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TP 13215E

FEASIBILITY OF A SIMPLIFIED FUEL ADDITIVE EVALUATION PROTOCOL

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FEASIBILITY OF A SIMPLIFIED FUEL ADDITIVE EVALUATION PROTOCOL

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ENGINE SYSTEM DEVELOPMENT CENTRE

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16. Abstract

The Simplified Fuel Additive Test (SFAT) project was initiated in conjunction with the Transportation Development Centre (TDC), Transport Canada. The first phase of this project involved the determination of the feasibility of replacing the Association of American Railroads (AAR) Recommended Practice (RP) 503 protocol for testing diesel fuel oil additives with a new procedure, using the Single Cylinder Research Engine (SCRE-251) as the laboratory test engine, which tests for both engine performance as well as emissions compliance.

This report describes the work carried out during the four stages of the first phase of the SFAT project. Following a literature search, a review of the new U.S. Environmental Protection Agency (EPA) regulations is provided, a comparison between the AAR RP-503 test engines and the SCRE-251 is made, and finally, a study of the SCRE-251's ability to represent a multi-cylinder medium-speed diesel engine is conducted.

The report concludes that it is feasible to develop a new Simplified Fuel Additive Test that replaces the AAR RP-503, reflecting the requirements of the EPA locomotive emissions regulations using the medium-speed SCRE-251.

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16. Résumé

Le projet d'étude d'un protocole d'essai simplifié des additifs pour carburants (SFAT pour Simplified Fuel Additive Test) a été lancé en collaboration avec le Centre de développement des transports (CDT), de Transports Canada. La première phase visait à établir la faisabilité d'un nouveau protocole d'essai d'additifs pour carburants diesel qui remplacerait la Pratique recommandée 503 de l'Association of American Railroads (AAR) et qui utiliserait le moteur de recherche monocylindre (SCRE-251) comme banc d'essai en laboratoire servant aussi bien à déterminer les performances qu'à mesurer les émissions polluantes.

Ce rapport documente les travaux réalisés au cours des quatre premières étapes de la phase I de l'étude SFAT. Il présente les résultats d'une recherche documentaire, un examen de la nouvelle réglementation antipollution de la U.S. Environmental Protection Agency (EPA), une étude comparative des moteurs d'essai AAR RP-503 et SCRE-251 et, enfin, une étude de la capacité du SCRE-251 à bien représenter le fonctionnement d'un moteur diesel multi-cylindres à vitesse moyenne.

Les chercheurs ont conclu qu'il est possible de développer un nouveau protocole simplifié d'évaluation des additifs pour carburants en remplacement de la PR 503 de l'AAR, protocole qui intégrerait la réglementation EPA sur les émissions polluantes des locomotives et qui serait réalisé à l'aide du SCRE-251 à vitesse moyenne.

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Moteur de recherche monocylindre, locomotive, moteur diesel, réglementation antipollution, additifs, huile de lubrification, mazout, optimiseurs de rendement

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EXECUTIVE SUMMARY

One significant operating cost railways face today is the cost of fuel; consequently, any reduction in fuel consumption would result in large savings. There are numerous after-market Performance Enhancing Product (PEP) suppliers who wish to sell into the locomotive market; however, they face a financial hurdle in that the railways often stipulate that their product be evaluated by a reputable laboratory before they consider in-service trials. The only procedure existing for testing these after-market products is the Association of American Railroads (AAR) Recommended Practice (RP) 503 that was adopted in 1980 and is currently performed at Southwest Research Institute (SwRI). This procedure does not measure emissions to the recently promulgated U.S. Environmental Protection Agency (EPA) rules for locomotives. These rules affect the entire locomotive community including manufacturers, rebuilders, and the after-market suppliers, with a great deal of the background work having been done at SwRI.

The overall purpose of the first phase of the Simplified Fuel Additive Test (SFAT) project is to assess the feasibility of developing a test protocol that will replace the AAR RP-503, and will reflect the new EPA emission rules for locomotives. The project is divided into four tasks – a literature search, an analysis of the EPA regulations, a comparison of the Single Cylinder Research Engine (SCRE-251) to the Caterpillar 1G2 engine, and a comparison of the SCRE-251 to a multi-cylinder engine.

The literature search produced many informative papers on the topics under consideration and a search of the Internet yielded information on after-market suppliers. In addition, a list of EPA tested after-market products was acquired.

The new EPA emission standards affect locomotive engines that had previously been unregulated and should achieve a significant reduction in emissions. The regulations, which take effect on January 1, 2000, will affect North American manufacturers, re-manufacturers, and importers of locomotives and locomotive engines, and railways and operators. The impact for Canadian railway companies that operate divisions in the U.S. and for Canadian companies that supply the U.S. market – be they manufacturers, re-manufacturers, or parts suppliers – is that they will be required to meet the regulations. To ensure compliance, the EPA will conduct both production line certification testing and in-use verification tests. The in-use tests are meant to ensure that manufacturers and re-manufacturers produce units that continue to meet emission standards beyond the production and certification stages and during actual operation. Upon the determination of a non-compliant unit, the actual repair will apply to all locomotives of that family regardless of whether or not the locomotives have exceeded their useful life. Also, Class I railways will be required to annually test a sample of their locomotive fleet that have surpassed their useful life. The regulations include an anti-tampering provision that calls for severe criminal penalties, not only for the corporation, but for the “responsible corporate officials” as well. Tampering is defined as knowingly altering the emission characteristics of a locomotive and includes removing emission control devices or applying uncertified systems or kits.

It is concluded that a procedure that utilizes a single cylinder research engine derived from a medium-speed diesel engine will not only be more economical, but will be less complex, since two intermediate engines, the 1G2 and EMD 567-twin, used in the AAR RP-503 test sequence, would not be required. The new procedure will require less time to complete and will be more representative of modern locomotive diesel engines. In addition, the upgrading of the exhaust emissions section of the current procedure to reflect the new EPA regulations will produce a comprehensive but simplified fuel additive screening and evaluation procedure.

SOMMAIRE

Les dépenses en carburant représentent une part importante des frais d'exploitation des compagnies ferroviaires. Aussi, toute mesure permettant de réduire la consommation des locomotives entraînera des économies substantielles. De nombreux fournisseurs de produits d'optimisation du rendement sont intéressés par le marché des locomotives, mais ils se butent à un obstacle financier majeur du fait que les compagnies ferroviaires exigent fréquemment qu'un laboratoire reconnu procède à une évaluation indépendante des produits qui leur sont proposés, avant même d'envisager un programme d'essai en service. Il existe un seul protocole d'essai des produits en question, soit la Pratique recommandée 503 de l'Association of American Railroads (AAR) adoptée en 1980 et appliquée à l'heure actuelle par le Southwest Research Institute (SwRI). Ce protocole ne comporte aucune disposition concernant la vérification de la conformité des locomotives aux nouvelles normes antipollution mises en place par la U.S. Environmental Protection Agency (EPA). Ces normes, fondées en majeure partie sur les travaux préparatoires réalisés au SwRI, ont une incidence sur tous les intervenants du marché des locomotives, fabricants, ateliers de reconstruction, fournisseurs de produits d'optimisation du rendement et autres.

La première phase du projet d'étude d'un protocole simplifié d'essai des additifs pour carburants (SFAT pour Simplified Fuel Additive Test) a pour objectif général d'évaluer la faisabilité d'un protocole d'essai qui remplacerait l'actuelle Pratique recommandée 503 de l'AAR et permettrait en même temps de vérifier la conformité des locomotives aux nouvelles normes antipollution de l'EPA. Ce projet comporte quatre étapes : une recherche documentaire, une analyse de la réglementation EPA, une comparaison du moteur de recherche monocylindre (SCRE-251) et du moteur Caterpillar 1G2, et une comparaison du SCRE-251 à un moteur multi-cylindres.

La recherche documentaire a permis de trouver de nombreuses études intéressantes consacrées à l'objet de la présente étude, tandis qu'une recherche sur Internet a livré des informations sur les fournisseurs de produits d'optimisation du rendement. De plus, on a obtenu une liste de produits de cette catégorie testés par l'EPA.

Les nouvelles normes antipollution de l'EPA s'appliqueront à des locomotives qui échappaient jusqu'ici à toute réglementation et devraient donc déboucher sur une réduction appréciable des émissions polluantes par l'industrie ferroviaire. Ces normes, qui doivent entrer en vigueur le 1er janvier 2000, auront une incidence sur tout le secteur ferroviaire nord-américain : constructeurs, importateurs de locomotives et de moteurs de locomotives, ateliers de reconstruction, chemins de fer et exploitants de lignes ferroviaires. Elles toucheront les compagnies ferroviaires canadiennes qui exploitent des divisions en territoire américain et toute entreprise canadienne du secteur ferroviaire ayant des débouchés aux États-Unis, qu'il s'agisse de constructeurs, d'atelier de reconstruction ou de fournisseurs de pièces. Pour faire respecter sa réglementation, l'EPA procédera aussi bien à des essais d'homologation de type en usine qu'à des vérifications de conformité en service. Ces dernières viseront à faire en sorte que les constructeurs et les ateliers de reconstruction mettent sur le marché des locomotives dont les émissions restent à l'intérieur des plages admissibles après les essais d'homologation et en cours d'exploitation. Dans le cas où une locomotive serait trouvée non conforme aux normes, les correctifs devront viser toutes les locomotives de la même famille, qu'elles aient dépassé leur durée de vie utile ou non. Par ailleurs, les chemins de fer de classe I devront contrôler chaque année un échantillon de leur parc de locomotives ayant dépassé leur durée de vie utile. La réglementation prévoit aussi de lourdes sanctions pénales à l'encontre non seulement des sociétés qui auront trafiqué leur matériel, enlevé des dispositifs antipollution ou mis en service des équipements ou accessoires non homologués, mais aussi de leurs «dirigeants responsables».

L’étude a déterminé qu’un protocole faisant appel à un moteur de recherche monocylindre dérivé d’un moteur diesel à vitesse moyenne serait non seulement plus économique, mais également moins compliqué à exécuter que celui de la PR 503 de l’AAR qui suppose l’utilisation successive de deux moteurs intermédiaires, soit un 1G2 et un EMD 567 bi-cylindre. Le nouveau protocole prendra moins de temps et donnera des résultats caractérisant mieux les moteurs diesel ferroviaires modernes. De plus, avec un volet contrôle des émissions polluantes aligné sur la nouvelle réglementation antipollution de l’EPA, ce protocole deviendra un outil à la fois simple et exhaustif d’évaluation et de contrôle des additifs pour carburants.

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GLOSSARY

AAR	Association of American Railroads
ASME	American Society of Mechanical Engineers
CED	Combustion Enhancing Device
CFR	Code of Federal Regulations (U.S.)
CO	Carbon Monoxide
CRC	Coordinated Research Council (U.S.)
DI	Direct Injection
DIN	Deutsche Industrie Norm
EMD	Electro-Motive Division of General Motors
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine System Development Centre
FOA	Fuel Oil Additive
FTP	Federal Test Protocol (U.S.)
GE	General Electric
THC	Total Hydrocarbons
IDI	Indirect Injection
IMEP	Indicated Mean Effective Pressure
LOA	Lube Oil Additive
NO_X	Oxides of Nitrogen
PEP	Performance Enhancing Products
PM	Particulate Matter
RAC	The Railway Association of Canada
RP	Recommended Practice
SAE	SAE International
SCRE-251	ALCO 251 Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SwRI	Southwest Research Institute

1.0 INTRODUCTION

One of the major operating costs incurred by the railways today is the cost of diesel fuel; therefore, companies are constantly examining the possibility of increasing fuel efficiency with fuel oil additives (FOA), lubricating oil additives (LOA) and combustion enhancing devices (CED). However, products which increase fuel efficiency generally tend to affect engine components as well as emissions. The presently accepted standard of evaluating these performance enhancing products (PEP) is the Association of American Railroads (AAR) Recommended Practice (RP) 503, entitled, "Locomotive Diesel Fuel Additive Evaluation Procedure". This procedure was adopted in 1980, and consists of four different stages. It compares the effects of FOAs on fuel chemical properties, engine wear and deposits, as well as engine performance characteristics (1). Presently, the only organization that can carry out the AAR RP-503 test is Southwest Research Institute (SwRI). Each test requires over 1000 hours for completion and costs more than $240,000 US. Furthermore, it does not evaluate the effect of PEPs on engine emissions on a level representative of EPA's new emission standard known as 40 CFR 92 (2). Modification of the AAR RP-503 procedure to include testing to the 40 CFR 92 emission standard requirements would make this evaluation method even more expensive. The costly and time consuming test procedure imposes a financial burden for anyone who wishes to develop and market certified additive products.

The Simplified Fuel Additive Test (SFAT) project proposed by the Engine Systems Development Centre (ESDC) was initiated to develop a procedure that would address both the engine performance and wear effects as well as the emissions trend exhibited by the PEP. The proposed procedure would offer a lower analysis cost and would require less time for completion.

Hence, the purpose of the first phase of the SFAT project is to assess the feasibility of developing a PEP evaluation protocol that replaces the AAR RP-503 and includes emissions testing representative of the EPA 40 CFR 92 regulations while offering a lower overall evaluation cost to the PEP manufacturer. The following is a list of the objectives of this study:

- Literature search - conduct a comprehensive literature search of all documentation relating to fuel and lubricant additives and combustion enhancers as well as pertinent information on test engines.

- Review of the EPA regulations - identify and review the pertinent EPA emissions regulations and definition of test facility equipment requirements to carry out emission tests in accordance with the regulatory requirements.

- Review of the Caterpillar 1G2 Engine and comparison with the Single-Cylinder Research Engine (SCRE-251). Review the role and characteristics of the Caterpillar 1G2 engine used in the AAR RP-503 to measure the effect that additives may have on engine components and assess how the ESDC SCRE-251 can be used in its place. Compare the dimensions of the SCRE-251 and 1G2 and determine whether the existing 1G2 charts relating to the effects of the additive on deposits and wear will be applicable to the SCRE-251 or a new correlation has to be developed

- Performance correlation to current multi-cylinder engines - evaluate the use of the unique capability of the SCRE-251 to represent various engine configurations of current medium-speed locomotive diesel engines, and its use in place of the multi-cylinder engines.

The results of studying these objectives are detailed in the following sections after which a conclusion is presented along with the recommendations offered by the project team members.

2.0 LITERATURE SEARCH

As part of the evaluation of the feasibility of developing a Simplified Fuel Additive Test procedure that would be more affordable and accessible to aftermarket suppliers when compared to the current AAR RP-503, a comprehensive literature search was conducted. A large number of references were cited, including SAE technical papers and EPA reports. Furthermore, relevant information was obtained from suppliers of additives, bolt-on devices, and Internet web sites. Only those references that are relevant to this study are presented in the reference section.

The database and information sources used in this work are provided in Appendix A. Appendix B depicts relevant test procedures being used to test PEPs. Appendix C specifies the internet web sites employed to gather information in addition to sources previously mentioned in Appendix A. Appendix D includes reports and articles illustrating the different types of products being marketed as well as test results on these products being offered by the manufacturers or a third party. In addition, this section provides a list of devices and additives that were previously tested.

The review of the gathered data focused on; (a) the current state-of-the-art technology of screening and evaluating the effects of additives on engine performance, (b) the type of test engine mostly used, (c) understanding the mechanisms and controlling factors of the AAR RP-503 and, (d) the potential of using the ESDC single-cylinder engine as the screening and evaluation tool.

Numerous claims are being made by manufacturers of PEPs with respect to fuel saving, improved performance and reduced emissions (Appendix D) examples of which are provided below.

> “Laboratory and field tests of diesel engines using Ion Collider technology demonstrate the following benefits: reduces fuel consumption 5%-20%, increases power output 5%-15%, reduces heat production 5%-10%, reduces hydrocarbon emissions, reduces exhaust opacity, eliminates carbon deposits.”
>
> - Advanced Catalytic Technologies, Fuel Refinement Products for Diesel Engines, Brochure (see Appendix D)

> “The COMTEC combustion enhancement technology reforms the molecular structure of diesel, gasoline and other liquid fossil fuels. This will improve the combustion process resulting in: reduced fuel consumption, increased power, reduced smoke, reduced emissions, reduced exhaust gas temperatures, cleaner combustion chamber”
>
> - COMTEC Combustion Technologies Inc. Brochure (see Appendix D)

> “ADERCO maintains a higher performance (for a longer period of time) for maximum fuel savings. By treating diesel fuel with ADERCO additives, you will obtain better atomization and more complete combustion which will translate into: fuel savings (brochure indicates 4% on locomotive engines), reduced emissions, reduced maintenance.”
>
> - ADERCO Additives Brochure (see Appendix D)

These claims that are being made by the PEP suppliers could be substantiated using the SFAT protocol.

The obtained information tends to indicate that a single-cylinder research engine can be conveniently used to provide an alternative to the existing AAR RP-503 test procedure. These types of engines can be utilized to investigate the effect of fuel and lubricant additives on emission, engine wear, and deposits. Various methods have been found in the literature that are currently used for in-house research that examine the effect of fuel additives on emissions (3-9). These test procedures can be used as background information when developing a standard test protocol to replace the AAR RP-503. The trend observed in literature shows that the use of single-cylinder research engines in laboratories is rapidly increasing due to the advantages offered by this type of engine.

The results of this extensive survey are sufficient to assess the feasibility of developing a test protocol that will be an alternative to, or replace the AAR RP-503. Complete descriptions of these findings are covered in the following sections.

3.0 REVIEW OF THE EPA REGULATIONS

The promulgated emission standards published in the Federal Register on April 16, 1998, regulating locomotive diesel engine emissions of oxides of nitrogen (NO_x), total hydrocarbons (THC), carbon monoxide (CO), particulate matter (PM), and smoke are given in Tables 1 and 2. The three tier levels refer to date of manufacture of the diesel engine. After Tier 2 is enforced, the new standards will achieve approximately a two-thirds reduction in NO_x emissions while THC and PM emissions will be halved. The standards are effective January 1, 2000, and will affect locomotive manufacturers, re-manufacturers and importers, as well as locomotive diesel engine component suppliers and railroads.

Table 1 - Gaseous and Particulate Emissions For
Locomotives Under EPA (g/bhp.h)

	THC	CO	NO_x	PM
Tier 0 Locomotives - Manufactured from 1973- 2001				
Line Haul	1.0	5.0	9.5	0.60
Switch	2.1	8.0	14.0	0.72
Tier 1 Locomotives - Manufactured from 2002-2004				
Line Haul	0.55	2.2	7.4	0.45
Switch	1.2	2.5	11.0	0.54
Tier 2 Locomotives - Manufactured from 2005 and beyond				
Line Haul	0.3	1.5	5.5	0.20
Switch	0.6	2.4	8.1	0.24
Estimated Emissions 1997				
Line Haul	0.5	1.5	13.5	0.34
Switch	1.1	2.4	19.8	0.41

These new regulations pose a significant impact for the Canadian locomotive industry being that any U.S.-bound locomotive or engine component must comply with the new EPA regulations. Presently, Canadian locomotives are exempted from EPA regulations if their use in the U.S. is negligible. However, Canadian locomotives that operate extensively in the U.S. must conform to the EPA regulations (2). This requires frequent and extensive testing and certification of those affected Canadian locomotives.

Table 2 – Smoke Standards For Locomotives Under EPA
(% Opacity – Normalized)

	Steady State	30 sec Peak	3 sec Peak
Tier 0 Locomotives	30	40	50
Tier 1 Locomotives	25	40	50
Tier 2 Locomotives	20	40	50

The EPA regulation contains an anti-tampering provision, which provides for severe criminal penalties for corporations and responsible corporate officials (2). Tampering, in the current context, includes knowingly changing the emissions characteristics of a regulated diesel engine by installing a non-EPA-approved component or removing an engine component. Therefore, the use of any non-EPA-approved PEP will be considered tampering.

To ensure that all diesel engine locomotives meet the new EPA standards as they roll off the production line, the EPA will conduct production line testing of new and re-manufactured locomotives. An in-use testing program will evaluate the ability of locomotives to continue to comply with the new standards by requiring the locomotives be tested at 50%-75% of useful life and that Class 1 railroads annually test 0.15% of their locomotives that have met or exceeded their useful life.

The exhaust gas sampling and analytical system shown in Figure 1 was developed for the EPA at SwRI and no variation is allowed from the equipment indicated unless permitted by the administrator as a result of a proponent proving functional equivalence. The actual equipment required is: NO_x detection - chemiluminescence detector, CO and CO_2 non-dispersive infrared analyzer, and a heated flame ionization detector is used for the hydrocarbon detection. Particulate matter measurement requires the use of a dilution tunnel that is built to SAE specifications. Portable mini-dilution tunnels are available; however, EPA has not yet approved them for regulatory purposes. The remainder of the equipment required is mainly gas tubing and instrumentation. A significant item that is not on the flow sheet is a temperature and humidity controlled weighing room used in the particulate matter determination.

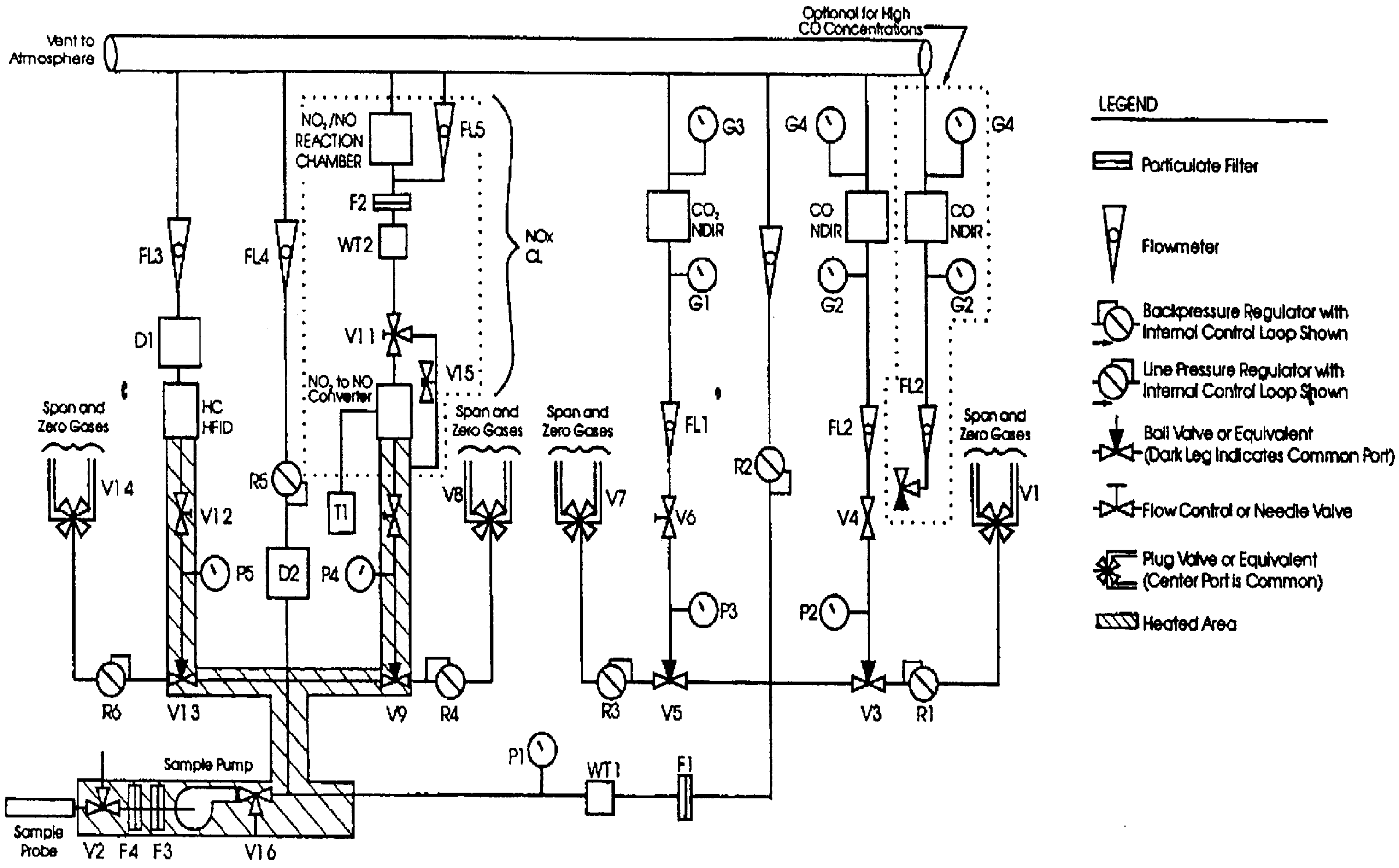


Figure 1 – Exhaust Gas Sampling and Analytical Train

4.0 REVIEW OF THE AAR RP-503 AND PROPOSED SFAT PROCEDURE

The currently accepted method of testing fuel oil additives for use in locomotive engines is the AAR RP-503 procedure entitled “Locomotive Diesel Fuel Additive Evaluation Procedure” which was adopted in 1980. This procedure consists of four individual phases of evaluation; a chemical analysis of the treated diesel fuel, a wear and deposit evaluation conducted on a Caterpillar 1G2 test engine, a performance evaluation conducted on an EMD twin-cylinder test engine, and a final performance evaluation on a multi-cylinder GE or EMD locomotive engine. The AAR RP-503 procedure does not address lube oil additives nor combustion enhancing devices. The results of conducting multiple engine tests are that the RP-503 procedure requires in excess of 1000 hours of testing and may cost upwards of $240,000 US. Furthermore, the only institution currently equipped to carry out this procedure is SwRI in San Antonio, Texas. The flow chart displayed on pages F-234 and F-235 of the AAR Mechanical Division Manual of Standards and Recommended Practices outlines the activities involved in the AAR RP-503 procedure and is summarized for comparison in Figure 2.

The “Feasibility of a Simplified Fuel Additive Evaluation Protocol” project was initiated in order to assess the feasibility of developing a new test procedure that provided to the aftermarket performance enhancing product suppliers a simplified, less costly alternative to the existing AAR RP-503 protocol. In addition to fuel oil additive evaluation, this proposed protocol would provide a means for testing lube oil additives and combustion enhancing devices, for both performance and engine wear characteristics while also examining the effects on the exhaust emissions. A study of the recently published EPA regulations was included in the project scope in order to establish a target for the emissions segment of the proposed protocol and to create an awareness of the ever increasingly stringent emission regulations, thereby showing the importance of putting in service the available products. The proposed SFAT procedure would require less time and money than the existing AAR RP-503 while conducting an analysis of the effects of aftermarket products on performance, wear, and emissions with results more representative of today’s locomotive engines.

As shown in Figure 3, the preliminary activities of the proposed SFAT procedure would be identical to those of the existing AAR RP-503, involving mainly the initial information gathering and contracting between the supplier and the testing facility, and the chemical analysis of the treated fuel or oil. However, the three phases of engine testing called for by the RP-503 would be replaced in the SFAT procedure through the conducting of performance and engine wear testing on a sole medium-speed single-cylinder diesel engine, the SCRE-251. In order to validate the replacement of the Caterpillar 1G2, EMD twin-cylinder, and GE or EMD multi-cylinder test engines with the SCRE-251, a comparison of these engines must be made. As shown in the following sections, the ability of this single-cylinder engine to represent current high horsepower multi-cylinder engines eliminates the need for testing on full size locomotive engines, provides a more representative engine wear analysis tool, and consequently dramatically reduces the overall time and cost involved with the test procedure. The battery of tests performed in the RP-503 includes the option to evaluate the emission effects of an additive, while the proposed SFAT protocol would include an emphasized emissions trending analysis based on the EPA regulations and federal testing procedures.

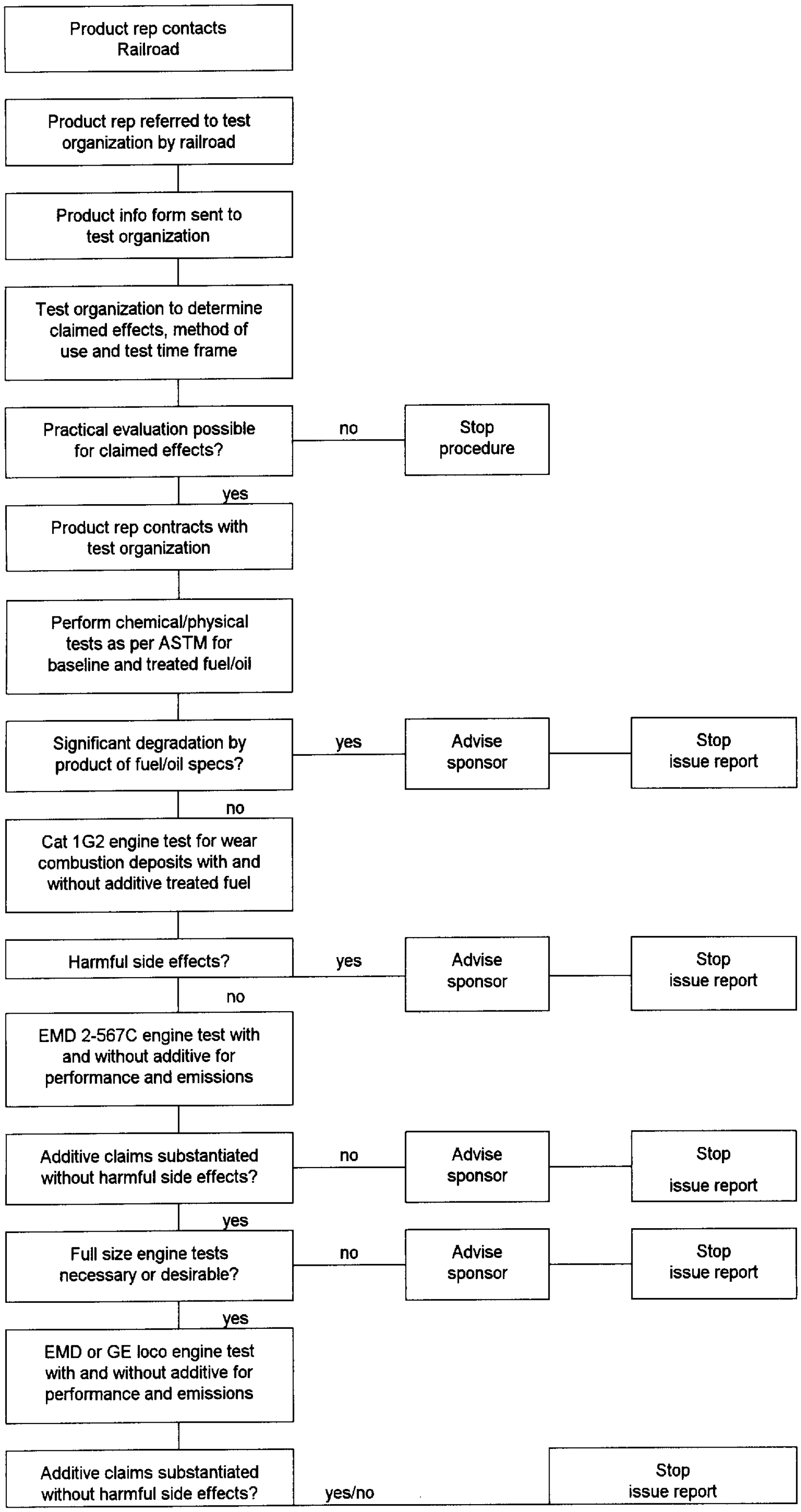


Figure 2 - Existing AAR RP-503 Procedure

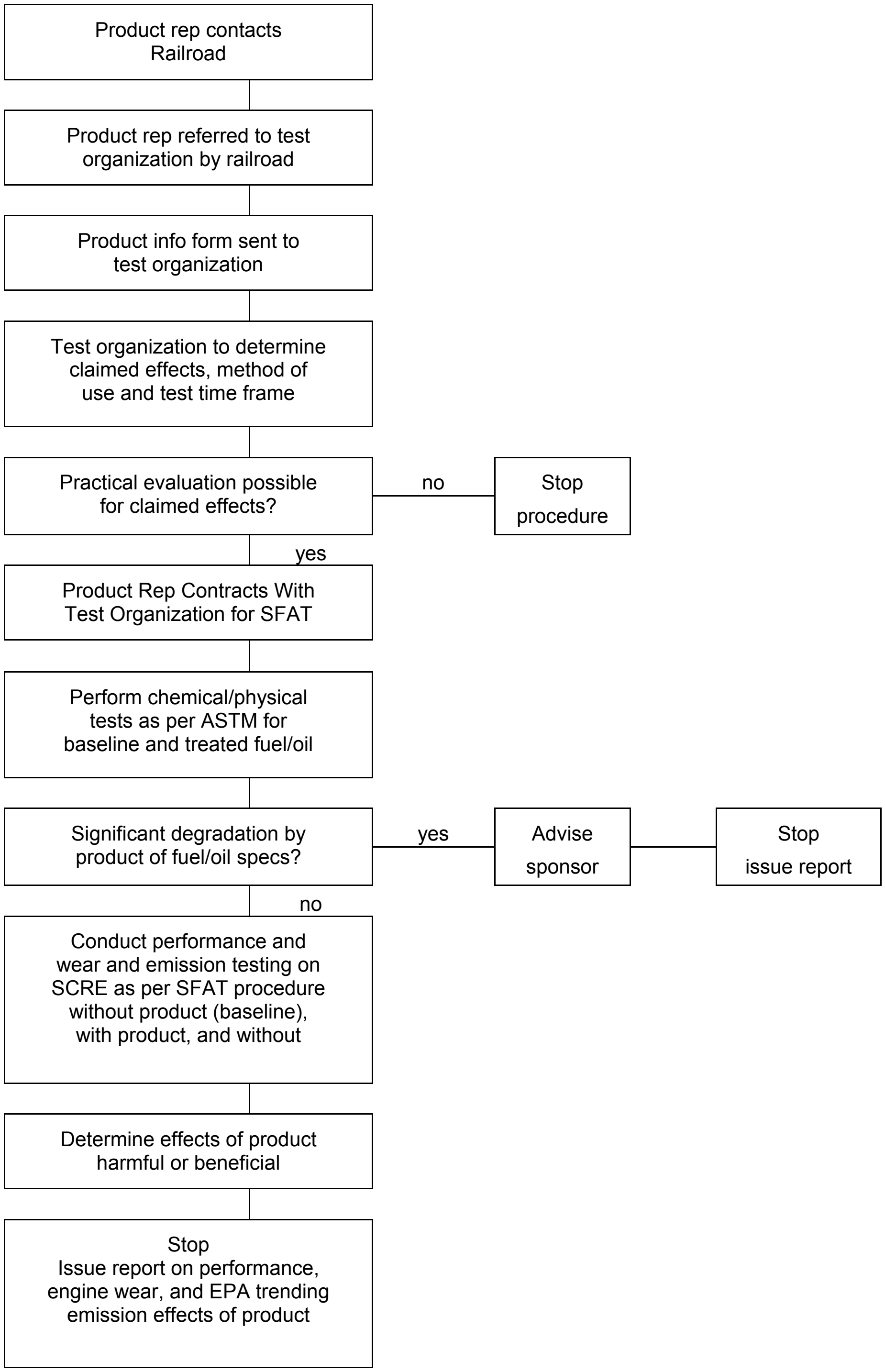


Figure 3 - Proposed SFAT Procedure

5.0 REVIEW OF THE CATERPILLAR 1G2 AND COMPARISON WITH THE SCRE-251

The main objective of this task is to determine the feasibility of utilizing the ESDC SCRE-251 in the proposed SFAT procedure in place of the Caterpillar 1G2 test engine used in Phase II of the AAR RP-503 procedure. This includes reviewing the role and characteristics of the Caterpillar 1G2 engine and determining whether the existing Caterpillar 1G2 demerit charts are applicable to the SCRE-251 for deposit and wear analysis.

The 1G2 is an indirect-injection (IDI), aluminum piston engine with a rated speed of 1800 RPM and a rated power of 33 kW that is nearly fifty years old. It was replaced first by the Caterpillar 1K test engine and most recently by the Caterpillar 1P test engine, both of which are direct injection (DI), steel cap-aluminum body piston engines with rated speeds of 1800 RPM, rendering the 1G series engines obsolete. The 1G2 is no longer manufactured and the replacement parts supply for this engine is severely limited.

The main role of the Caterpillar 1G2 engine in the AAR RP-503 procedure is to provide a preliminary evaluation of the fuel additive with respect to engine performance, wear and deposits (1). The results obtained from the 1G2 test will determine the merit of continuing the AAR RP-503 test procedure. The 1G2 was selected for use in the AAR RP-503 procedure because it was the standard tool for lubricant and fuel testing at the time. The 1G2 is not capable of simulating conditions expected on a medium-speed diesel engine; however, it was used to eliminate the financial burden of conducting preliminary testing on a full-size locomotive engine (1).

The Caterpillar 1G2 test involves comparison of the piston with demerit charts to determine the wear and deposit conditions of the 1G2 after burning the test fuel. The demerit charts deal only with the piston condition and are specific for the Caterpillar 1G2 test engine. Therefore, these demerit charts are not applicable to the ESDC SCRE-251 and new charts would have to be developed for the SCRE-251 piston. In addition, demerit charts should be developed for the other power assembly components of the SCRE-251. There are several standard rating methods including the Coordinating Research Council (CRC) rating method and the Deutsche Industrie Norm (DIN) 51361 rating method (10). Whether a completely new method is developed for the SCRE-251 or a standard rating method is adopted, the important issue is consistency of method usage when comparing results.

As shown in Table 3 and Figure 2, the Caterpillar 1G2 engine does not represent the characteristics of a medium-speed diesel engine. From the research done during Task IV of this project, it is evident that using the SCRE-251 in place of the Caterpillar 1G2 test engine would result in a wear and deposit analysis much more representative of medium-speed locomotive diesel engines without the financial burden involved with testing on a multi-cylinder locomotive engine. The added benefit of utilizing the SCRE-251 as a test engine for the SFAT is that the first stage of fuel additive testing could incorporate both a preliminary wear/deposit analysis similar to the 1G2 test simultaneous with performance testing similar to the Phase III and IV testing of the AAR RP-503 procedure.

It should be noted that the trend apparent in the literature (11-13,17) is towards conducting research and development testing on single-cylinder engines that are representative of the fleet for which testing is being done.

Table 3 - 1G2, SCRE-251, and SCRE-B2400 Specifications

	Caterpillar 1G2	SCRE-251	SCRE-B2400
Bore x Stroke (mm)	13 x 16.5	229 x 267	240 x 270
Displacement (L)	2.2	11.0	12.2
Rated Speed (RPM)	1800	1200	1200
Rated Power (kW)	33	253	305
IMEP (Bar)	n/a	23.0	25.0
P_{max} (Bar)	n/a	145.0	175.0
Injection	IDI	DI	DI

6.0 SCRE-251 TO MULTI-CYLINDER COMPARISON

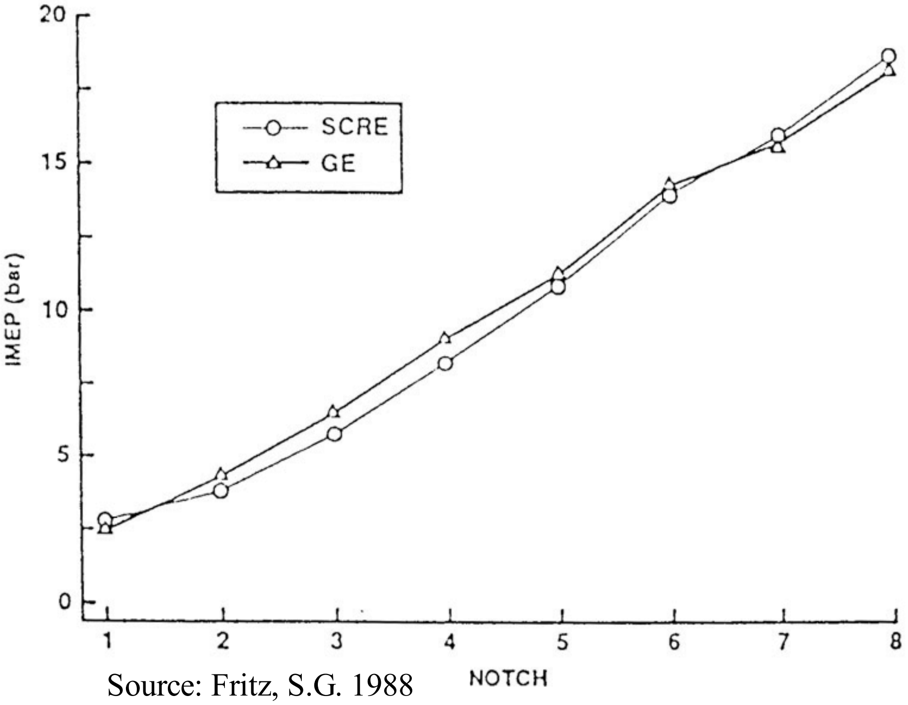
The SCRE-251 is a four-stroke, high Indicated Mean Effective Pressure (IMEP) diesel engine with a 1200 RPM rated speed, originally designed by Bombardier as a joint project with Transport Canada - Transportation Development Centre, as a development tool for the ALCO-251 medium-speed diesel engine, as a research tool for off-spec and alternative fuels in medium-speed diesel engine use, and as a lubricating oil research and classification tool (14). The most obvious benefits gained through use of a single-cylinder engine include lower operating costs, reduced maintenance time, expanded flexibility, minimized instrumentation requirements, and precise investigations with minimum components to adjust.

The conditions required by a single-cylinder engine to represent the performance of a multi-cylinder engine are quoted below, as published by E.M.J. McKenzie and S.G. Dexter in the Ricardo paper number DP82/1667 entitled "The Use of a Single-Cylinder Test Engine for Research and Development of Medium Speed Diesels" (15).

> "There are five main conditions which a single-cylinder engine should fulfill if the measured fuel consumption and other performance parameters are to be directly related to a multi-cylinder engine. It is also advisable to attempt to fulfill these conditions if fully representative conditions for component testing are to be supplied. These conditions are:
>
> (i) The in-cylinder components of the single should be identical to those of the multi-cylinder engine;
>
> (ii) The single should operate at the same IMEP as the multi-cylinder engine;
>
> (iii) Coolant and lubricant flows and temperatures should be identical to those on the multi- cylinder engine;
>
> (iv) The conditions before the intake ports on the cylinder head should be identical to those on the multi-cylinder engine;
>
> (v) The conditions after the exhaust ports on the cylinder head should be identical to those on the multi-cylinder engine."

The SCRE-251 was designed specifically to meet these requirements (16) using a standard power assembly, fuel pump, fuel pump support and main bearings, and incorporating the necessary flexibility required to represent future medium-speed diesel engines of higher IMEPs and rated RPMs. Because of the incorporation of many standard components, the availability of replacement parts for the SCRE-251 is not a significant concern. Simulation of modern turbo-charging boost pressures on the SCRE-251 is accomplished with a variable compressor and air-heater system. Exhaust back pressure can be varied through a butterfly valve, while blow-down pressures may be simulated with an orifice plate. Through use of an electronic governor, either gen-set type or locomotive type loading characteristics may be adopted.

To show that the SCRE-251 can accurately represent multi-cylinder engines, SwRI's Bombardier SCRE-251 was configured to represent a General Electric (GE) 7FDL 12-cylinder engine with excellent results (17). Figure 4 shows the relationship in IMEP of the SCRE-251 and the GE-7FDL after the SwRI experiment. Note that the SCRE-251 employs the same bore and stroke (229 mm x 267 mm) as the GE-7FDL. The close correlation between the IMEP of the configured SCRE-251 and GE-7FDL indicates a direct agreement between the performance characteristics witnessed on the SCRE-251 and those expected on the GE-7FDL.



Source: Fritz, S.G. 1988

Figure 4 - SCRE-251 to GE 7FDL Emulation

The ability of ESDCs SCRE-251 to represent wear and deposit tests representative of medium-speed locomotive diesel engine has been demonstrated in this section. Its unique design features, allows easy modification and reconfiguration of the engine to perform various tests. Furthermore, the engine can be easily equipped with instruments required to evaluate the emissions. Based on these findings, it is feasible to use ESDCs SCRE-251 to develop a new Simplified Fuel Additive Test, which may replace the AAR RP-503 test procedure.

7.0 THE FEASIBILITY ASSESSMENT

The feasibility of developing a simplified fuel additive evaluation test has been explored extensively. A literature search was conducted to obtain relevant information relating to PEPs and test procedures. According to these findings a simple fuel additive evaluation test can be devised to replace the AAR RP-503 which will utilize the SCRE-251 to examine the effect of PEPs on engine wear and deposits while also trending the emissions effects.

The utilization of the SCRE-251 for the SFAT stems from the unique advantages offered by its design. The engine is mechanically similar to the multi-cylinder GE-7FDL engine presently used by SwRI for the AAR RP-503 evaluation procedure. Therefore, data generated with the SCRE-251 will correlate well with today's full-size high power locomotive engines. The mechanical simplicity of the engine allows for very precise in-engine instrumentation. This system can be used to carry out engine wear and lubricating oil analysis at a much lower cost, since a single locomotive cylinder is being used instead of a multi-cylinder locomotive engine.

Unlike the AAR RP-503, where the wear and deposit evaluation test is conducted in three different phases, the simplified fuel additive test would require only a single step for engine wear and deposit evaluation due to the use of the SCRE-251. However, demerit charts used for AAR RP-503 cannot be utilized and new demerit charts have to be developed for this procedure. According to the gathered information, establishing a correlation between a single-cylinder engine and a multi-cylinder engine with respect to emission would be a very complicated project in itself. However, a test procedure can be developed to determine the emissions trend exhibited by PEPs.

Based on the above explanations, developing a simplified fuel additive test that can be used to evaluate the engine wear and deposits effects as well as the emissions trend for PEPs is feasible and would be a cost effective alternative to the existing AAR RP-503.

8.0 CONCLUSIONS

The literature search produced sufficient information to determine the diverse types of fuel oil and lube oil additives and combustion enhancing devices that are presently available and/or have been tested in the recent past. Also examined were the methods utilized during testing of these above-mentioned products from which a trend was observed towards testing with single-cylinder engines representative of the fleet in question (11,12,18-20). Information was also gathered concerning the Caterpillar 1G2 Test Engine, the ESDC SCRE-251 and the EPA regulations pertinent to future emissions requirements.

Following a review of the new EPA regulations, the testing equipment required to perform EPA emissions testing was determined. A review of the regulations was provided and the most important aspects highlighted.

It was determined that the SCRE-251 could certainly replace the Caterpillar 1G2 test engine and would consequently produce test results much more representative of those expected from a multi-cylinder medium-speed diesel engine while remaining cost efficient. In addition, wear and deposit demerit charts would need to be developed specifically for the ESDC SCRE-251 based on the current standard rating methods such as DIN 51361 and the CRC method.

From the documentation obtained during the literature search concerning the design of the SCRE-251, it is evident that not only was this research engine designed and built to simulate multi-cylinder medium-speed diesel engines with major cost and time advantages, but, also, there exists the flexibility to configure the SCRE-251 to simulate performance conditions representative of current high IMEP multi-cylinder diesel engines.

In conclusion, it was determined that it is definitely feasible to develop a new test procedure to replace the AAR RP-503 protocol to test FOA, LOA, and CED effects on engine performance while simultaneously incorporating emissions trending representative of the EPA 40 CFR Part 92 Emissions Standards for Locomotive Engines. It was also determined that it is feasible to specify the ESDC SCRE-251 as replacements for the Caterpillar 1G2 and other test engines used in the AAR RP-503 protocol while obtaining performance results indicative of those expected from modern multi-cylinder medium-speed diesel engines as used in today’s locomotives.

9.0 RECOMMENDATIONS

The results pertaining to the work carried out during the course of this feasibility study emphasize the limitations imposed by the current standard AAR RP-503 test procedure, rendering it unsuitable for testing representative of today's high-output locomotive engines. It is therefore imperative that a new more representative protocol be developed so that North American railways may realize the lucrative benefits of the products available from PEP suppliers. In addition to the conclusions stated from this work, it is recommended to proceed in the following manner to develop the Simplified Fuel Additive Test Procedure.

Considerable time will be required to gather the necessary information and equipment required to continue this project. Suppliers of PEPs should be contacted and samples of their products, along with all the information and specifications relating to them, obtained. Emphasis should be placed on acquiring products that have already been tested and documented according to other protocols. A baseline fuel will need to be acquired in order to conduct trending tests representative of the EPA regulations. With the PEPs and baseline fuel in hand, the test cell instrumentation should be designed to enable performance testing of the PEPs. This will include designing both low-speed and crank-angle based instrumentation as well as determining the equipment required to examine emission trends. The final step before commencing testing is to develop a test sequence for determining the demerit charts that will be utilized during the SFAT.

With completion of the above-mentioned steps, testing of the PEPs may commence. This testing will produce the demerit charts to be used later on during the SFAT. During the testing, the SCRE-251 test engine will be run and disassembled multiple times in order to determine the extent of the effects which each PEP caused. These effects will be correlated to the known effects of the respective PEP when compiling the demerit charts. Upon completion of the required charts, the SFAT protocol can be designed and test cell instrumentation configured. The final step will require proof of concept testing of the SFAT procedure in order to acquire certification and third party approvals.

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APPENDIX A

INFORMATION SOURCES AND DATABASES

MAGAZINES

A-1. Diesel Fuel News

A-2. Octane Week

A-3. 21st Century Fuels

A-4. Diesel Progress

A-5. Lubricants World

A-6. Lubes-n-Greases

A-7. Diesel & Gas Turbine Worldwide

A-8. Lubrication Engineering

A-9. Automotive Engineering

DATABASES

A-10 SAE WEBDEX

A-11 SAE FUELS AND LUBRICANTS CONFERENCE PAPERS ON CD-ROM

APPENDIX B

TECHNICAL PAPERS THAT ADDRESS DIFFERENT TYPES OF TEST PROCEDURES USED FOR EMISSION EVALUATIONS AND ENGINE PERFORMANCE

B-1. Fritz, S.G., McNett, B., and Schandelmeier, R., "Exhaust Emissions from Heavy-Duty Diesel Engines Operating on JP-8 Blended with Used Engine Oil", ASME Paper No. 98-ICE-76, Vol. 30-1, pp. 1-7, 1998.

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B-3. Knothe, G., Bagby, M.O., and Ryan, T.W., "Cetane Numbers of Fatty Compounds: Influence of Compound Structure and Various Potential Cetane Improvers", SAE Paper No. 971681.

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B-8. Reading, K., "A Study of the Clean-Up Activity of a High-Performance Diesel Fuel Detergent in IDI Engines", ASE Paper No. 961942.

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B-12. Mather, D.K. and Reitz, R.D., "Modeling the Use of Air-Injection for Emissions Reduction in a Direct-Injected Diesel Engine", SAE Paper No. 952359.

B-13. Youdan, G.H. and Wharton, M.H., "IDI Lubrication and Wear", SAE Paper No. 810500.

APPENDIX C

INTERNET WEB SITES USED TO ACQUIRE RELEVANT INFORMATION

C-1. WWW.jenbacher.com

C-2. WWW.drdiesel.com

C-3. WWW.designinfo.com/sierra/ref/appnote2.htm

C-4. WWW.montana.com/sfr/sfr2000.htm

C-5. WWW.cat.com

C-6. WWW.growmark.com/energy/diesel/index.html

C-7. WWW.shellcan.com

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C-11. WWW.avl.com

C-12. WWW.dieselnet.com/papers/9712bailey.html#0

C-13. WWW.nova-gas.com

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C-17. WWW.emitec.com

C-18. WWW.mmm.com

APPENDIX D

PEP PRODUCTS AND CLAIMS MADE BY MANUFACTURERS

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TP 13494E

SIMPLIFIED FUEL ADDITIVE TEST
PHASE II: PROCEDURE DEVELOPMENT AND METHODOLOGY

PREPARED FOR
TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA

BY
ENGINE SYSTEMS DEVELOPMENT CENTER

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SIMPLIFIED FUEL ADDITIVE TEST
PHASE II: PROCEDURE DEVELOPMENT AND METHODOLOGY

BY
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16. Abstract

This report describes a preliminary methodology developed for the Simplified Fuel Additive Test (SFAT) protocol. The report discusses proposed test sequences based on available information on tests performed by others on single-cylinder and multi-cylinder research engines. The test consists of preliminary chemical analyses, followed by baseline, conditioning, and performance engine tests. Emissions trending is also incorporated into the test sequence. The validity of the recommended tests will be verified through proof-of-concept, which will follow this phase of the project. Any necessary changes to the test sequences proposed in the report will take place during the proof-of-concept stage.

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16. Résumé

Ce rapport présente un protocole préliminaire mis au point pour l'essai simplifié des additifs pour carburants (SFAT, pour *Simplified Fuel Additive Test*). Les séquences d'essais proposées se fondent sur les résultats d'une étude comparative de moteurs de recherche monocylindre et multi-cylindres réalisée lors d'une phase antérieure du projet. Ces séquences débutent par des analyses chimiques, suivies de trois types d'essais sur moteur (de référence, de rodage et de performances). La mesure des émissions polluantes est également intégrée au protocole. Les essais recommandés seront validés au cours de la prochaine phase du projet, soit celle de la validation de principe. C'est alors que seront apportées les modifications nécessaires aux séquences d'essais proposées.

17. Mots clés
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EXECUTIVE SUMMARY

Operating cost reduction through fuel economy is a major challenge in the railway industry. Such a reduction can be realized through approved aftermarket performance-enhancing products. Certification of these products requires performance and emissions tests in accordance with the Association of American Railroads Recommended Practice (AAR RP-503) test procedure and Environmental Protection Agency (EPA) emissions regulations. The existing test is lengthy and expensive, preventing small businesses from entering the market. The need for an alternative procedure that could provide similar results with inclusion of emission tests faster and at lower cost resulted in the Simplified Fuel Additive Test (SFAT) project.

The SFAT project (Phase I) examined the feasibility of developing a test procedure that could properly evaluate the claimed benefits of aftermarket products at faster time and lower cost. This study showed that the ALCO 251 single-cylinder research engine (SCRE-251) can be used to develop such a procedure (TP 13215E). It was concluded that using a single-cylinder research engine derived from a medium-speed diesel engine would not only be more economical, but also less complex and more representative of modern locomotive diesel engines.

The current phase of the SFAT project was undertaken to develop a test procedure based on the information gathered in the feasibility report. Existing test procedures such as RP-503, SAE J304, SAE J1423, DIN 51 361, ASTM STP 509A Part I, and CEC L-42-A-92 were reviewed. Based on the information gathered from this review, a tentative test procedure was developed.

The test consists of two steps. The first step determines the fuel properties with and without additive through chemical analyses to ensure its suitability for engine testing. The next step is the engine test, which includes 40 hours baseline with base fuel, 160 hours conditioning, and 40 hours performance test with treated fuel. The emission analyses will be conducted during baseline and performance tests for comparison purposes. This procedure is also suitable for evaluation of lubrication oil additives.

The ESDC test cell and data acquisition system were reconfigured and automated for both low- and high-speed data collection and processing. The fuel and lubrication oil laboratory was upgraded for fuel analyses.

The test sequence must be finalized through the next proof-of-concept phase. For this reason ASTM-2D railroad diesel fuel and lubrication oil SAE 40 railroad oil with a high total base number (TBN 17) were purchased and stored. Nine candidates were acquired, including three fuel additives, three oil additives, and three performance enhancing devices. These materials will be used to complete the SFAT project.

SOMMAIRE

La réduction des dépenses d'exploitation par une économie de carburant représente un défi de taille pour les compagnies ferroviaires. Il est possible d'obtenir une telle réduction en ajoutant au carburant des produits d'optimisation du rendement qui doivent être approuvés. Pour être homologués, ces produits doivent subir des essais de performances selon la Pratique recommandée 503 de l'Association of American Railroads, et satisfaire à la réglementation antipollution de l'Environmental Protection Agency (EPA). Le protocole d'essai actuel est long et coûteux, ce qui limite l'accès des petites entreprises au marché des additifs. D'où le besoin d'un nouveau protocole, plus rapide et moins coûteux, qui serait aussi probant que le protocole actuel et intégrerait en plus la mesure des émissions polluantes. Ce besoin est à l'origine du projet d'essai simplifié des additifs pour carburants (SFAT, pour *Simplified Fuel Additive Test*).

La phase I du projet a consisté à étudier la faisabilité d'un protocole d'essai qui pourrait évaluer correctement les avantages prétendus des produits d'optimisation du rendement, en moins de temps et à moindre coût que le protocole actuel. Cette étude (TP 13215E) a confirmé la possibilité de faire appel à un moteur de recherche monocylindre ALCO 251 (SCRE-251) pour la mise au point du nouveau protocole. Elle a en outre déterminé qu'un protocole faisant appel à un moteur de recherche monocylindre dérivé d'un moteur diesel multi-cylindres à vitesse moyenne serait non seulement plus économique, mais encore plus simple et plus représentatif du fonctionnement des moteurs diesel modernes pour locomotives.

La présente phase du projet SFAT visait à développer un protocole d'essai fondé sur les données du rapport de l'étude de faisabilité. Après examen des protocoles d'essai existants (RP-503, SAE J304, SAE J1423, DIN 51 361, ASTM STP 509A Part I et CEC L-42-A-92), un nouveau protocole a été développé, qui reste à valider.

L'essai se divise en deux étapes. La première consiste en des analyses chimiques destinées à déterminer les propriétés du carburant, avec et sans additifs, afin de s'assurer qu'il soit compatible avec les essais envisagés. La deuxième étape est l'essai sur moteur : 40 heures de marche avec le carburant de référence (sans additif), 160 heures d'essais de rodage et 40 heures d'essais de performance avec le carburant traité (avec additif). Les analyses des émissions seront effectuées au cours des essais de référence et des essais de performances, pour des fins de comparaison. Ce protocole est également valable pour l'évaluation des additifs pour huiles lubrifiantes.

Le banc d'essai ESDC, qui permet aussi l'acquisition de données, a été reconfiguré et automatisé pour la collecte et le traitement de données aussi bien à faible qu'à grande vitesse. Le laboratoire des carburants et lubrifiants a été modifié pour permettre les analyses de carburants.

La séquence d'essai sera finalisée lors de la validation de principe qui fera suite à la présente phase. Du carburant diesel pour locomotives ASTM-2D et de l'huile lubrifiante

SAE 40 à indice élevé d’alcalinité (TBN de 17) ont été achetés et stockés à cette fin. En tout, neuf produits candidats ont été achetés, soit trois additifs pour carburants, trois additifs pour huiles et trois dispositifs optimiseurs de rendement. Ils seront utilisés pour mener à bien le projet SFAT.

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GLOSSARY

AAR	Association of American Railroads
ASTM	American Society for Testing Materials
BMEP	Brake Mean Effective Pressure
BMHP	Brake Mean Horsepower
BSFC	Brake Specific Fuel Consumption
CEC	Coordinating European Council
CFH	Cubic Feet per Hour
CO_2	Carbon Dioxide
CO	Carbon Monoxide
CRC	Coordinated Research Council (U.S.)
DAECS	Data Acquisition and Engine Control System
DIN	Deutsche Industrie Norm
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Center
FC	Fuel Consumption
NHR	Net Heat Release
NO_x	Oxides of Nitrogen
PED	Performance Enhancing Devices
PEP	Performance Enhancing Product
RP	Recommended Practice
SAE	SAE International (U.S.)
SCRE-251	ALCO 251 Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SO_2	Sulfur Dioxide
SwRI	Southwest Research Institute
TBN	Total Base Number
THC	Total Hydrocarbons

1.0 INTRODUCTION

Introduction of an approved after-market performance-enhancing product (PEP) to the North American locomotive market is an extremely difficult task with respect to the associated testing and evaluation cost. The only approved test procedure available is the AAR RP-503 that was adopted in 1980. This procedure consists of four stages and is designed to compare the effects of fuel oil additives on fuel chemical properties, engine wear and deposits, as well as engine performance characteristics. Presently, the only organization that can carry out the AAR RP-503 test is Southwest Research Institute (SwRI). Each test requires more than 1000 hours for completion and costs over $240,000 US. Furthermore, it does not address engine emissions measurements required by the EPA, which take effect on January 1, 2000. Inclusion of emission testing into the AAR RP-503 to the level representative of the EPA emissions standard requirements makes this procedure even more expensive.

The first phase of the SFAT project was initiated by Engine Systems Development Center (ESDC) to study the feasibility of developing an alternative test procedure. This test procedure would address both the engine performance and power assembly deposits as well as the emissions trend exhibited by the PEP at lower cost and reduced analysis time. According to the findings in phase I, it is feasible to develop a new test procedure to replace the AAR RP-503 protocol to test PEPs' effects on engine performance while concurrently collecting emissions trending representative of the EPA 40 CFR 92 emissions standards for locomotive engines. Based on SFAT phase I recommendations, a SCRE-251 representative of multi-cylinder medium-speed diesel engine (EMD or GE) would be used instead of the 1G2 Caterpillar engine and the multi-cylinder locomotive engines, resulting in time and cost reduction associated with this test protocol.

The positive outcome from the feasibility study conducted in the first phase of SFAT project has resulted in the initiation of a second phase. The aim of this phase is to develop a detailed methodology for engine and emissions testing comparable to that of the RP-503 test procedure. The following are the objectives of the second phase of the SFAT project:

i) *Procedure Development*
To complete the definition of the preliminary simplified test procedure outlined in the ESDC feasibility study in order to define the required configuration of the SCRE-251 test cell and the fuels and lubricants laboratory.

ii) *Test Cell Configuration*
To determine the instrumentation requirements of the engine test cell and fuels and lubricants laboratory to meet the performance and emissions measurement capabilities for the SFAT test procedure, and to reconfigure the test cell accordingly, including data processing capability.

iii) *Test Material Acquisition*
To acquire the required consumable material including specification fuel and test additives, and reference documentations on ASTM, DIN, and CRC testing and evaluation methods.

The following sections detail the content and outcome of this work after which a conclusion is presented along with the recommendations.

2.0 PROCEDURE DEVELOPMENT

This section describes the steps taken to develop a simplified methodology for engine and emissions testing analogous to that of the RP-503 test procedure. The following test sequence is based on a review of several accepted test methods used for evaluation of aftermarket fuel and lubricants additives. These test procedures included: SAE J304, SAE J1423, DIN 51 361, guide for evaluating aftermarket fuel and lubricant additives (U.S. Army), AAR RP-503, ASTM STP 509A Part I, and Coordinating European Council Test Method CEC L-42-A-92.

The procedure is initiated by issuing a questionnaire to the PEPs manufacturer. The purpose is to identify the claim made by the manufacturer and to recognize any additive's ingredient that may have an adverse effect on the engine components and performance (appendix A). Following this step, preliminary chemical analyses will be performed on the treated fuel or treated lubricating oil. These tests would be used to evaluate the quality of treated fuel/oil relative to that of untreated fuel/oil and its suitability for engine testing. The required tests should evaluate the fuel/oil for its ignition quality and combustion roughness, storability, contribution to engine deposits, and finally, its corrosiveness. The gathered information from these tests will allow ESDC to approve or reject an engine test.

The engine test is divided into two parts; baseline on base fuel/oil and performance test on a treated fuel/oil. The baseline takes forty hours. During this period, the performance and exhaust emissions are measured at various speeds and loads on untreated fuel/oil. The baseline test is followed by one hundred and sixty hours conditioning period with the candidate PEP. The conditioning duration may vary depending on the treated fuel/oil properties. Finally, the performance and emissions data are collected on treated fuel/oil during forty hours performance test and compared to those collected for baseline to evaluate the claimed benefits. The flow chart Figure 1 summarizes the procedure sequence. Detailed descriptions of these steps are given in the following sub-sections.

2.1 Chemical Tests for Fuel/Oil Additives and Performance Enhancing Devices

Prior to the engine test performed on the SCRE-251, preliminary chemical analyses have to be executed on both untreated fuel or oil, and the treated fuel or treated lubricating oil. The information will be used to compare the properties of treated fuel or oil to that of base fuel or oil. These results will allow ESDC to approve or reject an engine testing on the SCRE-251. The following ASTM test methods were selected for this purpose.

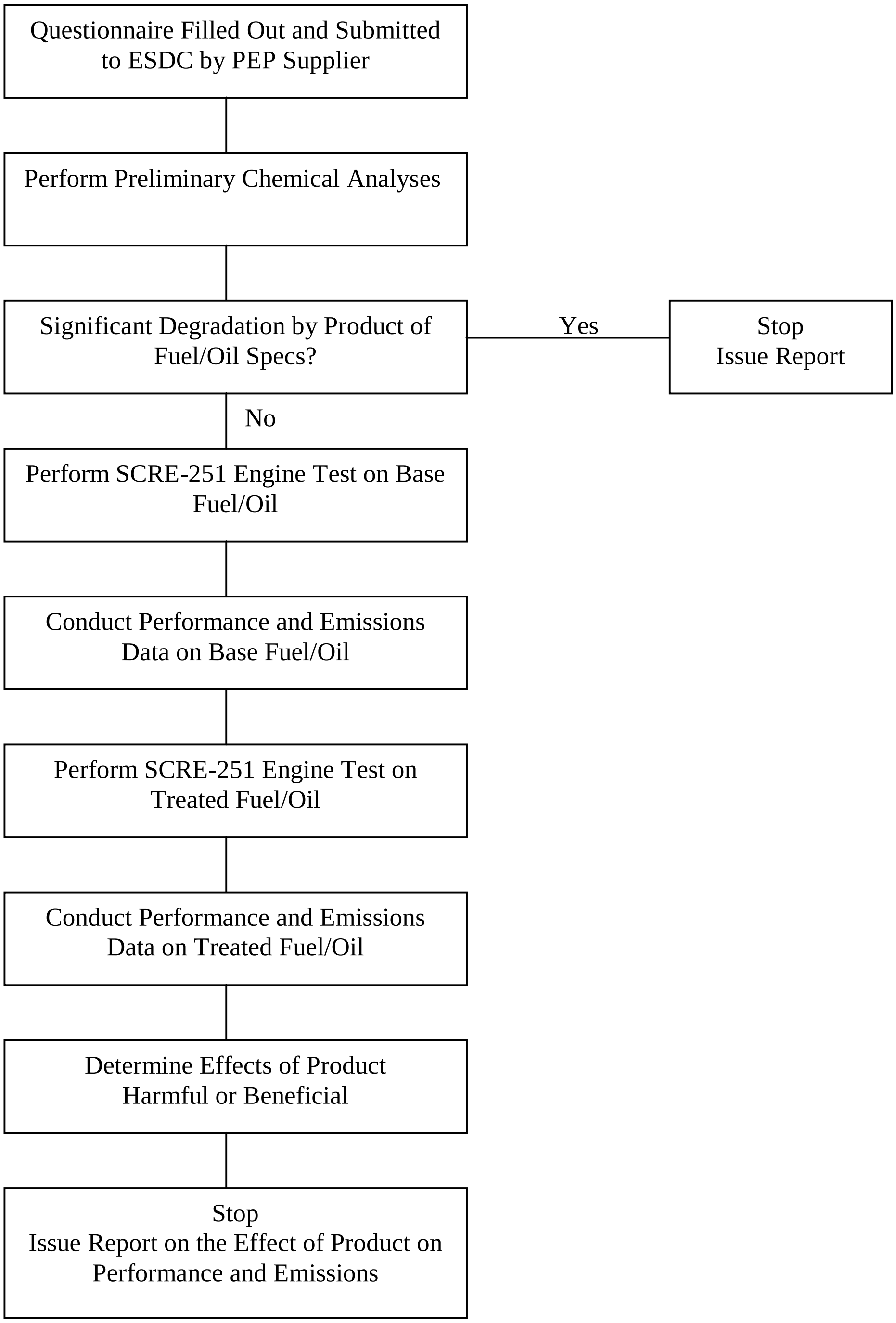


Figure1: Test Sequence for SFAT Procedure

2.1.1 *Fuel Property Tests*

These ASTM tests should be performed on both a sample of diesel fuel and a sample of the same fuel treated with fuel additives or performance enhancing devices (PED). Diesel fuel conforming to ASTM specification grade 2D shall be used unless otherwise specified. The purpose of these tests is to evaluate effects of the additives or PED on limiting fuel specification requirements. This set of tests (Table 1) is used as a general guideline and may be modified to include additional tests if necessary due to the nature of the additives or PED being tested.

Table 1: ASTM Tests for Fuel Analysis

Property	ASTM Test Method No.
Gravity, API	D 287
Flash Point	D 93
Cloud Point	D 2500
Pour Point	D 97
Kinematic Viscosity	D 445
Distillation, 50%, 90%, and End-Point	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

Significance of Tests Required for Diesel Fuel Aadditives and PEDs

Test Parameter	**Test Method**	**Significance**
Gravity, API	D 287	Approximate indication of fuel quality.
Flash Point	D 93	Required for safety precautions involved in fuel handling and storage.
Cloud Point	D 2500	Indicates tendency of filter plugging due to wax formation.
Pour Point	D 97	Determine lowest temperature at which the product can be pumped.
Kinematic Viscosity	D 445	Measure of resistance to flow.
Distillation	D 86	Determines the volatility which effects power output, fuel economy viscosity, and starting.
Carbon Residue	D 524	Indicates relative coke or carbon forming tendency.
Sulfur	D 1552, D 129, or D 2622	Measure sulfur content.
Copper Strip Corrosion	D 130	Measures the relative degree of copper corrosion due to sulfur content.
Ash	D 482	Measure the non-combustible residue.
Water and Sediment	D 2709	Indicative of emulsification and filter plugging of fuel.
Accelerated Stability	D 2274	Measures the stability under accelerated oxidizing conditions.
Neutralization	D 974	Measures the acidity or alkalinity of fuel.
Particulate Contamination	D 2276	Indicates tendency of filter plugging.

Test Parameter	Test Method	Significance
Cetane Number	D 613 or D 976	Indication of fuel quality as a function of ignition delay.
Heat of Combustion	D 240	Measures the energy available from a fuel.

2.1.2 Lubricating Oil Property Tests

The necessity for properly lubricating the dynamic components of any engine is readily apparent. It should be recognized that the only real measure of quality in a lubricating oil is its actual performance in the diesel engine. This is apparent because of the impossibility of establishing limits on all physical and chemical properties of lubricating oils, which can affect their performance in the engine over a broad range of environmental influences. However, the quality and performance of lubricating oils and additives may be judged through a set of laboratory tests, which would identify their suitability for engine testing. For this reason, the following tests are being recommended by ESDC as an initial step in the SFAT program for evaluation of oil additives and lube oil PED (Table 2).

Table 2: ASTM Tests for Lube Oil Analysis

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 664 or D 2896
Evaporative loss	D 2887
Carbon Residue	D 524
Sulfated Residue	D 874

2.2 Engine Test Procedure for Performance and Emissions Evaluations

This test is intended to evaluate the effects of fuel/oil additives or PEDs on the engine performance and emissions. For each test, a set of new power assembly (piston, liner, rings, and cylinder head) is employed. The engine is filled with fresh oil (SAE 40 Railway lube oil) for each set of the test. Fresh oil is added to the engine at 10-hour intervals to compensate for oil consumption. The following sub-sections describe the proposed test sequence.

2.2.1 Baseline Test

The baseline test is performed at a speed of 1050 rpm and a load of 1696 Nm. Results are collected every 30 minutes for 17 hours. From collected data the following parameters are determined: brake specific fuel consumption (BSFC), fuel consumption (FC), brake mean effective pressure (BMEP), brake mean horsepower (BMHP), oil consumption, and net heat release (NHR).

At the end of the 17-hour performance measurement, an exhaust emissions test is conducted according to the sequence given in Table 1. The performance measurements are repeated for another seventeen hours and again the emissions information is collected.

Table 3: Emissions Test Sequence for the SCRE-251 Test Engine

Mode no	Notch setting	Speed/load (rpm/N.m)	Time in notch
1	Idle	400/-	6 min minimum
2	Notch 1	480/213	6 min minimum
3	Notch 2	560/425	6 min minimum
4	Notch 3	643/638	6 min minimum
5	Notch 4	725/850	6 min minimum
6	Notch 5	805/1063	6 min minimum
7	Notch 6	885/1275	6 min minimum
8	Notch 7	968/1486	6 min minimum
9	Notch 8	1050/1696	15 min minimum

2.2.2 Engine Conditioning

At this point, the additive is added to the fuel/oil (in the case of performance enhancing devices, the device will be added to the system) and the engine is operated for 160 hours conditioning period at full load. The conditioning period may vary from one additive to another. For this reason, the BSFC is measured during this stage at 5-hour intervals until a steady level is reached.

2.2.3 Treated Fuel/Oil Performance Test

Following the conditioning stage, a 40-hour performance and exhaust emissions test will be completed on the treated fuel/oil. These tests will be identical to those acquired during baseline test. Upon completion of these tests, the acquired results for base fuel and treated fuel will be compared to determine the validity of claims made by the additive manufacturer.

2.2.4 Exhaust Emissions Test

As mentioned previously, the exhaust emissions are measured twice during the baseline test and twice during the performance test. The emissions test follows the sequence given in Table 3 and measures the smoke, NO_X, CO, CO_2, SO_2, and THC under various loads and speeds.

3.0 TEST CELL CONFIGURATION AND LABORATORY UPGRADES

This section is intended to describe the capability of fuel and lubricants laboratory with respect to the required fuel and oil analyses for the SFAT project. In addition, the test cell configuration, its individual components, data acquisition system, and emissions measuring system are described in detail.

3.1 Fuel and Lubricants Laboratory's Capability

The chemical laboratory was initially equipped to perform chemical analyses on lubricating oil with limited ability to do fuel analyses. Due to the extensive need for detailed fuel analyses during the SFAT project, the laboratory was upgraded to meet the requirements. Following the upgrade, the laboratory is now able to perform the majority of the required tests in accordance to ASTM standards. There are several tests such as heat of combustion and cetane number, which require special equipment and setup. These tests will have to be performed by external qualified laboratories that can carry out these tests according to the conditions set by ASTM. Appendix B provides a general view of the fuel and lubricants laboratory.

3.2 Test Engine System

The test engine is a single-cylinder, direct fuel injection, four-stroke diesel engine. Its specifications are listed in Table 2. The features of engine subsystems are summarized in the following sections. The test sequence and cell configuration are illustrated in Figure 2. The test cell and control room are shown in Appendix C.

Table 4: SCRE-251 Engine Specifications

SCRE-251 SPECIFICATIONS	
Type	**BSCRE-251-002** **ALCO**
Bore and Stroke	9.0 in × 10.5 in
Injector	9 holes x 0.40 mm x 145°
Displacement	668 in^3
Rated speed /Rated power	1050 rpm/250 H.P
IMEP max	334 psi
P_{max}	2300 psi
Fuel injection	1530 mm^3/inj
Idle Speed	400 rpm
Compression Ratio	12.5:1
Fuel Injection Time	27.5° BTDC
Piston	251 Mexican hat
Mean Piston Speed (@1200 rpm)	35 ft/s

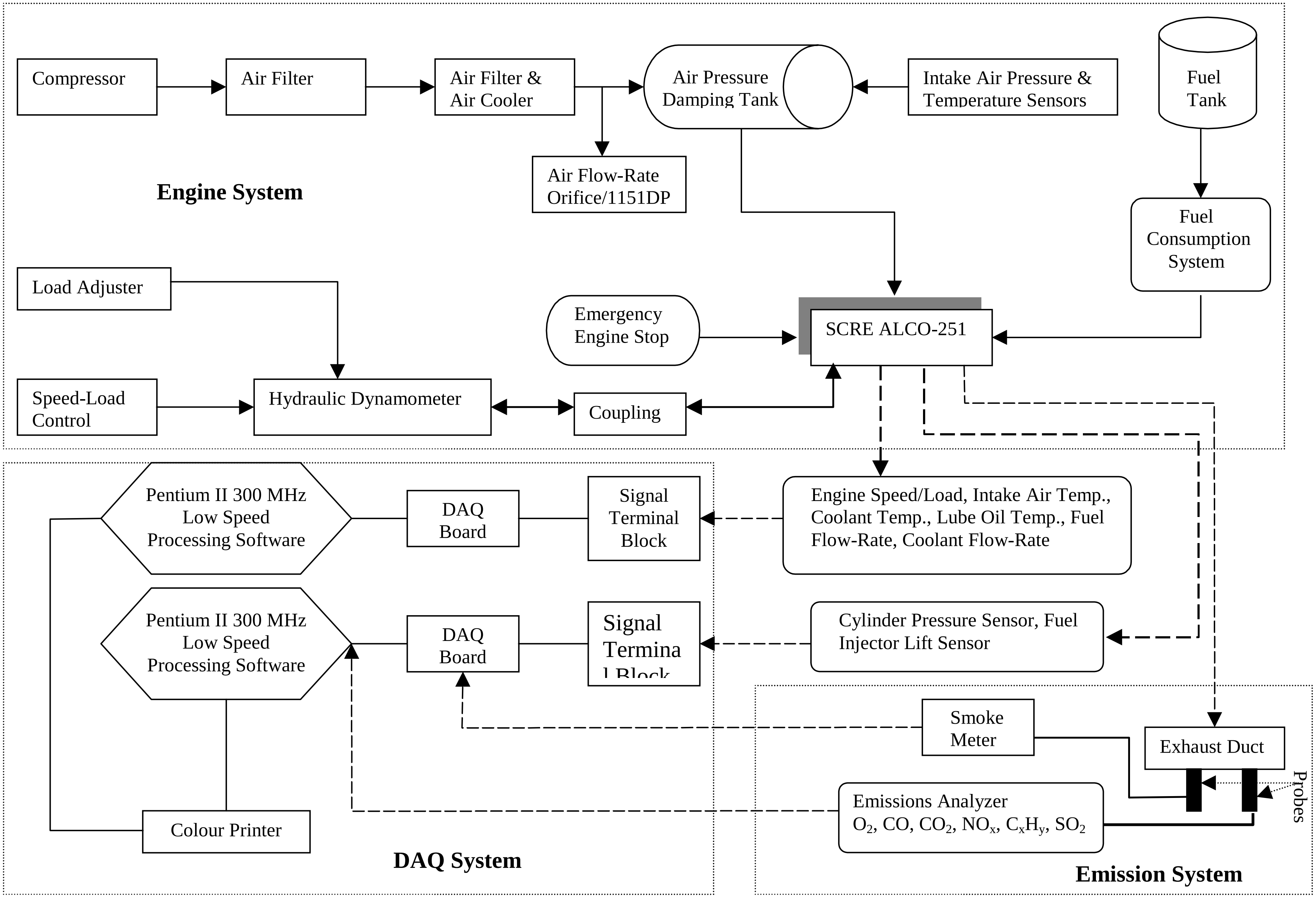


Figure 2: Test Cell Set up and Configuration

3.2.1 *Cooling System*

The engine is equipped with a circulating cooling system with an electric motor driven water pump that circulates water through the engine jacket and heat exchanger. The flow through the engine jacket is measured by an electromagnetic flow meter with an accuracy of ±0.25%/full scale. The temperature of the jacket water system is controlled to any desired set-point by a temperature control valve on the process cooling water side (shell side) of the heat exchanger.

The system header tank (expansion tank) maintains the system filled and vented during operation. This tank will also compensate for the expansion of water during operation.

The system includes a pre-warmer (thermostatically controlled) in the recovery tank that heats and circulates the jacket water to aid cold starting. This recovery tank is also used for water treatment of the engine jacket water system.

To simulate the water flow variation proportional to the engine speed in comparison with a multi-cylinder engine, a remote controlled throttling valve is installed on the jacket water system.

3.2.2 *Lubricating Oil System*

The test cell is equipped with an electric motor driven pump, which draws oil from the sump and passes it through a magnetic filter, heat exchanger, and filter then into the engine main bearing.

A thermostatic controlled oil-warmer is installed in the sump of the engine, for heating the lube oil to aid cold starting.

To simulate multi-cylinder engine oil flow variation proportional to the engine speed of an engine driven pump, a motorized valve with bypass pipe-work is installed on the lube oil system. The lube oil flow is measured using an orifice with an accuracy of ±1.5%.

3.2.3 *Fuel System*

Diesel fuel is pumped to the day-tank from the main storage tank; a level switch controls the level of the day-tank.

Fuel flows by gravity into a small weighing tank within the fuel flow measuring device, when the solenoid valve is energized by the fuel. The fuel measuring device consists of a single channel microprocessor based process monitor (Visipak VIP 524 W) connected to a load cell, which carries the weighing tank. The accuracy of the device is ±0.03%/full scale.

The fuel is drawn from the fuel consumption device by the engine booster pump, which then passes it through a filter to the engine fuel pump. This pump incorporates a pressure relief valve that returns excess fuel.

3.2.4 Intake Air System

The engine is equipped with a compressor and a surge tank to simulate turbocharging. The air passes through a control valve into the pressure reducer (from 100 psi to 2 psi) ,which is remotely controlled from the console for desired testing pressure ratios. The air temperature is regulated by electric heaters that are positioned after the surge tank. Using this setup, the inlet air temperature can be raised to preset points as required. The inlet airflow is measured with an accuracy of ±1.5% and a range of 72,000 cubic feet per hour (CFH).

3.2.5 Exhaust System

The exhaust surge tank and silencer in the system are installed close to the engine. A restricting orifice and butterfly valve are installed in the exhaust ducting to simulate multi-cylinder exhaust pulsation and back-pressure.

3.2.6 Start System

An air start-system connected to the main air supply header is used to start the engine. The air passes through a shut-off valve into a pressure reducer. The air pressure, 150 psi is required to start the engine. The air passes through a filter and a lubricator before reaching the start motor. The actuation of the starter is by a solenoid valve, controlled by a starter switch at the console.

3.2.7 Load/Speed Control System

The speed of the engine is controlled by an electronic engine governor, the set-point for which is adjusted by a servo motor. The governor adjusts the fuel pump rack to suit the load on the engine and to maintain a constant engine speed.

The load on the engine is controlled and measured by the Schenk D 1100 hydraulic dynamometer. The required load is maintained by controlling the amount of water in the casing, which is determined by the position of the outlet valve. The load is measured by a strain-gauged cell fixed between the casing and dynamometer bed-plate.

3.3 Data Acquisition System

The test cell control and data collection is accomplished by a computerized and fully automated Data Acquisition and Engine Control System (DAECS) developed by ESDC. The system is designed to readily acquire data on a crank-angle time base (high speed) and on a seconds time base (low speed). The engine and auxiliaries are also controlled by this system.

Low-speed and high-speed data acquisitions are accomplished simultaneously by two separate computers. Signals such as those from temperature sensors, flow-rate transducers, and speed transducer are measured by the low-speed system, while parameters such as crank-angle, fuel injector needle lift, and fuel injection pressure are collected by the high-speed data acquisition system. Data acquisition and control system schematic is shown in Figure 3.

3.4 Emissions Measurement System

A portable emissions analyzer (ECOM) is used for exhaust emissions measurements. The exhaust sample is drawn via a high flow pump assembly with an in-line water trap and particulate filter for proper conditioning prior to the gas sensors. An internal reservoir separates the gas samples to the individual sensors. Integrated software provides dampening for any background interference allowing for accurate analysis. Collected data are processed and viewed through a software program supplied by the analyzer’s manufacturer. Smoke is measured with a smoke opacity meter mounted on the top of the exhaust stack extension, or a Bosch smoke meter.

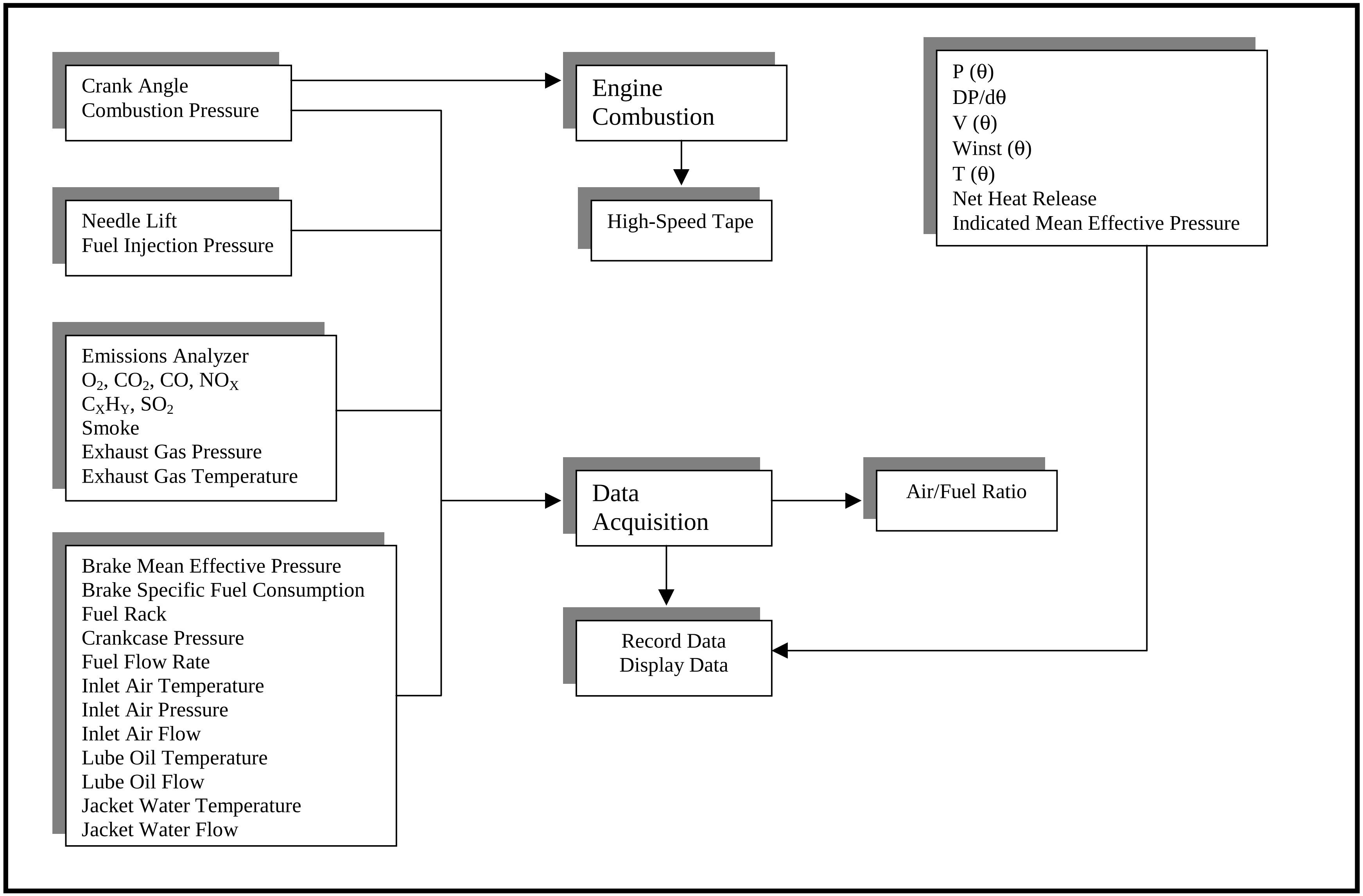


Figure 3: Data Acquisition System

4.0 TEST MATERIALS

Validation of the methodology developed for the SFAT protocol will require experimental engine testing. Such an engine testing would provide the necessary proofs that the SCRE-251 can produce adequate results within 90 percent confidence level and can replace the multi engine test, used in AAR RP-503 test procedure. Furthermore, the suitability of the SFAT test procedure for evaluation of fuel efficiency and emissions reduction claimed by PEPs suppliers can be demonstrated. Any necessary modification to the test procedure will take place during this stage. For this reason, standard fuel and lubrication oil used by railway industry were acquired. The fuel oil is ASTM-2D railroad diesel fuel. The lubrication oil is high total base number (TBN 17) SAE 40 railroad oil.

In addition to the standard fuel and lubrication oil, nine candidate samples were gathered. These samples include three fuel additives, three oil additives, and three performance enhancing devices. The claimed benefits made by individual manufacturers include lower emissions, improved performance, and better fuel economy. These additives will be used to validate the developed methodology for SFAT, through experimental engine testing, which will follow the current stage of the project.

5.0 CONCLUSIONS

This project was undertaken to develop the required methodology for a simplified test procedure that could verify both the performance and emissions benefits claimed by aftermarket suppliers. A tentative test procedure was developed based on the review of existing test procedures such as AAR RP-503, SAE J304, SAEJ1423, DIN 51 361, ASTM STP 509A Part I, CEC L-42-A-92, and U.S. Army guide for evaluating aftermarket fuel and lubricant additives.

The test sequence includes preliminary chemical analyses followed by baseline, conditioning, and performance engine test. Emission analyses are conducted during baseline and performance tests for comparison purposes. The test cell and fuel and lube laboratory were upgraded to meet the performance and emissions measurements capabilities. The necessary equipment and glassware were purchased for fuel analyses. The emission analyzer was set up, calibrated, and connected to the main PC for automatic detection and data collections during the engine testing period. The engine control and data collection at low and high speed were automated using DAECS software, developed by ESDC.

The test cell upgrades allow low-speed and high-speed data acquisitions and emissions measurement under various loads and speeds. Data are collected and processed by PC-based software.

Standard railroad fuel and lubrication oil, as well as candidate additives, were acquired and stored for the engine test that will precede this phase of the project.

6.0 RECOMMENDATIONS

To validate the methodology developed in this stage of the SFAT project, the experimental SFAT engine testing is strongly recommended. During the actual engine test, the necessary modifications and improvements can be made in terms of test procedure and required cell configurations. For this reason, nine candidates were chosen: three fuel additives, three oil additives, and three add-on devices. Tentatively, 40/160/40 time intervals were recommended for baseline, conditioning, and the performance test, including emissions measurements. This timetable can be verified and, if necessary, modified to provide optimum time required for an adequate sequence of engine test.

In addition to the primary objective, phase III will attempt to determine time intervals and the number of data points needed for performance and emission measurements that would satisfy the 90 percent confidence level.

Upon completion of the experimental engine testing on the above-mentioned candidates, the procedure will be finalized and documented. The finalized version of the SFAT procedure will be presented to the AAR as an alternative, economic evaluation tool for aftermarket products, and recommended to the Railway Association of Canada (RAC) as a standard method for the evaluation of railway aftermarket products in Canada.

APPENDIX A: QUESTIONNAIRE FOR DIESEL FUEL AND OIL ADDITIVE EVALUATION PROCEDURE

DIESEL FUEL ADDITIVE EVALUATION PROCEDURE

QUESTIONNAIRE

Complete and send the questionnaire, along with existing data pertinent to the additive's effects, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY NAME:____

ADDRESS & PHONE NO.: ____
____
____

PERSON TO CONTACT: ____

ADDITIVE NAME OR CODE: ____

What are the additive's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

____
____
____

(2) EXHAUST EMISSIONS (Including Smoke)

____
____
____

(3) COMBUSTION DEPOSITS (Including Sparking)

____
____
____

(4) LUBE OIL

____

____

____

(5) WEAR

____

____

____

(6) FUEL SYSTEM

____

____

____

What are the effects of the additive on the following diesel fuel properties.

(1) Cetane Number: ________________________________

(2) Viscosity: ________________________________

(3) API Gravity: ________________________________

(4) Distillation Range: ________________________________

(5) Sulfur Content: ________________________________

(6) Carbon Residue: ________________________________

(7) Flash Point: ________________________________

(8) Cloud Point: ________________________________

(9) Pour Point: ________________________________

(10) Ash Content: ________________________________

(11) Corrosiveness: ________________________________

(12) Filterability: ________________________________

(13) Water Absorption: ________________________________

(14) Stability: ________________________________

(15) Foaming: ____

(16) Bacterial Resistance: ____________________________________

(17) Vapor Pressure: ____

(18) Miscibility Limits: ______________________________________

How is this additive used?

(1) How is it mixed with diesel fuel? ____________________________

____

(2) In what proportions? _____________________________________

____

(3) How stable is the mixture? _________________________________

____

(4) How long is the mixture storable? ___________________________

____

Does the additive contain any zinc? ____________________________________

Are there any chemicals, elements, or physical conditions, which can neutralize or otherwise influence the effectiveness of the additive? If so, describe in detail on a separate sheet.

What are the claimed effects of the additive? (Attach any pertinent material.) __________

____

____

What tests have been conducted to substantiate these claims? (Attach any pertinent material.) ____

____

____

What were the results of these tests? (Include data) ________________________

____

____

Where were these tests performed? ____

____

____

Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.

LUBRICATING OIL ADDITIVE EVALUATION PROCEDURE

QUESTIONNAIRE

Complete and send the questionnaire, along with existing data pertinent to the additive's effects, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY NAME:____

ADDRESS & PHONE NO.: ____

____

____

PERSON TO CONTACT: ____

ADDITIVE NAME OR CODE: ____

What are the additive's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

____

____

____

(2) EXHAUST EMISSIONS (Including Smoke)

____

____

____

(3) COMBUSTION DEPOSITS (Including Sparking)

____

____

____

(4) LUBE OIL

____

____

____

(5) WEAR

____

____

____

(6) FUEL SYSTEM

____

____

____

What are the effects of the additive on the following lubricant oil properties.

(1) Viscosity: ____

(2) Viscosity Index: ____

(3) API Gravity: ____

(4) Flash Point: ____

(5) Fire Point: ____

(6) Pour Point: ____

(7) Zinc Content: ____

(8) Total Base Number: ____

(9) Corrosiveness: ____

(10) Anti-Foaming: ____

How is this additive used?

(5) How is it mixed with lubricant oil? ____________________________________

____

(6) In what proportions? ____

____

(7) How stable is the mixture? ____

____

(8) How long is the mixture storable? _____________________________________

____

Does the additive contain any zinc? ____

Are there any chemicals, elements, or physical conditions, which can neutralize or otherwise influence the effectiveness of the additive? If so, describe in detail on a separate sheet.

What are the claimed effects of the additive? (Attach any pertinent material.) __________

____

____

What tests have been conducted to substantiate these claims? (Attach any pertinent material.) ____

____

____

What were the results of these tests? (Include data) _________________________________

____

____

Where were these tests performed? ____

____

____

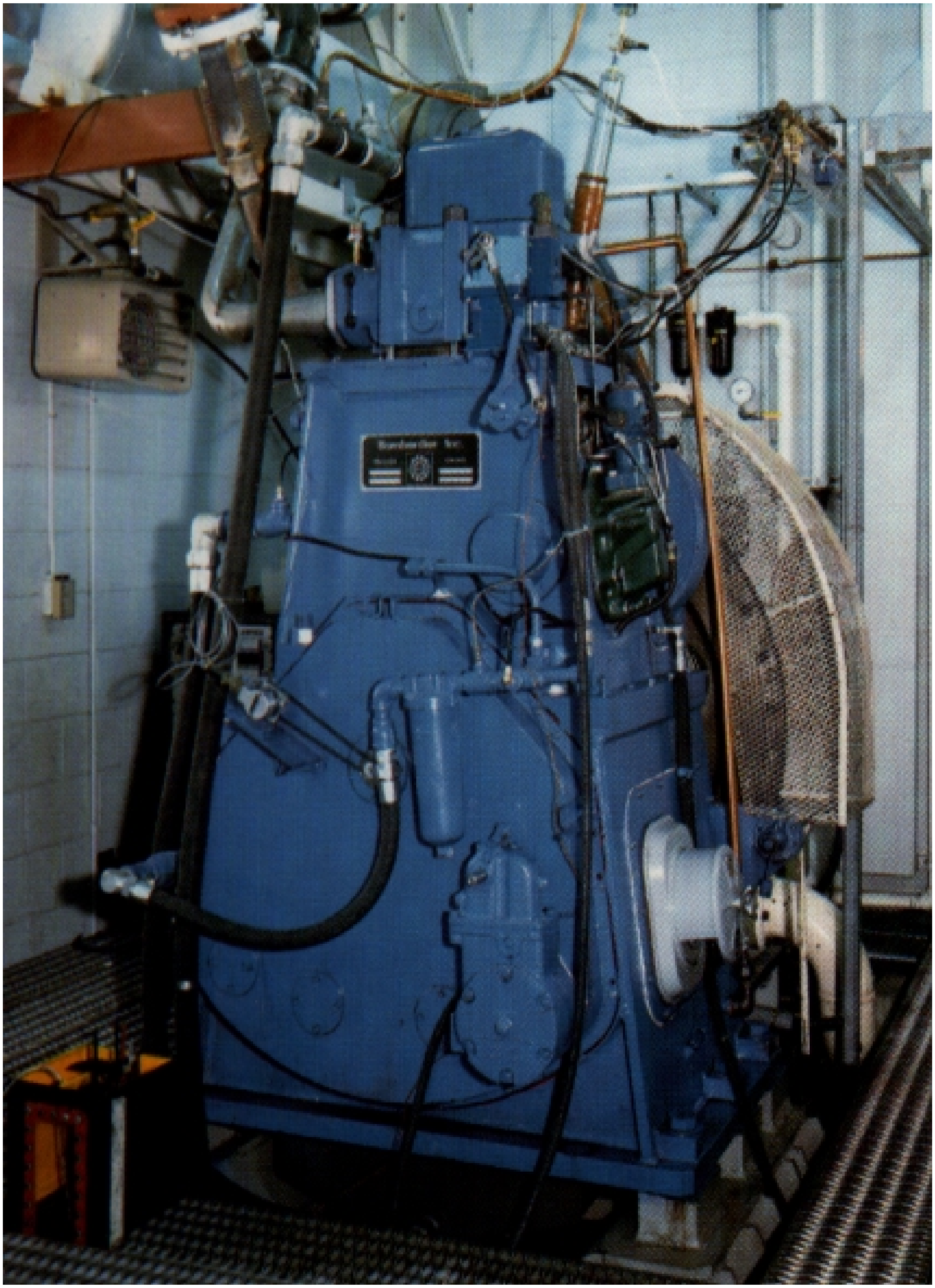
Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.

APPENDIX B: GENERAL VIEW OF FUEL AND LUBRICANTS LABORATORY


MABLE
RE AWAY
RDEZ
GNÉES

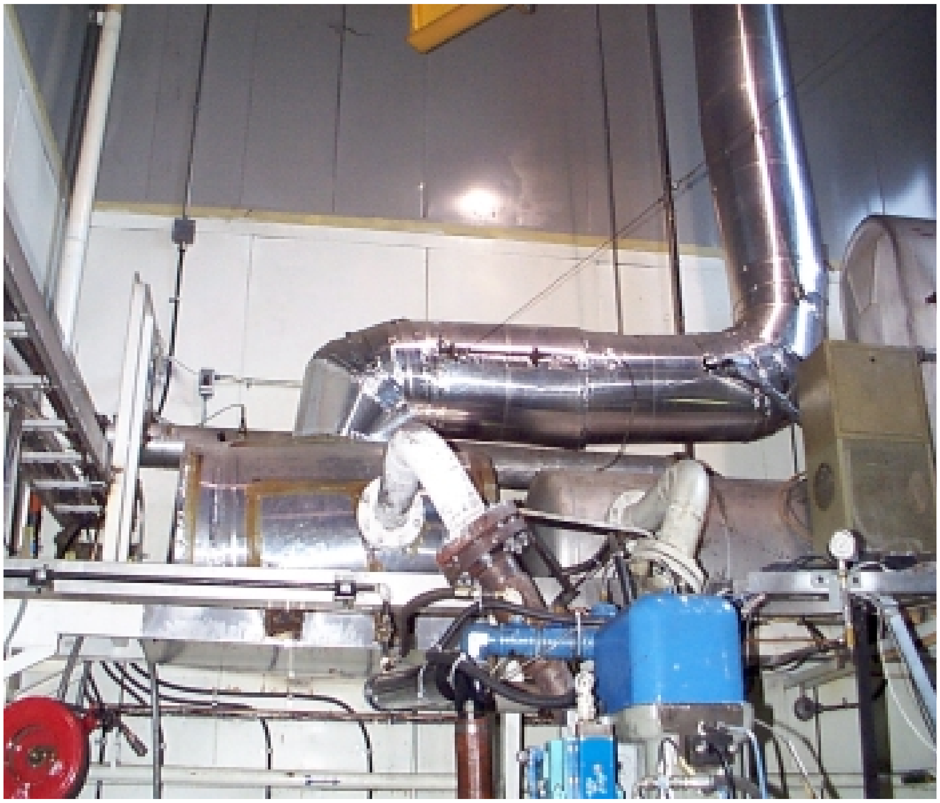

EYE W
STA
DANGER
ACID

APPENDIX C: GENERAL VIEW OF TEST CELL AND CONTROL UNIT



C-1: SCRE-251

C-2: Control Unit



C-3: SCRE-251 Exhaust System

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TP 13823E

SIMPLIFIED FUEL ADDITIVE TEST PHASE III: TESTING AND VERIFICATION

PREPARED FOR
TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA

BY

ENGINE SYSTEMS DEVELOPMENT CENTRE

AUGUST 2001

TP 13823E

SIMPLIFIED FUEL ADDITIVE TEST PHASE III:
TESTING AND VERIFICATION

BY
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ENGINE SYSTEMS DEVELOPMENT CENTRE

AUGUST 2001

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.

17. Mots clés Moteur de recherche monocylindre, locomotive, moteur diesel, émissions, optimiseur de rendement, additifs, essai, analyse chimique, analyse de carburants et d'huiles lubrifiantes	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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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

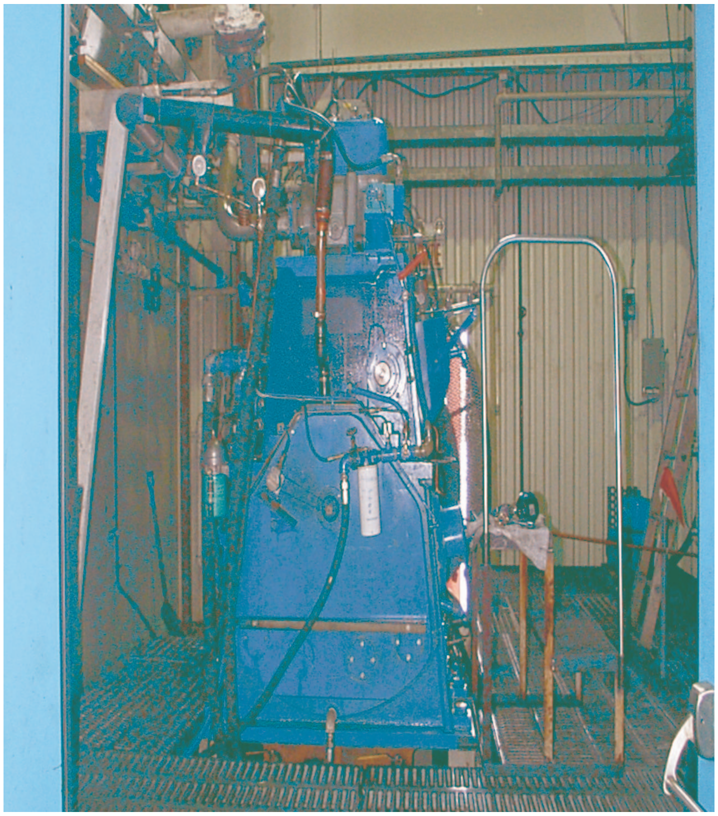

Figure 1: SCRE-251 test engine

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:

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

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.

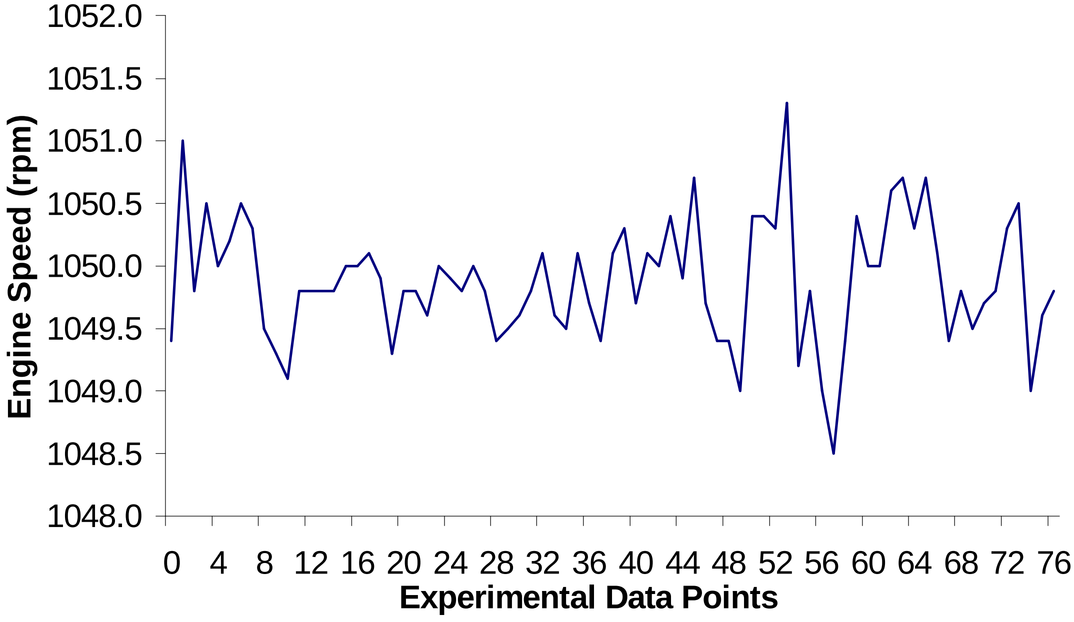

Figure 2a: Engine speed

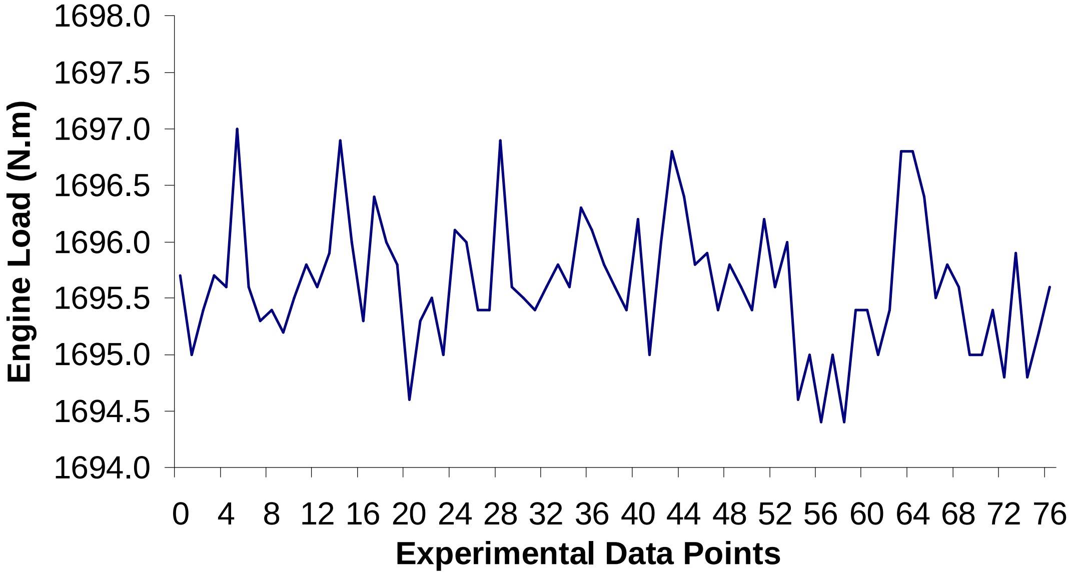

Figure 2b: Engine load

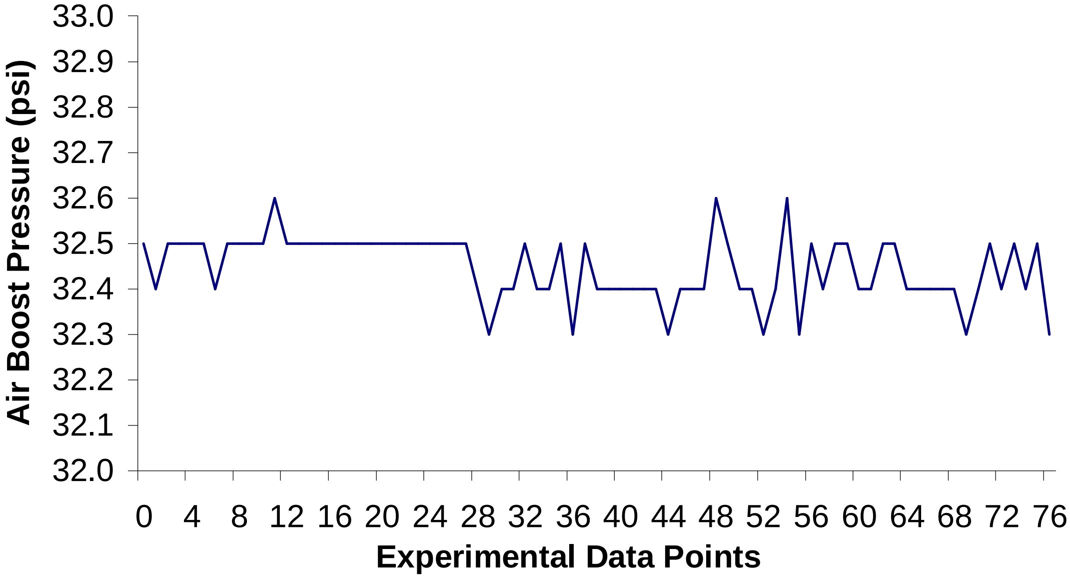

Figure 2c: Engine intake air pressure

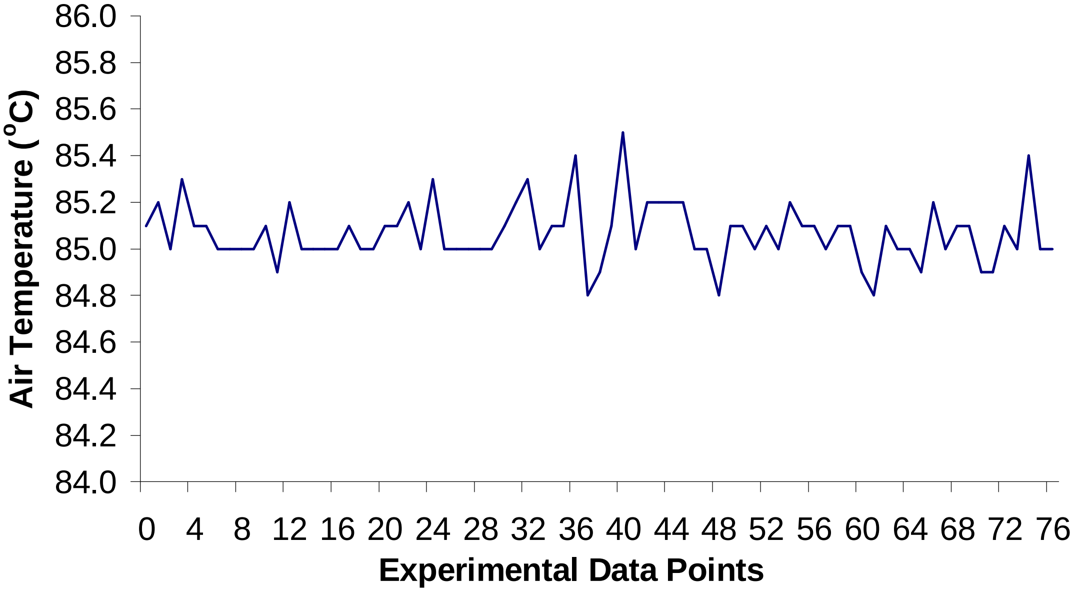

Figure 2d: Engine intake air temperature

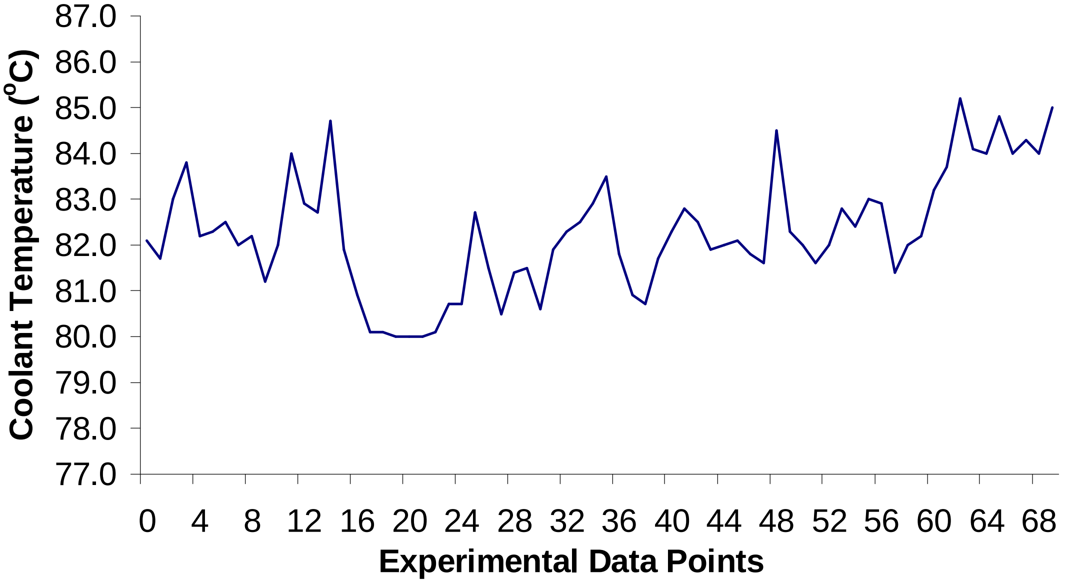

Figure 2e: Engine cooling water outlet temperature

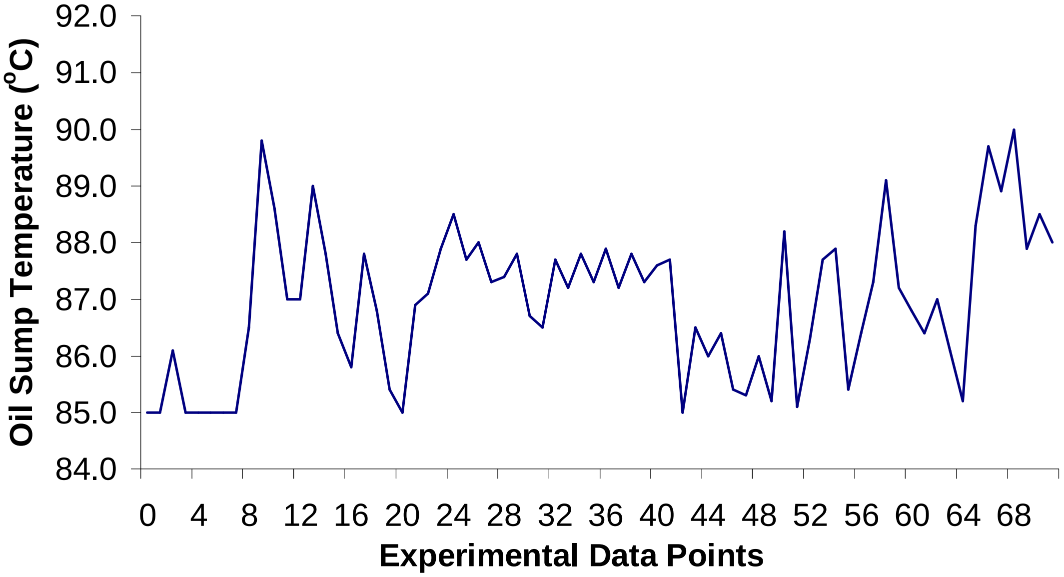

Figure 2f: Engine oil sump temperature

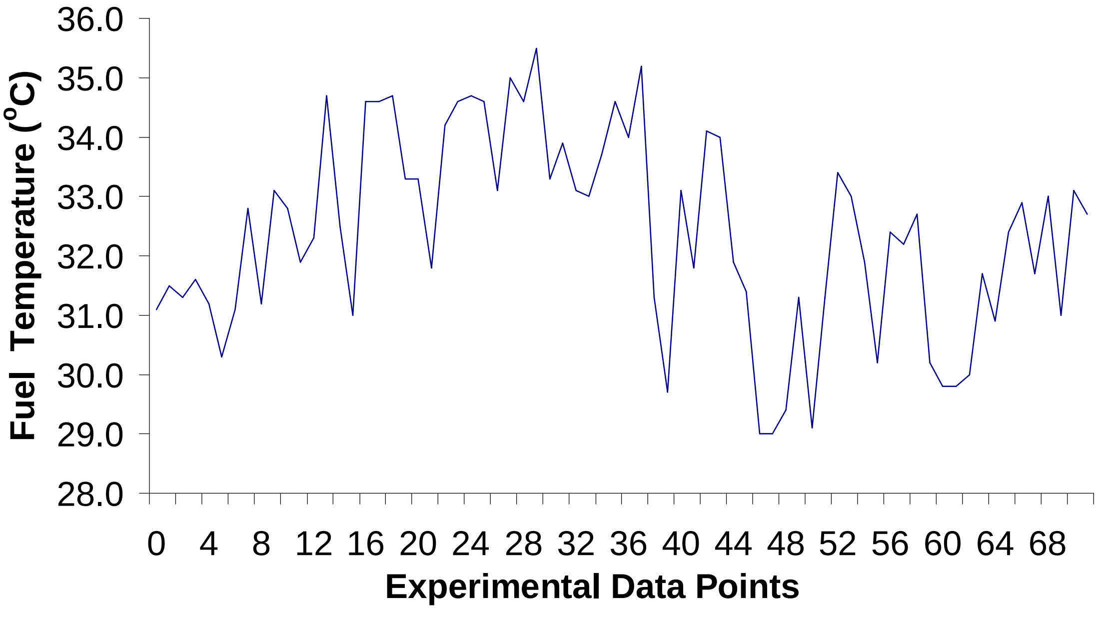

Figure 2g: Engine fuel inlet temperature

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.

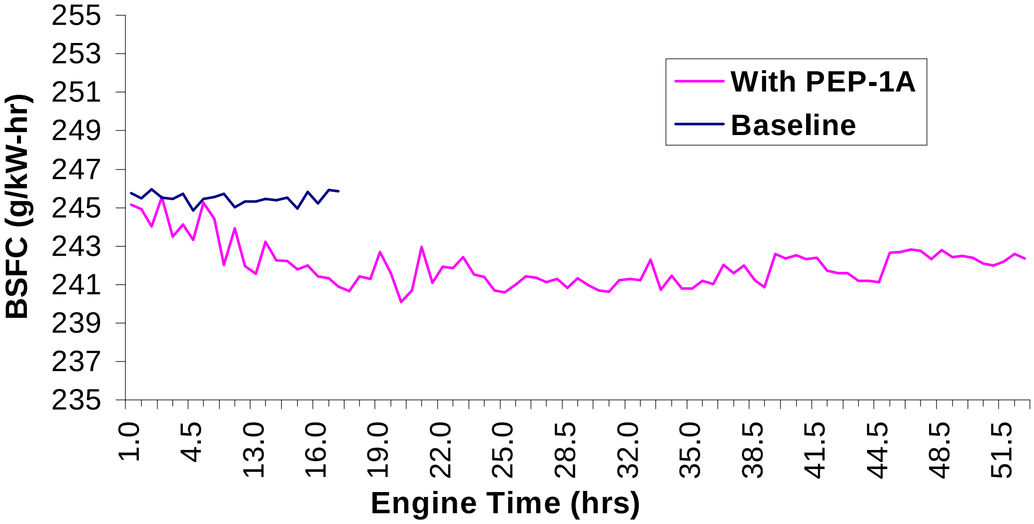

Figure 3a: BSFC data of PEP-1A

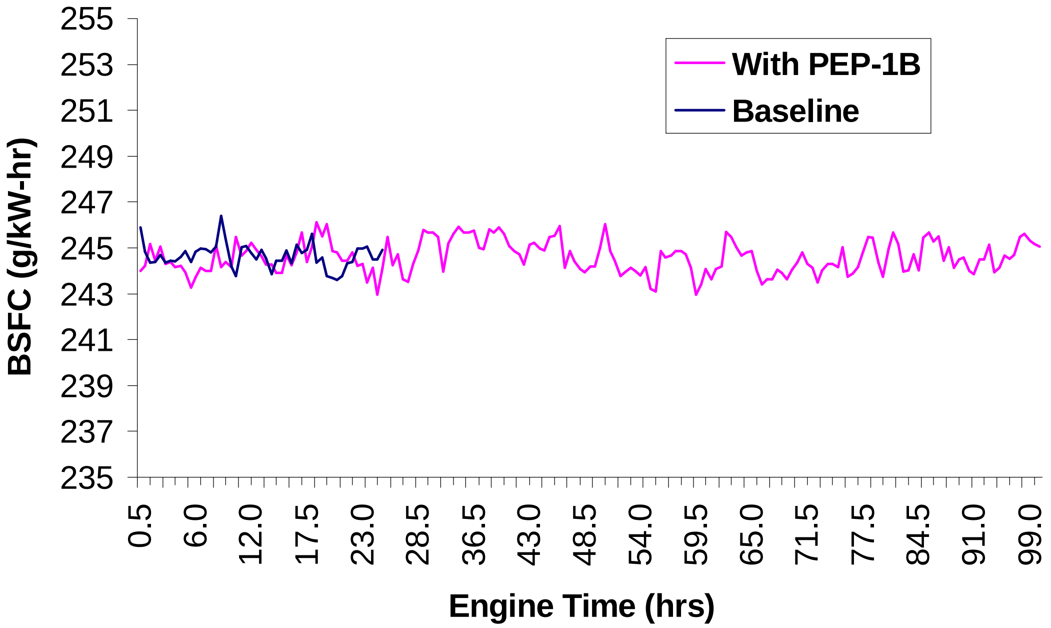

Figure 3b: BSFC data of PEP-1B

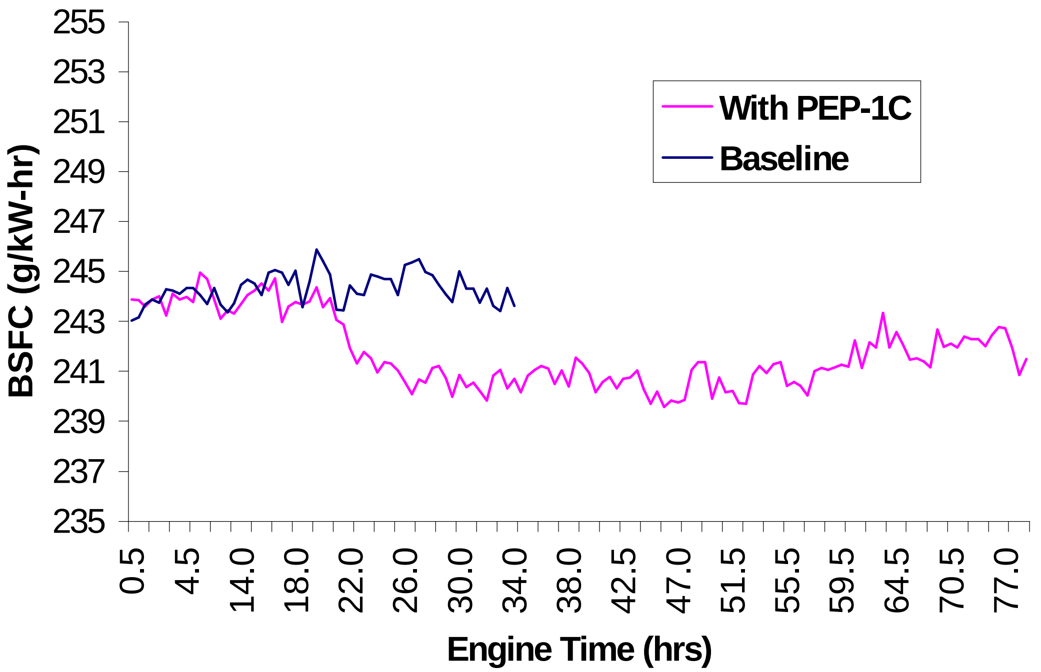

Figure 3c: BSFC data of PEP-1C

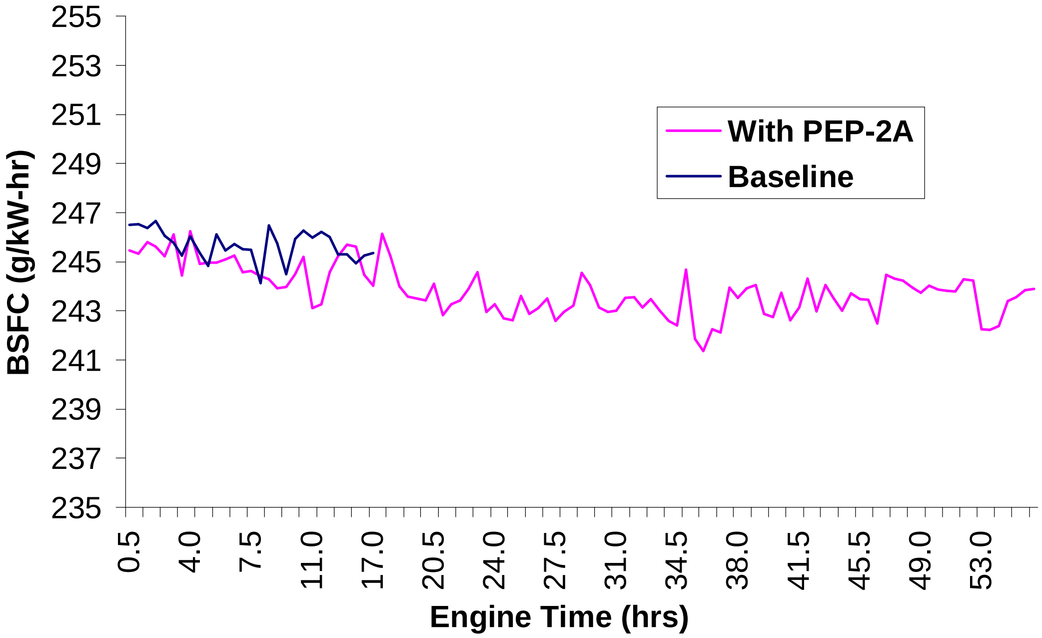

Figure 3d: BSFC data of PEP-2A

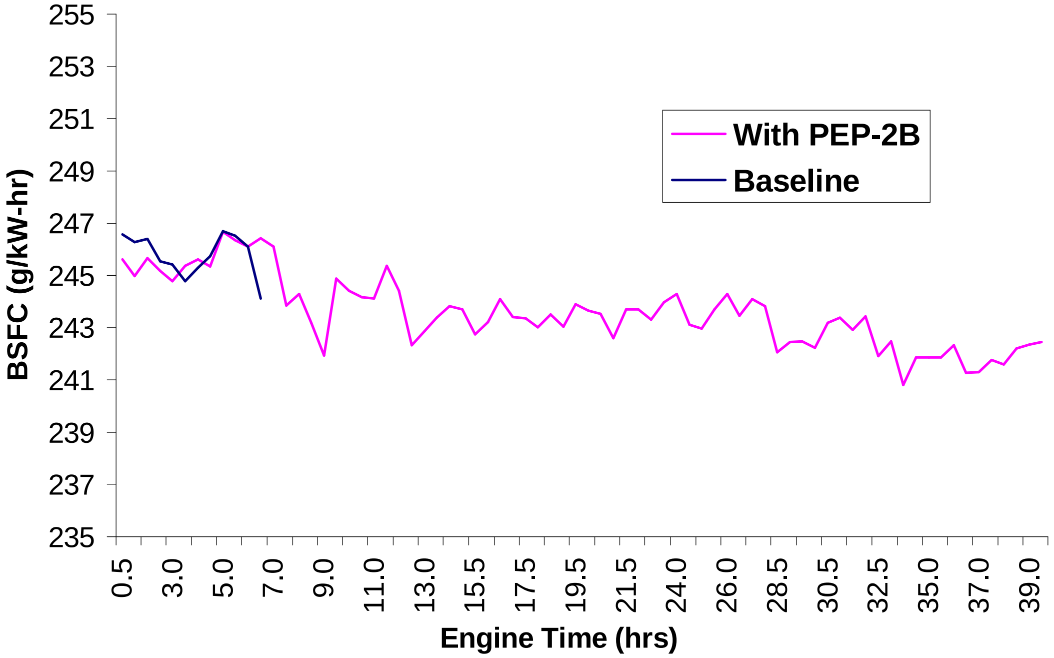

Figure 3e: BSFC data of PEP-2B

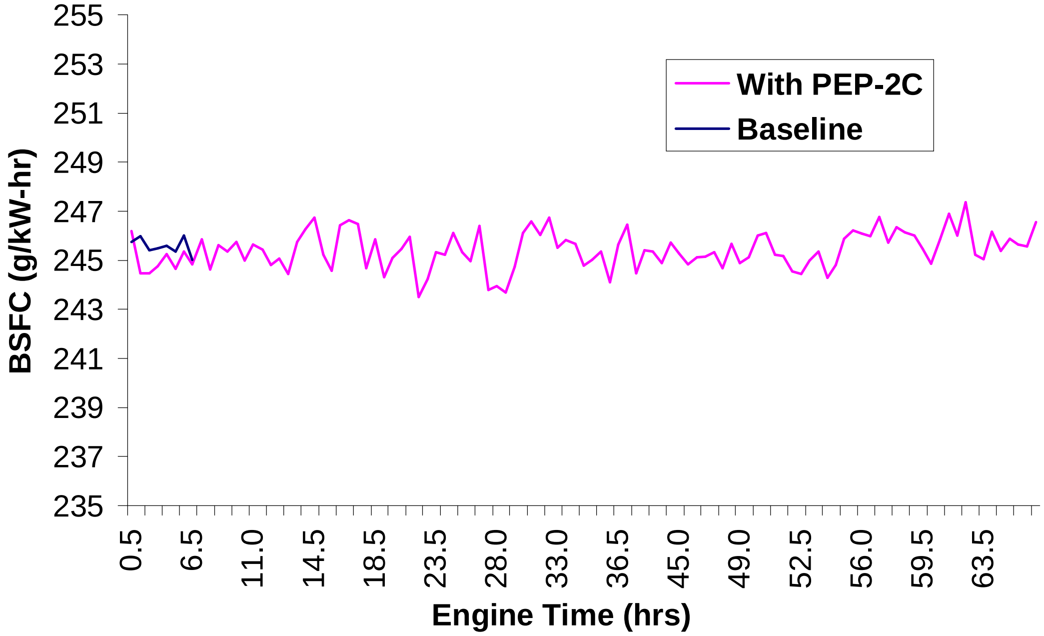

Figure 3f: BSFC data of PEP-2C

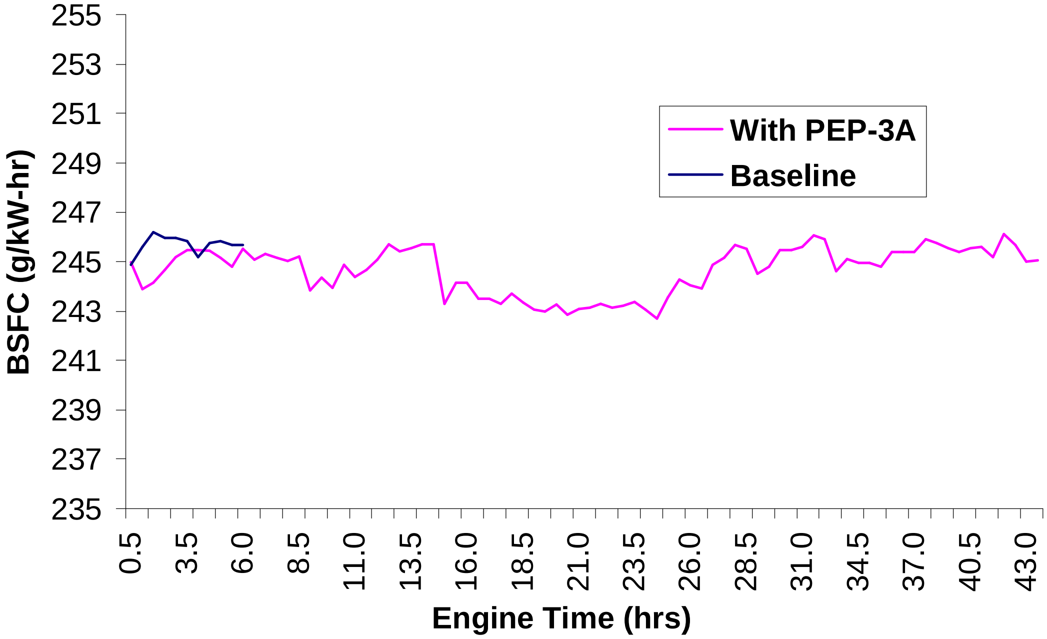

Figure 3g: BSFC data of PEP-3A

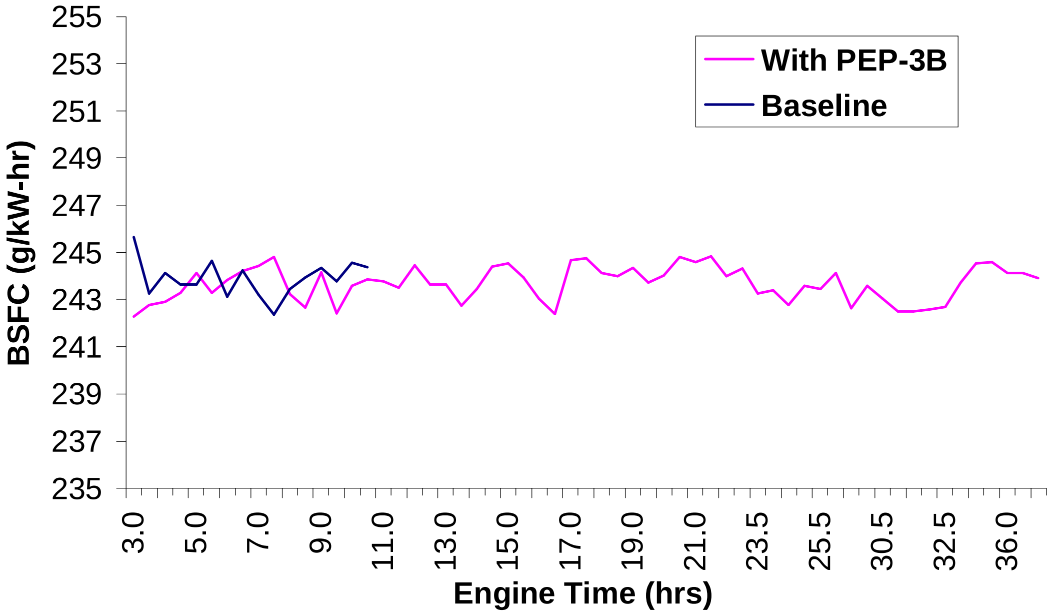

Figure 3h: BSFC data of PEP-3B

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).

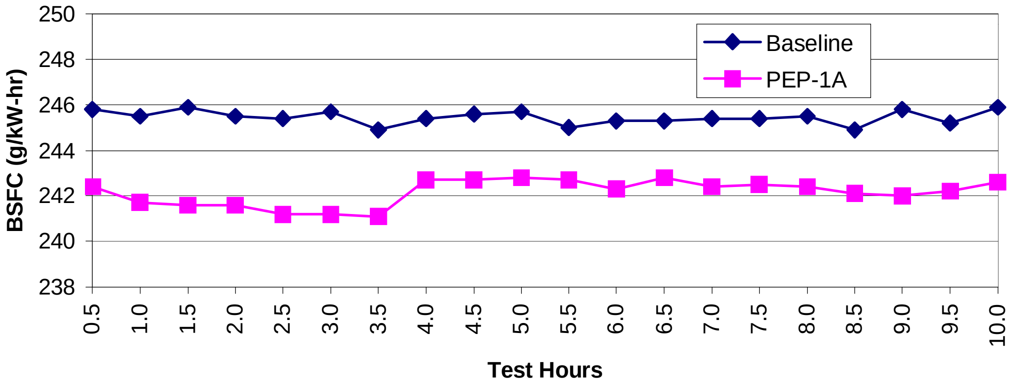

Figure 4a: Comparison of BSFC values (PEP-1A)

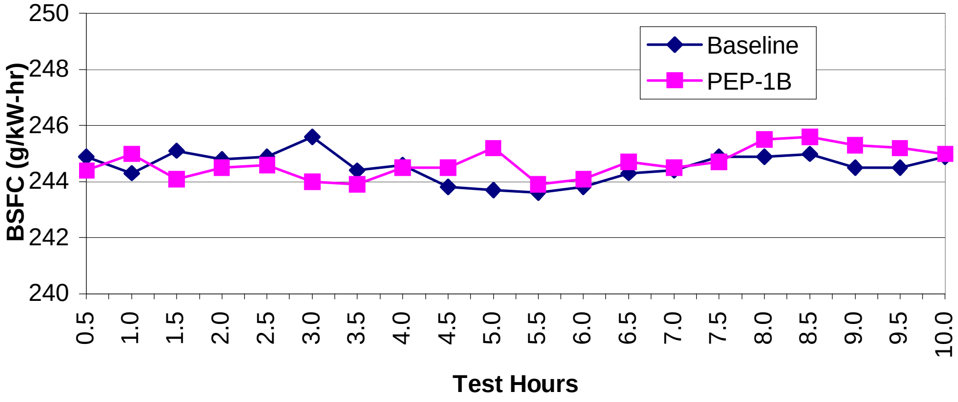

Figure 4b: Comparison of BSFC values (PEP-1B)

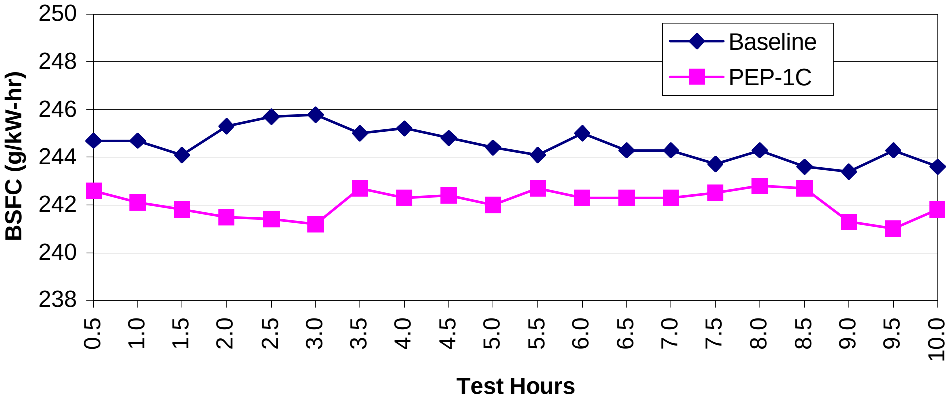

Figure 4c: Comparison of BSFC values (PEP-1C)

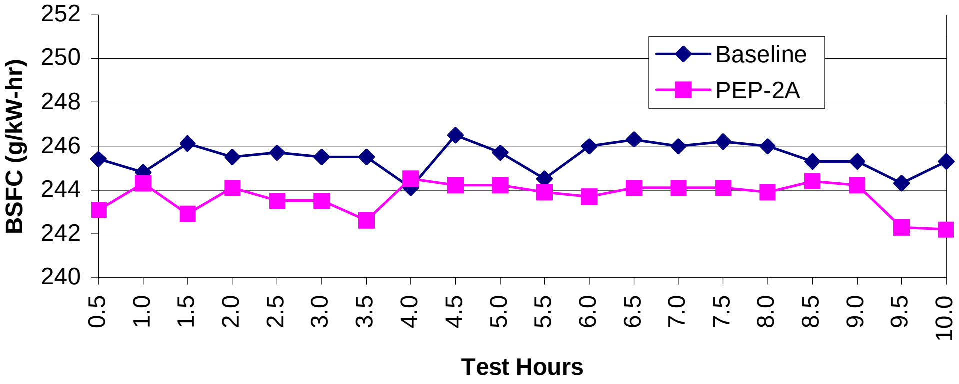

Figure 4d: Comparison of BSFC values (PEP-2A)

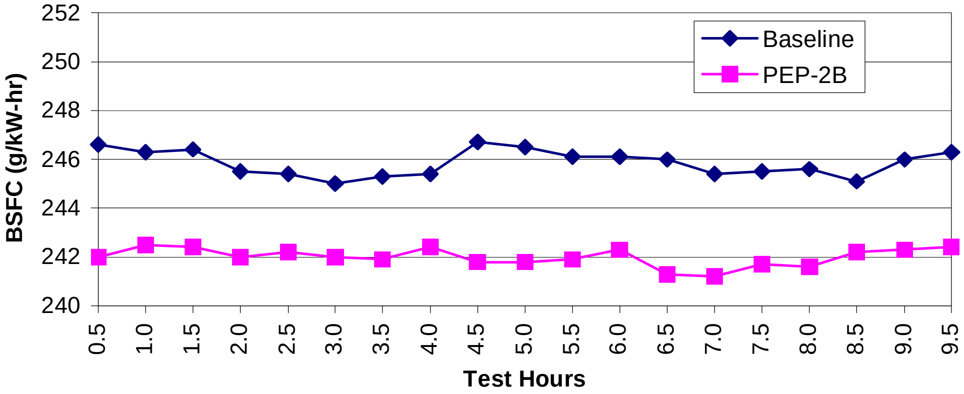

Figure 4e: Comparison of BSFC values (PEP-2B)

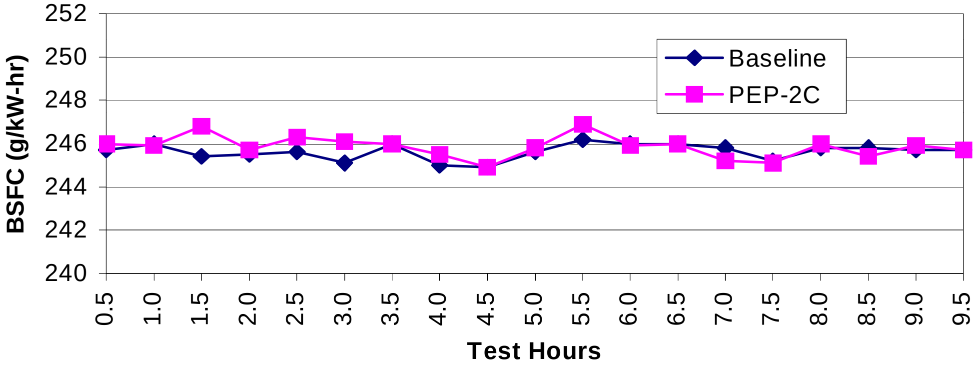

Figure 4f: Comparison of BSFC values (PEP-2C)

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.

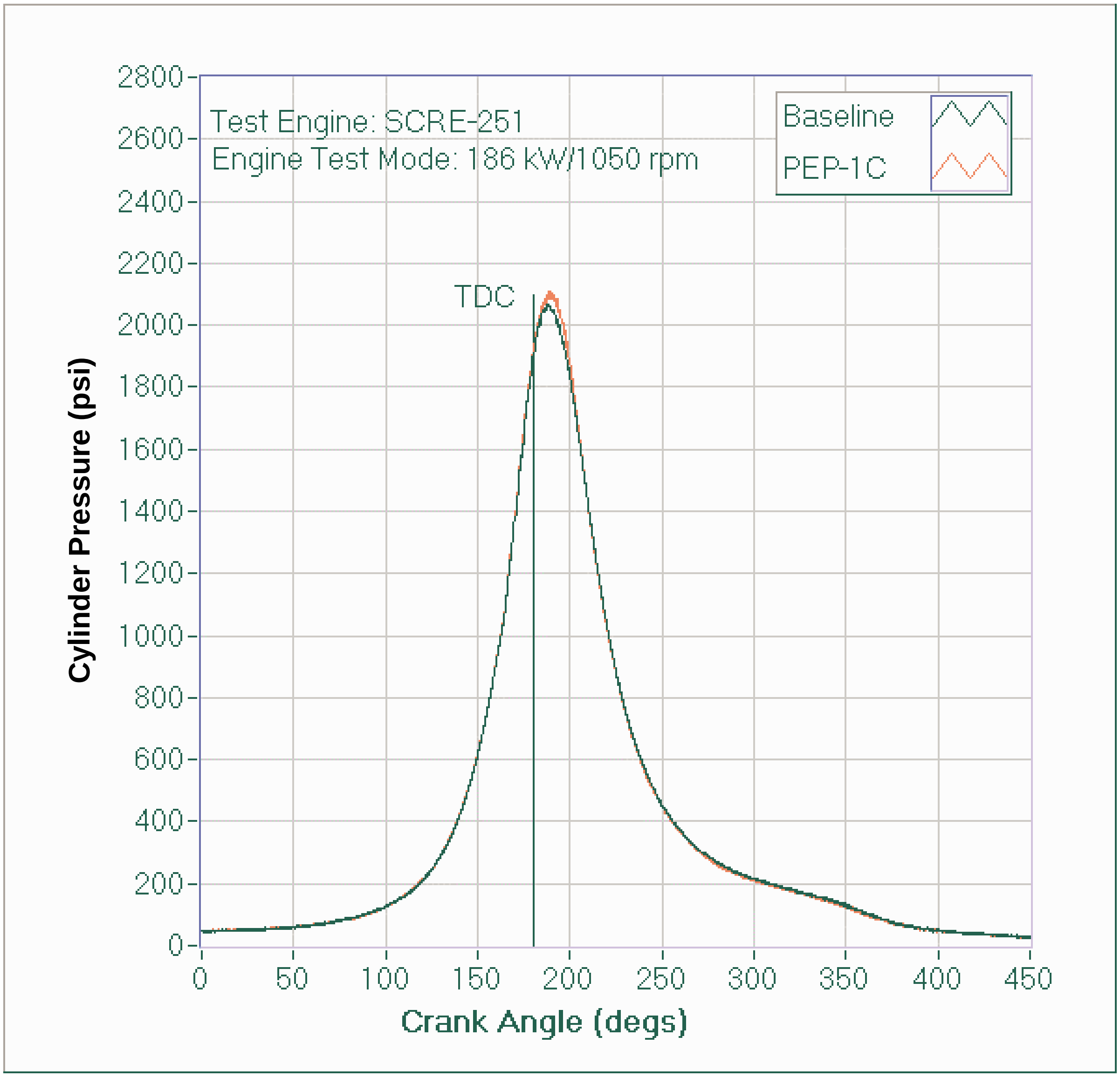

Figure 5: Comparison of cylinder pressures between the baseline and PEP-1C

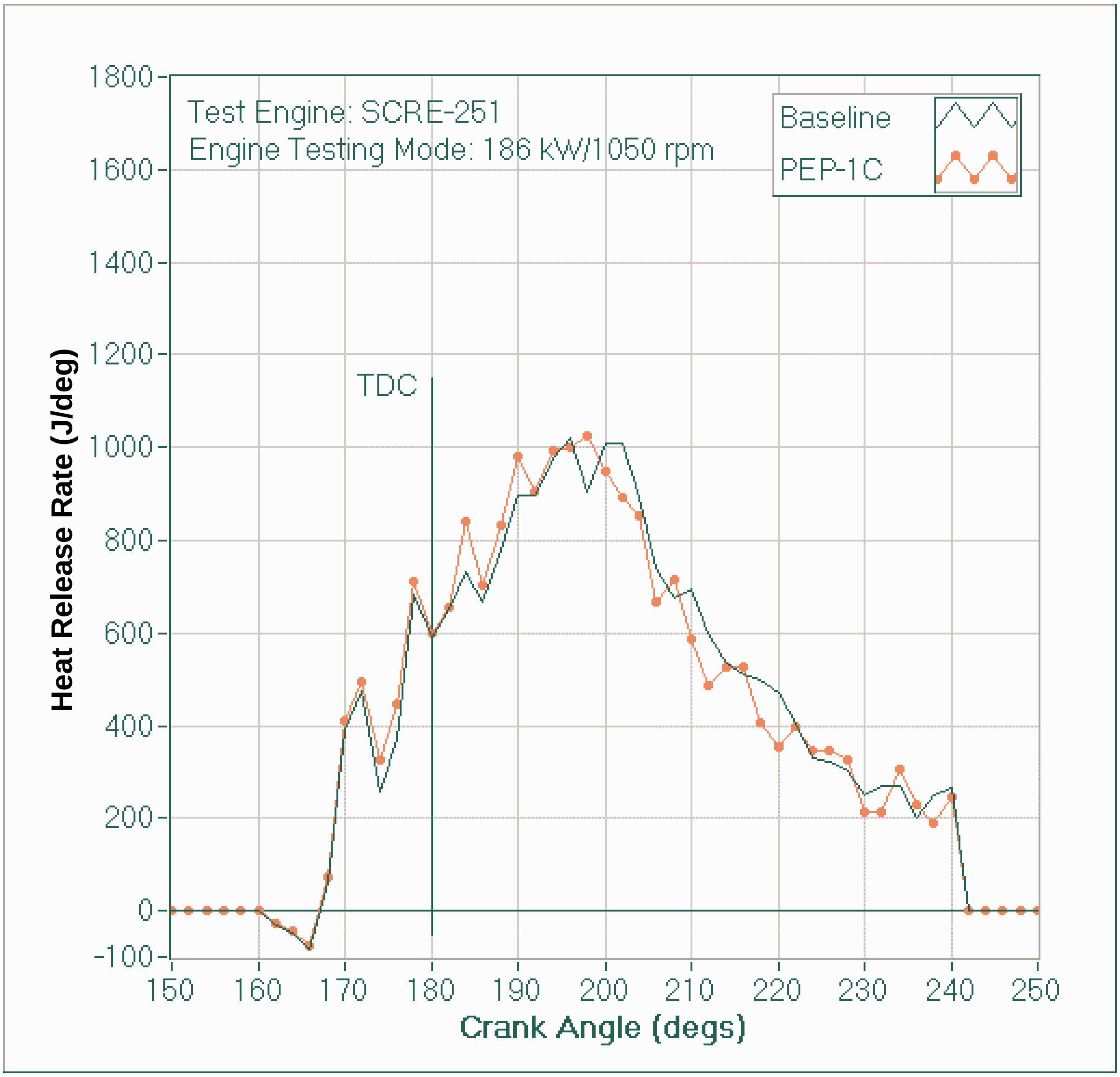

Figure 6: Comparison of net heat release rate between the baseline and PEP-1C

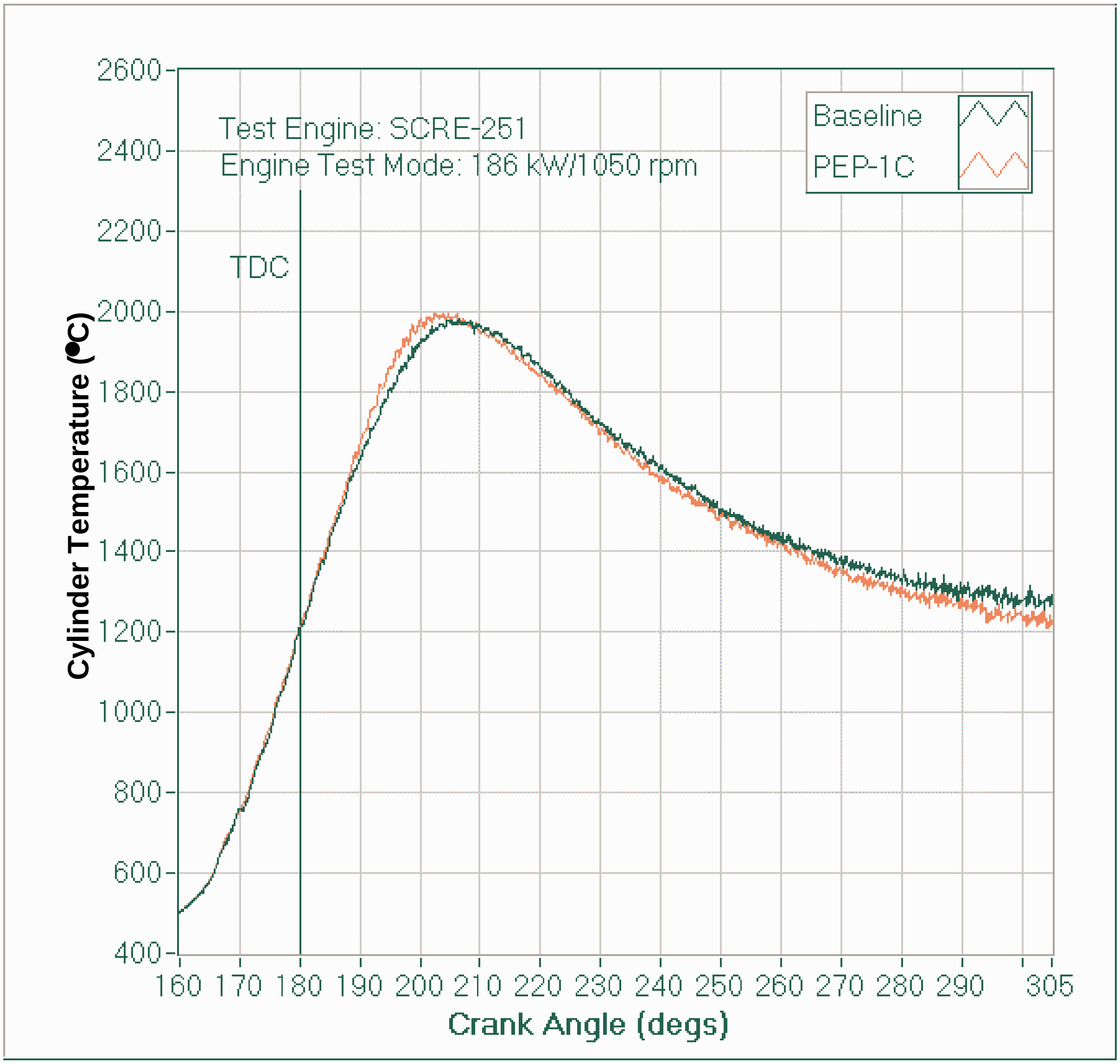

Figure 7: Comparison of cylinder temperatures between the baseline and PEP-1C

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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SIMPLIFIED FUEL ADDITIVE TEST PHASE IV: TEST PROTOCOL

PREPARED FOR

TRANSPORTATION DEVELOPMENT CENTRE
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BY
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SIMPLIFIED FUEL ADDITIVE TEST PHASE IV: TEST PROTOCOL

BY

FAN SU, MALCOLM L. PAYNE, MANUEL VASQUEZ AND AREF TAGHIZADEH
ENGINE SYSTEMS DEVELOPMENT CENTRE

MAY 2003

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

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16. Abstract

The methodology and the development of the Simplified Fuel Additive Test (SFAT) protocol as a lower cost alternative to AAR RP-503 are described in this report on Phase IV, the final part of the project, which validates work completed in the earlier phases.

Repeated runs on two products (a fuel additive and a fuel system add-on device), which were evaluated in Phase III, were carried out. Chemical analysis of baseline and treated fuel, showing the same results of Phase III, revealed no significant effects of the products on fuel chemical properties. Engine brake-specific fuel consumption (BSFC) and emissions changes detected for the products appear to be consistent with that of Phase III. The 1.66% improvement on engine BSFC (average of Phase III and Phase IV results) and non-significant changes detected on emissions were similar to those reported earlier by other investigators for the same fuel additive.

Based on the Phase IV results, the SFAT procedure was finalized and is presented in this report. The procedure proves to be efficient, accurate and cost-effective for evaluation of fuel additives and engine fuel system add-on devices.

17. Key Words
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16. Résumé

Le présent rapport rend compte de la quatrième et dernière phase du projet, qui a consisté à valider les tâches exécutées au cours des phases antérieures. Il rappelle également les travaux qui ont mené à la mise au point du protocole SFAT (pour *Simplified Fuel Additive Test*) en tant que solution de rechange économique à la norme PR 503 de l'AAR.

Deux produits (un additif pour carburants et un dispositif d'optimisation pour système d'alimentation) évalués au cours de la phase III ont été soumis à des essais répétés. L'analyse chimique d'un carburant de référence et d'un carburant traité a donné les mêmes résultats qu'à la phase III et n'a donc révélé aucun effet significatif des produits sur les propriétés chimiques des carburants. En effet, dans le cas des deux carburants analysés, la fluctuation de la puissance au frein et du niveau des émissions polluantes est comparable à celle observée au cours de la phase III. Par ailleurs, l'amélioration de 1,66 % de la puissance au frein (moyenne des résultats de la phase III et de la phase IV) et l'absence d'effet significatif sur les émissions polluantes corroborent les résultats d'études faites par d'autres sur le même additif pour carburant.

Les chercheurs se sont fondés sur les résultats de la phase IV pour mettre au point la version définitive du protocole SFAT, exposé dans le présent rapport. Ce protocole se révèle efficace, précis et économique pour l'évaluation d'additifs pour carburants et de dispositifs d'optimisation pour système d'alimentation.

17. Mots clés Moteur de recherche monocylindre, locomotive, moteur diesel, émissions, optimiseur de rendement, additif pour carburants, analyse chimique, analyse de carburants et d'huiles lubrifiantes	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

The Simplified Fuel Additive Test (SFAT) project was initiated in 1998. The objective of this work was to develop a method for the evaluation of fuel additives, performance-enhancing devices, and lubricating oil additives at a reduced cost and time relative to the current test procedure, AAR RP-503. The development process consisted of the following phases.

Phase I: Feasibility of SFAT protocol (TP 13215E)
Phase II: SFAT procedure development and methodology (TP 13494E)
Phase III: Testing and verification (TP 13823E)
Phase IV: Test procedure validation, data reduction and finalization of protocol

Phase I results indicated that a single-cylinder medium-speed diesel engine would not only be technically feasible but also economically feasible in conducting evaluation tests because of special design features and mechanical simplicity. From these results, a preliminary test methodology was proposed in Phase II based on a literature survey and other researchers' work on both the single-cylinder engine and multi-cylinder engine. To verify the test procedure, eight candidate engine performance enhancing products (PEPs), including three add-on devices, three fuel additives and two lube oil additives, were tested in Phase III. The work completed in Phase III suggested that 75 hours of engine tests (engine operating at full load) would be sufficient to detect fuel additive (or add-on device) effects on engine fuel economy, emissions and deposits. The testing system was also proved to be effective in determining a minimum of 1 percent change in the brake specific fuel consumption and a minimum 5 percent (on average) in exhaust emissions. In addition, the data obtained for a fuel additive appear to be very similar to those reported earlier by other investigators. However, no experimental evidence has come from studies of the same test sequence as being suitable for the evaluation of oil additives.

The test procedure was validated and fine-tuned in Phase IV by conducting repeated tests on a fuel additive and a fuel system add-on device, which were tested in Phase III. Consistent evaluation results confirmed the reliability of conducting tests using the Single-Cylinder Research Engine (SCRE) facility.

Further investigations on test results revealed that some issues, such as identical engine components, information about a candidate, etc., are critical for accurately evaluating a product. They are the sources of errors that might mask effects of the product. It was also observed that the test sequence was not appropriate for oil system add-on devices because of dynamic changes of oil properties affecting engine performance and emissions.

On the basis of tests and the analysis of results, the final test procedure for fuel additives and fuel system add-on devices was derived. It is a two-step test procedure: chemical analysis and SCRE tests. The engine tests will be a minimum of 75 hours (engine operating at full load), including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of product performance testing. Following these tests, a baseline check-up test shall be performed to determine whether the same baseline can be obtained as before the test. Testing at additional engine operating modes is also recommended. The developed SFAT test procedure is cost-effective and efficient in evaluating a product.

SOMMAIRE

Le projet Essai simplifié d'additifs pour carburants (SFAT, pour *Simplified Fuel Additive Test*) a débuté en 1998. L'objectif de cette étude était de mettre au point une méthode pour évaluer les additifs pour carburants, les optimiseurs de rendement et les additifs pour huiles lubrifiantes, qui serait à la fois plus économique et moins longue à appliquer que le protocole d'essai actuel, soit celui de la PR 503 de l'AAR. Les travaux se sont déroulés en quatre phases successives :

Phase I : Faisabilité d'un protocole simplifié d'évaluation des additifs pour carburants (TP 13215E)
Phase II : Développement du protocole (TP 13494E)
Phase III : Essais et vérification (TP 13823E)
Phase IV : Validation du protocole d'essai, réduction des données et mise au point définitive du protocole

Les résultats de la phase I ont confirmé qu'il est faisable techniquement et avantageux économiquement de se servir d'un moteur de recherche monocylindre dérivé d'un moteur diesel à vitesse moyenne en tant qu'outil d'évaluation, en raison des caractéristiques de conception particulières de ce moteur et de sa simplicité sur le plan mécanique. Une fois établie la faisabilité du projet, les chercheurs ont mis au point, au cours de la phase II, un protocole préliminaire fondé sur les résultats d'une recherche documentaire et sur des données concernant les moteurs monocylindres et les moteurs multi-cylindres issues des travaux d'autres chercheurs. La phase III a consisté à vérifier ce protocole sur huit produits candidats, soit trois dispositifs d'optimisation du rendement, trois additifs pour carburants et deux additifs pour huiles lubrifiantes. Les résultats obtenus donnent à penser qu'il suffit de 75 heures d'essai sur moteur (moteur fonctionnant à plein régime) pour détecter les effets d'un additif pour carburants (ou d'un dispositif d'optimisation) sur la consommation de carburant, les émissions polluantes et les dépôts. Le protocole s'est en outre révélé efficace à détecter une fluctuation d'au moins 1 p. 100 de la puissance au frein et d'au moins 5 p. 100 (en moyenne) des émissions d'échappement. De plus, les données recueillies concernant un additif pour carburants ressemblent beaucoup à celles déjà publiées par d'autres chercheurs. Toutefois, l'étude n'a pas permis de conclure au bien-fondé de la séquence d'essais pour l'évaluation d'additifs pour huiles lubrifiantes.

Le protocole d'essai a été validé et mis au point dans sa forme définitive au cours de la phase IV. Des essais répétés ont été effectués sur un additif pour carburants et un dispositif d'optimisation pour système d'alimentation déjà évalués au cours de la phase III. Des résultats cohérents ont confirmé la fiabilité des essais menés à l'aide du moteur de recherche monocylindre.

Une analyse approfondie des résultats d'essais a révélé que certains critères (organes de moteur identiques, information sur un produit candidat, etc.) sont essentiels pour évaluer avec précision un produit. Autrement, des erreurs peuvent être induites, qui risquent de masquer les effets du produit. Il a également été observé que la séquence d'essais ne convient pas à l'évaluation des dispositifs d'optimisation pour système de lubrification, à cause de la fluctuation dynamique des propriétés des huiles, qui se répercute sur le rendement du moteur et sur les émissions.

Au terme des essais et de l’analyse des résultats, les chercheurs ont mis au point le protocole définitif pour l’essai des additifs pour carburants et dispositifs d’optimisation pour système d’alimentation. Il s’agit d’un protocole en deux étapes qui comprend une analyse chimique suivie d’essais sur un moteur monocylindre. Les essais sur moteur doivent durer au moins 75 heures (le moteur fonctionnant à plein régime), soit 20 heures de marche avec le carburant de référence, 35 heures de rodage et 20 heures d’essai de performance du produit. Le protocole prévoit en outre, après cette séquence d’essais, un dernier essai de marche avec le carburant de référence, qui sert à déterminer si les conditions de référence sont identiques avant et après les essais. Des essais à d’autres régimes moteur sont également recommandés. En définitive, le protocole d’essai résultant de ces travaux s’avère à la fois économique et efficace pour l’évaluation d’un produit.

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GLOSSARY

AAR	Association of American Railroads
ASTM	American Society for Testing and Materials
BSFC	Brake-Specific Fuel Consumption
CA	Crank Angle
CFR	Code of Federal Register (U.S.)
CO_2	Carbon dioxide
CO	Carbon monoxide
CP	Canadian Pacific
DIN	Deutsche Industrie Norm
ECOM	ECOM America, Ltd.
EMD	Electro-Motive Division of General Motors Corp.
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Centre, Inc.
IMEP	Indicated Mean Effective Pressure
NO_x	Oxides of nitrogen
PEP	Performance-Enhancing Product
RAC	Railway Association of Canada
RP	Recommended Practice
SAE	Society of Automotive Engineers
SCRE	Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SD	Standard Deviation
STP	Standard Test Practice
SwRI	Southwest Research Institute

1 INTRODUCTION

Operating cost reduction through fuel economy is a major challenge in the railway transportation sector. Such a reduction can be realized via approved aftermarket performance-enhancing products (PEPs). Certification of these products requires performance and emissions tests in accordance with Association of American Railroads (AAR) Recommended Practice test procedure AAR RP-503 (adopted in 1980 and revised in 1994). This procedure consists of four stages and is designed to compare the effects of fuel oil additives on fuel chemical properties, engine wear and deposits, as well as engine performance characteristics. Currently, the only organization that can carry out the AAR RP-503 test is the Southwest Research Institute (SwRI). Each test requires more than 1000 hours for completion, with a high price tag attached to it. The existing test is lengthy and expensive, preventing small businesses from entering the market. The need for an alternative procedure that could provide similar results and include emissions tests at a lower cost and reduced time resulted in the development of a Simplified Fuel Additive Test (SFAT) protocol.

The SFAT project aims to develop a protocol that can be used to properly evaluate the claimed benefits of PEPs (such as fuel additives and engine add-on devices) at a lower cost and reduced time. The project began in 1998 and was divided into four phases:

Phase I: Feasibility of SFAT protocol
Phase II: SFAT procedure development and methodology
Phase III: Testing and verification
Phase IV: Test procedure validation, data reduction and finalization of protocol

The preliminary feasibility study [1] showed that utilization of a single-cylinder research engine derived from a medium-speed diesel engine would be more economical and less complex. Additionally, it would be more representative of modern locomotive diesel engines for performance evaluation of fuel additives, oil additives, and add-on devices.

During the second stage of this project, an attempt was made to put together a methodology that would apply a universal test sequence to wide range of after-market engine PEPs. Therefore, a tentative test methodology and procedure was proposed based on a literature survey in Phase II of the project [2].

Initial experimental work was conducted on eight selected PEPs (three add-on devices, three fuel additives and two oil additives) to verify the preliminary test procedure in Phase III [3]. Based on the experimental results, a test procedure was derived for fuel additives and fuel system add-on devices. The experimental data seemed to indicate that a single test sequence could not be applied to both fuel and oil additives. Therefore, it was decided that the established method would be applied only to fuel additives and add-on devices, and that a separate method should be developed for oil additive evaluation.

This report consists of the final SFAT test protocol derived from the work performed during the four phases of the project and discusses the validity and repeatability of the results and the limitations imposed by the test parameters.

2 SFAT PROJECT OVERVIEW

2.1 Phase I – Feasibility Study [1]

The focus of this phase was to determine the feasibility of replacing the AAR RP-503 protocol for testing diesel fuel oil additives with a new procedure, using the Single-Cylinder Research Engine (SCRE-251) as the laboratory test engine that tests for both engine performance and emissions compliance.

A literature search was conducted to obtain relevant information relating to PEPs and test procedures. The EPA regulations were reviewed and required testing equipment was determined. The review of documentation concerning the design of SCRE-251 revealed that this engine was designed to simulate multi-cylinder medium-speed diesel engines with major cost and time advantages. In addition, there exists the flexibility to configure the SCRE-251 to simulate the performance conditions representative of current high IMEP multi-cylinder diesel engines.

It was concluded that a test protocol could be established using SCRE-251 to evaluate the performance of fuel/oil additives and add-on devices in place of AAR RP-503 at reduced cost and time, while determining the emissions trend exhibited by the PEPs.

2.2 Phase II – Procedure Development and Methodology [2]

The information obtained in Phase I was used to establish a tentative test methodology for SCRE-251. The test procedure was based on the review of existing test protocols, which included AAR RP-503, SAE J304, SAE J1423, DIN 51361, ASTM STP 509A Part I, and the U.S. Army guide for evaluating aftermarket fuel and lubricant additives. The facility was upgraded and the test engine was configured accordingly to conform to the required parameters.

The developed test sequence included a questionnaire to be completed by the PEP manufacturer, a preliminary chemical analysis baseline engine test and emissions measurements, preconditioning, and performance engine test and emissions analysis.

The test cell upgrades allow low-speed and high-speed data acquisitions and emissions measurements under various loads and speeds using PC-based software for data collection and data processing. Required materials, including fuel, lubricant and candidate additives, were acquired and stored for the engine test that would precede this phase of the project.

2.3 Phase III – Testing and Verification [3]

The validity of the tentative test procedure that was developed in Phase II was verified in this phase. The eight selected aftermarket products were tested on the SCRE-251 to verify the suitability of the procedure. Upon completion of this phase it was determined that a test sequence consisting of 20 hours of baseline testing, 35 hours of preconditioning testing, and 20 hours of performance testing would be sufficient for performance and emissions evaluations of fuel additives and add-on devices. It was also noted that this procedure would not be applicable to oil additives.

According to the gathered experimental results, the oil additives would require a longer preconditioning period (approximately 200 hours). Inclusion of oil additives into the test procedure would have extended the time required for the test, while not offering any benefit to the manufacturers of the 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 and exhaust emissions.

Further investigations on test results of an oil system add-on device enabled us to suggest that a separate test procedure would be more suitable for the evaluation of oil system add-on devices. The device tested in this phase is claimed to remove the volatile fraction of the lube oil and thereby improve the combustion process. Though fuel economy and emissions changes could be observed after a preconditioning time similar to the fuel additive evaluation tests, dynamic changes of oil properties with higher engine oil consumption rate (0.8 to 0.9% of fuel consumption) might require more hours of testing and more detections, such as the effects of oil refilling on test results and the effects of oil soot concentrations on engine deposits, to fully understand the device.

2.4 Phase IV – Validation and Finalization

The current phase of the project was undertaken to verify the repeatability and reproducibility of the test results under the test sequence established in Phase III. The outcome of the work is discussed in the following sections.

3 PHASE IV RESULTS AND DISCUSSIONS

Repeated runs on PEP-1A and PEP-2B, which were tested in Phase III, were carried out to validate the developed test procedure. Results and discussions are provided in this section.

3.1 Chemical Analysis Results

Chemical and physical parameters of the baseline and treated fuel were determined before engine tests to verify the effects of a product on limiting fuel specification requirements. Test results (Table 1) showed changes on some parameters, such as carbon residue and heating values; however, they are considered to be either minimal or within test-to-test repeatability. The treated fuel properties were within fuel limiting specifications and were acceptable for engine tests.

Table 1: Baseline and product-treated fuel properties

Fuel Property		ASTM	PEP-1A		PEP-1B	
			Baseline	Treated Fuel	Baseline	Treated Fuel
Density @ 15°C (kg/L)		D1298	0.834	0.832	0.835	0.833
Flash point (°C)		D56	52	54	N/A	N/A
Cloud point (°C)		D2500	-21	-24	-23	-22
Pour point (°C)		D97	-33	-33	-36	-30
Viscosity @ 40°C		D445	2.2	2.2	2.1	2.1
Distillation	- Initial boiling point	D86	163	163	164	159
	- 10% recovered (°C)		185	184	190	188
	- 50% recovered (°C)		249	252	244	238
	- 90% recovered (°C)		323	320	309	300
	- Final boiling point		362	355	N/A	N/A
	- Loss (%)		1.0	1.0	N/A	N/A
	- Recovered (%)		N/A	N/A	N/A	N/A
Ash (%)		D482	< 0.001	< 0.001	< 0.001	< 0.001
Copper strip corrosion		D130	1A	1A	1A	1B
Water & sediment (%, v/v)		D2709	< 0.05	< 0.05	< 0.05	<0.05
Sulfur (%, p/p)		D129	0.04	0.02	0.03	0.03
Heating value (kJ/kg)		D240	44884	45057	45456	45400
Carbon residue (%)		D189	0.019	0.008	0.02	0.03
Particulate contamination		D2276	N/A	N/A	0	0
Cetane index		D976	48.4	49.8	46.5	45.5

Note: N/A- not available

3.2 Engine Test Results

Baseline brake-specific fuel consumption (BSFC) values of both PEP-1A and PEP-2B tests were investigated to determine variations of BSFC measurements. It was found that the repeatability of BSFC measurements was within 1% of mean value.

The engine brake horsepower was maintained during an evaluation run. This enabled the effect of a product on engine performance to be observed through engine fuel consumption changes. Figure 1 (a, b and c) and Figure 2 (a and b) show BSFC results obtained from PEP-1A and PEP-2B runs.

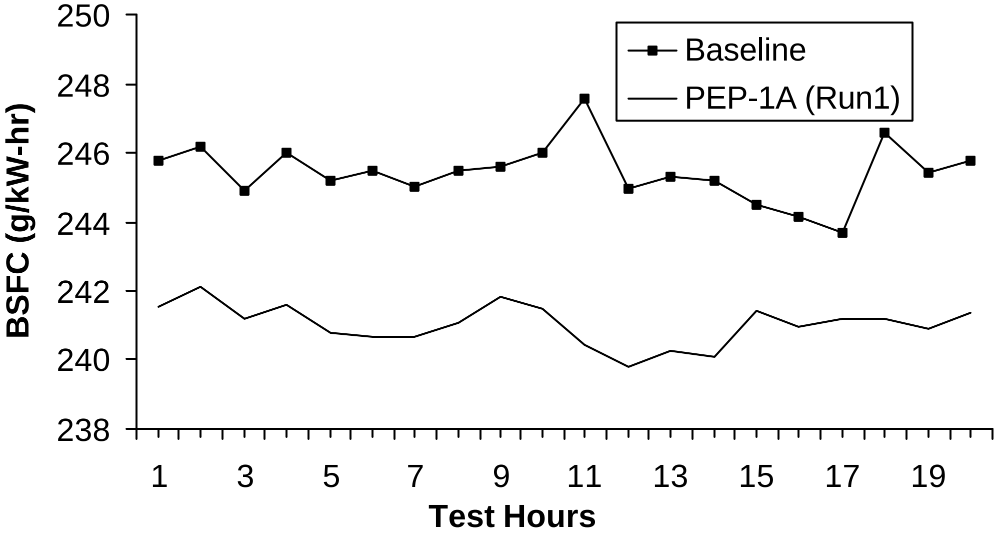


Figure 1a: Comparison of BSFC values (PEP-1A Run1)

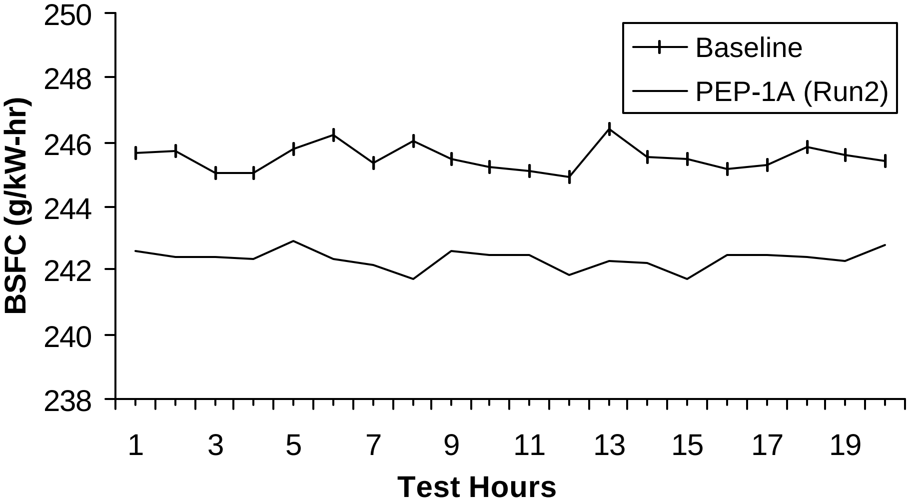


Figure 1b: Comparison of BSFC values (PEP-1A Run2)

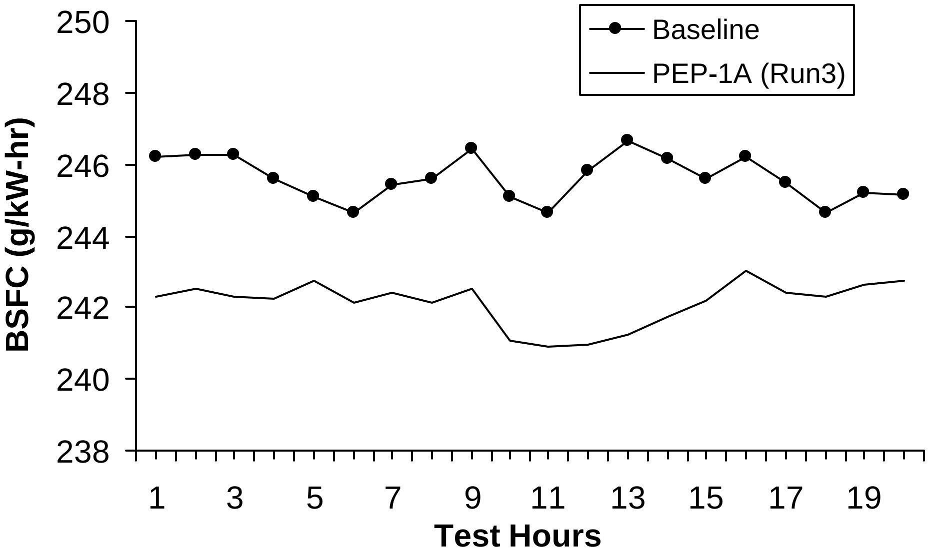


Figure 1c: Comparison of BSFC values (PEP-1A Run3)

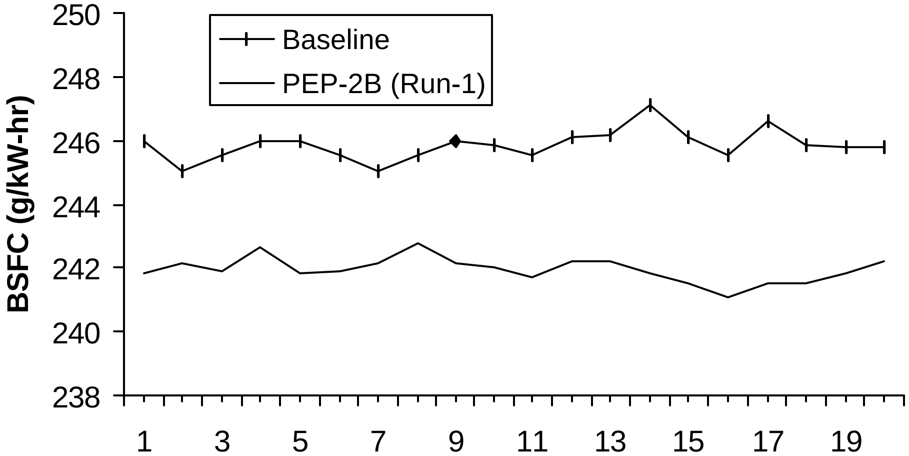


Figure 2a: Comparison of BSFC values (PEP-2B Run1)

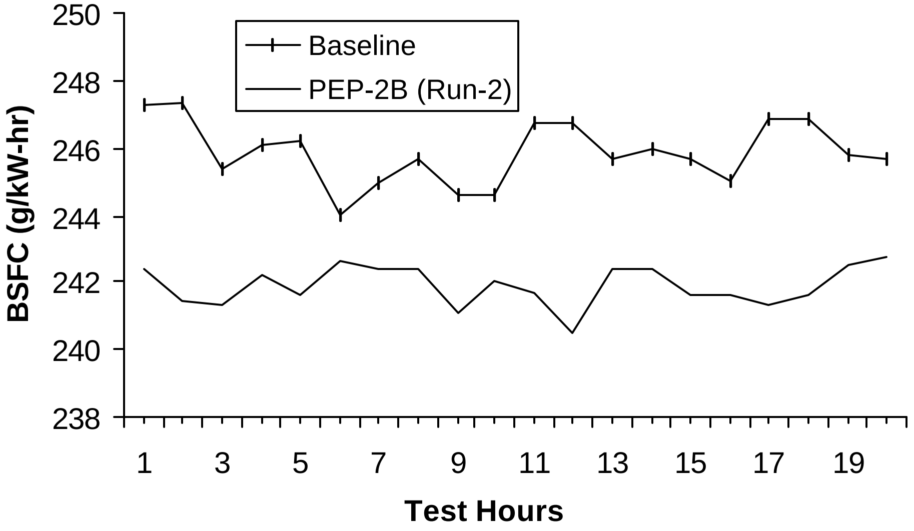


Figure 2b: Comparison of BSFC values (PEP-2B Run2)

Statistical analysis results of BSFC data are shown in Table 2. Similar standard deviations between baseline BSFC data and those of the treated fuel in each of these evaluation runs indicate that the baseline and treated fuel data sets are comparable. The BSFC changes detected from PEP-1A runs were 1.75, 1.30 and 1.43%, respectively. The PEP-2B improved baseline BSFC by up to 1.71%.

Table 2: BSFC comparison of PEP-1A and PEP-2B tests

Test Run	**PEP-1A**					**PEP-2B**				
	Baseline BSFC		**Treated BSFC**		**Changes (%)**	**Baseline BSFC**		**Treated BSFC**		**Changes (%)**
	Mean (g/kW-hr)	**S.D.**	**Mean (g/kW-hr)**	**S.D.**		**Mean (g/kW-hr)**	**S.D.**	**Mean (g/kW-hr)**	**S.D.**	
Run1	245.4	0.8	241.1	0.6	-1.75	246.0	0.5	241.8	0.4	-1.71
Run2	245.5	0.4	242.3	0.3	-1.30	245.9	0.8	241.8	0.6	-1.67
Run3	245.6	0.6	242.1	0.6	-1.43	\	\	\	\	\

Note: Changes (%) = (Treated Mean Value – Baseline Mean Value) /(Baseline Mean Value)

Cylinder pressure recordings of 20 successive engine cycles allowed variation of indicated mean effective pressure (IMEP) measurements to be demonstrated. IMEPs of each combustion cycle were plotted in terms of Relative-IMEP, which is defined as the relative change between an IMEP and the mean value of all the test cycles, versus the test cycle (Figure 3). Approximately 1.0% standard deviation of IMEP measurements is within 1.5% of the transducer manufacturer-specified IMEP stability.

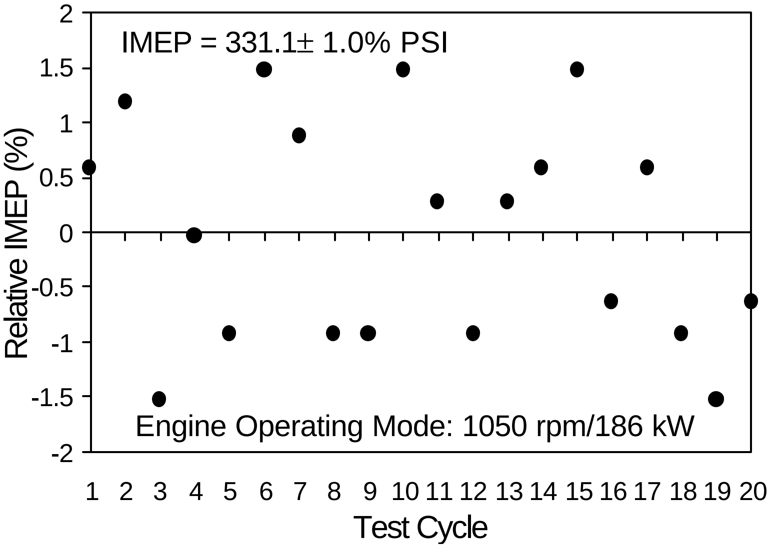


Figure 3: Variation of IMEP measurements

Engine high-speed data are briefly summarized in Table 3. Slight variations observed on the maximum cylinder pressure (Pmax) of each run are attributed to the nature of the combustion process. No obvious changes between the baseline fuel and treated fuel test were detected in the IMEP of an evaluation run, and this finding seems to suggest that fuel consumption improvements of the two products are attributed to augmented combustion processes.

Table 3: Engine combustion analysis results

Product	Test Run	IMEP (psi)	Pmax (psi)	Cumulated Heat Release (kJ)
PEP-1A	Run1 (Baseline)	331	2016	38
	Run1 (Treated)	334	1986	38
	Run2 (Baseline)	328	1989	37
	Run2 (Treated)	330	1980	38
	Run3 (Baseline)	331	2025	37
	Run3 (Treated)	334	2058	38
PEP-2B	Run1 (Baseline)	332	2010	37
	Run1 (Treated)	334	2013	37
	Run2 (Baseline)	333	2058	37
	Run2 (Treated)	334	2025	38

Table 4 shows the emissions results collected during the tests. The PEP-1A reduced baseline CO emissions by 4% on average. NOx increased by 2% on average with application of the device. Similar changes were observed from PEP-2B test results. These changes may not be statistically significant beyond test-to-test repeatability detected during the Phase III test.

Table 4: Comparison of emissions results

Index	CO (g/hp-hr)			NOx (g/hp-hr)			Smoke (BOSCH)		
	AB	AP	Changes (%)	AB	AP	Changes (%)	AB	AP	Changes (%)
PEP-1A (Run1)	3.3	3.1	-6.0	12.2	12.7	4.1	1.35	1.32	-2.2
PEP-1A (Run2)	3.2	3.1	-3.1	12.5	12.6	1.0	1.34	1.32	-1.5
PEP-1A (Run3)	3.2	3.1	-3.1	13.1	13.2	0.8	1.37	1.34	-2.2
PEP-2B (Run1)	3.4	3.2	-5.9	12.4	12.7	2.4	1.34	1.32	-1.5
PEP-2B (Run2)	3.6	3.5	-2.8	12.5	12.6	1.0	1.35	1.33	-1.5
Note: AB – Average of baseline; AP – Average of product; Percentage change = (AP-AB)/AB.									

Carbon deposits on the piston top and valve surfaces (intake and exhaust), and wear conditions on the liner were detected using a bore-scope and engineering judgment. No significant changes between the baseline test and the treated fuel test could be observed.

3.3 Comparison with Phase III Test Results

Test results of Phase IV were compared to that of the Phase III. Engine BSFC improvements were observed in both the Phase III and Phase IV runs for the PEP-1A. These are within 1.46±0.2% (Figure 4).

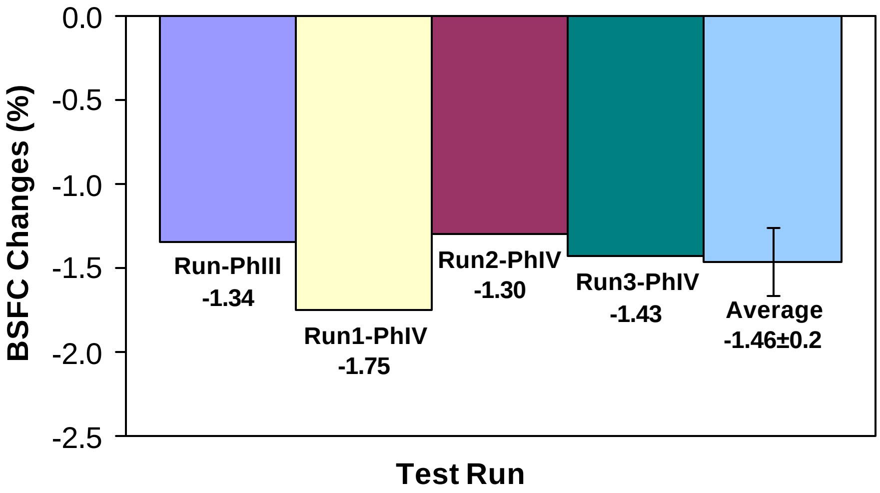


Figure 4: BSFC changes (%) of Phase III and Phase IV test runs for PEP-1A

Figure 5 gives evaluation results of emissions for the PEP-1A. Results of each of these runs show that baseline CO and smoke emissions were reduced with the device. Though an increase in NOx was experienced in the Phase III run and a reduction in NOx was experienced in the Phase IV runs, the percentage changes are within test-to-test repeatability [3] and are considered non-significant.

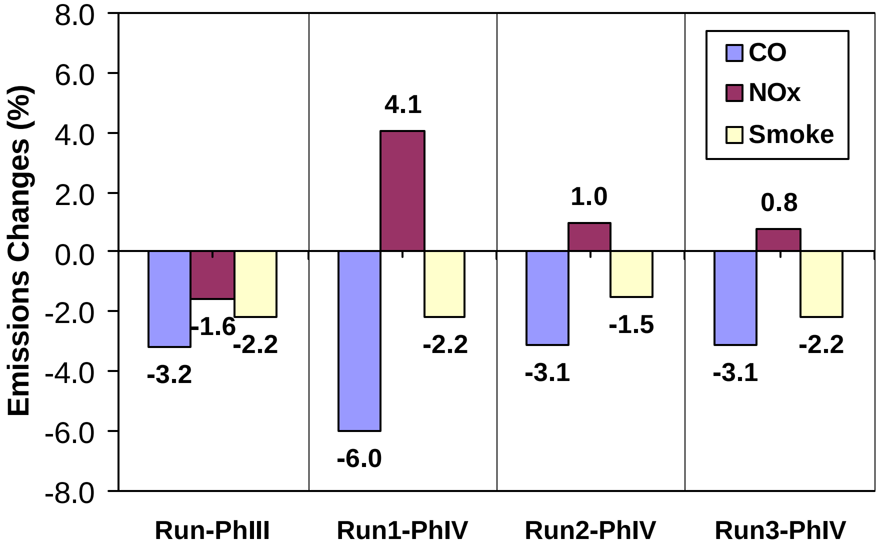


Figure 5: Emissions changes (%) of Phase III and Phase IV test runs for PEP-1A

Figures 6 and 7 present the data provided by runs on the PEP-2B. The PEP-2B improved baseline BSFC by 1.66±0.05%. The results of Phase III agree with those of Phase IV. Emissions results of Phase III (Figure 8) show the same trends as those of Phase IV. Experimental errors are responsible for variations on these percentage changes.

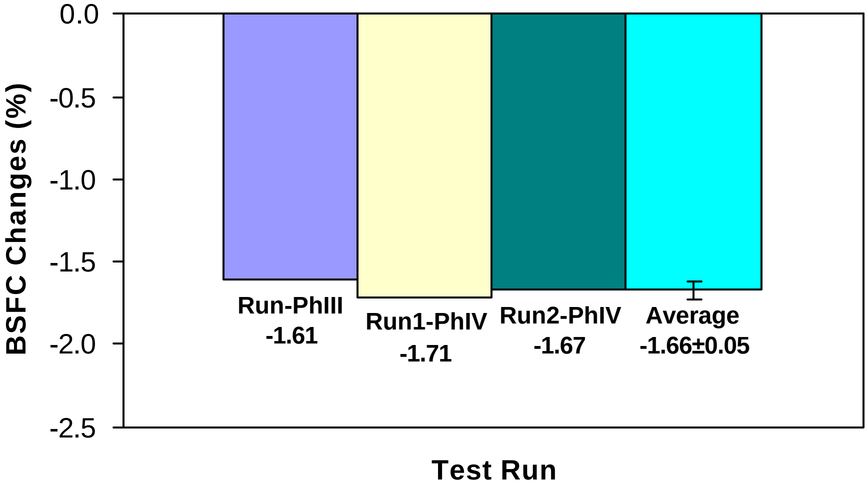


Figure 6: BSFC changes (%) of Phase III and Phase IV test runs for PEP-2B

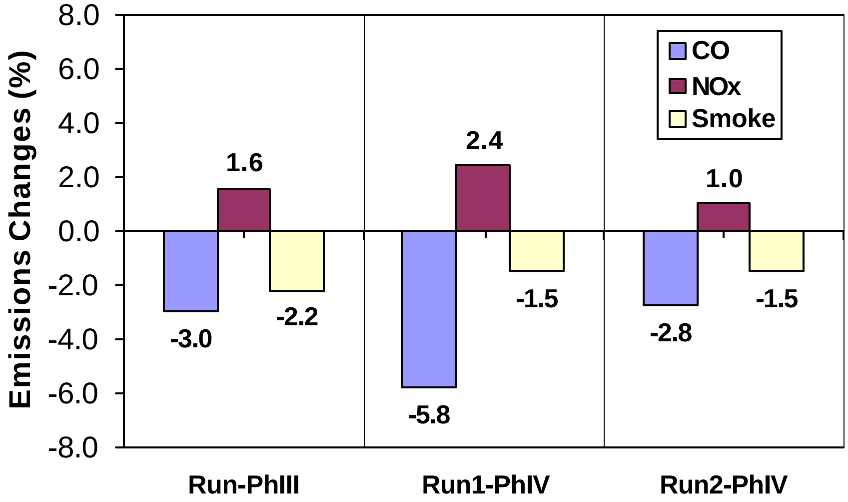


Figure 7: Emissions changes (%) of Phase III and Phase IV test runs for PEP-2B

3.4 Comparison with Other Investigator's Results

Comparison with existing test results obtained under controlled conditions may provide valuable information to the SFAT procedure. Unfortunately, there are not many published data that are obtained either under controlled conditions or for medium-speed engine applications. The only test for evaluating a fuel additive for locomotive engine applications was conducted at Southwest Research Institute (SwRI) by following the RP-503 procedure. Its results were compared to those obtained from using the present simplified procedure for the same fuel additive product (PEP-2B). The SFAT tests carried out, with the same results of SwRI, revealed non-significant effects of the additive on fuel chemical properties and engine emissions. However, both investigations suggested improvements on engine fuel BSFC (1.74% improvements were detected by SwRI and an average of 1.66% by the SFAT).

Results from the two tests might not be directly correlated since the EMD 645 is a two-stroke engine and SCRE-251 is a four-stroke engine. However, due to similar size in engine power components, the comparisons can provide preliminary information for evaluating the simplified test procedure.

3.5 Summary of Phase IV Test

Tests were carried out on the PEP-1A and PEP-2B to validate the SFAT test procedure. Triplicate runs were performed on the PEP-1A. Due to problems with an ECOM emissions analyzer sensor and the cylinder pressure transducer, only two runs were completed for the PEP-2B. However, it was enough to demonstrate repeatability of the evaluation tests with comparison of the Phase III results.

No clear advancement in fuel properties, engine emissions and combustion deposits was observed from using the PEP-1A and PEP-2B, though 1~2% improvements in BSFC were detected. Results from both the PEP-1A and PEP-2B appear to be very similar to those of Phase III. On average, the PEP-1A improved baseline BSFC by 1.46±0.2% and the PEP-2B by 1.66±0.05%. Similar evaluation results between SFAT and those of SwRI for the PEP-2B showed that reliable evaluation results can be obtained using the SFAT procedure.

4 SIMPLIFIED FUEL ADDITIVE TEST PROCEDURE

4.1 Scope

The SFAT procedure is intended to evaluate the effectiveness of engine performance-enhancing products (PEPs), including fuel additives and fuel system add-on devices, for medium-speed diesel engine use. Both positive and negative effects on engine performance, emissions and engine combustion deposits (based on observations and engineering judgments) arising from use of these products are determined from the test. The procedure provides results that may serve as one indicator to the potential user of the comparative use of an untreated fuel (or engine without an add-on device) versus that of an additive-treated fuel (or engine with an add-on device).

4.2 Evaluation Procedure

The evaluation procedure consists of two steps: fuel properties test and engine test. A flow chart of the test procedure is shown in Appendix A. These tests are organized first to determine that the additive (or add-on device) will cause no harmful effects, and second to verify the claimed benefits. Before conducting these tests, a questionnaire (Appendices B and C) is issued to the customer to obtain information for identifying the claimed benefits, recognizing any features of the PEP that may have an adverse effect on engine component and engine performance, and defining possible errors due to preparation of the evaluation test.

Step I: Fuel Properties – Standard ASTM tests for baseline and treated fuel are mandatory. Class one railroad diesel fuel is used as baseline fuel.

Step II: Single-Cylinder Engine Test – Tests are conducted on a single-cylinder research engine (for specifications see [3]) with new engine power components such as piston, rings, cylinder liner, intake and exhaust valves, and injector. The tests are conducted in a “baseline-preconditioning-product-baseline” manner. The preconditioning test is necessary for stabilizing engine performance with additive-treated fuel. After the product test, a check-up baseline test follows to verify the test results.

4.3 Fuel Property Tests (Step I)

The following physical and chemical fuel properties are 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 is 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 @ 40°C	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

4.4 SCRE Tests (Step II)

Engine power is measured either by dynamometer or by an engine-driven generator with load bank. The instruments are calibrated to an accuracy of ±2% of full scale. Engine fuel consumption is measured either by weighting scale or flow meter, and instruments are calibrated to ±1% of full scale. Emissions analyzers meeting specifications described in EPA locomotive emissions standards (40 CFR, Part 92) are used for emissions measurements. The analyzers are calibrated before a test according to the procedure recommended by manufacturer.

The test is conducted at engine full load (250 hp). Testing at additional engine operating modes is recommended and optional to customers. The test is conducted under the following engine conditions:

- Engine intake air temperature shall be controlled within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine oil sump temperature shall be controlled within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine coolant water outlet temperature shall be maintained within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine fuel temperature shall be maintained at 90±10°F, measured at the fuel supply line (or fuel filters) before the fuel pump.
- Engine intake air pressure shall be maintained within ±0.1 psi between the baseline and treated fuel tests at the same engine test modes.

The baseline test and the product test are conducted for minimum of 20 hours (at least three days). The preconditioning test is performed until stable engine conditions are obtained. A 35 hour preconditioning period (engine is operated at full load) is recommended; however, more preconditioning hours may be required due to the nature of the product. A baseline check-up test is performed to validate the evaluation test results. During the baseline and the product test, engine performance data are taken at every half-hour, and emissions (smoke, gaseous, and particulate matter) and combustion pressure data are recorded at least once midway or at the end of the tests.

Brake-specific fuel consumption (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% confidence level.

Engine emissions data is statistically analyzed to determine any changes due to the product. To investigate the effects of a product on the engine combustion process, the apparent net heat release rates are calculated from the recorded cylinder pressure data by applying the first law of thermodynamics to the content of the combustion chamber. The combustion temperatures are calculated from the cylinder pressure data by assuming a uniform temperature distribution and ideal gas within the cylinder.

5 CONCLUSIONS

The SFAT project was initiated in the hope of obtaining a test procedure that is a less expensive alternative to the existing AAR RP-503 for evaluation of PEPs for medium-speed diesel engine use. The project was divided into four phases to develop the procedure. On the basis of test results and discussions, the following conclusions were made.

a. The SCRE employs the same bore and stroke as GE 7FDL, a locomotive engine extensively used in North America and currently used by the Southwest Research

Institute (SwRI) for the AAR RP-503 evaluation procedure. It is representative of four-stroke multi-cylinder railway, marine and small power-plant diesel engines. With unique engine design features and many standard engine components the test facility centred around the SCRE can establish representative conditions that are directly related to an actual four-stroke medium-speed locomotive diesel engine. The SCRE has the flexibility of satisfying various research studies that were performed without major modifications to the engine. The engine component is accessible, without the need to remove unrelated items, and enables precise instrumentation. Testing systems can be set up quickly for an evaluation test and maintenance is much easier than that of the multi-cylinder engine. Unlike the AAR RP-503 procedure, the single-cylinder engine used in the SFAT requires less consumables (fuel, lubricating oil, etc.) for completion of an evaluation test, especially for tests conducted at different test modes. The SCRE facility is a useful platform for accurate PEP evaluation tests because of its flexibility in control, precise in-engine instrumentation, and lower operating cost, especially for the evaluation of an enhancing product for a medium-speed diesel engine used in rail, marine and stationary applications.

b. Stability of the SCRE facility was investigated through a repeatability analysis of controlled engine operating parameters, fuel consumption and emissions measurements. Engine operating parameters are largely dependent on the characteristics of engine systems design and control of instrumentation. As a powerful tool for medium-speed diesel engine research and development, the SCRE testing system has special design features, such as the fact that the engine intake air is supplied by an external compressor, which is designed to simulate the turbocharger pressure of locomotive engine. Because these are externally controlled, the reliability and accuracy of these devices and their control systems are the main factors in the stability of engine operating parameters. Overall measurement uncertainty of a system was experimentally determined by investigating the tolerance limit of controlled engine operating parameters. Results indicated that the tolerance limits of controlled engine operating parameters are within those specified in the AAR RP-503. Repeatability of engine measurements under controlled conditions is considered critical for evaluating fuel additives, since it represents precision of the measurement process. Unrepeatable data demonstrate errors in the magnitude of measurement, data recording or experimental equipment. In this project, engine power output was maintained constant and fuel consumption and emissions changes were used as indicators of performance of a PEP. Baseline fuel tests were conducted to investigate the repeatability of fuel consumption and emissions measurements. The testing system was proved to be effective in determining a minimum of 1% change in the BSFC and a minimum 5% (on average) in exhaust emissions.

c. The preliminary test procedure was proposed for evaluation of a PEP. It was verified through testing on eight aftermarket PEPs: three engine add-on devices, three fuel additives and two lube oil additives. The verification test results suggested that 75 hours of engine testing, including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of performance testing would be enough for an evaluation of fuel additives and fuel system add-on devices. In addition, no experimental evidence has come from studies of the same test sequence as being suitable for the evaluation of oil additives and oil system add-on devices.

d. The test procedure was validated and fine-tuned in Phase IV of the project by conducting repeated tests on a fuel additive and a fuel system add-on device, which were tested in Phase III. Test results showed good agreements with those of the verification tests (Phase III) for the same products. Additionally, test data obtained for the fuel additive appears to be very similar to those reported previously by Markworth [4]. These findings confirm that the SFAT procedure is reliable for the evaluation of fuel additives or engine add-on devices.

e. The finalized procedure is intended to evaluate the effectiveness, and ineffectiveness, of fuel additives and engine fuel system add-on devices for medium-speed diesel engine use. The test procedure consists of fuel property tests to determine whether a product causes harmful effects to the engine, and SCRE tests for verifying the claimed benefits. Before an evaluation test, a questionnaire form is issued to the customer to obtain product information. The engine test is a minimum of 75 hours at engine full load, including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of performance testing. The baseline check-up test is performed to verify that the same baseline as obtained before the test can be obtained after the performance test. Generally, more confidence in the test results is established by this back-to-back comparison test. New engine power components and fuel injector are used for the engine test. Combustion deposit and wear conditions are determined using a bore-scope detector and engineering judgment. Product performance was different on different engine test modes. Therefore, multi-mode tests are strongly recommended to fully evaluate the product.

f. The SFAT provides to potential users preliminary comparison results of using a fuel additive or an engine fuel system add-on device. The final procedure has proved to be useful in conducting evaluation tests of the product at low cost and high efficiency.

g. The procedure was submitted to SwRI and AAR for approval. Their feedback indicated a good possibility that the procedure would be adopted partially by the AAR for locomotive fuel additive evaluations.

6 RECOMMENDATIONS

Gaseous and smoke exhaust emissions were measured during the evaluation tests. However, particulate emissions data could not be obtained due to the absence of testing equipment. It is therefore recommended that a particulate measuring system be developed and that evaluation tests on a fuel additive be conducted.

REFERENCES

1. S. Lister, R. Hunginger and A. Taghizadeh, "Feasibility of a Simplified Fuel Additive Evaluation Protocol", Transportation Development Centre, Transport Canada, TP 13215E, 1998.

2. A. Taghizadeh, M. Payne, F. Su and M. Vasquez, "Simplified Fuel Additive Test Phase II: Procedure Development and Methodology", Transportation Development Centre, Transport Canada, TP 13494E, 1999.

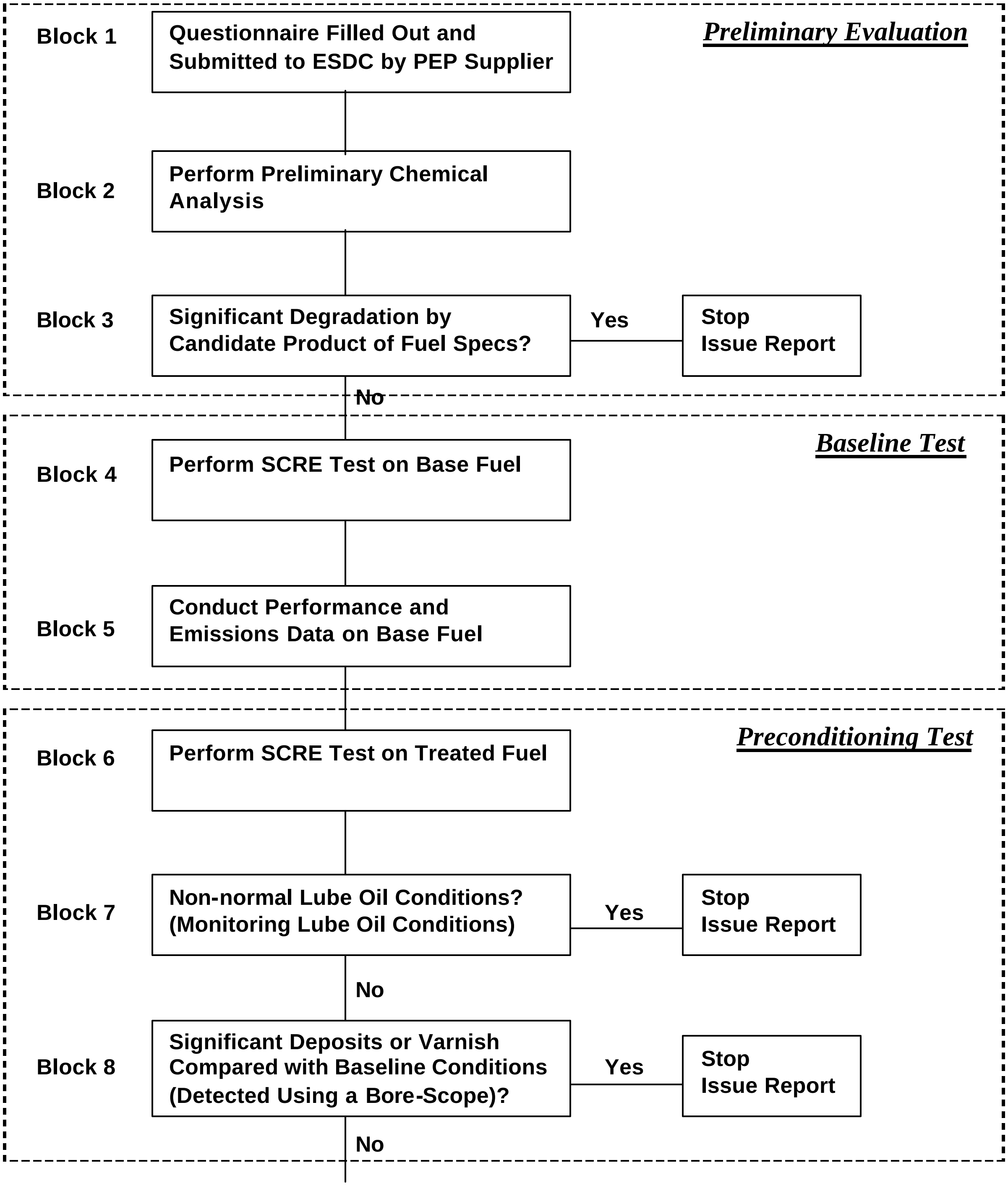
3. F. Su, M. Payne, M. Vasquez and A. Taghizadeh, "Simplified Additive Test Phase III: Testing and Verification", Transportation Development Centre, Transport Canada, TP 13823E, 2001.

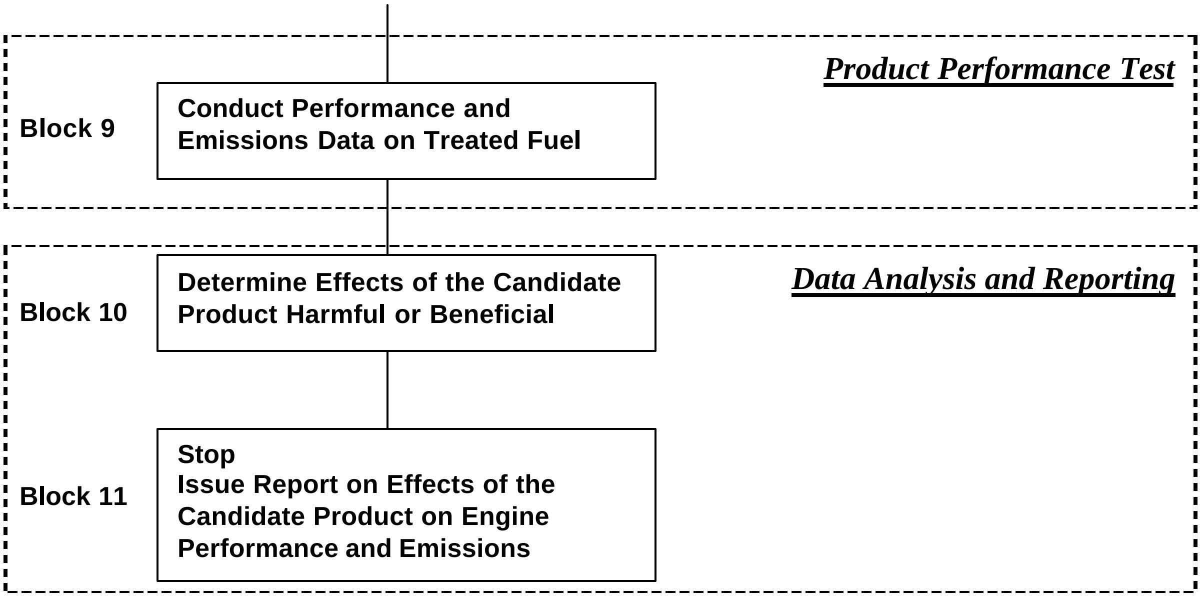
4. V. Markworth, "Evaluation of a Fuel Additives – Final Report", Vol. 1, SwRI report, July 1992.

APPENDIX A:

FLOW CHART OF RECOMMENDED SFAT EVALUATION PROCEDURE

Evaluation Test Flow Chart:





Explanation of the Flow Chart:

Preliminary Evaluation – includes three blocks (Block 1 to Block 3). Each block is described as below:

Block 1 - The procedure is initiated by issuing a questionnaire to the PEP manufacturer. The purpose is to identify the claims made by the manufacturer and to recognize any adverse effects of the PEP on engine components and performance.

Block 2 - Preliminary chemical analyses are performed on both base and treated fuel. These tests are used to evaluate the quality of treated fuel relative to that of untreated fuel and its suitability for engine testing. The required tests should evaluate the fuel for its ignition quality and combustion roughness, storability, contribution to engine deposits, and corrosiveness.

Block 3 - The gathered information from Block 2 tests enable ESDC to approve or reject an engine test.

Baseline Test – includes Blocks 4 and 5. Before the baseline test, deposit (or varnish) conditions are recorded using a bore-scope for engine piston, liner, intake valves and exhaust valves.

Block 4 - If the treated fuel is approved in Block 3, a baseline test is conducted for the engine operating with base fuel at the designed test mode. Otherwise, the evaluation procedure is stopped and a report issued.

Block 5 - During the baseline test, the engine performance and exhaust emissions are measured on untreated fuel.

Preconditioning Test – Blocks 6 to 8 are conducted during the preconditioning period.

Block 6 - The baseline test is followed by a preconditioning test with the treated fuel.

Block 7 - During this test, engine lube oil conditions are monitored by periodically analyzing oil samples. Oil properties, such as viscosity and concentration of metal components, are used to determine normal or non-normal conditions. If non-normal conditions are observed, the test is stopped.

Block 8 - After completion of this test, deposit (or varnish) conditions of engine piston, liner, intake values and exhaust values are detected using the bore-scope to compare to the baseline data. If the deposit (or varnish) is significant, the test is stopped. This test is based on observations and engineering judgments.

Product Performance Test – After the preconditioning test, the product performance test is conducted.

Block 9 - The engine performance and exhaust emissions are measured on treated fuel. During this test, the engine operating conditions are maintained the same as those of the baseline test.

Data Analysis and Reporting – Data is analyzed (Block 10) and reported (Block 11) in this part.

Block 10 - Results of the product performance test are compared to those of the baseline test to determine the effects of the product on engine performance and emissions, and thereby evaluate the claimed benefits.

Block 11 - A comprehensive test report is issued to give observations, discussions and conclusions on the effects of the product on engine performance and emissions.

APPENDIX B:
DIESEL FUEL ADDITIVE QUESTIONNAIRE FOR EVALUATION PROCEDURE

Complete and send the questionnaire, along with existing data pertinent to the additive's effects, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY OR PATENT NAME: ______________________________

ADDRESS & PHONE NO.: ______________________________

____

____

PERSON TO CONTACT: ______________________________

ADDITIVE NAME OR CODE: ______________________________

ADDITIVE DESCRIPTION AND CATEGORY (CLEANER, CATALYST, ETC.):

____

____

____

What are the additive's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

____

____

____

(2) EXHAUST EMISSIONS (Including Smoke and Particulate Emissions)

____

____

(3) COMBUSTION DEPOSITS (Including Sparking)

____

____

(4) LUBE OIL

____

____

____

(5) WEAR

____

(6) FUEL SYSTEM

What are the effects of the additive on the following diesel fuel properties?

(1) Cetane Number:

(2) Viscosity:

(3) API Gravity:

(4) Distillation Range:

(5) Sulfur Content:

(6) Carbon Residue:

(7) Flash Point:

(8) Cloud Point:

(9) Pour Point:

(10) Ash Content:

(11) Corrosiveness:

(12) Aromatics:

(13) Filterability:

(14) Water Absorption: ____________________

(15) Stability: ____________________

(16) Foaming: ____________________

(17) Bacterial Resistance: ____________________

(18) Vapor Pressure: ____________________

(19) Miscibility Limits: ____________________

What are the effects of the additive on polymers, filter media and other fuel system components?

____

____

How is this additive used?

(1) How is it mixed with diesel fuel? ____________________

____

(2) In what proportions? ____________________

____

(3) How stable is the mixture? ____________________

____

(4) How long is the mixture storable? ____________________

____

(5) MSDS for safe handling

____

How does the additive react with winder fuel?

How stable is the additive itself?

Does the additive contain any zinc?

Are there any chemicals, elements, or physical conditions that can neutralize or otherwise influence the effectiveness of the additive? If so, describe in detail on a separate sheet.
What are the claimed effects of the additive? (Attach any pertinent material.)

What tests have been conducted to substantiate these claims? (Attach any pertinent material.)

What were the results of these tests? (Include formal report issued.)

Where were these tests performed?

Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.

APPENDIX C:
QUESTIONNAIRE FOR ENGINE FUEL SYSTEM ADD-ON DEVICE EVALUATION PROCEDURE

Complete and return questionnaire, along with existing data pertinent to the effects of the add-on device, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY OR PATENT NAME:

ADDRESS & PHONE NO.:

PERSON TO CONTACT:

ADD-ON DEVICE NAME OR CODE:

DESCRIPTION OF THE DEVICE:

What are the device's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

(2) EXHAUST EMISSIONS (Including Smoke and Particulate Emissions)

(3) COMBUSTION DEPOSITS (Including Sparking)

(4) LUBE OIL

(5) WEAR

(6) FUEL SYSTEM

What are the effects of the add-on device on the following diesel fuel properties (if the device is for engine fuel system)?

(1) Cetane Number:

(2) Viscosity:

(3) API Gravity:

(4) Distillation Range:

(5) Sulfur Content:

(6) Carbon Residue:

(7) Flash Point:

(8) Cloud Point:

(9) Pour Point:

(10) Ash Content:

(11) Corrosiveness: ____

(12) Filterability: ____

(13) Water Absorption: ____

(14) Stability: ____

(15) Foaming: ____

(16) Bacterial Resistance: ____

(17) Vapor Pressure: ____

(18) Miscibility Limits: ____

What are the effects of the add-on device on the following lubricant oil properties (if the device is for engine lube oil system)?

(1) Viscosity: ____

(2) Viscosity Index: ____

(3) API Gravity: ____

(4) Flash Point: ____

(5) Fire Point: ____

(6) Pour Point: ____

(7) Zinc Content: ____

(8) Total Base Number: ______________________________

(9) Corrosiveness: ______________________________

(10) Anti-Foaming: ______________________________

How is this add-on device used?

(1) How is the device installed?

____

____

(2) Are there special requirements for operation of the device?

____

____

Are there any chemicals, elements, or physical conditions that can influence the effectiveness of the device? If so, describe in detail on a separate sheet.

What are the claimed effects of the device? (Attach any pertinent material.)

____

____

____

What tests have been conducted to substantiate these claims? (Attach any pertinent material.)

____

____

What were the results of these tests? (Include formal report issued.)

____

____

Where were these tests performed?

____

____

Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.