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INFLUENCE OF FUEL VARIABLES ON THE OPERATION OF AUTOMOTIVE OPEN AND PRE-CHAMBER DIESEL AND SPARK IGNITED STRATIFIED CHARGE ENGINES: A LITERATURE STUDY COVERING PETROLEUM AND SYNCRUDE DERIVED FUELS

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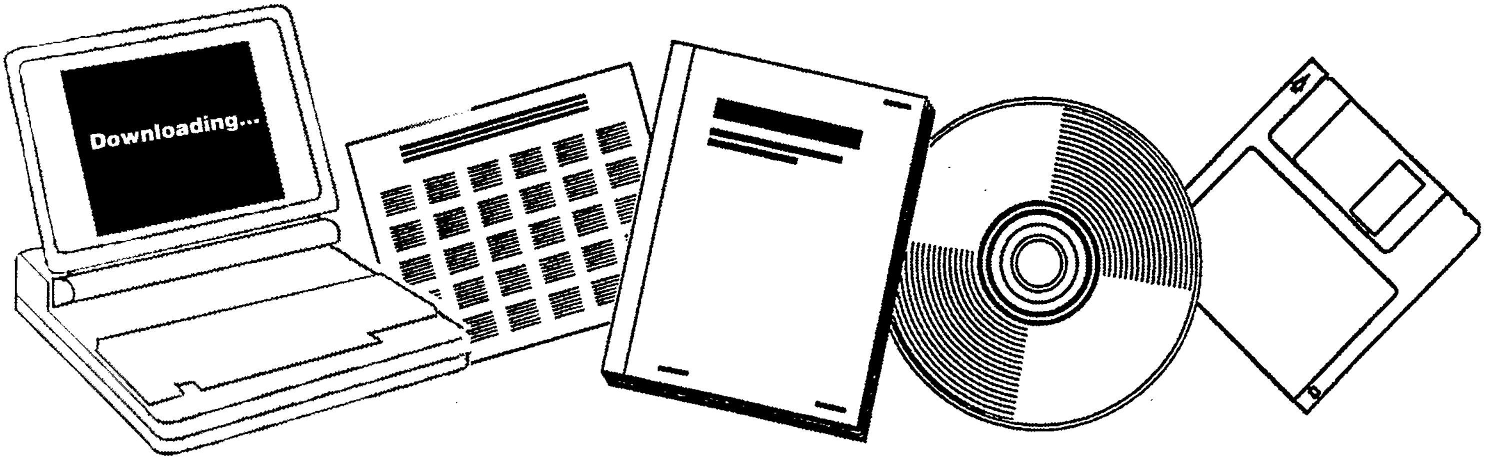

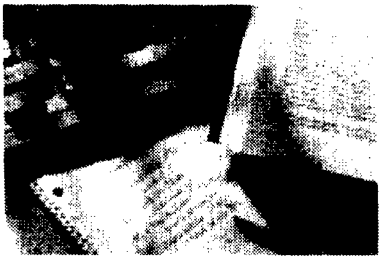

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The Influence of Fuel Variables on the Operation of Automotive Open and Pre-Chamber Diesel and Spark Ignited Stratified Charge Engines:

A Literature Study Covering Petroleum and Syncrude Derived Fuels

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ABSTRACT

A literature study has been carried out to ascertain the influence of fuels and fuel variables on the operation of automotive diesel and spark ignited stratified charge engines with a view to understanding the impact of future fuels derived from Syncrude. The findings from the search are presented and discussed in detail, conclusions reached and recommendations made.

CONTENTS

Page No.

Page No.

Page No.

APPENDIX 11 THE M.A.N. FM COMBUSTION SYSTEM 193 - 199

27 March 1981

1. INTRODUCTION

It is an unequivocal fact that without access to vast resources of energy the United States and other civilised countries would not exist as we know them today nor could they continue to do so. This energy is required to fuel industry and transport both of which dictate the social and economic climate. At present in the US, domestic energy production is declining whilst demand increases. To combat this deficit and preserve social and economic standards, an energy policy revolving around expanded development of domestic supplies or increased importation is required.

The latter alternative would not seem attractive in view of recent experience with oil embargoes and price escalations. In addition the desire for OPEC nations to extend the time scale of maintained buoyant economies due to energy autonomy makes it doubtful that production would be increased to satisfy demand.

Regarding domestic supplies, recent future energy projections suggest that unrestricted exploration and development of new sources of natural gas and oil would only result in a temporary escalation of energy production peaking in the period 1990-95 (1)*. The fall in output after this period dictates that the US must develop a syncrude industry by the 1990-95 era to avoid reliance upon the vulnerable option of high import levels.

Utilising technology which has been under development for many years, syncrude can be extracted from coal and oil shale for the manufacture of liquid hydrocarbon fuels. The refining of such synfuels will therefore form an integral part of the syncrude industry.

Regarding engines for road transport, the reciprocating internal combustion engine has been utilised virtually exclusively, a trend which is likely to continue in the future (2). Over the years, these engines have been developed to operate on fuels of a specific type. Gasoline engines require fuels of high octane rating to avoid detonation when utilising high compression ratios for improved efficiency, whilst at the other end of the spectrum, the compression ignition diesel engine requires a fuel of high self ignition characteristics and is therefore naturally intolerant of high octane gasoline fuels.

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* Numbers in parentheses designate references listed in the bibliography.

In embarking upon an energy policy incorporating the use of alternative fuels such as syncrude products, it is prudent to study the potential impact of these fuels upon the systems that will be exposed to their use. This is particularly valid for the automotive engine. In a recent study, "Identification of probable automotive fuels composition: 1985-2000" (1), it was concluded that projected specifications of automotive fuels within the time frame will not be significantly at variance with current fuels, as it is anticipated that syncrude will be blended with petroleum crudes and refined at conventional refineries. This view is based upon projected domestic fuel demands.

In reality, however, actual future fuel specifications may differ from current standards owing to, for example, deviations from projected domestic demand. In addition, a hitherto unused broadcut option seems attractive (1) from a refinery economics point of view. Knowledge of fuel/engine relationships, and indeed other fuel/systems relationships, will therefore still be vitally important to assist with defining the most cost effective adaptions for future fuels and should assist with refineries remaining flexible to optimise the use of syncrudes.

This report presents and discusses data pertaining to the fuel/engine relationship that can be extracted from published and Ricardo in-house literature to date, and aims to assist with the understanding of the potential impact of future automotive fuels upon power plant operation and requirements. The report provides a precursor (Task 1) to a complementary test programme under the same contract (Tasks 2 and 3). The range of data incorporated has broadly been restricted to fuels and engine types regarded as pertinent to the proposed test programme.

The complementary test programme, Tasks 2 and 3, is divided into a preliminary screening study, Task 2, followed by a more fundamental study, Task 3.

Task 2 will explore the operation of two standard, multi-cylinder, contemporary, light duty diesel engines representing indirect (IDI) and direct injection (DI) combustion systems. With these engines, a relatively narrow range of fuels will be utilised to screen the influence of such fuel variables as ignition quality and volatility upon performance and emissions without undertaking any fuel/engine optimisation.

The fundamental study, Task 3, will examine the influence of fuels upon several combustion systems encompassing IDI and DI diesel, and spark ignited stratified charge (TCCS, MAN FM, spark ignited Comet IDI diesel). This will be accomplished utilising a single cylinder engine and injection and/or ignition timing will be suitably varied to achieve a degree of optimisation for each fuel. Fuels will have wide ranging specifications.

2. OBJECTIVES

The objectives of this study are stated as follows:-

a) To perform a literature search of published and Ricardo in-house data relating to the use of alternative liquid fuels in internal combustion engines.

b) To survey the literature and to extract where confidentiality permits the data regarded as pertinent to the proposed test programme.

c) To analyse the pertinent data and to present the findings, recommendations and conclusions in a report in order to understand more fully the fuel/engine relationship.

3. SCOPE OF THE LITERATURE SEARCH

The literature search has been based on an examination of the following sources:-

a) Ricardo Library catalogues and indexes, including in-house databases, containing references from a wide range of published and unpublished literature. The latter covers Ricardo reports which have been utilised when confidentiality permits.

b) Published abstracts and indexes such as British Technology Index (B.T.I.), Motor Industry Research Association abstracts (M.I.R.A.), Institution of Mechanical Engineers Index (I. Mech. E.), American Society of Mechanical Engineers Index (A.S.M.E.) and Society of Automotive Engineers Index (S.A.E.).

c) External on line computer databases such as Compendex.

Utilising these sources, potentially useful references covering the use of alternative liquid fuels in internal combustion engines were located. These references were screened for information regarded as pertinent to the test programme using the selection criteria reported in section 4.

The literature search covers the period 1940 to c. June 1980.

4. PERTINENT DATA - SELECTION CRITERIA

The selection criteria for those data regarded as pertinent for inclusion in this study are broadly based upon the contents of the proposed test programme as follows.

4.1 Pertinent Fuels

For the complementary test programme, it has been decided to explore the fuel/engine relationship with a range of fuels whose leading parameters fully encompass the potential specifications of future broadcut fuels derived from syncrude. In the absence of actual syncrude products, it is proposed that petroleum derived diesel fuel and straight run naphtha will be blended to provide simulated broadcut fuels. In addition, the individual base fuels will also be evaluated.

The range of leading fuel parameters that will be studied are a function of the base fuels that will be utilised and are listed as follows:-

	No. 2 Diesel Fuel	Straight Run Naphtha
Cetane No.	c.45	c.27
Research Octane No.*	c.30	c.70
Distillation Range °F	c.400-700	c.190-400
Aromatic Content % Vol.	c.30	c.15
Sulphur Content % wt.	c.0.4	c.0.003
Gravity ° API	c.34	c.52

Broadcut blends of these fuels have intermediate properties dependent upon the blend ratio.

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* N.B. All references throughout this report to fuel octane numbers are research method unless expressly stated as motor method.

Notable by its absence from this scheme is high octane gasoline. This omission is deliberate and based upon the rationale that the most economically produced future broadcut fuels would not utilise high octane gasoline for blending, since the production of high octane gasoline is energy intensive owing to the various upgrading processes employed. Furthermore, power plants for which broadcut fuel will be designated will not include the conventional spark ignition gasoline engine thus eliminating the high octane requirement.

Based upon these experimental fuels for the complementary test programme, data that are regarded as pertinent for this study are defined by liquid petroleum fuels, with the exception of data relating to the evaluation of syncrude products which have naturally been included. Such fuels as alchohols, liquid gases and vegetable oils have therefore been excluded.

In addition, the influence of fuel additives such as cetane improvers, cold flow improvers, smoke suppressants, etc., have also not been expressly studied. Data involving the use of cetane improvers have however been included when utilised for specifically studying the influence of ignition quality.

4.2 Pertinent Engines

Pertinent engines have been isolated primarily by three major factors; namely: type of combustion system, means of fuelling and application.

4.2.1 Pertinent Combustion Systems

The following combustion systems based upon reciprocating piston engines have been designated for the test programme and are therefore regarded as pertinent to this study:-

a) Indirect injection diesel - IDI
b) Direct injection diesel - DI
c) Spark ignited, indirect injection diesel - (Ricardo Comet).
d) Spark ignited, direct injection - MAN FM.
e) Spark ignited, direct injection - Texaco Controlled Combustion System, TCCS.

Although in the test programme the IDI diesel will be represented by a Ricardo Comet V swirl chamber combustion system, it has been decided not to restrict this study solely to this system but to include other developed forms of swirl and pre-chamber engines.

Similarly, the test programme will also utilise a toroidal swirling DI engine and, by adopting the same philosophy as for the IDI diesel, data relating to the use of other developed forms of DI engine e.g. quiescent chamber, have been incorporated.

The three spark ignited systems are all of the 'late' injection type (i.e. injection commences later than 50° BTDC on compression stroke). Of these, the MAN FM and TCCS processes represent two of the most developed, late injection, open chamber, stratified charge engines. Other stratified charge processes with multi-fuel capability, e.g. Mitsubishi MCP and Deutz AD, are acknowledged in this report but not studied in detail.

The choice of these combustion systems is entirely logical. IDI and DI diesel engines currently represent the most fuel efficient power plants for automotive applications. For the future, it will be desirable to retain this advantage provided the specification of fuels permits. A study of the fuel/engine relationship for these combustion systems is therefore essential in order to be able to define acceptable minimum fuel requirements. The spark ignited systems chosen for detailed study all represent designs which have demonstrated multi-fuel capability although they have to date reached different levels of development status. All of these systems represent unthrottled, late injection, stratified charge engines. By being unthrottled like the diesel engine, high thermodynamic efficiency is obtained in the interests of good fuel economy. By employing late injection, excessive levels of pre-mixed combustion can be avoided with the resultant elimination of fuel octane requirement. The addition of a positive ignition source in the form of a sparking plug also avoids the necessity to use fuels of high cetane number. By using the sparking plug for ignition, thereby not relying on the natural cetane number of the fuel to attain compression ignition, as in the case of the multi-fuel diesel engine, wide fuel tolerance is achieved with favourably lower compression ratios. This provides the direct advantage of lower mechanical stresses and hence lighter engines and attenuated high friction levels characteristic of the diesel engine.

4.2.2 Pertinent Fuelling Methods

In keeping with the test programme, engines utilising pertinent combustion systems and fuels but incorporating dual fuelling, whether in the form of dual injection or aspiration with pilot injection,have also been excluded. Data have therefore been restricted to single fuel, single in-cylinder injection systems.

4.2.3 Pertinent Engine Applications

For this study, only engines classified as light to heavy duty, high speed automotive have been included. Non-automotive and low/medium speed engines for marine and locomotive applications have therefore been omitted. This is a generalised statement since in a few isolated cases data obtained from small non-automotive diesel engines have been included to provide corroborative support for results obtained from automotive types.

4.3 The Relevance of Omitted Data

The omission from this study of any fuel, combustion system, method of fuelling or engine application is not intended to suggest that similar studies of fuel/engine relationships covering these areas would not be beneficial. In fact they would be essential to encompass and comprehend fully the entire scenario.

These equally important areas are not studied here because it is considered that the inclusion and analysis of such data lie outside the scope of the work defined in the current contract.

4.4 Bibliography

Based upon these selection criteria, the references identified and utilised in the formation of this report are presented in the attached bibliography. In addition, some further references of potential interest were identified but were located too late in the programme to include in the report; these references are appended to the bibliography.

5. ANALYSIS OF PERTINENT DATA

For analysis, the data were broadly subdividied into two major classes as follows:-

- compression ignition combustion

- spark ignitied combustion

5.1 Compression Ignition Combustion

Analysis in this category has been carried out to develop information relating to the way in which leading fuel parameters influence the operation of compression ignition engines. This has been achieved, where data permit, by extracting the reported effects of fuel parameters, or fuel type, on the following topics:-

- Cold starting characteristics
- Exhaust smoke following cold starting
- Exhaust smoke at normal engine operating temperatures
- Performance, fuel economy, combustion characteristics, etc.
- Gaseous exhaust emissions
- Exhaust particulate emissions
- Potential health hazards of emitted particulates
- Noise
- Exhaust odour
- Engine deposits and wear
- Fuel injection equipment considerations

These topics are thought to represent areas of current interest. The format of the listing is not intended to indicate relative importance.

For each of these topics, where appropriate, the influence of the following fuel variables were investigated:-

- Ignition quality - cetane number
- Volatility
- Chemical composition
- Viscosity
- Density
- Impurities
- Low temperature performance
- Alternative fuels

Alternative fuels aside, the individual fuel variables have been investigated by various workers in differing degrees of isolation, as permitted by the complex nature of liquid hydrocarbon fuels and the strong inter-relationship of several of the variables. For this reason, fuel sets have frequently been utilised with wide ranging variables and the engine observations treated statistically, together with the fuel variables, to obtain the strongest relationships.

The inclusion of alternative fuels has been made to cover data relating to the use of, for example, jet fuels and gasolines in compression ignition engines. In this case all fuel variables can markedly differ. In the case of jet fuels, which can have specifications closely akin to diesel fuel, the results of the other "controlled" experiments could probably be used to predict their performance with varying degrees of reliability. In the case of radically different fuels however such as gasoline, major leading fuel variables generally lie outside the ranges explored during the "controlled" studies, and hence predictions of their performance could not reliably be made in all areas. Resort must therefore be made to the actual operational results. Furthermore, the simultaneous interaction of several variables, as in the case of alternative fuels, may provide completely different operational characteristics, making the validity of predictions from the "controlled" experiments suspect. In short, the results of the "controlled" and alternative fuels studies should be viewed in unison to provide a complete picture.

The analysis of these data revealed at an early stage that there are several major areas of disagreement, or differences in sensitivity regarding the influence of fuel variables upon the various facets of diesel engine operation. No doubt in many cases such differences could be more fully understood if comparisons of relative injection timings, or other leading engine parameters, could be made between test engines. Unfortunately, such valuable data are all too frequently not reported. Because of these areas of inconsistency between the reported observations and the lack of supporting data, it is not thought to develop an engine/ fuel model, so this has not been attempted. The various data have therefore been presented in some detail to illustrate this point and predictions have only been made where general agreement of observation permits, although speculative comments have been included. Owing to the differing sensitivities, such predictions are generally only of a qualitative nature.

5.2 Spark Ignited Combustion

Reported data for the three spark ignited stratified charge systems of direct interest to this project have been analysed under the following topics of for the different fuels utilised where results permit.

- Combustion characteristics
- Performance

- Fuel economy
- Gaseous exhaust emissions
- Response to gaseous exhaust emissions controls
- Exhaust particulate emissions
- Exhaust odour
- Noise
- Cold Starting characteristics

For these combustion systems, the various topics have been examined for the influence of fuel type where data permits and, in addition, comparisons with the compression ignition engine have been made.

5.3 Additional Analysis

From the findings of this search, it is clear that the analysis cannot be fully developed to cover comparisons of the various combustion chambers operating with different ranges of fuels. Consideration to the selection of suitable combustion systems for ranges of fuels has, however, been given in the report discussion.

6. PRESENTATION OF PERTINENT DATA FROM THE LITERATURE SEARCH

Following the comments made in Section 5 relating to the general inconsistency of trends and sensitivities when studying the influence of fuel variables upon aspects of diesel engine operation, it has been decided to present the findings of the search, in some detail, within appendices to the main document.

The various figures referred to in these appendices and attached to this report have been extracted or compiled from the various references consulted. They are presented to illustrate observations that have been made and are not summary results which represent generalised trends.

In this manner it has been attempted to keep the discussion of the report as succinct as possible. For reasons of continuity, the findings from the search pertaining to the spark ignited stratified charge combustion systems have also been restricted to the appendices.

Because the discussion, conclusions and recommendations of this document have in the main been evolved from the findings of the literature search, it is strongly recommended that the reader should initially become familiar with the contents of these appendices.

The appendices are formulated as follows:-

6.1 Data relating to Compression Ignition Engines

Findings from the search relating to the influence of fuel variables or alternative fuels on the operation of compression ignition engines are reported as follows:-

Appendix 1 - The influence of fuel ignition quality - cetane number

Appendix 2 - The influence of fuel volatility

Appendix 3 - The influence of fuel chemical composition

Appendix 4 - The influence of fuel viscosity

Appendix 5 - The influence of fuel density

Appendix 6 - The influence of fuel impurities

Appendix 7 - Fuel low temperature performance

Appendix 8 - Alternative fuels

Where appropriate for each appendix, the topics listed in Section 5.1 are commented upon where data exists.

6.2 Data relating to Spark Ignited Stratified Charge Engines

Findings from the search in this area can be located as follows:-

Appendix 9 - The Spark Ignited Comet

Appendix 10 - The Texaco Controlled Combustion System - TCCS

Appendix 11 - The MAN FM combustion system

For each of these appendices, the topics listed in section 5.2 are covered, data permitting. In addition, a brief history and description of the system design and combustion process has been provided.

7. DISCUSSION AND CONCLUSIONS

This section has been subdivided as follows:-

In Part A, the influence of fuels and fuel variables upon various aspects of the operation of both diesel engines and the spark ignited stratified charge engines of direct interest to this study is discussed and conclusions reached.

In Part B, the suitability of combustion systems with respect to future fuels is discussed and conclusions drawn.

In Part C, the overall conclusions of the study are stated.

PART A

7.1 Cold Starting Characteristics

7.1.1 Discussion

For successful cold starting, fuel must flow through the fuel systems. For future fuels having a wax content, low temperature flow performance should be comparable to current fuels. The relative importance of such parameters as cloud, pour and cold filter plugging points, with respect to low temperature flow, will therefore need to be determined.

Under cold starting conditions, the startability of diesel engines is closely linked to cetane number, the sensitivity being particularly pronounced for cetane number below c. 40-50 for most engines. Startability is defined as the time to sustained running without assistance from the starter motor. In the case of the DI diesel engine the time to both firing and sustained running is influenced by cetane number. In the case of the light duty IDI diesel engine fitted with heater plugs, it is generally believed that the time to first fire is relatively insensitive to cetane number since the heater plug acts as a positive ignition source. The influence of cetane number becomes critical therefore for maintaining sustained running.

For both engine classes, the cetane number required for good startability can be in excess of that required for normal operation.

In the case of the heavy duty DI engine, cylinder temperatures and pressures are low during cranking due to a combination of factors. These include low ambient temperature and air charge loss due to losses past the piston and the intake valve after bottom dead centre. The resultant low temperatures and pressures are not conducive to obtaining auto-ignition and hence fuels of higher cetane number are beneficial for attaining first firing without excessive cranking.

The same physical problems also exist for the light duty diesel except that, in this case, the positive ignition source supplied by the heater plug should result in virtually instant first fire independent of cetane rating.

Following firing, sufficient power must be developed to overcome engine friction and hence allow sustained running without assistance from the starter and acceleration up to the governed idle speed. In the case of the IDI engine, the heater plugs remain active until the engine begins to accelerate, the starter motor is thrown out and the key is released. In this manner, the heater plugs probably assist in the initial development of sustained running by providing early ignition of the fuel. Shortly after the key is released, however, and the plugs cooled, the ignition quality of the fuel must be commensurate with providing early ignition in order to attain sufficient power output to achieve sustained running and accelerate the engine to idle. It is during this period that high cetane number is beneficial. The same situation for the DI engine exists, except that the initial development of sustained running assisted by the heater plugs is not available, and startability can therefore be characterised by more prolonged cranking periods.

Because such factors as compression ratio, valve timing and cranking speed can have a profound influence upon startability it is not possible to quantify accurately minimum cetane requirements, although guidance can be offered.

It is known from existing operational experience that heavy duty DI engines will start unaided with fuels of c.42-45 cetane down to ambient temperatures within the range 15-5°F (-10 to-15°C) although cranking times, dependent upon compression ratio, cranking speed, battery condition etc., may be high i.e. c.40-60 seconds. In the case of the light duty IDI engine with adequate heater plug capacity, starts can be made down to ambient temperatures of

5 to - 13°F(-15 to -25°C) with relatively instant response to the key.

For both classes of engine, starting can be extended to much lower ambient temperatures if required by the use of external aids such as ether or manifold flame heaters.

In the case of current diesel engine designs, these unaided starting characteristics are regarded as acceptable. Owing to the high sensitivity of starting characteristics with cetane number within the range under consideration, it is speculated that further cetane reduction to c.35 with future fuels will seriously affect the startability of many engines at low ambient temperatures without the proliferation of the use of external aids. The extent to which this may create a problem depends upon application.

In the case of the heavy duty DI engine, the use of lower ignition quality fuels and the attendant requirement for even longer cranking time and/or more frequent application of external aids is not thought to pose a problem from the driver's point of view provided a start is ultimately achieved. In the case of the operator, there are of course the potential disadvantages of reduced starter motor life, larger battery capacity and the need to specify such items as manifold flame heaters. In the latter case, the relative percentage increase in first cost would be small.

For the light duty IDI diesel, starting ability must remain competitive with the gasoline engine. The inability to obtain sustained running within c.3-5 seconds of key application will be judged as unacceptable. Similarly the need to resort to ether will also be unacceptable whilst the use of manifold flame heaters may pass unnoticed if programmed to the key. Such devices would, however, need to have rapid response in order to act beneficially within the cranking period limitations. These additional features may however be unattractive from a first cost standpoint. The light duty diesel will also be judged unacceptable alongside the gasoline engine if the use of these lower cetane fuels induces misfiring or adversely influences throttle response and hence driveability following cold starting. It is thought that this could be a potential problem, especially in the case of vehicles retarded for NOx control and may require the adoption of low engine temperature fuel injection advance mechanisms. In this case, noise levels may be penalised.

The cold start performance of light duty IDI diesel engines with fuels of this cetane range has to remain speculative as reliable data with representative engines were not located. It is however anticipated that the previously stipulated acceptability limits may not readily be met. In this case, the attainment of acceptable starting characteristics may be achieved by the application of increased compression ratio and/or advanced inlet valve closing.

Regarding increased compression ratio, light duty IDI engines already utilise high compression ratios of typically 20-23:1 for improved cold operability. Raising compression ratio beyond these values without penalising air utilisation will require reducing cylinder lost volumes. This can be achieved by reducing piston to head clearance and/or minimising valve pocket volumes. The former variable is already a limiting factor and cannot therefore be altered. In this respect, under-square engines will be less sensitive when raising compression ratio compared with over-square engines. Valve pocket volume can be reduced by minimising valve recesses. This will automatically lower engine rating by attenuating the high speed breathing potential due to the requirement for small or zero overlap camshafts to avoid piston/valve clash. Similar penalties will also exist if the inlet valve closure is advanced to improve cold starting.

Other potential solutions that should prove beneficial in respect of cold starting with low cetane fuels would be the provision of combustion chamber thermal insulations and attention to chamber geometry to minimise surface to volume ratio.

In the case of the heavy duty DI engine, the same philosophies will be applicable to improving cold starting characteristics although the air utilisation penalty due to raised compression ratio should not be as accentuated and corrective actions may not be required.

In both classes of engine, raising the compression ratio will adversely influence rating in some cases due to maximum cylinder pressure limitations with current crankshaft/con-rod/piston pin assemblies. This will be especially true for turbocharged applications and the light duty IDI engines based upon the current US philosophy of dieselisation based upon gasoline components. In these cases, redesign would be necessary to avoid de-rating with all of the obvious implications whilst, in addition, larger components would be required to reduce stresses and bearing loads with the attendant adverse effects upon friction levels and weight.

To avoid these redesign or de-rating problems, the wider spread use of external starting aids may therefore have to be considered. In the case of the IDI, heater plug thermal capacity may be raised or plugs programmed to stay energised after key release.

For fuels of even lower cetane number, i.e. c.30, the DI engine will most certainly require somewhat higher compression ratio and the use of external aids. In the case of the IDI, the same design changes would prove beneficial although the use of heater plugs programmed to stay energised after key release may continue to be adequate. In this context, heater plugs could be fitted to DI engines although there will be practical limitations in smaller cylinder sizes.

For fuels of very low ignition quality, i.e. c.20-25, the diesel engine will require considerable modifications for cold starting in the direction of the multi-fuel developments of the recent past along with the resultant imposed penalties. These penalties are more fully discussed later in this report.

If fuels of such low ignition quality are foreseen for the future, spark ignited stratified charge systems will become attractive in respect of cold starting and warm-up performance. Of the systems under consideration in this study, the TCCS system appears to have demonstrated unaided startability at low temperatures with all fuels to a degree that can be extrapolated to acceptable standards for light duty applications. Although actual data are not available at low temperatures, it is reasonable to assume that the spark ignited Comet will also provide acceptable starting characteristics, whilst the MAN FM may require intake pre-heating if low volatility fuels are utilsied owing to the characteristic spraying of the fuel onto the combustion chamber wall.

In the context of volatility, it has been demonstrated that the adverse influence of low cetane number on starting can be somewhat offset by increased volatility. This is obviously due to the more readily formable pre-mixed fuel in which ignition is known to occur. Whilst this is entirely coherent and implies that broadcut fuels of low cetane may present easier starting characteristics than low cetane fuels of diesel distillation range, the experience of EPA should be noted. In this case, EPA observed difficult starting of a light duty IDI vehicle with a 100-600°F broadcut fuel of 35 cetane, implying that volatility cannot completely offset the deleterious effect of low ignition quality.

In the case of hot starting, higher volatility fuels can impose problems due to vapour locking with high under-bonnet temperatures. To avoid this problem, it will be necessary to equip vehicle fuel systems with electric fuel pumps to purge the fuel system via the injection pump of vapour for several seconds prior to starting after hot soaking. This poses an additional operational problem should future broadcut fuels be adopted.

Logically, it has been reported that fuels of low viscosity can aggravate starting. This occurs in engines where pump internal leakage is significantly affected by viscosity with the resultant reduction in excess starting fuel. This will not prove problematical in the application of future fuels as suitable compensations would be made.

7.1.2 Conclusions

a) Low temperature flow performance of future fuels will need to be comparable with current fuels. The relative importance of cloud, pour and cold filter plugging points will need to be determined.

b) Ideally, future fuels for diesel engines should have cetane numbers of c.42 minimum to ensure the retention of acceptable cold starting characteristics. The adoption of a more volatile broadcut fuel with this ignition quality may in fact tend to improve starting, providing excess fuel delivery characteristics are maintained.

c) Reducing cetane number to c.35 will generally adversely influence cold starting characteristics. In the case of heavy duty DI applications, it is considered that the implications may be tolerable to the driver but have commercial repercussions for the operator. In the case of the light duty IDI diesel with more stringent acceptability standards, it is speculated that these standards may not be reliably met at low ambient temperatures with current designs.

d) To obtain acceptable cold starting at low ambient temperatures with fuels of c.35 cetane, engines may require modification to incorporate higher compression ratio or revised valve timing. This will have adverse implications upon engine rating or in some cases require redesign with attendant frictional and weight penalties. To overcome this, the wider adoption of external aids will be required and in the case of the light duty IDI, the use of larger capacity heater plugs or plugs which stay energised after key release should prove beneficial.

e) For fuels of even lower cetane number, i.e. c.30, DI engines will require design modifications and the widespread adoption of external aids. In the case of the IDI engine, design modifications will prove beneficial although continuously energised heater plugs should continue to be adequate.

f) For fuels of very low cetane number, i.e. c.20-25, the spark ignited stratified charge system becomes attractive in respect of cold starting.

g) Increased volatility assists in offsetting lower cetane number. Limited evidence suggests however that a broadcut fuel of c.35 cetane will provide difficult starting in a standard light duty IDI vehicle.

h) Attention must be paid in the future to ensure that lower viscosity broadcut fuels do not penalise excess starting fuel delivery characteristics due to internal pump leakage.

i) With more volatile broadcut fuels, hot starting may prove difficult due to vapour locking if pre-start purge facilities are not made available.

7.2 Exhaust Smoke Following Cold Starting

7.2.1 Discussion

It has long been appreciated that blue/white smoke emitted from diesel engines following cold starting is the result of unburnt or partially burnt fuel droplets released to atmosphere. Frequently termed cold smoke, the blue or white smoke cast is a function of droplet size which determines the light scattering characteristics. The smaller droplets (c.0.5µm mean diameter) result in blue smoke and the larger droplets (c.1.3µm) are responsible for white smoke.

The release of these droplets is the product of low cylinder temperatures and pressures following cold starting giving rise to long ignition delays resulting in marginal incomplete combustion. Furthermore, fuel deposited in the exhaust system during cranking is also expelled and aggravates cold smoking if starting characteristics are not good. Combustion under these conditions can be improved if high ignition quality fuels are employed. This, in combination with the influence of cetane number on starting characteristics, results in a strong relationship between cold smoking and ignition quality.

Since cold smoke is frequently highly lachrymatory, aesthetically undesirable and, in the case of certain legislative test procedures, a direct contributor to HC and particulate output, its control is important.

In the case of heavy duty DI engines, agreement between various results is excellent and all demonstrate that for a given ambient temperature, reducing the cetane number increases time to clear cold smoking at idle following start-up. These data demonstrate a marked sensitivity to ambient temperature, with cold smoking time being particularly sensitive to ignition quality at low ambient temperature.

The acceptability criteria for heavy duty vehicles to cold smoke severity and duration cannot be readily stipulated as standards are so dependent upon application and the environment in which starts are made. Acceptable standards are presumably met in most cases with current vehicles using today's typical diesel fuels with minimum cetane numbers of c.42.

The acceptability standards for cold smoke with the light duty IDI diesel are significantly more stringent than those for heavy duty vehicles. In this case, cold smoke must not be severe in intensity and should clear fully in less than c.60 seconds. In addition, at higher ambient temperatures in accord with the 1975 FTP test procedure, cold smoking should be negligible for compatibility with HC and particulate legislation. With current specification diesel fuels these standards are generally met.

The adoption of future fuels with lower ignition quality will aggravate cold smoking, especially at low ambient temperatures in both classes of vehicle. The extent to which this presents a problem will depend upon such factors as compression ratio and injection timing.

In both cases, the first step towards alleviating cold smoking with lower cetane fuels will be to ensure that starting characteristics are acceptable utilising the techniques discussed earlier. If for good starting compression ratio has been raised then this will also act beneficially upon cold smoke. One of the most important considerations will be to match the injection timing to the fuel to achieve minimum ignition delay during the running period after cold starting. These injection timings are most likely to be in advance of the requirements under similar hot running conditions. To avoid the risk of noise penalties, injection timing will need to be controlled by engine temperature.

Additional items will be advantageous in controlling cold smoke with lower cetane fuels. These include, in the case of the IDI engine, the retention of energised heater plugs and, for both classes of engine, the application of exhaust back pressure to increase load factor. The latter device is currently successfully utilised by Volvo. The application of a back pressure will be particularly beneficial in cases where for various reasons compression ratio cannot be raised.

For fuels of very low ignition quality, i.e. less than c.30, it is speculated that the DI engine will continue to cold smoke at idle even up to normal engine running temperature if resort to very high compression ratios and/or high exhaust back pressure is not taken. The use of such high compression ratios will be undesirable in the context of mechanical stresses at higher load factor whilst under some operating schedules; the high idling fuel consumption as a result of elevated exhaust back pressure will not be attractive. In the case of the IDI engine, it is felt that energised heater plugs will continue to be beneficial.

It is also felt that exhaust gas recycle (EGR) may prove effective in being able to control persistent cold smoke with low cetane fuels. Similarly, combustion chamber thermal insulation may be advantageous.

With fuels of such low ignition quality, the spark ignited stratified charge engine should provide effective control of cold smoke although this cannot be supported by experimental evidence. The possible exception to this is the MAN FM system which appears to cold smoke on less volatile diesel type fuels due to inefficient evaporation of the fuel from the combustion chamber wall.

Increasing fuel volatility appears to reduce cold smoking tendency in both DI and IDI engines. Limited experimental data suggest that the sensitivity of both DI and IDI engines are similar in this respect. Increased volatility obviously acts more efficiently under cold cylinder conditions in the formation of more readily ignitable premixed fuel. More volatile fuels to a certain extent will also resist condensation within the exhaust system during cranking and help to reduce cold smoke density in this manner.

Despite the advantage that more volatile fuels provide, the limited data available in the literature suggest that ignition quality remains as the dominant factor. This can be judged by the fact that a large reduction in mid-boiling point of c.40°F has been demonstrated to have only the same beneficial influence as a plus one increase in cetane number. Quite clearly therefore, unrealistically low mid-boiling points would be required from a broadcut fuel to fully compensate a reduction of say 7 cetane numbers from 42 to 35.

Although trends can be established between cold smoking tendency, ignition quality and fuel volatility, data are somewhat restricted. More significantly, data have not been uncovered to relate how effective engine modifications such as increased compression ratio, the application of exhaust back pressure, optimised injection timing etc., can be in helping moderate cold smoking tendency with relatively low cetane fuels. Such information will be required to fully assess the implications of adopting future fuels upon the cold smoking tendency of diesel engines where it is known that specification will differ from current diesel fuel standards. In addition, it is not sufficiently well documented how successful spark ignited stratified charge engines are in this respect to enable full judgements to be made.

7.2.2 Conclusions

a) The maintainance of current diesel fuel ignition quality in combination with more volatile broadcut fuels may improve cold smoking tendency beyond current levels.

b) Reduction in fuel ignition quality below current standards will aggravate cold smoking tendency.

c) More volatile broadcut fuels should assist in moderating cold smoking tendency with lower cetane fuels although the latter parameter will probably remain dominant.

d) To alleviate cold smoking tendency with lower cetane fuels, diesel engines will require adapting by such means as raising compression ratio, optimising injection timing, raising exhaust back pressure and insulating combustion chambers. Exhaust gas recycle may also prove beneficial. In the case of IDI engines, the retention of energised heater plugs may impart considerable improvements.

e) With very low cetane fuels, i.e. less than c.30, the DI engine may continue to smoke at idle even up to normal operating temperatures. In this case a cure may be effected by employing significantly higher compression ratio and levels of exhaust back pressure but with adverse implications in other respects. For IDI engines, the continued application of energised heater plugs may be adequate.

f) For very low cetane fuels, the spark ignited stratified charge engine may prove very successful in respect of cold smoking.

g) Results exist to understand the implications of lower cetane fuels upon the cold smoking tendency of diesel engines. Similar trends are also available for the influence of volatility. Data have not been uncovered however to assess possible future fuels which encompass both appreciably lower ignition quality and higher volatility i.e. possible broadcuts. Similarly, the potential moderating influence upon cold smoke with lower cetane fuels of engine modifications such as increased compression ratio, optimised injection timing etc., is not known. In addition, the potential benefits of the spark ignited stratified charge engine in respect of cold smoking are also not known.

h) Much more work must be carried out in the context of cold smoking tendency to appreciate fully the implications with respect to future fuels.

7.3. Exhaust Smoke at Normal Engine Operating Temperatures

7.3.1 Discussion

Exhaust smoke at normal engine operating temperatures may broadly be classified as black smoke and blue smoke.

Black smoke is caused by the emission of carbon particles resulting from combustion within zones that are deficient in excess air and is therefore a characteristic of high load factor. In most automotive diesels, acceptable levels of black smoke govern the maximum torque curve.

Discounting the contribution of lubricating oil consumption, blue smoke, unlike black smoke, represents the products of combustion with excess air and is therefore observed from some diesels at idle or light load. Blue smoke represents the release of unburnt or partially burnt fuel droplets and is the result of marginal combustion. Some diesels may only tend to blue smoke at idle. Prolonged periods of idling deposit fuel within the exhaust system which is subsequently expelled during acceleration conditions by evaporation, resulting in a dense cloud of blue smoke which may persist for a considerable period of time. Blue smoke does not limit the engine rating but is visually objectionable and odorous. Blue smoke also contributes directly to the HC fraction of the exhaust and,together with black smoke, particulate output.

In the interest of engine rating, odour,HC and particulate emission and visual acceptability, smoke emissions under normal engine operating temperatures should not be allowed to rise beyond current levels due to the influence of future fuel specifications.

Because blue smoke is the result of marginal combustion under light load conditions, degrading ignition quality from current standards with future fuels will increase blue smoking tendency. Corrective measures as previously mentioned and discussed under cold smoke will therefore be required,i.e. optimised injection timing, higher compression ratio, insulated combustion chambers, energised heater plugs etc.

It may not be possible in some cases to clear blue smoking with very low cetane fuels without resorting to unacceptably high compression ratios or other severe control techniques. In this case the spark ignited stratified charge engine should prove beneficial, although blue smoking tendencies have not been reported for the systems under consideration. In the case of the MAN FM system, however, fuels of diesel type distillation characteristics will cause blue smoke due to inefficient fuel evaporation from the chamber wall. Increasing the fuel volatility to gasoline levels appears to cure this problem. Broadcut fuels may tend to blue smoke therefore, although there should be a considerable improvement relative to diesel type fuels.

The influence of cetane number on black smoke provides one of the areas of disagreement between workers in the field. Many workers have observed reduced smoke with fuels of lower ignition quality, others have recorded elevated smoke with lower ignition quality whilst some have noted little influence. These results have generally been obtained at high load conditions and it appears from the literature that no concessions when changing fuels to optimising engine parameters such as injection timing have been made. In addition, results have been obtained from a range of engines encompassing both DI and IDI combustion chambers and the smoke/cetane trends recorded cannot be broadly categorised by type of combustion systems.

It is well documented that reducing the ignition quality of the fuel generally increases the delay period. The sensitivity of the change in delay will however vary and be dependent upon such factors as injection timing, rate of mixing and compression ratio. It is commonly believed that longer ignition delay allows a greater proportion of the fuel to be burnt in a pre-mixed flame which is intrinsically less smoky than the turbulent diffusion burning characteristic of the diesel engine. Whether or not this will ultimately result in less smoke will probably be due to the relative injection timing between engines. In engines which for various reasons are set relatively retarded, it is a possibility that the advantages of the greater degree of pre-mixed combustion with low ignition quality fuels will be offset, or outweighed, by retarded combustion interval resulting in quenching and the release of carbon. In this context it may be expected that low cetane fuels will limit smoke limited power output at high speed in light duty IDI diesels unless the long ignition delay is combated. In the case of engines with relatively advanced injection timings, the results of later combustion interval may be suppressed, and hence the advantages of the pre-mixed flame can be observed as lower smoke. It is speculated that such reasoning may be responsible for the array of trends in the published literature. This cannot be confirmed however owing to the over frequent omission of injection timing data.

One possibly significant observation is that, based upon the previously formulated line of reasoning, it may be expected that diesel engines which are currently retarded for NOx control may tend to suffer higher smoke emissions with low cetane fuels, unless steps are taken to counteract the later start of combustion.

From limited available data in the literature, it would appear that increased fuel volatility can improve smoke at idle and light load. Such smoke is likely to be of the blue type. These findings are entirely coherent and suggest that higher volatility is conducive to more efficient combustion most probably by promoting smaller droplet size. In addition, more volatile fuels will tend to condense to a lesser degree in the exhaust system during prolonged idling periods. Blue smoke plumes should therefore be attenuated during subsequent acceleration as the collected fuel is expelled.

Many, but not all workers, are also in agreement that improving volatility assists in the reduction of black smoke at higher load factors. In this case there are disagreements between which portion of the distillation curve is important. Some workers have found that changes to both high and low boiling fractions can influence smoke whilst others comment that the high boiling fractions are not as important as the lighter fractions. By way of contradiction, other workers have submitted data which reveal that smoke can be elevated by reduced mid-boiling point whilst others report little influence of fuel volatility upon smoke.

The reasons for these conflicts could be due to many factors such as the influence of the injection equipment upon droplet size, relative levels of air swirl, injection timing etc.

In the context of volatility a note of caution should be sounded. Some workers have noted that increasing smoke can be correlated with increased viscosity. This has generally been dismissed however and the results explained by the adverse influence of the attendant reduction in volatility. It should be borne in mind that increased viscosity may influence the injection characteristics due, for example, to differences in pump plunger leakage and pressure drops in fuel pipes. It is suggested therefore that in some cases the correlations observed for fuel volatility may be compounded by other factors associated with the fuel injection equipment.

Regarding fuel chemical composition, it is known from laboratory experiments that aromatic compounds require a greater excess air factor during combustion to smoke equally in comparison with paraffinic fuels. This would suggest that in the case of the diesel engine where efficient air utilization can be a problem that more aromatic fuels would tend to produce greater smoke output.

From the literature survey a categorical statement cannot be made as there are areas of conflict. Generally speaking however, the data suggest an association between high aromatic content and elevated smoke. Where conflicts exist, no appreciable influence upon smoke was observed although aromatic content was varied considerably. Possibly in these cases more favourable fuel/air mixing was achieved.

The degree to which alternative fuels such as gasoline and kerosenes have been noted to influence exhaust smoke provides in some cases corroborative evidence to the previously discussed data.

Gasoline, which is both of very low ignition quality and highly volatile, has been generally observed to reduce smoke output at equal power in comparison with diesel fuel. Cases are cited however of gasoline increasing smoke at high speed, no doubt due to late combustion with the very low ignition quality. Ricardo experience suggests that marked improvements in smoke limited bmep can be achieved with gasoline in DI engines but this would appear not to be the case with swirl chamber IDI engines. This is presumably due to extreme differences in the rate of mixing.

The effects of more volatile fuels such as kerosenes and jet fuels with ignition qualities generally more closely in accord with diesel fuel is mixed. Some studies have noted that these fuels are capable of suppressing smoke at part load. In cases where fuelling levels have been increased with these lighter fuels to match the original diesel torque curve, there is evidence to suggest that smoke can be increased. This can probably be attributed to longer injection periods and implies that without increasing injection rate such fuels will limit the torque curve. If however fuelling levels are reduced to make comparisons at the same power output as dictated by the lighter fuels, then smoke output does not seem to be significantly influenced by fuel type within this range.

Syncrude products have been examined in DI diesel engines although the data are limited.

Studies with shale and tar sands derived diesel fuels in a DI engine have shown that smoke was influenced with respect to regular diesel fuel. Such differences however can be explained by changes in specification and there is no evidence of exceptionally different smoking tendencies for the synfuels compared with that which may have been expected of petroleum products of equivalent character.

Shale derived products have been examined as dilutent extenders for diesel fuel (20% blend). Smoke limited power output was little affected by the shale/diesel blend. Coal products have also been evaluated as diesel extenders by dilution with diesel fuel. Smoke limited power has been demonstrated to be severely handicapped in this case owing to slow rates of combustion due to the very low H/C ratios of the blended coal products. For these tests, hydrogenated creosote oil was utilised.

Ricardo DI engine experience with highly hydrogenated coal derived fuels having cetane numbers comparable with diesel fuel demonstrated that smoking tendency was not adversely affected by the coal derived fuels. In some cases, the coal derived products returned marginally lower smoke.

These limited data imply that syncrude products will not adversely affect the smoking of diesel engines provided physical character and H/C ratio are similar to current diesel fuels. In addition, it appears that the use of coal derived products without sufficient hydrogenation to provide adequate H/C ratio will not be suitable even as extenders for diesel fuel although shale fluids can be utilised in this respect without adversely affecting smoke limited performance. Much more information with syncrude products is required however to understand fully their implications.

The discussion formulated under this topic clearly shows that reasonable predictions of the performance of future fuels in diesel engines cannot be made. This arises from the various conflicts that abound and the lack of supporting data available to resolve them. Furthermore, past work in this area has been undertaken without recourse to engine re-optimisation when examining fuels of different specification to those for which the engine was designed. Such optimisation is clearly required for fuels of lower ignition quality for example to minimise possible noise and emissions penalities. Programmes of work directed at resolving these issues are therefore required.

In the case of the spark ignited stratified charge engine, it would appear that for all three systems under direct consideration for this project the use of more volatile fuels should improve the smoke limited torque output. This can be judged by comparing published data on gasoline and diesel fuels.

7.3.2 Conclusions

a) Assuming that future fuel specifications may differ from those of current diesel fuels, the data available does not enable reliable predictions in all areas relative to the smoking performance of diesel engines. This is because of major areas of conflict and the fact that re-optimisation for fuels has not been carried out. Further comprehensive test programmes are therefore required before the full implications upon smoke and smoke limited power output can be evaluated.

b) Reducing cetane number will tend to aggravate blue smoke experienced with many diesels at light load. Engine modifications will help to alleviate this problem. With very low cetane fuels, blue smoke will be most apparent unless major steps are taken in the form of engine modifications to effect a cure. In this instance, the spark ignited stratified charge engine may prove beneficial although light load smoking tendencies for this class of engine are not fully reported.

c) It appears that fuels of higher volatility will assist in moderating light load blue smoke. In the case of the MAN FM engine, volatile fuels are required to cure light load smoke.

d) Published data generally suggest that more aromatic fuels increase smoke output from diesel engines.

e) The effects of cetane number upon black smoke output from diesel engines at higher load factors cannot reliably be judged from the conflicting data available. A similar situation exists regarding the influence of fuel volatility.

f) Limited data available for synfuels with specifications similar to current diesel fuels demonstrates that no major impact upon smoke is apparent. Coal derived products with very low H/C ratio have been used as extenders for diesel fuel and provided significantly worse smoke performance. Shale fluids as diesel extenders seem acceptable as regards no adverse influence upon smoke limited power output. Much more work with synfuels is however required.

g) The spark ignited stratified charge engines under direct consideration in this study should return improved smoke limited output with fuels more volatile than diesel fuel.

7.4 Engine Performance

7.4.1 Discussion

It is well documented that reducing cetane number of fuels results in longer ignition delay in diesel engines. The response of ignition delay to cetane number is generally not linear and is more pronounced at the lower cetane numbers. In addition, the delay for a given cetane number will vary between engines owing to such factors as compression ratio, fuel/air mixing, inlet temperatures and injection timing. The ignition delay is probably the major key to the success of a diesel engine and it has already been observed that it is an important consideration in cold starting and smoking characteristics. It will also be shown in the subsequent sections that it appears to be a leading factor in defining HC, CO, NOx and noise characteristics and may also be linked with particulates and odour. In addition, long ignition delay can limit the speed range of the engine and is also known to cause misfiring, particularly at high speed, light load.

Commensurate with longer ignition delay is higher mean rate of pressure rise. This does not automatically result in higher peak cylinder pressures as this depends upon where the start of pressure rise lies in relationship to TDC.

The effect upon specific fuel consumption is likely to be negligible when changing cetane number provided the timing of the point of peak pressure is optimised. Even without cetane number optimisation, fuel consumption generally suffers little for fuels within the cetane number range c.40-60. Reducing cetane below this value will possibly penalise some engines without re-optimisation where the sensitivity to ignition delay is pronounced. In the extreme low cetane fuels are represented by gasolines. Various results that have been obtained with such fuels generally indicate that fuel consumption in most engines is significantly affected although data indicating little adverse affect have also been published. In the long run however for successful operation on these fuels, the multi-fuel diesel engine has been developed and in these cases, fuel consumption in gasoline operation is not penalised with respect to diesel. The penalities lie with high compression ratios and other means to achieve starting, reduce noise and eliminate light load misfire.

There is little experimental evidence to suggest that fuel volatility influences economy. It may be speculated however that increased volatility, under light load conditions with low cetane fuels providing long ignition delay, may cause misfiring by inducing more efficient evaporation and dispersal of the fuel throughout the air thus losing the charge stratification essential to good ignition. This potential problem should be minimised by measures to curtail the longer ignition delay.

There is also little data to suggest that fuel viscosity influences economy. In this context in some engines viscosity may influence injection characteristics and adversely affect economy. Viscosity can also with some pumps influence injection timing. These viscosity related characteristics will not present a future problem since these variables will be suitably compensated when adapting future engines for future fuels.

There is also little evidence to suggest that fuel chemical composition affects economy. If future fuels having H/C ratios appreciably lower than current fuels are utilised however it may be speculated that economy will be penalised because of slower rates of combustion.

Data relating economy to the use of synfuels are very limited. Diesel fuels derived from tar sands and shale have been evaluated and demonstrated a small adverse influence upon fuel economy at higher load factors with respect to diesel fuel. These results are not thought to represent problems due to the origin of the fuel but simply reflect the response of the particular test engine to differences in fuel specification that were evident i.e. cetane number.

Coal derived diesel fuels having specifications very similar to regular diesel fuel have also received limited examination. With these fuels economy was competitive with diesel operation. Straight run coal distillates without hydrogenation and having very low cetane numbers have also been examined when blended with diesel fuel. In this case the engine returned unacceptably worse levels of economy. These results reflect upon the problems associated with low H/C ratio fuels.

Probably the major impact of fuel specification upon operational fuel economy is that of differences in volumetric heating content influencing volumetric fuel consumption. This represents an intractable problem and, to the engine operator, fuel economy will be penalised if volumetric heat content falls with future fuels although engine thermal efficiency may not have changed. The extent to which this poses a problem of course depends upon the changes made to volumetric heat content. In the case of a broadcut fuel, this may represent an increase in volumetric consumption of c.5% with respect to diesel fuel assuming equivalent thermal efficiency.

Regarding the spark ignited stratified charge systems of direct interest to this study, available data allow an assessment of the differences in fuel economy between fuels. In the case of the spark ignited Comet, indicated fuel consumption is very similar for either gasoline or diesel fuel. Multi-fuel FM engines also demonstrate little difference in fuel consumption between gasoline and diesel fuels. The TCCS engine also generally displays insensitivity to fuel type in respect of brake specific fuel consumption. This is also reflected in 1975 FTP transient fuel economy results, where various fuels ranging from gasoline to diesel with intermediates have been evaluated and demonstrated that fuel economy varies little between fuels outside of the expected differences due to volumetric heat content. Experimental evidence does not exist to make similar transient comparisons for the other two stratified charge systems. It is anticipated however that similar characteristics will be observed.

The resilience of these systems to fuels of wide ranging specification is of course due to the spark ignition. For each combustion system, there is little appreciable difference in the shape of the cylinder pressure diagram between fuels and hence economy is not adversely affected.

For both diesel engines and the spark ignited stratified charge systems, peak output will be influenced when changing fuels primarily by the influence of fuel upon smoke output since each engine is smoke limited. This has already been discussed in the previous section.

7.4.2 Conclusions

a) Low ignition quality fuels need not penalise fuel consumption provided that diesel engines are suitably adapted to compensate for longer ignition delay and to maintain the timing of peak pressure relative to TDC at optimum. Such adaptation will be required automatically for other considerations such as emissions and noise. Thermal efficiency may therefore be maintained within acceptable limits.

b) There is little experimental evidence to suggest that fuel volatility, viscosity or chemical character influence economy. The possible influence of volatility and chemical character should be examined in more detail for clarification. Viscosity effects if evident should automatically be compensated for when optimising diesel engines for future fuels.

c) Data regarding the influence of synfuels upon fuel economy are limited. It is speculated that providing engines are suitably optimised for such fuels then fuel consumption will not suffer. If however future synfuels are allowed to have appreciably lower H/C ratios compared with current diesel fuels, it is speculated that fuel economy will be penalised. These speculations require experimental verification.

d) The spark ignited Comet, TCCS and FM combustion systems appear resilient to wide ranging fuel specifications in respect of brake specific fuel consumption. In the case of the TCCS system, this resilience has also been demonstrated over the 1975 FTP test and although experimental evidence is not available, it is anticipated that the other two systems will behave similarly.

e) The maximum torque output of both diesel and these spark ignited stratified charge engines will be governed by the influence of fuel upon smoke output, as each engine type has a smoke limited rating.

7.5 Gaseous Exhaust Hydrocarbon Emissions (HC)

7.5.1 Discussion

Legislative standards for HC emissions make it necessary to avoid the possibility of future fuel specifications inducing higher HC emissions. This is especially true for the stratified charge engine with inherently higher HC emissions than the diesel engine.

Naturally for future fuels, fuel injection characteristics may require re-optimising along with air swirl matching to assist in minimising any potential adverse effects upon HC emissions. Owing to positive ignition, it is thought that the spark assisted stratified charge engine may be somewhat less sensitive in this respect.

In addition to the potential adverse influence of future fuels upon air/fuel mixing, two other popular explanations for the source of HC emissions lie with the escape of fuel to remote parts of the combustion chamber and the evacuation of fuel late in the expansion stroke from the uncontrolled volume beneath the needle in the injector tip. It is known that there is a combination of factors since DI engines with virtually no uncontrolled volume at the injector tip (zero-sac nozzles) still produce HC emissions.

Considering the two above mechanisms believed in part responsible for HC emission, it would be expected that fuels of higher volatility would return increased HC emissions. Experimental evidence in the literature confirms this with few exceptions. Some data suggest that increasing the volatility of the lower distillation fractions is the most important factor and that changes to the higher boiling fractions are less significant.

If generally true, this would indicate that broadcut fuels would pose particular problems. Experimental data relating to the influence of broadcut fuels (100-600°F) upon HC emission are limited but have demonstrated unacceptable increases in 1975 FTP HC emissions from light duty diesel vehicles in comparison with regular diesel fuel. In one case, the increase in HC emission was no doubt enhanced by lower ignition quality but in the other cases the broadcut fuel had an ignition quality much more closely in accord with diesel fuel and is therefore thought to reflect a true volatility effect.

To help solve this problem with more volatile fuels it would seem that remote volumes in the cylinders, i.e. piston top land, valve and injector pockets etc should be minimised. This will pose difficulties with, for example, the implication upon breathing by using shallower valve recessions owing to the necessity to use narrower camshaft overlap to avoid valve/piston clash. Furthermore, such volumes will be more difficult to control as a percentage of the actual combustion chamber volume if compression ratios have to be increased to combat the use of lower cetane fuels. This will be especially marked in the case of the light duty IDI diesel.

In addition, the uncontrolled volume in the injector tip should be minimised. This trend is already being established with DI engines where lower sac volume nozzles have been adopted. The move towards zero-sac volume nozzles should be encouraged if more volatile future fuels are planned. In the case of the light duty IDI engine utilising pintle type injectors, the contribution of the uncontrolled volume surrounding the pintle to HC emissions appears not to be documented and it can only be speculated that similar problems may exist.

It should be remembered however that whilst zero-sac volume nozzles should be attractive in respect of constraining HC increases with more volatile fuels, such nozzles currently have durability problems.

In the context of fuel evacuation from the nozzle, some studies have correlated higher HC emissions with fuels of lower viscosity. In some cases this is no doubt due to the interrelated increase in volatility. Low viscosity is however thought to encourage fuel evacuation from the nozzle tip and furthermore may adversely influence injection characteristics. If the latter is a contributing factor, this should not represent a problem with future fuels as injection equipment would be suitably re-optimised.

Regarding ignition quality, all workers are in agreement that lower cetane number increases HC emissions although the sensitivity between engines can be different. This effect is no doubt due to retarded combustion and is analogous to retarded injection timing which is known to increase HC emissions. No data are available however indicating how effective engine modifications, i.e increased compression ratio or re-optimised injection timing, can be in assisting with HC emissions when using lower ignition quality fuels. Work is required in this area therefore.

The experimental evidence linking the influence of fuel chemical character with HC emission is limited but some studies suggest that aromatic content has little influence upon HC emissions. There are conflicting reports however and it is judged that more work is required in this field to establish reliable trends.

Limited data have been uncovered concerning HC emissions when using diesel fuels derived from tar sands, shale and coal. These data which are restricted to heavy duty DI engines reveal that HC emissions in comparison to those obtained with diesel fuel were not adversely influenced owing to the origin of the fuels and differences that were evident would have been expected of petroleum derived products having the same specifications.

The addition of hydrogenated creosote oil obtained from coal and blended in relatively small proportions with diesel fuel has been demonstrated to affect adversely HC emissions. This can be attributed to the very low H/C ratio of the coal product reducing rates of combustion. Whilst the observed increase in HC emissions with this fuel was not excessive (12%) the unacceptable reduction in smoke limited output recorded as previously discussed would not make such fuels attractive for the future.

Regarding the spark ignited stratified charge engines of direct interest to this study, emissions data are generally limited but fuel effects are believed to be evident.

In the case of the spark ignited Comet, gasoline returns higher light load HC emissions than diesel fuel. High cetane fuels are thought to be advantageous in this respect by assisting combustion within the pre-chamber by auto-ignition after the flame front has been established from the sparking plug. Future fuels having relatively high ignition quality should therefore be beneficial in this respect.

Data are very limited for the MAN FM combustion system but it is known that with gasoline as fuel HC emissions are very high in relation to the diesel engine. It is thought that the reason for this is fuel which is evaporated off the fringe of the spray causing mixtures too lean for successful combustion. By inference, less volatile fuels may therefore reduce HC emissions. It should be borne in mind however that with diesel fuels the FM engine produces blue/white smoke at light load owing to the inefficient evaporation of the fuel from the walls of the combustion chamber. A HC trade-off with volatility may therefore exist which requires examination. If apparent, broadcut fuels may suit this particular combustion system.

For the TCCS combustion system, limited available data generally suggest that more volatile gasoline gives higher HC emissions than diesel fuel whilst jet and broadcut fuels tend to return intermediate levels. Reasons for this are not clear but it may be that like the FM, more volatile fuels encourage fuel to be more readily evaporated from the fringe of the spray or that, as in the case of the spark ignited Comet, higher ignition quality is advantageous by allowing auto-ignition to occur.

7.5.2 Conclusions

a) Fuel injection characteristics may require re-optimisation, along with air swirl matching, to assist in minimising any potential adverse effects upon HC emissions. Owing to positive ignition, spark assisted stratified charge engines may be somewhat less sensitive in this respect.

b) Fuels having higher volatility or

lower ignition quality with respect to diesel fuels will tend to increase HC emissions in current diesel engines. In respect of volatility, attention must be focused on minimising uncontrolled volumes at the injector tip and further reducing combustion chamber lost volume to minimise the penalties. In respect of lower cetane number, the extent to which HC control can be regained by taking action to combat the longer ignition delay and avoid late combustion cannot be ascertained from the literature. More work is therefore required in this area.

c) More work is required to generate reliable trends linking fuel chemical composition and HC emissions.

d) Limited data regarding the use of diesel synfuels suggests that HC emissions were only influenced in comparison with regular diesel fuel to an extent that would have been expected of petroleum products of the same specification. Diluting diesel fuel with hydrogenated creosote oil of low H/C ratio increases HC emissions due to reduced rates of combustion.

   Much more data need to be acquired concerning the use of synfuels to understand fully the situation.

e) The spark ignited Comet engine requires higher cetane fuels for low light load HC emissions.

f) Insufficient data exists for the MAN FM engine concerning HC emissions and fuel tolerance. It is speculated that a trade-off exists with volatility, with fuels of intermediate distillation characteristics to either diesel or gasoline having the potential for lower light load HC emissions. Work is required in this area.

g) More volatile fuels appear to increase generally HC emissions with the TCCS combustion system.

7.6 Gaseous Exhaust Carbon Monoxide Emissions (CO)

7.6.1 Discussion

Carbon monoxide emissions from diesel engines are low in comparison with gasoline vehicles due to unthrottled operation at very lean AFR. Generally speaking, CO emissions represent the least problematical gaseous emission for the diesel engine in terms of meeting legislative standards. Despite this, it will remain advantageous to continue to maintain the low CO emissions of current diesel engines with future fuels.

The bulk of the data in the literature indicate that reducing fuel cetane number without recourse to re-optimising the engine adversely affects CO emissions. Logically this can be explained by retarded combustion and it is likely that advancing the injection or reducing ignition delay by raising the compression ratio would greatly assist in counteracting this trend. This information does not exist and is therefore required for a complete understanding of the future impact of future fuels.

The influence of fuel volatility is less clear from the limited data available in the literature. Some workers suggest that fuel 90% point can influence CO emissions but others have recorded little influence of volatility. Contradictions between various engines may arise because of different levels of air/fuel mixing and fuel droplet size provided by the injection equipment. Controlled data have not been generated for the effects of very wide ranging distillation characteristics as in the case of broadcut fuels and should therefore be obtained. Limited 1975 FTP results with 100-600°F broadcut fuels that have been obtained suggest that CO emissions are increased. This could not be related to lower ignition quality in all instances.

The situation regarding the connection between CO emissions and fuel chemical composition is again not clear and requires further controlled study. Some papers have reported that CO emissions are increased with more aromatic fuels. This is logical on first sight since aromatic compounds are known to require greater excess air factor for successful combustion compared with paraffinic compounds. CO and aromatics have not provided strong correlations in other studies however and caution should therefore be observed.

Published results for comparisons of such fuels as jet fuels, kerosenes and light diesel fuels with standard diesel fuel are conflicting but generally reveal that such fuels have little significant influence upon CO emissions.

Limited data relating to the use of diesel fuels derived from tar sands, shale and coal illustrate no severe penalty upon CO emissions due to the origin of the fuel. CO emissions varied to an extent that would have been expected of petroleum derived diesel fuels of the same specification. Blending hydrogenated creosote oil obtained from coal with diesel fuel resulted in a marginal increase in CO emissions. Although this increase was tolerable, the unacceptable influence of this particular fuel upon smoke limited output as previously discussed would not make its use attractive.

It is again stressed that much more information in connection with the influence of synfuels is required.

Regarding the spark ignited stratified charge engine, both the spark ignited Comet and the TCCS appear to have CO emission characteristics favoured by the use of higher volatility fuels. This is presumably due to the ease with which the lighter fuels can form a more readily burnable mixture. The response of the FM in this respect is not known and must be evaluated although it is speculated that similar characteristics will be observed.

7.6.2 Conclusions

a) It must be anticipated that CO emissions will rise if the ignition quality of future fuels is allowed to reduce. The possibilities of restoring CO emissions by engine re-optimisation for lower ignition quality fuels should be examined.

b) The influence of fuel volatility upon CO emissions is contradictory. The influence of wide ranging distillation characteristics representative of broadcut fuels have not been examined and an examination in this area is required. Limited 1975 FTP test results obtained with broadcut fuels suggest that CO emissions will increase even if reasonable ignition qualities are maintained.

c) The relationship between CO emissions and fuel chemical composition is also not clear as contradictions exist and therefore requires controlled experimental evaluation.

d) Data with synfuels in respect of CO emissions are again limited and needs strengthening. The data uncovered for this study suggest that diesel synfuels will not materially affect CO emissions outside of what may be expected of petroleum derived fuels with similar specifications. The blending of hydrogenated creosote oil obtained from coal with diesel fuel increases CO emissions. The low H/C ratio of this dilutent and the unacceptable reduction in smoke limited output due to slow rates of combustion would not make such a dilutent extender for diesel fuel attractive.

e) The use of more volatile fuel in both the spark ignited Comet and TCCS spark ignited stratified charge systems favour lower CO emissions. The response of the MAN FM system in this respect is not known and needs evaluating.

7.7 Gaseous Exhaust Nitrogen Oxide Emissions (NOx)

7.7.1 Discussion

As far as the diesel engine is concerned NOx emissions pose one of the most difficult problems as regards meeting legislative standards. In addition, NOx control generally adversely affects HC and particulate output. Ideally therefore, future fuel specifications should be suitably tailored to ensure that NOx emissions are not permitted to rise.

NOx emissions are formed within the cylinders when nitrogen is exposed to oxygen at high temperature and pressure. NOx formation is dependent upon the degree of both temperature and pressure and any fuel variable which influences these parameters may affect NOx output. In this context it may reasonably be anticipated that NOx emission would be influenced by both ignition quality and volatility, since both may control the degree of pre-mixed combustion which in turn can influence peak cylinder pressures and temperature.

From the literature there is reasonably strong evidence that,with fixed injection timing, reduced cetane number to c.30-35 causes increased NOx emissions. In this case it is generally believed that the longer ignition delay allows a greater proportion of the total fuel charge to become pre-mixed resulting in higher rates of pressure rise and the generation of higher peak cylinder temperatures and pressures that favour NOx formation.

It should be borne in mind however that these trends have been obtained from engines which have not been optimised to run with lower cetane fuels. Simply advancing the injection timing to regain optimum start of combustion with low cetane fuels in some cases may aggravate the NOx problem. It is necessary, therefore, to re-optimise the engine not only to regain the start of combustion but also to reduce ignition delay with the lower cetane fuels if NOx emissions are to be maintained. Such re-optimisation will of course also be necessary to avoid other possible penalties of low cetane fuels such as starting difficulties, smoking, noise, excessive peak pressures etc. The extent to which this re-optimisation will be effective in controlling NOx emissions cannot be ascertained without recourse to further study.

More recent engines operating retarded for NOx control may return lower NOx emissions with low cetane fuels owing to even further retardation of combustion. This will probably not be permissible for reasons of performance, HC and other penalties and hence engine re-optimisation will again be required. It is not anticipated therefore that lower ignition quality fuels will enable lower NOx emissions to be achieved.

Further studies will also be required to resolve the issue of the influence of fuel volatility upon NOx emissions.

Some workers have observed that more volatile fuels can increase NOx in DI engines but there is also contradictory evidence available.

With IDI engines, it has been recorded that fuels of increased volatility suppress NOx formation. In this case,a pre-chamber engine was utilised and NOx emissions were examined when comparing ignition improved gasoline with kerosene and ignition improved kerosene with diesel fuel. In each case,when compared on an equal cetane basis, NOx emissions were lower for the more volatile fuels. It was speculated that the more rapid, pre-mixed combustion induced by higher volatility, reduced residence time within the pre-chamber with oxygen for the formation of NOx. Perhaps for similar reasons, NOx emissions from an IDI engine have been noted to decrease with fuels of lower 90% point. Similar results can be traced in published data when using a 100-600°F broadcut fuel having comparable ignition quality to diesel fuel in IDI engines. In this case, 1975 FTP NOx levels were reduced 16% with the broadcut fuel in comparison with diesel fuel. Other studies have revealed that low ignition quality 100-600°F broadcut fuels did not influence NOx output from an IDI engine, possibly implying that the volatility effect is off-set by the action of the longer ignition delay.

Whilst it is interesting to speculate in this fashion, other data with IDI engines indicating little influence of volatility upon NOx emissions impose a note of caution and demonstrate the requirement for more detailed studies before accurate judgements can be made.

Limited data have been uncovered which suggest an association between higher NOx emissions and more aromatic fuels. In two instances, the data would suggest that associated factors of volatility and ignition quality may have been the controlling parameter. In another case, more aromatic fuels increased delay period in three different engines despite constant cetane number. This resulted in increased fuelling levels being required to maintain test conditions and hence higher NOx emissions. Whether or not similar factors were evident in the other data is not known to resolve whether the aromatic content per se directly influenced NOx emissions.

No relationship between NOx output and fuel viscosity has been discovered in this study.

Regarding alternative fuels, it appears from the literature that NOx emissions are generally little affected when comparing the lighter Jet A, kerosene and No. 1 type fuels with No. 2 fuels. These results are for fuels having very similar cetane number and therefore tend to support the view that fuel volatility and aromatic content do not influence NOx emissions. From limited data available for the more volatile, lower cetane, JP-4 type fuels, NOx trends are mixed. On the one hand NOx was little affected in comparison with other diesel type fuels and in the other case NOx emissions were reduced and attributed to late combustion with the lower ignition quality jet fuel. Engine response to ignition quality and relative injection timings are likely to be an important factor in deciding what the outcome of a fuel change will be in this respect.

NOx emissions data for operation with the very low cetane, highly volatile gasoline fuels are again restricted.

In the case of a DI engine, retarded combustion with the long ignition delays imposed by gasoline has been noted to appreciably reduce NOx over the load range.

In a pre-chamber engine, two gasolines of radically different ignition quality (35 and 16 cetane) provided different trends. The higher ignition quality gasoline increased NOx emissions for load factors up to about 60% but at higher load factors returned lower emission rates with respect to diesel. The very low cetane gasoline markedly attenuated NOx emissions at low load factor but had little influence at higher load. In the case of the higher cetane gasoline, the results are generally in accord with the tendency for low ignition quality fuels to increase NOx emissions whilst the emission reduction observed with the very low cetane gasoline at light loads probably reflects retarded combustion. The reason for the differences in trends at higher load factors is not clear.

From these limited data, it cannot be assessed whether or not these results are characteristic for operation with gasoline type fuels in either DI or pre-chamber engines.

Insufficient data regarding the use of synfuels has been located to assess fully their implications upon NOx emissions.

Limited data available for diesel synfuels derived from tar sands, shale and coal however suggest that NOx emissions only varied with respect to regular diesel fuel in a manner commensurate with differences in fuel specification,i.e. cetane number, implying that the origin of the fuel was not an important factor.

Shale and coal derived liquids have also been examined as diesel dilutent extenders. Diesel blended with shale fluid (20%) did not influence NOx output in any significant fashion. Hydrogenated creosote oil having very low H/C ratio was also blended with diesel fuel (25%) and in this case, increased NOx output by 24%, probably due to the low rates of combustion demanding increased fuelling levels to maintain load. These limited data suggest that the use of such coal derived products with low H/C ratios will not be acceptable as extenders for diesel fuel.

Considering the various spark ignited stratified charge engines under consideration, observations of the influence of fuel can be made.

In the case of the spark ignited Comet, diesel fuel returns appreciably lower NOx emissions in comparison with gasoline and limited tests with various fuels have confirmed that the magnitude of NOx levels are closely allied to fuel volatility. The performance of broadcut fuels in this respect has not been established however. It is thought that higher volatility improves mixture preparation and enhances oxygen availability for NOx generation.

For the MAN FM system there are few data available comparing emissions with fuels but there is some evidence to suggest that diesel fuel returns higher NOx emissions towards higher load factors than gasoline. Addditional work is required however to confirm this point.

With the TCCS system, there is some contradictory test bed evidence as regards the influence of fuel type upon NOx emissions. Available 1975 FTP results with TCCS equipped vehicles however demonstrate little appreciable difference of NOx emissions between fuels ranging from gasoline to diesel fuel and with broadcut intermediates.

7.7.2 Conclusions

a) There is reasonably strong evidence to suggest that reducing cetane number to c.30-35 in current diesel engines will adversely affect NOx emissions. It is thought that the longer ignition delay is responsible. Whether or not engine optimisation to reduce delay with low cetane fuels will restore NOx emissions is not known. Test work is required to clarify this point.

b) The influence of volatility upon Nox emissions cannot be accurately judged from the available data due to various contradictions. Some evidence suggests that more volatile fuels suppress NOx emissions from pre-chamber engines. If truly characteristic this will favour the use of broadcut fuels. Additional studies are required in this field however for full clarification.

c) Fuel viscosity has not been related to NOx emissions. The influence of fuel chemical composition upon NOx emissions requires clarification to determine whether or not aromatics per se influence NOx formation.

d) Data relating to the use of very low ignition quality, highly volatile gasoline fuels are restricted and contradictory. The characteristics of such fuels upon NOx emissions cannot be accurately judged therefore without access to further data. Other light fuels such as jet fuels, kerosenes and No. 1 diesel fuels generally appear not to affect adversely NOx in comparison with No. 2 fuels.

e) Many more data need to be generated in respect of synfuels. Limited data suggest that synfuels with specifications similar to regular diesel fuel do not adversely affect NOx formation, differences that were apparent being commensurate with differences in fuel properties such as ignition quality. Tentative data would also imply that shale fluids can be used as diesel dilutent extenders without adversely affecting NOx but that low H/C ratio coal products in the form of hydrogenated creosote oil cannot.

f) The spark ignited Comet engine favours less volatile fuels for low NOx emissions whilst the converse may be true of the MAN FM system. FTP results with TCCS equipped vehicles imply that this system is insensitive to fuel specification with respect to NOx emissions.

7.8 Exhaust Particulate Emissions

7.8.1 Discussion

Interest in particulate emissions from diesel engines has risen dramatically in recent years with the result of the introduction of legislation aimed at their control. This has largely stemmed from the realisation of increased dieselization within the US and, since the diesel emits an order of magnitude more particulate material than the gasoline engine, environmental considerations have dictated control. Furthermore, there is tentative evidence to suggest that extracts from these particulate emissions are carcinogenic. It is anticipated that the future standards for light duty diesel particulates will be difficult to achieve without the use of specialist technology which currently remains undefined. It may also be anticipated that similar problems will face the heavy duty diesel engine. It is important therefore that future fuel specifications should be guided by the requirements for low particulate emissions.

There is reasonably strong experimental evidence to suggest that particulate output from both IDI and DI diesel engines is significantly reduced by using No. 1 type diesel fuels in lieu of No. 2 fuels. This appears to correlate well with fuels of higher aromaticity and upper distillation characteristics being conducive to particulate formation, therefore implying that, for particulate considerations, future fuels should have both lower aromatics and upper distillation characteristics compared with current No. 2 diesel fuels.

These results however were obtained with fuels having typical diesel fuel ignition quality. Little is known of the particulate response for low cetane fuels. Limited data available suggest that in IDI engines particulate emissions are reduced with lower cetane fuels due to the inducement of cleaner, pre-mixed combustion during the longer delay period. In respect of light duty diesel FTP particulate emissions, it should be noted that the particulate matter is generally predominantly comprised of the organic HC fraction. Since lower cetane fuels are thought to increase HC emissions, it should not be assumed that the data previously cited imply that lower cetane fuels will automatically reduce particulate emissions in all cases. In general, it is thought that, for most light duty diesels, FTP particulate emissions may be increased with low cetane fuels due to elevated HC fraction, assuming re-optimisation is not carried out. Owing to higher load factor operation it is possible that heavy duty particulate emissions may benefit from the mechanism previously discussed. Even in this case however, the need to re-optimise to curtail longer ignition delay with lower cetane fuels for reasons of HC emissions, noise, etc., would probably not manifest in reduced particulate output. Suitable re-optimisation with light duty diesels to combat increased HC emissions with lower cetane fuels should also enable particulate increases to be moderated.

The influence upon particulate emissions of fuels having very low cetane numbers with respect to diesel fuel have not been examined.

Particulate emissions represent one important area where little is known about the influence of fuel specifications lying well beyond that of diesel fuels such as low ignition quality broadcuts with suitably re-optimised engines. Work in this area should strongly be encouraged.

Hydrogenated synfuels obtained from coal and having specifications very similar to No. 2 diesel fuel have been examined in a DI engine. Although the results were preliminary, they suggested that particulate output was competitive with regular diesel fuel operation. In addition to the experimental programmes required to generate more information on the influence of fuel specification upon particulates, data with actual synfuels should be obtained owing to the fact that they may perform differently from petroleum products on account of impurities and/or other unknown factors.

Particulate data from spark ignited Comet and FM stratified charge engines are not available. Limited data available for a catalyst equipped TCCS engine reveal that, with unleaded gasoline, the particulate emission rate is considerably lower than that which may be expected from a similar vehicle equipped with an IDI diesel engine incorporating a catalyst. Shale derived gasoline and blends of gasoline and diesel fuel simulating broadcut returned higher emission levels much more in accord with the diesel vehicle. The reasons for this are more fully discussed later in this report, but it is speculated that the influence of the catalyst upon sulphate formation may have been responsible.

7.8.2 Conclusions

a) For fuels having ignition qualities comparable with No. 2 diesel fuel, there is reasonable experimental evidence to suggest that minimising aromatic content and lowering upper distillation characteristics relative to current No. 2 diesel fuel will impart significant particulate reductions.

b) Limited data available suggest that reducing ignition quality in IDI engines may reduce particulate emissions. Since light duty FTP diesel particulate emissions are largely comprised of the organic HC fraction and lower cetane fuels induce higher HC emissions, it is thought that lower ignition quality will generally increase light duty particulate emissions. This effect should however be moderated by engine re-optimisation.

Fuels having cetane numbers significantly lower than diesel fuels have not been examined regarding their influence upon particulate emissions.

c) Preliminary results with hydrogenated diesel fuel obtained from coal of similar specification to No. 2 diesel fuel returned competitive particulate emissions.

d) The performance of the spark ignited Comet and MAN FM combustion systems with regard to particulates is not known for any fuel and must be examined. Limited data with a TCCS engined vehicle reveal that the particulate output with unleaded gasoline as fuel is very low in comparison with what may be expected from a similar vehicle equipped with an IDI diesel engine. Shale derived gasoline and gasoline/diesel blends returned particulate emissions closely in accord with the IDI diesel. Factors other than combustion differences are thought to be responsible.

e) Insufficient data exist to predict the performance of future fuels in respect of particulate emissions where it is anticipated that distillation range and ignition quality will be significantly at variance with current diesel fuels. Experimental work with engine re-optimisation where appropriate is required. In addition, similar studies are required with actual synfuels since expected impurities may contribute to particulate output.

7.9 Noise

7.9.1 Discussion

There is little doubt, based upon the data available in the literature, that reducing ignition quality from current standards will increase noise levels in diesel engines, although the response will vary dependent upon the sensitivity of ignition delay to cetane number between engines. This has frequently been demonstrated with a range of fuels, in the limit represented by gasolines, where noise levels can be exceptionally high. The reason for elevated noise lies with the longer ignition delay which results in higher rates of pressure rise. In the case of high speed, light duty, Comet IDI diesels, the problem is further compounded by the need to advance the injection timing to clear high speed, light load misfire. In doing so, the full load noise threshold of timing is approached. This threshold is largely independent of cetane ratings down to c.40-45 in this class of engine.

It should of course be possible to regain acceptable levels of noise with lower ignition quality fuels by engine modifications to reduce delay periods. In the extreme this has been demonstrated with multi-fuel diesels adapted for very low cetane gasoline fuels. By suitable development to curtail ignition delay, by using such features as high compression ratio, noise levels with gasoline can be made indistinguishable from diesel fuel operation.

It has been stressed repeatedly before that if ignition quality of future fuels is allowed to decline significantly below current norms, diesel engines will require adaptation to control other parameters and in doing so noise should automatically be moderated. This should be confirmed by monitoring noise levels during future test programmes.

Other fuel variables are generally ascribed as not being an important factor in diesel engine noise.

Fiat have published data however indicating that, for equal cetane number, aromatic and cycloparaffinic fuels produce more noise from a high speed swirl chamber IDI engine than Iso or n - paraffinic fuels. Whether or not this is a characteristic of other engines cannot be ascertained owing to a lack of data.

Fiat also concluded that noise was independent of both fuel viscosity and volatility. In the latter context, Ricardo have observed that a 100-700°F broadcut fuel did not influence noise ascertained aurally in two Comet IDI diesel engines with respect to diesel fuel operation. Both fuels had similar cetane numbers. Whilst these data would suggest that fuel volatility is not an important factor, further studies for clarification would be recommended.

Data are not available for noise levels when running on syncrude products. It is strongly suspected that the performance in this respect will be highly correlated with the ignition quality of the fuel as in the case of petroleum derived products. This assumption requires experimental verification.

As might be anticipated, noise emissions from the spark ignited Comet and TCCS stratified charge systems appear virtually indistinguishable between fuels ranging from gasoline to diesel. This characteristic would also be expected from the MAN FM system although experimental data are not available.

7.9.2 Conclusions

a) Diesel engine noise levels will rise with fuels of lower ignition qualities than current standards. It is thought that adaptation to moderate ignition delay with such fuels to avoid penalties in other areas will automatically assist in controlling noise. It is also believed that noise in synfuel operation will be characterised by the ignition quality of the fuel. Noise should be monitored during future test programmes to confirm these speculations.

b) Limited evidence would suggest that fuel volatility is not a dominant factor in noise generation. Test work to clarify this point is required however.

c) One reliable source of data suggests that noise in high speed IDI diesel engines is influenced by fuel chemical character. This point should be investigated to observe whether it is a general characteristic of diesel engines.

d) Noise from spark ignited Comet and TCCS stratified charge engines appears to be insensitive to fuel specification defined by gasoline and diesel fuels. It is speculated that the MAN FM system will also behave in this fashion although experimental evidence is not available.

7.10 Exhaust Odour

7.10.1 Discussion

Although not currently legislated against, the exhaust odour characteristic of diesel engines is an undesirable feature and for environmental considerations odour should not be promoted by future fuel specifications. Odour data from diesel engines with regard to fuel specification are very scant and generally contradictory. It is well known that odour is difficult to quantify and in some cases, aldehyde emissions have been measured to represent odour, the correlation between aldehyde emissions and odour being fairly well established.

Odour of course represents the products of incomplete combustion. Since reducing ignition quality can induce or aggravate conditions of marginal combustion, it is not surprising that on several occasions increased odour has been observed when reducing cetane number. Odour has not been correlated with ignition quality on other occasions however, so contradiction does exist, and this would probably reflect the differences in ignition delay response to cetane number between engines.

Judgement of the influence of fuel volatility upon odour cannot be made owing to limited data. Isolated reference has been made to reduced odour with less volatile fuels and corroborative evidence is given in another paper although the latter can only be deduced by implication. A similar situation exists concerning the influence of chemical composition upon exhaust odour. Studies with fuels of wide ranging chemical character have been undertaken and concluded no correlation of odour with fuel composition. An isolated reference to increased odour with more aromatic fuels has been consulted although the authors concluded that the results were not statistically significant.

Some workers have observed a tendency for exhaust odour to increase with higher levels of fuel sulphur although other studies have recorded little correlation.

Limited data are also available concerning measured aldehyde emissions or established odour ratings when comparing kerosene/No. 1 type fuels with No. 2 fuels. The results are contradictory and difficult to interpret. An isolated reference has also been located acknowledging greater exhaust odour from a diesel engine running on gasoline, in comparison with diesel fuel. Possibly this result can be linked to those data which accord increased odour to low cetane fuels.

No odour data for diesel engines running on broadcut or syncrude derived fuels have been located during this search.

Odour data do not exist for the spark ignited Comet engine and is only dealt with briefly in relation to both the MAN FM and TCCS stratified charge systems. In the case of the FM system, limited data available indicate that light load and idling odour is very noticeable and irritant. Little is known of the response to various fuels. Because of the high HC emissions from the FM engine, control in this respect may achieve some improvement in exhaust odour. In the case of the TCCS engine, limited odour data have been obtained and indicate that with gasoline fuel, odour is slightly better than the average IDI diesel but is comparable in diesel fuel operation.

These data show that odour has generally received little attention in respect of the influence of fuels. Possibly this reflects upon the unreliability of assessment but more probably reflects upon the lack of status accorded to its evaluation. Whilst it is important to have knowledge in this area, it is believed that odour should be regarded as a secondary consideration in relation to data acquisition of other leading parameters such as performance and emissions.

7.10.2 Conclusions

a) Exhaust odour data are limited and at times contradictory and difficult to interpret. It is suggested that odour should be further evaluated in respect of the influence of fuels but it is considered that odour studies may adopt secondary importance to the study of other more leading parameters.

7.11 Other Considerations

7.11.1 Discussion

7.11.1.1 Engine Deposits and Wear

In the context of this report, the influence of fuel specification upon engine deposit and wear levels has been considered based upon the data consulted. It should be borne in mind that even for fuels of equivalent basic specification there may be differences in impurity levels such as metallic compounds. Such impurities may influence engine deposit and wear levels but this has not been considered in this report. Furthermore, deposits may influence engine performance, emissions, etc.. This may be especially true in the case of injector related deposits. The influence of deposits upon engine performance etc.. has not been studied however in this report.

Limited available references to increased engine deposits accorded to fuels of lower ignition quality have been consulted. The reasons for these trends are not clear but in these cases may presumably be related to the release of more carbon within the cylinders due to less efficient, retarded combustion.

Low cetane fuels have also been observed to cause damage to pistons resembling detonation damage that can occur in gasoline engines. This has been attributed to operation under conditions of unusually long ignition delay.

Assuming these features are characteristic for some diesels, this problem should not prevail in the future with low cetane fuels as diesel engines should be suitably adapted to reduce ignition delay for other considerations.

A few workers have observed that engine deposits and in one case top ring wear were attenuated by utilising more volatile fuels. Reduced upper distillation characteristics appear to be the dominant factor inferring control of carbon precipitated within the cylinders.

Very limited data are also available to suggest an association between fuel chemical composition with engine deposits and/or wear. Both engine deposits and top ring wear have been observed to increase when operating with a highly aromatic diesel fuel. A fuel which has been hydrogenated by the Unifining process has also been observed to reduce significantly injector deposits in comparison with other No.2 fuels, despite essentially no differences in the smoking tendency of each fuel.

Fuel sulphur content has also been correlated with increased levels of wear and deposits on several occasions. Sulphur levels appear to have to be raised in excess of c.0.5% before significant adverse influence is observed.

One important consideration with very low sulphur fuels is that of the fuel injection equipment. Ricardo have observed that kerosene fuels having very low sulphur levels can seriously damage the cam ring of rotary type fuel injection pumps. This can be related to the fact that the sulphur within the fuel contributes directly towards its extreme pressure lubricity. Similar problems with fuel injection equipment when using low lubricity fuels such as gasoline have been recorded on many occasions. In the case of inline injection pumps this has been overcome by utilising additional externally supplied lubrication. In the case of the rotary pump, where additional lubrication cannot readily be supplied, material specifications have to be improved and working clearances increased, although this may adversely influence pumping efficiency at low speed.

Although these factors may be regarded as relatively insignificant compared with the major issues of performance, emissions, etc.. they are included here as they may pose additional problems for the operability of engines with future fuels.

Consideration to these parameters must be given therefore.

7.11.1.2 The Influence of Fuel Impurities upon Exhaust Emissions

There is some concern that future synfuels, in particular shale derived products, may contain significantly higher levels of fuel bound nitrogen than current fuels and which may contribute to both particulate and NOx emissions.

The influence of fuel bound nitrogen upon NOx emissions has been evaluated in a DI engine using base fuels doped with pyridine. Base fuels were selected to cover a wide range of both aromatics and volatility as turbine burner studies suggest that these variables influence nitrogen conversion. The results obtained indicated that no significant fuel bound nitrogen to NOx conversion was apparent. It was speculated that this occurred because NOx attained equilibrium concentrations in the major formation zones and that this was induced by the engine running advanced with high NOx output. It is therefore thought that more representative retarded injection will result in equilibrium not being achieved with the possibility therefore of fuel bound nitrogen being converted to NOx.

No data have been uncovered for this study relating to the possible implications of fuel bound nitrogen on particulate emissions. In view of the apparent lack of data in this area, the influence of fuel bound nitrogen on both NOx and particulate emissions must be further examined.

It is now well documented that fuel sulphur is converted within the engine predominantly to gaseous sulphur dioxide (SO_2) while a smaller fraction is emitted as sulphate (SO_4). Various studies have ascertained that 1-6% of the fuel sulphur input to the engine is converted to sulphate. Sulphate is emitted in the form of particulate.

For non-catalyst equipped light duty diesel vehicles operated over the 1975 FTP cycle, 2-5% of the total particulate is in the form of sulphate for typical diesel fuels containing 0.2-0.3% by weight of sulphur. The impact upon particulate emissions of fuel sulphur is therefore not very significant.

The problem of fuel sulphur normally becomes apparent if catalysts are fitted to the diesel engine as may possibly be seen in the future for particulate control. Under high load conditions with exhaust temperatures above 570-670°F, most catalysts efficiently convert gaseous SO_2 to sulphate. This results in overall particulate emissions being significantly elevated above the levels normally observed with the standard exhaust system, despite the fact that the normal major particulate fractions of HC and carbon are being suppressed by the catalyst. At lower temperatures, the catalyst acts less efficiently in this respect and overall particulate control can be restored. With very low sulphur fuel ($<$0.1%), particulate control can be retained over the entire load range.

Catalysts for particulate control do not significantly influence sulphate output in the 1975 FTP test since mean exhaust temperatures of diesel vehicles are low. The situation can be reversed however in the higher load factor Highway cycle where it has been observed that catalysts which provide 25-40% particulate control in the FTP test provide little or no overall control due to sulphate generation.

This would also present a problem if future generations of heavy duty vehicles were equipped with catalysts for particulate control. In addition to the loss of overall particulate control the output of such elevated levels of sulphate, predominantly in the form of sulphuric acid, is environmentally unacceptable.

For these reasons, if catalysts have to be used for future particulate control then fuel sulphur levels may need to be controlled to low levels. This assumes that catalytic materials with low efficiency as regards sulphate formation are not developed.

It is speculated that the generation of particulate sulphate in this manner may have been one of the contributing factors to the higher particulate emissions of the TCCS Gremlin vehicle equipped with catalysts, observed when comparing shale derived gasoline and gasoline/ diesel blends with regular unleaded gasoline.

7.11.1.3 The Potential Health Hazard of Exhaust Particulate

It is now well documented that soluble extracts of diesel particulate emissions contain carcinogenic compounds. There is considerable controversy however relating to whether or not a health hazard to man exists. It is known that diesel particulates lie within the respirable range and are therefore inhaled into the lung. The controversy would seem to lie in whether or not the carcinogenic compounds are extracted by the body fluids and absorbed. Without conclusive evidence either way in this respect, particulate emissions will continue to be considered as potentially hazardous.

Numerous studies have now measured the benzo (a) pyrene (BAP) content of diesel particulate. This substance is regarded as one of the most potent polynuclear aromatic (PNA) compounds emitted in diesel particulate.

Whilst all of the limited results in this field are somewhat preliminary they are of general interest for this study. Emitted BAP emissions have been recorded at a maximum from light duty IDI vehicles when utilising low cetane "minimum quality" No. 2 diesel fuels in comparison with higher cetane "premium quality" No. 2 fuels. In addition, the mutagenic activity of extracted solubles assessed by the Ames test have demonstrated the greatest activity when analysing those samples obtained from the tests with "minimum quality" low cetane fuel. Ricardo have also observed similar results when comparing diesel fuels of different ignition quality in a light duty IDI vehicle.

The preliminary nature of these results is emphasised and it is not intended that these data should be construed as implying that low cetane fuels are at a disadvantage in this respect. Whilst more extensive studies may well indicate that this is the case, for the present moment in time, it is adequate to remain aware of the fact that fuel specification may influence particulate emissions in this manner. As a matter of low priority in the short term at least these aspects are regarded as worthy of investigation.

7.11.2 Conclusions

a) When considering future fuels, one must be aware of the implications of fuel specification upon such features as engine deposit and wear levels. Ignition quality, volatility and chemical character may be important factors based upon results from limited studies. An examination of these parameters must therefore be included in future test programmes since it appears that there is insufficient data available at present to allow accurate judgement.

b) In the interests of low engine deposits and wear, fuel sulphur level should not be allowed to rise significantly above current standards. Assuming exhaust catalysts are utilised in the future for particulate control, fuel sulphur levels should be maintained as low as economically possible. Exceptionally low levels of fuel sulphur may cause damage to fuel injection pump components however because of depressed extreme pressure lubricity. The lubricity of future fuels must therefore be examined for compatibility with fuel injection equipment.

c) There are insufficient data to ascertain whether or not fuel bound nitrogen contributes to NOx emissions. There are no data to ascertain whether fuel bound nitrogen contributes towards particulate emissions. Data are therefore required in this field.

d) Due regard for the influence of future fuel specifications upon the potential health hazard of particulate emissions should be given and examined in future test programmes, although in the short term this can be ascribed a low priority status.

PART B

7.12 Suitability of Combustion Systems for Future Fuels

7.12.1 Discussion

From the preceding sections concerning the influence of fuel specification upon the operation of diesel engines, it is clear that fuel specification can have a major influence in various areas. Not surprisingly, fuel ignition quality appears in many cases to be one of the prime factors and can have a marked influence upon starting, light load smoke, economy, gaseous emissions and noise and is also probably linked with high load smoke, hence rated output, particulates, odour and other variables.

Based upon this and despite the possible influence of other fuel variables such as volatility and chemical character it will be necessary to adapt diesel engines for future fuels if ignition quality is degraded. The extent of adaption required will of course depend upon the degree of degradation in ignition quality and to a lesser extent differences that occur in the sensitivity to cetane number between engines.

The judgement of the suitability of diesel engines to meet future fuel requirements in respect of ignition quality and where the potential of the spark ignited stratified charge engine lies in relation is difficult to make.

This is simply because the diesel engine has been developed to operate successfully with fuels of c.40 cetane or higher and out of necessity, diesel engines have not been developed for optimum performance, emissions, noise, etc. with fuels of lower ignition quality.

The exception to this generalised statement is the case of past multi-fuel developments, primarily for military applications, where diesel engines have been adapted to operate very successfully upon fuels of c.15-25 cetane in the form of high octane gasolines. These adaptations have involved primarily high compression ratio and,in different degrees, attention to reducing heat losses from the combustion chamber. In addition, such features as intake throttling, intake manifold heating, intake air pre-heating and aftercooling with turbocharge, have been frequently required to maintain light load combustion. Furthermore, attention to higher quality materials for pistons, valves and injectors are often required to combat higher firing pressures and high rates of heat release.

If future fuels of such low ignition quality are made available, the required extensive adaptation of diesel engines for widespread automotive use would not present an attractive proposition for commercial considerations, especially in the case of light duty applications. Furthermore, little is known of the emissions characteristics of such engines and these may of course be adversely affected. In addition, it should be remembered that such multi-fuel developments have not been applied to the light duty high speed diesel engine and it is speculated that there will be particular problems in this area.

Based upon these views, it is considered that, for light duty applications especially, the spark ignited stratified charge engine will become dominant if such low ignition quality fuels are adopted. The difficulty of judgement between the suitability of combustion systems occurs when intermediate ignition quality fuels of say c.30-35 cetane are considered.

In this case, it is known that the spark ignited stratified charge engine will consume such fuels with little problem. Whether or not the diesel engine can also be adapted to burn successfully such fuels whilst retaining competitive economy and emissions characteristics in addition to favourable commercial considerations cannot be judged without test programmes to ascertain such factors. It is therefore considered that, for fuels of this intermediate ignition quality range, judgement and recommendation of the most suitable combustion system cannot be made.

It has been cited in Part A of this discussion that issues such as the influence of wider ranging distillation characteristics and chemical composition upon such features for example as diesel engine emissions need to be resolved before the full impact of future fuels can be ascertained. Assuming that such issues are resolved and indicate no adverse reaction on behalf of the diesel engine, there is little doubt that for future fuels of high ignition quality, i.e. above c.40, the diesel engine will remain competitive in relation to the spark ignited stratified charge engine.

This view is based upon consideration of the emission comparisons between the various combustion systems and the attainment of economy standards. In respect of emissions, the available data suggest that with a minimum of emission controls the light duty diesel will more readily meet legislation with regard to HC emissions in comparison with the spark ignited stratified charge engine. These latter combustion systems will require considerable after-treatment to meet diesel levels. Regarding the economy aspect, to date TCCS and FM light duty applications have not demonstrated IDI diesel fuel economy during the Urban cycle, on either an mpg or fuel efficiency basis, despite excellent test bed economy. The reasons for this are not fully clear. These details may of course simply reflect standards of development relative to the diesel. The head start in this respect offered by the diesel engine will however continue to make it difficult for the stratified charge engine to compete. In this context it should also be remembered that the stratified charge engine has generally been developed as a multi-fuel engine. This may not be a valid requirement for the future and these systems must be examined as a fuel optimised engine. Some improvement relative to the current standard of HC emissions and fuel economy may therefore be expected.

In the context of the technical programme of this contract only certain combustion systems are being considered. There are however other systems which have been accorded multi-fuel characteristics and are worthy of examination as possible future automotive power plants to meet the requirements of future fuels.

In the case of compression ignition engines, the pre-chamber MWM and MAN M DI systems may have superior fuel tolerance to other IDI and DI diesel combustion systems although it is thought that this does not necessarily reflect upon the intrinsic qualities of the system but that these systems have been developed towards a degree of fuel tolerance. In addition, the MAN M system has been demonstrated as a small, high speed light duty diesel power plant.

In the context of fuel tolerant compression ignition engines, the opposed piston 2 stroke appears from very limited available data to have favourable characteristics which enables fuel tolerance to be achieved at moderate compression ratio. The relatively large package volumes, complexity and long development programmes associated with such engines however give rise to doubts whether the system is worthy of future consideration.

Other spark ignited systems which have demonstrated fuel tolerance should also be considered. These systems cover the Witsky, Mitsubishi MCP and Deutz AD developments.

7.12.2 Conclusions

a) The response of diesel engines to fuel ignition quality appears to be the prime controlling factor which will govern the suitability of the diesel engine for future fuels.

b) If fuels of very low ignition quality ie c.15-25 are anticipated as being widely available in the future, then the spark ignited stratified charge engine will represent the most viable combustion system. This is based upon the view that for diesel engines to successfully operate on such low cetane fuels, considerable adaptation towards past multi-fuel developments will be required which will be commercially unattractive. In addition, the high speed potential of light duty diesel engines may be restricted and emissions characteristics may be adversely affected.

c) Assuming that the currently unresolved issues of wider fuel distillation characteristics and chemical composition upon such features as diesel engine emissions show no adverse implications, then the retention of high ignition quality for future fuels ie above c.40 will enable the diesel engine to continue as the most competitive automotive power plant. This view is based upon the high state of development of the diesel engine with generally better emissions levels and transient fuel economy than the spark ignited stratified charge engine.

d) For fuels of intermediate ignition quality ie c.30-35 cetane, a judgement cannot be made without further data. This is based upon the fact that the required degree of adaptation of the diesel engine to operate successfully in respect of performance, economy, emissions etc. has not been established to enable comparison with the spark ignited stratified charge engine.

PART C

7.13 Overall Conclusions

1. Considering the extensive worldwide utilisation of diesel engines with a variety of combustion chambers and different applications, there is relatively little information available from structured programmes on the detailed effects of fuels and fuel variables related to the many facets of engine operation.

2. In the available literature there are many conflicts and areas of insufficient data and it is impossible to predict the overall effect of fuel variables upon diesel engine operation.

3. Insufficient data are available to evaluate syncrude derived products or to know whether syncrude products, having the same basic specification as petroleum derived products, behave in a similar fashion.

4. The data currently available on the influence of fuels and fuel variables have been acquired without recourse to engine re-optimization for fuels. In addition, the light duty IDI diesel engine requires more detailed attention. Future work should therefore cover a wider range of diesel engines and optimization of the engines for the various test fuels used.

5. (a) For fuels of very low ignition quality spark ignited stratified charge engines will probably be required as they have been demonstrated to have good fuel tolerance.

   (b) For fuels of relatively high ignition quality, re-optimized diesel engines should be suitable.

   (c) For fuels of intermediate ignition quality ie c.30-35, it is not clear without further data which type of combustion system would be most suitable.

6. A significant reduction in fuel ignition quality will require considerable design and development effort, either to adapt diesel engines or to apply spark ignited stratified charge engines on a large scale.

7. A large amount of carefully structured test work is required to obtain detailed information to understand fully the implications of future fuels upon the operation of engines with various combustion systems.

8.0 RECOMMENDATIONS

1. Continue to update the literature study particularly as regards synfuel operation because more data are likely to be generated in this area in the near future.

2. Give high priority to making synfuels available for future test programmes.

3. Give consideration to other potentially fuel tolerant combustion systems.

4. Define a test programme which will provide the required information in the areas where insufficient data currently exist.

5. Study the trade-off between the refinery implications of maintaining fuel quality so that existing diesel engines and design philosophy can be retained against reducing fuel quality with the attendant research and design/development implications, particularly with regard to lead time for production.

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