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A Study of Dimethyl Ether (DME) as an Alternative Fuel for Diesel Engine Applications

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by
Advanced Engine Technology Ltd.

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by
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16. Abstract

Advanced Engine Technology Ltd., in a government/industry cooperative study, investigated the feasibility of developing a cost-effective, low-emissions fuel system for the alternative fuel dimethyl ether (DME) for use in compression ignition (CI) engines. A Bosch fuel injection system for a 5.9-litre Cummins diesel engine (Dodge Ram pickup truck) was modified for use with DME.

Engine testing indicated comparable peak engine torque and power for DME and diesel operation. Peak combustion pressures, rates of combustion pressure rise, and audible engine combustion noise were low for DME operation.

ISO 8-mode steady state emissions tests indicated a reduction in oxides of nitrogen emissions (5.9 percent), particulate emissions (75 percent), ethylene and propylene emissions, and four of five unregulated emissions. Methane and total hydrocarbon (THC) emissions were low, although higher than for diesel operation. THC emissions were primarily in the form of unburned DME, which has very low toxicity and is environmentally benign relative to hydrocarbons from diesel fuel.

Further significant reductions in exhaust emissions could be achieved by optimizing the DME injection/combustion systems, incorporating an exhaust gas recirculation system, and installing a more effective exhaust catalyst. DME-fuelled CI engines may also provide a low-emissions alternative to spark ignition engines.

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16. Résumé

Advanced Engine Technology Ltd. a étudié, dans le cadre d'une recherche coopérative réunissant le gouvernement et l'industrie, la faisabilité de développer un circuit d'alimentation économique et à faible niveau d'émissions pour le diméthyléther (DME), un carburant de substitution destiné aux moteurs à allumage par compression. Un système d'injection Bosch, conçu pour un moteur diesel Cummins de 5,9 L (équipant une camionnette Dodge Ram), a été modifié pour être utilisé avec du DME.

Les essais ont révélé un couple moteur et une puissance de pointe comparables, que le moteur brûle du diesel ou du DME. Les pressions de combustion, les taux d'accroissement de pression de combustion et le bruit audible produit par la combustion étaient relativement faibles lorsque le moteur brûlait du DME.

Des essais de contrôle des émissions en huit modes de régime permanent (homologués ISO) ont révélé, dans le cas du DME, une réduction des émissions d'oxydes d'azote (5,9 p. 100), de particules (75 p. 100), d'éthylène et de propylène, et de quatre gaz non réglementés sur cinq. Les émissions de méthane et d'hydrocarbures totaux (HT) étaient faibles, mais supérieures aux émissions mesurées avec du diesel. Les émissions d'HT étaient principalement sous forme de DME imbrûlé, lequel est très peu toxique et inoffensif pour l'environnement, comparé aux hydrocarbures rejetés par le carburant diesel.

Il serait possible de diminuer encore de façon importante les émissions de gaz polluants, pour peu que l'on optimise les systèmes d'injection et de combustion du DME et que l'on dote le moteur d'un système de recyclage des gaz d'échappement et d'un catalyseur plus efficace. Les moteurs à combustion interne alimentés au DME peuvent également constituer une solution de rechange propre aux moteurs à allumage commandé.

17. Mots clés
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EXECUTIVE SUMMARY

New regulations aimed at lowering diesel engine emissions levels are being implemented in most industrialized countries. In North America, both the U.S. Environmental Protection Agency and the California Air Resources Board have adopted emissions limits covering the full range of engine sizes. As emissions standards continue to be tightened, substantial engine research and development will be required to reduce diesel engine exhaust emissions levels. Early indications are that expensive engine/fuel injection equipment modifications and emissions equipment will be required if compression ignition (CI) engines are to continue operating on conventional diesel fuel.

Alternative fuels have been considered as a replacement for diesel fuel in CI engines. One fuel in particular, dimethyl ether (DME), has shown promise. Early test results indicate that fuelling CI engines with DME instead of diesel fuel would allow the 1998 California Ultra Low Emission Vehicle emissions standard to be met without the addition of expensive emissions systems. DME operation results in near zero particulate (smoke) emissions, low oxides of nitrogen (NO_x) emissions and considerably reduced combustion noise levels.

In an effort to acquire additional information regarding the potential use of DME, the Transportation Energy Technology Division of Natural Resources Canada contracted Advanced Engine Technology Ltd. (AET) to perform a literature search in conjunction with limited in-house testing of DME (Phase I). AET was also contracted by the Transportation Development Centre (TDC) of Transport Canada to determine the safety considerations of operating a diesel engine on DME.

A Phase II federal government/industry cooperative study, based on the Phase I recommendations, was initiated. The main objectives of the Phase II study were to:

- determine the exhaust emissions characteristics of a light-duty diesel engine operating on liquid DME;
- determine the feasibility of modifying a light-duty mechanical fuel injection system to permit DME to be injected as a liquid;
- investigate combustion parameters with regard to combustion and exhaust emissions characteristics for a light-duty diesel engine operating on DME;
- determine the major safety concerns and develop preliminary safety-related design guidelines for a DME-fuelled, light-duty diesel engine vehicle fuel system;
- develop a knowledge base of DME physical properties and related fuel handling/storage considerations.

A 5.9-litre, turbocharged, intercooled Cummins diesel engine (direct injection/exhaust catalyst) from a Dodge Ram pickup truck was acquired and installed in AET's test cell #2 for test purposes. The test cell and engine fuel systems were fabricated based on the safety-related guidelines established in the DME safety study. Initially, one cylinder of the six-cylinder engine was fuelled with DME while the remaining five cylinders were fuelled with diesel fuel. Several sensors were used to allow engine temperatures and pressures to be monitored by a computer data acquisition system (DAS).

Additional safety guidelines were developed based on conclusions drawn from ongoing testing of a 5.9-litre Cummins turbocharged diesel engine operating on DME. A failure mode and effect analysis of the laboratory test engine and potential vehicle fuel system was conducted by AET for the International Energy Agency workshops on DME. The test cell fuel system was designed to minimize the potential for DME leakage into the engine's cylinders, crankcase lubricating oil sump, fuel injection pump and the atmosphere, as well as to minimize the possibility of a fire/explosion.

DME is known to adversely affect many types of plastics and rubbers, with the exception of PTFE (Teflon^{TM}) and butyl-n (Buna-N^{TM}) rubber. However, it was found that DME also generates very low temperatures upon vaporization and temperature cycling of PTFE causes embrittlement, which may lead to valve seal failure. In a fire situation both materials may melt, causing the seal to fail. It was concluded that metal-to-metal seals using non-sparking metals would be the most effective type of seal. The safety valves used on the Cummins engine were quarter-turn ball valves with graph-oil packing, chosen because of their high temperature resistance.

Based on the vehicle fuel system design, efforts were made to determine whether the injector nozzles would leak DME from the high-pressure fuel line upon engine shutdown. Preliminary injection nozzle leakdown testing was performed on new injection nozzles to determine the mass leak rate of DME past the injection nozzle needle and seat valve during the TDC DME safety study. It was determined that at pressures from 687 to 4000 kPa and temperatures from 22 to 290 C, the injection nozzle did not leak measurable quantities of DME. Efforts were undertaken to repeat the leak rate test using worn injection nozzles (90 percent of the expected useful lifetime). Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected and plotted versus time using a computer DAS. Efforts were also made to allow more accurate thermal cycling of the injectors. Injector temperatures could then be correlated with DME leak rates using the DAS. It is anticipated that measurable DME leakage may occur under these conditions.

Design of the DME fuel system for one cylinder of the engine was carried out using computer-aided design software. The Bosch fuel injection pump operated on diesel fuel in the normal manner; however, the diesel fuel passing through the pump was not injected into the cylinder of the engine for combustion purposes. The diesel fuel served only as a pumping medium and was not consumed during engine operation. A shuttle valve was used to transfer the pumping action from the diesel fuel injection pump to the DME in the high-pressure fuel injection line. A high-pressure check valve was used to regulate DME flow from the low-pressure fuel supply line to the high-pressure fuel injection line.

Significant effort was directed at overcoming difficulties with DME leakage in the fuel injection system and at modifying the fuel system to provide the appropriate injection characteristics. Difficulties were encountered during much of the ongoing engine test program with DME leakage past the check valve and shuttle valve systems. Several discussions with the valve manufacturers were held to solve the DME leakage problem. Significant redesign and fabrication of the shuttle valve system was required to minimize DME leakage and provide improved sealing. The fabricated shuttle valve system, with a high-pressure lubrication system and improved check valve design, significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods over the entire range of engine speeds and loads with consistent DME injection.

Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests carried out on AET's mass leak rate measuring system using new, unused injection nozzle indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550 F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

Upon successful operation of the engine on one DME-fuelled cylinder, the remaining five cylinders were converted to operate on DME. Peak output torque/power from the DME-fuelled engine was the same as for operation on diesel fuel. In addition, low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation. The engine was then transported to Environment Canada (EC) for AVL LIST GMBH 8 mode steady state emissions testing. Emissions testing was performed with the engine operating on DME and on diesel fuel.

Based on EC emissions results, operation on DME resulted in a reduction in regulated exhaust emissions with the exception of total hydrocarbons (THC), which were primarily in the form of unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME emissions. It is anticipated that further significant reductions in NO_x could be attained for DME operation by optimizing the fuel injection timing for low NO_x emissions, as was done by the engine manufacturer for diesel fuel operation.

Particulate matter (PM) emissions were reduced by 75 percent for DME operation. The very low particulate emission levels may be attributed to normal minute rates of crankcase lubricating oil consumption. It is anticipated that a cleaner burning crankcase lubricating oil formulation could be employed to further reduce PM and THC emissions. Low PM emissions for DME operation would reduce particulate contamination of the engine lubricating oil.

Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels, and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel are typically very low. It is anticipated that a properly sized exhaust gas oxidation catalyst would reduce the toxic non-regulated emissions.

Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.

Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

In conclusion, DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emission regulations. Significant reductions in many regulated and unregulated exhaust emissions were observed for DME operation without performing additional engine modifications directed at lowering emissions. It is anticipated that further reductions in NO_x , THC (as unburned DME), formaldehyde and methane emissions could be obtained. With regard to vehicle operation on DME, there is a need to incorporate additional fuel handling/supply safety precautions to minimize the potential for fire or explosion. DME is significantly more flammable (lower flashpoint temperature and lower auto-ignition temperature) and volatile than diesel fuel. DME fuel system components such as valves, lines and fittings should be constructed from non-sparking metals such as stainless steel or brass to minimize the possibility of generating a spark, which might lead to a fire situation. In addition, it would be necessary to ground the DME fuel tank and fuel lines to prevent electrostatic charge buildup and a potential spark discharge.

It is anticipated that further significant reductions in exhaust emissions can be realized by optimizing the DME injection/combustion systems, incorporating an exhaust gas recirculation (EGR) system and installing a more effective exhaust catalyst. Due to very low PM emissions, large quantities of EGR could be implemented for DME operation without incurring engine reliability penalties associated with high levels of PM entering the combustion chamber.

It is recommended that the following tasks be performed to further reduce the DME exhaust emissions:

1) Re-assemble the DME fuel system for the 5.9-litre Cummins engine and install the engine on the EC dynamometer in preparation for further emissions testing.

2) Install a PC-based weigh scale and associated components to allow fuel consumption rates to be determined.

3) Modify the DME injection timing to reduce NO_x emissions.

4) Modify the intake/exhaust system to incorporate EGR for NO_x reduction purposes.

5) Acquire information on various types of exhaust catalysts to determine whether there is potential to reduce NO_x, unburned DME and toxic non-regulated emissions using a specialized catalyst for DME operation.

6) Investigate the potential for reducing methane emissions.

7) Perform additional DME emissions testing implementing information and hardware arising from Tasks 1 to 5.

SOMMAIRE

La plupart des pays industrialisés mettent en place de nouveaux règlements qui visent à diminuer les niveaux d'émissions des moteurs diesel. En Amérique du Nord, l'Environmental Protection Agency (EPA) des États-Unis et le California Air Resources Board ont établi des limites d'émissions couvrant tous les types de moteurs. Ce resserrement continu des normes touchant les émissions ne peut aller sans d'intenses travaux de recherche et développement destinés à réduire les niveaux d'émission des moteurs diesel. À première vue, tout indique que, pour qu'ils puissent continuer à brûler du carburant diesel classique, les véhicules équipés d'un moteur à allumage par compression devront être l'objet de mesures coûteuses, qu'il s'agisse d'en modifier le moteur et le système d'injection ou de les doter de dispositifs antipollution.

Une solution consiste à recourir à un autre carburant, plus propre que le diesel, pour alimenter les moteurs à allumage par compression. Un carburant de substitution, le diméthyléther (DME), s'est révélé particulièrement prometteur. Selon les résultats des premiers essais, les moteurs à allumage par compression brûlant du DME plutôt que du diesel respecteraient les limites d'émissions des véhicules établies par la Californie en 1998, sans qu'il soit nécessaire de les doter de coûteux systèmes antipollution. En effet, un moteur brûlant du DME produit peu ou pas de particules (fumée), peu d'oxydes d'azote (NO_x) et ses niveaux de bruit de combustion sont considérablement réduits.

Souhaitant en savoir plus sur le potentiel du DME en tant que carburant de substitution, la Division des technologies de l'énergétique dans les transports de Ressources naturelles Canada a demandé à Advanced Engine Technology Ltd. (AET) d'effectuer une recherche documentaire et de mener des essais limités à l'interne sur le DME (phase I). AET a également reçu le mandat du Centre de développement des transports (CDT) de Transports Canada d'évaluer les incidences sur la sécurité de la conversion d'un moteur diesel au DME.

Une étude menée en commun par le gouvernement fédéral et l'industrie a ensuite été entreprise, pour donner suite aux recommandations de la phase 1. Voici les principaux objectifs assignés à cette étude :

- caractériser les émissions d'un moteur diesel pour camion léger brûlant du DME liquide;
- étudier la possibilité de modifier le système d'injection mécanique pour camion léger pour permettre l'injection de DME sous forme liquide;
- étudier les paramètres de combustion influant sur les résidus de combustion et les gaz d'échappement d'un moteur diesel pour camion léger brûlant du DME;
- déterminer les principales incidences sur la sécurité associées à l'utilisation de DME et établir des lignes directrices préliminaires visant la conception d'un circuit d'alimentation de moteur diesel pour camion léger alimenté au DME;

- constituer une base de connaissances concernant les propriétés physiques du DME et les incidences de celles-ci sur la manutention et le stockage de ce carburant.

Un moteur diesel turbocompressé Cummins de 5,9 L, à échangeur thermique (injection directe/catalyseur), qui équipe normalement une camionnette Dodge Ram, a été acheté et monté sur le banc d'essai n^{o} 2 de AET. Pour le montage du moteur et le raccordement du circuit d'alimentation, les chercheurs ont respecté les lignes directrices en matière de sécurité issues de l'étude sur les incidences du DME sur la sécurité. Dans un premier temps, un seul des six cylindres du moteur était alimenté au DME (les cinq autres étaient alimentés au diesel). Plusieurs capteurs mesuraient les températures et les pressions à l'intérieur du moteur, et relayaient l'information à un système automatisé d'acquisition des données.

Des mesures de sécurité supplémentaires ont été élaborées à la lumière des résultats d'essais continus d'un moteur diesel turbocompressé Cummins de 5,9 L brûlant du DME. Une analyse des modes de panne et de leurs effets effectuée sur le moteur d'essai équipé de différents circuits d'alimentation potentiels a été effectuée par AET, en vue d'ateliers sur le DME organisés par l'Agence internationale de l'énergie. Le circuit d'alimentation du banc d'essai a été conçu de façon à minimiser les risques de fuite de DME dans les cylindres, la conduite de retour d'huile du carter, la pompe d'injection et l'atmosphère, et à minimiser les risques d'incendie et d'explosion.

Le DME est reconnu pour causer la détérioration de nombreux élastomères. Font exception le PTFE (Teflon^{MD}) et le butyl-n (Buna-N^{MD}). Mais il a été constaté que la vaporisation du DME s'accompagne d'une forte baisse de température et que les fluctuations répétées de température rendent le PTFE friable, ce qui compromet l'étanchéité des joints. En cas de feu, tant le PTFE que le butyl-n risquent de fondre, entraînant la perte d'étanchéité. D'où il a été conclu que les meilleurs joints seraient des joints métal/métal, pour autant que le métal utilisé ne produise pas d'étincelles. Les robinets d'arrêt d'urgence équipant le moteur Cummins étaient des robinets à boule quart-de-tour avec garnitures à l'huile graphitée, choisis en raison de leur capacité de résister à des températures élevées.

Les chercheurs ont tenté de déterminer le risque de fuite de DME par les injecteurs du circuit d'alimentation haute pression, une fois le moteur coupé. Au cours de l'étude du CDT sur les incidences du DME sur la sécurité, un nouvel injecteur a été soumis à des essais d'étanchéité qui visaient à déterminer le débit de fuite, en masse, de DME au delà de l'aiguille et du siège de l'injecteur : à des pressions de 687 à 4 000 kPa et à des températures de 22 à 290 □C, les fuites de DME se sont révélées négligeables. Les essais d'étanchéité ont alors été repris avec des injecteurs usagés (à 90 p. 100 de leur durée de vie utile). Des modifications importantes ont été apportées au système de mesure du débit de fuite en masse, afin de permettre la détection de débits minimes de fuite de DME en fonction du temps, à l'aide d'un système automatisé d'acquisition des données. Les chercheurs ont également tenté de rendre plus précis les cycles thermiques des injecteurs. La température des injecteurs pouvait alors être mise en rapport avec les débits de fuite de DME, toujours grâce au système automatisé d'acquisition des données. On pense qu'un fuite perceptible de DME est prévisible dans ces conditions.

Les chercheurs ont eu recours à un logiciel de conception assistée par ordinateur pour étudier le circuit d'alimentation en DME d'un seul cylindre du moteur. Pour ce qui est des autres cylindres fonctionnant au diesel, ils étaient alimentés de la manière habituelle par la pompe d'injection Bosch; mais le carburant diesel ainsi injecté n'était pas brûlé par le moteur : il ne servait que de support de pompage. Un piston d'injection a été utilisé pour communiquer l'effet de pompage de la pompe d'injection du carburant diesel au DME se trouvant dans la tuyauterie d'injection haute pression. Un clapet anti-retour haute pression régulait le débit de DME passant de la tuyauterie d'alimentation basse pression à la tuyauterie d'injection haute pression.

D'intenses efforts ont été déployés pour solutionner le problème des fuites de DME dans le système d'injection et pour adapter le circuit d'alimentation au DME. Pendant la plupart des essais continus sur moteur, des fuites de DME ont été constatées au delà du clapet anti-retour et du piston d'injection. Des consultations ont eu lieu avec les fabricants de ces appareils pour tenter de solutionner le problème. Il a fallu complètement repenser le piston d'injection de façon à en améliorer l'étanchéité et à minimiser ainsi les fuites de DME. Le nouveau piston, combiné à un système de lubrification haute pression et à un clapet anti-retour perfectionné, a grandement amélioré l'injection : le moteur peut tourner pendant de longues périodes, dans un large éventail de régimes et de charges, l'injection de DME demeurant constante.

Des modifications importantes ont été apportées au système de mesure du débit de fuite en masse, afin qu'il soit possible de détecter les moindres débits de fuite de DME. Des efforts ont également été déployés pour accroître la précision des cycles thermiques des injecteurs. Des mesures de débit de fuite de DME faites au moyen d'un système AET sur un injecteur neuf n'ont révélé aucune fuite mesurable de DME à des pressions allant jusqu'à 600 lb/po^2 (à température ambiante) et à des températures atteignant 550 °F (à une pression de 150 lb/po^2). Les essais de débit de fuite mettant en jeu des injecteurs usagés (à 90 p. 100 de leur durée de vie utile) n'ont pas, non plus, révélé de fuite mesurable de DME. Tout indique, donc, que les fuites de DME dans les cylindres, au delà des injecteurs, seraient négligeables, et qu'il n'y a pas lieu de craindre des problèmes associés à la présence de vapeur de DME dans les cylindres, une fois le moteur coupé.

L'essai du moteur à un cylindre alimenté au DME ayant été concluant, les cinq autres cylindres ont été convertis au DME. Le couple moteur et la puissance de pointe du moteur «tout DME» se sont avérés les mêmes que lorsque le moteur brûlait du carburant diesel. De plus, les pressions de combustion et les taux d'accroissement de la pression dans les cylindres étaient faibles. Le moteur a alors été transporté aux installations d'Environnement Canada (EC) pour y subir l'essai de contrôle des émissions en régime permanent selon huit modes conçu par AVL LIST GMBH. Le moteur a été mis à l'essai alors qu'il brûlait tour à tour du DME et du diesel.

Selon les résultats des essais menés dans les installations d'EC, le moteur brûlant du DME rejette moins de gaz d'échappement réglementés, si ce n'est des hydrocarbures totaux, qui se présentent surtout sous la forme de DME imbrûlé. Le DME est considéré comme étant très peu toxique et inoffensif pour l'environnement. Des recherches supplémentaires sur les catalyseurs pourraient ouvrir la voie à une réduction des émissions de DME imbrûlé. D'autres diminutions importantes des émissions de NO_x seraient possibles, pour peu que l'on optimise l'avance à l'injection en fonction d'une diminution des émissions de NO_x, comme l'a fait le fabricant du moteur pour mieux l'adapter à la combustion de diesel.

Le moteur fonctionnant au DME a émis 75 p. 100 moins de particules que lorsqu'il brûlait du diesel. Ces niveaux très faibles peuvent être attribués à la consommation minime d'huile de lubrification. On peut penser que l'utilisation d'une huile de lubrification produisant moins de résidus en brûlant réduirait encore plus les émissions de particules et de HT. En outre, le moteur alimenté en DME émettant peu de particules, il s'ensuivrait une diminution de la contamination de l'huile de lubrification par des particules.

Sur cinq gaz d'échappement toxiques non réglementés mesurés au cours des essais, quatre ont été substantiellement réduits lorsque le moteur brûlait du DME. Ainsi, les émissions d'acétaldéhyde ont été réduites de 79 p. 100, celles d'acétone, de 77 p. 100, et celles d'acrylaldéhyde et de propionaldéhyde étaient devenues négligeables. Quant aux émissions de formaldéhyde, elles ont augmenté de 382 p. 100; il faut toutefois noter que les émissions de formaldéhyde sont toujours très faibles de la part de moteurs brûlant du carburant diesel. Un convertisseur catalytique d'oxydation correctement dimensionné devrait permettre de réduire les émissions toxiques non réglementées.

Les émissions de méthane (gaz à effet de serre) ont été plus importantes dans le cas du DME que du carburant diesel. Mais, encore une fois, les moteurs diesel ordinaires qui brûlent du carburant diesel rejettent très peu de méthane. Donc, les émissions de méthane étaient peut-être 24,18 fois plus importantes lorsque le moteur brûlait du DME plutôt que du diesel, mais elles étaient tout de même très faibles. Il serait possible de réduire les émissions de méthane en optimisant les systèmes d'injection et de combustion du carburant.

Les émissions d'éthylène et de propylène ont été abaissées à des niveaux négligeables dans le cas du DME. Par contraste, les émissions combinées d'éthylène et de propylène (des composants de l'ozone troposphérique) étaient importantes dans le cas du carburant diesel.

En conclusion, le DME semble constituer une solution d'avenir pour le remplacement du diesel dans les moteurs à combustion interne, notamment dans la perspective de la conformité aux nouvelles règles antipollution. Les essais ont révélé d'importantes réductions des émissions de nombreux gaz d'échappement réglementés et non réglementés par le moteur brûlant du DME, sans que le moteur comme tel ait été modifié. Et il est pensable que l'on puisse réduire encore plus les émissions de NO_x, de HT (sous forme de DME imbrûlé), de formaldéhyde et de méthane. Pour ce qui est de la conduite d'un véhicule mû au DME, d'autres mesures de sécurité s'imposent pour la manutention et la distribution du carburant, afin de minimiser les risques d'incendie et d'explosion. En effet, le DME est beaucoup plus inflammable et volatil que le diesel (son point d'éclair et sa température d'auto-inflammation sont plus bas). Les composants du circuit d'alimentation en carburant DME, comme les robinets, les tuyaux et les raccords devraient être fabriqués de métal ne produisant pas d'étincelles, comme l'acier inoxydable ou le laiton, de façon à réduire au minimum le risque d'étincelles pouvant déclencher un incendie.

Il y aurait lieu, en outre, de mettre à la masse le réservoir de carburant DME et les circuits de distribution afin d'empêcher la formation d'une charge électrostatique et le jaillissement potentiel d'une étincelle.

D'autres réductions importantes des gaz d'échappement sont à prévoir, à la faveur d'une optimisation des systèmes d'injection et de combustion du DME, de l'ajout d'un système de recyclage des gaz d'échappement (RGE) et de l'installation d'un catalyseur plus efficace. Étant donné les très faibles quantités de particules rejetées, il serait possible de recycler une grande proportion des gaz d'échappement sans nuire à la fiabilité du moteur; le bon fonctionnement du moteur est en effet compromis lorsque de grandes quantités de particules pénètrent dans la chambre de combustion.

Les mesures ci-après sont recommandées pour réduire encore plus les gaz d'échappement produits par des moteurs brûlant du DME :

1) Monter de nouveau le circuit d'alimentation en carburant DME pour le moteur Cummins 5,9 L et installer le moteur sur le dynamomètre d'EC en prévision d'autres essais de contrôle des émissions.

2) Installer un dispositif de pesage piloté par PC et les composants connexes, pour la mesure des taux de consommation de carburant.

3) Modifier l'avance à l'injection du DME de façon à réduire les émissions de NO_x.

4) Modifier le système d'admission et d'échappement pour y incorporer un mécanisme de RGE afin de réduire les émissions de NO_x.

5) Obtenir des données sur divers types de catalyseurs de gaz d'échappement, afin de déterminer s'il existe un modèle adapté au DME, capable de réduire les émissions de NO_x, d'imbrûlés et de gaz non réglementés.

6) Étudier la possibilité de réduire les émissions de méthane.

7) Reprendre les essais de contrôle des émissions de moteurs brûlant du DME, en tirant parti de l'information et du matériel nouveaux découlant de l'exécution des tâches 1 à 5.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AET	Advanced Engine Technology Ltd.
AVL	AVL LIST GMBH
BTDC	Before Top Dead Centre
CI	Compression Ignition
CO	Carbon Monoxide (If BS precedes CO, it refers to Brake Specific CO)
CO_2	Carbon Dioxide (If BS precedes CO_2 , it refers to Brake Specific CO_2)
DAS	Data Acquisition System
DME	Dimethyl Ether
EC	Environment Canada
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FMEA	Failure Mode and Effect Analysis
g/bhp-hr	Grams per Brake Horsepower Hour
IEA	International Energy Agency
NO_x	Oxides of Nitrogen (If BS precedes NO_x, it refers to Brake Specific NO_x)
NPT	National Pipe Thread
PM	Pariculate Matter (If BS precedes PM, it refers to Brake Specific PM)
TDC	Transportation Development Centre
THC	Total (Unburned) Hydrocarbons (If BS precedes HC, it refers to Brake Specific HC)

1. INTRODUCTION

New regulations aimed at lowering diesel engine emissions levels are being implemented in most industrialized countries. In North America, both the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board have adopted emissions limits covering the full range of engine sizes. As emissions standards continue to be tightened, substantial engine research and development will be required to reduce engine exhaust emissions levels. Early indications are that expensive engine/fuel injection equipment modifications and emissions equipment will be required if compression ignition (CI) engines are to continue operating on conventional diesel fuel.

Alternative fuels have been considered as potential replacements or supplements for diesel fuel in CI engines. One fuel in particular, dimethyl ether (DME), has shown promise [1][2][3][4]. A comparison of the physical and chemical properties of DME, diesel fuel and propane is provided in Appendix A. Early test results indicate that fuelling CI engines with DME instead of diesel fuel would allow the 1998 California Ultra Low Emission Vehicle emissions requirements to be met without the addition of expensive emissions systems. Of particular relevance is its almost smokeless operation, low oxides of nitrogen (NO_x) emissions and considerably reduced noise levels.

Combining the inherently low exhaust emissions of DME with the fuel consumption benefits of CI engines in a simple engine design would be a significant step toward a cost-effective solution in a number of transportation areas that require low exhaust emissions. Low noise levels and reduced engine weight would also be particularly attractive for hybrid vehicle technology.

In an effort to acquire additional information regarding the potential use of DME, the Transportation Energy Technology Division of Natural Resources Canada contracted Advanced Engine Technology Ltd. (AET) to perform a literature search in conjunction with limited in-house testing of DME (Phase I)[5]. In addition, a DME fuel safety study was undertaken for the Transportation Development Centre (TDC) of Transport Canada to verify the major safety concerns related to DME and develop a set of preliminary guidelines for an automotive fuel system employing DME [6][7]. A Phase II federal government/industry cooperative study, based on the Phase I recommendations, was initiated.

The main objectives of the Phase II study were to:

- determine the exhaust emissions characteristics of a light-duty diesel engine operating on liquid DME;
- determine the feasibility of modifying a light-duty mechanical fuel injection system to permit DME to be injected as a liquid;

- investigate combustion parameters with regard to combustion and exhaust emissions characteristics for a light-duty diesel engine operating on DME;
- determine the major safety concerns and develop preliminary safety-related design guidelines for a DME-fuelled, light-duty diesel engine vehicle fuel system;
- develop a knowledge base of DME physical properties and related fuel handling/storage considerations.

A 5.9-litre, turbocharged, intercooled, Cummins diesel engine (direct injection/exhaust catalyst) from a Dodge Ram pickup truck was acquired and installed in AET's test cell #2 **for test purposes** (please refer to Appendix B, Figures B-1 and B-2). Initially, one cylinder of the six- cylinder engine was fuelled with DME while the remaining five cylinders were fuelled with diesel fuel. Several sensors were used to allow engine temperatures and pressures to be monitored by a computer data acquisition system (DAS). Upon successful operation of the engine on one DME-fuelled cylinder, the remaining five cylinders were converted to operate on DME. The engine was then transported to Environment Canada for AVL LIST GMBH (AVL) 8 mode steady state emissions testing. Emissions testing was performed with the engine operating on DME and on diesel fuel.

2. WORK ACCOMPLISHED

SECTION I ENGINE INSTALLATION

2.1 Install Cummins B Series Diesel Engine

A support stand was fabricated on which to mount the engine/dynamometer. The Cummins 5.9-litre engine was coupled to an automotive-type water brake dynamometer using a vibration damping coupling. Upon shakedown testing it was determined that the dynamometer aluminum casting had porosity problems in a few areas and as such was deemed unsuitable for loading the test engine without substantial modifications. An eddy current dynamometer was acquired to replace the water brake dynamometer and another engine/dynamometer support stand fabricated.

A closed-loop cooling system for the eddy current dynamometer was fabricated. It consisted of an in-ground coolant reservoir, a large radiator/cooling fan, two cooling water circulation pumps/motors, hoses and support stands. Unanticipated difficulties with the eddy current dynamometer drainage system were encountered that required significant modifications to the closed-loop cooling system. Modifications to the dynamometer controller were also required to allow engine loading within the constraints of the test program.

Two AET DAS's were used to collect data from the test cell instrumentation. Fourteen thermocouples were used to measure engine, dynamometer and ambient temperatures. Engine torque was measured using a load cell. Cylinder #1 of the Cummins engine was instrumented with a piezoelectric pressure transducer to measure cylinder combustion pressures. Cylinder pressures were then correlated to crankshaft angular position using an optical encoder mounted on the crankshaft. The Bosch P7100 fuel injection nozzle in Cylinder #1 was instrumented with a needle lift proximity sensor by an external instrumentation source. The needle lift sensor was used to correlate the injection nozzle needle opening period with crankshaft angular position. Modifications were made to the high-pressure fuel injection line on Cylinder #1, allowing a piezoelectric pressure transducer to be installed in the line near the injection nozzle. The fuel line pressure transducer was used to correlate pressure waveforms in the injection line with crankshaft angular position. Computer software to operate the two DAS's was developed in-house.

2.2 Measure Steady State/Transient Emissions

During the interim between the water brake dynamometer shakedown tests and installation of the eddy current dynamometer, the Cummins B Series engine was shipped to the Mobile Sources Emissions Division of Environment Canada (EC) for emissions testing. The engine was tested at EC with all six cylinders operating on diesel fuel. EC emissions results are compared to the Cummins emissions results for an EPA heavy-duty transient test cycle in Table 1.

Test Location	**BSHC (g/bhp-hr)**	**BSNO$_x$ (g/bhp-hr)**	**BSCO (g/bhp-hr)**	**BSCO$_2$ (g/bhp-hr)**	**BSPM (g/bhp-hr)**
Cummins	0.18	4.78	0.91	564	0.07
EC	0.22	8.31	2.45	660	0.19

Table 1 EPA Heavy-Duty Transient Regulated Emissions Test Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with Diesel Fuel

The emissions results in Table 1 are composite numbers, approximated by 1/7 of the value of the cold start emissions results and 6/7 of the value of the hot start emissions results. EC emissions results were greater than the Cummins emissions results, particularly for NO$_x$, carbon monoxide (CO) and particulate matter (PM). This discrepancy may be due to difficulties encountered at EC with the intake aftercooler located between the turbocharger and the engine cylinder head on the inlet air system.

2.3 Instrument and Install Prototype DME Fuel System to One Cylinder and Carry Out Preliminary Optimization Study

Design discussions were carried out with DuPont representatives regarding the components required for AET's laboratory DME fuel system with regard to safety considerations. Additional information was gathered through discussions with other parties involved with DME and from literature relating to DME fuelling of diesel engines. Cadkey drawings of AET's DME engine/test cell/storage facilities were made and submitted to DuPont representatives for approval. Upon completion of the engine/test cell DME fuel systems, a comprehensive safety audit of AET was organized and carried out by DuPont.

The DME fuel system (low pressure side) consisted of a high-pressure DME storage reservoir, a helium pressure tank/regulator, high-pressure copper fuel lines, check valves, blow off valves, shut-off valves, couplers and two fire-safe emergency shut-off valves. Regulated high pressure helium (20 bar) was forced into the dual-fitting DME fuel reservoir, thereby pressurizing the DME in the tank and low-pressure lines leading to the engine. Helium was employed because of its low solubility in DME. Blow off valves were installed on the fuel reservoir and copper fuel lines to release DME to the atmosphere in a controlled manner during a fire, thereby minimizing the possibility of an explosion. Fire-safe emergency shut-off valves were installed (one on the fuel reservoir, one on the engine) to allow the operator to stop the flow of DME to the engine and laboratory during a fire or potential fire situation. In addition, a large carbon dioxide (CO_2) fire extinguisher was plumbed from outside the test cell to a diffuser just above the DME fuel system on Cylinder #1 as an additional safety feature.

The following design guidelines were adhered to during fabrication of the laboratory DME fuel system:

- Non-sparking metals (stainless or brass) were used for the DME fuel tank, fuel line fittings and valves to eliminate spark generation from wrenches, which might lead to a fire situation.

- The DME fuel tank, fuel line and engine were grounded to grounding rods to prevent electrostatic charge buildup and discharge, thereby further minimizing the possibility of a charge buildup and the occurrence of a spark that might lead to a fire situation.

- Substantial over-pressure capability was designed into all DME fuel system components (based on a normal DME operating pressure of up to 600 psi) to allow for pressure increases generated by temperature fluctuations in the fuel system and the high thermal expansion rates of DME.

- A protective metal covering was placed along the DME fuel line to prevent possible puncture of the line and the potential for a fire situation.

- Remotely activated, fire-safe emergency shut-off valves were used to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire.
- A blowdown valve was installed on the DME fuel tank to vent the DME during a fire, thereby preventing an explosion of the fuel tank from over-pressurization caused by excessive temperatures (fire).
- Water spray was made available to cool the DME fuel tank in the event of a fire. Cooling the tank would reduce the DME pressure in the tank and consequently reduce the rate at which DME would be vented through the fuel tank blowdown valve.
- DME exiting the fuel injection nozzle return line was vented to atmosphere well away from the high-temperature engine components and other sources of ignition.

Design of the DME fuel system for one cylinder of the engine was carried out using computer aided design software. The Bosch fuel injection pump operated on diesel fuel in the normal manner; however, the diesel fuel passing through the pump was not injected into the cylinder of the engine for combustion purposes. The diesel fuel served only as a pumping medium and was not consumed during engine operation. A shuttle valve was used to transfer the pumping action from the diesel fuel injection pump to the DME in the high-pressure fuel injection line. A high-pressure check valve was used to regulate DME flow from the low-pressure fuel supply line to the high-pressure fuel injection line. Numerous discussions were held with Robert Bosch Corporation to assist with the design/fabrication of the fuel system shuttle valve.

Difficulties were encountered during much of the early portions of the engine test program as DME leakage past the check valve and shuttle valve systems resulted in poor injection characteristics, vapour lock in the injection pump, and sporadic engine operation.

In addition to DME leakage, difficulties were encountered with breakage of the shuttle valve return spring. It was hypothesized that the DME was vaporizing for a brief period during closing of the shuttle valve resulting in momentary low temperatures around the valve spring. The low temperatures, followed by warmer temperatures once the fuel line filled with DME liquid under pressure, would cause thermal cycling of the spring and possible thermal fatigue/cracking/failure. Efforts were directed at acquiring a larger diameter check valve, which would allow DME liquid to flow from the DME supply line to the shuttle valve area more rapidly, thereby minimizing DME vaporization in the high-pressure fuel line.

Based on discussions with check valve manufacturers, it was concluded that a larger check valve with higher cracking pressures and greater high-frequency response would improve the valve's operation and engine performance. Modifications were made to the fuel system to incorporate a larger check valve. No noticeable improvement in engine operation was observed.

Further investigation indicated that DME leakage was also occurring with the new check valves. Substantial additional effort was required to select a suitable check valve. Difficulties were encountered in finding an appropriate check valve due to the size, leak rate and pressure characteristics required. Several automotive-type check valves were tested, each iteration requiring significant effort to modify the fuel system for each check valve evaluation. The automotive-type check valve was replaced with a high flow rate, high-pressure, aerospace check valve to reduce the rates of DME leakage and increase the longevity of the check valve system. No difficulties were encountered throughout the remainder of the test program with the aerospace check valves.

Design modifications were made to eliminate DME leakage past the shuttle valve. Initial design modifications reduced leakage past the shuttle valve, allowing brief engine operation on DME. Numerous attempts to modify the original shuttle valve concept to improve sealing resulted in only minor success. It was concluded that excessive DME leakage was due to the clearances between the shuttle valve and valve body as supplied by Bosch. To improve sealing, additional shuttle valves with reduced clearances were fabricated by Bosch and forwarded to AET to replace the original shuttle valves. No significant improvements, however, were observed.

Further discussions were held with Bosch to acquire a shuttle valve with the appropriate clearances. It was concluded that Bosch was not in a position to make a limited quantity of prototype shuttle valves with the required clearances. It was agreed that Bosch would send AET an existing fuel injection system component with the desired clearances. AET would then fabricate a shuttle valve/valve body from the Bosch component. The AET fabricated shuttle valve was designed with a significantly larger diameter than the Bosch fabricated shuttle valves, thereby reducing the shuttle valve travel required to displace the DME. It was anticipated that the reduction in shuttle valve travel would be beneficial in terms of decreasing the shuttle valve's lubrication requirements and reducing shuttle valve and return spring stresses.

A high-pressure lubrication system was fabricated to lubricate the shuttle valve to reduce the anticipated high wear rates associated with exposure of the shuttle valve to neat DME without lubricating additives. In addition to improving the lubricity of the DME, the lubrication system improved sealing around the shuttle valve, check valve and injection nozzle needle/seat areas. The lubricant (diesel fuel) was forced into the small clearance gap of the shuttle valve under significant pressure, thereby acting as a barrier to DME migration through the shuttle valve clearance gap.

The fabricated shuttle valve system (please refer to Appendix C), with its high-pressure lubrication system and improved check valve design, significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods of time over the entire range of engine speeds and a wide range of loads with consistent DME injection. However, output torque from the DME-fuelled cylinder was approximately the same as for the diesel-fuelled cylinders only at engine speeds below 1500 rpm. At higher engine speeds, output torque decreased as a result of a limitation in the quantity of fuel that could be injected into the cylinder and inadequate fuel injection timing. It was concluded, based on cylinder pressure, fuel line pressure traces and needle lift traces, that additional work would be required to provide optimal injection timing and increased delivery quantities (injection nozzle orifice diameters) over the entire range of engine speed/load conditions.

2.4 Document Results in Section I Interim Report

The results of Part I were documented as part of a TDC report entitled *Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel*, TP 13456E.

SECTION II FINAL OPTIMIZATION - ENGINE/DYNAMOMETER

2.5 Prepare Engine for Safe Emissions Testing with DME Fuel System

As indicated in Section I, AET was contracted by TDC to verify the major safety concerns associated with operating an engine on DME and to develop a set of preliminary safety guidelines for an automotive fuel system designed for use with DME as an alternative diesel fuel. Because DME is more flammable (lower flashpoint and higher vapour pressure) than diesel fuel, engine operation on DME requires special safety precautions to minimize the potential for a fire or explosion. The DME safety-related study concentrated on an evaluation of different types of valves for the automotive fuel system, in particular DME fuel system emergency shutoff valves and DME fuel injection system needle valves in fuel injection system nozzles.

An AET representative attended three International Energy Agency (IEA) workshops on DME. A Failure Mode and Effect Analysis (FMEA) was performed for AET's DME fuel system and compared to other IEA workshop participants' DME fuel systems. Significant effort was directed toward preparing an FMEA for a DME fuel system to be employed for light-duty vehicle applications. The vehicle fuel system was designed to minimize the potential for DME leakage into the engine's cylinders, crankcase lubricating oil sump, fuel injection pump and the atmosphere, as well as minimize the possibility of a fire/explosion. Cadkey drawings of the DME fuel injection system boundary conditions, the vehicle fuel system and an engine/fuel state summary were prepared for submission to IEA. Additional preparation included a summary of implicit assumptions regarding the DME fuel system and tables describing the function, potential failure and cause/effect of failures related to all DME vehicular fuel system components (please refer to section 2.9 for additional information).

Based on the aforementioned DME safety study and DME fuel system FMEA, modifications were made to AET's test cell DME fuel system to ensure that appropriate safety guidelines were met. These guidelines were also followed during fabrication of the DME fuel system for emissions testing at EC.

2.6 Measure Steady State Emissions and Continue Optimization

Preliminary test results with Cylinder #1 operating on DME indicated that faster rates of DME injection would be required at high engine speeds as well as changes in injection timing to maintain the output power characteristics of the engine. The diameter of the orifices in the Cylinder #1 injection nozzle were enlarged to increase the flow of DME through the injection nozzle. Several iterations were required to optimize the injection nozzle orifice diameter and injection timing for low-speed and high-speed engine operation.

Upon completion of the optimization process for Cylinder #1, modifications were made to the engine/DME fuel system to allow the remaining five cylinders to operate on DME (please refer to Appendix B, Figures B-4 and B-5). Dynamometer testing of the Cummins engine operating with all six cylinders on the optimized DME fuel system confirmed that satisfactory engine power could be obtained at all engine speeds. The injection timing for DME operation was optimized to provide near peak power, corresponding to high thermal efficiency and low fuel consumption rates, while maintaining moderate combustion pressures and low rates of combustion pressure (please refer to Appendix D, Figures D-1 through D-4). Since the Bosch mechanical fuel injection pump did not have variable injection timing with regard to engine speed, it was necessary to shut the engine down and re-time the injection pump for varying load and speed conditions. To simplify testing, two DME injection timings were used during the operability and emissions tests: 10 before top dead centre (BTDC) for low engine speeds and 20 BTDC for high engine speeds. Newer Bosch electronic fuel injection pump systems have variable timing capabilities; however, it was not within the scope of the project to try to retrofit the engine with this type of system.

EC personnel visited AET to review the engine test program requirements, the test schedule for emissions testing at EC, DME fuel safety, DME fuel storage/handling requirements, the AET DME fuel system and the proposed DME fuel system at EC. AET personnel visited EC on several occasions to review installation of the test apparatus, including the engine, a 2000-lb. high-pressure reservoir (1000 lb. of DME) and the copper fuel lines connecting the reservoir to the engine (please refer to Appendix B, Figure B-3). The test cell ventilation system was also evaluated in terms of safety. A comprehensive safety audit of EC was carried out by AET upon completion of the EC DME engine/test cell fuel systems.

Engine/dynamometer shakedown testing at EC indicated significant difficulties with the water brake dynamometer. AET offered advice to EC personnel with regard to repairing the dynamometer, based on similar experiences at AET with a water brake dynamometer used in another project. Upon repair of the dynamometer by EC personnel, engine/dynamometer/test cell shakedown testing was performed. Minor difficulties were encountered with DME leakage at the fittings in the copper fuel line running through the test cell area.

Additional difficulties with the EC dynamometer were encountered with regard to maintaining the required load and speed for Mode 5 of the AVL 8 mode emissions test (please refer to Appendix E for loads/speeds). To rectify the dynamometer difficulties it was necessary to operate the Cummins engine for extended lengths of time at Mode 5 conditions (low load/high speed). During this time, injector nozzle tip difficulties (scored/seized needles) were encountered as a result of the low lubricity of DME and extended Mode 5 operation. During Mode 5 operation the opening/closing frequency of the injector needles was high because of the high engine speed; however, the flow of DME over the injector needles for lubrication was low because of the low load. The amount of DME present for lubrication during each injector needle opening/closing period was therefore minimal, leading to insufficient lubrication and seizure. Six additional nozzle tips were acquired and the orifices enlarged to the desired diameter.

To complete the test program as rapidly as possible with minimal risk of subsequent nozzle tip difficulties, AET designed and fabricated a pressurized DME injector return flow system to improve lubrication of the injector needle. The pressurized system maintained the DME as a liquid as it returned from the nozzle tip. The previous non-pressurized system allowed the DME return from the injector to vaporize along the bearing area of the needle. It was anticipated that maintaining the DME as a liquid along the bearing area of the needle would provide significantly improved needle lubrication. No further needle lubrication difficulties were encountered during the remainder of the test program.

The AVL 8 mode emissions test was performed for the 5.9-litre Cummins engine operating on DME and on diesel fuel with the standard oxidation catalyst for this engine installed in the exhaust system. Three emissions tests were performed on DME (please refer to Appendix B, Figures B-6 through B-8). Upon completion of the DME tests, the DME fuel system was removed and the original diesel fuel system components were re-installed. Two emissions tests were then performed on diesel fuel for comparison purposes. Data collected during the tests included: 1) regulated and non-regulated exhaust emissions; 2) exhaust temperatures; 3) coolant temperature; 4) crankcase lubricating oil temperature; 5) cylinder pressure; 6) fuel line pressure; and 7) fuel injector needle lift.

The injection timing for DME operation was optimized to provide near peak power, corresponding to high thermal efficiency and low fuel consumption rates, while maintaining moderate combustion pressures and low rates of combustion pressure rise. It was anticipated that the diesel fuel injection timing had been optimized similarly. However, during diesel emissions testing it became evident, based on combustion pressure traces, that the manufacturer (Cummins) had not optimized the injection timing in the aforementioned manner. The diesel injection timing was significantly retarded by the manufacturer to produce low NO_x emissions (especially at high engine speeds) at the expense of thermal efficiency, power and fuel consumption rates.

Time constraints prevented the engine from being re-tested on DME with the injection timing retarded to better correlate with the diesel fuel tests. It is anticipated that significant additional NO_x reductions would have been obtained for operation on DME with retarded injection timing.

Table 2 summarizes the overall average for the regulated exhaust emissions with the engine operating on DME and diesel fuel.

Fuel	**CO (g/bhp-hr)**	**CO_2 (g/bhp-hr)**	**NO_x (g/bhp-hr)**	**THC (g/bhp-hr)**	**PM (g/bhp-hr)**
DME	0.253	544.7	3.33	0.427	0.02
Diesel	0.445	588.5	3.54	0.180	0.08

Table 2: Regulated Emissions Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with DME and Diesel Fuel

With regard to regulated emission results, engine operation on DME reduced CO emissions from 0.445 to 0.253 g/bhp-hr (43 percent reduction). CO_2 emissions were reduced from 588.5 to 544.7 g/bhp-hr (7.4 percent reduction). NO_x emissions were reduced from 3.54 to 3.33 g/bhp-hr (5.9 percent reduction). Further reductions in NO_x (DME) could be attained by optimizing the timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation. Total hydrocarbon (THC) emissions increased from 0.18 to 0.427 g/bhp-hr. (237 percent increase) for DME operation. THC emissions for DME operation were primarily unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME and methane emissions. PM emissions were reduced from 0.08 to 0.02 g/bhp-hr (75 percent reduction).

Table 3 summarizes the ozone reactivity and toxicity values for unregulated emissions compounds.

Compound	**Percent Change in Emissions for DME Operation**	**Reactivity (grams of ozone per gram of compound)**	**National Occupational Standards Permissible Exposure Limit (over 8 hr period)**
Formaldehyde	(+) 382%	7.15	3 ppm
Acetaldehyde	- 79%	5.52	200 ppm
Propionaldehyde	- 99%	6.53	Not available
Acrolein	- 99%	6.77	0.1 ppm
Acetone	- 77%	0.56	1000 ppm

Table 3: Unregulated Emissions Results for 5.9-Litre Cummins Engine (with Oxidation Catalyst) Fuelled with DME and Diesel Fuel

With regard to unregulated emissions, absolute emissions values in g/bhp-hr cannot be reported because of emissions collection difficulties at EC. However, the results can be compared between DME and diesel fuel on a relative basis. Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. It is anticipated that a more appropriately sized oxidation catalyst in the exhaust system would significantly reduce the toxic exhaust emissions.

Methane emissions (greenhouse gas) increased by a factor of 24.18 for DME as compared to diesel fuel. However, it should be noted that although methane emissions were higher than for diesel operation, typically diesel engines operating on diesel fuel produce very low methane emissions. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were substantial. Ethylene and propylene emissions were reduced to insignificant levels for operation on DME.

2.7 Measure Transient Emissions and Continue Optimization Study

It was determined that operation on DME required variable injection timing with regard to engine speed. Substantial changes in injection timing were required between low-speed (10 BTDC) and high-speed (20 BTDC) operation. However, the Bosch mechanical fuel injection pump on the engine did not offer variable timing capability. It was concluded that performing a transient test with varying engine speeds and loads with a single injection timing would not provide meaningful emissions results.

Efforts made to find a solution to the variable timing difficulty indicated that significant engine modifications not within the scope of the project would be required to install a mechanical system that would support and rotate the Bosch fuel injection pump relative to the crankshaft during engine operation, thereby altering the injection timing. Retrofitting the engine with a newer Bosch electronic fuel injection pump system with variable timing capabilities was also deemed not to be within the scope of the project. This task was therefore not undertaken.

2.8 Document Results in Section II Interim Report

The results of Part II were documented as a series of interim progress reports.

SECTION III A STUDY OF SPECIFIC OF SPECIFIC CONCERNS OF DME AS AN ALTERNATIVE FUEL FOR DIESEL ENGINE APPLICATIONS

2.9 From a Design Guidelines Perspective, Complete the Failure Mode and Effect Analysis (FMEA) for the Proposed Vehicular DME Fuel System

Significant effort was directed toward further modifying the DME fuel system design based on recommendations from the FMEA workshops. The proposed DME vehicle fuel system received a favourable rating by IEA participants with regard to the FMEA risk assessment.

The following design guidelines refer to a DME fuel system based on the AET laboratory engine DME fuel system design. It is anticipated that the AET DME fuel system design would differ from other DME fuel system designs in that a small reservoir of diesel fuel or other similar fluid in terms of viscosity, density and lubricity would be employed. The reservoir of diesel fuel or similar fluid would be used to operate the injection pump and lubricate the injection system shuttle valve. A minute quantity of diesel fuel would leak past the shuttle valve to lubricate the injection nozzle needle. This minute quantity of diesel fuel would be combusted along with the DME in the engine's combustion chamber. It is anticipated that the rate of diesel fuel usage would be insignificant, such that the diesel fuel reservoir could be filled up at the same frequency as an oil level check or oil change.

Based on the FMEA study, the following guidelines should be adhered to during fabrication of a vehicle DME fuel system:

- Non-sparking metals (stainless or brass) should be used for the DME fuel tank, fuel line fittings and valves to eliminate spark generation from wrenches, which might lead to a fire situation.
- All wrenches used for assembling/disassembling the DME fuel system should be non-sparking.
- The vehicle refuelling system should have provision for grounding to the vehicle DME fuel system such that there can be no electrostatic charge potential between the vehicle and the vehicle refueling system. Electrostatic charge buildup can lead to an electrical discharge in the form of a spark, which might lead to a fire situation.
- All DME fuel system components, including the DME fuel reservoir, fuel line fittings/valves and fuel filler line, should be electrically continuous and grounded to prevent electrostatic charge buildup. Because of the poor electrical conductivity of DME, DME fuel system components are susceptible to electrostatic charge buildup. Electrostatic charge buildup on fuel system components can lead to an electrical discharge in the form of a spark, which might lead to a fire situation.

- An explosion-proof fuel pump should be employed to pump the DME from the fuel reservoir to the high-pressure fuel lines.

- National Pipe Thread fittings in the DME fuel system should not be used; instead, all fittings should be butt-welded American National Standards Institute flanges.

- A fuel storage level fill shut-off system should be employed to ensure that the reservoir is not filled above 80 percent capacity, thereby allowing room for expansion of the DME during varying ambient temperature conditions. DME has a high thermal expansion rate and it is therefore necessary to leave 20 percent additional reservoir volume to allow for DME expansion during temperature fluctuations.

- Substantial over-pressure capability must be designed into all DME fuel system components (based on a normal DME operating pressure of up to 600 psi) to allow for pressure increases generated by temperature fluctuations in the fuel system and the high thermal expansion rates of DME.

- A blowdown valve should be installed on the DME fuel tank to vent the DME during a fire, thereby preventing an explosion of the fuel tank from over-pressurization caused by excessive temperatures (fire).

- Vehicle operators should be instructed to spray the DME fuel tank with water (if available) in the event of a fire. Cooling the tank with the water spray will reduce the DME pressure in the tank and consequently reduce the rate at which DME would be vented through the fuel tank blowdown valve.

- A pressure relief valve should be installed in all locations where the DME fuel is contained, including the fuel reservoir and the fuel lines between shut-off valves. The pressure of DME in a confined space varies substantially with temperature. High temperatures including fire situations may result in excessive DME pressures and fuel system ruptures unless a pressure relief valve is installed.

- Remotely operated emergency shut-off (fire-safe) valves, constructed from DME compatible materials, should be installed to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire.

- The DME purge tank should be located such that its vent is outside the vehicle so that DME is not vented in the area of high underhood temperatures, exhaust system components and electrical system components. During engine operation the DME in the purge tank should be combusted in the engine at a controlled rate.

- Threaded fasteners and bracketry used to attach DME fuel system components should be corrosion (salt/oxidation) resistant.

- The vehicle DME fuel tank should be corrosion (salt/oxidation) resistant and positioned such that it is not subjected to sand/salt/water.
- A protective metal covering should be placed along the DME fuel line from the fuel storage reservoir and the high-pressure injection pump to prevent possible puncture of the line and the potential for a fire situation.
- Sensors should be installed on the vehicle to warn the operator of DME leaks. DME leaks could be determined by inexpensive pressure sensors monitoring DME pressure and by a DME gas detector.
- The vehicle DME fuel system should be tested extensively for crashworthiness. It is anticipated that employing safety measures similar to those used on propane vehicles would provide a good starting point.
- Lubricating additives compatible with DME should be added to the DME to extend the life of the fuel system components, thereby reducing the potential for undesirable leaks.
- Engine overspeed protection should be employed such as an air shut-off flap in the intake air system. Leakage of DME into the engine's intake air system or cylinders due to a malfunction could cause engine overspeeding since the rate of fuel entering the engine would not be controlled. Similar circumstances with diesel fuel would be less likely to cause engine overspeeding since, unlike DME, diesel fuel does not atomize readily unless injected under high pressures.

2.10 Carry Out Leak Rate Tests on Leak Rate Test Rig with Worn Injection Nozzles

During the DME safety study contracted by TDC, a DME fuel mass leak rate measuring system was developed to determine the rate of DME leakage past the fuel injection nozzle needle and seat of the 5.9-litre Cummins engine. The injection nozzles used during this study were new (unused). It was anticipated that significant DME leak rates past the injection nozzle would result in DME entering the DME-fuelled cylinder upon engine shutdown. Upon engine startup the cylinder would be full of DME vapour, causing excessive combustion pressures, combustion knock and engine speeds.

The fuel mass leak rate measuring system consisted of a weigh scale, pressure vessel, high-pressure fuel line, fuel injection nozzle (with the return vent sealed) and thermostatically controlled heating system (please refer to Appendix B, Figures B-9 and B-10). The mass leak rate measuring system allowed the rate of DME mass loss from the injector nozzle to be determined at varying pressures and temperatures, allowing simulation of injector conditions upon engine shutdown, as well as testing at more extreme temperature/pressure conditions.

Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests on new, unused injection nozzles indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550 F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

2.11 Research and Fabricate a Prototype Fuel System Purge Tank

A purge tank was fabricated to collect DME vapours from the DME fuel injection system, upon engine shutdown. Several DME fuel system purge tanks were considered and evaluated using the FMEA. Upon completion of the task descibed in section 2.10, it was concluded that the DME leak rates from worn injectors (worst case) was very small, suggesting that a purge tank might not be required, particularly for applications in which the fuel system cost was a major consideration.

Because of time and budget constraints brought about by unanticipated difficulties encountered in other tasks with operation of the DME fuel system, the purge tank was not tested on the engine.

2.12 Report Complete Study Findings

The results of the study were documented as part of this report.

3. STUDY CONCLUSIONS

The following conclusions were drawn during this study.

DME Engine Operation/Emissions

- The relatively simple, low-cost DME fuel injection system provided power levels equivalent to diesel fuel operation when employed on the Cummins engine.
- Low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation. Although the combustion pressures and rates of cylinder pressure rise for DME operation were as high or slightly higher than for diesel operation, this can be attributed to the significantly retarded injection timing employed by the engine manufacturer for diesel operation.
- PM emissions were reduced by 75 percent for DME operation. The very low PM emissions levels may be attributed to normal minute rates of crankcase lubricating oil

consumption. It is anticipated that a cleaner burning crankcase lubricating oil formulation could be employed to further reduce PM and THC emissions.

- Low PM emissions for DME operation would reduce particulate contamination of the engine lubricating oil.
- CO emissions were reduced by 43 percent for DME operation.
- CO_2 emissions were reduced 7.4 percent for DME operation.
- NO_x emissions were reduced by 5.9 percent for DME operation. It is anticipated that further significant reductions in NO_x (DME) could be attained by optimizing the timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation.
- THC emissions increased by 237 percent for DME operation. However, THC emissions for DME operation were primarily unburned DME, which is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME and methane emissions.
- Four of five toxic unregulated exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. Toxic emissions including formaldehyde can be oxidized using a more appropriately sized exhaust catalyst.
- Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.
- Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

DME Fuel System

- Because DME is more flammable (lower flashpoint and higher vapour pressure) than diesel fuel, engine operation on DME requires special safety precautions to minimize the potential for a fire or explosion.

- Metal fuel system components should be non-sparking, such as stainless steel or brass, to minimize the possibility of generating a spark that might lead to a fire situation.

- Grounding of the DME fuel tank and fuel line is required to prevent electrostatic charge buildup and discharge to minimize the possibility of generating a spark that might lead to a fire situation.

- Plastic and rubber fuel system components typically used for vehicle applications should be replaced with non-sparking metal components such as stainless steel or brass. Components that cannot be replaced with the aforementioned metals should be constructed from Teflon or Butyl-N rubber, which are chemically resistant to DME and the traces of methanol typically found in commercial DME.

- Fire-safe ball valves with graph-oil packing should be used as emergency DME shut-off valves. Graph-oil packing was recommended by DuPont because of its high temperature capabilities and resistance to temperature cycling. These types of valves are designed to withstand fire situations without allowing fuel (DME) leakage.

- New and worn Bosch fuel injection nozzles provided a good seal against DME leakage in the needle and seat areas. The effects of needle and seat wear and/or deposits in the needle and seat area on sealing were not determined.

- The small quantity of DME in the high-pressure injection line leaked through the injection nozzle return into the purge tank within a few minutes of engine shutdown, further minimizing the opportunity for DME to leak past the injection nozzle needle into the engine's cylinders.

- The fabricated shuttle valve system with a high-pressure lubrication system and improved check valve design significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods of time over the entire range of engine speeds and loads with consistent DME injection.

4. CONCLUDING DISCUSSION

In conclusion, DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emissions regulations. Operation of AET's test engine on DME indicated consistent DME injection and smooth combustion at all engine speeds and loads. Peak output torque/power from the DME fuelled engine was the same as for operation on diesel fuel. In addition, low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation.

Regulated exhaust emissions were reduced with the exception of THC, which was primarily in the form of unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME emissions. It is anticipated that further significant reductions in NO_x (DME) could be attained by optimizing the fuel injection timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation. Further reductions in NO_x could also be realized with exhaust gas recirculation (EGR). Because of very low PM emissions, large quantities of EGR could be implemented for DME operation without incurring engine reliability penalties associated with high levels of PM entering the combustion chamber.

Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. It is anticipated that a properly sized exhaust gas oxidation catalyst would reduce the toxic non-regulated emissions.

Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.

Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

It is anticipated that further significant reductions in exhaust emissions can be realized by optimizing the DME injection/combustion systems, incorporating an EGR system and installing a more effective exhaust catalyst. It is recommended that follow-on work as outlined in Section 5 be performed to further reduce the DME exhaust emissions.

With regard to vehicle operation on DME, there is a need to incorporate additional fuel handling/supply safety precautions to minimize the potential for fire or explosion. DME is significantly more flammable (lower flashpoint temperature and lower auto-ignition temperature) and volatile than diesel fuel. DME fuel system components such as valves, lines and fittings should be constructed from non-sparking metals such as stainless steel or brass to minimize the possibility of generating a spark, which might lead to a fire situation. In addition, it would be necessary to ground the DME fuel tank and fuel lines to prevent electrostatic charge buildup and a potential spark discharge.

Components that cannot be replaced with stainless steel or brass should be constructed from Teflon or Butyl-N rubber, which are chemically resistant to DME and the traces of methanol typically found in commercial in DME. Fire-safe ball valves with graph-oil packing are recommended for use as emergency DME shut-off valves. The graph-oil packing provides high temperature capabilities and resistance to temperature cycling, allowing the valve to seal even during a fire situation.

Based on the vehicle fuel system design, efforts were made to determine if the injector nozzles would leak DME from the high-pressure fuel line upon engine shutdown. Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests carried out on new unused injection nozzle indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550 F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

5. RECOMMENDATIONS FOR FOLLOW-ON WORK

DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emissions regulations. Significant reductions in many regulated and unregulated exhaust emissions were observed for DME operation without performing additional engine modifications directed at lowering emissions. It is anticipated that further reductions in NO_x , THC (as unburned DME), formaldehyde and methane emissions could be obtained.

It is recommended that the following tasks be performed to reduce the aforementioned emissions.

Tasks

1) Re-assemble the DME fuel system for the 5.9-litre Cummins engine and install the engine on the EC dynamometer in preparation for further emissions testing.

2) Install a PC-based weigh scale and associated components to allow fuel consumption rates to be determined.

3) Modify the DME injection timing to reduce NO_x emissions.

4) Modify the intake/exhaust system to incorporate EGR for NO_x reduction purposes.

5) Acquire information on various types of exhaust catalysts to determine whether there is potential to reduce NO_x, unburned DME and toxic non-regulated emissions using a specialized catalyst for DME operation.

6) Investigate the potential for reducing methane emissions.

7) Perform additional DME emissions testing implementing information and hardware arising from Tasks 1 to 5.

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Appendix A

Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Properties	**DME (l)**	**Propane (l)**	**Diesel**
Chemical Formula	CH_3OCH_3	C_3H_8	$C_nH_{1.8n}$
Molecular Weight	46	44	>100
Lower Heating Value - kJ/kg	28,800	46,400	42,500
Liquid Density - gm/ml @ 15˚C	0.668	0.509	0.84
Boiling Point - ˚C	-24.9	-42.17	180 to 350
Viscosity - kg/m.s @ 25˚C	~0.13	~0.2	2.0 to 4.0
Vapour Pressure - bar @ 25˚C	5.1	9.4	
Bulk Modulus of Elasticity - Pa @ 25˚C & 20 bar	0.05×10^{10}		0.2×10^{10}
Cetane Number	~70	~20	40 to 50
Relative Density of Gaseous Fuel vs. Air	Heavier	Heavier	Heavier

Appendix B

Photographic Documentation of AET Research Engine/DME Apparatus

(not available in electronic format)

Appendix C

AET DME/Diesel Fuel Shuttle Valve

(not available in electronic format)

Appendix D

Comparison of Cylinder Pressure and Rates of Cylinder Pressure Rise for DME and Diesel Operation

(not available in electronic format)

Appendix E

AVL 8 Mode Emissions Test Engine Load and Speed Specifications

AVL 8 Mode Emissions Test Engine Load and Speed Specifications

Mode	Engine Speed (RPM)	Load (bhp)	Weighting Factor (%)
1	850	0	35
2	1031	17	6.34
3	1163	56	2.91
4	1378	93	3.34
5	2500	62	8.4
6	2417	71	10.45
7	2417	122	10.21
8	2318	165	7.34

Note - The actual engine load (62 bhp) for Mode 5 was approximately twice the desired load value (32 bhp) because of difficulties with the EC dynamometer maintaining very light loads at high engine speeds.

Appendix F

Failure Mode and Effect Analysis (FMEA) of a Dimethylether (DME) Fuel System for Light-Duty Vehicle Applications

(not available in electronic format)

Appendix G

AVL LIST GMBH Report No. BE 0472
Design Guidelines for Dimethyl Ether Injection Systems

(not available in electronic format)