Evaluation of a Water Emulsion Fuel in Air Force Aircraft Ground Support Equipment Diesel Generator Sets

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PREPARED FOR

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1. INTRODUCTION

In preparation for the possibility that combustion sources at U.S. Air Force bases may be required to reduce their oxides of nitrogen (NO_x) emissions, the Air Force has become interested in the evaluation of possible approaches to controlling NO_x emissions from aircraft ground support equipment (AGSE) diesel generators. Diesels, in general, and the A/M 32A-86 (-86) model generators, in particular, are very high NO_x emitters. The –86 generator is the Air Force standard flight line generator. It has been determined that the AGSE accounts for nearly 40 to 60 percent of a typical base's emissions of NO_x and the –86 accounts for 70 to 90 percent of the AGSE emissions. One NO_x control approach applicable to these engines is the use of a diesel/water emulsion fuel in place of standard diesel fuel.

The use of diesel/water emulsions containing nominally 5-percent methanol have been shown to be effective in achieving nominally 40-percent NO_x reductions from some engines. However, the diesel/water emulsion experience base is quite limited, and the long-term effects of such emulsions on engine performance are unknown at present. Thus, there is a need to evaluate the effectiveness and the long-term performance of this NO_x control approach when applied to AGSE.

In this project, an extended evaluation of the use of a diesel/water/methanol emulsion, prepared using liquid-phase methanol (LPMEOH™) as the methanol component, was planned on an Air Force flight line generator at Tyndall Air Force Base, Florida. The Full-Scale Drone Launch Facility at Tyndall AFB, operated by Lockheed-Martin, has four -86 generators, with

Detroit Diesel Corporation (DDC) Series 71 engines in routine operation. The -86 generator is the Air Force standard flight line generator. Two of these generators at Tyndall AFB were made available to this project. Of these, one was to be operated on the emulsion fuel during the evaluation, and the other was to be run on JP-8 fuel. JP-8 Mil Spec jet fuel is used in the mobility applications of the generators, and the Air Force has standardized the use of JP-8 in diesel engines to reduce the need to manage and maintain two fuel types and fueling systems

Previous work supported by the Air Force Green AGSE Program developed an additive package that is effective in both stabilizing a diesel/water emulsion and preventing engine part corrosion. The water-in-fuel (WIF) emulsion containing methanol produced by the liquid phase process (liquid phase methanol – LPMEOH™) and additives was the emulsion fuel that was evaluated in these tests. The WIF emulsion was prepared to contain nominally 30 percent water, 5 percent methanol, and 1 percent additives, with the balance being JP-8. JP-8 was selected as the base fuel for the control engine and the "diesel" base for the WIF because of the Air Force's move to this fuel as the single base supply.

When this project was originally planned, substantial support of the effort was offered by several Air Force and contractor organizations at Tyndall AFB. The Air Force Research Laboratory (AFRL) and an AFRL contractor, Applied Research Associates, Inc. (ARA), offered to coordinate the project on site, prepare the WIF emulsion, perform the performance and emissions tests to establish achievable emissions reductions, and monitor generator use during an extended period of routine operation. The 325th Maintenance Squadron offered to perform maintenance inspections of the test generators before and after the evaluation. The 83rd Fighter Weapons Squadron and their support contractor, Lockheed-Martin, offered to operate the test generator in routine use, and make all logistics arrangements to ensure that test generators received their specified fuel during the evaluation.

As the project proceeded, however, mission priorities for all these organizations at Tyndall saw changes occur. As a result of these changes, support for the project could no longer be offered after May 1999, and the project needed to be terminated. Up to that point, a series of initial performance and emissions tests had been completed, and the test generators were ready to begin a period of routine flight line use. With project termination, this period was never initiated. This report summarizes the results of the initial performance and emissions tests that were completed. Section 2 outlines the evaluation program planned and the actual testing completed. Section 3 summarizes the initial performance and emission test results achieved. Section 4 summarizes project conclusions

2. TEST PROGRAM

The objective of the originally planned project was to evaluate the long-term performance of the WIF emulsion fuel in reducing NO_x emissions from the -86 generator, with acceptable impacts on engine performance and durability and acceptable emissions of pollutants other than NO_x. It was planned to operate the two test generators, one fueled with WIF and the other with JP-8, for a period of 6 months. Engine performance and emissions testing was planned to be conducted before the start and after the end of this 6-month period to quantitate emission reductions and performance impacts. Engine inspections were also planned, to address durability and corrosion issues.

Details of the test facility, the performance and emissions tests performed, and the planned long-term (6-month) evaluation test period are discussed in the subsections that follow.

2.1 TEST FACILITY

As noted in Section 1, the evaluation tests that were completed were performed at the Full-Scale Drone Launch Facility at Tyndall AFB. This facility launches QF-106 and QF-4 target drones for pilot training. Four A/M 32A-86 engine/generator units are in routine use to support ground operations associated with the drones. Two of these generators were designated for use in this evaluation test program, one to be fueled with JP-8 and the other with the test WIF emulsion. The -86 generator is powered by a DDC Model 4-71N engine. This engine is a 4-cylinder, 2-stroke, blower-scavenged (nonturbocharged) engine that delivers 110 hp at 1,800 rpm. The generator supplies up to 72 kilowatts (kW) of regulated 400-Hz, 3-phase power, at 115/200 V or 230/400 V, to parked aircraft for operation of the aircraft electrical equipment when the onboard auxiliary power units are not running.

The -86 generators at Tyndall AFB are equipped with standard DF-65 fuel injectors. Normally, when a diesel engine is modified for emulsion fuel use, higher capacity injectors need to be retrofitted to the engine. This is needed to account for the higher fuel volumetric feedrates (gal/hr) needed with the emulsion fuel, owing to its decreased specific heating value (Btu/gal). However, the -86 generators are oversized for their use at Tyndall AFB. While capable of generating 200-amps of current, they are rarely, if ever, run at more than 100 amps in use. Thus, the standard injectors were expected to suffice for use with the WIF emulsion in these tests; new injectors were not installed on either test engine.

2.2 PERFORMANCE AND EMISSIONS TESTS

Before and after the planned long-term evaluation period, the test engines were scheduled for a set of performance and emissions tests. In these tests, each engine was to be connected to a load bank and operated over a load range while its emissions were measured. The initial performance and emissions tests were completed during the time period of November 1998 through January 1999.

The emissions test protocol for these tests followed the International Organization for Standardization (ISO) International Standard ISO 8178. ISO 8178 outlines a number of load cycles to be used for emissions testing of reciprocating internal combustion engines. The load cycle used for the performance and emissions tests in this project was the D2 cycle. This cycle is specified for use on engine-driven generator sets with intermittent load. This cycle is summarized in Table 2-1. ISO 8178 specifies performing test cycle D2 in the sequence of the test modes 1 to 5, respectively. The minimum test mode length is 10 minutes. If necessary, the mode length may be extended, e.g., to collect sufficient particulate mass or to achieve stabilization of engine operation. The weighting factors noted in Table 2-1 are the weights to be applied to the emission factors measured for each mode in the calculation of a single weighted-average emission factor for the test cycle.

Table 2-1. ISO 8178 Test Cycle D2

Mode number	1	2	3	4	5
Engine speed	Rated speed				
% Torque	100	75	50	25	10
Weighting factor	0.05	0.25	.030	0.30	0.10

For these tests, generator load was used as the measure of engine torque. The test cycle performed for these tests is summarized in Table 2-2. While the –86 is capable of supplying a maximum of 200 amps, the flight line needs typically do not exceed 100 amps. Therefore, in this evaluation, 150 amps was chosen to represent 100 percent load. The 150-amp load corresponds to a nominal generator output of 57 kW. As indicated in the table, the engine was sequentially tested at nominally 150-, 113-, 75-, 38-, and 15-amp loads. Engine speed was the rated speed (1,800 rpm) at all loads. The test time at each load was 30 minutes, which allowed sufficient time for engine operation stabilization and changing of particulate collection filters.

Table 2-2. Test cycle

Generator Load (amps)	Corresponding Power Output (kW)	Time at Load (min)
150	56.5	30
113	45.0	30
75	20.5	30
38	14.2	30
15	5.7	30
	Total	150

The ambient condition and engine operating parameters that were recorded for each test are listed in Table 2-3. In addition, engine exhaust concentrations of oxygen (O_2), carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbon (UHC) were measured using a continuous emissions monitoring system (CEMS). The CEMS used was an Enerac 3000 electrochemical cell system. The specifications for the Enerac 3000 are given in Table 2-4. The Enerac 3000 included a heated sampling probe with desiccant to absorb moisture in the exhaust to prevent damaging the electrochemical sensors. Exhaust gas temperature was measured using a chromel-alumel (Omega K-type) thermocouple with a digital readout.

Engine exhaust particulate emissions measurements were attempted using a dilution tunnel method as specified in ISO 8178. One set of particulate filters was collected using the dilution tunnel at each test load point. The dilution tunnel apparatus used was an EPA Wood Stove Dilution Sampling System that was provided by the Air Pollution Prevention and Control Division (APPCD) of EPA's National Risk Management Research Laboratory (NRMRL) in Research Triangle Park, North Carolina. The dilution tunnel apparatus sampled 5 to 6 ft^3 of exhaust gas over a 30-minute time period at each load point. Photographs of the experimental setup, which was located outdoors at a location adjacent to the flight line at Tyndall, are given in Figures 2-1 and 2-2.

WIF emulsion fuel mixtures were hand-prepared by ARA personnel. An industrial high-speed clarifier was used to blend the water, fuel, and additives in desired concentrations. The composition of the WIF emulsion was nominally 64 percent JP-8, 30 percent water, 5 percent LPMEOH™, and 1 percent additives. The additives are needed to promote emulsion stability and prevent engine corrosion.

Table 2-3. Ambient conditions and engine operating parameters recorded

Parameter	Measurement Frequency
Ambient conditions:	
Temperature	At beginning and end of load point
Relative humidity	At beginning and end of load point
Barometric pressure	At beginning and end of load point
Engine operating parameters:	
Generator load	After start and before end of each load point
Engine rpm	After start and before end of each load point
Exhaust temperature	After start and before end of each load point

Table 2-4. Enerac 3000 specifications

Measurement	Range	Resolution	Uncertainity, ±%
O_2	0 – 25%	0.1%	0.2
NO	0 – 300 ppm	1 ppm	2
	0 – 1,000 ppm	1 ppm	2
	0 – 3,500 ppm	1ppm	2
NO_2	0 – 500 ppm	1 ppm	2
CO	0 – 500 ppm	1 ppm	2
	0 – 2,000 ppm	1 ppm	2
	0 – 20,000 ppm	1 ppm	2
UHC as (CH_4)	0 – 6%	0.01%	10

ppm = parts per million

Figure 2-1. Load bank

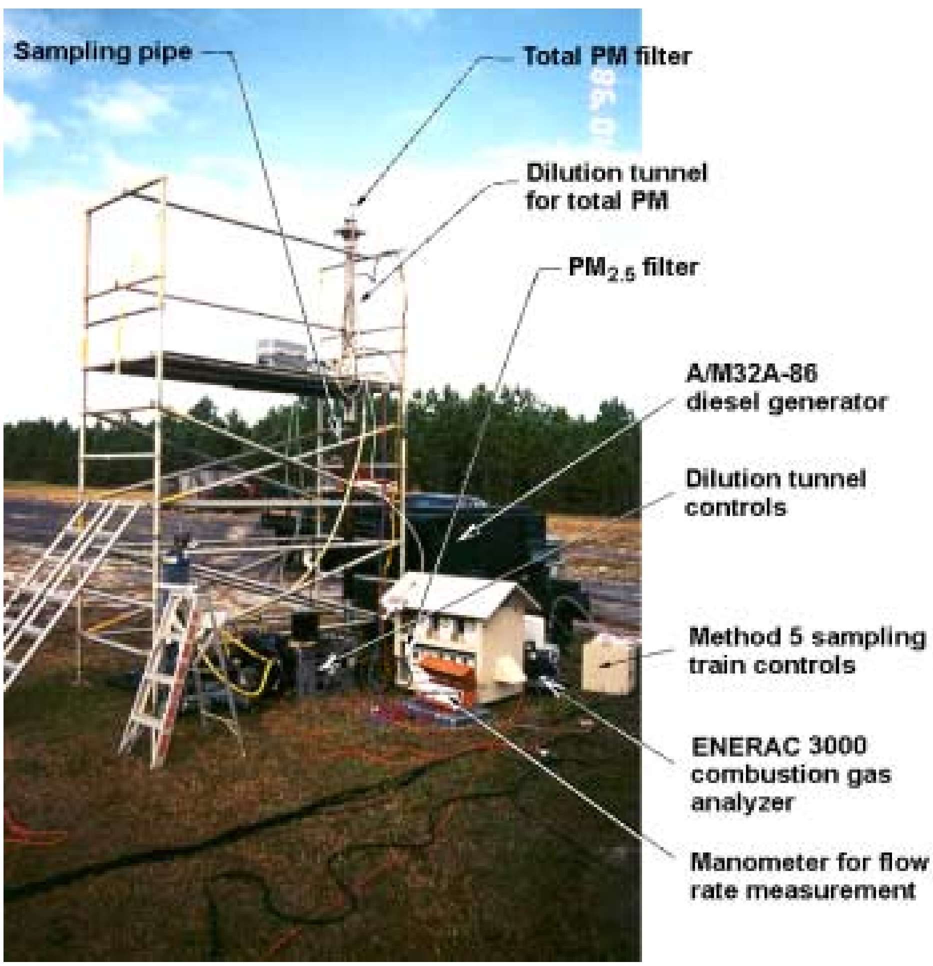

Figure 2-2. Engine test setup

2.3 LONG-TERM OPERATION

After the initial performance and emissions test were complete, a long-term evaluation was planned to encompass 6 months of operation in routine service for the two test generators. In this evaluation, the test generators were to be afforded first priority on the flight line when a generator was needed. That is, the two test generators were to see the most service of all the generators at the Full-Scale Drone Launch Facility. However, as noted above, because of changing mission priorities, continued Air Force support of the project at Tyndall AFB was not possible after May 1999. So the long-term operation phase of the project was not initiated and the project was terminated.

3. TEST RESULTS

The initial performance and emissions test program outlined in Section 2 was initiated the week beginning November 9, 1998. Final equipment setup at the test site was completed on November 9 and testing initiated on November 10. The two generators were provided by the Air Force for testing. These were designated as DG-21 and DG-23. The emissions testing matrix followed is summarized in Table 3-1.

Table 3-1. Emissions testing matrix

Test Date	Nov 10, 1998	Nov 11, 1998	Nov 12, 1998	Jan 20, 1999	Jan 20, 1999
Generator tested	DG-23	DG-23[a]	DG-21[a]	DG-23	DG-23[a]
Fuel type	JP-8	WIF	JP-8	JP-8	WIF

[a]Tests were performed in duplicate.

Emissions testing of DG-23 with JP-8 fuel was completed on November 10, 1998. On November 11, emissions testing of DG-23 was performed in duplicate with WIF as the fuel. On November 12, DG-21 was tested in duplicate with JP-8 as the fuel. Testing of DG-21 with WIF as the fuel was scheduled for November 13. However, while the generator started with the residual JP-8 in the fuel lines, as soon as the WIF fuel displaced the residual JP-8, the engine died. This generator would not operate on the emulsion fuel. It was suspected that the engine's compression ratio had deteriorated to the point that the emulsion fuel would not ignite. Subsequent to this setback, it was decided to verify that DG-23 would continue to run on the WIF as on November 11. However, in the interim, the weather at the outdoor test site turned colder and even DG-23 would not cold start with the WIF emulsion fuel. Various approaches to achieving successful cold start were tried, including heating the intake air and varying the water content of the WIF emulsion all of which were unsuccessful.

In mid-January 1999, Lockheed-Martin put the test program on notice that they were running low on generators and that they might need to retrieve DG-23 and place it back into flight line service at any time. Thus, it was decided to complete another set of baseline emissions tests before DG-23 was placed back into service. This second set of tests were completed on January 20. Emission data were obtained for two loads with DG-23 running on JP-8. The generator was started on JP-8, then successfully switched to the WIF emulsion. Emission data from DG-23 on WIF were obtained for two sets of varying load conditions. Continuous emission monitor data and particulate measurement results are discussed in the subsections that follow.

3.1 CEM DATA

Tables 3-2 through 3-9 summarize the CEM data collected for each test day completed. Copies of raw measurement data records are presented in Appendix A. The following subsections discuss the evaluation of these results.

3.1.1 NO_x Emissions

The NO_x emission data from Tables 3-2, 3-5, and 3-6 for the tests performed in November with JP-8 fuel, corrected to 15 percent O_2, are plotted as a function of engine load in Figure 3-1. A corresponding plot of the corrected data from Tables 3-3 and 3-4 with the WIF emulsion is given in Figure 3-2. The data in Figure 3-1 show that the NO_x emissions from both engines tested with JP-8 (one in duplicate) were comparable at respective loads. Similarly, the data in Figure 3-2 show that NO_x emissions from DG-23 for both sets of tests with WIF were

Table 3-2. Test data from November 10, 1998: DG-23/JP-8

Parameter	Measurement					
Engine load	kW	56.5	45.0	28.5	14.2	5.7
NO	ppm	1,322	1,021	748	508	381
NO_2	ppm	328	233	156	105	84
NO_x	ppm	1,650	1,254	904	613	465
CO	ppm	485	380	283	212	192
CO_2	%	4.2	3.5	2.7	2.0	1.6
UHC	%	0.3	0.3	0.4	0.4	0.3
O_2	%	15.2	16.2	17.3	18.3	18.8
Exhaust temperature	°C	306	268	222	182	161
	°F	582	515	431	359	322
Ambient temperature	°C	27	28	27	26	25
	°F	80	82	81	79	77
Relative humidity	%	73	73	75	79	83
Barometric pressure	in Hg	30.21	30.21	30.21	30.21	30.21
Emissions @ 15% O_2						
NO_x	ppm	1,708	1,574	1,482	1,391	1,306
CO	ppm	502	477	464	481	539
UHC	%	0.3	0.4	0.7	0.9	0.8

Table 3-3. Test data from November 11, 1998: DG-23/WIF

Parameter	Measurement					
Engine load	kW	56.5	45.0	28.5	14.2	5.7
NO	ppm	1,092	854	540	254	141
NO_2	ppm	303	222	130	74	56
NO_x	ppm	1,395	1,076	670	328	197
CO	ppm	402	334	277	317	474
CO_2	%	4.5	3.8	3.0	2.3	1.9
UHC	%	0.0	0.0	0.0	0.0	0.0
O_2	%	14.8	15.7	16.9	17.9	18.4
Exhaust temperature	°C	281	248	203	167	151
	°F	538	478	397	332	304
Ambient temperature	°C	17	17	18	18	19
	°F	63	63	65	64	66
Relative humidity	%	91	85	82	82	79
Barometric pressure	in Hg	30.26	30.26	30.26	30.26	30.26
Emissions @ 15% O_2						
NO_x	ppm	1,349	1,221	988	645	465
CO	ppm	389	379	409	623	1,119
UHC	%	0.0	0.0	0.0	0.0	0.0

Table 3-4. Test data from November 11, 1998: DG-23/WIF duplicate

Parameter	Measurement					
Engine load	kW	56.5	45.0	28.5	14.2	5.7
NO	ppm	1,212	937	680	385	203
NO_2	ppm	344	250	155	92	65
NO_x	ppm	1,556	1,187	835	477	268
CO	ppm	379	332	286	325	446
CO_2	%	4.4	3.7	2.9	2.3	1.9
UHC	%	0.0	0.0	0.0	0.0	0.0
O_2	%	14.9	15.9	17.0	17.9	18.4
Exhaust temperature	°C	286	251	206	169	149
	°F	548	484	402	336	300
Ambient temperature	°C	17.9	17.4	16.7	17.8	16.1
	°F	64	63	62	64	61
Relative humidity	%	82	85	86	87	91
Barometric pressure	in Hg	30.26	30.26	30.26	30.26	30.26
Emissions @ 15% O_2						
NO_x	ppm	1,530	1,401	1,263	938	632
CO	ppm	373	392	433	639	1,053
UHC	%	0.0	0.0	0.0	0.0	0.0

Table 3-5. Test data from November 12, 1998: DG-21/JP-8

Parameter	Measurement					
Engine load	kW	56.5	45.0	28.5	14.2	5.7
NO	ppm	1,467	1,196	871	612	452
NO_2	ppm	447	337	216	141	104
NO_x	ppm	1,914	1,533	1,087	753	556
CO	ppm	523	448	337	286	258
CO_2	%	4.5	3.7	2.9	2.2	1.9
UHC	%	0.3	0.1	0.1	0.1	0.1
O_2	%	14.8	15.9	17.0	17.9	18.4
Exhaust temperature	°C	306	268	220	184	163
	°F	583	514	428	364	325
Ambient temperature	°C	24	24	24	22	23
	°F	75	75	76	72	73
Relative humidity	%	46	46	45	45	47
Barometric pressure	in Hg	30.27	30.27	30.27	30.27	30.27
Emissions @ 15% O_2						
NO_x	ppm	1,851	1,809	1,644	1,481	1,312
CO	ppm	506	529	510	562	609
UHC	%	0.3	0.1	0.2	0.2	0.2

Table 3-6. Test data from November 12, 1998: DG-21/JP-8 duplicate

Parameter	Measurement					
Engine load	kW	56.5	45.0	28.5	14.2	5.7
NO	ppm	1,507	1,184	866	621	446
NO_2	ppm	465	315	211	140	100
NO_x	ppm	1,972	1,499	1,077	761	546
CO	ppm	497	399	318	271	248
CO_2	%	4.5	3.8	3.0	2.3	1.7
UHC	%	0.2	0.1	0.2	0.2	0.1
O_2	%	14.8	15.8	16.9	17.8	18.3
Exhaust temperature	°C °F	307 585	268 514	221 430	184 364	162 324
Ambient temperature	°C °F	22 72	22 72	22 72	22 72	22 71
Relative humidity	%	48	51	53	57	59
Barometric pressure	in Hg	30.27	30.27	30.27	30.27	30.27
Emissions @ 15% O_2						
NO_x	ppm	1,907	1,734	1,589	1,448	1,239
CO	ppm	481	462	469	516	563
UHC	%	0.2	0.1	0.3	0.4	0.2

Table 3-7. Test data from January 20, 1999: DG-23/JP-8

Parameter	Measurement		
Engine load	kW	59.0	31.5
NO	ppm	449	279
NO_2	ppm	374	189
NO_x	ppm	823	468
CO	ppm	562	369
CO_2	%	4.4	2.9
UHC	%	0.4	0.5
O_2	%	14.9	17.0
Exhaust temperature	°C °F	314 597	234 454
Ambient temperature	°C °F	23 74	24 75
Relative humidity	%	81	82
Emissions @ 15% O_2			
NO_x	ppm	809	708
CO	ppm	553	558
UHC	%	0.4	0.8

Table 3-8. Test data from January 20, 1999: DG-23/WIF

Parameter	Measurement					
Engine load	kW	54.0	44.0	32.5	18.0	11.7
NO	ppm	301	214	148	64	32
NO_2	ppm	165	94	80	50	39
NO_x	ppm	466	308	228	115	71
CO	ppm	1,237	1,260	1,032	1,197	1,346
CO_2	%	4.1	3.5	3.0	2.3	1.9
UHC	%	0.6	0.6	0.7	0.6	0.7
O_2	%	15.3	16.1	16.9	17.9	18.3
Exhaust temperature	°C	281	249	221	188	172
	°F	537	481	430	371	341
Ambient temperature	°C	27	27	25	267	25
	°F	81	81	78	80	77
Relative humidity	%	73	70	77	71	78
Emissions @ 15% O_2						
NO_x	ppm	491	380	338	226	161
CO	ppm	1,303	1,549	1,522	2,354	3,054
UHC	%	0.6	0.7	1.0	1.2	1.6

Table 3-9. Test data from January 20, 1999: DG-23/WIF duplicate

Parameter	Measurement					
Engine load	kW	49.0	45.5	29.0	12.4	4.2
NO	ppm	257	241	137	38	13
NO_2	ppm	144	133	79	43	29
NO_x	ppm	401	374	216	81	43
CO	ppm	1,158	1,131	1,044	1,261	1,500
CO_2	%	3.8	3.7	2.8	2.0	1.6
UHC	%	0.6	0.5	0.6	0.7	0.7
O_2	%	15.7	15.9	17.1	18.2	18.8
Exhaust temperature	°C	265	259	218	176	156
	°F	509	498	424	349	312
Ambient temperature	°C	26	26	27	27	27
	°F	79	79	81	80	80
Relative humidity	%	74	74	74	75	77
Emissions @ 15% O_2						
NO_x	ppm	455	441	335	177	121
CO	ppm	1,314	1,335	1,621	2,756	4,214
UHC	%	0.7	0.6	0.9	1.5	2.0

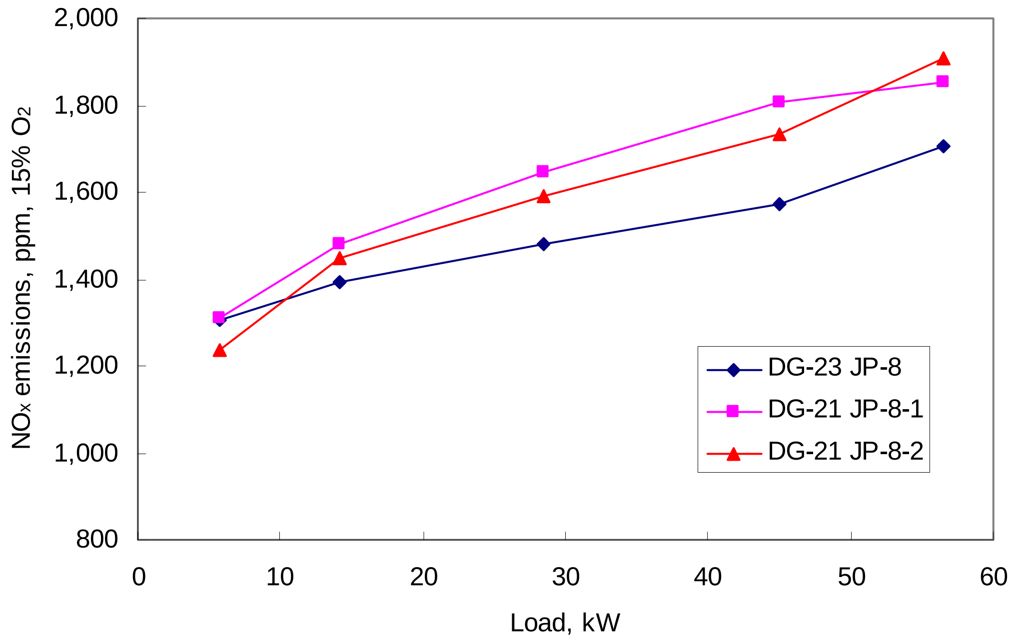

Figure 3-1. Engine NO_x emissions for the November tests with JP-8

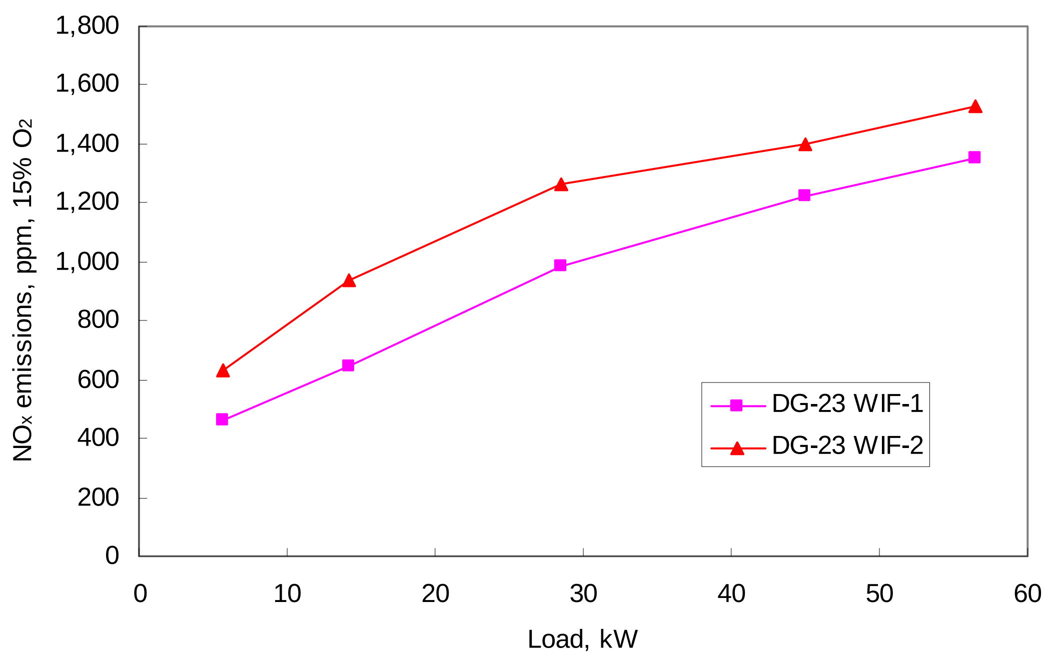

Figure 3-2. Engine NO_x emissions for the November tests with WIF

comparable. Thus, in evaluating the emissions reduction performance of WIF use, comparing the average emissions at a given load is defensible.

Table 3-10 summarizes all the corrected NO_x emissions data from the November tests. Average emissions for the three tests with JP-8 and two tests with WIF are also given in the table. Corresponding NO_x emissions reductions with the WIF emulsion are also noted in the table. The data in the table show that NO_x reductions achieved, based on corresponding average emissions, ranged from 21 percent at maximum load to 57 percent at low load. Average emission data for both the fuels are illustrated in Figure 3-3. Emission reductions achieved, based on the emissions averages, as a function of load are illustrated in Figure 3-4. NO_x weighted average emissions with both fuels using weighting factors from ISO 8178 for the D2 cycle were 1,550 ppm at 15 percent O_2 with JP-8 and were reduced 34 percent to 1,030 ppm at 15 percent O_2 with the WIF emulsion.

Table 3-10. NO_x emission data for the November baseline tests

Test Date	Nov 10 1998	Nov 12 1998	Nov 12 1998		Nov 11 1998	Nov 11 1998		NO_x Reduction with WIF, %	ISO 8178 D2 Cycle Weighting Factor
Engine	DG-23	DG-21	DG-21		DG-23	DG-23			
Fuel	JP-8				WIF				
Load, kW	NO_x, ppm at 15% O_2			Average	NO_x, ppm at 15% O_2		Average		
56.5	1,708	1,851	1,907	1,822	1,349	1,530	1,440	21	0.05
45.0	1,574	1,809	1,734	1,706	1,221	1,401	1,311	23	0.25
28.5	1,482	1,644	1,589	1,572	988	1,263	1,126	28	0.3
14.2	1,391	1,481	1,448	1,440	645	938	792	45	0.3
5.7	1,306	1,312	1,239	1,286	465	632	549	57	0.1
Weighted average emissions				1,550			1,030	34	

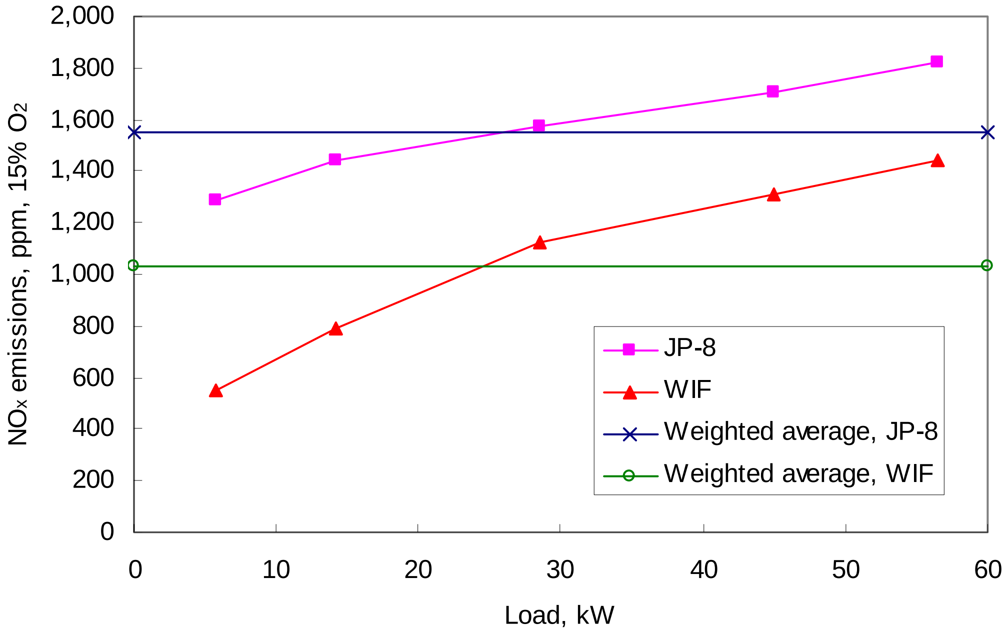

Figure 3-3. Average engine NO_x emissions for the November tests

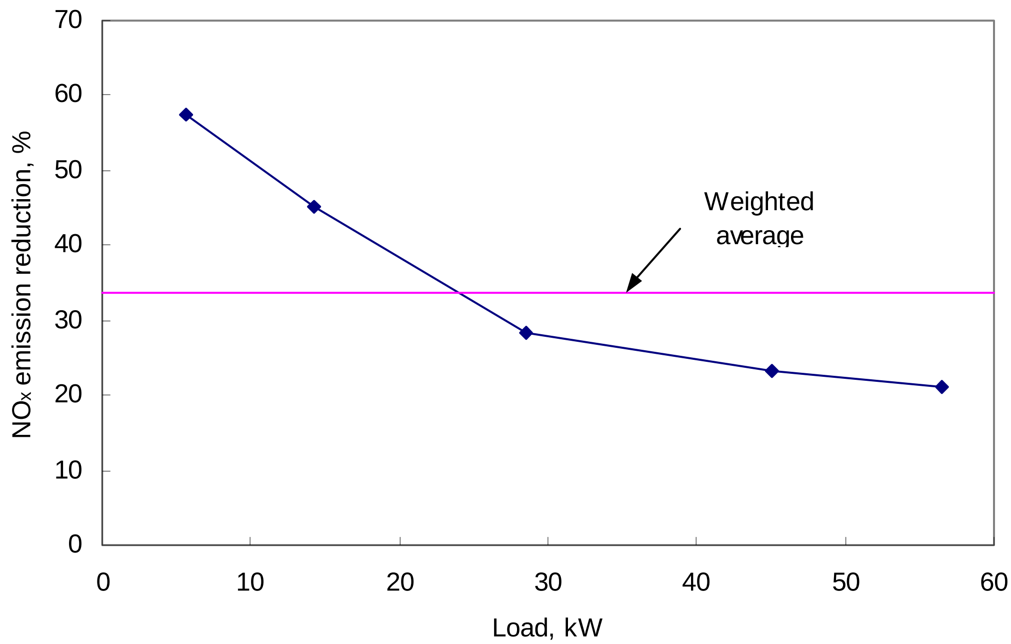

Figure 3-4. NO_x emissions reductions achieved with the WIF emulsion for the November tests

The NO_x emission data from Tables 3-7 through 3-9 for the January tests (corrected to 15 percent O_2) are summarized in Table 3-11. These data are plotted as a function of engine load in Figure 3-5. Again, the data from the duplicate test series with the WIF emulsion are quite comparable. As indicated in Table 3-11, NO_x emissions reductions with the WIF emulsion were 42 percent at nominally 50 kW load, and increased, at 52 percent, at nominally 30 kW load.

For interest, Figure 3-6 shows the combined average NO_x emissions data for both the November and the January tests, and Figure 3-7 shows the NO_x emissions reductions achieved for the two test series. The figures show that engine NO_x emissions were uniformly lower in the January tests, while percentage NO_x reductions achieved were greater. The reason for the differences is not clear. Perhaps the characteristics of the JP-8 used in the January tests, both as the baseline engine fuel and as the base for the WIF emulsion, differed from those used in the November tests. The different emission characteristics also appear in the CO data, discussed in Section 3.1.2.

Water emulsion fuels decrease engine NO_x emissions by reducing the peak cylinder temperature reached during the combustion process. The latent heat of vaporization of the water in the emulsion fuel provides the heat sink giving rise to the peak temperature reduction. The decrease in peak cylinder temperature can be seen in reduced engine exhaust temperatures when operating on the WIF emulsion.

Table 3-12 summarizes the exhaust gas temperature from Tables 3-2 through 3-6 for the November tests. Table 3-13 is the corresponding summary of exhaust gas temperature data from Tables 3-6 through 3-9 for the January tests. The engine exhaust temperature data from Table 3-12 for the November tests are plotted versus engine load in Figure 3-8. Figure 3-9 is the analogous plot for the January test data in Table 3-12. Figure 3-8 shows that engine exhaust

Table 3-11. NO_x emission data for the January baseline tests

JP-8		WIF-1		WIF-2		WIF Average NO_x, ppm at 15% O_2	NO_x Reduction with WIF, %
Load, kW	NO_x, ppm at 15% O_2	Load, kW	NO_x, ppm at 15% O_2	Load, kW	NO_x, ppm at 15% O_2		
59.0	809	54.0	491	49.0	455	473	42
		44.0	380	45.5	441	411	
31.5	708	32.5	338	29.0	335	337	52
		19.0	226	12.4	177	202	
		11.7	161	4.2	121	141	

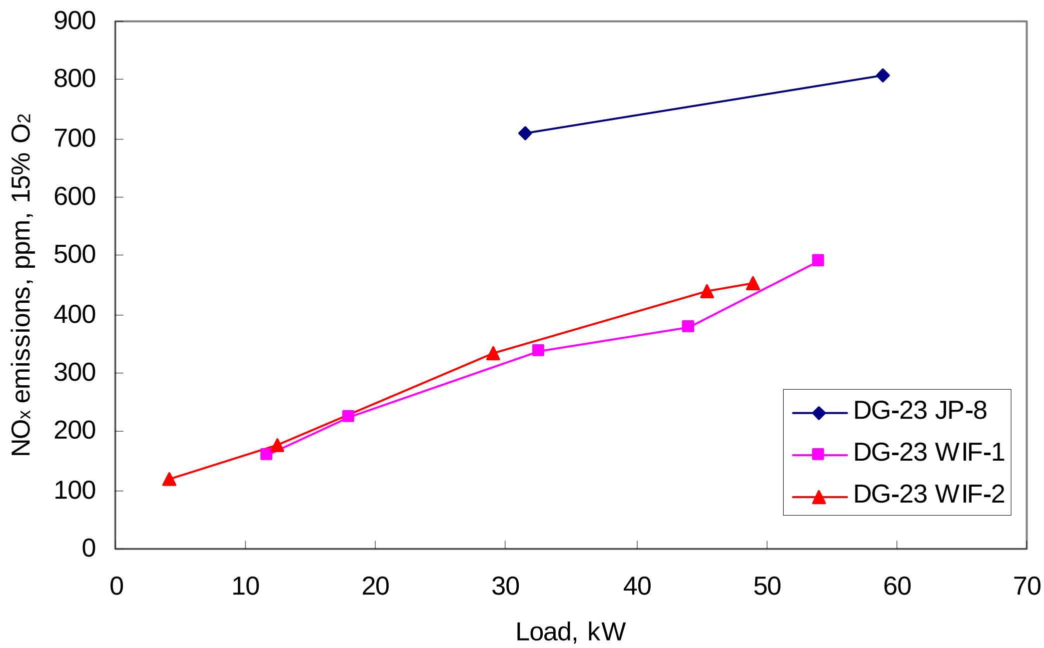

Figure 3-5. Engine NO_x emissions for the January tests

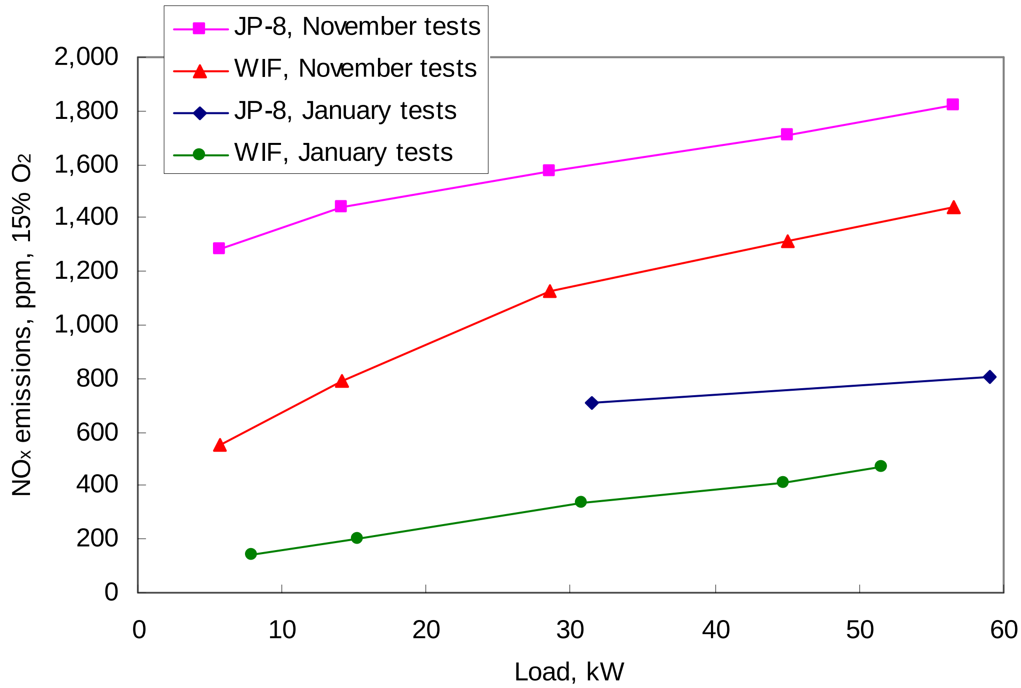

Figure 3-6. Average NO_x emissions data for all tests

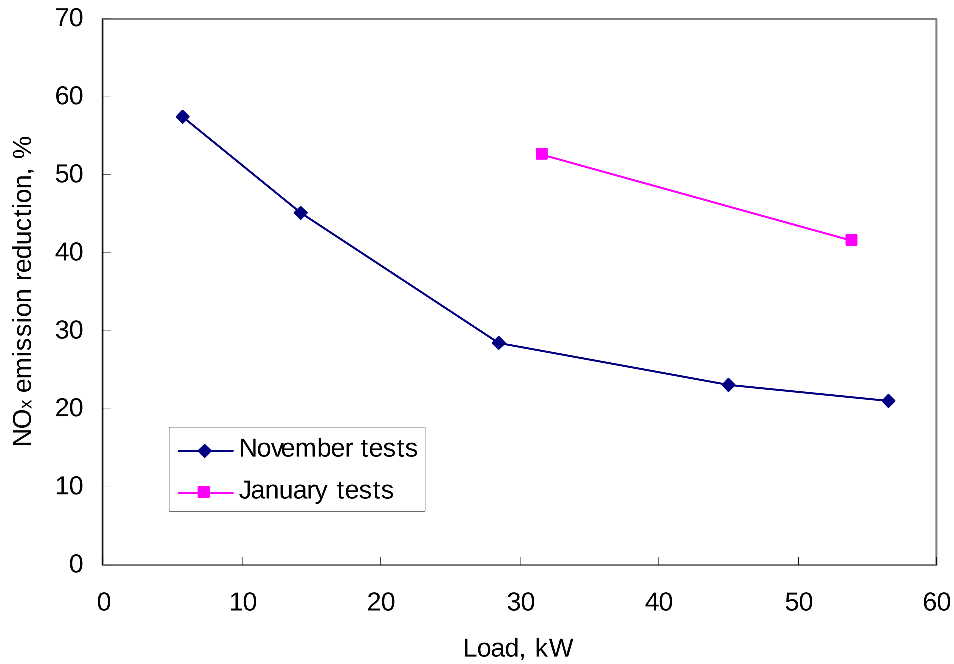

Figure 3-7. Average NO_x emissions reductions achieved

Table 3-12. Exhaust gas temperatures for the November tests

Test Date	Nov 10 1998	Nov 12 1998	Nov 12 1998		Nov 11 1998	Nov 11 1998		Reduction In Exhaust Temperature With WIF, °F
Engine	DG-23	DG-21	DG-21		DG-23	DG-23		
Fuel	JP-8				WIF			
Load, kW	Engine Exhaust Temperature, °F			Average	Engine Exhaust Temperature, °F		Average	
56.5	582	583	585	583	538	548	543	41
45.0	515	514	514	514	478	484	481	33
28.5	431	428	430	430	397	402	400	30
14.2	359	364	364	362	332	336	334	28
5.7	322	325	324	324	304	300	302	22

Table 3-13. Exhaust gas temperatures for the January tests

JP-8		WIF-1		WIF-2		WIF Average
Load, kW	Engine Exhaust Temperature, °F	Load, kW	Engine Exhaust Temperature, °F	Load, kW	Engine Exhaust Temperature, °F	Engine Exhaust Temperature, °F
59.0	597	54.0	537	49.0	509	523
		44.0	481	45.5	498	490
31.5	454	32.5	430	29.0	424	427
		19.0	370	12.4	349	360
		11.7	341	4.2	312	327

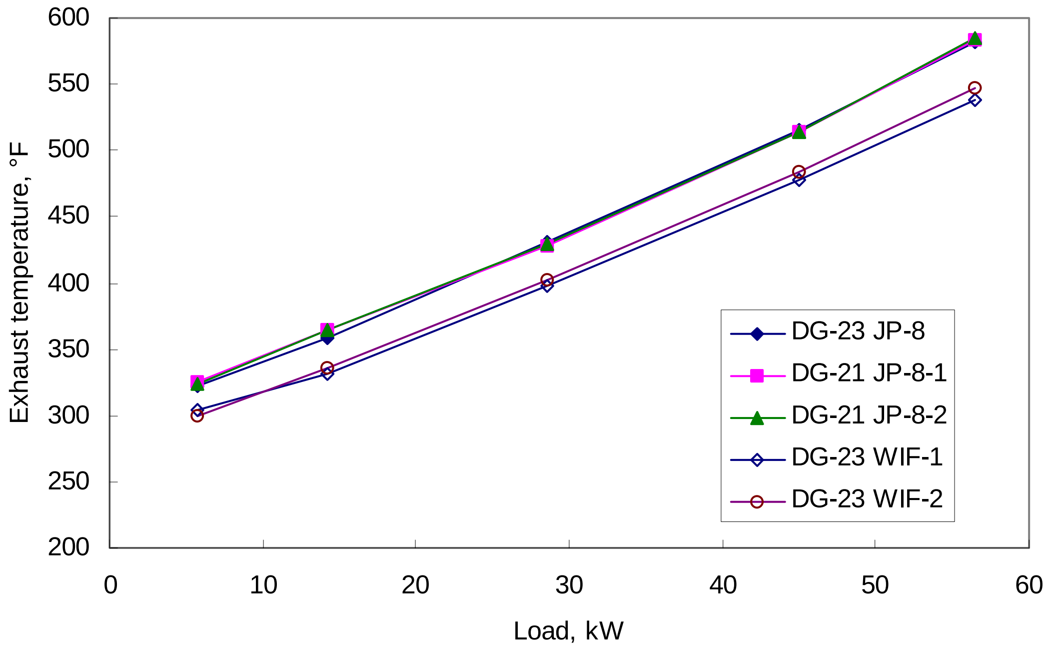

Figure 3-8. Engine exhaust temperatures for the November tests

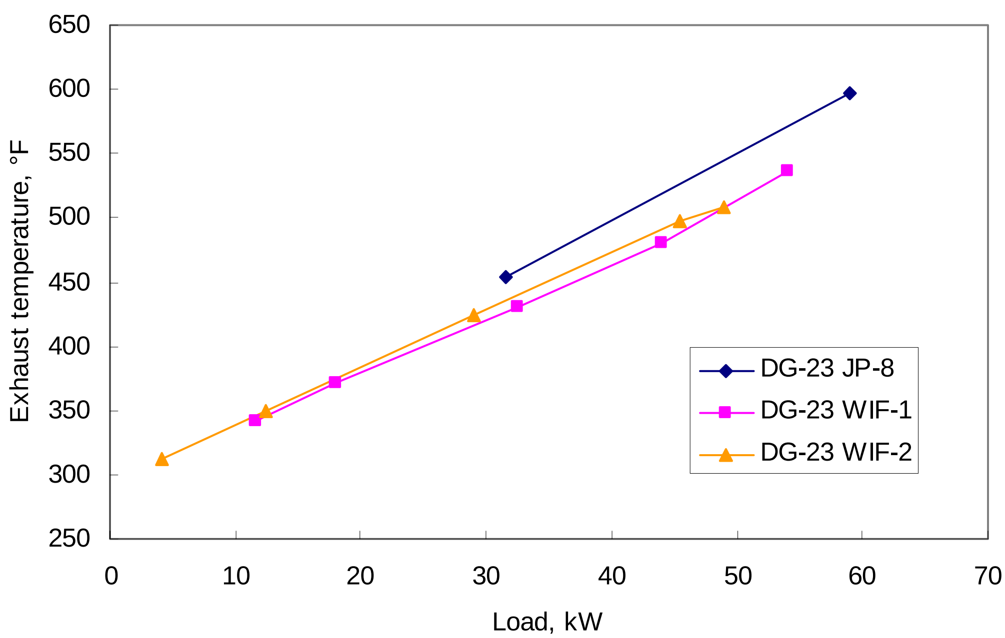

Figure 3-9. Engine exhaust temperatures for the January tests

temperatures for both engines tested with JP-8, one in duplicate, were essentially identical over the engine load range. Similarly, engine exhaust temperatures for the two tests with the WIF emulsion were essentially the same over the engine load range. The exhaust temperature reductions experienced with the WIF emulsion fuel ranged from 22°F at low load to 41°F at high load, as noted in Table 3-12. Figure 3-9 shows similar conclusions for the January tests: exhaust temperatures were comparable for the duplicate WIF tests across the engine load range and temperature reductions with the WIF emulsion were nominally the same as experienced in the November tests.

The average exhaust temperature data from Tables 3-12 and 3-13 for both series of tests are illustrated in Figure 3-10. These average temperatures were quite similar with the JP-8 fuel for both test series and were comparable at the higher loads tested with the WIF. However, at lower loads, the temperature reductions experienced during the November tests were somewhat greater than those seen in January. The greater NO_x reductions seen in January, and the lower NO_x emissions for both fuels experienced in the January tests cannot be explained by the exhaust temperature measurements. Figure 3-11 further illustrates this observation. This figure shows average NO_x emissions as a function of average exhaust temperature for both the November and the January tests. The figure shows that NO_x emissions decreased monotonically with decreasing exhaust temperature in all cases, but emission levels measured for each fuel were substantially different between the November tests and the January tests.

3.1.2 CO Emissions

Table 3-14 summarizes the CO emissions data for the November tests from Tables 3-2 through 3-6, corrected to 15 percent O_2. Table 3-15 is the analogous summary of the CO emissions data for the January tests from Tables 3-7 through 3-9. The emission data from Table 3-14 for the JP-8 tests are plotted versus engine load in Figure 3-12. Figure 3-13 is the

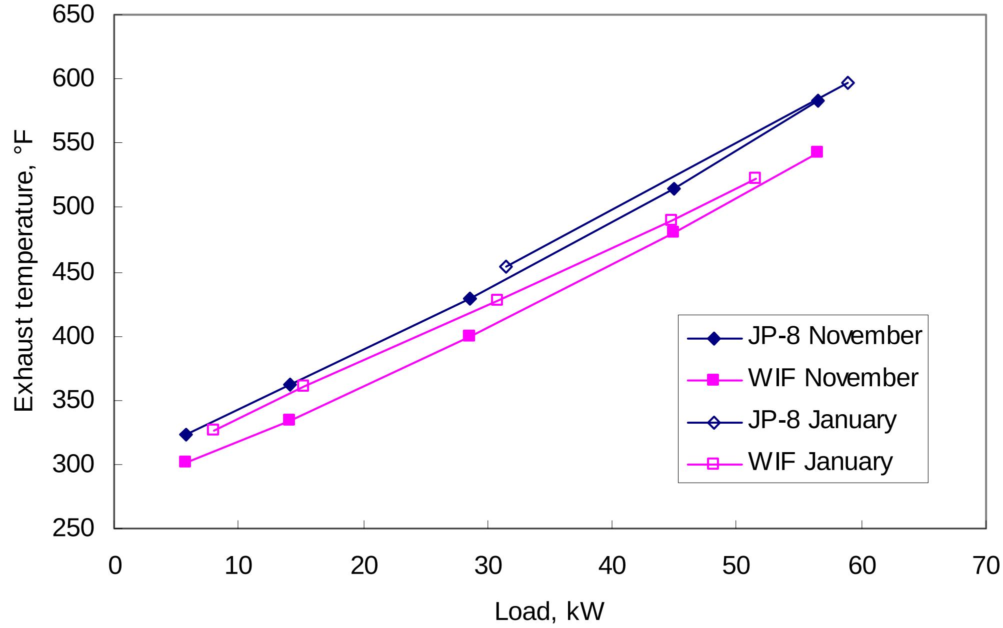

Figure 3-10. Average exhaust temperatures measured

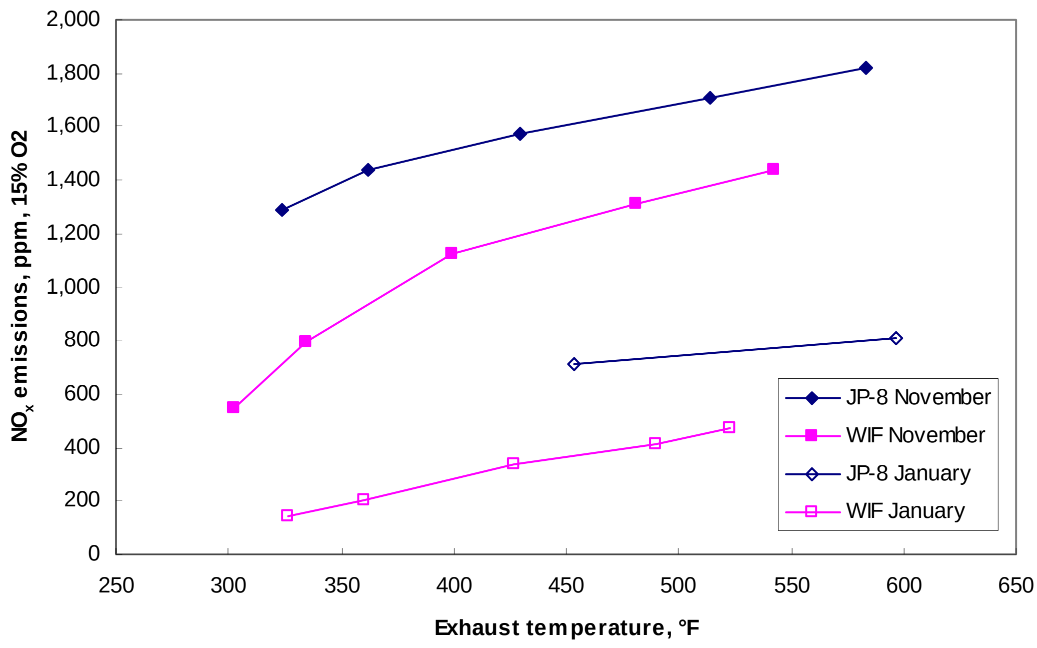

Figure 3-11. Average engine NO_x emissions versus exhaust emperature

Table 3-14. CO emission data for the November baseline tests

Test Date	Nov 10 1998	Nov 12 1998	Nov 12 1998		Nov 11 1998	Nov 11 1998		ISO 8178 D2 Cycle Weighting Factor
Engine	DG-23	DG-21	DG-21		DG-23	DG-23		
Fuel	JP-8				WIF			
Load, kW	CO, ppm at 15% O_2			Average	CO, ppm at 15% O_2		Average	
56.5	502	506	481	496	389	373	381	0.05
45.0	477	529	462	489	379	392	385	0.25
28.5	464	510	469	481	409	433	421	0.3
14.2	481	562	516	520	623	639	631	0.3
5.7	539	609	563	570	1,119	1,053	1,086	0.1
Weighted average emissions				504			540	

Table 3-15. CO emission data for the January baseline tests

JP-8		WIF-1		WIF-2		WIF Average
Load, kW	CO, ppm at 15% O_2	Load, kW	CO, ppm at 15% O_2	Load, kW	CO, ppm at 15% O_2	CO, ppm at 15% O_2
59.0	553	54.0	1,303	49.0	1,314	1,309
		44.0	1,549	45.5	1,335	1,442
31.5	558	32.5	1,522	29.0	1,621	1,572
		19.0	2,354	12.4	2,756	2,555
		11.7	3,054	4.2	4,214	3,634

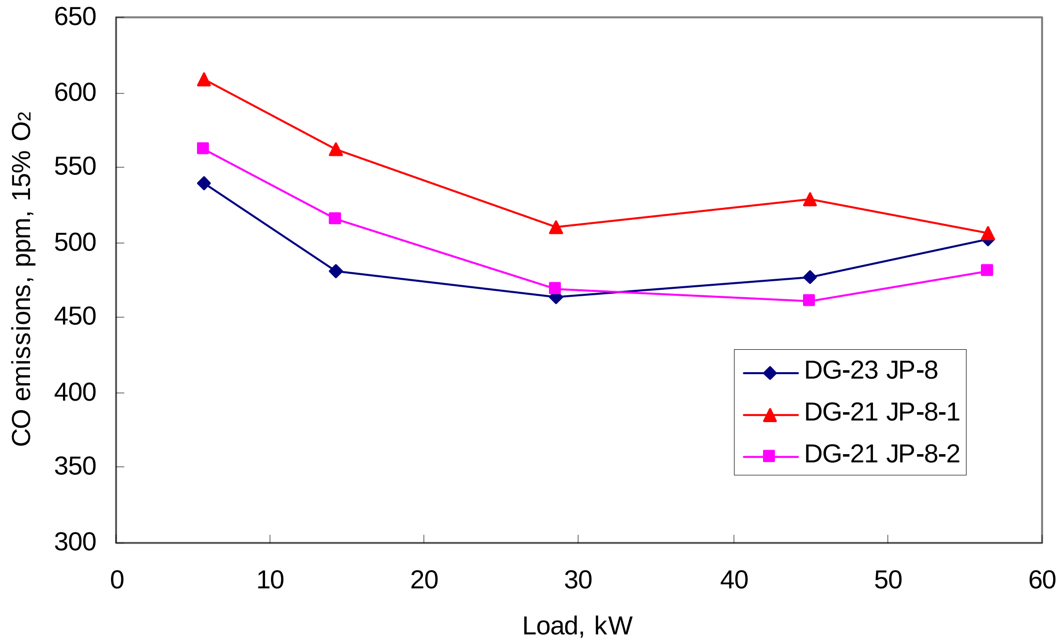

Figure 3-12. Engine CO emissions for the November tests with JP-8

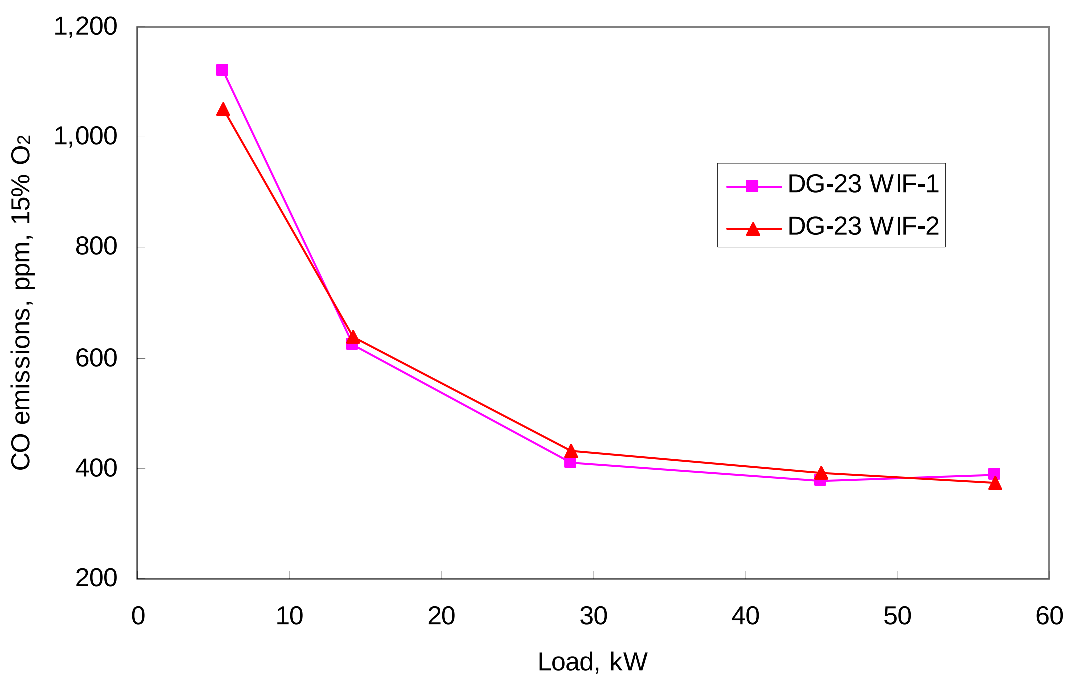

Figure 3-13. Engine CO emissions for the November tests with WIF

corresponding plot of the WIF test data from Table 3-14. As was the case for the NO_x emissions data discussed in Section 3.1.1, CO emissions for the two engines tested with JP-8 fuel, one in duplicate, were comparable over the load range, as were the emissions for the duplicate WIF tests.

Figure 3-14 is a plot of the average emissions measured with each fuel during the November tests. Average CO emissions for JP-8 were relatively constant over the load range at 480 to 570 ppm at 15 percent O_2, and a weighted average for the D2 cycle of 504 ppm at 15 percent O_2. For the WIF emulsion, CO emissions were relatively constant from 100 down to 50 percent load, and lower than those at corresponding load with JP-8 fuel. However, CO emissions with WIF increased significantly at lower (10 percent and 25 percent) load. Overall weighted average emissions with the WIF emulsion at 540 ppm at 15 percent O_2, were only 8 percent greater than the weighted average JP-8 fuel emissions.

Figure 3-15 shows the CO emissions data for the January tests from Table 3-15. Again, emissions with JP-8 fuel were essentially constant over the two load points tested, though 11 to 16 percent greater than at corresponding load points for the November tests. CO emissions with the WIF emulsion showed the same general characteristics as seen in the November tests, exhibiting significant increase as engine load is decreased below 50 percent. However, all levels measured in the January tests were much increased over those measured in November. No apparent explanation for this behavior exists, other than possible changes in JP-8 characteristics, as mentioned in Section 3.1.1.

Figure 3-16 shows the average CO emissions for all the tests and provides a summary illustration of observations stated above, namely:

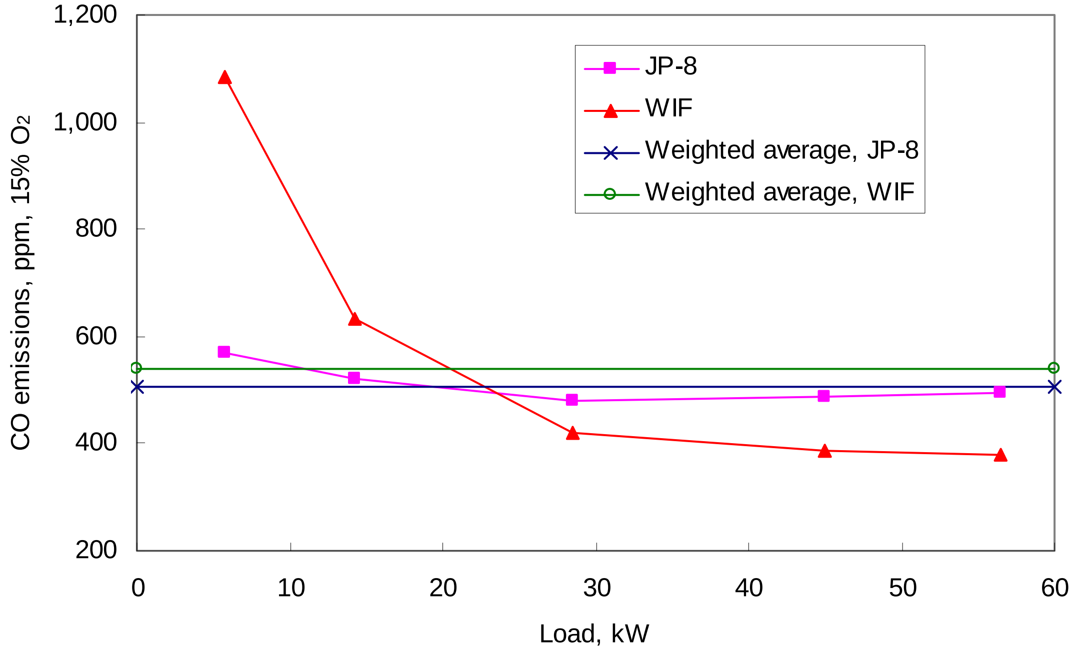

Figure 3-14. Average engine CO emissions for the November tests

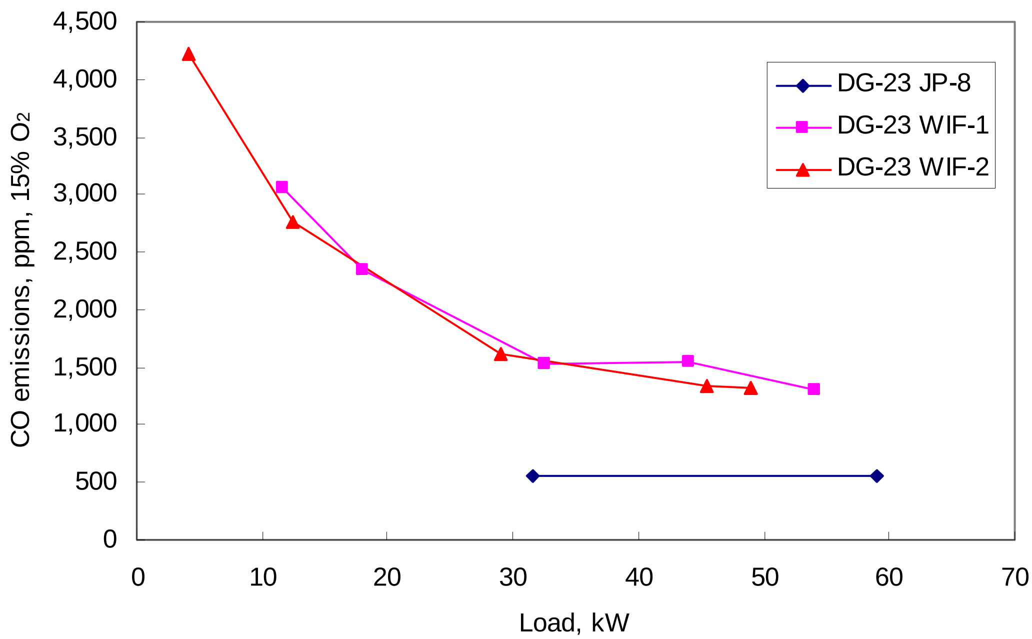

Figure 3-15. Engine CO emissions for January tests

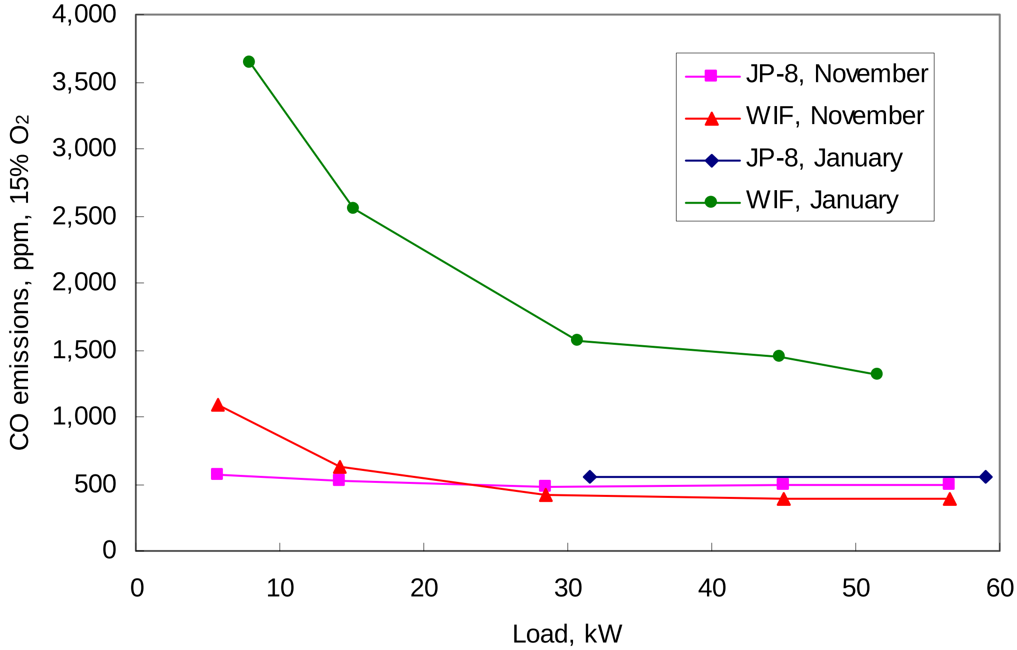

Figure 3-16. Average CO emissions for all tests

- CO emissions were relatively constant over the load range with JP-8 fuel
- CO emissions increased significantly with WIF as load falls below 50 percent
- CO emissions with WIF were substantially greater for the January tests than for the November tests

3.2 PARTICULATE EMISSIONS

As noted in Section 2, engine particulate emissions measurements using a dilution tunnel apparatus as specified in ISO 8178 were attempted during the November testing. Dilution tunnel sampling times of 30 minutes at each load condition were used, an acceptable sampling time within method specifications. However, none of the sampling train particulate collection filters showed measurable weight gains over their tare weights. Thus, no particulate emissions data were obtained. Evidently, a 30-minute sampling period was not sufficient to allow collection of a quantitatible mass of emitted particulate.

4. CONCLUSIONS

A series of performance and emissions tests to evaluate the potential use of a WIF emulsion as a low emission replacement fuel for standard JP-8 in U.S. Air Force AGSE diesel generators. The WIF emulsion was prepared to contain nominally 64 percent JP-8, 30 percent water, 5 percent methanol and 1 percent additives. The methanol used was that produced from coal by the liquid phase process, and is termed liquid phase methanol, LPMEOH™. The additives included emulsion stabilizers and a corrosion inhibitor. Interest in the use of low emission emulsion fuels in AGSE diesel generators is of interest to the Air Force because AGSE accounts for 40 to 60 percent of a typical Air Force base NO_x emissions and the –86 diesel generator accounts for 70 to 90 percent of the AGSE emissions. Air Force bases in the United States are coming under increasing pressure to reduce basewide NO_x emissions and the Air Force is evaluating approaches to do this.

The performance and emission testing completed was to have been the initial phase of an extended evaluation of the WIF emulsion in which two generators were to have been operated in routine flight line use for an extended, 6-month period, one fueled with the WIF and the other fueled with JP-8. However, shortly after completion of the initial emissions testing, mission priorities of all the Air Force organizations supporting the evaluation changed to the point that further support of the project was not possible. So, the evaluation project did not proceed beyond completion of the initial emissions testing.

In the tests completed, engine emissions of O_2, CO, CO_2, NO_x, and UHC were measured from engines fueled with both WIF and JP-8. The ISO 8178 D2 test cycle was used. Particulate emissions measurements were also performed using a dilution tunnel measurement technique as specified by the ISO procedure. However, the 30-minute sampling time at each test load was not long enough to allow collecting measurable quantities of particulate on the sampling train filters.

Results of the tests were as follows:

- Use of the WIF emulsion reduced engine NO_x emissions by 21 to 57 percent over the engine load range, with the greater emission reductions achieved at lower engine loads. The ISO cycle weighted average NO_x emissions were reduced 34 percent from 1,550 ppm at 15 percent O_2 with JP-8 fuel to 1,030 ppm at 15 percent O_2 with WIF
- CO emissions from the engine did not vary significantly with load for the JP-8 fuel, and were nominally 500 ppm at 15 percent O_2. With the WIF emulsion, CO emissions were relatively constant at engine loads from full load to 50 percent load, but increased substantially at lower engine loads.
- Relative CO emissions for the two test fuels showed inconsistent behavior. For one series of tests, CO emissions with the WIF emulsion were lower than with JP-8 at engines loads of 50 percent or greater, but were higher at lower engine loads. ISO-cycle weighted average emissions for this test series were comparable for both fuels. For a second test series, CO emissions were substantially higher with the WIF emulsion than with JP-8 at all engine loads tested.

Although the planned long-term evaluation encompassing extended flight line operation with both fuels was not completed, project results suggest that use of the WIF emulsion tested would not be a good approach to reducing diesel generator NO_x emissions in Air Force applications. Although NO_x emissions reduction with the WIF were impressive, severe problems with cold starting and operation at low ambient temperatures were experienced. There are several potential approaches to solving these problems. A few were tried in this project without success. Until the cold start problem is solved, WIF use in Air Force applications is not recommended.

APPENDIX A. TEST DATA RECORDS