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Subcontractor Report

Biodiesel Blends in Space Heating Equipment

January 31, 2001–September 28, 2001

C.R. Krishna
Brookhaven National Laboratory
Upton, New York

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

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C.R. Krishna
Brookhaven National Laboratory
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NREL Technical Monitor: K. Shaine Tyson

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1. EXECUTIVE SUMMARY

Biodiesel is a “diesel-like” fuel derived from processing oils and fats from various sources, such as soy, rapeseed, or canola oil, and waste greases resulting from cooking use. Brookhaven National Laboratory (BNL) initiated an evaluation of the performance of blends of biodiesel and home heating oil in space heating applications under the sponsorship of the Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL). This report is a result of the work performed by BNL.

A number of blends of biodiesel and home heating fuel were tested in a residential heating system and a commercial size boiler. The results demonstrate that blends of biodiesel and heating oil can be used with few or no modifications to the equipment or operating practices in space heating. The results also showed that there were environmental benefits from the biodiesel blends including smoke reductions and lower nitrogen oxides (NO_x). Residential size combustion equipment is presently not subject to NO_x regulation. If reductions in NO_x similar to those observed here hold up in larger size (commercial and industrial) boilers, a significant increase in the use of biodiesel-fuel oil blends could become popular.

Biodiesel Blends in Space Heating Equipment

2. INTRODUCTION

Biodiesel is a "diesel-like" fuel derived from processing vegetable oils and fats from various sources, such as soy, rapeseed, or canola oil, and also waste greases resulting from cooking. The American Society for Testing and Materials (ASTM) sets U.S. fuel standards for biodiesel (D 6751-02, previously PS 121). The German standard (DIN 51606) is used widely in Europe while a European standard is in preparation. In view of its similarity to diesel fuel, biodiesel has been tested extensively in diesel engines. It has not been as widely tested for boiler applications or in residential heating applications.

Brookhaven National Laboratory (BNL) evaluated the performance of blends of biodiesel and home heating oil in space heating applications under the sponsorship of the Department of Energy (DOE) through the National Renewable Energy Laboratory (NREL). The New York State Energy Research and Development Administration (NYSERDA) sponsored a second phase of this work with BNL that included industrial boiler applications and field trials of home heating use of B20. This report presents the results obtained from the tasks performed under NREL sponsorship.

If researchers can demonstrate that blends of biodiesel and heating oil can be used with few or no modifications to the equipment or operating practices in space heating, substantial benefits may be realizable. Up to 10% of the nation's diesel fuel needs could be met with domestically produced agricultural based fuels, which are renewable, environmentally benign, low-sulfur, biodegradable, and nontoxic. Biodiesel could also contribute to fuel diversity for space heating, reducing the vulnerability to petroleum market disruptions and providing a cushion for the effects of future price spikes.

3. BACKGROUND

3.1 Biodiesel

Biodiesel is a fuel manufactured by the esterification of renewable oils, fats, and fatty acids. The fatty acids may be derived from vegetable oils such as soybean or rapeseed (canola), rendered tallow, or waste materials such as cooking and trap greases [1]. The resulting product has 10%-12% oxygen by weight, little sulfur, and has been shown to reduce particulate emissions in diesel engines. Chemically, it is non-aromatic and has a higher cetane number than normal diesel fuel. It has a heating value of about 123,000 BTU per gallon compared to about 140,000 BTU per gallon of #2 fuel oil. It has a slightly higher density. Pure (100%) biodiesel also has higher cloud and pour point temperatures than home heating oil. Biodiesel is completely miscible with home heating oil and blends can be easily generated if mixed well. Without mixing, the differences in density lead to fuel stratification. The blends are made in *volumetric* percentages and designated as B*X* where *X* is the percentage of biodiesel in the blend. For example, B10 has 10% biodiesel and 90% heating oil. B100 is pure biodiesel.

3.2 Brief Review of Past Work

Biodiesel has been extensively tested in diesel engines [1] and is sold at approximately 900 gas stations in Germany [2]. That work will not be reviewed here, as it is not immediately relevant to the space heating application. However, all attempts to obtain test data or any reports on the use of biodiesel in space heating were unsuccessful. The only past documented work of relevance identified was conducted by the R.W. Beckett Corporation under the sponsorship of Ag Environmental Products in 1993. The report on this proprietary work [3] was made available through the National Biodiesel Board (NBB) and Dr. K. Shaine Tyson (NREL). Beckett Corp. conducted some material compatibility tests and combustion performance tests using neat biodiesel (B100). The material compatibility tests consisted of leaving samples of the pump shaft seals in jars of B100 and fuel oil for 120 hours after which they were heated to 120°F for 72 hours. They were checked for swelling after the soaking and after the heating. Samples of plastics, label, gaskets, and painted metal were soaked in the B100 for extended periods of time. The combustion tests were performed using a 3-section wet-base boiler and a Beckett retention head burner. Steady state tests were conducted and the switch to firing B100 occurred without changing any burner setting. Their summary is reproduced below [3].

A. **"**Due to the lack of varnish stains on the inside of the glass jar containing SoyDiesel when heated to 200°F for 72 hours, we predict that SoyDiesel would tend to minimize the varnishing of the nozzle caused by the proximity of the electrodes to nozzle as seen with fuel oil. Long term cycling would be required to verify this theory.
B. Although we were unable to test cold SoyDiesel it would seem that, due to the higher viscosity of SoyDiesel compared to fuel oil, SoyDiesel would pose problems lighting off when cold. A nozzle line heater would probably assist the lighting of SoyDiesel.
C. Based on our testing, it would appear that the plastics we use on our burners are unaffected by direct contact with SoyDiesel. However, the gasket materials we use shrank in the presence of SoyDiesel and the adhesives dissolved. Also, the label adhesives dissolved.
D. At ambient temperature (65° – 70°F) both fuels were close in performance, with SoyDiesel showing a tendency towards less smoke and SO_2 [sulfur dioxide], while fuel oil showed a tendency towards a brighter flame.
E. With selections of compatible materials for our gaskets and label adhesives, our burners could easily be usable by both fuel oil and SoyDiesel.**"**

Some observations may be made from their test results. The gaskets that were reported as affected were made of vinyl, vinyl/PVC blend and neoprene. A key point that will be remarked on later is that they felt that the pump shaft seal behaved similarly with the biodiesel and the fuel oil. From the combustion test measurements, when the fuel was switched to B100 with burner settings unchanged, the nitrogen oxide (NO_x) level in ppm was about 15% lower and the smoke level changed from a "trace" to "zero."

The Agricultural Research Service (ARS), the research agency within the United States Department of Agriculture (USDA), announced its intention to use a blend of 5% biodiesel (B5) in its heating oil this past winter. ARS already uses a B20 blend of biodiesel and petroleum diesel in a diverse fleet of 150 diesel vehicles [2]. Their experience in the heating application using B5, will be reviewed if the data are made available.

A small number of tests were performed at BNL prior to the start of this work. The results are reported in Krishna et al. [4]. Primarily, they were steady state tests with measurements of performance variation with excess air. The results indicated that the NO_x emissions were lower with the blends (see below). Otherwise, the combustion performances were similar with the blends and the fuel oil. One difficulty was noticed and reported on in these preliminary tests: when firing neat biodiesel at high excess air levels, the flame proving control displayed a tendency to shut off the system even though the flame was lit and operation seemed normal. This was attributed to the “less bright flame” seen when compared with fuel oil and the consequent response of the cad cell used to sense it. The photosensitive cell’s dark resistance is higher and the control is set to shut off if it gets above a certain level.

4. PROJECT OVERVIEW

4.1 Tasks

The current project consists of the following tasks:

Task 1: Fuel selection, acquisition, and characterization. In this task, the biodiesel will be acquired and blends will be prepared with No. 2 fuel oil to B10, B20, and B30 specifications. One blend, designated BK50 will be prepared with 50% Kerosene. These will be sent to a fuel testing laboratory to be characterized by measuring properties considered relevant to use in a space heating system. Discussions with burner system manufacturers will be used to determine problem areas of material compatibility.

Task 2: Measure Ignition Performance and Material Compatibility. Transient tests will be conducted to measure ignition performance in a conventional wet-base boiler using the blends and No. 2 heating oil for baseline. Again, if problem areas are observed, possible remedies will be identified through discussions.

At the end of tasks 1 and 2, one low-level blend will be recommended for further testing.

Task 3: Measure steady state performance in a wet base residential boiler. The selected low-level blend and the BK50 and will be tested in a wet-base boiler for steady state performance. The cad cell will be checked by measuring the resistance to estimate the reliability of the control system.

Task 4: Measure steady state performance in a commercial hot water boiler. The two blends used in Task 3 will be tested in a 2 million per hour commercial hot water/steam boiler in the laboratory. Steady state performance will be measured and compared with that obtained using No.2 fuel oil.

4.2 Experimental Details

Task 1: Biodiesel was obtained in a 55-gallon plastic drum from a manufacturer. The biodiesel was made, according to the manufacturer, from soy oil. Stock fuels (kerosene and fuel oil) were used to make the test blends: B10, B20, B30, and BK50. Blend samples were prepared in 500 ml lots, on a volumetric basis measured by graduated cylinders. The fuels were manually agitated for several minutes to obtain a uniform mixture. As the biodiesel and the stock fuels have different colors, the uniform color of the blended fuel was used as an indication of thorough mixing. The stock fuels, the biodiesel and the blends were kept inside the laboratory at "indoor ambient" temperatures. A maximum error of 3% of the value is expected in making the blends.

Samples of the blends and of the stock fuels were sent to a fuels testing laboratory for analysis. The biodiesel was also tested at a second laboratory. The testing was done to appropriate ASTM standards where applicable. The B100 used to prepare the blends met the draft ASTM specification, PS 121.

Tasks 2 and 3: The test facilities in the oilheat research lab were used for these tasks. A three section, cast iron, wet base boiler was used for the tests. The boiler water is cooled by circulation through a plate heat exchanger, which in turn is cooled by building water. A modern retention head type burner with a pressure nozzle rated at 0.6 gallons per hour, fired at a pump pressure of 140 psi was used in the tests. Again, these conditions were maintained for all the blends and hence the fuel flows change slightly depending on the blend. The burner operating conditions were set using the value of oxygen in the stack. The Bacharach smoke number was set for the No. 2 oil and was left unaltered for subsequent runs with the different blends. No changes were made to the nozzle, the ignitor, the cad cell, or the control. Figure 1 is a photograph of the test set up. [4]

Constant sampling flue gas emission analyzers were used to measure the concentration of oxygen (paramagnetic measurement), NO_x (chemi-luminescent measurement) and carbon monoxide (CO) (infrared measurement) in the exhaust stack. A special sampling line built to meet the requirements of the analyzers is used to draw the sample from the stack. Smoke was measured using the ASTM D2156-80 method and a manually operated piston type sample pump.

The transient tests were started from a "cold" boiler condition. The "cold" condition was obtained by reducing the measured boiler water temperature to around 55°F by prolonged circulation through the plate heat exchanger prior to starting the burner. It should be emphasized that this is not normal operation of the system, which cycles normally, under aquastat control, between 140°F and 180°F for boiler water temperature. Transient measurements of CO and smoke were made during startup from "cold" conditions. The analyzer output was fed to a data acquisition system for later analysis, while the smoke measurements were made using the manual system on a timed basis. No. 2 fuel oil, B100, B10, B20, B30, and BK50 were used in these tests.

The steady state tests were conducted by letting the boiler warm up to the normal operating temperature of about 140°–150°F. The smoke number, NO_x, and CO were measured at different excess air levels by changing the settings of the air damper on the burner which were reflected by changes in the measured oxygen concentration in the stack. Cad cell resistance was measured in separate tests for No. 2 fuel oil and B100.

Task 4: These steady state tests were conducted in a hot water boiler of "commercial" size, which can supply hot water or steam and has a nominal rating of 1.8 million Btu per hour. A standard retention head burner was used with a nozzle rated at 7.0 GPH and a 70° solid cone spray. The fuel pump pressure was set at 150 PSI as recommended by the burner manufacturer, and at this pressure the fuel oil firing rate measured was 8.05 GPH (1.12 million Btu per hour). The boiler steady state conditions were defined by steam output conditions of 5 psig and 100°C. The boiler was started up and warmed to the steady state conditions on #2 fuel oil. The fuel input was then switched to the "blend" under test and the measurements were taken when steady state was reached again. The tests were conducted with the same small positive draft in the stack of about 0.15 inches of water to avoid skewing the stack measurements by intrusion of extraneous room air.

The burner has different air settings that can be set to give different excess air levels for combustion and the tests were conducted at the same four settings for the stock fuels and the blends. The same set of instruments as above was intended to be used to make the measurements. However, the NO_x analyzer failed after tests with a couple of blends. Later, another instrument of similar design (Chemi-luminescent measurement technique) was obtained. The limitations of the sampling system with this instrument prevented the simultaneous use of the above CO and oxygen analyzers with this NO_x analyzer. Hence, they were replaced by an instrument that is used for combustion analysis in residential and light commercial boilers and is based on electro-chemical sensors. Figure 2 is a photograph of the boiler set up. Only steady state tests were conducted. The start-ups with the blends were all "hot starts," as the boiler had been warmed up on fuel oil.

5. RESULTS AND DISCUSSION

5.1 Blend Properties

The results from property testing conducted by the outside test laboratories have been plotted in Figure 3, Figure 4, Figure 5, and Figure 6. Figure 3 shows that the flash point of the blends is quite close to that of the fuel oil even with 30% biodiesel. In fact, from Figure 5, it can be seen that the 50% blend had only a 7°C increase over neat kerosene. This suggests that ignition with the blends would not be a problem and this was indeed apparent from the tests.

Figure 4 shows that viscosity is more or less a linear function of the blend concentration and the values are within the ASTM limits of heating oil. This suggests that the volumetric flow rate through the nozzle would be constant, as was indeed observed in the tests. It also suggests that the atomization characteristics would also be similar, though no measurements were made to verify this. One could infer from the similarity of the combustion behavior in the tests that this was probably borne out in practice.

Figure 6 indicates that the measured pour point temperature increased more or less linearly with the biodiesel concentration. While the increase is expected, it is not obvious whether the operational problems with a particular blend would be consistent with the higher pour point temperature of the blend or different. A more detailed study and/or extensive practical experience with blends is probably needed to answer this question.

Table 2 gives the blend sulfur and nitrogen concentrations measured in a commercial test laboratory. The data need some explanation. The sulfur contents of the blends seem to be consistent with their mass concentrations in the stock fuels and the blending concentrations within reasonable measurement errors. As no sulfur dioxide measurements were made, there are no secondary confirmations of the laboratory data. However, the first row of nitrogen data indicates that there is definitely inconsistency in the blend values. One would expect the values in the blends to be a linear function of the values of the neat fuels by mass in the blend. However, this was not so and the samples were retested by the same laboratory. The next row in the table gives these results and it can be seen that they are quite different from the results of the earlier test. These seem consistent within reasonable measurement errors. The fuel nitrogen value is a significant number in view of the results reported below (unexpected reduction of NO_x in the stack). ASTM D3228 does suggest in Note 1 that "This test method may not be applicable to certain materials containing N-O or N-N linkage." We do not know whether this could be one reason for the inconsistent results. In any case, it would seem that further work clarifying this aspect of the fuel analysis would be useful and possibly be beneficial to furthering the use of biodiesel as a fuel.

5.2 Industry Discussion

Discussions were held with personnel from the oil heat equipment manufacturers to obtain a perspective on what they see as potential problems with using biodiesel blends. Two burner manufacturers, one of whom has some experience with testing biodiesel in their burner, and a leading pump manufacturer were contacted. The representative of one burner manufacturer felt that the only concern was burner set up with the blend. A more detailed response was provided by the engineering manager of the burner manufacturer who had tested biodiesel. He felt that potential problems with non-metallic material in contact with biodiesel such as seals could be avoided by switching to Viton. He also felt that, for example, the specific design of the lip seal, in addition to the material of construction, could have a bearing on whether it failed functionally. He also felt that the erasure of labels, while not affecting performance, could lead to loss of marking, traceability, etc. With regard to the problem of stability of the blends and of gumming, it was suggested that the use of a low level blend such as B20 would be a reasonable approach.

The representative from the pump manufacturer suggested that the current shaft seals used in their residential burner pumps were not appropriate for use with biodiesel as they are constructed from Nitrile. He said the pumps manufactured in Europe for use with rapeseed biodiesel used Viton seals. He said they were going to start testing their pumps with biodiesel blends and would probably have a pump with a suitable seal developed in a year. He felt that Viton and Teflon were possible materials for use with biodiesel. He said that in previous testing, the seals had failed when the pump was tested with a B20 blend and so he could not recommend using the standard pump even with B20. However, he did not seem to recall the test results in the Beckett report [3], which had suggested that the pump seals had responded similarly in the soaking tests with #2 fuel oil and with soy biodiesel.

A brief discussion was conducted with a large diesel fuel and heating oil distributor, who expressed an interest in biodiesel. The intention was to sound out their possible participation in a field test under the NYSERDA-sponsored part of the project. The company had not pursued biodiesel procurement because of the “unfavorable” economics of the fuel. However, they may be willing to participate in a field demonstration. During the discussion, one of the areas of concern identified was the potential for biological activity due to the “hygroscopic nature” of the fuel, as they termed it, and the consequential sludge/clogging problem. The problem exists with diesel fuel as well, especially due to condensation in large tanks; and biocides are used to counter it. The problems of biological activity, of sludge formation, and of the solubilization of existing sludge by the different solubility characteristics of the biodiesel are storage concerns for bulk-storage tanks, tank trucks, and residential tanks.

Graboski and McCormick [1] document that the biodiesel is less stable than petroleum diesel. Diesel engine experience suggests that filter replacement was sometimes needed due to clogging soon after switching to the blend from diesel. Clearly, these problems also tend to be less severe as the percentage of biodiesel in the blend is reduced [5].

Figure 7 is a schematic of a residential boiler fuel system and indicates the various components that contain parts made of nonmetallic materials that come in contact with the fuel. This does not mean that all these parts are equally important nor does it suggest that any of them would necessarily be affected by biodiesel. The shaft seal in the pump would be the most significant part in terms of its duty. The leading manufacturer has begun testing their pumps with B20 and B100. Ordinarily, the common pressure nozzles do not have any nonmetallic parts. However, more recently there are manufacturers that have been using a check valve to control the fuel dripping after the burner shuts off. This valve might have an O-ring that might be affected by biodiesel blends. Table 1 below summarizes the above discussion.

Table 1. Snapshot of Manufacturer Concerns

Problem	Identifier	Solution	Present Effort
Pump Seal Integrity	Burner Manufacturer	Proper Seal Design and Material (Viton)	Not Addressed
Stability of Blends	Burner Manufacturer	Use Low Level Blends (eg. 20%)	Recommended B20 for field tests
Pump Seal Integrity	Pump Manufacturer	Replace Nitrile with Viton	Not Addressed
Storage Problems (Sludge, Solubility etc.)	Fuel Oil Dealer	Unknown at present	Not Addressed

5.3 Ignition Performance

The primary measurement during the transient tests is CO in the stack. The peak values and the duration of the transient are used as a qualitative measure of the ignition performance. The CO measurements are shown below in Figure 8 through Figure 12. The broad features indicate that the blends of biodiesel and fuel oil or kerosene behave similarly. The peak values seem to be somewhat higher with biodiesel in the blend, a somewhat surprising result. It is conceivable that this may be an artifact of measurement, as the peaks occur for such a short time interval. However, for practical purposes, this short duration peak is not a significant concern. This similarity of the transient performance should be considered along with the similarity of performance at steady state reported by Beckett in Reference 3, Krishna et al in Reference 4, and the results of steady state measurements given here. Transient smoke was also measured, but did not indicate any significant differences between the blends and No. 2 fuel oil.

5.4 Steady State Performance in a Residential Boiler

The comparative performances are reported in terms of CO and NO_x in the stack as a function of stack oxygen, which corresponds to excess air. As the biodiesel has about 12% oxygen, compared to practically zero for both fuel oil and kerosene, the blends will have slightly higher excess air at the same stack oxygen level. Figure 13 through Figure 16 compare the performance of the blends with fuel oil's performance. Broadly speaking, the addition of the biodiesel reduces CO emissions, probably as one would expect. Figure 17 is a composite of the NO_x emissions from all the blends and fuel oil. It is clearly evident that the NO_x levels are significantly lower, especially at the higher levels. This was somewhat unexpected, as the diesel engine data [1] indicate similar or slightly higher NO_x with biodiesel blends than with petroleum diesel. Of course, the combustion situations are vastly different. This reduction in NO_x in boilers, if confirmed, could be a significant advantage to the use of biodiesel (and blends) in such applications. While one could generally say this might be due to lower flame temperatures, a more detailed study would be needed to establish the reasons for it, especially in view of the apparent contrary results in engines.

It should be noted that during the runs for the measurements above, no control difficulties were noted with this burner/boiler combination and in the range of excess air levels tested. In view of the "control" problem previously observed (see background section above) however, the cad cell resistance was measured with fuel oil and with B100, thus bracketing the performance with the blends. Table 3 below compares values with the two fuels. The cad cell resistances are very similar and hence one would not anticipate control problems with the blends in this burner and boiler as long as the starting transients are similar. As a matter of fact, we did not observe any such problems.

5.5 Steady State Performance in a Commercial Boiler

A general observation from these tests is that the smoke levels were lower with the increase in the amount of biodiesel blend in the fuel oil. This is, qualitatively, similar to the results in the residential boiler tests. The results for the NO_x emission are given in Figure 18 below. We find that there is significant reduction in the NO_x levels with increasing amounts of biodiesel in the blend with fuel oil. The reduction is less significant with Kerosene because of the lower NO_x levels. Still, B100 produces lower NO_x under similar stack oxygen levels than the kerosene tested here. As stated earlier, these results are unlike those reported with diesel engines. Much more research needs to be carried out before these can be generalized and understood.

6. CONCLUSIONS

Blends of a biodiesel of 10%, 20%, and 30% by volume with no. 2 fuel oil and a blend of 50 percent biodiesel by volume with kerosene were tested for properties significant to combustion in space heating boilers. The flash point increased only by 5°C over that for fuel oil for the 30% blend and by 7°C over that for kerosene for the 50% blend. This partly accounts for similar ignition behavior of the blends and the base petroleum fuels. The change in viscosity is almost linear with biodiesel fraction in the blend and all values were within the ASTM specification for No. 2 fuel oil. From these fuel property considerations, one would recommend that blends of 30% or less could replace fuel oil with no noticeable changes in performance. This was demonstrated by the successful combustion in a "typical" residential burner and boiler. This success is measured by the fact that the system did not need to be adjusted to give performance similar to that with the fuel oil under steady state. Transient performance was also similar when measured by CO and smoke emissions at startup. A blend of 50% biodiesel in stock kerosene was also tested with similar results. While similar tests with neat biodiesel were also conducted and are reported, use of 100% biodiesel is not contemplated and hence enough attention was not given to identify any potential problems.

In steady state, the addition of biodiesel seems to lead to slightly lower CO and NO_x emissions. The latter, while a welcome result, was somewhat surprising because results with biodiesel blends in diesel engines reported in other works indicate either similar or slightly higher NO_x levels. Clearly, the combustion conditions are very different in the two cases. The reasons for this are not apparent without much more testing.

As these systems operate in a cyclic fashion in the field, long term cyclic testing ought to be done. While this was not a task in the current project, the aspect of cyclic performance during startup was included. The blends performed at least as well as the fuel oil as demonstrated by the results of the transient tests.

One of the concerns in using biodiesel in existing equipment, primarily diesel engines, has been the effect it might have on the non-metallic materials that come in contact with it. [6] Another concern, not unrelated to this, is the differences in “solubility” characteristics of biodiesel from diesel fuel. These questions were not directly addressed experimentally in this project and no problems were encountered during the tests. The discussions with the people in the industry did not provide clear answers to all the concerns. In fact, one of the pump manufacturers has just started long term testing of their pumps on biodiesel blends. These concerns should be addressed by appropriate testing and studies in the future. Hence, caution at this stage seems warranted and we recommend that a reasonably low level blend of 20% or less be used in field tests.

The tests in the commercial boiler confirmed the similarity of steady state combustion performance of the blends and the base fuels. Again, the one major benefit noticed was the reduction in the stack values of NO_x, which was more substantial than in the case of the residential boiler. The NO_x levels are lower than in the residential boiler, which would suggest a lower “average” flame temperature. However, the reason for the reduction with the blends is not apparent and needs more investigation.

7. RECOMMENDATIONS

The recommendations below follow from the work reported above.

a. A 20% by volume blend of biodiesel in fuel oil should be tested over several heating seasons in the field to establish practical use and identify any potential problems.
b. Laboratory testing should be carried out to answer concerns over biodiesel’s effect on nonmetallic materials (elastomers) that are used in pump seals, valve seats, etc. and appropriate changes determined if there are problems.
c. Research should be carried out to find the mechanisms for the reduction in NO_x in boilers and establish scale up rules.

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Figure 1. Test Setup for Transient Tests

Figure 2. Commercial Boiler Set Up

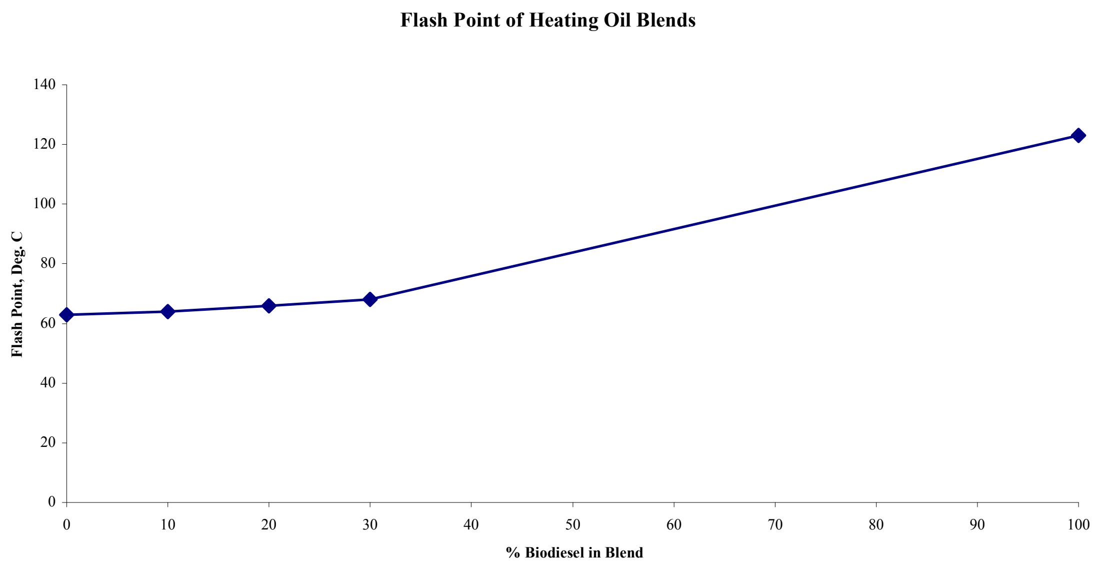

Figure 3. Flash Point of Biodiesel Blends in Fuel oil.

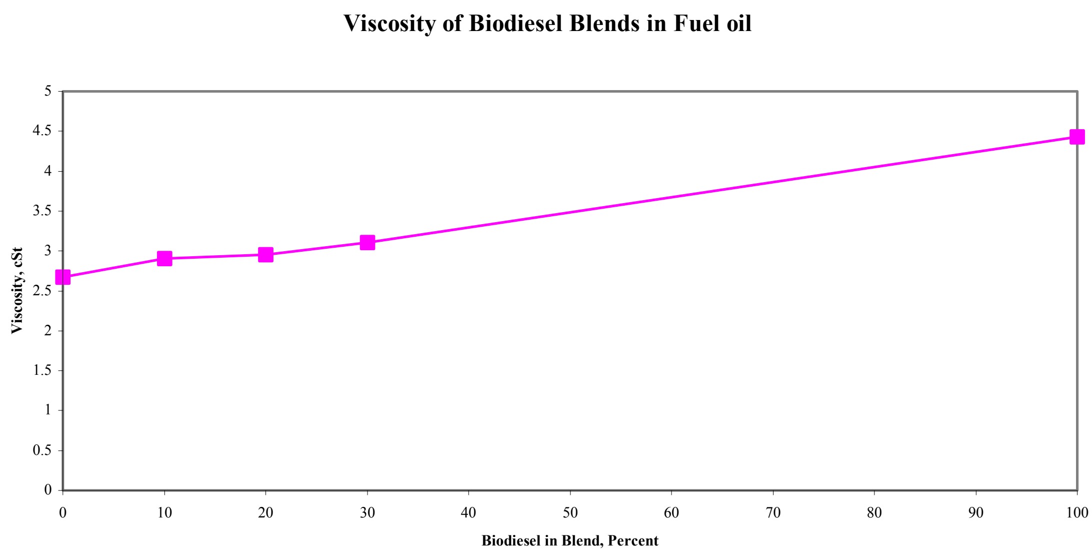

Figure 4. Viscosity Change with Biodiesel in Blend

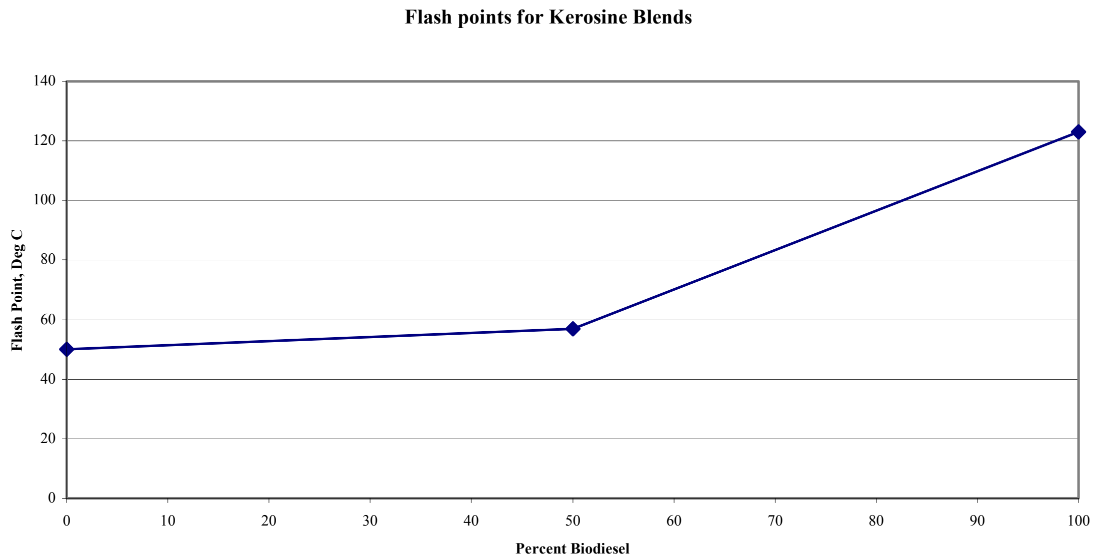

Figure 5. Flash Points for Biodiesel- Kerosene Blends

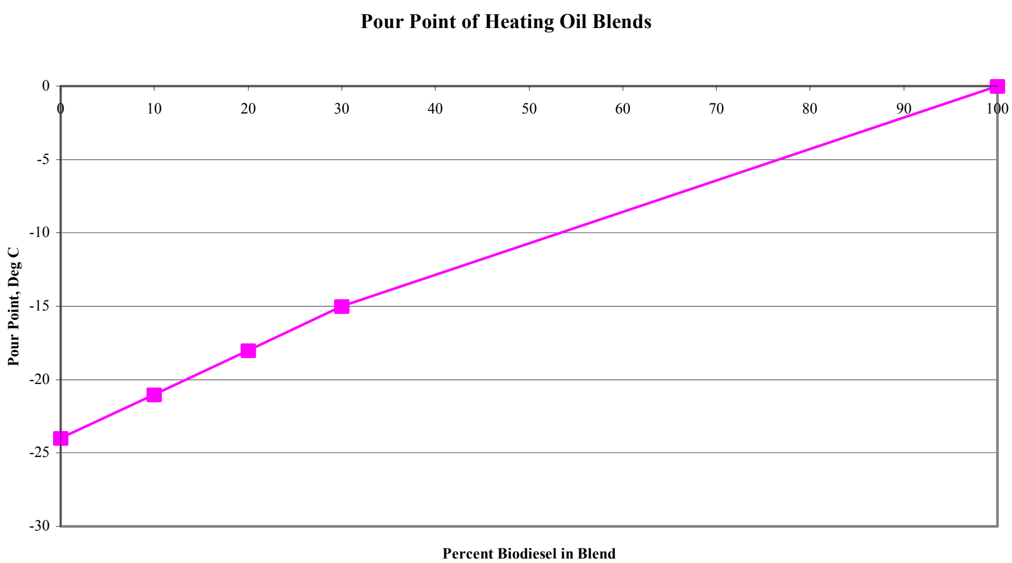

Figure 6. Pour Points for Biodiesel-Fuel Oil Blends

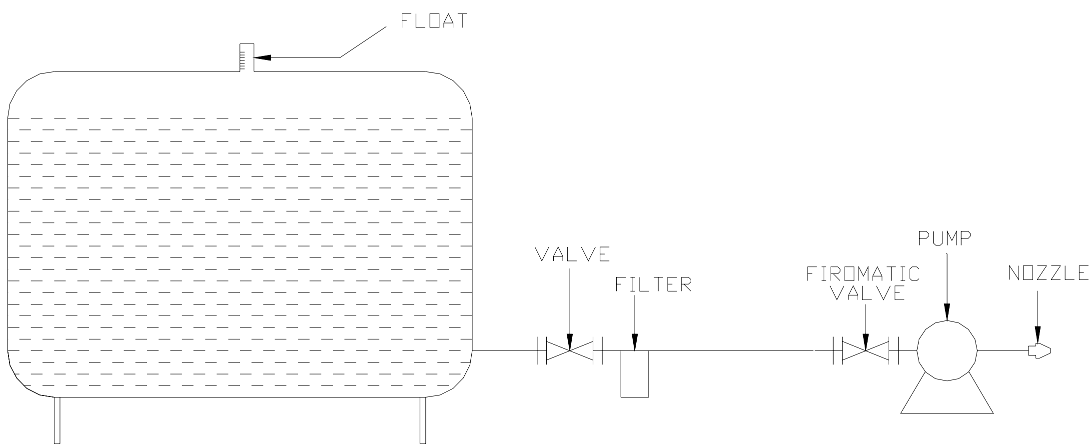

Figure 7. Schematic of a Residential Boiler Fuel System

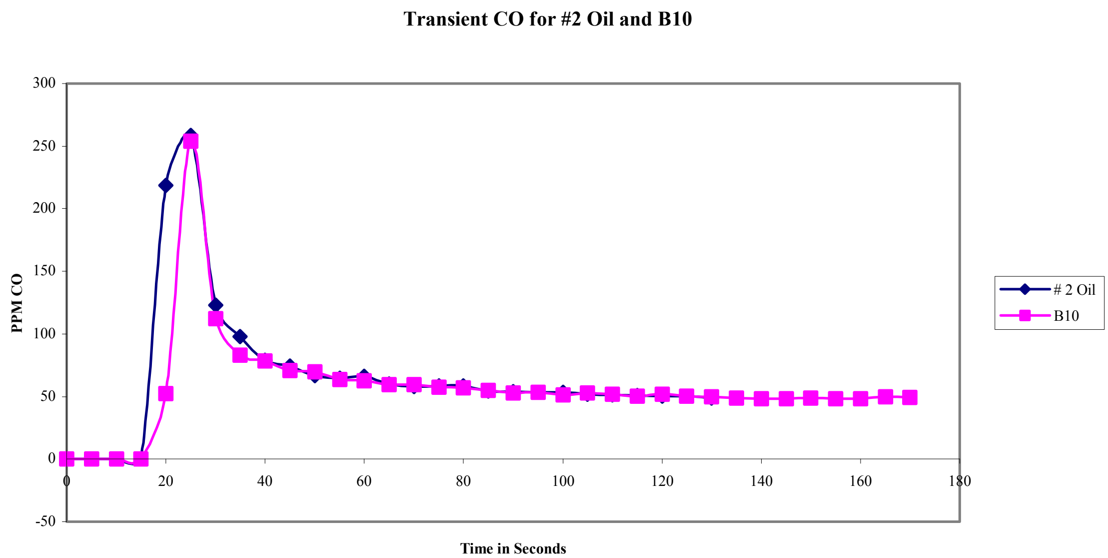

Figure 8. CO Transient for #2 Oil and B10

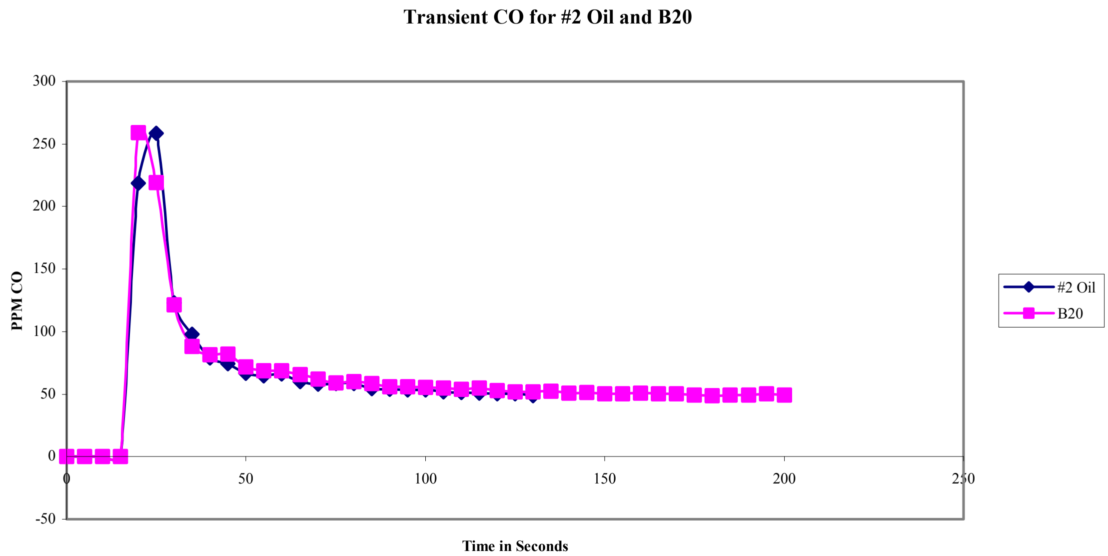

Figure 9. CO Transient for #2 Oil and B20

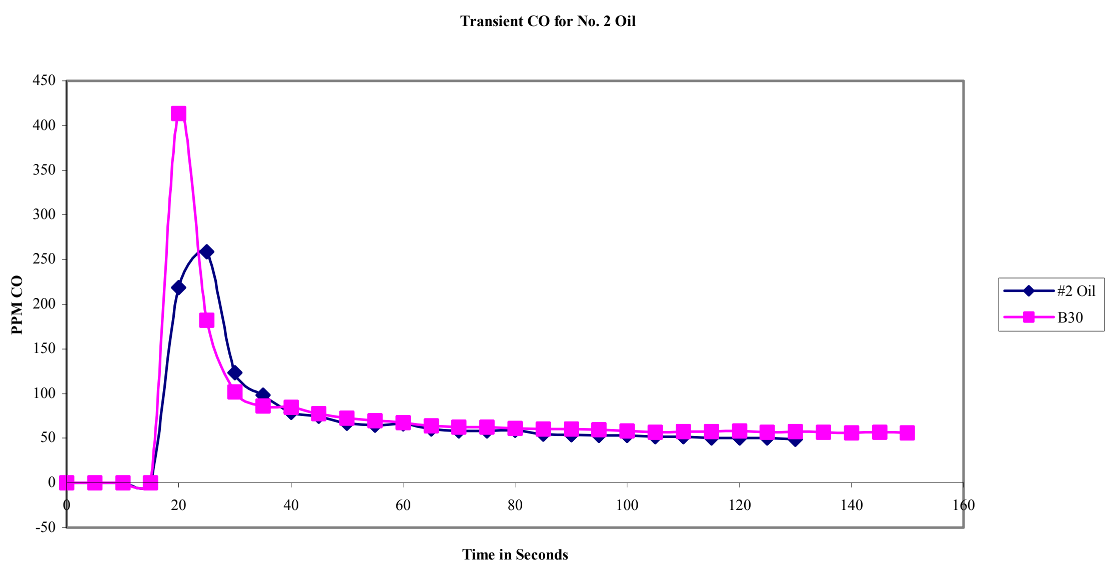

Figure 10. CO Transient for #2 Oil and B30

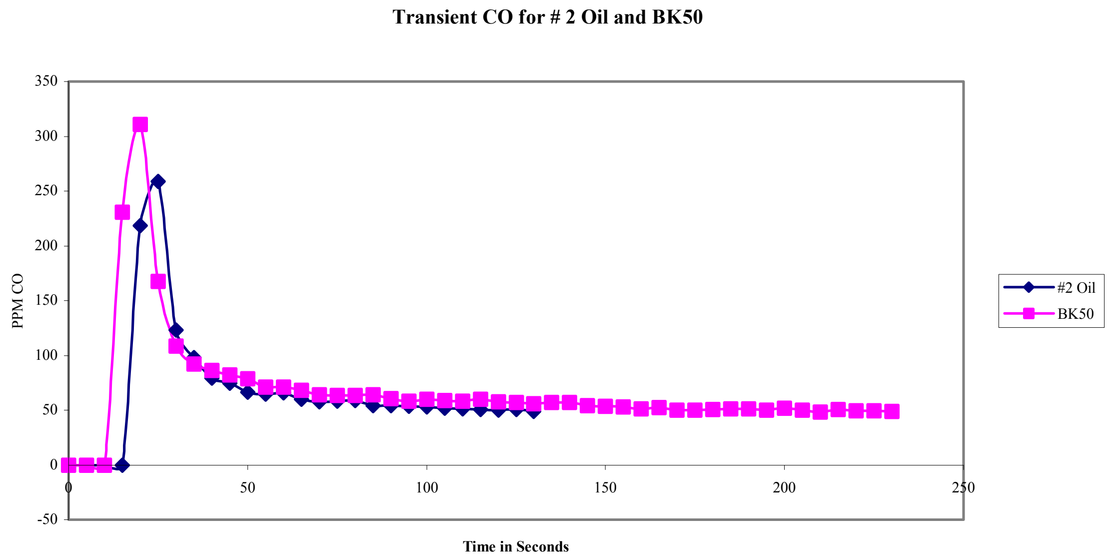

Figure 11. CO Transient for # 2 Oil and BK50

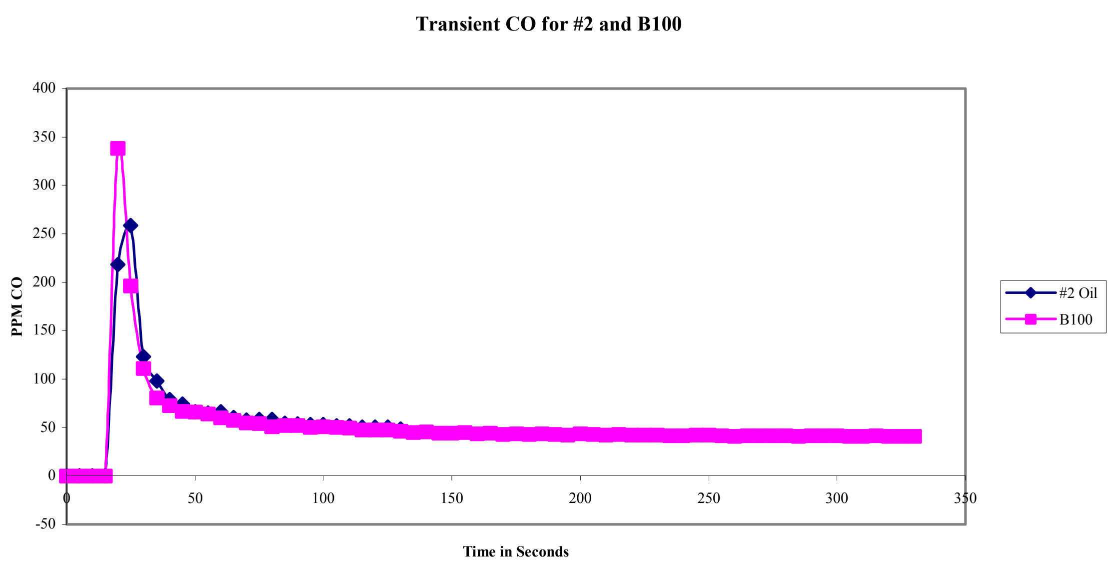

Figure 12. CO Transient for # 2 Oil and B100

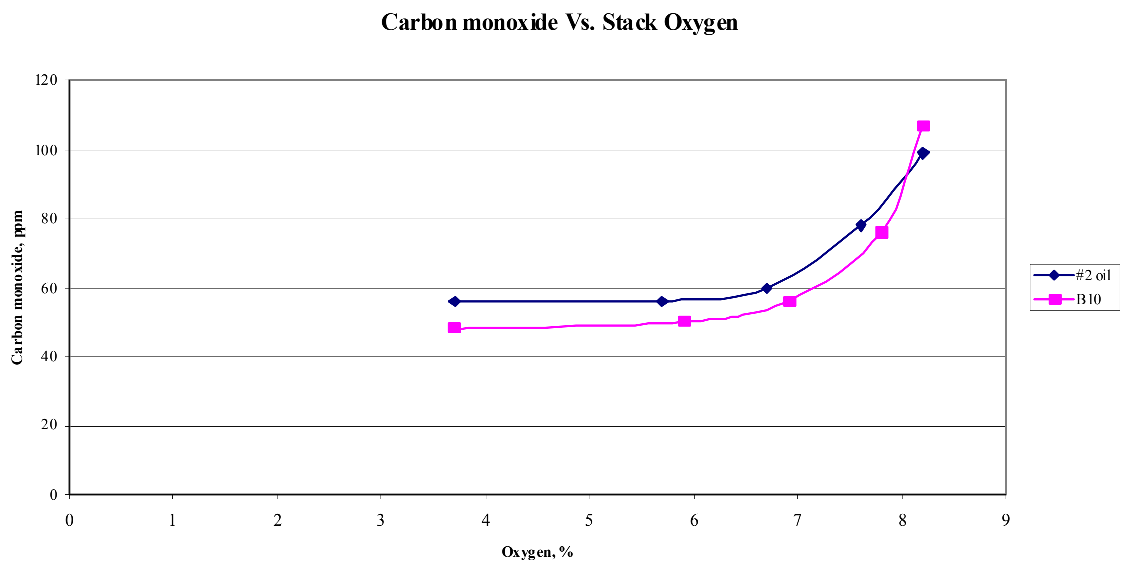

Figure 13. CO for B10

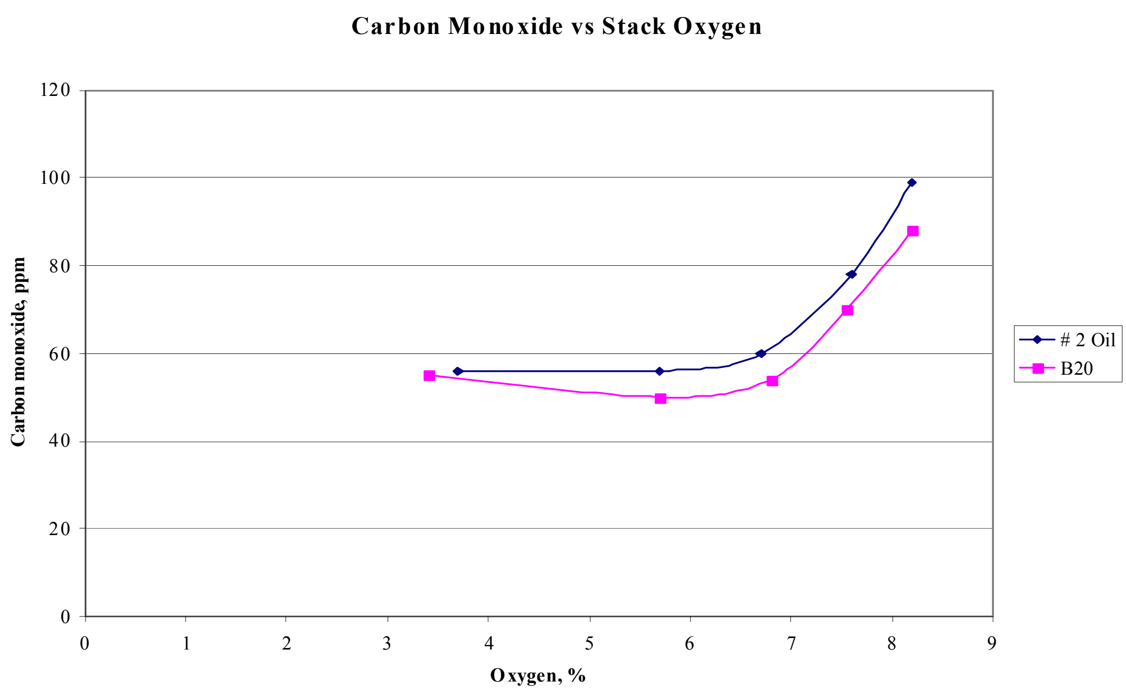

Figure 14. CO for B20

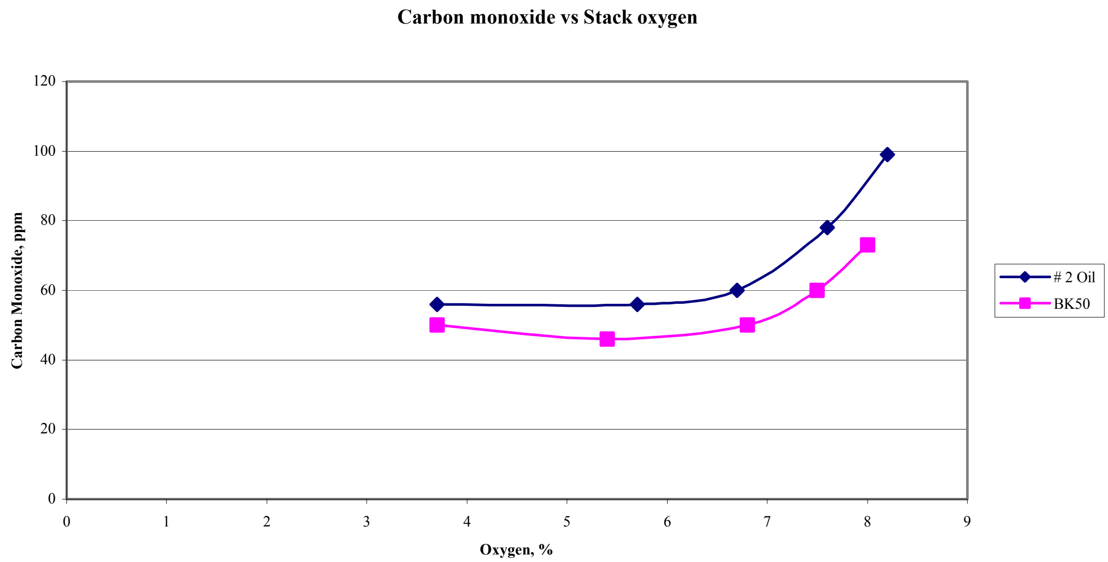

Figure 15. CO for BK50

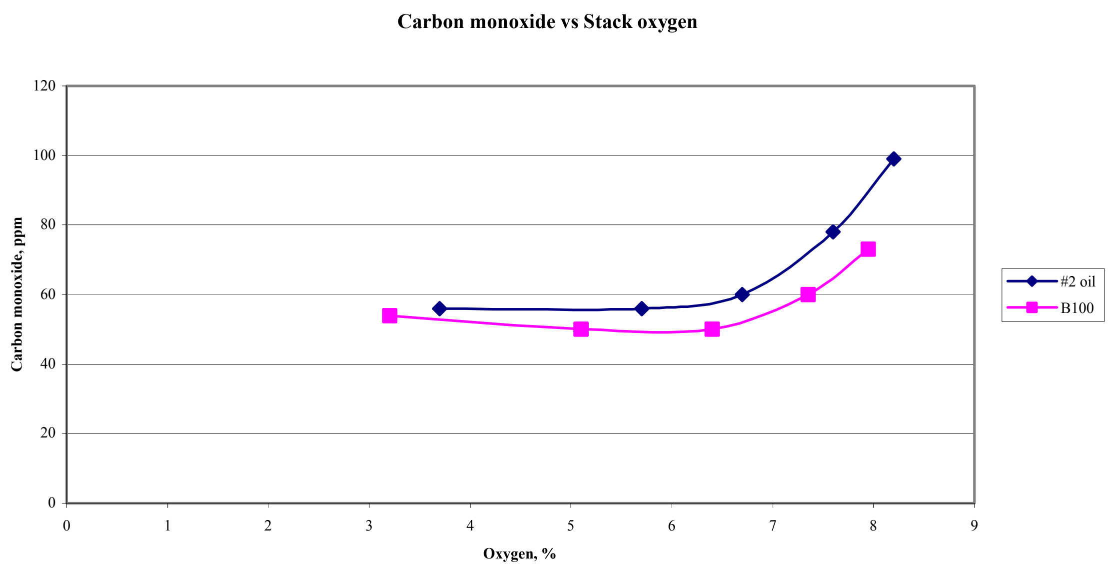

Figure 16. CO for B100

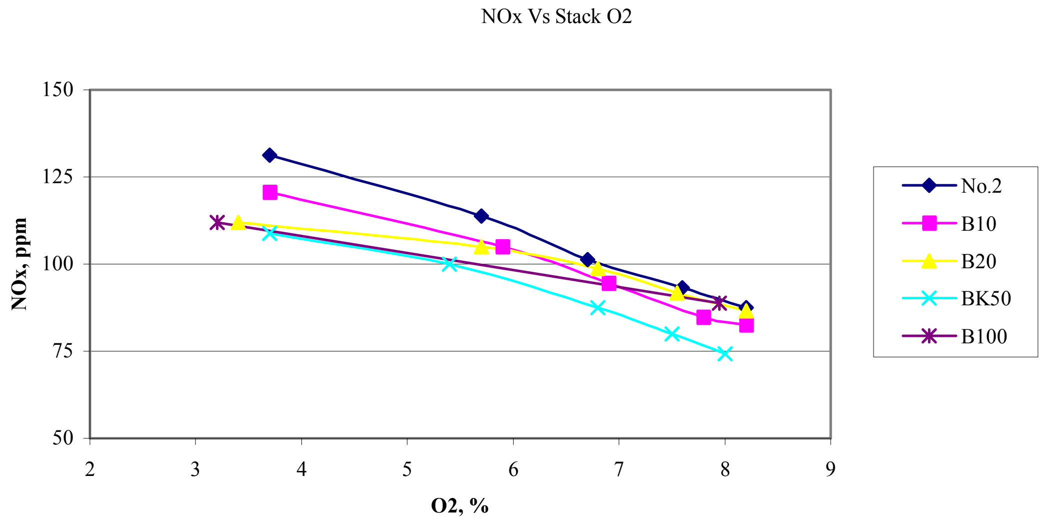

Figure 17. NO_x in Residential Boiler

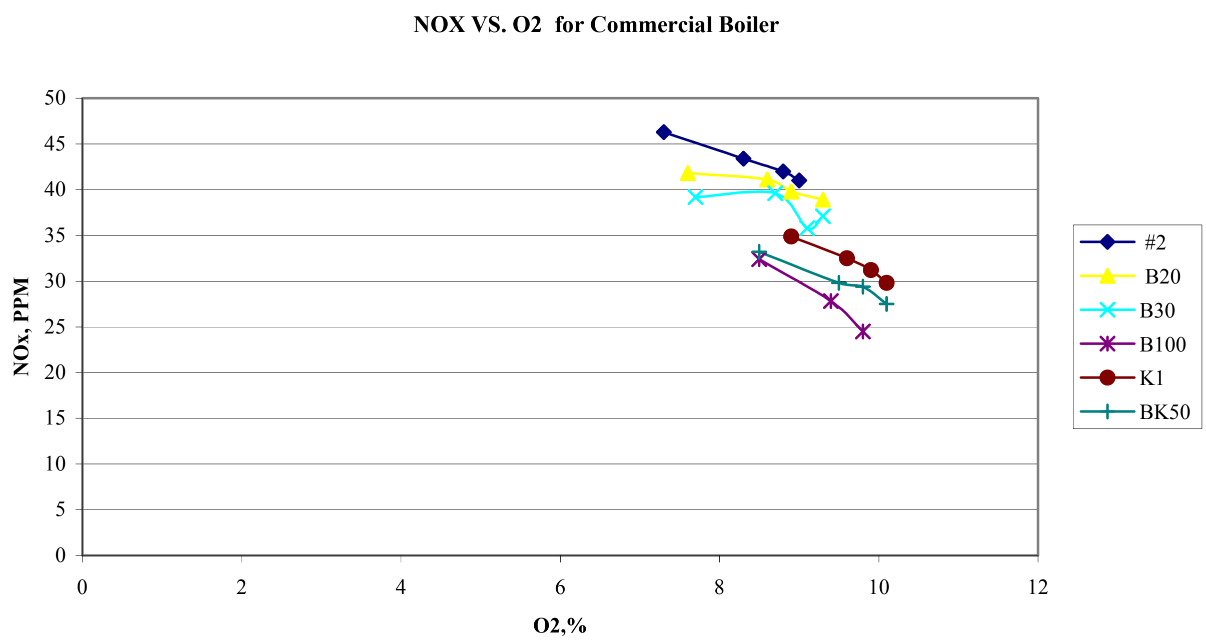

Figure 18. NO_x in the Commercial Boiler

Table 2. Sulfur and Nitrogen Content of Blends

Biodiesel in Blend	0% (#2 Fuel)	10%	20%	30%	100% (Biodiesel)
% Sulfur	.3767	0.3234	0.2930	0.2518	0.0011
% Nitrogen	0.1789	0.1154	0.1232	0.1588	0.1061
% Nitrogen (Retest)	0.036	0.037	0.032	0.033	<0.03

Table 3. Cad Cell Resistance

Fuel	Boiler Temp, °F	Stack O_2, %	Cad Cell, Ohms
No. 2 Fuel	160	4.9	960
B100	160	5.0	1000

Table 4. Blend Properties

% Biodiesel	Vis,cSt	Pour Pt., °C	Flash Pt., °C	% Bio in BK	BK Flash pt. °C
0	2.671	-24	63	0	50
10	2.905	-21	64	50	57
20	2.952	-18	66	100	
30	3.102	-15	68		
100	4.427	0	123		

Table 5. Data from Combustion Tests in Residential Boiler

Fuel	Oxygen, %	NO_x, ppm	CO, ppm
#2 Fuel	8.2	87.5	99
	7.6	93.25	78
	6.7	101.25	60
	5.7	113.75	56
	3.7	131.25	56
B10	8.2	82.5	107
	7.8	84.75	76
	6.9	94.5	56
	5.9	105.0	50
	3.7	120.5	48
B 20	8.2	86.5	88
	7.55	91.75	70
	6.8	98.75	54
	5.7	105.0	50
	3.4	112.0	55
BK50	8.0	74.25	73
	7.5	80.0	60
	6.8	87.5	50
	5.4	100.0	46
	3.7	108.75	50
B100	7.95	88.75	73
	7.35	93.75	60
	6.4	90.0	50
	5.1	106.25	50
	3.2	112.0	54

Table 6. Data from Combustion Tests in Commercial Boiler

FUEL	Oxygen, %	NO_x, PPM	CO,PPM
#2	7.3	46.3	19
	8.3	43.4	19
	8.8	42	18
	9	41	24
B20	7.6	41.8	18
	8.6	41.1	18
	8.9	39.8	21
	9.3	38.9	18
B30	7.7	39.2	15
	8.7	39.6	17
	9.1	35.8	16
	9.3	37.1	18
B100	8.5	32.4	10
	9.4	27.8	12
	9.8	24.5	12
	10		14
K1	8.9	34.9	9
	9.6	32.5	10
	9.9	31.2	12
	10.1	29.8	14
BK50	8.5	33.2	15
	9.5	29.8	18
	9.8	29.4	19
	10.1	27.5	20

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