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EFFECT OF FUEL BOUND NITROGEN ON OXIDES OF NITROGEN EMISSION FR--ETC(U)
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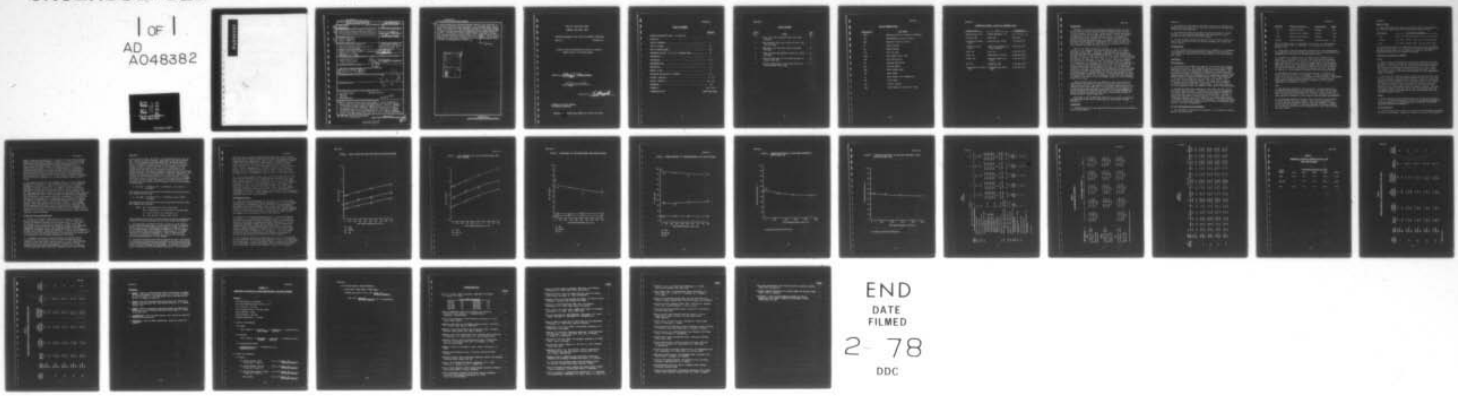

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Fuels of varying nitrogen content were tested in a T63-A-5A engine to measure their effects on exhaust gas emissions. Five test fuels varying in fuel bound nitrogen content from 3 (49) (nitrogen)/g (fuel) to 902 (49) (nitrogen)/g (fuel) were evaluated. The nitrogen content in the fuel was adjusted by mixing a JP-5 type fuel derived from shale oil (902 (49) (nitrogen)/g (fuel)) and regular petroleum JP-5 fuel (3 (49) (nitrogen)/g (fuel)). Nitrogen content of the fuel had no effect on engine performance.

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AB

The carbon monoxide and unburned hydrocarbon emissions were equivalent for all the fuels included in the test program. For the engine power ratings tested, the oxides of nitrogen emissions increased with increasing nitrogen content of the test fuel. The conversion efficiency of fuel bound nitrogen to oxides of nitrogen appears to be independent of the nitrogen content of the fuel. Difficulties in measuring small changes in oxides of nitrogen level resulting from low nitrogen content fuels (50 µg nitrogen/g (fuel) or less) caused the conversion efficiency to be very variable. The conversion efficiency for fuels with a nitrogen content of 250 µg (nitrogen)/g (fuel) or greater was approximately 45 percent.

microgram

NAVAL AIR PROPULSION CENTER

TRENTON, NEW JERSEY 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPC-PE-1

NOVEMBER 1977

EFFECT OF FUEL BOUND NITROGEN ON OXIDES OF NITROGEN EMISSION FROM A GAS TURBINE ENGINE

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Full Words
ASTM	American Society for Testing of Materials
EPA	Environmental Protection Agency
NAPC	Naval Air Propulsion Center
CO	carbon monoxide
CO_2	carbon dioxide
F/A	fuel air ratio
FCLA	Fuel Control Lever Angle
GTE	gas turbine engine
HC	unburned hydrocarbons
MIL	Military Rating
NPT	Power Turbine Speed
NR	Normal Rated
T_5	Power Turbine Inlet Temperature
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	total oxides of nitrogen ($NO + NO_2$)

CONVERSION FACTORS: SI TO U.S. CUSTOMARY UNITS

Convert From	To	Multiply by
degree Celsius (°C)	degree Fahrenheit (°F)	$t_{°F} = 1.8\ t_{°C} + 32$
kilogram (kg)	pound (lb)	2.204 622
kilogram per second (kg/s)	pound per hour (lb/hr)	$7.936\ 640 \times 10^{3}$
kilogram per watt (kg/w)	pound per horsepower per hour (lb/HP-hr)	$5.918\ 352 \times 10^{6}$
metre (m)	inch (in)	$3.937\ 007 \times 10^{1}$
newton (N)	pound-force (lb-force)	$2.248\ 089 \times 10^{-1}$
pascal (Pa)	pound per square inch (psi)	$1.450\ 377 \times 10^{-4}$
watt (W)	horsepower (HP)	$1.341\ 022 \times 10^{-3}$
revolutions per second (rps)	revolutions per minute (rpm)	$6.000\ 000 \times 10^{1}$

INTRODUCTION

The Navy, as a large user of petroleum products to power its ships and aircraft, is seriously concerned about the possible loss of this strategic material in the future. Naval aircraft consume approximately one billion gallons of JP-5 type fuel each year. In order to reduce its dependence on this critical material, the Navy is conducting extensive conservation programs and is evaluating petroleum products derived from alternate sources such as tar sands, shale oil and coal. The Chief of Naval Materials (Development) has assigned the Naval Air Propulsion Center (NAPC) the responsibility of evaluating JP-5 type fuels obtained from these alternate sources.

Back in 1975, NAPC successfully completed its first full scale evaluation of an alternate fuel derived from tar sands in a T63-A-5A gas turbine engine (GTE). Reference 1 reported that the tar sands alternate fuel would be an acceptable substitute for petroleum derived JP-5 fuel and that it would have little effect on engine exhaust emissions. Included in reference 2 are the results of an evaluation of a hydrotreated coal derived JP-5 type fuel in the same T63 GTE. Again the alternate fuel had little or no effect on engine performance or emission levels. In an evaluation of an alternate fuel derived from shale oil (reference 3), it was found that the alternate fuel did not meet the requirements of Military Specification MIL-T-5624K for JP-5 fuel. Due to high levels of solids in the fuel, in-line filters were employed to protect the engine during the evaluation. Even though this fuel did not meet specification, no change in the T63 GTE performance was observed when compared to the engine performance on regular JP-5 fuel. It was observed that the oxides of nitrogen (NO_x) levels were significantly higher than those obtained with regular JP-5 type fuel and are probably related to the high nitrogen content of the fuel.

The JP-5 derived from shale oil employed in this test program was reprocessed by distillation to improve its physical properties and to remove solids and gums. The fuel met the military specification for JP-5 type fuel except for freeze point. The objectives of this study were to confirm the presence of high levels of NO_x in the engine exhaust, to obtain information on conversion efficiency of fuel bound nitrogen into NO_x, and to assess the impact of this high nitrogen containing fuel on meeting pollution control regulations.

This study is part of NAPC Work Unit Plan No. 812 which was approved and authorized by the Chief of Naval Material (Development) through reference 4.

CONCLUSIONS

1. NO_x emissions for the same engine power rating increased with increasing fuel nitrogen content.

2. The conversion efficiency of fuel bound nitrogen to NO and NO_x was approximately 45 percent for the test data in which the NO and NO_x values could be accurately measured.

3. No significant effects were noted on engine performance or carbon monoxide (CO) and unburned hydrocarbons (HC) emissions due to the presence of high levels of fuel bound nitrogen.

4. The use of shale derived JP-5 fuel with a high nitrogen content will make it more difficult to meet the EPA NO_x standards for aircraft gas turbine engines.

RECOMMENDATION

1. A test program should be initiated using a combustor rig to determine those parameters (fuel properties and/or combustion characteristics) which affect the conversion of fuel bound nitrogen in oil shale derived fuel to NO_x.

DESCRIPTION

T63-A-5A Engine

1. An Allison T63-A-5A engine was used for the alternate fuel nitrogen conversion evaluation. This turboshaft engine is of the "free" turbine type and is used in the Army OH-58A and Navy TF-57A helicopters. The gas producer section is composed of a combination six-stage axial flow, one-stage centrifugal flow compressor directly coupled to a two-stage gas producer turbine which is gas coupled to the "free" power turbine. The engine contains an integral reduction gearbox (5.84:1) which provides an internal spline output drive at the front of the gearbox. The engine has a single combustion chamber. The output shaft centerline is located below the centerline of the engine rotor and the exhaust is directed upward through dual exhaust pipes. An air bleed valve at the fifth compressor stage is provided to insure surge free accelerations.

2. The T63-A-5A engine was installed in a sea level test cell using a three-point mounting system. A flywheel and an Industrial Engineering Water Brake, Type 400 were connected to the engine gearbox assembly at the forward power output pad to absorb the engine power. The brake reaction was measured by a Baldwin load cell. The power turbine inlet temperature indication (T_5) is an average of four thermocouples located at the power turbine inlet nozzle. All parameters to determine the engine starting and steady-state performance with the fuels were measured using standard test cell instrumentation.

Emission Instrumentation and Equipment

3. The instruments listed below were employed in the analysis of exhaust samples from this engine:

Pollutant	Analysis Principle	Manufacturer	Model
HC	flame ionization	Beckman	402
CO	nondispersive infrared	Beckman	315A
CO_2	nondispersive infrared	Beckman	315A
NO/NO_x	chemiluminescence	Thermo-Electron	10A

These instruments meet the requirements specified by the Environmental Protection Agency (EPA) in reference 5 for the analysis of aircraft exhaust gases.

4. Gases used to calibrate the above instrumentation were purchased from Scott Specialty Gases and Matheson Gas Products and the concentrations were guaranteed by the vendor to be accurate to ±2 percent.

5. An exhaust gas sampling probe was fabricated in accordance with reference 5. It was made of stainless steel with four arms extending from a central manifold. The plane of the probe was an ellipse with major and minor axes of 231.8 mm (9-1/8 inches) and 177.8 mm (7 inches). There were three 1.524 mm (0.060 inch) diameter holes at the centers of equal areas on each arm. The probe was centered in the exhaust stream 41.3 mm (1-5/8 inches) downstream of the exhaust pipe exit. The probe was mounted in the port exhaust tailpipe of this dual tailpipe engine.

6. The exhaust gas sampling line was approximately 7.6 m (25 ft) in length and 9.525 mm (0.375 in) in diameter. The line consisted of two 3.0 m (10 ft) and one 1.5 m (5 ft) sections of Technical Heater, Incorporated, Model JP 212 Heated Gas Analyses Sampling Hose. The sample line was maintained at a temperature of 149°C ± 5°C (300°F ± 9°F) to prevent condensation of material in the line.

Fuel

7. Two fuels were employed in this evaluation. One was regular JP-5 derived from petroleum, which was available at the Center, and the other was a JP-5 type fuel derived from crude shale oil. Prior to test, the shale oil JP-5 product was redistilled to remove the excessive solids and gums reported in reference 3, and to improve other marginal characteristics.

8. The nitrogen content of the test fuels was varied by mixing regular JP-5 and shale oil JP-5 fuel together. Test fuels corresponding to 0, 5, 30, 60, and 100 percent shale oil JP-5 were evaluated. A sample of each fuel was subjected to laboratory analyses to determine conformance to Military Specification MIL-T-5624K for JP-5 fuel, and fuel bound nitrogen content.

METHOD OF TEST

1. Engine performance and exhaust gas emission levels were measured at the following engine conditions for each of the five test fuels:

Power Rating	Controlling Parameters
Idle	FCLA = 0.52 rad (30°); NPT = 417 rps (25,000 rpm)
60% NR	T_5 = 577°C (1070°F); NPT = 583 rps (35,000 rpm)
MIL	T_5 = 749°C (1380°F); NPT = 583 rps (35,000 rpm)

The engine was allowed to stabilize for five minutes before performance and emission data were taken. No engine bleed air was extracted during emission sampling except at idle where the compressor fifth-stage acceleration bleed valve is automatically opened.

DISCUSSION AND ANALYSIS OF RESULTS

Fuels

1. Table I contains the results of the analysis performed on the five test fuels. The fuels met the JP-5 specification requirements with the exception of freeze point. The 30, 60 and 100 percent shale oil JP-5 had freeze points exceeding the specification limit of -46°C (-51°F). This deficiency had no impact on the test results obtained for these three fuels because all the tests were performed with fuel temperatures around 27°C (80°F).

2. Total fuel bound nitrogen content reported included both basic and non-basic nitrogen. Basic nitrogen was determined for each of the test fuels by non-aqueous perchloric acid titration. Non-basic nitrogen was determined by microcoulometry for the 100 percent shale oil JP-5, only. The non-basic nitrogen for the other fuels was calculated based upon the mixing ratio between regular JP-5 fuel and shale oil JP-5 fuel. Regular JP-5 fuel was assumed to have no non-basic nitrogen. The total fuel bound nitrogen content for the five test fuels varied from 34 g (nitrogen)/g (fuel) for regular JP-5 to 902 g (nitrogen)/g (fuel) for 100 percent shale oil JP-5.

Engine

3. Engine performance data obtained during the program can be found in Table II. The nitrogen content of the fuel had no significant effect on engine performance (cycle efficiency) and this confirms the findings previously reported in reference 3.

Exhaust Emissions

4. Table III contains the results of the exhaust gas measurements performed during the test program. Because of a mechanical failure of the sampling

pump, no data was obtained for the base line JP-5 fuel at the 60 percent normal rated (NR) power condition. Figures 1, 2, 3, and 4 show how the emissions from this engine varied with the nitrogen content of the test fuel. The nitric oxide (NO) and NO_x emissions (Figures 1 and 2, respectively) both show increases in emission levels with increases in fuel nitrogen content. Since NO and NO_x formation is a function of temperature and residence time, which remained virtually unchanged for each power setting during the study, the increase in emission levels has to be related to fuel nitrogen content. Further interpretation of the NO and NO_x data and discussion of fuel nitrogen conversion efficiency can be found in the Conversion of Fuel Bound Nitrogen section of this report.

5. The unburned hydrocarbon (HC) emissions (Figure 3) at idle appear to decrease with increasing nitrogen content of the fuel. This change was unexpected and could not be related to any physical and/or chemical property of the fuel (see Table I). In order to identify the cause of this change, the idle engine performance data presented in Table II was reviewed. It is apparent from Table II that the idle performance (F/A, T_5, and shaftpower) all increased in going from base line JP-5 to the nitrogen containing test fuels. This improvement in performance is consistent with the decrease in HC emissions observed. The change in HC emissions at idle has to be relegated to the engine operator's inability to reproduce the same idle power condition. Hydrocarbon emissions for the 60 percent NR and Military (MIL) power conditions show no effect of fuel nitrogen content. The carbon monoxide (CO) emissions (Figure 4) also decreased with increasing fuel nitrogen content at the idle power condition. Just as with the hydrocarbon emissions this decrease has to be related to the engine operator's inability to reset the same idle power condition for each test fuel. The CO emissions for the 60 percent NR and MIL power conditions remained virtually unchanged.

Conversion of Fuel Bound Nitrogen

6. The NO_x in the exhaust plume comes from two sources: nitrogen in air and nitrogen in fuel. The conversion of air nitrogen to NO_x is a function of combustion temperature and residence time. In this report the fixation of air nitrogen will be defined as thermal NO and NO_x. For the same engine power condition thermal NO and NO_x will be considered independent of the fuel tested. The difference between NO and NO_x measured in the exhaust gas and the thermal NO and NO_x is the contribution of fuel bound nitrogen. Conversion efficiency is defined as the ratio of the actual fuel bound nitrogen contribution to the theoretical fuel bound nitrogen contribution, and is usually expressed as a percentage.

7. In combustor rig testing, where the operating conditions can be environmentally controlled, it is easy to reset the same operating conditions, but in gas turbine engine testing, it is not always possible to reset the same test point every time due to changes in ambient conditions and engine operating parameters. From the data in Table II, it can be seen that Power Turbine Inlet Temperature (T_5) varied as much

as 22°C (40°F) at idle, 16°C (29°F) at 60 percent NR and 5°C (9°F) at MIL. Because of these variations, especially at idle and 60 percent NR, it is not possible to use the regular JP-5 NO and NO_x emission values as measures of thermal NO and NO_x value for each of the test fuels. In order to analyze the data, it was necessary to develop a thermal NO and NO_x value for each of the test fuels based on the conditions of that test. If it is assumed that NO and NO_x in the exhaust plume was a function of combustion temperature and fuel nitrogen content and that T_5 is a direct function of combustion temperature, then statistical techniques can be employed to isolate the effects of temperature and fuel nitrogen content on NO and NO_x emissions. Multiple Regression Analysis, an extension of the Least Square Analysis Concept for fitting a curve to data, was applied to the fourteen data points obtained during the program and the following equations were developed for NO and NO_x:

a. $NO\ (ppm) = 0.075814\ T_5\ (°C) + 0.010684\ N_f\ (\mu g/g\ (fuel)) - 31.854447$

The standard deviation obtained when the measured and predicted values were compared was ± 1.08 ppm.

b. $NO_x\ (ppm) = 0.073961\ T_5\ (°C) + 0.011833\ N_f\ (\mu g/g\ (fuel)) - 30.749173$

The standard deviation obtained when the measured and predicted values were compared was ± 1.08 ppm.

Where: NO = concentration of nitric oxide (ppm)

NO_x = concentration of total oxides of nitrogen (ppm)

T_5 = power turbine inlet temperature (°C)

N_f = fuel nitrogen content ($\mu g/g$ (fuel))

These equations can be used to predict exhaust NO and NO_x concentration, thermal NO and NO_x contributions and the fuel nitrogen contribution.

8. The theoretical contribution of fuel nitrogen to engine exhaust gas NO and NO_x emission levels, if all the fuel nitrogen is converted to NO or NO_x, can be calculated based on exhaust gas chemistry and fuel nitrogen content. The exhaust gas chemistry is used to correct for any sampling deficiencies through a carbon balance. An example calculation is presented in Appendix A. Table IV summarizes the theoretical NO and NO_x contributions for all the fuels and engine power conditions included in the test program.

9. The actual concentration of fuel nitrogen NO and NO_x in the exhaust can be obtained by subtracting the thermal NO or NO_x from the NO or NO_x concentration measured in the exhaust gases. The conversion efficiency, which is normally expressed as a percentage, is obtained by dividing the actual concentration by the theoretical contribution. The conversion

efficiency was calculated on both a NO and a NO_x basis and the results, along with total, thermal, theoretical and actual fuel nitrogen NO and NO_x concentrations are summarized in Tables V and VI, respectively. Figures 5 and 6 show how conversion efficiency was affected by the nitrogen content in the fuel. The data in both tables are almost identical which indicated that none of the fuel bound nitrogen is being converted to NO_2. Strict interpretation of the data presented in the tables would be that the conversion efficiency is slightly higher at low fuel nitrogen contents (approximately 55 percent) and it slowly drops off and finally levels off around 45 percent at high fuel nitrogen contents.

10. At low fuel nitrogen contents (less than 50 μg (nitrogen)/g (fuel)), the actual and theoretical fuel nitrogen NO/NO_x contributions are very small. These levels are below, or approach, the accuracy of the chemiluminescence analyzer as can be seen by the large variation in conversion efficiency for the 3 and 47 μg (nitrogen)/g (fuel) test fuels. With these fuels an error of $\pm$1 ppm can change the conversion efficiency from 0 to 100 percent, while, with the high nitrogen test fuel (902 μg (nitrogen)/g (fuel)), a change of $\pm$1 ppm only affects the conversion efficiency by ten percent. Most likely, conversion efficiency is actually independent of the fuel nitrogen content, and is a function of the combustion parameters that exist in the combustor.

Environmental Effect

11. Since more than fifty percent of the nitrogen in the fuel was not accounted for in NO/NO_x measurements, additional testing using a nitrogen balance method is necessary to resolve the question of what happens to the remaining fuel bound nitrogen. There are many possible molecules which could be formed, three of which are nitrogen gas, cyanide compounds (R-CN) or nitroso compounds ($R-NO_2$). These latter two types of compounds are highly reactive and could have a very detrimental effect on the environment if they are emitted in sufficient quantity.

12. The effect of increased NO/NO_x emissions on current Navy engines is variable. For low temperature combustion systems such as those in turboprop and turboshaft engines the NO/NO_x emissions, because of fuel nitrogen, could double the exhaust gas NO/NO_x concentration. In high temperature combustion systems used in high performance turbojet and turbofan engines which already have high NO/NO_x emission levels, the effect of NO/NO_x emissions will be small. Gas turbine engines using current technology combustion systems already exceed the limits established by the EPA for commercial aircraft engines. The use of shale derived JP-5 fuel with high nitrogen will aggravate the problem of meeting the EPA Standards for aircraft gas turbine engines.

13. The technology necessary to manufacture and refine usable petroleum products from coal and oil shale crude material is still in the laboratory/pilot plant stage. As this technology advances processes, catalysts, etc. must be developed to remove the nitrogen. When this happens the effect on the environment caused by the formation of NO_x will be minimized.

FIGURE 1. NITRIC OXIDE (NO) EMISSIONS VERSUS FUEL BOUND NITROGEN

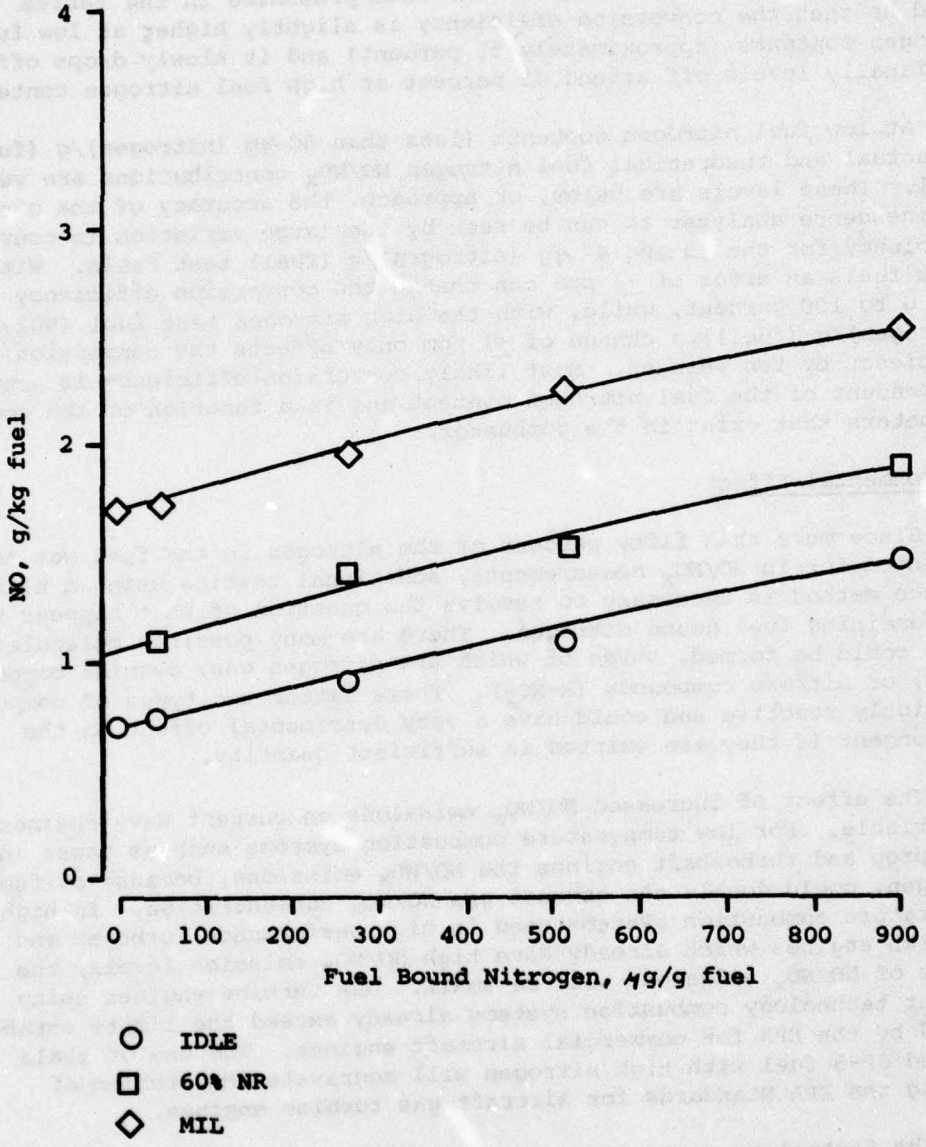

FIGURE 2. TOTAL NITROGEN OXIDE (NO_x) EMISSIONS VERSUS FUEL BOUND NITROGEN

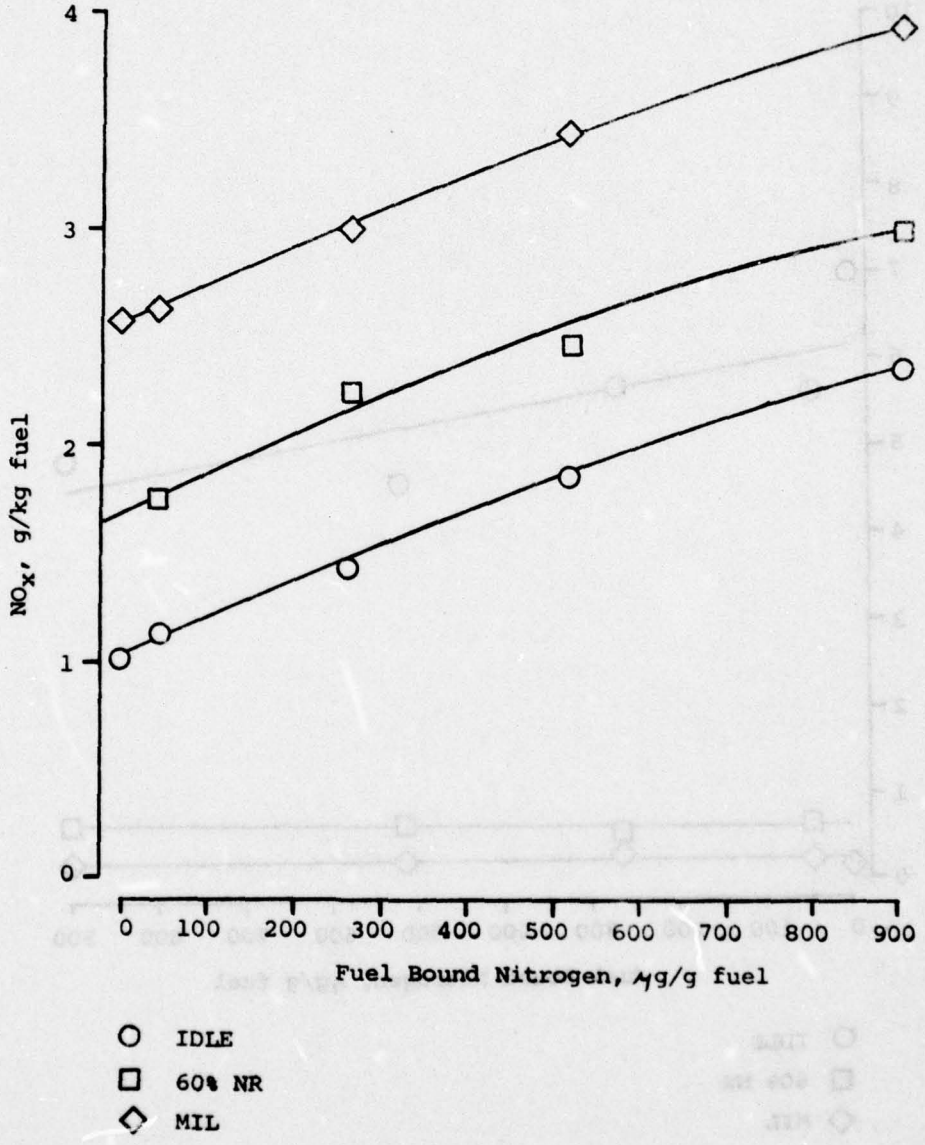

FIGURE 3. HYDROCARBON (HC) EMISSIONS VERSUS FUEL BOUND NITROGEN

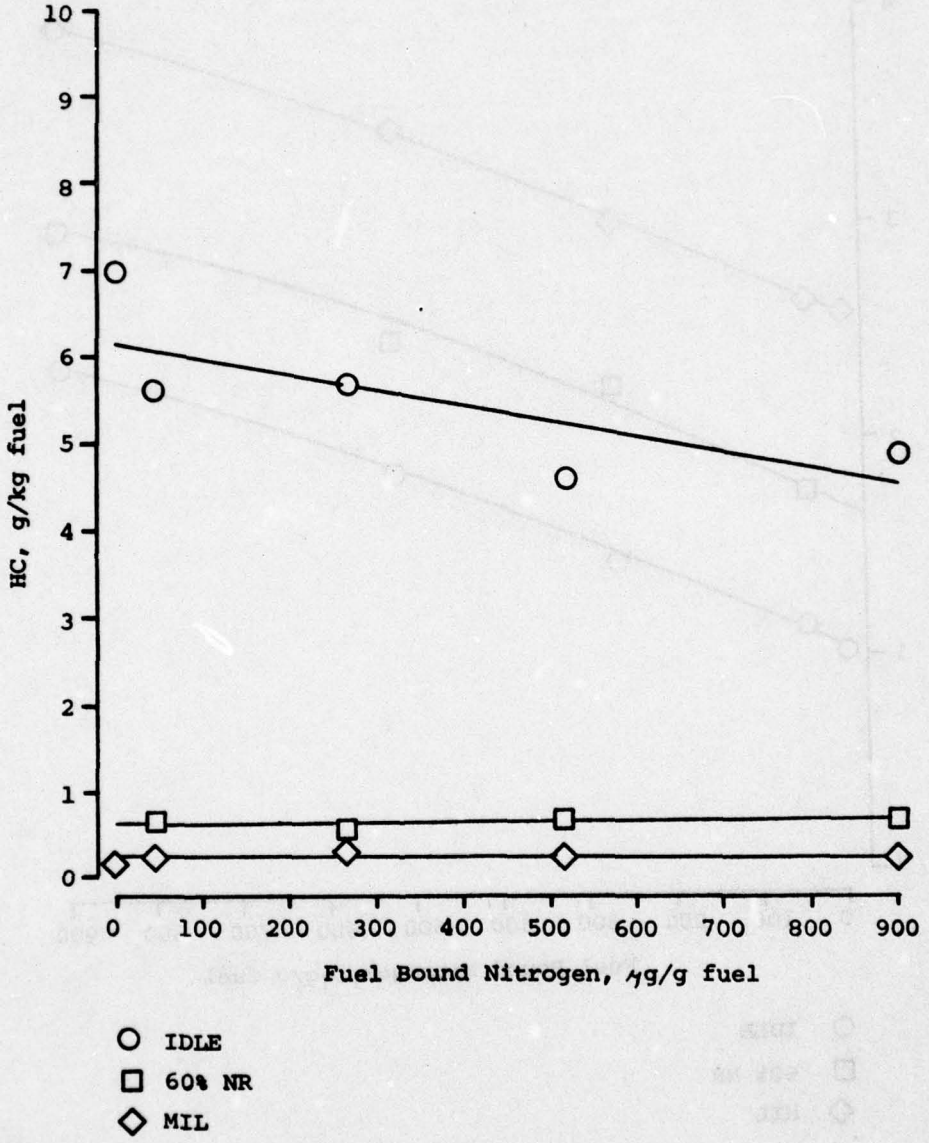

FIGURE 4. CARBON MONOXIDE (CO) EMISSIONS VERSUS FUEL BOUND NITROGEN

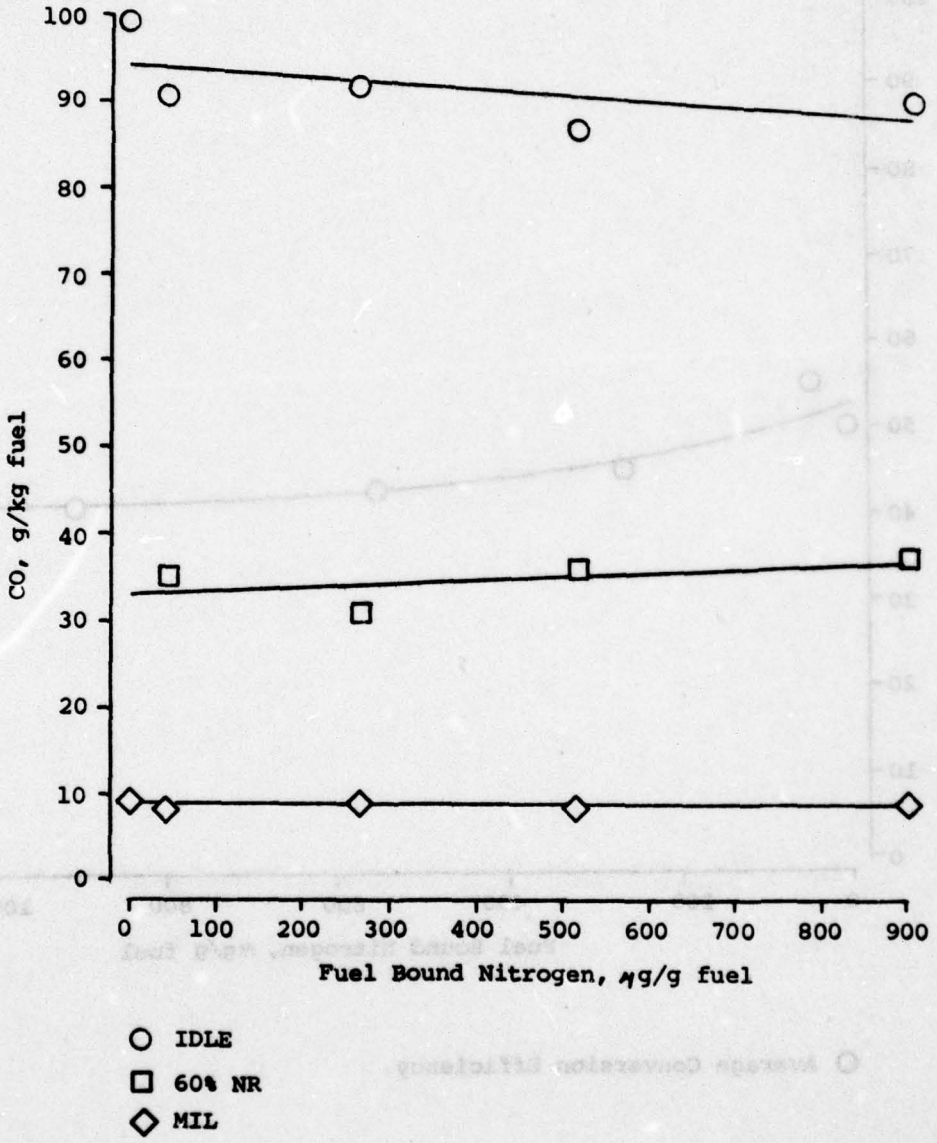

FIGURE 5. CONVERSION EFFICIENCY OF FUEL BOUND NITROGEN TO NITRIC OXIDE (NO)

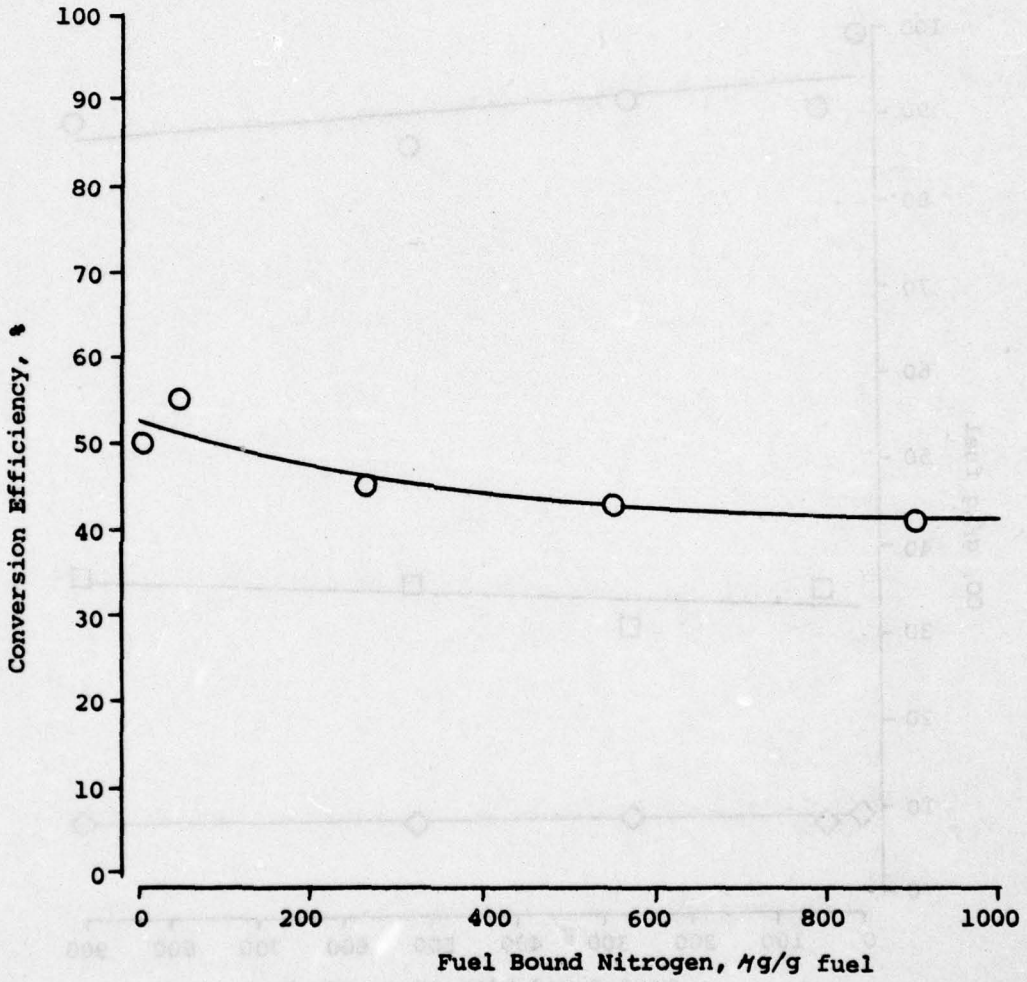

FIGURE 6. CONVERSION EFFICIENCY OF FUEL BOUND NITROGEN TO TOTAL NITROGEN OXIDES (NO_x)

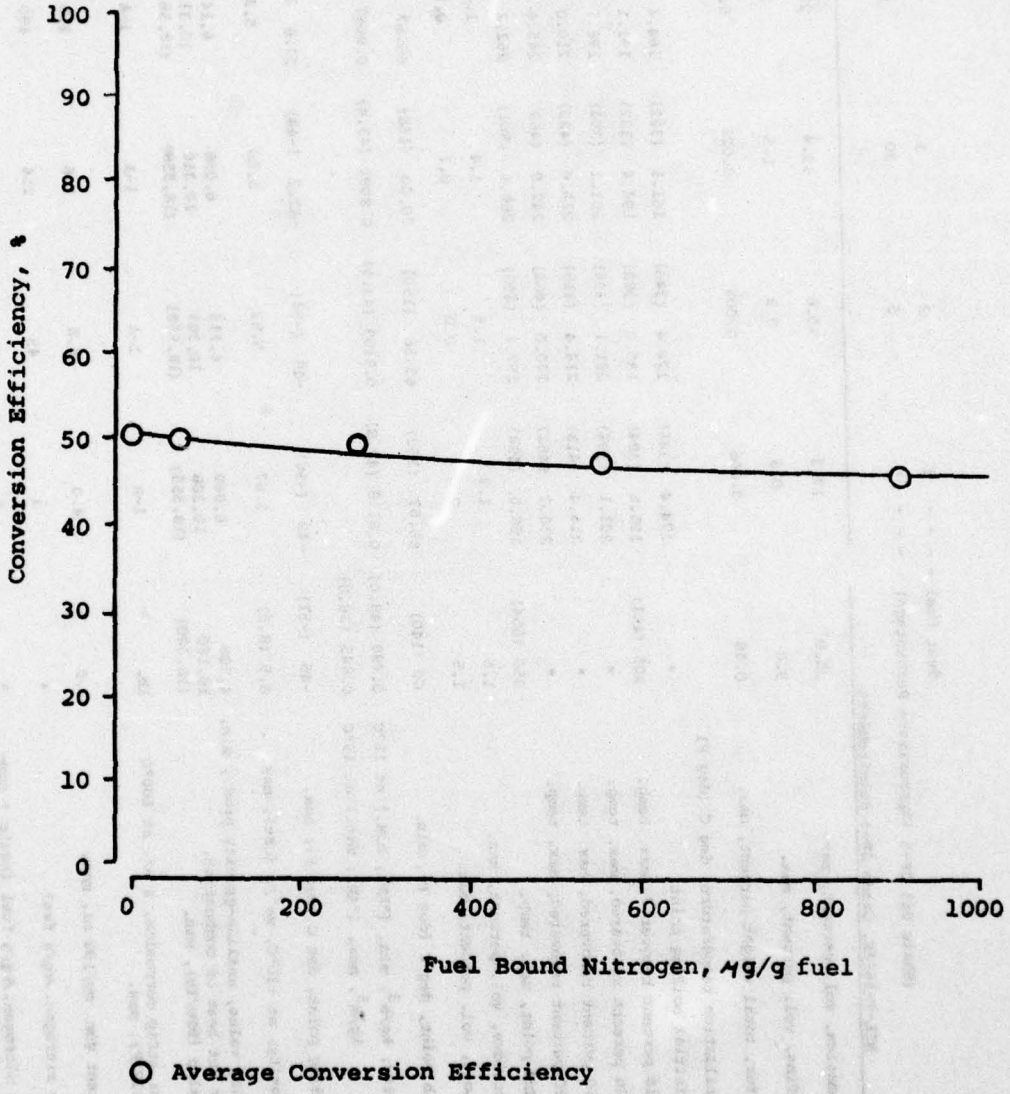

TABLE I

FUEL ANALYSIS

ASTM Standard	MIL-T-5624K, Grade JP-5 Requirements		Test Fuel - - - - 1	2	3	4	5
	(Shale Oil JP-5 (Approximate Percentage) - - - -		0	5	30	60	100
D1319	Aromatics, vol. percent, max.	25.0	17.3	19.6	19.4	22.8	23.1
D1319	Olefins, vol. percent, max.	5.0	0.8	0.8	1.5	3.4	4.6
D1266	Sulfur, total weight percent, max.	0.40	0.006	0.003	0.028	0.010	0.045
D86	Distillation temperature, deg C (deg F)						
	Initial boiling point	*	174.4 (346)	174.4 (346)	161.1 (322)	164.4 (328)	163.3 (326)
	10 percent recovered, max. temp.	205 (401)	195.6 (384)	195.0 (383)	194.4 (382)	191.1 (376)	187.8 (370)
	20 percent recovered, max. temp.	*	201.1 (394)	201.1 (394)	201.1 (394)	196.7 (386)	195.6 (384)
	50 percent recovered, max. temp.	*	214.4 (418)	214.4 (418)	215.6 (420)	210.0 (410)	215.6 (420)
	90 percent recovered, max. temp.	*	238.3 (461)	240.0 (464)	242.8 (469)	245.6 (474)	251.1 (484)
	End point, max. temp.	290 (554)	256.6 (494)	257.2 (495)	260.6 (501)	262.2 (504)	265.0 (509)
	Residue, vol. percent, max.	1.5	1.2	1.5	1.4	1.4	1.4
	Loss, vol. percent, max.	1.5	0.0	0.0	0.1	0.2	0.6
D93	Flash Point, deg C (deg F), min.	60 (140)	66.67 (152)	65.56 (150)	70.00 (158)	66.67 (152)	62.22 (144)
D1298	Density, kg/m^3, min. (°API, max.) at 15°C	0.788 (48.0)	0.8118 (42.8)	0.8109 (43.0)	0.8090 (43.4)	0.8067 (43.9)	0.8035 (44.6)
	kg/m^3, max. (°API, min.) at 15°C	0.845 (36.0)					
D2386	Freezing point, deg C (deg F), max.	-46 (-51)	-49 (-56)	-48 (-54)	-42.2 (-44)	37.8 (-36)	-32.2 (-26)
D445	Viscosity, at -20°C, mm^2/s (cSt), max.	8.5 (8.5)	5.67	5.63	5.50	5.33	5.21
D240	Heating value, aniline-gravity prod., min.	4,500	6,069	6,115	6,098	6,146	6,106
or	or net heat of combustion,	10,160	10,308	10,305	10,310	10,312	10,310
D2382	cal/g (BTU/lb), min.	(18,300)	(18,555)	(18,550)	(18,558)	(18,563)	(18,558)
D130	Copper strip corrosion, 2 hr. at 100°C (212°F), max.	lb.	1-A	1-A	1-A	1-A	1-B
D381	Existent gum, mg/100 ml, max.	7.0	4.0	5.8	1.6	2.0	1.4
	Basic nitrogen, $\mu g/g$ fuel	*	3	45	254	490	859
	Total nitrogen, $\mu g/g$ fuel (basic + non-basic nitrogen)	*	3	47	267	516	902

*Not limited.

TABLE II

ENGINE PERFORMANCE DATA (UNCORRECTED)

Engine Condition	Fuel Bound Nitrogen, μg/g fuel: 3	47	267	515	902
IDLE					
Air Flow, kg/s (lb/s)	0.626 (1.38)	0.558 (1.23)	0.517 (1.14)	0.554 (1.22)	0.517 (1.14)
Fuel Flow, g/s (lb/hr)	7.20 (57.18)	7.64 (60.6)	7.65 (60.6)	7.93 (62.94)	7.85 (62.30)
T_5, °C (°F)	494.02 (921.23)	507.48 (945.47)	511.25 (952.28)	516.33 (961.40)	515.61 (960.10)
Power, kW (SHP)	10.80 (14.48)	14.87 (19.94)	13.32 (17.87)	16.54 (22.18)	14.33 (19.22)
Fuel/Air Ratio*	0.0115	0.0137	0.0146	0.0143	0.0152
60% NR					
Air Flow, kg/s (lb/s)	-	0.957 (2.11)	1.152 (2.54)	0.939 (2.07)	0.921 (2.03)
Fuel Flow, g/s (lb/hr)	-	13.76 (109.26)	14.12 (112.08)	13.31 (105.66)	13.36 (106.02)
T_5, °C (°F)	-	576.67 (1070)	577.22 (1071)	571.11 (1060)	560.00 (1074)
Power, kW (SHP)	-	69.19 (92.78)	76.03 (101.96)	60.31 (80.88)	60.44 (81.05)
Fuel/Air Ratio	-	0.0144	0.0123	0.0142	0.0145
MIL					
Air Flow, kg/s (lb/s)	1.315 (2.90)	1.256 (2.7)	1.256 (2.77)	1.243 (2.74)	1.243 (2.74)
Fuel Flow, g/s (lb/hr)	24.58 (195.12)	24.06 (198.98)	24.19 (192.00)	24.40 (196.68)	24.38 (193.50)
T_5, °C (°F)	748.83 (1379.9)	752.06 (1385.7)	751.78 (1385.2)	750.55 (1383.0)	753.67 (1388.6)
Power, kW (SHP)	196.45 (263.45)	187.69 (251.70)	188.89 (253.30)	188.08 (252.22)	188.86 (253.27)
Fuel/Air Ratio	0.0187	0.0192	0.0193	0.0196	0.0196

*Does not take compressor bleed air into account.

TABLE III

EMISSION DATA

Fuel Nitrogen µg/g fuel	Engine Power Rate	CO_2 %	CO ppm	CO g/s	CO g/kg fuel	NO ppm	NO g/s	NO g/kg fuel	NO_x (as NO_2) ppm	NO_x (as NO_2) g/s	NO_x (as NO_2) g/kg fuel	HC ppm	HC g/s	HC g/kg fuel	F/A (calculated)
	IDLE	1.98	1035	0.714	99.2	6.7	0.00495	0.688	6.7	0.00690	1.06	157	0.0503	6.99	0.00979
3	60% NR	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	MIL	3.03	140	0.227	9.25	23.9	0.0416	1.69	23.9	0.0637	2.59	5.6	0.00422	0.172	0.0146
	IDLE	2.08	985	0.692	90.5	7.7	0.00579	0.758	7.3	0.00887	1.16	131	0.0427	5.59	0.0105
47	60% NR	2.43	430	0.482	35.0	12.7	0.0152	1.11	13.1	0.0241	1.75	18.3	0.00952	0.692	0.0119
	MIL	3.03	130	0.207	8.60	24.3	0.0415	1.72	24.3	0.0635	2.64	8.4	0.00621	0.258	0.0146
	IDLE	2.08	1005	0.698	92.3	9.1	0.00677	0.895	9.4	0.0108	1.42	134	0.0432	5.71	0.0105
267	60% NR	2.43	380	0.438	31.0	16.5	0.0204	1.44	16.7	0.0315	2.24	14.5	0.00775	0.549	0.0119
	MIL	3.03	140	0.224	9.26	27.6	0.0473	1.96	27.6	0.0726	3.00	11.1	0.00825	0.341	0.0146
	IDLE	2.10	950	0.688	86.7	11.6	0.00900	1.13	12.3	0.0146	1.85	109.6	0.0368	4.65	0.0106
515	60% NR	2.43	445	0.482	36.2	17.8	0.0206	1.55	18.4	0.0327	2.47	18.6	0.00935	0.702	0.0119
	MIL	3.03	130	0.210	8.60	31.6	0.0547	2.24	31.6	0.0838	3.44	8.7	0.00652	0.267	0.0146
	IDLE	2.10	992	0.710	90.4	14.9	0.0114	1.45	16.0	0.0188	2.39	116	0.0385	4.91	0.0106
902	60% NR	2.43	460	0.500	37.4	22.1	0.0257	1.92	22.5	0.0401	3.01	18.2	0.00918	0.687	0.0119
	MIL	3.03	135	0.218	8.93	35.9	0.0621	2.55	36.3	0.0962	3.95	8.4	0.00629	0.258	0.0146

TABLE IV

THEORETICAL OXIDES OF NITROGEN (NO/NO_x) FROM FUEL BOUND NITROGEN

Engine Power	Fuel Bound Nitrogen, ug/g fuel				
	3	47	267	515	902
IDLE	0.06	1.1	5.8	11.3	19.8
60% NR	-	1.2	6.6	12.7	22.2
MIL	0.09	1.4	8.1	15.6	27.3

TABLE V

PERCENT CONVERSION OF FUEL BOUND NITROGEN TO NITRIC OXIDE

Fuel Nitrogen µg/g	Engine Power	Measured NO ppm	Thermal Contribution NO ppm	Fuel Nitrogen Contribution NO ppm	Theoretical Fuel Nitrogen Contribution NO ppm	Percent Conversion	Average Percent Conversion
	IDLE	6.7	5.6	1.1	0.06	100	
3	60% NR	-	-	-	-	-	50
	MIL	23.9	24.9	(1.0)*	0.09	0	
	IDLE	7.7	6.6	1.1	1.1	100	
47	60% NR	12.7	11.9	0.8	1.2	67	56
	MIL	24.3	25.2	(0.9)*	1.4	0	
	IDLE	9.1	6.9	2.2	5.8	38	
267	60% NR	16.5	11.9	4.6	6.6	70	46
	MIL	27.6	25.1	2.5	8.1	31	
	IDLE	11.6	7.3	4.3	11.3	38	
515	60% NR	17.8	11.4	6.4	12.7	50	43
	MIL	31.6	25.1	6.5	15.6	42	
	IDLE	14.9	7.3	7.6	19.8	38	
902	60% NR	22.1	10.6	11.5	22.2	52	43
	MIL	35.9	25.3	10.6	27.3	39	

*Negative Value

TABLE VI

PERCENT CONVERSION OF FUEL BOUND NITROGEN TO TOTAL NITROGEN OXIDES

Fuel Nitrogen μg/g	Engine Power	Measured NO_x ppm	Thermal Contribution NO_x ppm	Fuel Nitrogen Contribution NO_x ppm	Theoretical Fuel Nitrogen Contribution NO_x ppm	Percent Conversion	Average Percent Conversion
	IDLE	6.7	5.8	0.9	0.06	100	
3	60% NR	-	-	-	-	-	50
	MIL	23.9	24.6	(0.7)	0.09	0	
	IDLE	7.3	6.8	0.5	1.1	45	
47	60% NR	13.1	11.9	1.2	1.2	100	48
	MIL	24.3	24.9	(0.6)	1.4	0	
	IDLE	9.4	7.1	2.3	5.8	40	
267	60% NR	16.7	11.9	4.8	6.6	73	49
	MIL	27.6	24.9	2.7	8.1	33	
	IDLE	12.3	7.4	4.9	11.3	43	
515	60% NR	18.4	11.5	6.9	12.7	54	47
	MIL	31.6	24.8	6.8	15.6	44	
	IDLE	16.0	7.4	8.6	19.8	43	
902	60% NR	22.5	10.7	11.8	22.2	53	46
	MIL	36.3	25.0	11.3	27.3	41	

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4. AUTHORIZATION - Chief of Naval Material Work Request No. N0003777-WR75020 of 1 October 1976

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APPENDIX A

THEORETICAL CALCULATION OF NO/NO_x EMISSION FROM FUEL BOUND NITROGEN

Example:

T63-A-5A engine at idle power

Fuel carbon/hydrogen atomic ratio - 1/1.9

Fuel flow rate - 7.85 g/s

Fuel nitrogen content - 902 μg/g (fuel)

Carbon dioxide - 2.10%

Carbon monoxide - 992 ppm

Unburned hydrocarbons - 116 ppm

I. Input to the Combustor

(a) Carbon

$$7.85 \text{ g (fuel)/s} \times \frac{12 \text{ g (C)}}{13.9 \text{ g (fuel)}} \times \frac{1 \text{ mole (C)}}{12 \text{ g (C)}} = 0.565 \text{ mole (C)/s}$$

(b) Nitrogen

$$7.85 \text{ g (fuel)/s} \times \frac{902 \mu\text{g(N)}}{\text{g (fuel)}} \times \frac{1 \text{ mole (N)}}{14 \text{ g (N)}} = 0.000506 \text{ mole (N)/s}$$

(c) Nitrogen/Carbon Ratio

$$\frac{0.000506 \text{ mole (N)/s}}{0.565 \text{ mole (C)/s}} = 0.000896 \text{ mole (N/C)}$$

II. Output from Combustor

(a) Carbon

(1) carbon dioxide, 2.10% ($1 \text{ mole } CO_2 = 1 \text{ mole C}$)	$2.10 \times 10^4 \frac{\text{moles (C)}}{10^6 \text{ moles (exhaust)}}$
(2) carbon monoxide, 992 ppm (1 mole CO = 1 mole C)	$9.92 \times 10^2 \frac{\text{moles (C)}}{10^6 \text{ moles (exhaust)}}$
(3) unburned hydrocarbon, 116 ppm (1 mole HC = 1 mole C)	$1.16 \times 10^2 \frac{\text{moles (C)}}{10^6 \text{ moles (exhaust)}}$
Total Carbon	$2.21 \times 10^4 \frac{\text{moles (C)}}{10^6 \text{ moles (exhaust)}}$

(b) Nitrogen Based on Input Conditions

1 mole (N) = 1 mole (NO) = 1 mole (NO_x)

$$0.000896 \text{ mole (N/C)} \times 2.21 \times 10^4 \frac{\text{moles (C)}}{10^6 \text{ moles (exhaust)}} =$$

$$1.98 \times 10^1 \frac{\text{moles (N)}}{10^6 \text{ moles (exhaust)}} \simeq 19.8 \text{ ppm NO/}NO_x$$

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