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SIMPLIFIED FUEL ADDITIVE TEST PHASE III: TESTING AND VERIFICATION

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BY

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ENGINE SYSTEMS DEVELOPMENT CENTRE

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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Un sommaire français se trouve avant la table des matières.

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16. Abstract

Eight products were tested to verify the test sequence and engine test procedure proposed in Phase II of the Simplified Fuel Additive Test project. These products were three engine performance-enhancing devices, three fuel additives, and two oil additives. The effects of each product on engine fuel/oil properties were chemically tested prior to engine tests. Repeatability of engine fuel consumption and emissions measurements were determined by analyzing baseline data. A suitable preconditioning period for evaluating fuel additives (or fuel system add-on devices) was determined by comparing experimental baseline and performance data. Finally, experimental results for two products were compared to those gathered by other investigators who had performed similar work on the same products.

Based on these analyses, the modified engine test procedure for evaluating a product was derived. Based on this test sequence, it was concluded that a total of approximately 75 hours of engine testing is adequate to evaluate any fuel additives or add-on devices with respect to their effect on engine performance and emissions. It was also determined that this test sequence is not suitable for oil additives, a separate test method for which should be developed.

To finalize and submit the protocol for adoption, fine tuning and validation tests are recommended.

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16. Résumé

Huit produits ont été testés afin de vérifier la séquence et la méthode d'essais sur moteur proposées au terme de la phase II du projet. Les produits étudiés comprenaient trois dispositifs d'optimisation du rendement, trois additifs pour carburants et deux additifs pour huiles lubrifiantes. Des analyses chimiques ont d'abord été réalisées, pour cerner les effets de chaque produit sur les propriétés des carburants et lubrifiants. La collecte et l'analyse de données de référence ont permis d'établir la répétabilité des résultats de mesurage de la consommation de carburant et des émissions polluantes. La durée de la période de rodage nécessaire pour permettre l'évaluation des additifs pour carburants (ou des dispositifs d'optimisation pour système d'alimentation) a été établie après comparaison des données issues des essais de référence et de performance. Finalement, les résultats se rapportant à deux des produits ont été comparés aux résultats obtenus par d'autres chercheurs qui avaient effectué des travaux semblables sur les mêmes produits.

Par suite de ces analyses, le protocole d'essai sur moteur a été modifié. L'application de ce protocole a mené les chercheurs à conclure qu'il suffit d'environ 75 heures d'essais sur moteur, au total, pour évaluer n'importe quel additif pour carburants ou optimiseur du rendement, quant à leurs effets sur le rendement du moteur et sur les émissions polluantes. Ils ont en outre constaté que ce protocole ne convient pas aux additifs pour lubrifiants et qu'il faudra donc mettre au point un protocole distinct pour ces produits.

Avant de mettre la dernière main au protocole et d'en promouvoir l'adoption, il est recommandé de procéder à d'autres essais de peaufinage et de validation.

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EXECUTIVE SUMMARY

The Simplified Fuel Additive Test (SFAT) project was initiated to develop a method for the evaluation of fuel additives, performance-enhancing devices, and oil additives at a reduced cost and time relative to the current test procedure RP-503. Phase I investigated the feasibility of establishing such a protocol. Phase II aimed to develop the theoretical test procedure that could be used as a universal protocol and would be applicable to all types of additives (e.g., fuel additives, add-on devices, oil additives). Phase III of the project was launched to experimentally verify the validity of the test procedure as a universal method and to determine the optimum time necessary to establish the baseline, pre-conditioning, and performance sequences for this protocol.

The engine test was conducted by following the "baseline-preconditioning-product" test sequence. A baseline test was performed for each of the products. The preconditioning period of an engine operating with product was determined by analyzing engine fuel consumption data. Emissions were taken during each baseline and with-product test. The engine baseline data, including engine operating parameters, were used to analyze the repeatability of experimental measurements.

Tests were completed for eight of the nine candidate products. Upon completion of the tests, results were analyzed and a test sequence and engine test procedure were derived. According to the data gathered in this Phase, a minimum of 1 percent change in the brake specific fuel consumption can be accurately measured. Comparison of the results obtained by the SFAT procedure to those acquired through RP-503 showed excellent similarity.

The change in engine exhaust emissions was also investigated for each candidate product and was found to be affected by the type of performance enhancing product being used. On average, a change of approximately 5 percent can be detected using the current set-up for emissions analysis.

Finally, it was determined that the derived test sequence was not suitable for evaluation of oil additives because of the longer preconditioning time required for this type of additive. Therefore, it was recommended that a separate test sequence be established that could adequately evaluate this type of additive. Moreover, to make the test procedure established in Phase III a viable alternative to RP-503, it was recommended to conduct another phase to validate the experimental repeatability and finalize the protocol.

SOMMAIRE

Le projet d'essai simplifié des additifs pour carburants (SFAT, pour *Simplified Fuel Additive Test*) a pour but de mettre au point une méthode pour l'évaluation des additifs pour carburants, des dispositifs d'optimisation du rendement et des additifs pour huiles lubrifiantes en moins de temps et à meilleur coût que le protocole d'essai actuellement utilisé, soit la Pratique recommandée 503. La phase I du projet consistait à établir la faisabilité d'un nouveau protocole d'essai. La phase II visait à développer un protocole d'essai théorique «universel», c.-à-d. convenant à tous les types d'additifs (additifs pour carburants, optimiseurs de rendement, additifs pour lubrifiants). La phase III a consisté à vérifier expérimentalement la validité du protocole d'essai en tant que méthode universelle, et à déterminer les durées optimales des essais de référence, de rodage et de performance constituant le protocole.

Les essais sur moteur suivaient la séquence «carburant de référence-rodage-carburant traité». Un essai de marche avec le carburant de référence (sans additif) a été réalisé pour chacun des produits. Pour déterminer la période de rodage du moteur avec le carburant traité, les chercheurs ont analysé les données de consommation de carburant. Des mesures des émissions ont été prises pendant chaque essai avec le carburant de référence et avec le carburant traité. Les caractéristiques de base du moteur, y compris ses paramètres d'exploitation, ont servi à analyser la répétabilité des résultats des mesures.

Huit des neuf produits candidats ont été testés. L'analyse qui a suivi ces essais a permis de perfectionner la séquence et la méthode d'essais sur moteur. Selon les données recueillies au cours de la présente phase, il est possible de mesurer avec précision une modification d'au moins 1 p. cent de la puissance au frein. Par ailleurs, les résultats obtenus avec le protocole SFAT affichent une grande similitude avec les résultats obtenus à l'aide de la PR 503.

L'effet de chaque produit candidat sur les émissions polluantes a également été étudié. Il s'est révélé que cet effet dépend du type d'optimiseur utilisé. Dans l'ensemble, la technique actuelle d'analyse des émissions permet de mesurer une fluctuation d'environ 5 p. cent.

Finalement, il a été déterminé que le nouveau protocole d'essai ne convient pas à l'évaluation des additifs pour lubrifiants, en raison de la longue période de rodage nécessaire pour ce type de produit. Il a donc été recommandé d'établir un protocole distinct pour l'évaluation de ce type d'additif. De plus, pour que le protocole d'essai établi au cours de la phase III puisse remplacer avantageusement la PR 503, il a été recommandé de prévoir une quatrième phase pour la validation de la répétabilité des résultats et le peaufinage du protocole.

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GLOSSARY

AAR	Association of American Railroads
Ag	Silver
Al	Aluminium
ASTM	American Society for Testing and Materials
ATDC	After Top Dead Center
B	Boron
Ba	Barium
Be	Beryllium
BSE	Brake-Specific Emissions
BSFC	Brake-Specific Fuel Consumption
BTDC	Before Top Dead Center
CA	Crank Angle
Ca	Calcium
C_xH_y	Combustibles
CO_2	Carbon dioxide
CO	Carbon monoxide
Cr	Chromium
Cu	Copper
EMD	Electro-Motive Division of General Motors Corp.
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Centre, Inc.
FC	Fuel Consumption
Fe	Iron
FS	Full Scale
KOH	Alkylate
Li	Lithium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum

Na	Sodium
NHR	Net Heat Release
Ni	Nickel
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
O_2	Oxygen
Pb	Lead
PEP	Performance-Enhancing Product
SAE	Society of Automobile Engineering
SCRE-251	ALCO 251 Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SD	Standard Deviation
Si	Silicon
Sn	Tin
SO_2	Sulfur dioxide
SwRI	Southwest Research Institute
TAN	Total Acid Number
TBN	Total Base Number
TDC	Top Dead Centre
THC	Total Hydrocarbons
Zn	Zinc

1 INTRODUCTION

The Simplified Fuel Additive Test (SFAT) Protocol was initiated to develop a test procedure that could properly evaluate the claimed benefits of aftermarket suppliers at a lower cost and reduced time relative to the Association of American Railroad (AAR) recommended practice (RP-503) [1]. The first phase of this project determined the feasibility of developing such a test procedure by examining the existing standard test methods as well as previous works performed by other investigators. The second phase of the project identified the experimental steps required to develop a universal test sequence applicable to add-on devices, fuel additives, and lube oil additives. During this phase, a tentative test procedure was developed. Phase III was designed to validate the test procedure and methodology that was proposed in Phase II.

Phase III of this project began in November 1999 and ended in April 2001. During this phase, eight aftermarket products were tested: three add-on devices, three fuel additives, and two oil additives. The tests conducted in this phase consisted of chemical analyses and engine tests. The chemical analyses were used to investigate the effect of aftermarket products on the fuel and lube oil, and to determine the suitability of these products for engine testing. These analyses were performed to ensure that the altered properties of the treated fuel and/or oil do not damage the engine during the test.

The engine tests were conducted to establish the optimum condition and test sequence necessary to detect any beneficial changes with respect to the engine performance and emissions as a result of the use of these products. Furthermore, the applicability of the test sequence as a universal procedure to wide range of additives (e.g., fuel additives, oil additives, and add-on devices) was examined.

This report details the experimental results and the final test sequence derived from these experimental observations. It also discusses the repeatability of the results based on the obtained results for baseline measurements and identifies the minimum detectable changes that can be measured with respect to brake-specific fuel consumption (BSFC) and emissions at 90 percent confidence level.

2 EXPERIMENT

2.1 Aftermarket Products

The candidate aftermarket products consisted of three add-on devices, three fuel additives, and three oil additives. The first fuel line add-on device was a chamber containing a series of pieces of metallic catalysts. It was claimed that the catalysts could promote the oxidation of hydrocarbon in the combustion chamber to carbon dioxide and water and thereby improve engine fuel economy and emissions. The second fuel-line add-on device was a magnetic device that was claimed to reduce emissions and fuel consumption by up to 10 percent. The last device was an oil recycler that would remove the volatile portion of the crankcase oil and consequently reduce the smoke and exhaust emissions.

The three fuel additives were formulated to solve diesel-related problems such as injector malfunctions, filter clogging, poor fuel economy, etc. They were claimed to reduce exhaust emissions ranging from 10 percent to as much as 40 percent with fuel savings of up to 10 percent.

The oil additives were claimed to provide lower friction resulting in better performance that would reduce the fuel consumption by as much as 6 percent. Table 1 displays the code and application of each aftermarket product used in this project.

Table 1: Engine performance-enhancing products selected for the engine test

Product	Code No.	Application
Add-on devices	PEP-1A	Fuel System
	PEP-1B	Fuel System
	PEP-1C	Oil System
Fuel additives	PEP-2A	Diesel Fuel
	PEP-2B	Diesel Fuel
	PEP-2C	Diesel Fuel
Oil additives	PEP-3A	Engine Lube Oil
	PEP-3B	Engine Lube Oil
	PEP-3C	Engine Lube Oil

2.2 Chemical Analysis

Chemical analyses were performed on the fuel (or oil) samples before and after treatment using the procedures outlined in Phase II. The purpose of these tests was to evaluate the effects of the products on the limiting fuel/oil specification requirements.

2.3 Engine Tests

2.3.1 Test Engine System

Tests were conducted using a single-cylinder, four-stroke, medium-speed, diesel research engine with a 9.0-inch bore and a 10.5-inch stroke (Figure 1). The engine specifications are shown in Table 2. The engine torque and speed were measured by a hydraulic dynamometer and a digital counter. The engine intake air pressure was controlled and maintained by a separate air compressor. An electronic heater and a cooler controlled the intake air temperature. A butterfly valve was used in the engine exhaust system to control exhaust back-pressure. Engine fuel consumption was measured using a high-accuracy electronic weighting scale. Filtered engine lube oil was delivered to the engine by an external pump. Oil and coolant temperatures were controlled by routing cooling water through external heat exchangers that were installed on the engine oil and coolant inlet lines.

To measure cylinder pressure, a high-temperature pressure transducer was mounted on the engine cylinder head. The engine crank-angle position was determined using an optical encoder.

A data acquisition and engine control system developed by ESDC was used to monitor engine operating conditions and to record experimental data during each test. The experimental data were recorded every half-hour. Averaged values of speed, torque, temperature, pressure, and fuel consumption were used in the calculation.

An emission sample probe was mounted in the exhaust stack to sample engine exhaust after a complete mixing of the exhaust gases in the mixing tank. The gas samples were drawn from the engine exhaust stack via a high-flow pump assembly with an in-line water trap and particulate filter for proper conditioning prior to the electrochemical gas sensors of the portable ECOM AC+ analyzer. The analyzer is capable of detecting concentrations of carbon monoxide (CO), oxygen (O_2), combustibles (C_xH_y), nitric oxide (NO), and nitrogen dioxide (NO_2), while also calculating carbon dioxide (CO_2). A separate probe was used to sample the engine smoke. The BOSCH smoke numbers were measured using an AVL smoke meter.

To ensure accurate measurements, instruments were calibrated before each test. Some important instruments such as the fuel consumption meter and the emissions analyzer were calibrated periodically.

The accuracy of some instruments, including the ECOM AC+ emissions analyzer and the AVL smoke meter, is shown in Table 3.

Table 2: SCRE-251 engine specifications

Cylinder	1
Engine Stroke	4
Rated Speed/Rated Power	1050 rpm/250 hp
Idle Speed	400 rpm
Bore & Stroke	9.0 in. & 10.5 in.
Displacement	668 cu. in.
Combustion Chamber	Semi-Quiescent
Compression Ratio	11.5:1
Fuel Injection Type	Direct Injection
Fuel Injector	9 holes × 0.40 mm × 145°
Fuel Injection Timing	27.5° CA BTDC (Variable)
Oil Sump Capacity	132 L

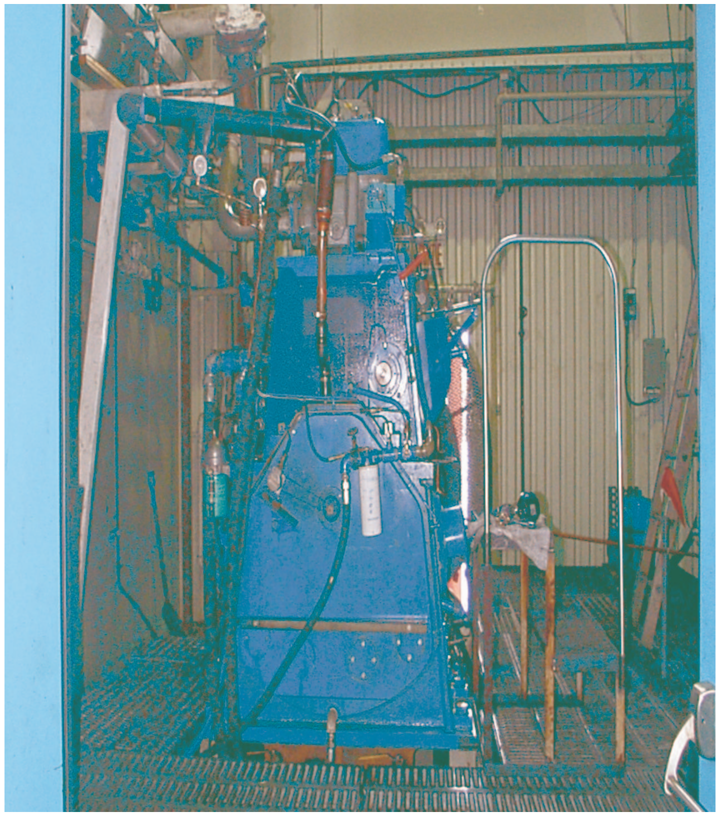

Figure 1: SCRE-251 test engine

Table 3: Accuracy of experimental instruments

Instrument	Accuracy
Engine Speed Indicator	±0.1% F.S.
Hydro-Dynamometer	±0.5% F.S.
Fuel Consumption Meter	±0.01% F.S.
AVL Pressure Transducer	Linearity: < ±0.2% F.S.
Fluid Temperatures	±1°C
Fluid Pressures	< ±1% F.S.
ECOM AC+	O_2: 2% of the reading CO: 2% of the reading NO: 2% of the reading NO_2 2% of the reading C_xH_y: 2% of the reading
AVL Smoke Meter	Zero drift: <0.004% Linearity error: <1%

2.3.2 Test Procedure

The engine was operated at the designed test mode with test fuel and oil for a certain period of operating hours as proposed in Phase II [2] (this was modified during the tests). Engine speed, load, fuel consumption, and operating parameters were recorded every half-hour. At least two emissions measurements were performed on different days to yield average emissions values. These experimental data were used as a baseline for reference. Similar tests were conducted on performance-enhancing products (PEPs). A pre-conditioning run was performed with each product until a stable baseline was achieved for the engine parameters of interest. Once stability was achieved, data were collected and compared to those obtained for the baseline. The proposed procedure was modified during the engine test to achieve the optimum setting. The finalized procedure is detailed in Section 4.

2.3.3 Data Processing

Average engine speed and load were used to calculate engine power. The power was corrected to standard conditions considering intake air temperature, fuel temperature, fuel density, heating value of fuel, and altitude effects. A total of 25 readings were averaged to obtain a value for fuel consumption at each given test point. To understand the engine combustion process, the measured data for cylinder pressure were analyzed, from which the combustion temperature and apparent net heat release rate were calculated.

A data acquisition program designed by ECOM America Ltd. was used to record engine emissions values. A total of 60 data points were recorded in 15 minutes. The averaged values of engine speed, power, and fuel consumption rate were recorded by another computer and used in the calculation of composite emissions. To compare baseline test emissions results with those obtained for the performance test, the measured raw emissions concentrations were converted to brake-specific values. In calculating the composite brake-specific emissions (BSEs), the following equation was used:

$$BSE = Emissions\ rate\ /\ Brake\ horsepower\ \ (g/bhp\text{-}hr)$$

The emissions rate, defined as mass exhaust emissions per hour, was calculated from measured emissions concentrations and the fuel consumption rate using the method provided by the manufacturer of the emissions analyzer. Considering intake air humidity effects, the oxides of nitrogen (NOx) emissions were corrected using formulas given in the U.S. Environmental Protection Agency (EPA) emissions standards for locomotives and locomotive engines [3].

The apparent net heat release rates were calculated from the recorded cylinder pressure data by applying the first law of thermodynamics to the content of the combustion chamber [4,5]. The combustion temperatures were calculated from the cylinder pressure data by assuming a uniform temperature distribution and ideal gas within the cylinder.

3 RESULTS AND DISCUSSION

3.1 Chemical Analysis Results

3.1.1 Add-On Devices

Treated and untreated fuel samples were analyzed for PEP-1A and PEP-1B. PEP-1C was an on-line add-on device for an engine lube oil system; therefore, no fuel analysis was necessary for this device. However, oil samples were obtained and analyzed at various time intervals to monitor its performance.

Table 4 illustrates the chemical and physical properties of the treated and untreated diesel fuels for the above-mentioned devices. The properties of both treated and untreated fuels remain almost the same. Small changes were observed that may be attributed to experimental errors.

Table 5 displays the properties of the treated and untreated engine lube oil using PEP-1C. No significant changes were found with respect to wear metals, viscosity, and total base number (TBN) values. Any variations for these parameters were due to an oil top-up that was performed approximately every 30 hours during engine operation. An initial increase in total acid number (TAN) value was observed for PEP-1C, which reached a plateau and remained constant thereafter.

3.1.2 Fuel Additives

The results for baseline fuels and treated fuels are shown in Table 6. It should be noted that the test fuel used for this project conforms to the specifications for type 2-D fuel used for exhaust emissions testing [6].

3.1.3 Oil Additives

Table 7 gives results of baseline oils and treated oils. The high concentration of copper, lithium, and lead are a result of the presence of these elements in the additive package. According to the gathered experimental results, the oil additives would require a long preconditioning period (approximately 200 hours). Inclusion of oil additives into the test method developed herein would have extended the time required for the test, while not offering any benefit to the manufacturers of fuel additives and add-on devices. For this reason, it was concluded that a separate test procedure should be developed for oil additives to fully investigate their effects on engine performance, fuel consumption, and exhaust emissions.

Table 4: Fuel property test results of baseline fuel and fuel treated with devices

Fuel Property	ASTM	PEP-1A		PEP-1B	
		Baseline	Treated Fuel	Baseline	Treated Fuel
Density @ 15°C (kg/L)	D1298	0.824	0.824	0.831	0.857
Flash point (°C)	D56	49	49	58	56
Cloud point (°C)	D2500	-30	-30	-21	-22
Pour point (°C)	D97	-36	-36	-33	-39
Viscosity @ 40°C	D445	1.8	1.8	1.6	1.5
Distillation	D86				
- Initial boiling point (°C)		153	151	171	170
- 10% recovered (°C)		183	182	192	194
- 50% recovered (°C)		233	232	255	260
- 90% recovered (°C)		297	293	325	327
- Final boiling point (°C)		327	323	342	348
- Loss (%)		1.0	1.0	2.8	1.0
- Recovered (%)		1.0	1.0	0.2	1.0
Ash (%)	D482	< 0.001	< 0.001	< 0.001	< 0.001
Copper strip corrosion	D130	1A	1A	1A	1A
Water & sediment (%, v/v)	D2709	<0.05	<0.05	< 0.05	N/A
Sulfur (%, p/p)	D129	0.04	0.03	0.04	0.05
Heating value (kJ/kg)	D240	44657	44943	46210	44469
Carbon residue (%)	D189	0.006	0.009	0.070	0.006
Particulate contamination	D2276	9.0	2.6	1.77	<0.5
Cetane index	D976	47	47	44	43

Table 5: Oil property test results of baseline oil and oil treated with PEP-1C

	Sampling time (hrs)	Al (ppm)	B (ppm)	Cr (ppm)	Cu (ppm)	Fe (ppm)	Pb (ppm)
Baseline	5	20	1	6	2	11	4
	25	23	1	7	3	14	5
	40	21	1	6	2	14	3
With PEP-1C	10	22	1	6	2	15	3
	25	22	1	6	3	15	4
	40	21	0	6	1	15	4
	50	20	0	6	1	14	2
	58	21	0	6	1	14	4
	64	18	0	5	1	11	4
	70	19	0	6	1	12	4
	74	20	0	6	1	13	4
	80	20	0	6	1	14	4
	Sampling time (hrs)	**Na (ppm)**	**Si (ppm)**	**Ni (ppm)**	**Viscosity @40●C cSt**	**TBN (mg KOH/g)**	**TAN (mg KOH/g)**
Baseline	5	0	31	0	152	9.45	1.72
	25	0	39	0	154	9.23	1.55
	40	0	37	0	152	9.38	4.78
With PEP-1C	10	0	38	0	153	9.47	4.48
	25	0	38	0	152	9.16	4.73
	40	0	37	0	154	9.31	4.73
	50	0	36	0	154	9.14	4.00
	58	0	34	0	155	8.94	4.39
	64	0	29	1	155	9.55	4.52
	70	0	31	1	155	9.44	4.96
	74	0	33	0	153	9.35	4.57
	80	0	34	1	155	9.32	5.13

Table 6: Fuel property test results for baseline fuel and fuel treated with additives

Fuel Property	ASTM	PEP-2A		PEP-2B		PEP-2C	
		Baseline	Treated Fuel	Baseline	Treated Fuel	Baseline	Treated Fuel
Density @ 15°C (kg/L)	D1298	0.831	0.831	0.833	0.840	0.842	0.844
Flash point (°C)	D56	58	57	56	51	52	52
Cloud point (°C)	D2500	-21	-14	-22	-22	-25	-25
Pour point (°C)	D97	-33	-24	-36	-39	-36	-42
Viscosity @ 40°C	D445	1.8	1.7	1.8	1.8	1.7	1.7
Distillation	D86						
- Initial boiling point (°C)		171	171	175	169	175	169
- 10% recovered (°C)		192	195	199	194	199	194
- 50% recovered (°C)		255	262	252	254	252	254
- 90% recovered (°C)		325	318	315	313	315	313
- Final boiling point (°C)		342	345	343	345	343	345
- Loss (%)		2.8	3.0	0.5	0.5	0.5	0.5
- Recovered (%)		0.2	N/A	0.5	0.5	0.5	0.5
Ash (%)	D482	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Copper strip corrosion	D130	1A	1B	1B	1B	1A	1A
Water & sediment (%, v/v)	D2709	< 0.05	< 0.05	< 0.05	< 0.05	<0.05	<0.05
Sulfur (%, p/p)	D129	0.04	0.08	0.05	0.05	0.05	0.05
Heating value (kJ/kg)	D240	46210	44863	45201	45267	45244	45193
Carbon residue (%)	D189	0.07	0.06	0.025	0.019	0.04	<0.005
Particulate contamination (mg/L)	D2276	1.77	10.1	0.45	1.25	23.6	2.43
Cetane index	D976	44	47	44.5	45	46	45

Table 7: Oil property test results for baseline oil and oil treated with additives

Property (ppm)	PEP-3A						PEP-3B					
	Test hours						Test hours					
	Baseline	1	10	20	30	40	Baseline	1	10	20	30	40
Ag	0	0	0	0	0	0	0	0	0	0	0	0
Al	4	16	17	17	16	15	4	8	8	7	8	8
Cr	0	14	14	16	16	15	0	1	2	2	3	4
Cu	0	0	0	1	1	1	0	0	0	20	47	51
Fe	0	18	18	19	17	17	0	8	8	9	10	14
Pb	3	3	4	4	4	5	3	0	0	57	296	209
Sn	1	8	9	12	10	3	1	0	1	1	0	1
Ni	0	0	0	1	0	0	0	0	0	0	0	0
B	0	2	2	2	2	2	0	2	2	3	4	5
Na	0	23	21	22	22	25	0	21	19	21	22	20
Si	5	14	15	15	14	14	5	12	8	7	9	12
Zn	0	5	5	5	5	4	0	19	21	33	46	67
Ba	1	3	3	3	3	3	1	0	0	0	0	0
Be	37	19	56	56	37	28	37	18	32	32	23	0
Ca	4415	5322	5503	5662	5228	4799	4415	4783	4877	4609	4582	5226
Mg	28	33	34	34	33	32	28	31	31	32	34	45
Mn	0	0	0	0	0	0	0	0	0	0	0	0
Mo	98	100	104	111	99	90	98	13	15	13	13	15
Li	76	2762	2404	2551	2508	2326	76	146	159	1723	4554	4279
Viscosity @ 40°C	143	146	146	145	147	145	143	139	139	137	140	141
TBN	9.78	5.28	5.13	5.09	5.19	5.53	9.78	8.71	8.34	7.89	7.69	8.01

3.2 Engine Test Results

3.2.1 Repeatability of Experimental Measurements

3.2.1.1 Engine Operating Parameters

A number of engine operating parameters such as engine speed, load, oil temperature, coolant temperature, intake air temperature, and intake air pressure were controlled in order to accurately measure the effect of aftermarket products on engine performance. Oil and coolant temperatures were measured at the oil sump and at the outlet of the engine cooling system respectively. Intake air temperature and pressure were measured at the air expansion tank, which was mounted just before engine air-intake manifold. These operating parameters were recorded during the tests and are shown in Figures 2a through 2g. Values shown in these figures are the average of at least 10 readings from both the baseline and performance steps for six evaluation tests. Results obtained for the statistical analyses of these parameters are shown in Table 8. It can be seen that the engine speed and load can be controlled within a very small range. The standard deviation of air temperature, oil sump temperature, and coolant temperature was 0.13, 1.31, and 1.30, respectively. Engine fuel temperature was maintained by controlling the test cell room temperature. The fuel temperatures were between 27°C and 37°C. The effect of the fuel temperature on the engine power was compensated for by applying correction factors. Based on the statistical analyses, the tolerance limits of each of these operating parameters were obtained and these are also shown in Table 8.

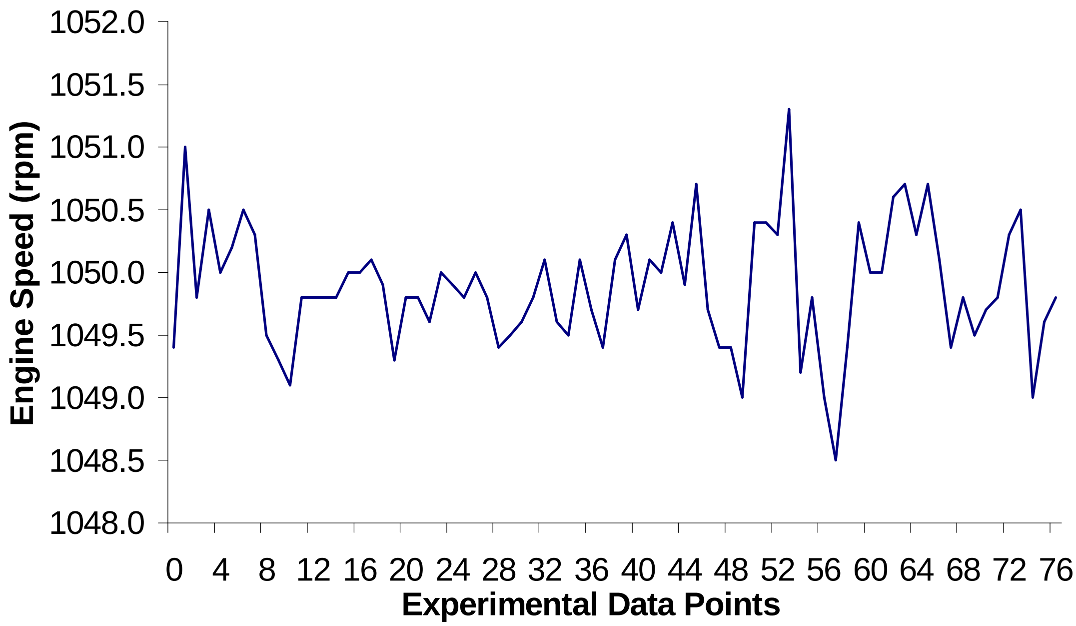

Figure 2a: Engine speed

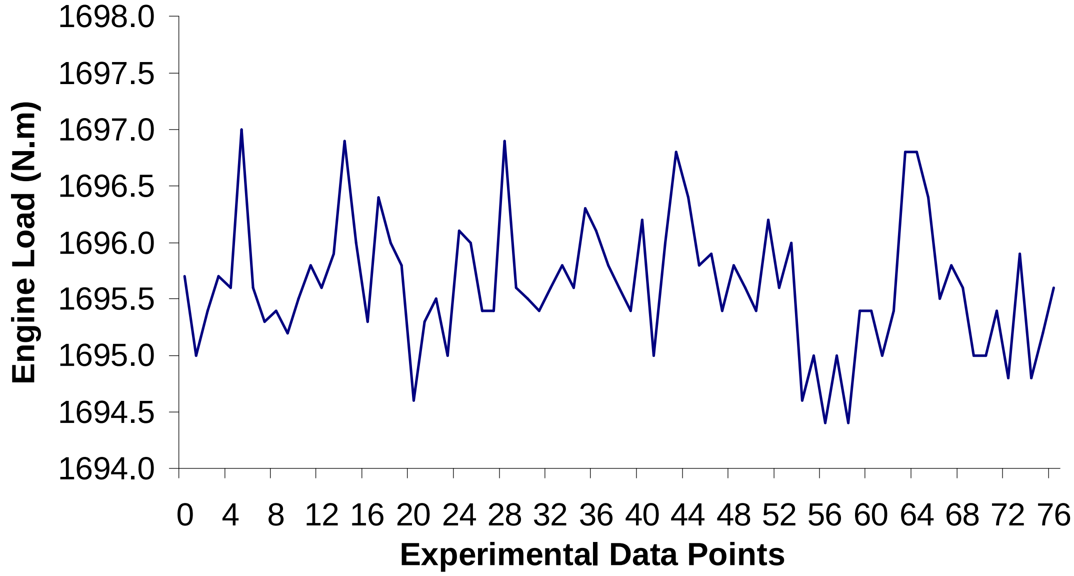

Figure 2b: Engine load

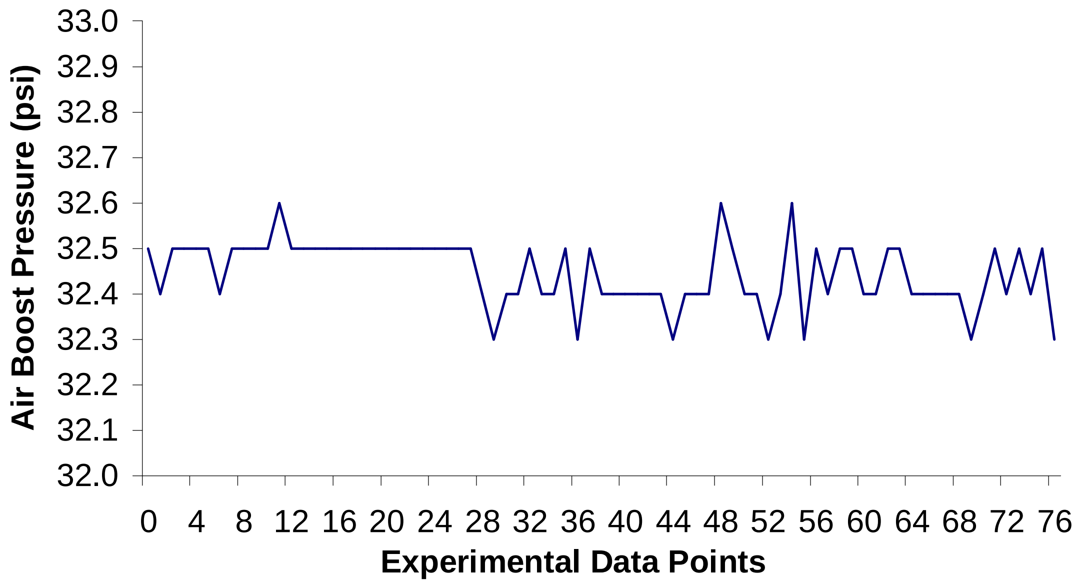

Figure 2c: Engine intake air pressure

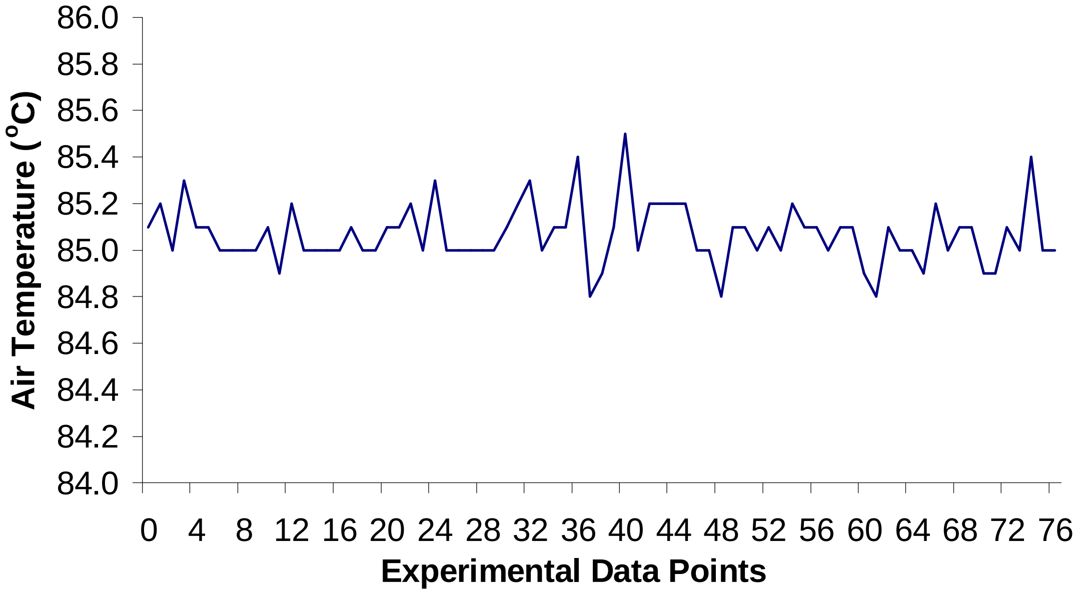

Figure 2d: Engine intake air temperature

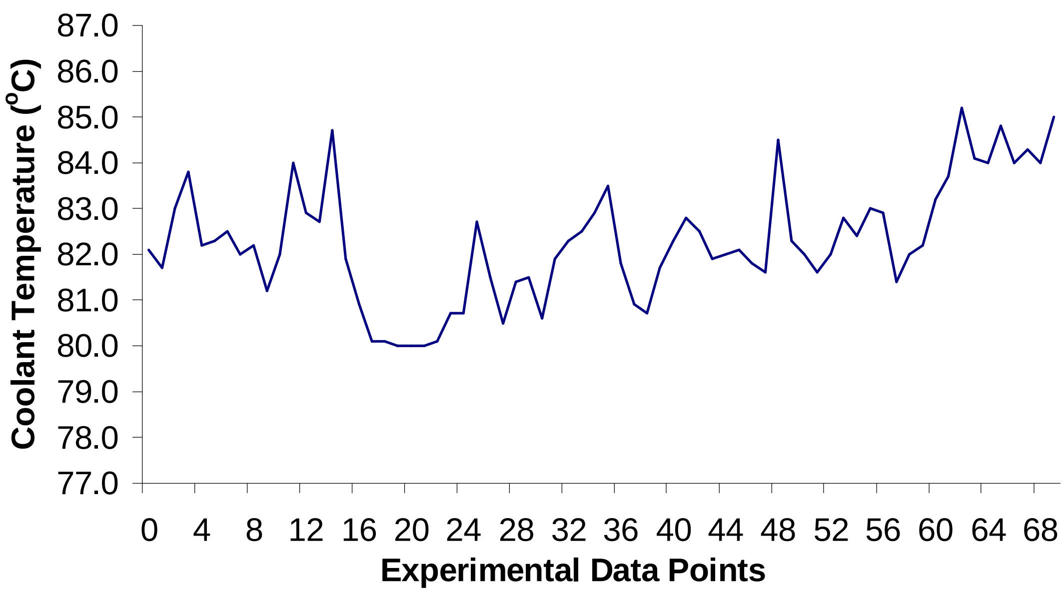

Figure 2e: Engine cooling water outlet temperature

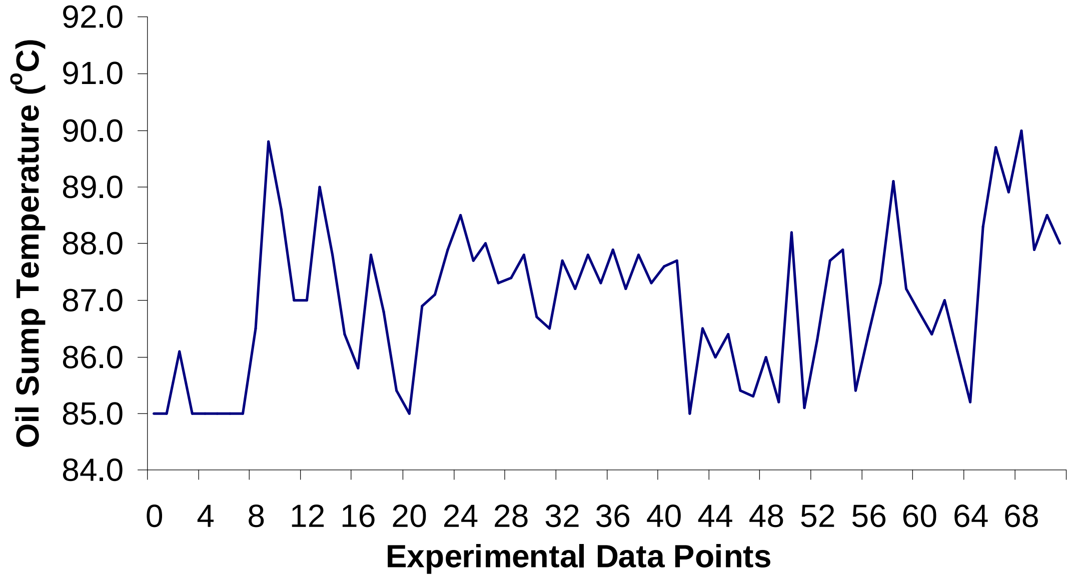

Figure 2f: Engine oil sump temperature

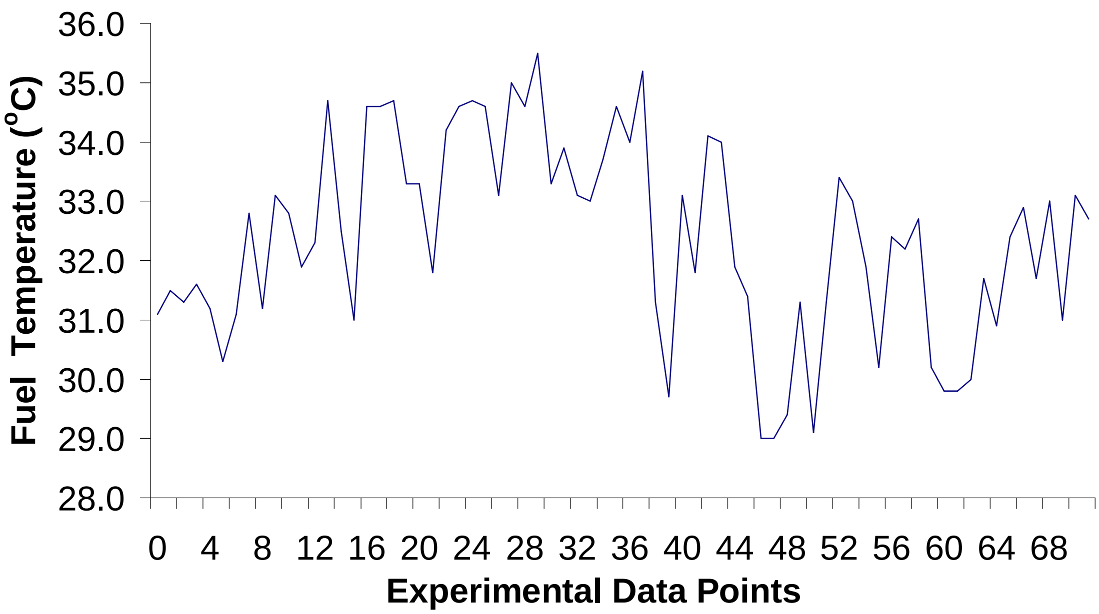

Figure 2g: Engine fuel inlet temperature

Table 8: Statistical analysis of the engine operating parameters

	Engine Operating Parameters						
	Engine Speed (rpm)	**Engine Load (N.m)**	**Intake Air Temp. (°C)**	**Intake Air Pressure (psi)**	**Oil Temp. (°C)**	**Coolant Temp. (°C)**	**Fuel Temp. (°C)**
Mean	1049.9	1695.6	85.1	32.5	87.0	82.3	32.4
S.D.	0.49	0.57	0.13	0.07	1.31	1.30	1.67
Tolerance Limit (95% of the data are within the limit (predicted with 99% confidence))	1049.9±1.1	1695.6±1.3	85.1±0.3	32.4±0.1	87±3.0	82.3±3.0	32.4±4.0

3.2.1.2 Engine Fuel Consumption

Baseline tests were conducted before each evaluation test. To minimize possible errors, identical parts (such as the power assembly and injector nozzles that were made by the same manufacturer) were used for the repeatability analyses. Engine intake manifold air temperatures were maintained constant during the tests; therefore, engine powers were not corrected to standard ambient conditions in this test program. Since no device was applied to maintain engine fuel inlet temperature, engine powers were corrected with respect to the fuel temperature. Table 9 gives the results for two add-on devices (PEP-2B and PEP-2C). The tests were conducted on four different days. Each fuel consumption value in Table 9 is the average of at least 25 readings. Based on these results, for any given test the smallest difference that can be detected with regard to the specific fuel consumption is approximately 1 percent.

3.2.1.3 Exhaust Emissions

Baseline emissions of PEP-2B and PEP-2C are shown in Table 10. Tests were run on four different days to measure the emissions. Each given emissions value is an average of at least 60 readings. Based on the values obtained for the baseline emissions, repeatability of emissions measurements was determined (Table 10). The results indicated random changes in engine emissions. Therefore, the experimental emissions data were not adjusted for engine and test system drift. The smallest distinguishable changes between emissions of baseline and PEP test were determined to be 5 percent for CO and 4.5 percent for NO_x.

Table 9: Engine fuel consumption repeat test (Baseline)

Test Index	Test Date	Speed (rpm)	Load (N.m)	F.C. (lb/min)	BSFC (g/kW-hr)
Baseline of PEP-2B	Dec.14, 00	1049	1696	1.709	246.43
		1049	1696	1.707	246.14
		1050	1695	1.706	245.90
		1049	1694	1.706	246.28
		1050	1695	1.705	245.76
		1050	1695	1.700	245.04
		1049	1695	1.705	245.99
	Jan. 08, 01	1051	1696	1.704	245.24
		1050	1695	1.709	246.34
		1050	1695	1.706	245.90
		1051	1695	1.706	245.67
		1051	1695	1.695	244.09
Baseline of PEP-2C	Feb. 02, 01	1048	1694	1.707	246.54
		1049	1696	1.708	245.25
		1050	1696	1.707	245.87
		1050	1695	1.708	246.24
	Mar. 08, 01	1050	1696	1.704	245.49
		1051	1696	1.704	245.17
		1050	1695	1.705	245.81
		1050	1696	1.700	244.89
Mean		1049.86	1695.34	1.705	245.75
S.D.		0.790	0.680	0.003	0.610
(Max-Min)/Mean (%)		0.250	0.120	0.820	0.950

Table 10: Repeat test of engine baseline emissions

Test Index	Test date	Engine Baseline Exhaust Emissions			
		CO (g/hp-hr)	NO_x (g/hp-hr)	CO_2 (%)	Smoke (BOSCH)
Baseline of PEP-2B	Dec. 08, 00	3.23	12.67	6.18	1.35
	Dec.14, 00	3.28	12.62	6.20	1.40
Baseline of PEP-2C	Feb. 02, 01	3.31	12.14	6.19	1.39
	Mar. 08, 01	3.39	12.24	6.18	1.41
Mean		3.30	12.42	6.19	1.39
S.D.		0.07	0.27	0.01	0.03
(Max-Min)/Mean (%)		4.84	4.30	0.32	4.30

3.2.2 Engine Performance

Engine fuel consumption data were obtained for all the test products. BSFC data of both the baseline and the treated fuel/oil were plotted versus engine time (Figures 3a through 3h). The data were analyzed to determine the minimum necessary time required for preconditioning and the change in fuel consumption as a result of the use of each product. Baseline tests were conducted for each product to check the consistency of the baselines after removing or disconnecting the products. The operating hours of these baseline tests could change depending on engine baseline conditions.

As seen in Figure 3a, the BSFC of the engine with PEP-1A started to decrease at about five engine hours and became relative stable after approximately 25 hours. The BSFC of PEP-1B varied very slightly compared to that of the baseline during the test (Figure 3b). Fuel consumption data for PEP-1C were plotted in terms of fuel consumption versus oil aging-time (Figure 3c). As seen in this figure, the fuel consumption started to decrease after about 20 hours and became stable after 27 hours until 55 hours. The slight increase of BSFC after 55 hours might be attributed to an accumulation of soot in the engine oil. During this test, engine oil consumption was monitored to be about 0.9 to 1.0 percent of fuel consumption. Engine oil sump was topped up twice, at 30 and at 60 hours. No significant effect of oil refilling on engine fuel consumption was observed. Similarly, products PEP-2A, PEP-2B, and PEP-2C (Figures 3d through 3f) also seem to stabilize within the same time interval. Therefore, the 30-hour period was assumed to be sufficient for preconditioning. Figure 3g shows BSFC curves for PEP-3A. The fuel consumption changed slightly during the test with treated oil. Since PEP-3B blocked up the engine oil filter twice during the 50-hour run, the evaluation test became more difficult and the BSFC values (shown in Figure 3h) were not reliable. Because of time restraints, only two oil additives were tested. More investigations on oil additives are therefore required to determine a suitable evaluation test procedure.

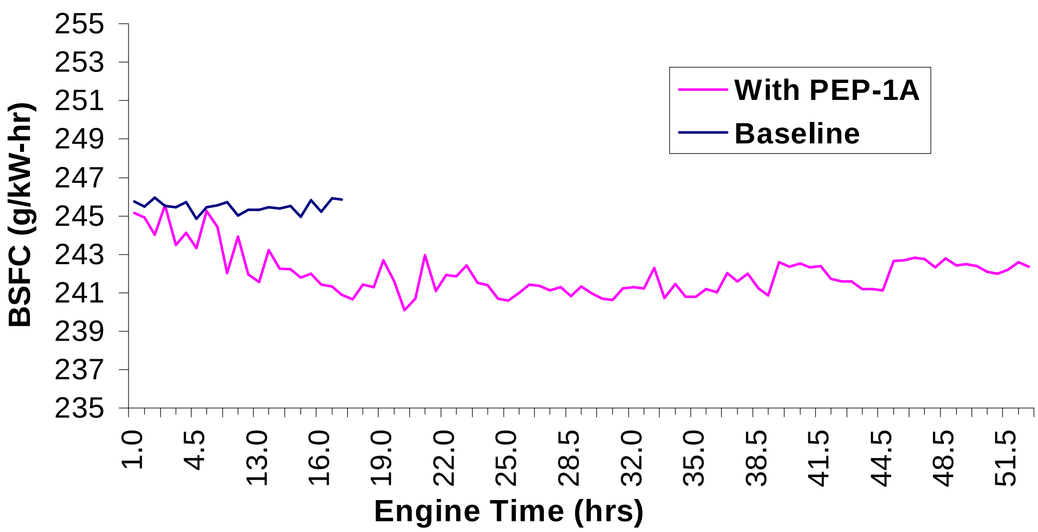

Figure 3a: BSFC data of PEP-1A

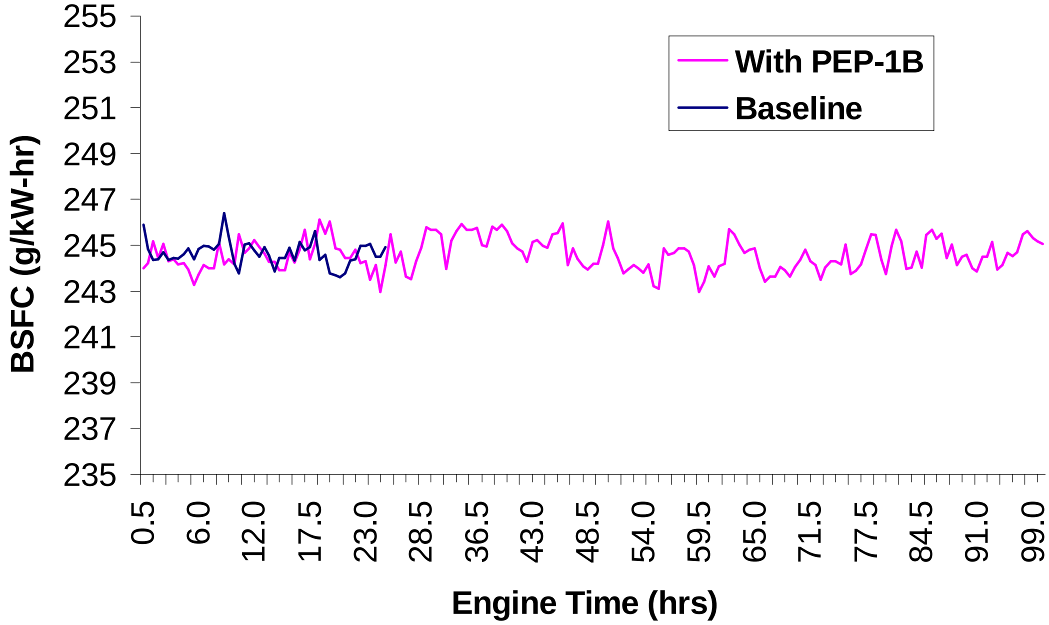

Figure 3b: BSFC data of PEP-1B

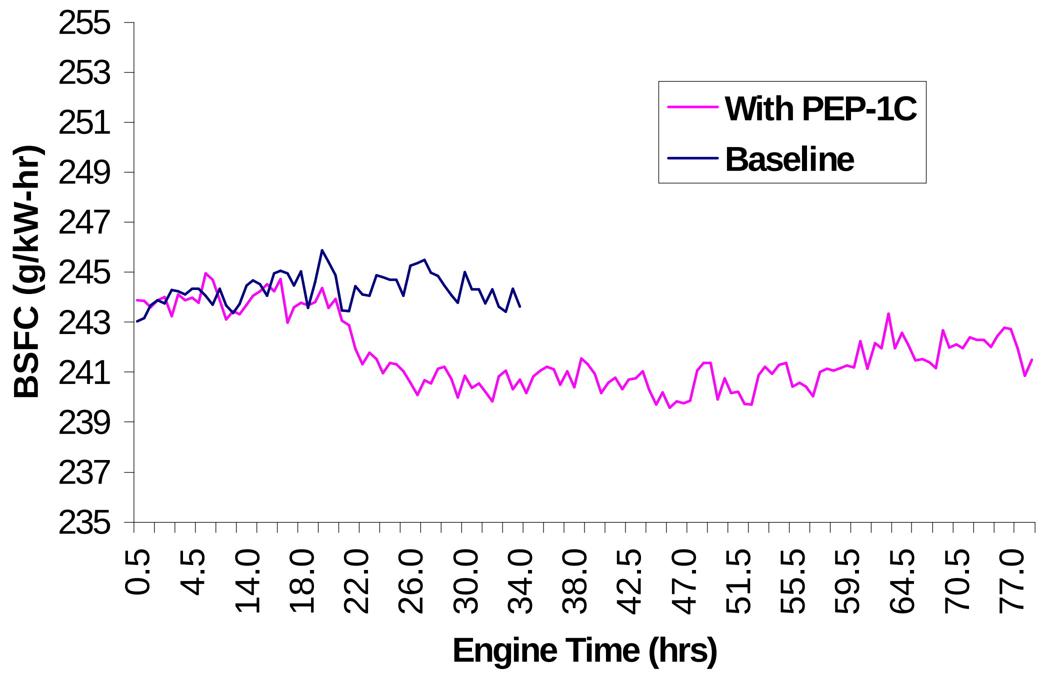

Figure 3c: BSFC data of PEP-1C

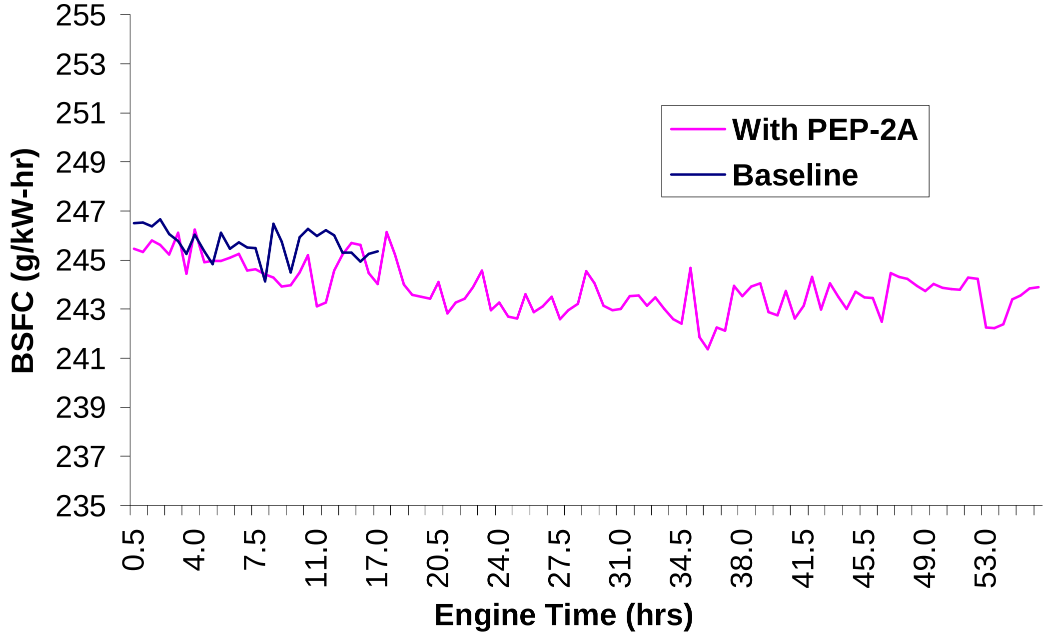

Figure 3d: BSFC data of PEP-2A

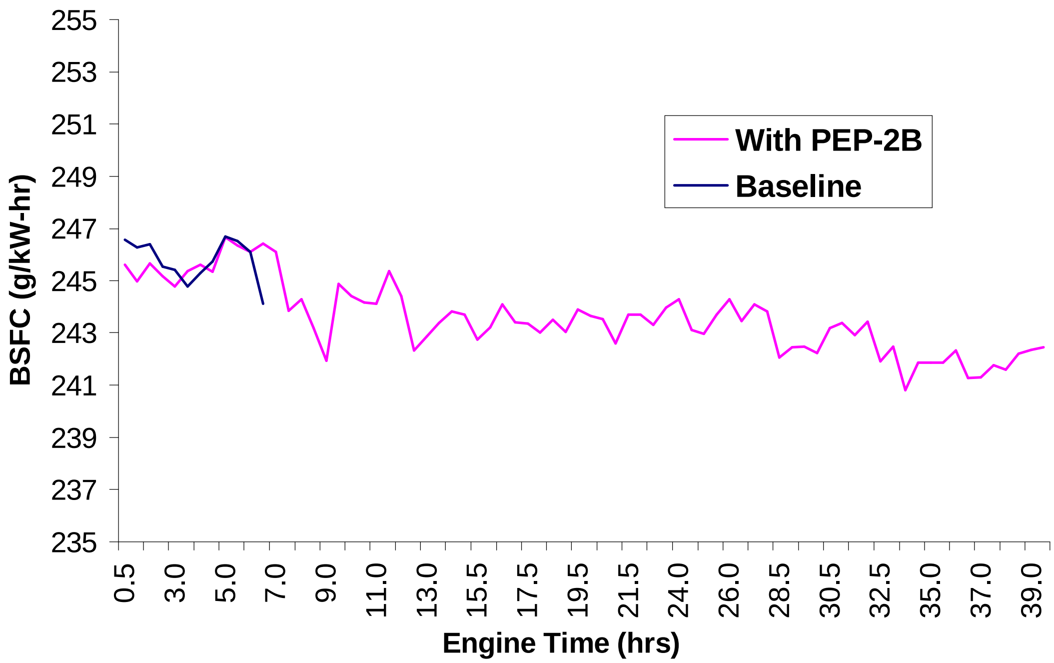

Figure 3e: BSFC data of PEP-2B

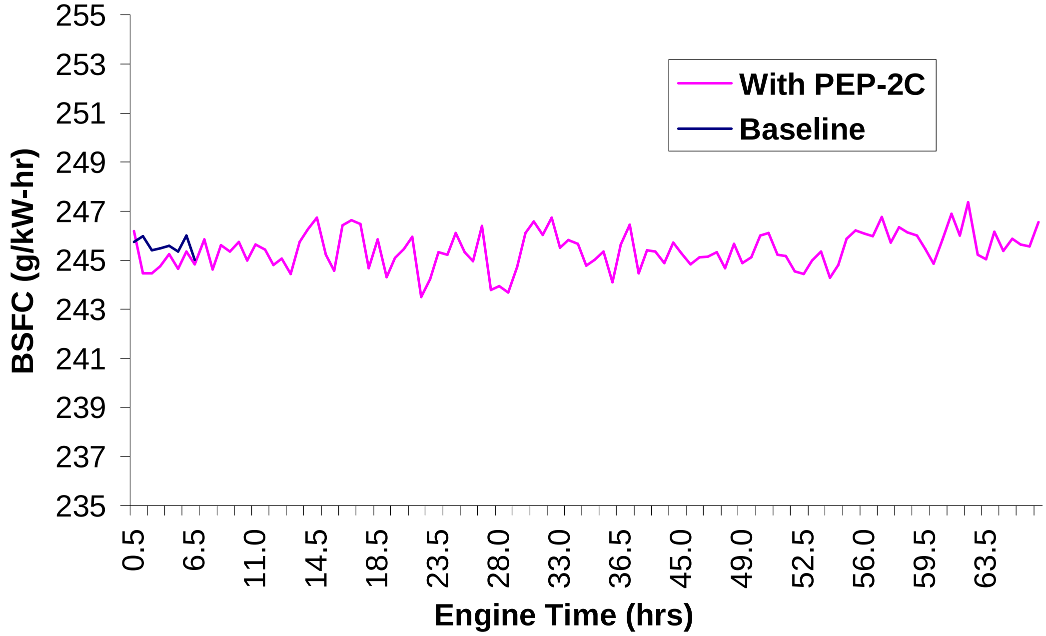

Figure 3f: BSFC data of PEP-2C

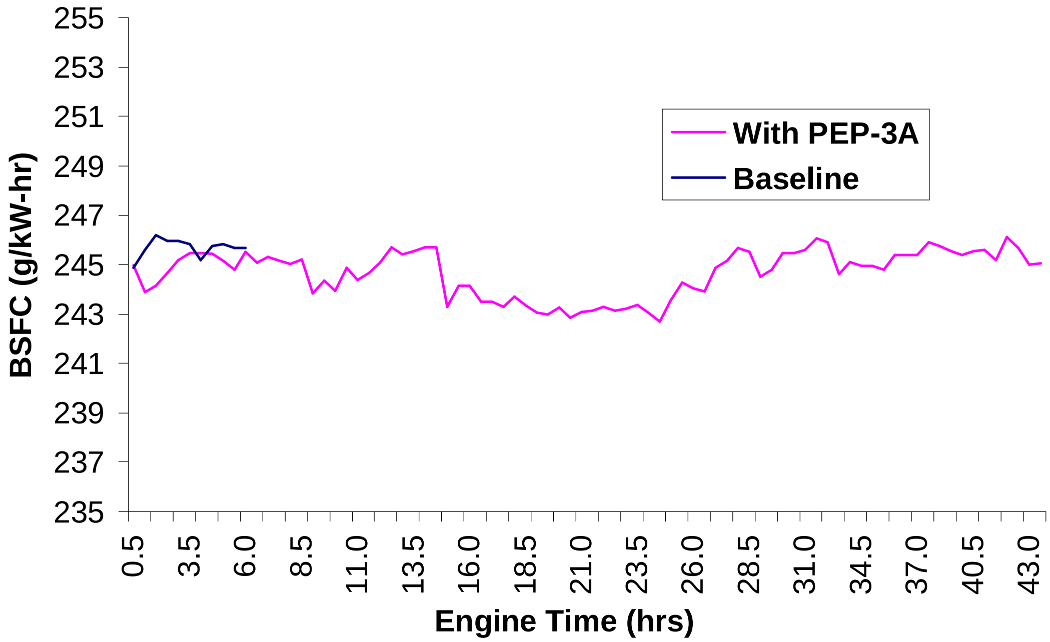

Figure 3g: BSFC data of PEP-3A

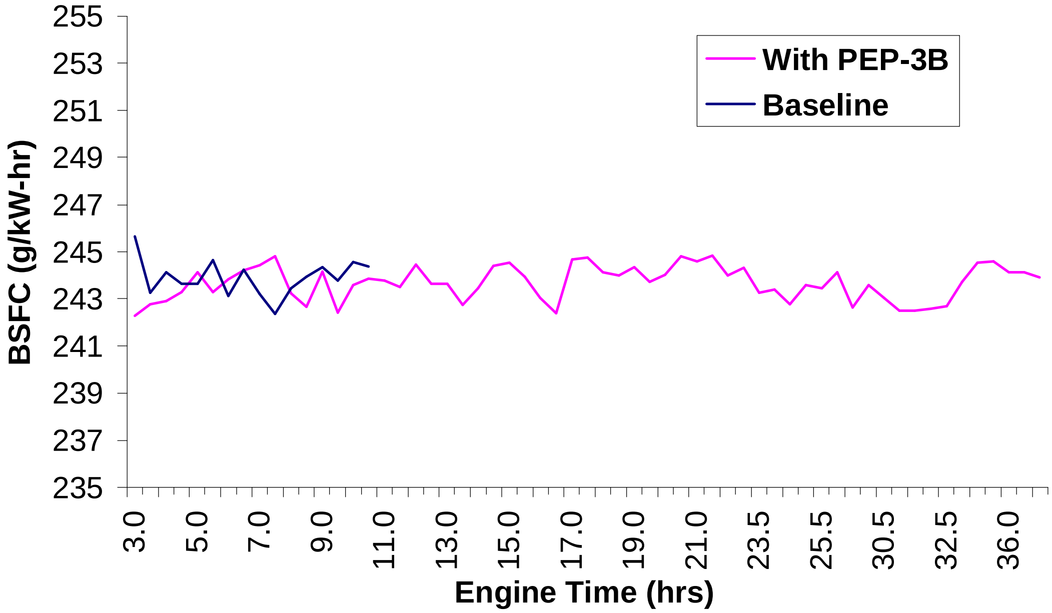

Figure 3h: BSFC data of PEP-3B

The BSFC data obtained during the test with baseline and products (after preconditioning) were plotted as a function of engine operating hours (Figures 4a through 4f). The data of last 10 hours shown in Figures 3a through 3f of product test are used to compare to each of their baseline results. If a baseline test was less than 10 hours, the baseline data of next test were combined. The size of each set of data for the comparison is 20 data points (one data point every half-hour).

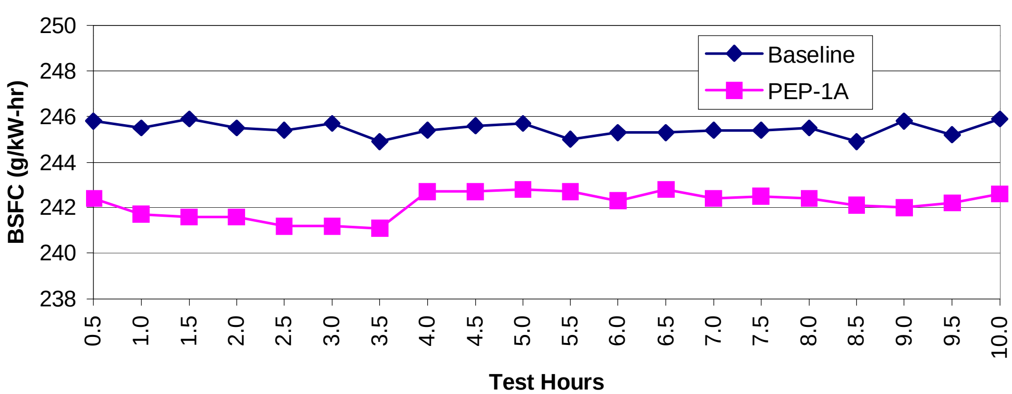

Figure 4a: Comparison of BSFC values (PEP-1A)

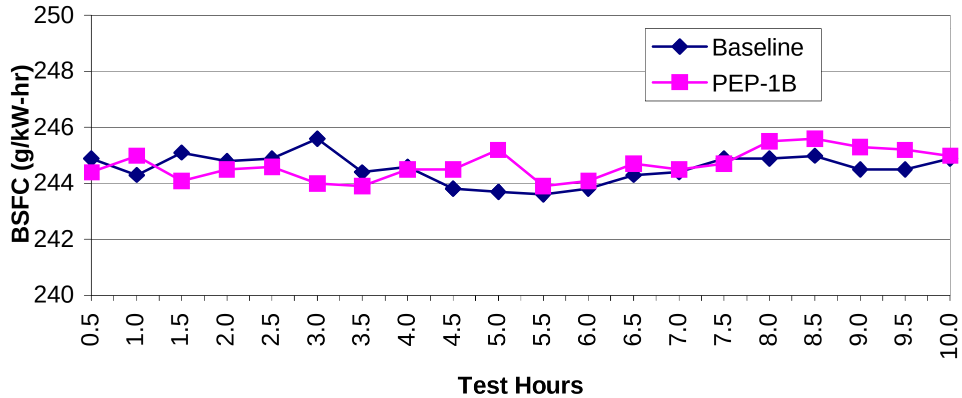

Figure 4b: Comparison of BSFC values (PEP-1B)

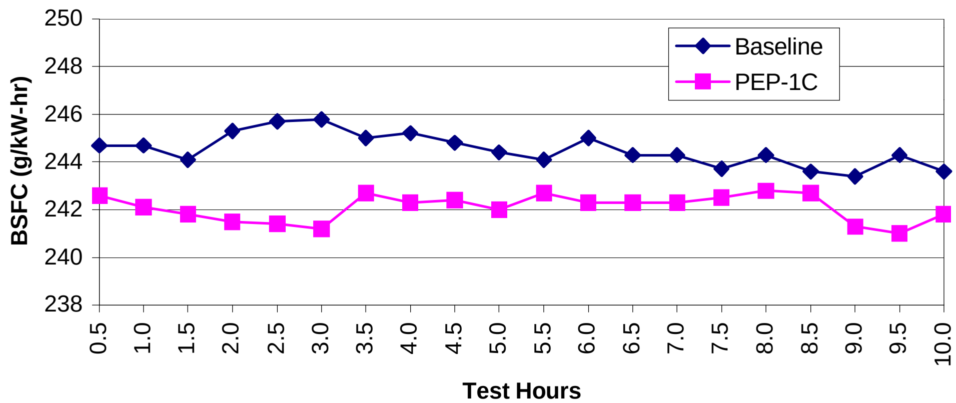

Figure 4c: Comparison of BSFC values (PEP-1C)

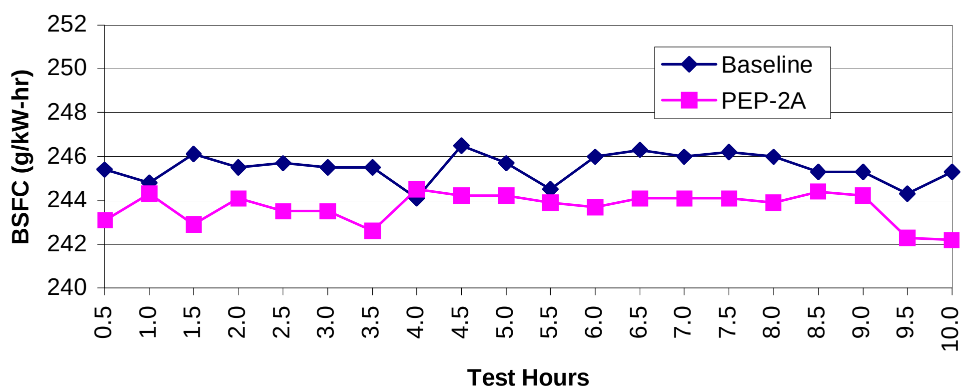

Figure 4d: Comparison of BSFC values (PEP-2A)

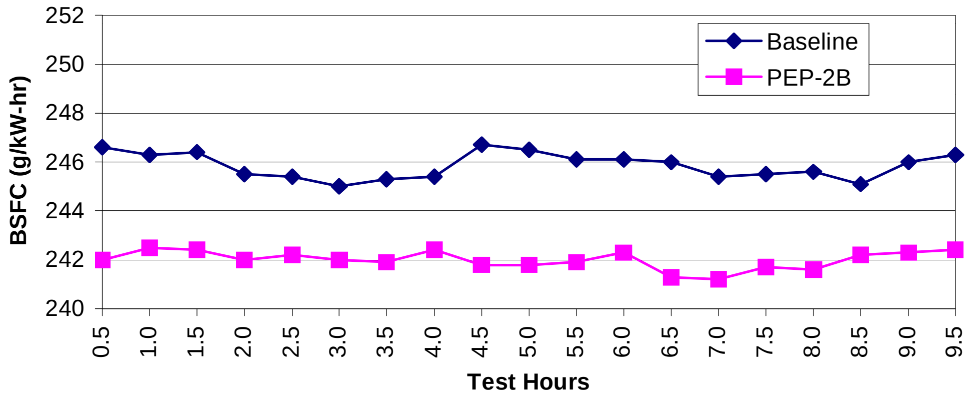

Figure 4e: Comparison of BSFC values (PEP-2B)

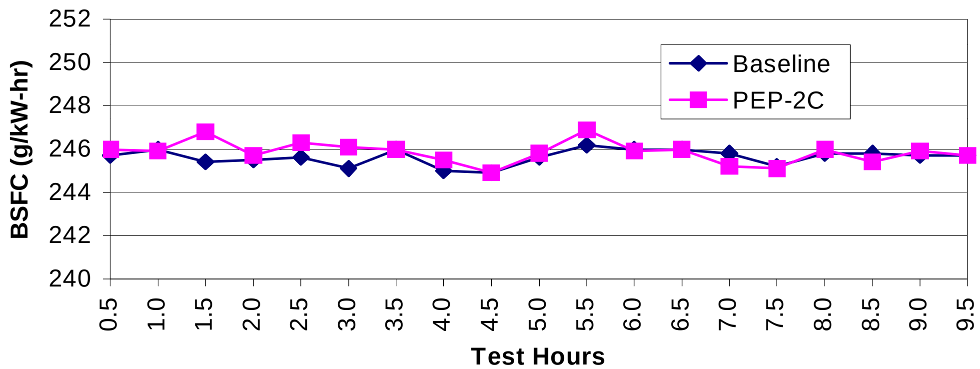

Figure 4f: Comparison of BSFC values (PEP-2C)

To determine whether there is a statistically significant difference in the mean values of the two sets of experimental data of an evaluation test, the data were analyzed using appropriate statistical methods. The difference was evaluated at a 90 percent confidence level. The analysis results are shown in Table 11, in which no significant changes in BSFC can be seen for PEP-1B, PEP-2A, PEP-2C, and PEP-3A. However, the BSFC with PEP-1A, PEP-1C, and PEP-2B seems to improve by as much as 1.6 percent.

Table 11: Summary of BSFC results

Product	Index	Baseline		With-product		Percentage changes (%)[a] (90% confidence level)
		Average BSFC (g/kW-hr)	S.D.	Average BSFC (g/kW-hr)	S.D.	
Device	PEP-1A	245.5	0.30	242.2	0.56	-1.34
	PEP-1B	244.5	0.52	244.7	0.52	N.S.[b]
	PEP-1C	244.5	0.68	242.0	0.56	-1.02
Fuel Additive	PEP-2A	245.5	0.68	243.6	0.70	N.S.
	PEP-2B	245.9	0.60	241.9	0.50	-1.61
	PEP-2C	245.6	0.41	245.8	0.43	N.S.
Oil Additive	PEP-3A	245.7	0.37	245.5	0.34	N.S.
	PEP-3B	243.6	0.66	/	/	/

Note: a - Percentage Change = (With-product BSFC - Baseline BSFC)/Baseline BSFC
b - Non-significant change

3.2.3 Combustion Analysis

Combustion analysis was used as a complementary method to further investigate the influence of PEPs on engine performance.

Engine cylinder pressure data were collected for PEP-1C. The pressure data (average of 20 cycles) were analyzed to calculate the apparent net heat release rate and engine combustion temperature. The average of five measurements for maximum cylinder pressures collected for baseline was used to investigate the variation of cylinder pressure measurements. It was found that the pressure values vary within ±1 percent of the mean value. Figure 5 displays cylinder pressures for baseline (19 hours) and those with PEP-1C (72 hours). The curves are plotted in terms of cylinder pressure versus engine crank angles. Slight differences were observed between top dead center (TDC) and 25° crank angle (CA) after top dead center (ATDC). Those before TDC and after 30° ATDC were found to be almost the same. PEP-1C has a relatively high peak pressure. Figure 6 was obtained by plotting the net heat release rates for baseline and PEP-1C. As seen in this figure, the heat release rates of pre-mixing and mixing controlled combustion periods of PEP-1C are higher than that of baseline, especially at the mixing controlled period. As for the late combustion phase, the heat release rates of PEP-1C are lower than that of the baseline. Figure 7 shows cylinder temperatures. PEP-1C has a relatively low temperature at exhaust opening of 302.5° CA. The combustion results tend to indicate improved combustion efficiency as a result of the use of this device. This is consistent with the observed fuel consumption change and engine exhaust temperature change.

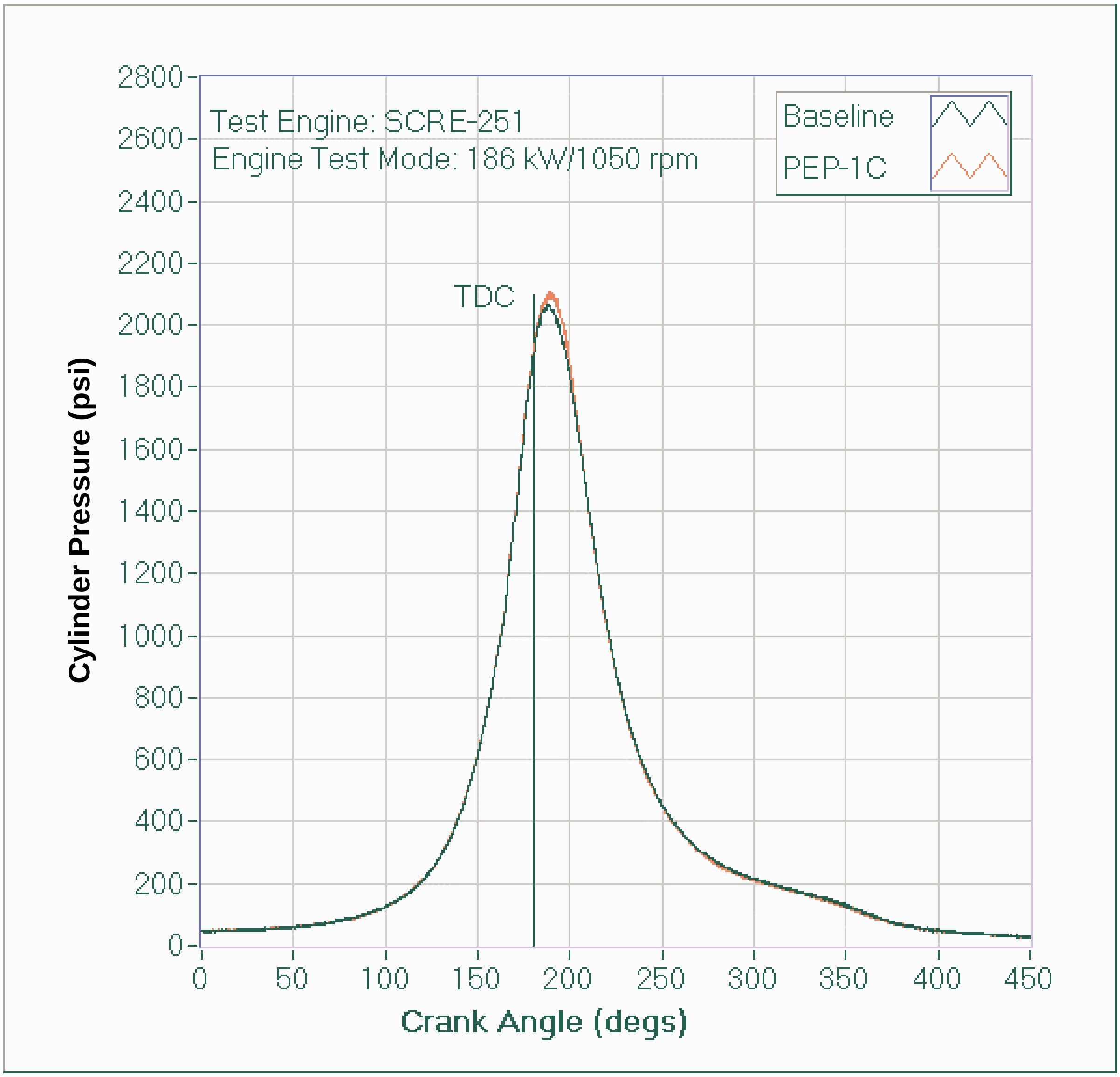

Figure 5: Comparison of cylinder pressures between the baseline and PEP-1C

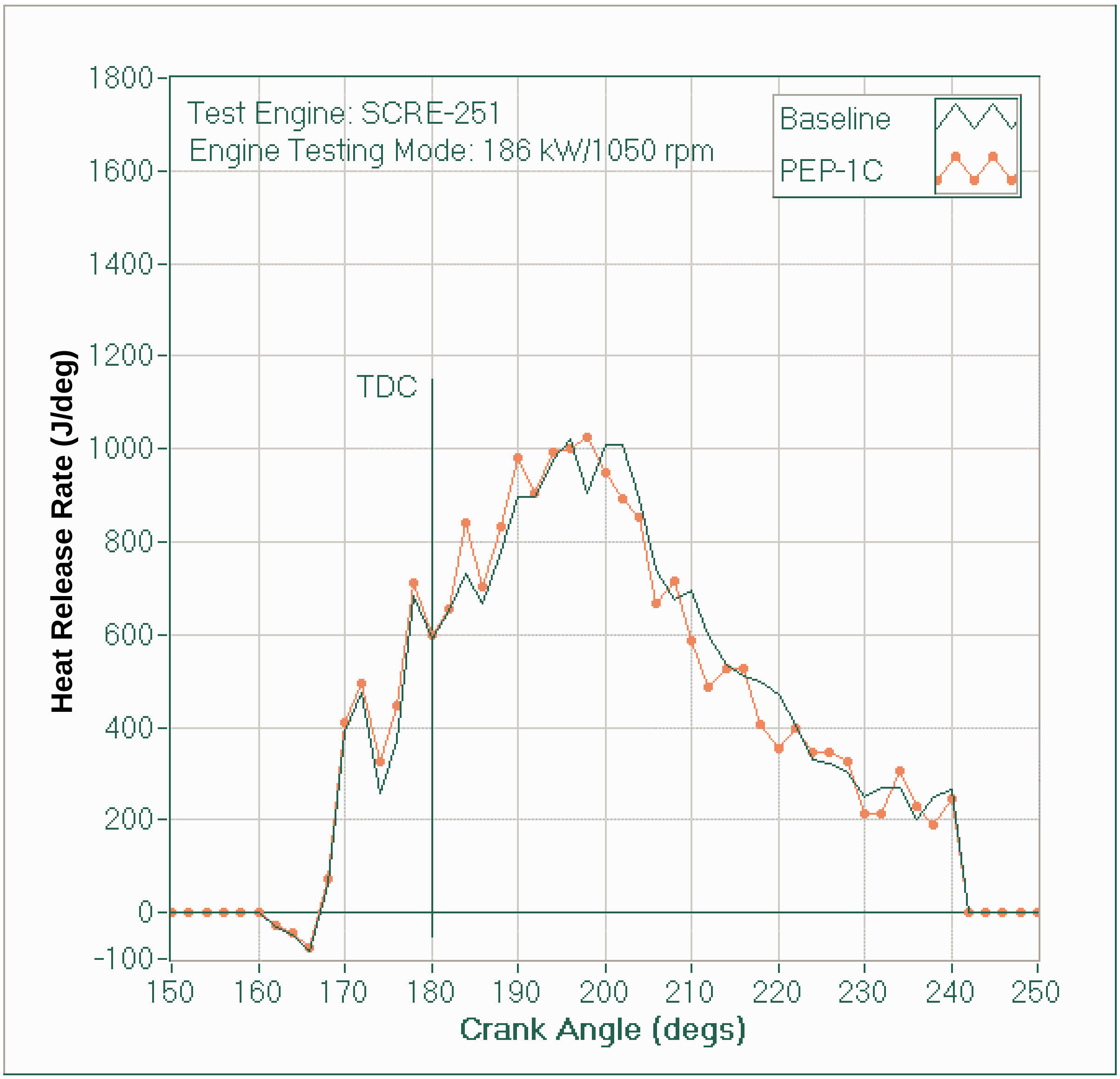

Figure 6: Comparison of net heat release rate between the baseline and PEP-1C

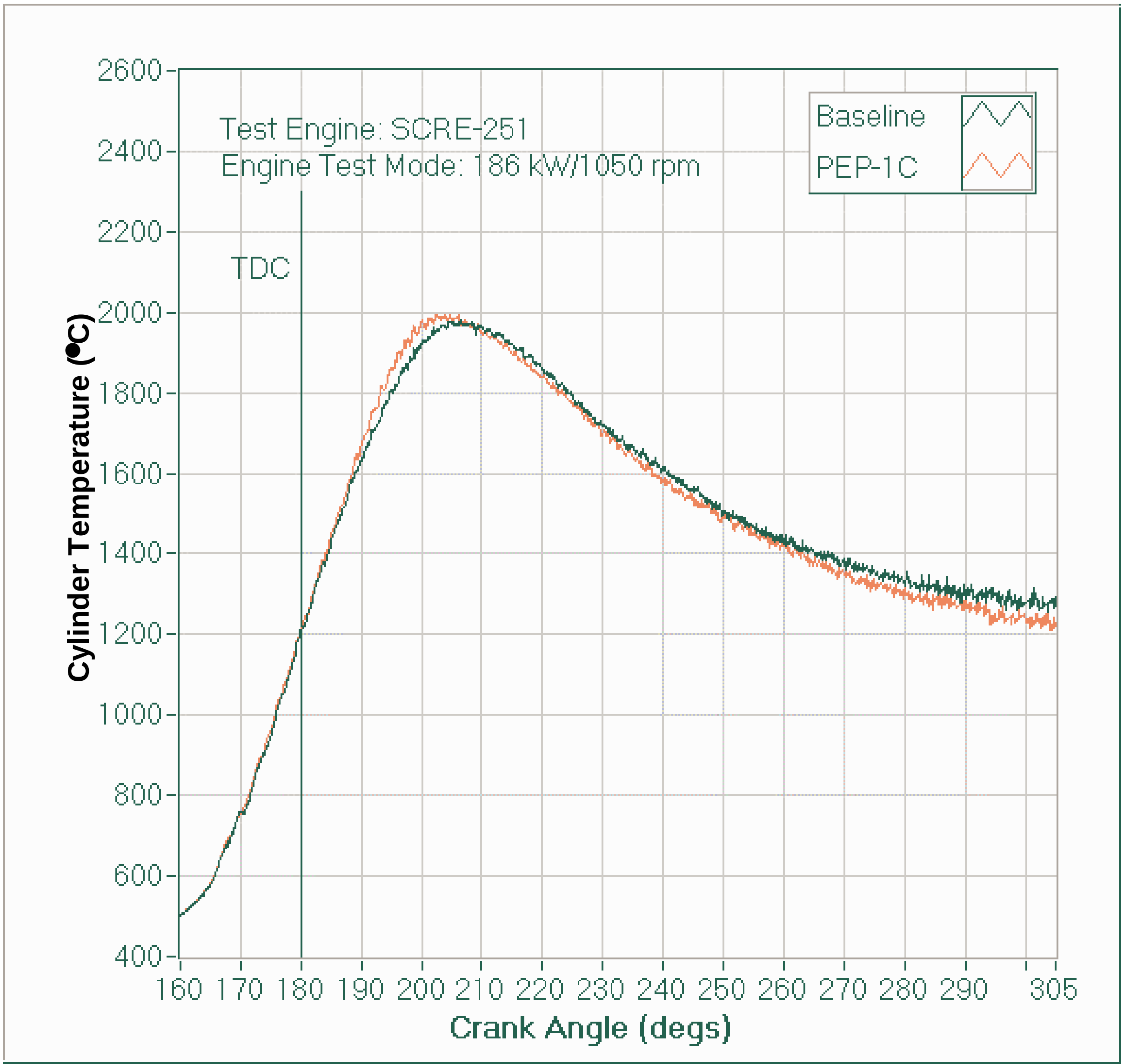

Figure 7: Comparison of cylinder temperatures between the baseline and PEP-1C

3.2.4 Emissions Results

Table 12 gives the measured emissions values for both the baseline and the performance test for each individual PEP. Each value in the table is an average of at least two runs. According to these results, the emissions values vary with the type of PEP being used. The calculated tolerance that would be expected for these values (based on the repeatability analyses performed for the baseline tests) tend to show that, on average, a 2.5 percent change in emissions can be easily detected by the equipment used for emissions analysis.

Table 12: Summary of emission results

Product	Index	CO			NOx			Smoke		
		AB [(a)]	AW [(b)]	Percentage change[(c)] (%)	AB	AW	Percentage change (%)	AB	AW	Percentage change (%)
Device	PEP-1A	3.1	3.0	-3.2	12.8	12.6	-1.5	1.37	1.34	-2.2
	PEP-1B	2.9	2.6	-10.3	12.1	12.0	-0.8	1.36	1.32	-2.9
	PEP-1C	2.8	2.4	-14.3	12.2	12.7	4.0	1.47	1.40	-4.8
Fuel Additive	PEP-2A	2.5	2.4	-4.0	13.0	12.9	-0.8	1.37	1.35	-1.5
	PEP-2B	3.3	3.2	-3.0	12.6	12.8	1.6	1.35	1.32	-2.2
	PEP-2C	3.3	3.2	-3.0	12.2	12.3	0.8	1.41	1.37	-2.8
Oil Additive	PEP-3A	3.8	3.9	2.6	12.1	11.8	-2.4	1.40	1.42	1.4
	PEP-3B	3.7	/[(d)]	/	12.5	/[(d)]	/	/	/[(d)]	/

Note:
(a) AB – Average of baseline; (b) AW – Average of with-product; (c) Percentage change = (AW-AB)/AB
(d) Since the engine oil filter was blocked up during the PEP-3B test, no reliable emissions data were obtained for an engine operating with the product.

3.2.5 Comparison with Existing Test Results

Efforts were made to select products that had been tested and documented by other investigators. Since most of the products had been tested under non-controlled conditions, they could not be used for comparison purposes. Therefore, only two products, which met the requirements, were used in the present discussion.

Add-On Device – Tests had been performed by Taylor [7] to investigate engine performance using an oil-cleaning device similar to PEP-1C. Those tests were conducted on a Lister-Petters (1.3 L) DI single-cylinder diesel engine. The engine was operated under controlled conditions. Since the engine size used was much smaller than the SCRE-251, the experimental results could only be qualitatively compared to the current results. A comparison between Taylor's test and the present test, with respect to engine fuel economy, emissions, and oil properties, is shown in Table 13.

Table 13: Comparison of experimental results between the present test (PEP-1C) and Taylor's test

Item		**Taylor's test**	**Present test**
Engine	Fuel consumption	D	D
Emissions	CO emissions	D	D
	NOx emissions	I	I
	Smoke	NS	D
Oil property	Oil flashpoint	I	I
	TAN	NS	NS
	TBN	NS	NS
Note: D – Decreased; I – Increased; NS – Non-significant change			

It can be clearly seen that the trends were very similar except for smoke, which was reduced with PEP-1C.

Fuel Additive – The same fuel additive as PEP-2B had been tested at the Southwest Research Institute (SwRI) [8] using the RP-503 protocol. These tests were conducted on a Caterpillar 1G2 test engine first, then on a 12-cylinder EMD 645 locomotive engine. All the tests were performed under controlled conditions. The experimental results from the RP-503 test are compared to the present test in Table 14.

As seen in Table 14, the change in fuel property obtained by SwRI was very similar to that of the present test. Engine operating parameters of the present test were also very close to those of SwRI's results. Engine BSFC and emissions results of the two tests were almost identical.

Table 14: Comparison of experimental results between the present test and SwRI's test

Item		**SwRI test**	**Present test**
Fuel property	Gravity	NS	NS
	Distillation range	NS	NS
	Carbon residue	NS	NS
	Cetane number	NS	NS
	Heat of combustion	NS	NS
Engine	Fuel consumption	-1.74%	-1.61%
Emissions	CO emissions	NS	NS
	NOx emissions	NS	NS
	Smoke	\	NS
Engine operating parameter	Air temperature	differ<20° F	185±2° F
	Fuel temperature	90±10° F	90±6° F
	Coolant temperature	differ<10° F	180±4.7° F
	Oil temperature	differ<10° F	189±4.5° F
Note: NS – Non-significant change			

4 SIMPLIFIED FUEL ADDITIVE TEST PROCEDURE

4.1 Scope

This procedure is intended to evaluate the effectiveness of fuel additives or engine add-on devices (engine fuel or oil system) for medium-speed diesel engine use. The effects on engine performance and emissions (both positive and negative) arising from use of these products will be determined from the test. The procedure will provide results that may serve as one indicator to the potential user of the comparative use of an untreated fuel (or an engine without add-on device) versus that of a fuel treated with an additive (or an engine with an add-on device).

4.2 Evaluation Procedure

This evaluation procedure consists of two steps: fuel (or oil) properties and engine tests.

Step 1: Fuel (or oil) Properties – Standard ASTM tests for baseline and treated fuel (or oil) are mandatory.

Step 2: Single-Cylinder Test Engine (SCRE-251) – Tests shall be conducted on a single-cylinder research engine (SCRE-251) operated at rated power (250 hp). The tests shall be conducted in a "baseline-preconditioning-product" manner. The duration of a test sequence shall be 75 hours per fuel, including 20 hours baseline, 35 hours pre-conditioning, which is necessary for stabilizing the engine performance, and 20 hours performance test.

These tests are detailed in Sections 4.3 and 4.4.

4.3 Fuel (or Oil) Property Tests (Step 1)

The following physical and chemical fuel properties shall be tested using ASTM methods. These ASTM tests should be performed on a sample of diesel fuel as well as a sample of the same fuel treated with a fuel additive or engine fuel-system add-on device. Diesel fuel conforming to ASTM specification grade 2-D shall be used unless otherwise specified. The purpose of these tests is to evaluate the effects of the additives or add-on devices on limiting fuel specification requirements. The tests are used as a general guideline and may be modified to include additional tests if necessary because of the nature of the additives or add-on devices being tested.

Property	**ASTM Test Method No.**
Density @ 15°C	D 1298
Flash Point	D 93
Cloud Point	D 2500
Pour Point	D 97
Kinematic Viscosity @ 100°F	D 445
Distillation, 50%, 90% and end points	D 86
Carbon Residue	D 524
Sulfur	D 1552, D 129, or D 2622
Copper Strip Corrosion	D 130
Ash	D 482
Water and Sediment	D 2709
Accelerated Stability	D 2274
Neutralization	D 974
Particle Contamination	D 2276
Cetane Number	D 613 or D 976
Heat of Combustion	D 240

It is impossible to establish limits on all the physical and chemical properties of lubricating oils that can affect performance in the engine over a broad range of environmental influences [2]. However, the quality and performance of lubricating oils may be judged through a set of laboratory tests, which would identify their suitability for engine testing. The following oil properties will be tested for the evaluation of oil-system add-on devices.

Property	ASTM Test Method No.
Viscosity	D 88 or D 445
Viscosity Index	D 567
Flash Point	D 92
Pour Point	D 97
Zinc Content	(10 ppm max.)
Total Base Number	D 2896 or D 664
Total Acid Number	D 664
Evaporative Loss	D 2887
Carbon Residue	D 524
Sulfated Residue	D 874

4.4 SCRE-251 Engine Tests (Step 2)

Engine power can be measured either by dynamometer or by an engine-driven generator with load bank. The instruments shall be calibrated to an accuracy of ±2 percent of full scale. Engine fuel consumption is measured either by weighting scale or flow meter, and instruments shall be calibrated to ±2 percent of full scale. A portable emissions analyzer (or emissions workbench) can be used for emissions measurements. The analyzers shall be calibrated before the tests according to the procedure recommended by manufacturer.

After the engine is started and warmed up according to normal procedure, the engine is operated at the test point (full load). The test shall be conducted under the following engine conditions:

- Engine speed shall be controlled within 1050±2 rpm, and engine load within 1695±2 N.m.
- Engine intake air temperature shall be controlled within 85±1°C.
- Engine oil sump temperature shall be controlled within 87±3°C.
- Engine coolant water outlet temperature shall be maintained at 82±3°C.
- Engine fuel temperature shall be maintained at 32±4°C.
- Engine intake air pressure shall be 32.5±0.1psi.

The test duration shall be 75 hours, including 20 hours baseline, 35 hours preconditioning, and 20 hours performance test. Engine performance data shall be taken every half-hour, including BOSCH smoke values. Gaseous emissions shall be measured at least once at mid-way or at the end of the test sequence for both the baseline and product test.

BSFC data obtained for baseline and product (after preconditioning) should be plotted as a function of engine operating time to show any discernible trends and consistency of the data. The two sets of BSFC data should be statistically analyzed to determine whether there is a statistically significant difference in the mean values of the two sets of data. The difference should be evaluated at a 90 percent confidence level [1].

5 CONCLUSIONS

Eight candidate products were tested during this study and the optimum test sequence, which would be sufficient for performance and emissions evaluation of PEPs, was established. The test sequence was found to be suitable only for the evaluation of add-on devices and fuel additives. Since the oil additives require longer preconditioning time, it was concluded that a separate test method would be required to properly evaluate their effect on engine performance and emissions.

Repeatability of engine fuel consumption and emissions measurements were determined by statistical analyses performed on the baseline data only. According to these analyses, a minimum of 1 percent in fuel consumption can be easily detected using the current test procedure and set-up. The test results can be further investigated using combustion analyses as a complementary method.

Based on the overall observation, a total of 75 hours of engine tests that include baseline, preconditioning, and performance sequence would be sufficient for an evaluation of PEPs with respect to their effects on fuel consumption and exhaust emissions.

6 RECOMMENDATIONS

A test sequence and procedure for evaluating fuel additives and engine add-on devices were established based on the test results from Phase III of the SFAT project. However, to make the procedure a viable alternative to AAR RP-503, fine tuning and validation of the test procedure are still required. It is therefore recommended to conduct another phase to validate the experimental repeatability, finalize the protocol, and formulate and submit the protocol for adoption.

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