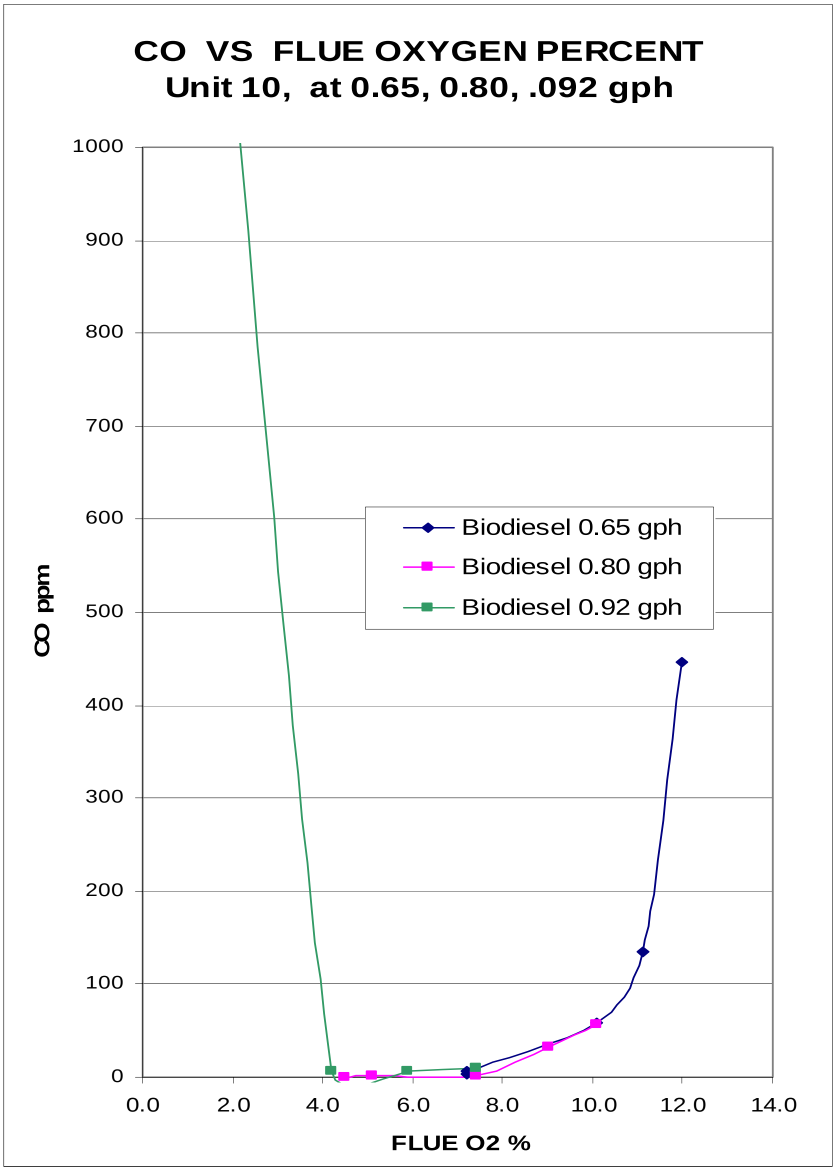
Attachment B-10b: Test Unit #10, 0.75 gph Nozzle at 175 psig



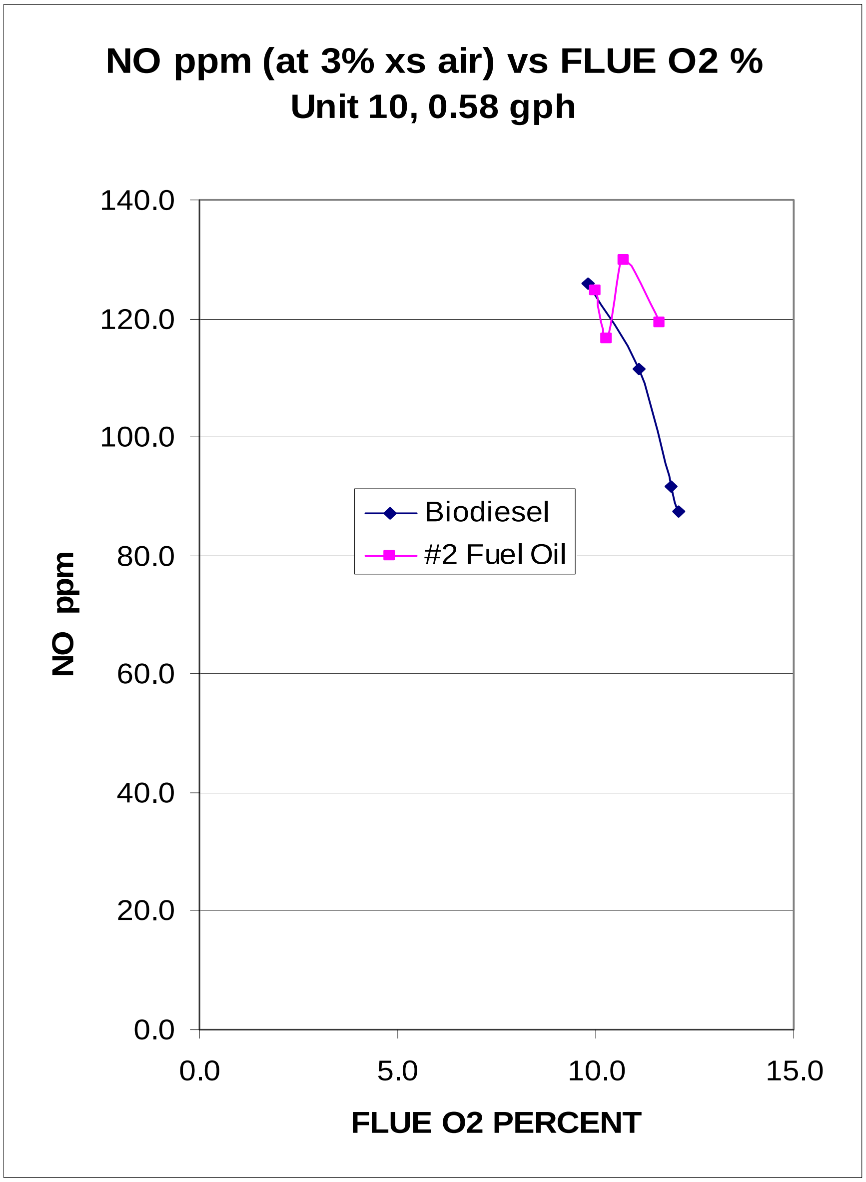
Attachment B-11a: Test Unit #10, 0.65 gph at 100/150/200 psig



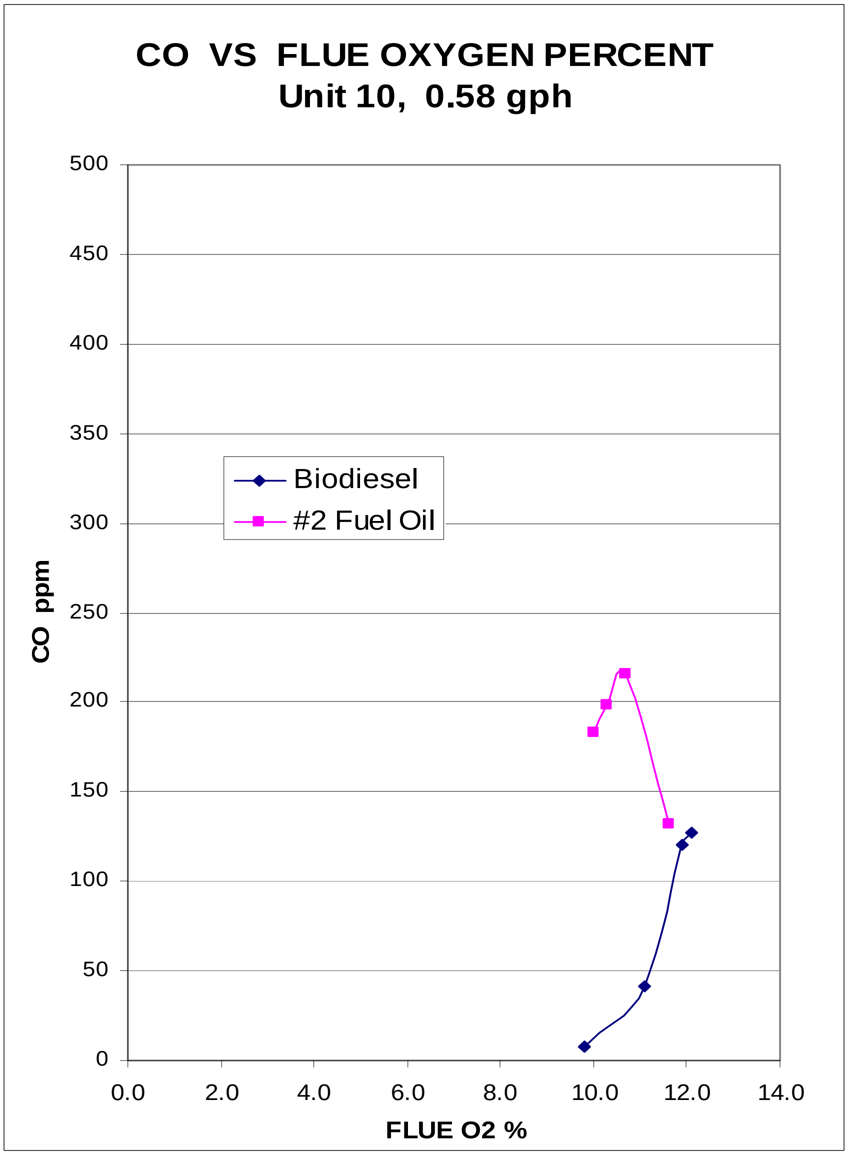
Attachment B-11b: Test Unit #10, 0.65 gph at 100/150/200 psig



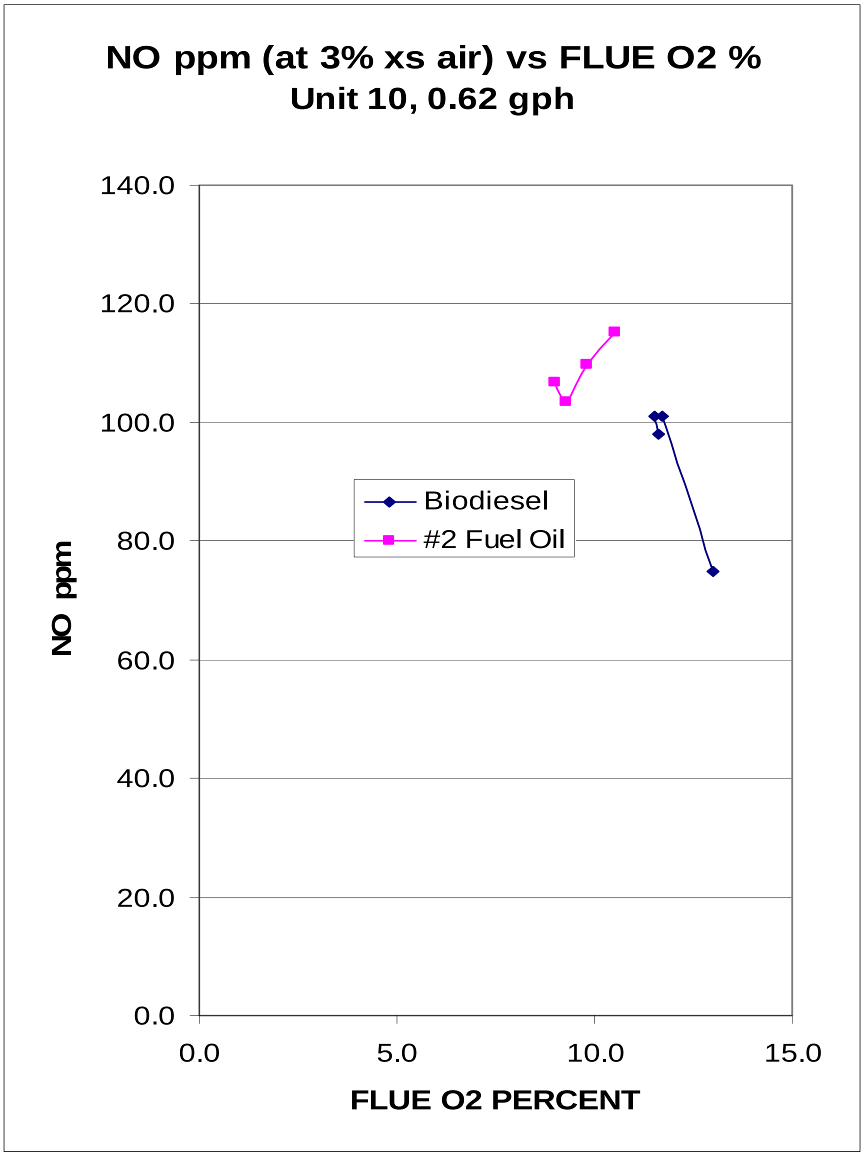
Attachment B-12a: Test Unit #10, 0.50 gph at 130 psig



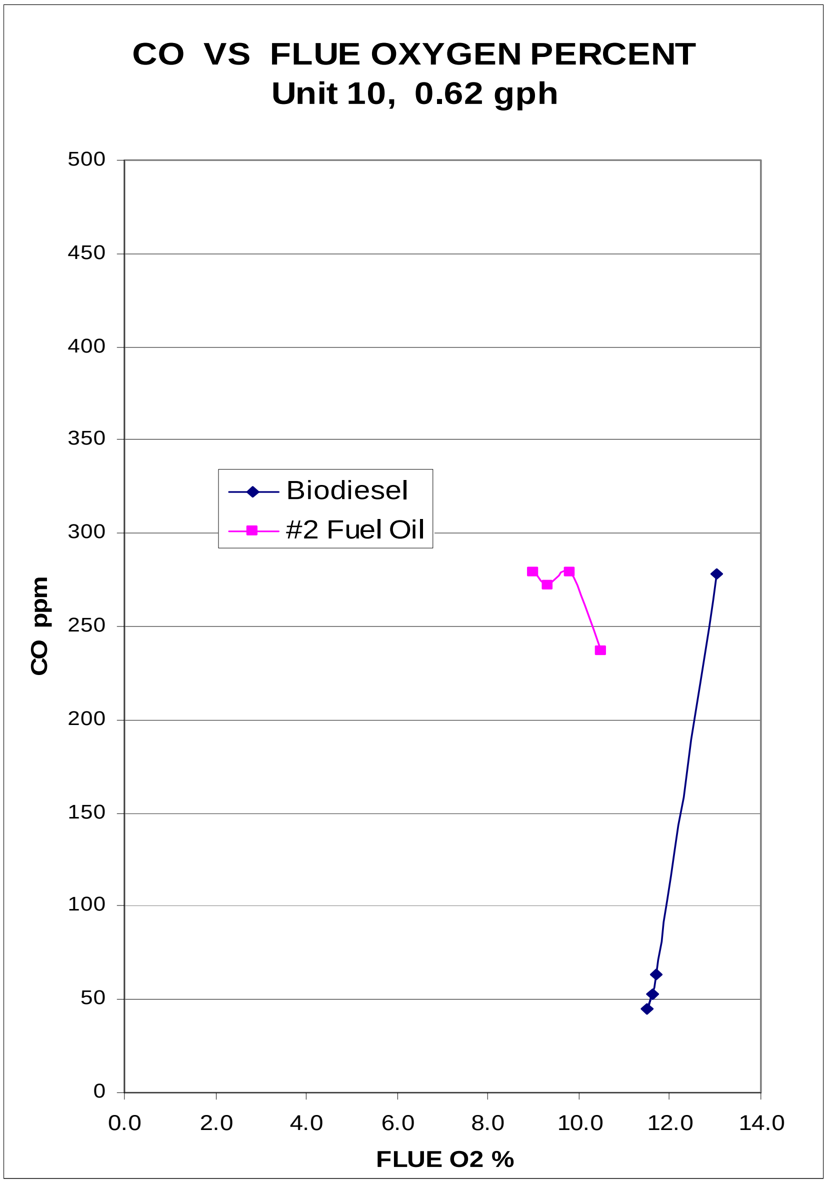
Attachment B-12b: Test Unit #10, 0.50 gph at 130 psig



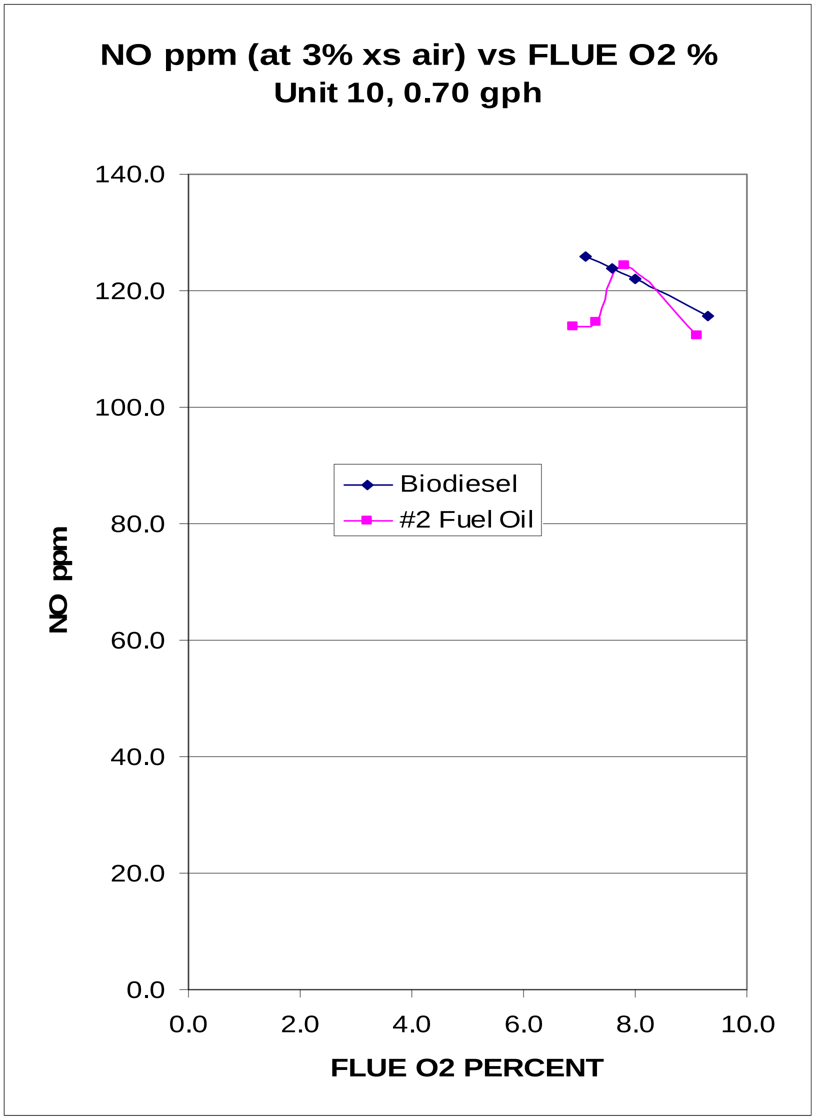
Attachment B-13a: Test Unit #10, 0.50 gph at 150 psig



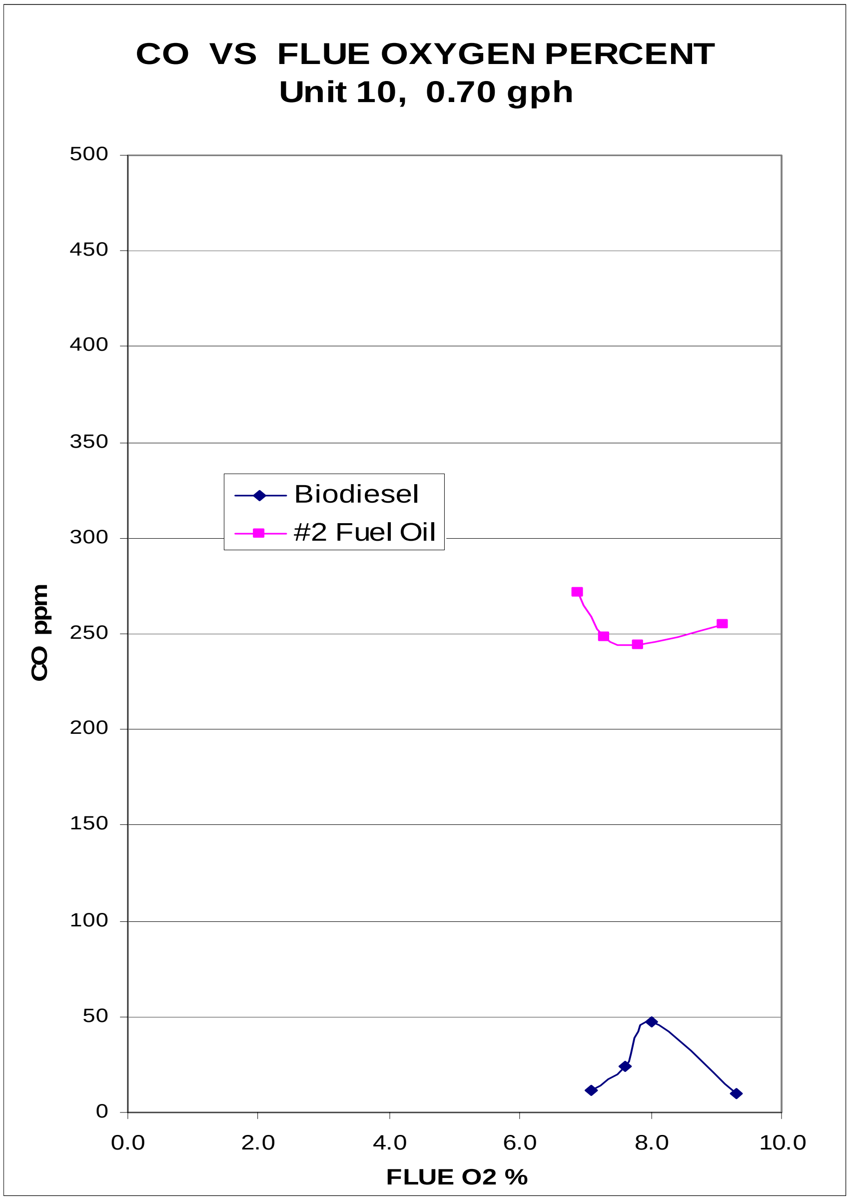
Attachment B-13b: Test Unit #10, 0.50 gph at 150 psig



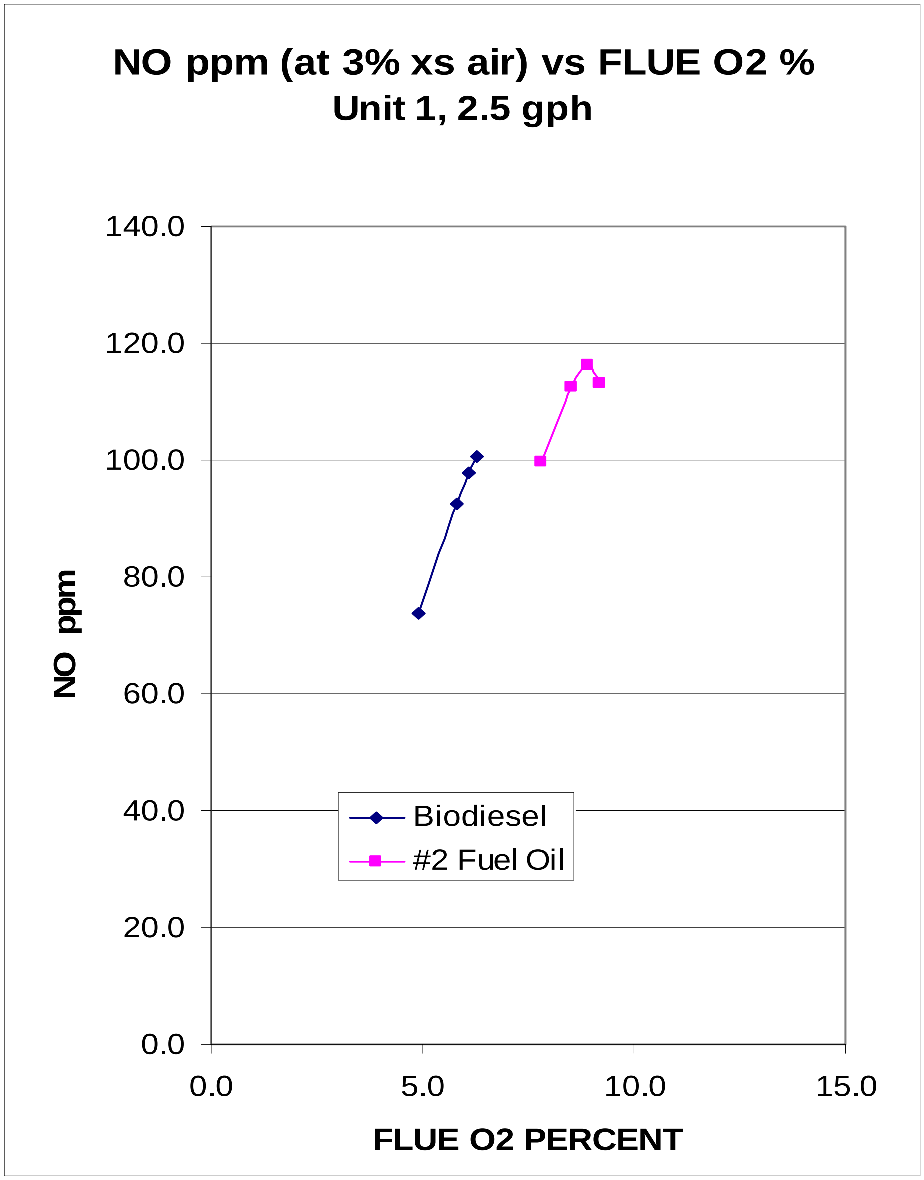
Attachment B-14a: Test Unit #10, 0.50 gph at 200 psig



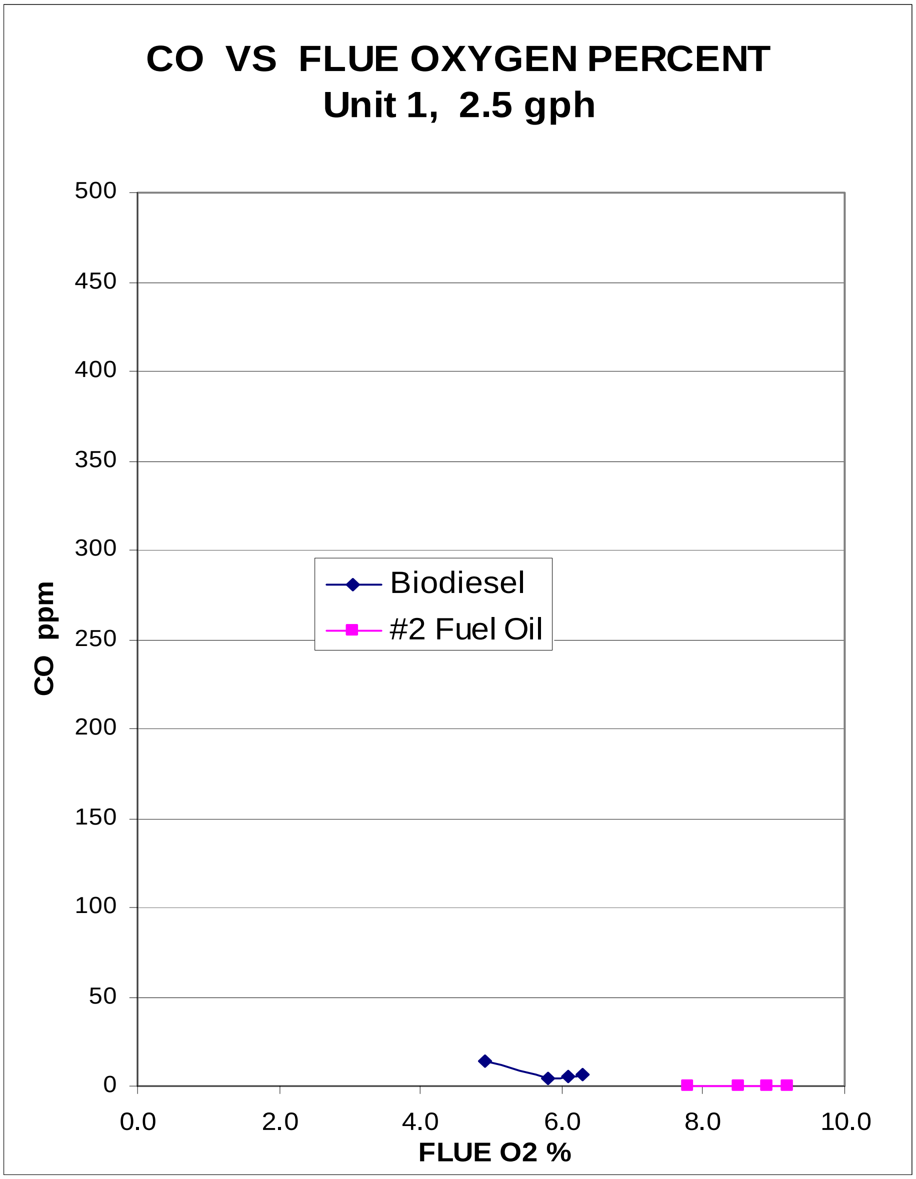
Attachment B-14b: Test Unit #10, 0.50 gph at 200 psig



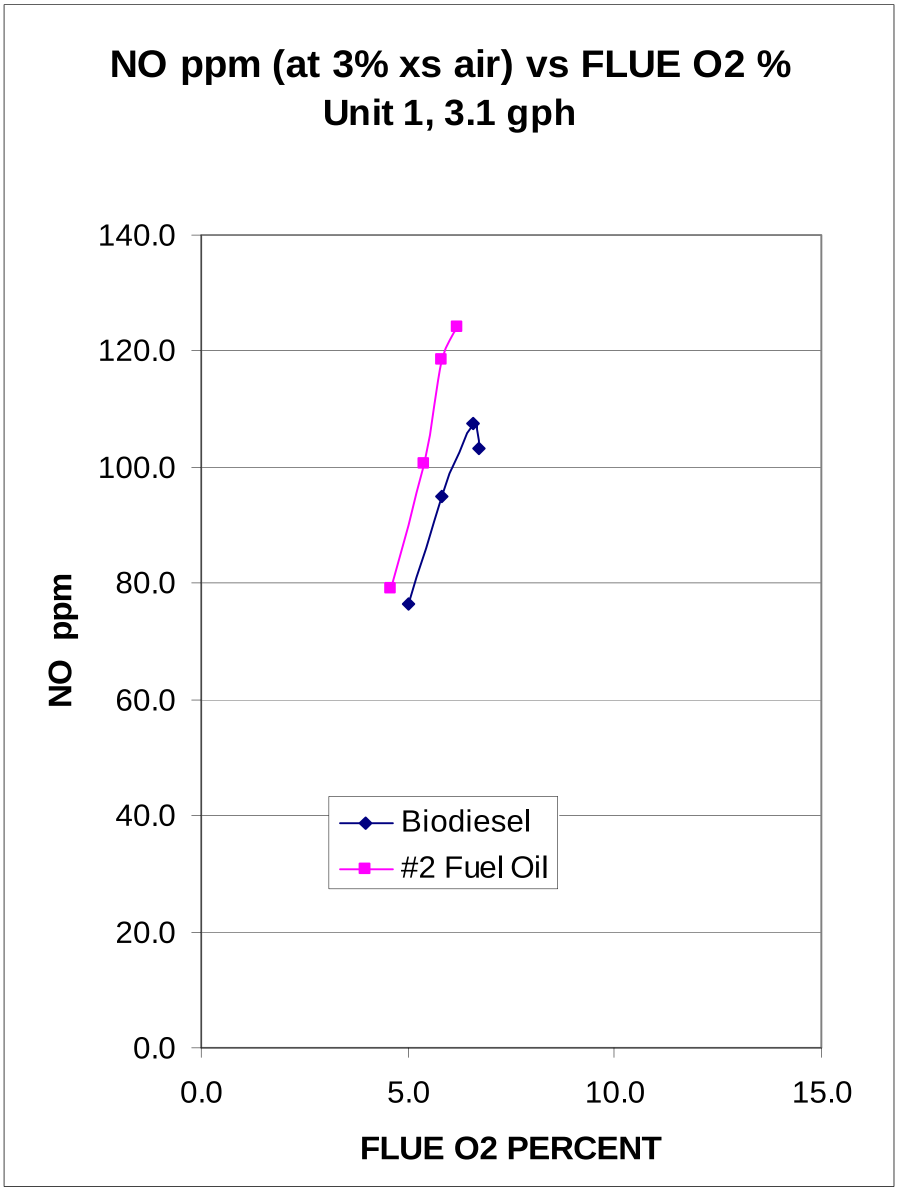
Attachment B-15a: Test Unit #1, 2.50 gph at 100 psig



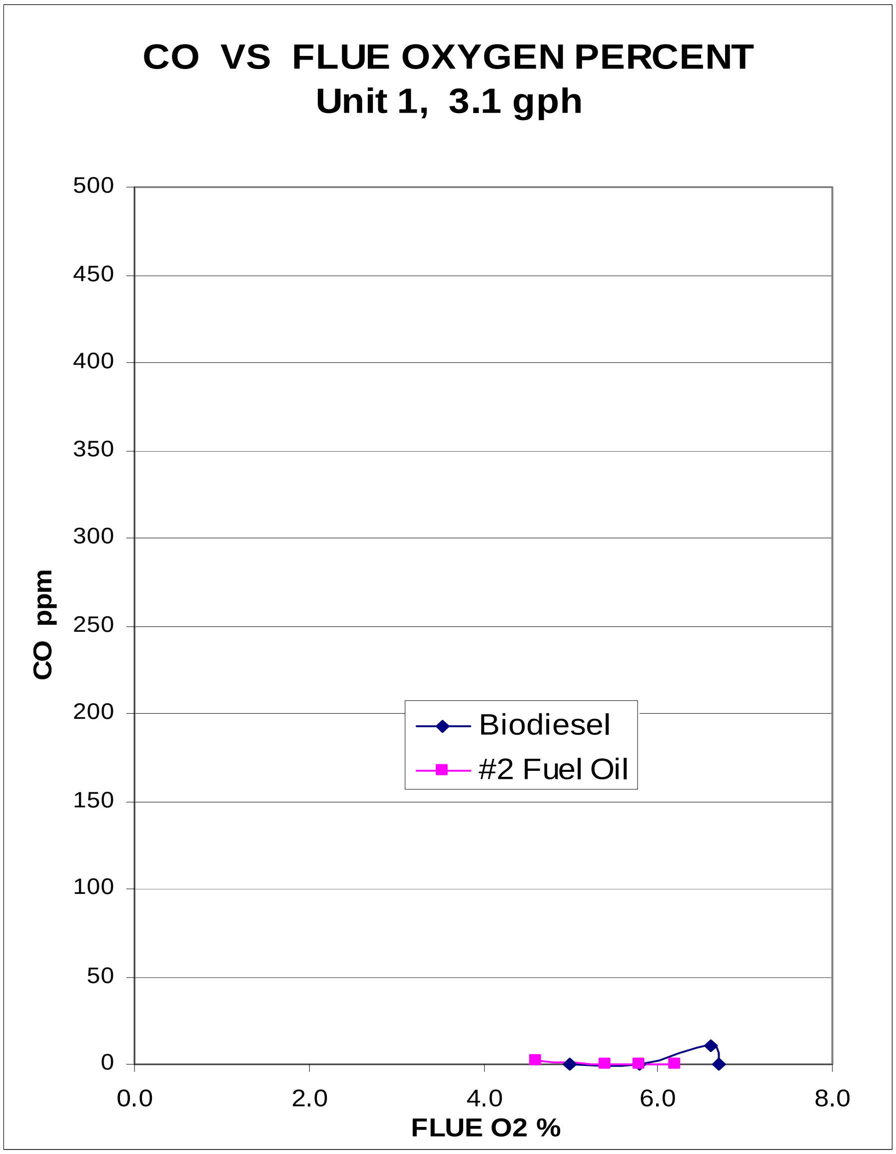
Attachment B-15b: Test Unit #1, 2.50 gph at 100 psig



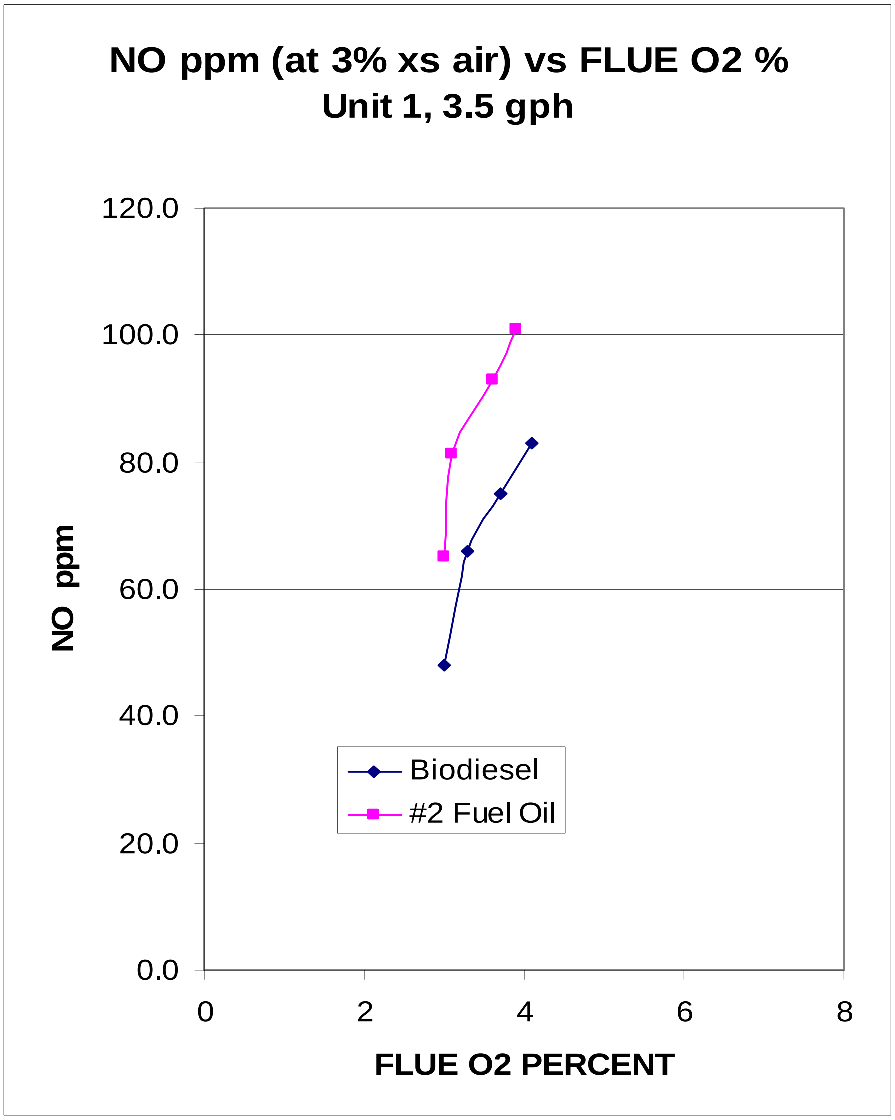
Attachment B-16a: Test Unit #1, 2.50 gph at 150 psig



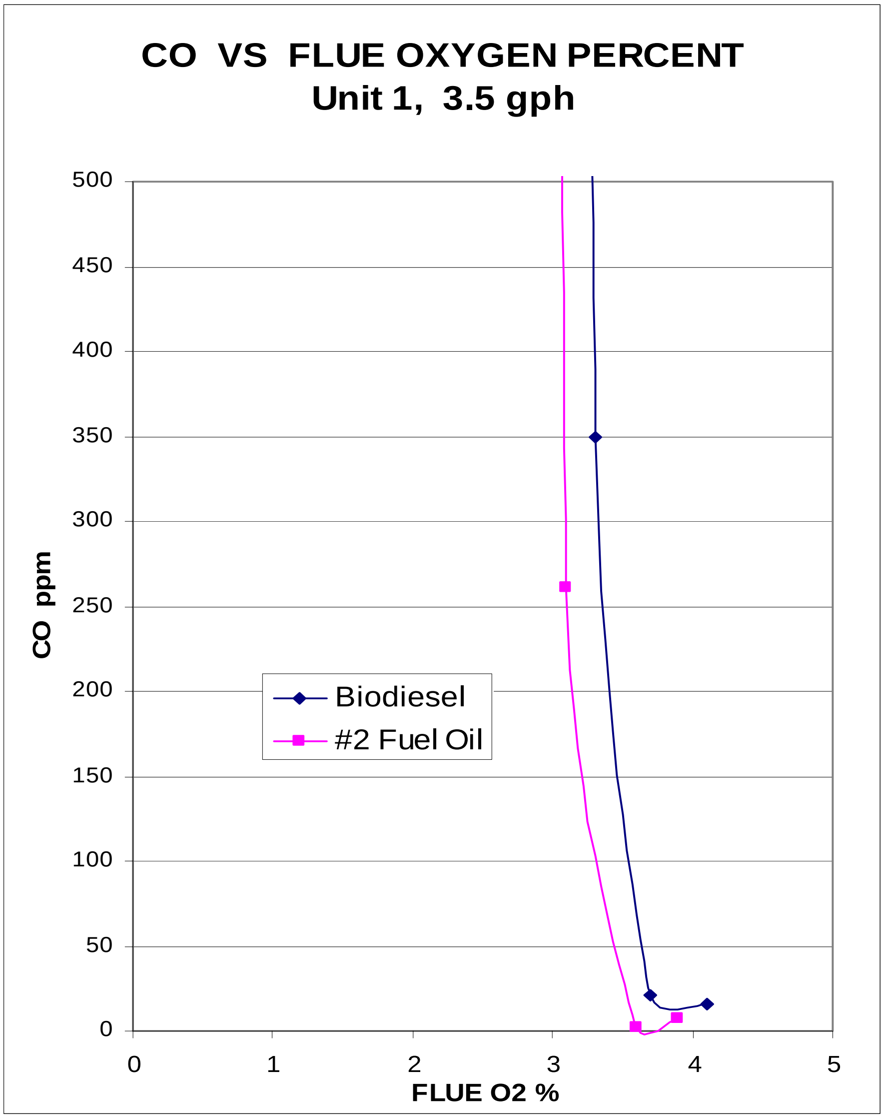
Attachment B-16b: Test Unit #1, 2.50 gph at 150 psig



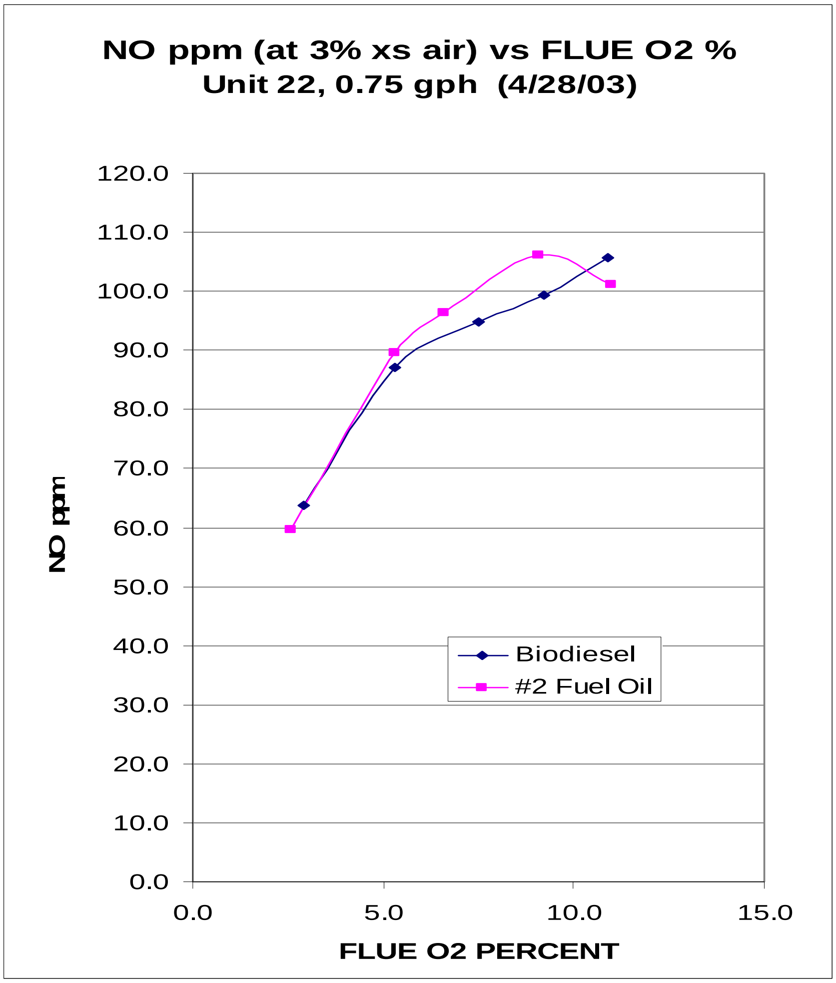
Attachment B-17a: Test Unit #1, 2.50 gph at 200 psig



Attachment B-17b: Test Unit #1, 2.50 gph at 200 psig



Attachment B-18a: Test Unit #22, 0.75 gph (20% Biodiesel / 80% #2 Oil Blend)



Attachment B-18a: Test Unit #22, 0.75 gph (20% Biodiesel / 80% #2 Oil Blend)