TP 13456E

Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel

Prepared for
Transportation Development Centre
Transport Canada

by
Advanced Engine Technology Ltd.

November 1999

TP 13456E

Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel

by
C. Gray and G. Webster
Advanced Engine Technology Ltd.

November 1999

This report reflects the views of Advanced Engine Technology Ltd. and not necessarily those of the Transportation Development Centre.

The Transportation Development Centre does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

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

Project Team

G. Webster, Principal
C. Gray, Research Engineer
N. Hole, Sr. Research Technologist
G. Rotheram, Sr. Research Technologist
G. Bracewell, Technical Officer

Un sommaire français se trouve avant la table des matières.

Transport Canada | Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 13456E	2. Project No. 9361	3. Recipient's Catalogue No.
4. Title and Subtitle Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel		5. Publication Date November 1999
		6. Performing Organization Document No.
7. Author(s) C. Gray and G. Webster		8. Transport Canada File No. ZCD2450-D-701
9. Performing Organization Name and Address Advanced Engine Technology Ltd. (AET) 17 Fitzgerald Rd. Suite 102 Nepean, Ontario K2H 9G1		10. PWGSC File No.
		11. PWGSC or Transport Canada Contract No.
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer Roy S. Nishizaki

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Funded by the Program of Energy Research and Development (PERD)

16. Abstract

Advanced Engine Technology Ltd. (AET) was contracted by Transport Canada's Transportation Development Centre (TDC) to determine and verify the major safety considerations associated with use of dimethyl ether (DME) in automotive compression ignition (diesel) engine/vehicular fuel systems and to develop a set of preliminary safety guidelines. DME compatibility with vehicle fuel system emergency shut-off valves and fuel injection system needle valves was evaluated. Preliminary data was also obtained on rates of DME leakage past engine fuel injection nozzles. Additional safety guidelines were developed based on laboratory testing of a DME fuelled 5.9 L Cummins turbocharged diesel engine. Further safety guidelines were developed based on a failure mode and effect analysis (FMEA) of the test engine and potential vehicle fuel systems.

Relative to diesel fuel, DME is more flammable and has a greater potential to leak to the atmosphere in gaseous form. It was concluded that there is a need to incorporate additional fuel handling/supply safety precautions when operating a compression ignition engine on DME fuel, to minimize the potential for fire or explosion.

17. Key Words Dimethyl ether (DME), DME safety, diesel engine, failure mode and effect analysis (FMEA), injection nozzle leakage, vehicle fuel systems	18. Distribution Statement Limited number of copies available from the Transportation Development Centre E-mail: *tdccdt@tc.gc.ca*

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xiv, 16, apps	Shipping/ Handling

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 13456E	2. N° de l'étude 9361	3. N° de catalogue du destinataire
4. Titre et sous-titre Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel		5. Date de la publication Novembre 1999 6. N° de document de l'organisme exécutant
7. Auteur(s) C. Gray et G. Webster		8. N° de dossier - Transports Canada ZCD2450-D-701
9. Nom et adresse de l'organisme exécutant Advanced Engine Technology Ltd. (AET) 17 Fitzgerald Rd. Suite 102 Nepean, Ontario K2H 9G1		10. N° de dossier - TPSGC 11. N° de contrat - TPSGC ou Transports Canada
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet Roy S. Nishizaki

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Projet financé par le Programme de R&D énergétiques (PRDE)

16. Résumé

Advanced Engine Technology Ltd. (AET) a reçu du Centre de développement des transports de Transports Canada le mandat de définir et d'étudier les principales menaces à la sécurité posées par l'utilisation du diméthyléther (DME) dans des moteurs à allumage par compression (diesel) et les circuits d'alimentation correspondants, et d'ébaucher une série de lignes directrices en matière de sécurité. Les travaux ont consisté à évaluer la compatibilité du DME avec les robinets d'arrêt d'urgence du circuit d'alimentation et avec les injecteurs à aiguille du système d'injection. Des données préliminaires ont également été obtenues concernant les débits de fuite de DME en aval des injecteurs. Des mesures de sécurité supplémentaires ont été élaborées à la lumière des résultats d'essais en laboratoire d'un moteur diesel turbocompressé Cummins de 5,9 L brûlant du DME. D'autres mesures de sécurité ont encore été mises au point par suite d'une analyse des modes de défaillance et de leurs effets (AMDE) effectuée sur le moteur d'essai équipé de différents circuits d'alimentation.

Comparé au carburant diesel, le DME est davantage inflammable et présente un plus grand risque de fuite dans l'atmosphère sous forme de gaz. D'où la nécessité, a-t-il été conclu, de définir des mesures de sécurité supplémentaires pour la manutention du carburant et le remplissage des réservoirs, lors de l'utilisation de DME dans un moteur à allumage par compression, de façon à minimiser le risque d'incendie ou d'explosion.

17. Mots clés Diméthyléther (DME), sûreté du DME, moteur diesel, analyse des modes de défaillance et de leurs effets (AMDE), fuite des injecteurs, circuits d'alimentation en carburant	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires. Courriel : *tdccdt@tc.gc.ca*

19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xiv, 16, ann.	23. Prix Port et manutention

ACKNOWLEDGEMENTS

The guidance of Roy S. Nishizaki, Transportation Development Centre, Transport Canada, and Andrew Beregszaszy and Ian MacIntyre, CANMET Energy Technology Centre, Natural Resources Canada is gratefully acknowledged. In addition, the technical assistance and contributions provided by the following organizations are gratefully acknowledged:

Robert Bosch Corporation
DuPont Speciality Chemicals
DuPont Canada Inc.
Cummins Engine Company, Inc.
Chrysler Canada

EXECUTIVE SUMMARY

The objectives of this project were to verify the major safety concerns associated with use of dimethyl ether (DME) in automotive compression ignition (diesel) engine fuel systems and to develop a set of preliminary safety guidelines.

The safety-related study was divided into two main areas of concern: DME fuel system emergency shut-off valves and DME fuel injection system needle valves were evaluated with regard to DME compatibility and emergency capabilities; and rates of DME leakage past the injector nozzles were evaluated to determine the potential for DME leakage into the engine combustion chambers at engine shutdown. The results of the study were used to develop preliminary safety guidelines, including those based on conclusions drawn from ongoing testing of a 5.9 L Cummins turbo-charged diesel engine operating on DME. In addition, a failure mode and effect analysis (FMEA) of the laboratory test engine and potential vehicle fuel systems was conducted. The 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.

Difficulties were encountered during much of the ongoing engine test program with DME leakage past the check valve and shuttle valve systems and valve manufacturers were consulted to solve the DME leakage problem. Significant redesign of the shuttle valve system was required to minimize DME leakage and provide improved sealing. The fabricated shuttle valve system, with 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.

Leakdown testing was performed on a new injection nozzle to determine the mass leak rate of DME past the injection nozzle needle and seat valve. It was determined that at pressures from 687 kPa to 4000 kPa and temperatures from 22°C to 290°C, the injection nozzle did not leak measurable quantities of DME.

DME is known to adversely affect many types of plastics and rubbers, with the exception of PTFE (Teflon™) and butyl-n (Buna-N™) 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.

Vehicle fuel system and test cell guidelines were developed based upon the results of the previously mentioned investigations, experience gained from the modification of the Cummins engine and the FMEA of the fuel system.

Conclusions

- To minimize the potential for fire or explosion, incorporation of additional fuel handling/supply safety precautions is needed when operating a compression ignition engine on DME fuel.

- The injection nozzle leak-down tests indicated that new Bosch fuel injection nozzles provided a good seal against DME leakage in the needle and seat areas. Tests on worn injection nozzles are needed.

- The ongoing DME fuel system FMEA and engine test program is expected to identify additional DME fuel system safety issues.

SOMMAIRE

Ce projet avait pour objectifs de définir et d’étudier les principales menaces à la sécurité posées par l'utilisation du diméthyléther (DME) dans des moteurs à allumage par compression (diesel) et les circuits d’alimentation correspondants, et d’ébaucher une série de lignes directrices en matière de sécurité.

L’étude comportait deux grands volets, soit l’évaluation des robinets d’arrêt d’urgence du circuit d’alimentation et des injecteurs à aiguille du système d’injection de carburant, sous l’angle de leur compatibilité avec le DME et de leur sûreté, et la mesure des débits de fuite du DME en aval des injecteurs, de façon à déterminer le risque que subsiste du DME dans les chambres de combustion du moteur une fois celui-ci coupé. Les résultats de l’étude, y compris les conclusions tirées d’essais d’un moteur diesel turbocompressé Cummins de 5,9 L brûlant du DME, ont servi à élaborer des mesures de sécurité préliminaires. De plus, le moteur d’essai équipé de différents circuits d’alimentation a été l’objet d’une analyse des modes de défaillance et de leurs effets (AMDE). Les circuits d’alimentation étaient conçus de façon à minimiser les risques de fuite de DME dans les cylindres du moteur, la conduite de retour d’huile du carter, la pompe d’injection et l’atmosphère, et à minimiser les risques d’incendie ou d’explosion.

Pendant la plupart des essais sur moteur, des fuites de DME ont été observées au clapet anti-retour et au 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 minimiser ainsi les fuites de DME. Ce nouveau piston, combiné à un système de lubrification haute pression et à un clapet anti-retour perfectionné, améliore grandement 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.

Un nouvel injecteur a été soumis à des essais d’étanchéité visant à déterminer le débit de fuite, en masse, de DME au delà de l’aiguille et du siège de l’injecteur : à des pressions comprises entre 687 kPa et 4 000 kPa et des températures de 22 °C à 290 °C, les fuites de DME se sont révélées négligeables.

Le DME est reconnu pour causer la détérioration de nombreux élastomères. Font exception le PTFE (Téflon^{MD}) et le caoutchouc (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 caoutchouc 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’étincelle. 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.

Enfin, des lignes directrices concernant les circuits d'alimentation en carburant et les bancs d'essai ont été élaborées, à la lumière des résultats des recherches déjà mentionnées, de l'expérience acquise lors de la modification du moteur Cummins et de l'AMDE portant sur le circuit d'alimentation dudit moteur.

Conclusions

- Pour minimiser les risques d'incendie ou d'explosion, il est impératif de prévoir des mesures de sécurité supplémentaires touchant la manutention du carburant et le remplissage des réservoirs, lors de l'utilisation de DME dans un moteur à allumage par compression.

- Les essais d'étanchéité des injecteurs ont révélé que les nouveaux injecteurs Bosch assuraient une protection satisfaisante contre les fuites de DME au delà de l'aiguille et du siège de l'injecteur. Il y a lieu de poursuivre les essais sur des injecteurs usés.

- La suite de l'AMDE touchant les circuits d'alimentation en DME et du programme d'essais sur moteur devrait permettre de cerner d'autres enjeux reliés à la sûreté des circuits d'alimentation en DME.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AET	Advanced Engine Technology Ltd.
CI	Compression Ignition
DAS	Data Acquisition System
DME	Dimethyl Ether
FIE	Fuel Injection Equipment
FMEA	Failure Mode and Effect Analysis
IEA	International Energy Agency
NOx	Oxides of Nitrogen
NRCan	Natural Resources Canada
TDC	Transportation Development Centre
ULEV	Ultra Low Emission Vehicle

1. INTRODUCTION

New regulations aimed at lowering diesel engine emissions levels are being implemented in most industrialized countries. In North America, both the US Environmental Protection Agency and the California Air Resources Board have adopted emissions limits covering the full range of engine sizes. Canada is expected to implement US regulations for 1998. As emission standards continue to tighten, substantial engine research and development will be required to reduce engine exhaust emissions levels. Early indications are that expensive engine/fuel injection equipment (FIE) 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 (ULEV) emissions requirements to be met without the addition of expensive emissions systems. Of particular relevance is its almost smokeless operation, low NOx 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 towards achieving 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, Natural Resources Canada (NRCan) Transportation Energy Technology Division contracted Advanced Engine Technology Ltd. (AET) to perform a literature search in conjunction with limited in-house testing of DME (Phase I). A Phase II federal government/industry cooperative study based on the Phase I recommendations, has been initiated and the first 16 months of this study have been completed. The main objective of the Phase II study is to investigate the feasibility of developing a cost effective fuel system for diesel powered vehicular applications. A 5.9 litre Cummins diesel engine from a Dodge Ram pickup truck was acquired for test purposes. One cylinder of the 6 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).

As part of DuPont's industrial participation (DME supplier) in the Phase II portion of the study, they requested that AET's test cell fuel handling/storage and dispensing systems undergo a risk assessment and safety audit. DME is more flammable (lower flash point temperature and lower auto-ignition temperature) than diesel fuel and as such engine operation on DME requires special safety precautions (refer to Appendix A). In addition, DME has very high rates of thermal expansion and low electrical conductivity. AET has worked closely with DuPont to incorporate several safety features into the overall DME fuel system.

In the course of developing the AET fuel system, a number of safety issues were identified. Some of these issues were not well understood by the DME North American industry when the Phase I and II studies were initiated. One of the less well understood safety issues is the problem of low conductivity of DME. A second recently identified safety issue is the need to use metal-to-metal valve seating to remove the difficulties of seating materials, like teflon, melting in the event of a fire. The low viscosity and low lubricity of DME make metal-to-metal valve seating in practical fuel systems a difficult obstacle to overcome and further research is required in this area.

As a result of the identification of these safety issues, a number of new research requirements evolved. AET was contracted by the Transportation Development Centre (TDC) to verify the major safety concerns and to develop a set of preliminary safety guidelines for an automotive fuel system designed for use with DME as an alternative diesel fuel. One portion of the DME safety-related study concentrated on 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 were investigated.

2. WORK ACCOMPLISHED

2.1 Description of DME Fuel System and System Safety Provisions

Design discussions were carried out with DuPont representatives regarding the components required for AET's laboratory DME fuel system with regard to safety concerns. Cadkey drawings of AET's DME engine/test cell/storage facilities were made and submitted to DuPont representatives for approval. Efforts were made to design the engine laboratory DME fuel system similar to the anticipated fuel system for vehicle applications (light duty truck), so as to simplify the conversion from a laboratory DME fuel system to a vehicle DME fuel system. Cadkey drawings were also made, based on the AET test cell fuel system design, showing the proposed components for the vehicle DME fuel application.

An AET representative attended the 3rd International Energy Agency (IEA) Workshop on DME in Naperville, Illinois, on February 26 and 27, 1998. It was concluded at the workshop that all DME fuel system research participants would prepare an outline of their proposed vehicle fuel system, to be submitted to IEA for Failure Mode and Effect Analysis (FMEA). Significant effort was directed towards preparing a FMEA for a DME fuel system to be employed for light-duty vehicle applications (please refer to Appendix B). The vehicle fuel system was designed to minimize the potential for DME leakage into the engines' 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 the 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.

It was important to demonstrate that the AET engine/test cell fuel system could be operated effectively before expanding the effort on performing an FMEA for the proposed vehicle fuel system. The ongoing engine test program has been performed in AET's Test Cell #2 using a 5.9 litre Cummins diesel engine (typically used in Dodge Ram pickup trucks) connected to an eddy current dynamometer (please refer to Appendix D - Figure 1). A computer data acquisition system has been used to acquire engine speed and temperatures as well as cylinder pressure for the DME fuelled cylinder (please refer to Appendix D - Figure 2).

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

a) 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.

b) The DME fuel tank and fuel line were grounded to prevent electrostatic charge buildup and discharge, thereby further minimizing the possibility of generating a spark that might lead to a fire situation.

c) 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.

d) 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.

e) Remotely activated emergency shutoff valves were used to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire.

f) A blowdown valve was used 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).

g) Provision was made to have water spray available to cool the DME fuel tank in the event of a fire. Cooling the tank 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.

h) 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.

Initially the AET - DME fuel injection system employed a typical diesel fuel injection pump operated on diesel fuel (please refer to Appendix D - Figure 3), a Bosch fabricated shuttle valve and a check valve to provide a mechanism for timed injection of DME into the cylinder of the test engine. Diesel fuel was used merely as a pumping medium and was not injected into the cylinder of the engine for combustion purposes. Difficulties were encountered during much of the engine test program with DME leakage past the check valve and shuttle valve systems resulting 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. As a result, 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 the potential for momentary 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 consequently engine performance. Modifications were made to the fuel system to incorporate the new check valves. 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 check valves were tested, each iteration required significant effort to modify the fuel system for each check valve evaluation. Near the end of the safety study a satisfactory check valve was determined.

Design modifications were made in an attempt 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 shuttle valve were made to the original shuttle valve concept in an attempt to improve sealing. Only minor success was observed due to excessive clearances between the shuttle valve and valve body as supplied by Bosch. Additional shuttle valves with reduced clearances were fabricated by Bosch and forwarded to AET to replace the original shuttle valves, with the intent to improve sealing. However, no significant improvements were observed.

Further discussions were carried out with Bosch in an attempt 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 (please refer to Appendix B). 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 stresses on the shuttle valve and return spring.

In addition to the AET fabricated shuttle valve, a high-pressure system was made to lubricate the shuttle valve, in an attempt to reduce the anticipated high wear rates associated with exposure of the shuttle valve to neat DME without lubricity 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 fabricated shuttle valve system, with 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. Although consistent DME injection and smooth combustion were achieved at all loads and speeds, peak 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, due to a limitation in the quantity of fuel that could be injected into the cylinder and inadequate fuel injection timing. It was concluded that additional work would be required to provide optimized injection timing and delivery quantities over the entire range of engine speed/load conditions, based on cylinder pressure and fuel line pressure traces as well as needle lift traces. It is anticipated that optimization of the DME fuel system will require further modifications to the injection nozzle orifice diameters and possibly the addition of a fuel injection timing advance mechanism controlled by engine speed.

2.2 Research on Valves for DME Fuel System Application

Substantial effort was directed towards investigating and comparing valves suitable for vehicular and laboratory fuel systems. Discussions were carried out with DuPont representatives, valve and seal manufacturers, as well as other DME fuel system participants, regarding the choice of materials and various valve safety aspects. It was determined that DME (which also contains small amounts of methanol) adversely affects many types of plastics and rubbers, with the notable exceptions of Teflon and Buna-N rubber. Teflon, although compatible with many chemicals including DME, also has some drawbacks for use in DME fuel systems. DME generates very low temperatures upon vaporization. Temperature cycling between low and ambient or high temperatures can result in teflon embrittlement thereby compromising the sealing capabilities of Teflon in a valve application. In addition, during a fire situation Teflon and Buna-N may melt, resulting in reduced sealing and the potential for DME to leak from the valve adding to the seriousness of the fire. It was concluded that metal to metal sealing with non-sparking metals such as stainless steel or brass would be the most effective type of seal provided that the surface finish/valve seat designs were adequate for the application. NPT fittings were not recommended; instead all fittings should be butt-welded ANSI flanges.

Based on initial recommendations from DuPont representatives and discussions with valve manufacturers, two fire-safe 1/4 turn ball valves with graph-oil packing were ordered to be used as emergency DME shutoff valves in the AET laboratory DME fuel system. Graph-oil packing was recommended by DuPont based on its high temperature capabilities and resistance to temperature cycling. These type of valves are designed to withstand fire situations without allowing fuel (DME) leakage.

2.3 Fuel Mass Leak Measuring System

A DME fuel mass leak rate measuring system was fabricated to determine the rate of DME leakage past the 5.9 L Cummins engine fuel injection nozzle needle and seat. It was anticipated that significant DME leak rates past the injection nozzle would result in DME entering the DME fuelled cylinders upon engine shutdown. Upon engine startup, the cylinder and/or crankcase would be full of DME vapor which could cause excessive combustion pressures, combustion knock, high engine speeds and possibly a crankcase explosion.

The fuel mass leak rate measuring system consisted of a weigh scale, pressure vessel, high pressure fuel line, fuel injection nozzle and thermostatically controlled heating system (please refer to Appendix D - Figure 4). 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.

2.4 Leak Rate Tests

Initial DME leak rate laboratory tests were carried out using a new Bosch fuel injection nozzle with the nozzle return vent plugged, such that all DME leakage would occur from the injection nozzle needle and seat. Four stages of testing were used to evaluate the injection nozzle leak rates as summarized in Table 1.

In Stage #1, the DME pressure vessel was charged to a pressure of 100 psi and the injection nozzle temperature maintained at 75°F. Over a 7-hour test period, no measurable leakage of DME could be determined using the weigh scale. In Stage #2, the DME pressure vessel was charged to a pressure of 150 psi and the injection nozzle was heated to a temperature of 155°F. Over a 12-hour test period, no measurable leakage of DME could be determined using the weigh scale. In Stage #3, the DME pressure vessel was charged to a pressure of 150 psi and the injection nozzle temperature cycled between 75°F and 550°F every 30 minutes. Over a 35-hour test period, no measurable leakage of DME could be determined using the weigh scale. In Stage #4, the DME pressure vessel was charged to a pressure of 600 psi and the injection nozzle temperature was maintained at 75°F. Over a 3-hour test period, no measurable leakage of DME could be determined using the weigh scale.

High injection nozzle temperatures were not used with 600 psi in the DME pressure vessel due to fire safety concerns. It was concluded that the new injection nozzle needles and seats would provide a good seal against DME leakage. The effects of needle and seat wear and/or deposits in the needle and seat area on sealing were not determined. It is recommended that additional testing be performed to evaluate DME leakage on worn injection nozzle needle and seats.

Test Stage	Duration (hours)	Temperature (°C)	Pressure (kPa)	Leakage (%)
1	7	22	687	0
2	12	68	1000	0
3	35	24 - 290	1000	0
4	3 (end of June 1998)	24	4000	0

Table 1: **Injection Nozzle Leak Rate Test Summary**

The highest test temperature employed (290°C) is significantly more severe than the conditions to which the injection nozzle would be exposed to either in operation or upon engine shutdown. The test pressures are significantly more severe than the conditions to which the injection nozzle would be exposed to upon engine shutdown.

Additional testing was carried out with the injection nozzle return vent unplugged as would be the case on the engine. It was demonstrated that the quantity of DME in the high pressure injection line would vent through the injection nozzle return within in a few minutes of engine shutdown to near atmospheric pressure. As such, DME could leak past the injection nozzle needle into the engine's cylinder only during the short time period after engine shutdown when the DME pressure in the high pressure line was above atmospheric.

3. VEHICLE FUEL SYSTEM DESIGN GUIDELINES

The following design guidelines refer to a DME fuel system based on the AET laboratory engine DME fuel system design (please refer to Appendix C). It is anticipated that the AET - DME fuel system design would differ from other DME fuel system designs only 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.

The following preliminary general design 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. Due to the poor electrical conductivity of DME, DME fuel system components are susceptible to electrostatic charge build. 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.

- NPT fittings in the DME fuel system are not recommended; instead all fittings should be butt-welded ANSI flanges.

- A fuel storage level fill shutoff system should be employed to ensure that the reservoir is not filled above the 80% full level thereby allowing room for expansion of the DME during varying ambient temperature conditions. DME has a high thermal expansion rate and as such it is necessary to leave 20% 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 used 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 shutoff 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 shutoff (fire-safe) valves, constructed from DME compatible materials, should be used 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 would 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 road 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 crash worthiness. It is anticipated that employing safety measures similar to those used on propane vehicles would provide a good starting point.

- Lubricity 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 can cause engine overspeeding since the rate of fuel entering the engine will 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 it is injected under high pressures.

As indicated in Section 2.1, the final AET - DME fuel injection system employed a typical diesel fuel injection pump operated on diesel fuel (please refer to Appendix D - Figure D-3). An AET fabricated shuttle valve based on Bosch injection system components (please refer to Appendix B) and a check valve were used to provide a mechanism for timed injection of DME into the cylinder of the test engine. Diesel fuel was used merely as a pumping medium and was not injected into the cylinder of the engine for combustion purposes. This system was the basis of the initial Failure Mode and Effect Analysis (FMEA) for light-duty vehicle applications. The FMEA was prepared and presented to the participants of the IEA/AMF Appendix 14 - R&D Task 3 Workshop in Graz, Austria during July 9 and 10, 1998. This FMEA, attached in Appendix C, forms the basis for the specific light-duty design guidelines that follow.

4. STUDY CONCLUSIONS

The following conclusions were drawn with regard to safety concerns relating to the use of DME in CI engines for laboratory testing and light-duty vehicle applications:

- DME is more flammable (lower flash point and higher vapor pressure) than diesel fuel, as such 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 fire.

- 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 traces of methanol typically found in commercial DME.

- Fire-safe ball valves with graph-oil packing are recommended for use as emergency DME shutoff valves. Graph-oil packing was recommended by DuPont based on its high temperature capabilities and resistance to temperature cycling. These type of valves are designed to withstand fire situations without allowing fuel (DME) leakage.

- It can be concluded that new Bosch fuel injection nozzles provide 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.

- It can be concluded that the quantity of DME in the high-pressure injection line would leak through the injection nozzle return into the purge tank (refer to Appendix C) within a few minutes of engine shutdown, minimizing the opportunity for DME to leak past the injection nozzle needle into the engines' cylinders.

- The fabricated shuttle valve system with 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. Although consistent DME injection was achieved it was concluded that additional work would be required to provide optimized injection timing and delivery quantities over the entire range of engine speed/load conditions, based on cylinder pressure and fuel line pressure traces as well as needle lift traces. It is anticipated that optimization of the DME fuel system will require further modifications to the injection nozzle orifice diameters and possibly the addition of a fuel injection timing advance mechanism controlled by engine speed.

5. CONCLUDING DISCUSSION

In conclusion, DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emission regulations. Operation of AET's test engine (one cylinder) on DME has indicated consistent DME injection and smooth combustion at all engine speeds and loads. Peak output torque from the DME fuelled cylinder was approximately the same as for the diesel-fuelled cylinders at engine speeds below 1500 rpm. At higher engine speeds output torque decreased due to a limitation in the quantity of fuel which could be injected into the cylinder and inadequate fuel injection timing. Based on cylinder pressure and fuel line pressure traces as well as needle lift traces, it was concluded that additional work would be required to provide optimized injection timing and delivery quantities over the entire range of engine speed/load conditions. It is anticipated that optimization of the DME fuel system will require further modifications to the injection nozzle orifice diameters and possibly the addition of a fuel injection timing advance mechanism controlled by engine speed.

It can be concluded that there is a need to incorporate additional fuel handling/supply safety precautions when operating a compression ignition engine on DME fuel to minimize the potential for fire or explosion. DME is significantly more flammable (lower flash point 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 the aforementioned metals should be constructed from Teflon or Butyl-N rubber, which are chemically resistant to DME and traces of methanol typically found in commercial in DME. Fire-safe ball valves with graph-oil packing are recommended for use as emergency DME shutoff valves. The graph-oil packing provides high temperature capabilities and resistance to temperature cycling, allowing the valve to seal even during a fire situation.

It can be concluded from the injection nozzle leak-down tests that new Bosch fuel injection nozzles provide a good seal against DME leakage in the needle and seat areas. Even if a small leak was to occur at the injection nozzle needle during engine shutdown the bulk of the DME in the high pressure injection line would leak through the injection nozzle return into the purge tank (refer to Appendix C) within a few minutes.

It is anticipated that additional DME fuel system safety issues will be highlighted through the ongoing DME fuel system FMEA. Safety considerations addressed during this study will assist in the development of a DME-fuelled vehicle that generates lower emissions levels than a comparable diesel-fuelled vehicle with similar safety characteristics.

6. RECOMMENDATIONS FOR FOLLOW-ON WORK

Although consistent DME injection was achieved, it was concluded that additional work would be required to provide optimized injection timing and delivery quantities over the entire range of engine speed/load conditions, based on cylinder pressure and fuel line pressure traces as well as needle lift traces. It is anticipated that optimization of the DME fuel system will require further modifications to the injection nozzle orifice diameters and possibly the addition of a fuel injection timing advance mechanism controlled by engine speed.

REFERENCES

[1] Christensen, R., Sorenson S. C., Jensen M. G., Hansen, K. F. "Engine Operation on Dimethyl Ether in a Naturally Aspirated, DI Diesel Engine", SAE Paper 971665, 1997.

[2] Sorenson, S. C., Glensvig, M., Abata, D. L., "Dimethyl Ether in Diesel Fuel Injection Systems", SAE Paper 981159, 1998.

[3] Ofner, H., Gill, D. W., Krotscheck, C., "Dimethyl Ether as Fuel for CI Engines - A New Technology and its Environmental Potential", SAE Paper 981158, 1998.

Appendix A

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

APPENDIX A

Table A-1: Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Properties	DME	Propane	Diesel
Chemical Formula	CH3OCH3	C3H8	CnH1.8n
Mol. 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 -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 Elast. - Pa @ 25 C & 20 bar	0.05x10-10		0.2x10-10
Cetane Number	~70	~20	40 to 50

Appendix B

AET - DME Fuel System Shuttle Valve

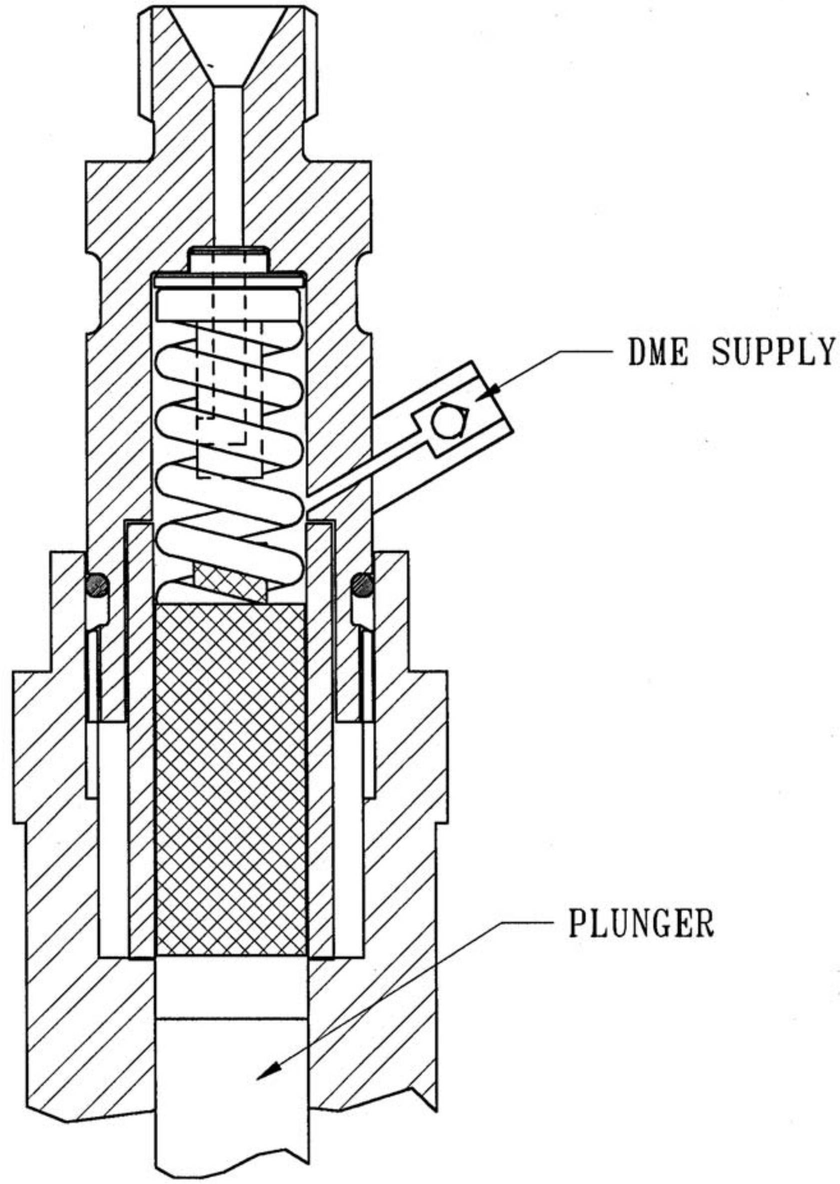

Figure B-1: AET DME Fuel System Shuttle Valve

BARREL CLAMP TOWER

SHUTTLE VALVE BARREL

INJECTOR PUMP BARREL

SHUTTLE VALVE

Appendix C

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

(Not available in electronic format/ Non disponible en format électronique)

Appendix D

Photographic Documentation of
AET Research Engine/DME Apparatus

(Not available in electronic format/
Non disponible en format électronique)