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# A STUDY OF STRATIFIED CHARGE FOR LIGHT DUTY POWER PLANTS: VOLUME 3. EXECUTIVE SUMMARY

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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by

Ricardo and Company Engineers (1927) LTD
Bridge Works
Shoreham-by-Sea, Sussex, BN4 5FG

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EPA Project Officers: T.C. Austin and J.J. McFadden

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## PREFACE

This report is the outcome of a stratified charge engine study carried out under a contract awarded by the Environmental Protection Agency. The report is divided into three parts, the first of which is an Executive Summary containing a brief description of the tests and methods used in the study and a presentation of the findings and recommendations. Volume I presents the results and conclusions of the literature survey section of the report while Volume II presents the configuration study, rating report and the specific discussions and conclusions of the complete project.

In an earlier work 'A Study of the Diesel as a Light-Duty Power Plant' (EPA-460/3 - 74-011) Ricardo and Company drew heavily on the expertise of their engineers in the diesel department, and the design phases of the exercise used engine designers with particular experience in diesel engines. In order to ensure balanced conclusions, however, the rating and discussion sections of the study were a joint effort involving engineers from both the gasoline and diesel departments.

In this study, although the targets, brief and overall programme were similar, the team of engineers and designers was changed to include engineers from the gasoline department and designers with gasoline (and stratified charge) design experience. During the rating exercise, however, the panel was essentially the same balanced panel as was used in the earlier study - this ensured that consistent and balanced decisions were made in this phase.

The team involved in the performance of the project would like to thank those members of the automotive and oil industries who commented on the interim reports produced during the study and were so helpful as to permit the publication of some of their latest information. The team also wish to express their appreciation of the action of the Environmental Protection Agency in arranging the interim exchanges of information and reports.

ABSTRACT

The objectives of this project were to determine the acceptability of various types of stratified charge engines as potential power plants for light duty vehicles and motorcycles in America. The light duty vehicle considered was a 4/5 seat compact sedan with good acceleration capabilities and exhaust emissions below a primary target of 0.41 g/mile HC, 3.4 g/mile CO, 1.5 g/mile $NO_x$. A secondary target of 0.41 g/mile HC, 3.4 g/mile CO and 0.4 g/mile $NO_x$ was also considered.

A literature survey was undertaken, comparing stratified charge engines with examples of good conventional gasoline and diesel engines. While some stratified charge engines had exhaust emission or fuel economy advantages, there were always sacrifices in other areas.

Eleven engines were configured, four of which were specifically directed towards the secondary emission targets. A method of rating the engines was derived, and the design concepts were compared with two gasoline engines by a jury panel. The overall result was that the Ford PROCO and Honda CVCC combustion processes were serious contenders to the gasoline engine at the primary emission target, and that both of these systems, together with the VW combustion process, might be suitable at the secondary targets.

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## INTRODUCTION

The combination of the provisions of the Clean Air Act and the steadily increasing cost of fuel has begun to influence the possible modes of transportation in America to such an extent that engines other than the conventional gasoline engine are now being actively considered and developed for passenger cars. Of the many forms of prime mover proposed for future passenger cars the stratified charge engine apparently offers the possibility of a low emissions engine with the ability to use gasoline fuel or even a variety of fuels while at the same time offering the increasingly important promise of good fuel economy associated with many engines of this type.

The object of this study was to determine the feasibility of the various types of stratified charge engine for light duty use. To achieve this aim a careful survey of current experience with all types of stratified charge engines was required and then, by the consideration of a target vehicle and an emissions environment, the design, performance and problem areas of the most promising types could be studied in detail.

For the purposes of this study the term 'light duty' was regarded as embracing passenger cars although consideration was also given to the motorcycle as a light duty vehicle.

The emissions targets proposed were such as to provide an interim target for a passenger car, i.e. Primary Emissions level

| | |
|---|---|
| HC | .41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 1.5 g/mile |

when tested by the CVS-CH procedure.

A longer term target for the passenger car was the provisions of the Clean Air Act, i.e. Secondary Emissions level

| | |
|---|---|
| HC | .41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 0.4 g/mile |

For the motorcycle the emissions targets were those currently proposed as an interim phase for this class of vehicle, i.e. Proposed Motorcycle Emissions level

| | | |
|---|---|---|
| HC | a sliding scale | |
| | 50-170 cc | 8 g/mile |
| | 170-750 cc | 8-22.4 g/mile |
| | Above 750 cc | 22.4 g/mile |
| CO | fixed level | 27 g/mile |
| $NO_x$ | fixed level | 1.92 g/mile |

In order to provide a specific reference for the detailed sections of the study a 'target' vehicle was defined. This was a 4/5 seat sedan with a loaded weight of about 1600 kg (3500 lb), capable of 0-97 km/h (0-60 mph) in 13.5 s and 40-113 km/h (25-70 mph) in 15 s, i.e. a compact size sedan but with standard performance capabilities. For motorcycle applications no specific target vehicle was defined due to the varied nature and use of these vehicles.

The first phase of the study required that a survey of all past and current experience with stratified charge engines be carried out. Because of the world-wide interest in these engines existing literature from published sources in America, Europe and Japan was to be included. Since it was recognised that many of the engines surveyed would be at an early stage of development it was decided to restrict this phase of the study to what was essentially published information so that future studies and resources would be concentrated on new developments with potentially viable engines.

The second phase of the study required that design schemes be made of all engines which the literature survey indicated as being feasible power plants for the passenger car target vehicle. During this process detailed calculations would be carried out to determine the likely performance and emissions levels of vehicles propelled by these engines.

In the next phase the various powerplants were to be compared on a numerical basis so that their potential performance, emissions or problem areas could be considered objectively.

In the final phase of the study the results of all the previous phases were to be considered so that overall conclusions could be drawn on the viability and likely potential of all the stratified charge engines considered. A further requirement of the fourth phase was the statement of recommendations for further action and study in order to achieve the most desirable light duty vehicle for an environment involving both emissions and fuel consumption constraints.

## CONCLUSIONS

At the completion of all the phases of the study the following broad conclusions were drawn:-

1. Unthrottled stratified charge engines always give high hydrocarbon emissions. Reduction of these can usually be achieved by throttling but they usually remain greater than those of conventional spark ignition engines. Acceptable levels can only be obtained by burning extra fuel to achieve hydrocarbon oxidation in the exhaust or by placing great reliance on catalytic reactors.

2. Existing methods of hydrocarbon control are unsatisfactory and a new method of initiating and propagating combustion, other than spark or compression ignition, is required to permit satisfactory oxidation of lean air fuel mixtures.

3. Although carbon monoxide emissions from stratified charge engines are usually low they generally give more than 3.4 g/mile (the target level) in CVS tests unless some form of after treatment is used.

4. $NO_x$ emissions are always lower than those from conventional gasoline engines. The pre-chamber type of stratified charge engine with fuel injection into the prechamber is capable of giving the lowest $NO_x$ emission of all the variants surveyed.

5. Although unthrottled operation with power controlled by fuel flow should yield the best possible fuel economy, the results obtained by the engines studied were disappointing. Only the direct injection type of stratified charge engine

showed any real improvement over a good conventional gasoline engine.

6. The specific output of naturally aspirated stratified charge engines is lower than that of conventional gasoline engines at the primary emissions target.

7. The only stratified charge engines to display any significant multi-fuel capability are those engines operating on principles similar to the MAN-FM and the TCCS systems.

8. Stratified charge engines are generally more complex and costly than conventional engines. Cost penalties range from a few per cent to over 100 per cent depending upon the system.

9. Stratified charge engines are generally larger and heavier than conventional engines. Only the Curtiss-Wright rotary system shows any advantage in this respect.

10. The drive-by noise of stratified charge engines depends upon the combustion system but no engine is significantly quieter than the conventional engine and most are more noisy.

11. Unthrottled engines give higher noise levels at idle and light load conditions than either throttled stratified charge engines or conventional engines.

12. None of the stratified charge engines showed any major starting problems.

13. At the primary emissions level the rating study indicated that the PROCO and CVCC systems were very close to the conventional gasoline engine when considering all aspects of operation. The PROCO system, however, places great reliance on catalyst durability.

14. At the secondary emissions level the CVCC and PROCO systems were the most viable power plants. The CVCC system, however, sacrifices fuel consumption to meet the secondary targets while the PROCO system relies even more heavily on catalyst durability.

15. At the emissions targets considered stratified charge engines are not attractive for motorcycle engines; mainly for economic reasons.

RECOMMENDATIONS

1 The scavenged prechamber engine (e.g. Honda CVCC) should continue to receive study as an interim measure to achieve the primary emission target. Although it has demonstrated the ability to meet the secondary target, it may not prove to be a satisfactory powerplant in the long term, due to poor fuel economy and driveability.

2. The Ford PROCO emerged high in the rating study and although catalyst durability, first cost and noise problems exist, it has some attractive features. Notably the secondary emission targets have been demonstrated with virtually no loss in fuel economy compared with existing gasoline engines. Continuity of production could be achieved as the emission levels were reduced.

3. As the engine with the lowest exhaust emissions and best test bed fuel consumption of any reviewed in this survey, the MAN-FM should be applied to an automotive vehicle, so that a direct comparison can be made with other stratified charge engines. The multi-fuel capability of this engine may also prove useful in other applications.

4. The Porsche and VW engines should receive further study as configurations most likely to achieve the secondary emission targets without sacrifice in durability or engine performance.

5. Research groups should be encouraged to study alternative methods for initiating and controlling combustion, besides compression and spark ignition. The basic premise that unthrottled engines, operating at moderate compression ratios could give better utilisation of energy than existing internal combustion engines, is sound. The exhaust emission limitations associated with existing stratified charge engines are related to the method of combustion, i.e. initiating the combustion with a spark and relying on flame propagation to oxidise all the fuel.

6. Our understanding of combustion and heat transfer in stratified charge engines is rather limited. Further experimental studies by combustion photography and instantaneous heat transfer measurements would establish empirical relationships, and help in the formulation of complex mathematical models. Existing models are of limited use, due to outmoded and non-applicable empirical relationships.

7. The next phase of emission levels proposed for motorcycles (the L.D.V. figures of .41 HC, 3.4CO, .4 $NO_x$) will be very difficult to achieve with existing engines. It is therefore recommended that work be carried out to investigate the application of a CVCC variant to the larger motorcycles. Although very restricted in configuration the Kushul engine offers the possibility of achieving the lower levels without the cost, economy and installation penalties of the CVCC system and thus the potential of this engine for larger motorcycles should also be investigated.

## ORGANISATION OF STUDY AND BASELINE DATA

Stratified charge engines can take many forms and may vary the degree of stratification throughout the load and speed range. A result of this great variety of concepts and mode of operation is that the definition of a 'stratified charge' can be a subject for considerable discussion. For the purposes of this study the following definition of stratified charge engines was determined:-

### Definition

A stratified charge engine is an engine with intermittent combustion initiated by a spark plug, where the element of mixture ignited by the spark plug is not typical of the mixture in the remainder of the working gas, over some portion of the engine operating regime. Before ignition, the remainder of the working gas will correspond to one of two cases:

(a) A mixture of air and fuel where the average mixture strength is leaner than that ignited by the spark. In addition there may be exhaust residuals from a previous working cycle distributed throughout the working gas.

(b) A mixture composed of the same ratio of air and fuel as that at the spark plug, but with considerable dilution by exhaust residuals from a previous working cycle.

## Classification

Within the above definition there are many engines lying between the general classes of throttled conventional gasoline engines and unthrottled diesel engines and these stratified charge engines can differ widely in their characteristics.

To simplify analysis and comparison, therefore, the general class of stratified engines was divided into different categories, each category being chosen so that it embraced all those engines with a similar combustion chamber configuration and nature of combustion.

Category 1 : Single combustion chamber with fuel injection before tdc, mixture formation by fuel injection and/or air movement.

Category 2 : Single combustion chamber with fuel injection during combustion and combustion controlled by injection.

Category 3 : Single combustion chamber with fuel injection onto the piston. Combustion controlled by fuel evaporation from the piston.

Category 4 : Split combustion chambers with fuel injection into a pre-chamber. Fuel can also be added to the inducted air.

Category 5 : Split combustion chambers with a separate inlet valve for the prechamber.

Category 6 : Other weak mixture spark ignition engines based on carburettors.

Category 7 : Two strokes, exhaust diluent engines and miscellaneous.

The table below shows how this classification was achieved and gives examples of some of the engines in each category.

STRATIFIED CHARGE ENGINE CATEGORIES

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| ← SINGLE CHAMBERS → | | | ← DUAL CHAMBERS → | | ← SINGLE CHAMBER → | |
| ← FUEL INJECTION → | | | | ← CARBURETTORS → | | |
| Early Injection into moving air | Late injection into moving air | Combustion Controlled by wall evaporation | Fuel Injection into prechamber also fuel addition to main chamber | Mixture supplied by carburettor(s) separate prechamber inlet valve | | Two strokes exhaust diluent engines Miscellaneous |
| EXAMPLES | | | | | | |
| Ford Proco<br>FCP<br>Mitsubishi<br>Hesselman<br>Witsky | Texaco TCCS<br>Curtiss-Wright | Man F-M | Newhall<br>VW<br>Huber | Honda CVCC<br>Nilov<br>Heintz | I.F.P. | Ricardo<br>Jessel<br>Kushul |

## Baseline Data

Because the stratified charge engines which were studied varied so much in their application, performance and emissions characteristics, it was necessary to derive baseline data to give a reliable basis for comparison and it was felt that the best results which could be achieved by existing gasoline and diesel passenger cars should be used. To derive these data a study was made of published gasoline and diesel CVS-CH results so that 'good' fuel consumption figures could be obtained for the two target emission levels. These data points were used throughout the study to provide constant reference lines.

Many of the engines studied had not been developed to the point where they could be installed in a vehicle, indeed much of the published information only covered single cylinder test bed results, and thus some means of predicting the performance of a light duty engine of appropriate power for the vehicle under consideration was required. Calculations had indicated that a 96 kW (128 BHP) engine was required to power the target passenger car and so all test bed results were modified to give values applicable to an engine of this output. This could usually be achieved by a simple scaling exercise.

In a previous study the test bed emissions and fuel consumption of a diesel engine specifically configured to power the target vehicle was presented and it was considered that these figures represented the best basis for comparison. This was because the diesel emissions figures were very much lower than those which conventional gasoline engines could achieve and the diesel figures were obtained without any exhaust treatment. The fuel consumption of the diesel was also lower than that of gasoline engines. As a result of the above all the stratified charge engine results relating to test bed figures were compared with those which could be achieved by the 96 kW (128 BHP) diesel engine.

Because no specific motorcycle was defined the results from the passenger car performance comparisons were used to predict the likely motorcycle performance.

## LITERATURE SURVEY

Stratified charge literature is available from sources throughout the world and dates almost from the original conception of the internal combustion engine. Since the primary objective of the literature survey was to provide a preliminary assessment of the feasibility of the various stratified charge engines as power plants for the target vehicles emissions levels considered, the period covered by the survey was from 1920 to the present day. It was felt that earlier publications would be unlikely to contain sufficient emissions, fuel consumption and durability information for the necessary predictions. In all, some 200 items of literature were studied and these emanated from sources throughout the world including America, Europe, U.S.S.R. and Japan.

All the literature surveyed was studied under a 'topic' system and the engines covered in the literature were, of course, classified according to the seven categories described above. Combining the 'topic' sub-classification with the seven engine categories allowed general conclusions to be formed on each category as well as permitting specific conclusions on individual engines. It also allowed a ready comparison to be made of the specific characteristics of engines in different categories. The topic areas used to review each category were as follows:

History
Combustion chamber and stratification technique

Combustion characteristics and heat rejection
Performance
Fuel consumption
Emissions
Multi-fuel capability
Engine Components and Manufacturability
Cost
Mathematical Models
Engine size and weight
Noise and Vibration
Durability and Starting
Driveability
Patents

The general conclusions drawn from the literature survey were:

1. Unthrottled stratified charge engines have demonstrated large potential improvements in fuel economy but the lack of throttling usually leads to high hydrocarbon emissions.

2. Throttled stratified charge engines can be shown to achieve satisfactory hydrocarbon levels but usually at the expense of fuel economy.

3. The nitrogen oxide emissions of all the stratified charge engines studied were lower than those of conventional gasoline engines and perhaps the most attractive feature of stratified charge engines is their ability to meet the secondary nitrogen oxide target of 0.4 g/mile.

4. The Ford Proco engines can be made to meet the secondary targets with little sacrifice in fuel economy but a larger, heavier engine is required to permit control of emissions during the CVS-CH tests.

5. The divided chamber category IV engines (e.g. VW and Porsche) have considerable practical and theoretical advantages and should be able to achieve the secondary emissions target with less performance and driveability sacrifices than any other internal combustion engine while still retaining an acceptable fuel consumption.

6. The following engines were considered as feasible power plants for the primary emissions targets:

PROCO

TCCS

Curtiss Wright Rotary

MAN-FM

VW Prechamber

CVCC

7. The following engines were considered as feasible power plants for the secondary emissions targets:

PROCO

TCCS

VW Prechamber

CVCC

Category 1 Literature Survey

(Single combustion chamber with fuel injection before tdc, mixture formation by fuel injection and/or air movement)

The engines covered within this category were:

1. Ford PROCO

2. Windsor-Smith

3. Hesselman

4. Starr

5. Witsky

6. Mitsubishi (MCP)

In general the engines in this category rely on the characteristics of the fuel injection to achieve stratification within a swirling air stream. Injector position, injection timing, spark plug position and spark timing are all critical factors in the operation of any of the systems but they all feature fuel injection direct into a more or less open type chamber with air swirl within the chamber.

The conclusions from the literature covering the above engines were

1. Stratification within direct injection engines can only be achieved with difficulty and requires the combination of suitable air movement and a tailored injection system.

2. The unthrottled stratified charge engines in this category can give a fuel economy approaching that of the diesel, but all have high hydrocarbon emissions. Meeting the emissions targets with this principle requires what are currently impossible conversion efficiencies from oxidation catalysts.

3. By throttling these stratified charge engines the hydrocarbon levels can be reduced with some sacrifice in fuel economy.

4. A PROCO engine fitted with an oxidation catalyst and using some exhaust gas recirculation would be able to achieve the primary target with fuel economy similar to that of a conventional engine at a $NO_x$ level of 2.4 g/mile.

5. By using high levels of exhaust gas recirculation at part load and by using an engine approximately 25% greater in swept volume to restrict load during the CVS-CH test procedure, a PROCO engine would achieve the secondary target

with little sacrifice in fuel economy. The high hydrocarbon levels with this quantity of exhaust gas recirculation, however, make it highly likely that catalyst durability will be a major problem.

6. The cost of the fuel injection equipment would be very high relative to the base cost of motorcycle engines and the application of the category 1 combustion process to small cylinders is likely to be difficult.

7. The performance penalties associated with these types of combustion system also make them unattractive for motorcycles.

Category 2 Literature Survey

(Single combustion chamber with fuel injection during combustion : mixture formed by fuel injection and/or air movement)

In this category, which is almost a sub-section of the category 1 classification the TCCS and Deutz systems were studied as reciprocating engines while the application of the principle to a rotary engine by Curtiss-Wright was also studied.

The mode of combustion is similar to that of category 1 engines except that the fuel is injected into the swirling air during combustion and the heat release rate is partially controlled by the injection rate.

The conclusions deduced from the literature survey were:

1. The combustion process in all these systems is extremely complex and depends on many other parameters besides fuel injection rate.

2. The output of all the engines in this category is limited by smoke emissions and air utilisation is relatively poor, although the rotary engine is not so limited by this consideration.

3. Hydrocarbon emissions from all the engines in this category are high particularly from the rotary engine.

4. In the absence of emission controls the fuel consumption of the reciprocating engines would be low.

5. The reciprocating engines have demonstrated multi-fuel capability with acceptable fuel economy.

6. The TCCS engine is potentially viable for the primary emissions target but great reliance is placed on catalyst conversion efficiency with a low temperature exhaust.

7. The TCCS engine is also viable for the secondary emission target where large quantities of EGR will be required and reliance on catalyst efficiency will still be required due to the high hydrocarbon emissions.

8. At the secondary target the fuel consumption of a TCCS engined passenger car will be poor.

9. The Curtiss-Wright Rotary Combustion engine could be made viable for the primary emissions target although it is likely to give a poor fuel consumption and place great reliance on catalyst conversion efficiency.

10. The complexity and cost of all the systems in this category makes them unsuitable for motorcycle use. There are doubts as to the effectiveness of these combustion processes in small cylinders and the intrinsically high hydrocarbon levels and performance penalties make the use of category 2 engines for this application extremely unattractive.

Category 3 Literature Survey

(Single combustion chamber with fuel injection onto the piston. Combustion controlled by fuel evaporation from the piston).

Only the 'FM' (Fremdzundung) system developed from the MAN-M system diesel engine fitted this category. In the 'FM' system high levels of air swirl are generated bv a helical inlet port and a spherical combustion cavity in the piston. During the compression stroke fuel is sprayed into the cavity when evaporation from the piston surface or from within the swirling charge air causes mixing and carries the fuel to the spark plug or flame front.

The literature survey indicated that:

1. Such a system could give extremely good fuel consumption.

2. The MAN-FM system will burn a wide range of fuels with consistently good fuel consumption.

3. This type of combustion system limits the power output of the engine due to smoke emissions. This and breathing penalties limit the specific output to that of diesel engines.

4. The base-line hydrocarbon levels of this system are low.

5. An engine operating on the MAN-FM system could be made viable for the primary emissions target when it would only require a single oxidation catalyst.

6. The MAN-FM system is rather complex for motorcycle use and the performance limitations make it unattractive for this application.

Category 4 Literature Survey

(Divided combustion chamber with fuel injection into a prechamber)

.n this category the prechamber may vary from a small prechamber acting almost as an ignition source to a large prechamber in which extensive charge stratification is used.

For convenience the engines within this category were divided into three classes identified by the size of the prechamber.

(a) Prechambers less than 20% of combustion chamber

The engines in this class include the Freeman, the Porsche and the Clawson systems. The engines all resemble the conventional gasoline engine in that load is controlled by throttling the intake air and the mixture strength is not varied over a wide range. The prechamber is enriched by a separate fuel injection system and combustion is initiated in the prechamber. The 'torch' issuing into the main chamber thus initiates combustion at a number of points and this gives more reliable combustion which permits operation at leaner overall mixture strengths than can be achieved in the conventional gasoline engine.

(b) Prechambers between 20 and 40% of the combustion chamber

These engines, which include the VW, Broderson and Schlamann systems, are generally a compromise between the very large and small pre-chambers and can thus usually operate in two modes. In the first mode the engine is unthrottled, the prechamber acts as in the class (a) engines but extra fuel is supplied to the main chamber for high load operation. In the second mode the engine is throttled so that approximately constant overall air fuel ratios are maintained in the two chambers at all loads.

(c) Prechambers greater than 40% of the combustion chamber

Engines in this class are usually unthrottled and load is controlled by the prechamber fuelling. At low loads the prechamber mixture is stratified to ensure combustion while at high loads the prechamber mixture strength is greater than stoichiometric and the rich mixture is finally burnt as it is expelled into the main chamber. The Huber and Newhall systems fall within this classification.

Careful study of the published information on the nine engine types yielded the following conclusions:

1. The results obtained from the VW and Porsche* systems (throttled, using a small pre-chamber as an ignition cell) were quite good.

2. The good fuel consumptions from test bed results were not repeated in vehicle tests.

3. The hydrocarbon emissions are similar to those from conventional gasoline engines.

4. Nitrogen oxide emission levels are exceptionally low and levels below 1 g/mile can be achieved without EGR.

5. A VW prechamber engine would be able to meet the primary emissions targets using only an oxidation catalyst but fuel economy would be little better than a conventional gasoline engine.

6. By the use of EGR and a further catalyst the same engine should be capable of meeting the secondary emissions target with only a slight fuel economy sacrifice.

7. All of the engines examined could be designed to fit into a motorcycle application but their great complexity and reduced specific output make them all unattractive.

* Some recent results from Porsche, referring to a six cylinder engine installed in a car indicate good specific output and low emissions. Taken with the good test bed fuel consumptions the system appears to be extremely attractive.

Category 5 Literature Survey

(Divided combustion chamber with a separate inlet valve for the pre-chamber)

Probably the best known system within this category is the Honda CVCC although many recently developed scavenged pre-chamber engines were reviewed. These were the Ford, G.M., VW. Eaton and Heintz scavenged prechambers. Several Russian engines in this category including the Nilov, GAZ and ZIL engines were examined. In addition many early publications describing engines falling into this category were studied including the results from recent retrofit approaches such as those of Morghan, Philips, Teledyne and Walker.

The general principle of operation is that the engine induces a lean mixture through the main intake valve while a very rich mixture is induced into the pre-chamber via the third valve. The compression process gives some dilution of the prechamber mixture so that at ignition an air/fuel ratio of 9 to 12:1 exists at the spark plug in the prechamber. After ignition the hot gas in the prechamber is expelled as a 'torch' into the main chamber so initiating combustion in the leaner mixture.

The large quantity of publications studied in this category gave the following general conclusions:

1. The specific output of this class of engine can be similar to that of conventional gasoline engines if stratification is sacrificed at full load. If stratification is maintained then a loss of some 10% in specific output results.

2. The fuel economy of a car equipped with a scavenged pre-chamber engine should only be slightly inferior to a conventionally powered vehicle.

3. If stratification is maintained at full load the emissions should be within the primary targets. Hydrocarbon and carbon monoxide levels are controlled by a thermal reactor.

4. The secondary emissions target is attainable with a scavenged pre-chamber engine, at the expense of economy, driveability and performance, by the use of EGR.

5. At the emissions targets considered for motorcycles in this study the use of scavenged pre-chamber engines would give very little advantage while the size of the components and orifices for small cylinders would present production problems. For the emissions levels ultimately intended, however, the CVCC principle could be attractive in the larger engine sizes providing the installation problems involved with the large number and nature of external devices can be solved.

Category 6 Literature Survey

(Other weak mixture spark ignition engines - single combustion chamber with carburetted mixture).

The only system within this category is the I.F.P. (Institut Francais du Petrole) process which was developed round about 1960. The object of the system was to permit operation with lean mixtures without the use of pre-chambers, fuel injection or air swirl. This was achieved by dividing the carburetted mixture into a rich and a weak stream. The rich stream is discharged through a small diameter tube within the intake port so that it flows into the vicinity of the spark plug. The weaker mixture flowed into the cylinder in the normal manner.

The main conclusions reached after studying the literature on this engine were:

1. Insufficient data were available to predict the likely emissions performance under transient conditions.

2. The maximum output would be the same as for a conventional gasoline engine since at full load the system operates as a homogeneous charge system.

3. Test bed results indicated that the low load fuel consumption might be better than obtained from a conventional gasoline engine although no vehicle fuel consumptions are available to confirm this.

5. The test bed results did indicate the ability to maintain the minimum levels of hydrocarbons and carbon monoxide over a wider range of mixture strengths than a conventional engine, although the absolute levels were no lower.

6. Because a weak mixture carburetted system can be applied easily to existing engines it may present a means of reducing the hydrocarbon and carbon monoxide emissions from existing four-stroke motorcycle engines and improve the fuel economy at the same time. The use of some variation of the IFP system in this application may provide a worthwhile palliative approach in view of the proposed emission levels and the operating range of motorcycle engines.

Category 7 Literature Survey

(Two stroke, exhaust diluent and miscellaneous engines)

Many different types of engine were covered in this category. The first of these the Nippon Clean Engine - NICE is a modified two-stroke engine relying on air motion produced by three transfer ports. The positioning of the third transfer port, a wedge shaped combustion chamber and the design of the transfer passages are essential for the controlled scavenging process. An exhaust control valve is also required in the exhaust port to prevent over-rapid blow down and in fact both inlet and exhaust are throttled throughout the speed range.

The YOCP engine (Yuo and Ohnishi Combustion Process) is a Schnurle scavenged two-stroke with in-cylinder injection of the fuel and throttling is only required at light load.

The Fairbanks Morse engine is an opposed piston design utilising two very small pre-chambers for each cylinder and is only used as a gas engine. Gas is injected into the pre-chambers where ignition occurs and torch ignition is used.

Both the Kataoka and Hirako (K and H) and the Clawson two-stroke systems apply an unscavenged pre-chamber to a loop scavenged two stroke with fuel addition to both the main and pre chambers and are unthrottled engines at the present state of development.

The Heintz Ram Straticharge system was a scavenged pre-chamber two stroke with pre-chamber scavenge supplied from the second stage of a two stage Roots blower and the main chamber scavenge from the first stage.

The Ricardo two strokes were sleeve valve two strokes with fuel injection into a bulb shaped pre-chamber.

In the Jessel engine, stratification was achieved by the control of exhaust dilution by exhaust recirculation through an additional valve.

In the Kushul engine two separate cylinders were connected by a transfer port and one cylinder, the mixture cylinder containing the fuel and air and where ignition occurs leads the air cylinder by 20 - 30$^{o}$ crank. Complete combustion and wide burning ranges were claimed due to the intense air and gas motion during combustion.

Early Ricardo work was also carried out on a 4 stroke sleeve valve achieving charge stratification by means of a second row of intake air ports low down in the cylinder.

The general conclusions from the survey of published information on these engines were:

1. All of the two stroke systems reviewed added expense and complexity to the basic engines without overcoming the failings.

2. The fuel consumption of all the two stroke engines was poor. The Kushul engine, however, would seem to be capable of giving fuel economies comparable with that of an I.D.I. diesel.

3. As far as could be determined from the published results all the engines were likely to give high levels of hydrocarbons and carbon monoxide while giving low levels of oxides of nitrogen.

4. The only engine to achieve the primary target (and the secondary target) was the NICE equipped with a very complex afterburner system.

5. None of the engines was considered viable for the target passenger car.

6. The NICE might be suitable for the two-stroke motorcycles but the degree of after treatment required for the various emissions levels cannot be predicted easily.

ENGINE CONFIGURATION STUDY

The literature study indicated that some stratified charge engines could provide viable power plants for a passenger car and thus the study required that all potentially viable variants be designed in sufficient detail to allow their likely performance to be assessed realistically. The vehicle to be powered by any of the candidate power plants was a 4/5 seat sedan weighing less than 1600 kg (3500 lb) and capable of meeting the EPA standard car performance specifications, i.e. 0.97 km/h (0-60 mph) in less than 13.5 s, 40-113 km/h (25-70 mph) in less than 15 s and capable of overtaking a 80 km/h (50 mph) truck in less than 15 s. The emission targets were:

Primary (or short term)

| | |
|---|---|
| HC | 0.41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 1.5 g/mile |

Secondary (or long term)

| | |
|---|---|
| HC | 0.41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 0.4 g/mile |

and were to be obtained when the vehicle was tested according to the CVS-CH procedure. Computer calculations indicated that a 3-speed automatic gear box would require an installed power of approximately 97 kw (130 bhp) for engines with normal torque characteristics, and thus all the power plants were designed with this in mind.

In order to provide a firm basis for comparison in the rating section of the study typical gasoline engines were specified briefly at the commencement of the configuration study phase. Two engines, a V-8 following current good American practice and an IL-6 more representative of European designs were specified.

The stratified charge engines selected as potentially viable were all schemed out in some detail so that the true potential of each system could be realised and also so that design problem areas and restrictions on configuration, installation or performance could be foreseen. As far as possible the V-8 and IL-6 designs followed current American gasoline engine practice while the emissions control gear on all of the power plants was specified to permit operation for 50,000 miles or at least 25,000 miles with little maintenance.

To provide a further basis for comparison and to maintain continuity with the earlier diesel study the naturally aspirated V-8 indirect injection diesel from that study was also included in this phase.

A brief description of the 2 gasoline engines, 12 stratified charge engines and the diesel engine is given below while salient engine dimensions, performance and emissions control gear are all compared in the Summary Table at the end of this section.

## 1. V-8 Gasoline Engine

8 cylinder 97 mm x 76 mm (3.82" x 3.00") - 4.5 litre (275 CID)

96 kW (128 BHP) at 66.7 rev/s

285 N m (210 lb.ft) at 41.6 rev/s

245 kg (540 lb) estimated weight.

For the primary emission target (1.5 g/mile $NO_x$) the engine would require modulated exhaust gas recirculation, sophisticated close tolerance carburettors, air injection into the exhaust manifold and an oxidation catalyst in the exhaust system.

The 'good performance' target gasline engine for this study will have a fuel consumption of approximately 14.6 l/100 km (16.0 mile/U.S. gallon) over the CVS-CH cycle in the primary emissions build.

Driveability noise level would be 71 dBA under U.S. Federal Test conditions.

2. In-Line Gasoline Engine

6 cylinder 88 mm x 82 mm (3.46" x 3.22")

3 litre (183 CID)

96 kW (128 BHP) at 83.3 rev/s

232 N m (171 lb.ft) at 50 rev/s

204 kg (450 lb) estimated weight.

The engine would be equipped with similar emissions control gear to the V-8 engine.

Fuel consumption in primary emissions build would be approximately 13.5 l/100 km (17.4 miles/U.S. gallon) over the CVS-CH cycle.

Drive-by noise level will be 73 dBA.

3. V-8 PROCO Engine Primary Target

8 cylinder 87 mm x 87 mm (3.43" x 3.43")

4.15 litre (254 CID)

96 kW (128 BHP) at 66.7 rev/s

292 N m (215 lb.ft) at 38 rev/s

250 kg (550 lb) estimated weight

To meet the primary emissions target, some exhaust gas must be recirculated. A large oxidation catalyst will also be required.

Predicted fuel consumption is 12.5 l/100 km (18.7 mile/U.S. gallon) over the CVS-CH cycle.

Drive-by noise level will be 71 dBA.

4. In-Line 6 PROCO Engine - Primary Target

6 cylinder 96 mm x 96 mm (3.78" x 3.78")

4.15 litre (254 CID)

96 kW (128 BHP) at 66.7 rev/s

293 N m (216 lb.ft) at 37 rev/s

263 kg (580 lb) estimated weight

The same emissions control will be required as on the V 8.

Predicted fuel consumption is 12.7 l/100 km (18.4 mile/U.S. gallon) over the CVS-CH cycle.

Drive-by noise level will be 75 dBA.

5. V-8 PROCO Engine - Secondary Target

8 cylinder 94 m x 94 m (3.7" x 3.7")

5.22 litre (320 CID)

122 kW (163 BHP) at 66.7 rev/s

365 N m (270 lb.ft) at 40 rev/s

259 kg (570 lb) estimated weight

For the secondary emissions target it will be necessary to employ higher exhaust gas recirculation rates than for the primary targets with modulation of this rate with load. The resulting increase in HC emissions will require a large volume of oxidation catalyst to give satisfactory durability.

Predicted fuel consumption is 14.2 l/100 km (16.5 miles/U.S. gallon).

Drive-by noise will be 72.5 dBA.

6. V-8 TCCS Engine - Primary Target

8 cylinder 95 mm x 95 mm (3.74" x 3.74")

5.4 litre (330 CID)

96 kW (128 BHP) at 66.7 rev/s

280 N m (206 lb.ft) at 29 rev/s

273 kg (600 lb) estimated weight.

Modulated exhaust gas recirculation together with two catalysts for HC and CO control will be required.

Predicted fuel consumption is 13.8 l/100 km (17 miles/US gallon).

Drive-by noise will be 70.5 dBA.

7. In-Line 6 Turbocharged TCCS Engine - Primary Target

6 cylinder 96 mm x 96 mm (3.78" x 3.78")

4.16 litres (254 CID)

96 kW (128 BHP) at 66.7 rev/s

298 N m (210 lb.ft) at 42 rev/s

260 kg (572 lb) estimated weight

Similar emission control gear will be required to that fitted to the V-8 TCCS engine.

Drive-by noise will be 71 dBA.

Predicted fuel consumption is 13.8 l/100 km (17 miles/U.S. gallon)

8. Rotary, 2 Bank Engine - Primary Target

2 rotors 5.5 litre (336 CID)

97 kW (130 BHP) at 83 rev/s

214 N m (158 lb.ft) at 56 rev/s

150 kg (330 lb) estimated weight

Due to the high inherent HC emissions from rotary engines, two oxidation catalysts will be required.

Predicted fuel consumption is 16.74 l/100 km (14 miles/U.S. gallon)

Drive-by noise is estimated at 71 dBA.

9. V-8 Turbocharged TCCS Engine - Secondary Target

101 mm x 92 mm (3.96" x 3.64")

5.87 litres (358 CID)

135 kW (181 BHP) at 66.7 rev/s

423 N m (312 lb.ft) at 41 rev/s

286 kg (630 lb) estimated weight.

For emissions control, ignition retard and modulated exhaust gas recirculation are required together with two oxidation catalysts. It might be possible to replace one of the catalysts by a thermal reactor.

Predicted fuel consumption is 16.74 l/100 km (14 miles/U.S. gallon)

Drive-by noise will be 72.5 dBA.

10. V-8 MAN-FM Engine - Primary Target

93 mm x 93 mm (3.66" x 3.66")

5.05 litre (309 CID)

96 kW (128 BHP) at 66.7 rev/s

298 N m (219 lb.ft) at 33 rev/s

300 kg (660 lb) estimated weight

This engine has inherently low $NO_x$ emissions but will require an oxidising catalyst for HC and CO control.

Predicted fuel consumption is 12.3 l/100 km (19 miles/US gallon)

Drive-by noise will be 72 dBA.

11. V-8 VW Engine - Primary Target

86 mm x 79 mm (3.39" x 3.11")

3.67 litre (224 CID)

96.5 kW (129 BHP) at 75 rev/s

228 N m (168 lb.ft) at 66 rev/s

250 kg (550 lb) estimated weight

This engine has inherently low $NO_x$ emissions but will require an oxidising catalyst for HC and CO control.

Predicted fuel consumption is 14.2 1/100 kw (16.5 mile/U.S. gallon)

Drive-by noise will be 73 dBA.

## 12. V-8 VW Engine - Secondary Target

Engine specification identical to VW for Primary Target.

Modulated exhaust gas recirculation and two oxidising catalysts will be required for emissions control.

Predicted fuel consumption is 15.1 1/100 km (15.5 miles/U.S. gallon)

Drive-by noise will be 73 dBA.

## 13. V-8 CVCC Engine - Primary Target

88 mm x 88 mm (3.46" x 3.46")

4.28 litres (260 CID)

97.5 kW (130.5 BHP) at 73.5 rev/s

268 N m (197 lb.ft.) at 35 rev/s

250 kg (550 lb) estimated weight.

A thermal reactor will be required for emissions control.

Predicted fuel consumption is 13.95 1/100 km (16.8 mile/U.S. gallon)

## 14. V-8 CVCC Engine - Secondary Target

96 mm x 96 mm (3.78" x 3.78")

5.56 litres (340 CID)

121 kW (162 BHP) at 66.7 rev/s

350 N m (258 lb.ft.) at 33.5 rev/s

273 (600 lb) estimated weight.

Modulated exhaust gas recirculation and a thermal reactor will be required for emissions control. (An additional oxidising catalyst may be found to be necessary for HC and CO control).

Predicted fuel consumption is 15.6 1/100 km (15 miles U.S. gallon)

Drive-by noise will be 73 dBA.

15. V-8 Diesel - Primary Target

While no diesel engine has been configured, it is convenient, for comparison purposes to repeat the specification produced in the previous study.

88 mm x 98 mm (3.46" x 3.86")

4.78 litre (292 CID)

96 kW (128 BHP) at 66.7 rev/s

290 N m (210 lb.ft.) at 33.3 rev/s

320 kg (700 lb) estimated wight

Apart from retardation of injection timing, no add-on devices are required for emission control.

Predicted fuel consumption on diesel fuel is 11 l/100 km (21 miles/U.S.gallon).

Drive-by noise will be 74 dBA.

# SUMMARY TABLE

| | CATEGORY | EMISSION TARGET | ENGINE SPECIFICATION: BORE mm | STROKE mm | CONFIGURATION | DISPLACEMENT L | C.R | PACKAGE: LENGTH mm | HEIGHT mm | WIDTH mm | BOX VOLUME $m^3$ | WEIGHT kg | COST $ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GASOLINE V8 | GASOLINE | PRIMARY | 97 | 76 | NA V8 | 4.5 | | NOT CONFIGURED | | | | 245 | 595 |
| GASOLINE IL6 | GASOLINE | PRIMARY | 88 | 82 | NA IL6 | 2.99 | | NOT CONFIGURED | | | | 204 | 598 |
| PROCO V8 | I | PRIMARY | 87 | 87 | NA V8 | 4 15 | 11 0 | 770 | 597 | 600 | .275 | 250 | 741 |
| PROCO IL6 | I | PRIMARY | 96 | 96 | NA IL6 | 4.15 | 11 0 | 995 | 638 | 528 | .335 | 263 | 664 |
| PROCO V8 | I | SECONDARY | 94 | 94 | NA V8 | 5.25 | 11 0 | 800 | 609 | 622 | .303 | 259 | 827 |
| TCCS V8 | II | PRIMARY | 95 | 95 | NA V8 | 5.4 | 10 0 | 823 | 658 | 622 | .337 | 273 | 811 |
| TCCS IL6 | II | PRIMARY | 96 | 96 | TC IL6 | 4 16 | 9 0 | 981 | 610 | 578 | 346 | 260 | 827 |
| CW ROTARY | II | PRIMARY | | | 2 BANK ROTARY | 5 5 | 8.5 | 523 | 660 | 695 | .24 | 150 | 667 |
| TCCS V8 | II | SECONDARY | 101 | 92 | TC V8 | 5 87 | 9.0 | 845 | 645 | 630 | 343 | 286 | 985 |
| MAN FM V8 | III | PRIMARY | 93 | 93 | NA V8 | 5 05 | 15 0 | 745 | 643 | 640 | .307 | 300 | 756 |
| VW V8 | IV | PRIMARY | 86 | 79 | NA V8 | 3 67 | 8 5 | 763 | 610 | 610 | .284 | 250 | (EFI 764) 844 |
| VW V8 | IV | SECONDARY | 86 | 79 | NA V8 | 3 67 | 8 5 | 763 | 610 | 610 | 284 | 250 | (EFI 819) 899 |
| CVCC V8 | V | PRIMARY | [illegible] | 88 | NA V8 | 4.28 | 7 9 | 761 | 660 | 642 | 322 | 250 | 600 |
| CVCC V8 | V | SECONDARY | 96 | 96 | NA V8 | 5 56 | 7 9 | 795 | 675 | 6.4 | 362 | 273 | 670 |
| DIESEL V8 | | PRIMARY | 88 | 98 | NA V8 | 4 78 | 20 | 758 | 604 | 692 | 320 | 320 | 701 |

| | PERFORMANCE: POWER kW at rev/s | TORQUE Nm at rev/s | TORQUE BACKUP % | VEHICLE PERFORMANCE: ECONOMY m/USgal | CONSUMPTION L/100 km | HC CONTROL / HC BASE | CO CONTROL / CO BASE | NOx | NOISE dBA | EMISSION CONTROL: CATALYST | THERMAL REACTOR | EGR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GASOLINE V8 | 96 66 7 | 285 41.6 | 25 | 16 | 14 6 | 0 2 1 8 | 1.0 30 0 | 1.3 | 71 | 1 EXH AIR INJ. | | X |
| GASOLINE IL6 | 96 83.0 | 232 50 | 20 | 17 4 | 13.5 | 0 2 1 8 | 1.0 30.0 | 1 3 | 73 | . EXH. AIR INJ. | | X |
| PROCO V8 | 96 66 7 | 292 38 | 19 | 18.7 | 12.5 | 0.15 1 0 | 1 0 8 0 | 1 4 | 71 | 1 | | X |
| PROCO IL6 | 96 5 66 7 | 293 37 | 26 | 18 4 | 12.75 | 0 15 1.0 | 0 8 8 0 | 1.3 | 75 | 1 | | X |
| PROCO V8 | 122 66.7 | 365 40 | 13 | 16.5 | 14.2 | 0.25 2.5 | 0 8 12 | 0.37 | 72 5 | 2 | | X |
| TCCS V8 | 96 66.7 | 280 29 | 23 | 17 0 | 13.8 | 0 3 2.5 | 1.5 10 | 0 8 | 70.5 | 2 | | X |
| TCCS IL6 | 96 66.7 | 298 42 | 15.4 | 17.0 | 13 8 | 0 22 2 0 | 1 5 10 | 0 8 | 71 | 2 | | X |
| CW ROTARY | 97 83 | 214 56 | 17 4 | 14 0 | 16.74 | 0 3 3 0 | 0 8 15 | 1 0 | 71 | 2 | | |
| TCCS V8 | 135 66 7 | 423 41 | 19 0 | 14.0 | 16.74 | 0.25 4.5 | 1 0 12.0 | 0 33 | 72.5 | 2 | | X |
| MAN FM V8 | 96 66.7 | 298 33 | 24.6 | 19.0 | 12.3 | 0.3 0 8 | 0.8 8 0 | 1 0 | 72 | | | |
| VW V8 | 96.5 75 | 228 66 | 9 8 | 16.5 | 14.2 | 0 23 1 8 | 0.8 8.0 | 1 0 | 73 | . | | |
| VW V8 | 96 5 75 | 228 66 | 9.8 | 15 5 | 15 13 | 0 28 2 5 | 1 0 12 0 | 0 35 | 73 | 2 | | X |
| CVCC V8 | 97 5 73 5 | 268 35 | 26 4 | 16.8 | 13 95 | 0.2 - | 2 7 - | 1.3 | 73 | | X | |
| CVCC V8 | 121 66 7 | 350 33 5 | 21.5 | 15.0 | 15 6 | 0.37 - | 3 0 - | 0 37 | 73 | | X | X |
| DIESEL V8 | 96 66.7 | 286 33 4 | 24 0 | 21 0 | 11 0 | 0 46 - | 2 0 - | 1 2 | [illegible] | | | |

COST ANALYSIS

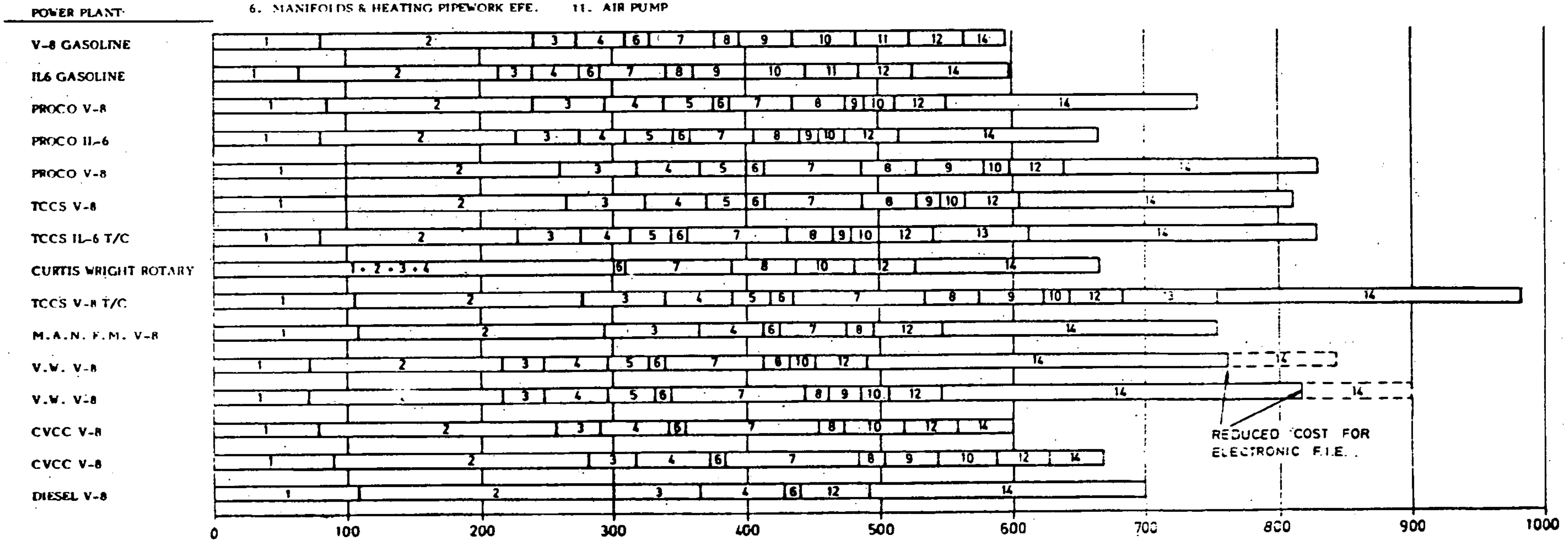
The literature survey yielded virtually no information on the likely production costs of many of the stratified charge engines considered in the configuration study. It was felt that the aspect of production cost was so important to the overall aims of the study that a separate task should be made of this one aspect. As a result a detailed cost estimate was made for each of the engines schemed in the configuration study. For the cost estimates information was taken mainly from 'in-house' unpublished sources and from surveys carried out by NAS into engine production costs. An allowance was made for inflation when information from previous surveys was used and the bar chart below gives the estimated production costs (1975 U.S. dollars) for each power plant involved in the configuration study.

The production costs obtained in this task were used as input for the rating phase of the study.

## STRATIFIED CHARGE ENGINE - FEASIBILITY STUDY

BAR CHART SHOWING ESTIMATED MANUFACTURING COST BREAKDOWN FOR THE VARIOUS POWER PLANTS - U.S. DOLLARS

1. CYLINDER BLOCK
2. CON-RODS, CRANKSHAFT, VALVE GEAR, FLYWHEEL, ETC.
3. PISTONS
4. CYLINDER HEAD(S)
5. CONTROL GEAR BETWEEN EGR, THROTTLE, DISTRIBUTOR AND INJECTION PUMP
6. MANIFOLDS & HEATING PIPEWORK ETC.
7. EXHAUST REACTOR AND/OR CATALYST
8. IGNITION DISTRIBUTOR, COIL, PLUGS
9. EGR VALVE AND PIPEWORK
10. OTHER EMISSION CONTROL GEAR: EVAP CONTROL, P.C.V. INTAKE HEATER, TRANSMISSION CONTROLLED SPARK, SPARK ADVANCE CONTROL, ANTI DIESELING SOLENOID, ETC. ETC.
11. AIR PUMP
12. STARTER MOTOR, ALTERNATOR VACUUM PUMP, HYDRAULIC PUMP
13. TURBOCHARGER
14. CARBURETTOR AND/OR INJECTION PUMP, PRIMARY INJECTORS, SECONDARY INJECTORS



## POWER PLANT RATING

In order to provide a quantitative assessment of the relative merits of the various power plants selected, a major aim of the study was to rate the performance aspects of each power plant. The methodology already developed for the light duty diesel engine study was considered suitable for this application. By the use of the existing methodology a direct comparison between the assessment of the existing power plants and those rated in the earlier survey was possible and those aspects which render a particular power plant viable or not for a light duty application identified and quantified. Furthermore, the methodology allows an assessment of changes in a particular area as well as highlighting areas worthy of effort to make a particular configuration more suitable for use in a given environment

The fitness of any power plant for a given duty is a combination of the excellence with which it meets various performance aspects or requirements and the relative importance of those individual aspects.

The methodology employed in the light duty diesel engine study established twenty-six performance aspects by which a power plant was rated. Each of these performance aspects was also individually weighted as a measure of its relative importance. For the current study the same performance aspects were employed.

The performance aspects are listed in the following table together with the weighting factors.

| | Aspect | Weighting |
|---|---|---|
| 1 | Smoke | 4.48 |
| 2 | Particulates | 2.14 |
| 3 | Odour | 4.48 |
| 4 | $NO_x$ | 3 92 |
| 5 | HC | 3.99 |
| 6 | CO | 3.61 |
| 7 | $SO_2$ | 3.48 |
| 8 | HC reactivity | 1.83 |
| 9 | Evaporative Emissions | 1.60 |
| 10 | Miscellaneous Emissions | 0.98 |
| 11 | Noise (Drive-by) | 6.32 |
| 12 | Package volume | 2.61 |
| 13 | Package weight | 2.59 |
| 14 | Fuel economy | 12.20 |
| 15 | Fuel cost | 5.40 |
| 16 | Vehicle first cost | 4.65 |
| 17 | Maintenance cost | 4.35 |
| 18 | Startability | 4.85 |
| 19 | Hot driveability | 4.48 |
| 20 | Cold driveability | 3.52 |

| | Aspect | Weighting |
|---|---|---|
| 21 | Torque back-up | 1.98 |
| 22 | Durability | 4.80 |
| 23 | Heat loss | 2.18 |
| 24 | Fire risk | 3.55 |
| 25 | Idling noise | 3.83 |
| 26 | Vibration and torque recoil | 2.18 |

It is necessary that a rating scale be devised so that a quantitative assessment of how well a particular power plant meets a given performance aspect can be made. The above list of performance aspects shows that although some aspects could be quickly assessed in a numerical fashion, many others are essentially qualitative and any rating scale should be able to cover all aspects.

As expected, some difficulty was experiences in relating a purely subjective impression to a linear quantitative scale, but after some consideration the following system was adopted as giving a numerical scale with several easily relatable, subjective key points, the numbers without definition being an interpolation of the surrounding merit definitions.

Merit rating scale

| | |
|---|---|
| 0 | Totally unacceptable |
| 1 | |
| 2 | Bad |
| 3 | |
| 4 | Poor |
| 5 | Acceptable |
| 6 | |
| 7 | Good |
| 8 | |
| 9 | Best practical |
| 10 | Perfect |

The rating system evolved allows an immediate quantitative assessment of the overall merit of the power plant and this is accomplished by multiplying each aspect 'rating' by its appropriate 'weighting' and summing all the products. With a total weighting of 100 and a merit scale of 0-10 as above the maximum possible is 1000.

The relative merit of various power plants can be assessed immediately comparing their total scores, the power plant with the highest score being the best. An idea of the absolute merit of the power plants can also be obtained if the score is divided by 100 and the quotient related to the above rating scale e.g. a score of 1000/100 = 10 is a 'perfect' power plant. A score of 500/100 = 5 is an 'acceptable' power plant.

In order to apply the rating system to the power plants considered in this study a committee was used to assess the various ratings. The committee consisted of experienced members of Ricardo staff and great care was taken to ensure that the committee had no bias to diesel, gasoline or any of the stratified charge configurations considered in this study. The power plants considered were those described in the 'engine configuration' section of this report with the addition of the two gasoline engines and the IDI diesel engine described briefly in that section. The engines considered are listed below, together with the categories in which they are divided and their respective emission targets:-

| | | Category | Emission Target |
|---|---|---|---|
| 1. | V-8 'American' Gasoline | - | primary |
| 2. | IL6 'European' Gasoline | - | primary |
| 3. | PROCO V-8 | I | primary |
| 4. | PROCO IL6 | I | primary |
| 5. | PROCO V-8 | I | secondary |
| 6. | TCCS V-8 | II | primary |
| 7. | TCCS IL6 T/C | II | primary |
| 8. | Curtiss Wright Rotary | II | primary |
| 9. | TCCS V-8 T/C | II | primary |
| 10. | MAN FM V-8 | III | primary |
| 11. | VW V-8 | IV | primary |
| 12. | VW V-8 | IV | secondary |
| 13. | CVCC V-8 | V | primary |
| 14. | CVCC V-8 | V | secondary |
| 15. | IDI Diesel V-8 | - | primary |

Each of the power plants above were considered for the emission targets shown and where a secondary target is not included it indicates that the particular power plant was not considered viable for such an emission level. The quantity of exhaust pollutants for the two target levels are shown below measured according to the CVS-CH test procedure:

Primary Targets

| | |
|---|---|
| HC | 0.41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 1.5 g/mile |

Secondary Targets

| | |
|---|---|
| HC | 0.41 g/mile |
| CO | 3.4 g/mile |
| $NO_x$ | 0.4 g/mile |

A table, showing the ratings awarded for each aspect may be found at the end of this section.

The product of the rating and the weighting for each performance aspect was summed for each power plant and the results are shown in the table below:-

| Engine | Final Score (to nearest whole number) | Primary Target Position | Secondary Target Position |
|---|---|---|---|
| V-8 Gasoline | 616 | 2 | |
| IL-6 Gasoline | 627 | 1 | |
| PROCO V-8 | 615 | 3 | |
| PROCO IL-6 | 599 | 5 | |
| PROCO V-8 | 576 | | 2 |
| TCCS V-8 | 566 | 9 | |
| TCCS IL-6 T/C | 547 | 11 | |
| Curtiss Wright Rotary | 552 | 10 | |
| TCCS V-8 T/C | 517 | | 4 |
| MAN-FM V-8 | 574 | 8 | |
| VW V-8 | 586 | 6 | |
| VW V-8 | 561 | | 3 |
| CVCC V-8 | 613 | 4 | |
| CVCC V-8 | 583 | | 1 |
| Diesel V-8 | 581 | 7 | |

These results are revealing in that they indicate how small the relative differences are between the power plants. With the rating methodology employed a power plant rated as acceptable in each of the performance aspects would achieve a score of 500 but if a zero were to occur in any score, that power plant must be rejected whatever its final total. As none of the candidates rate zero in any of the performance aspects and all achieved a total score in excess of 500, all must be considered as viable alternatives.

The highest scoring power plant, the IL-6 gasoline engine scored approximately 20% more points than the lowest, the TCCS secondary emissions engine. Of particular interest is the score attained by the PROCO primary emissions engine which attained a similar rating to the conventional V-8 gasoline engine, mainly on the grounds of improved fuel economy. With a slightly lower total score than the PROCO V-8 engine came the CVCC primary engine followed by the PROCO IL-6. The conventional I.D.I. diesel rated 7th in the listing, but since its fuel economy was taken using diesel fuel whereas all the other power plants used gasoline, there may be some error in the relative position of this engine.

This application of the rating method indicated that none of the candidate power plants was better than existing gasoline engines for the primary emissions target but that both the PROCO and CVCC systems were almost as good.

At the secondary emissions target (0.4 g/mile $NO_x$) the CVCC and PROCO engines achieved the highest score with the CVCC system having an almost insignificant numerical advantage. The scores achieved by all the secondary engines considered however indicate that none of the combustion systems can be regarded as completely non-viable.

| | | V-8 Gasoline | IL-6 Gasoline | PROCO V-8 Primary | PROCO IL-6 Primary | PROCO V-8 Secondary | TCCS V-8 Primary | TCCS IL-6 T/C Primary | Curtiss-Wright Primary | TCCS V-8 T/C Secondary | MAN-FM Primary | VW V-8 Primary | VW V-8 Secondary | CVCC V-8 Primary | CVCC V-8 Secondary | Diesel V-8 Primary |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Smoke | 9 | 9 | 8 5 | 8 5 | 8 5 | 6 | 5 5 | 6 | 5 5 | 6 | 8 5 | 8 5 | 9 | 9 | 6 |
| 2 | Particulates | 7 | 7 | 6 5 | 6 5 | 6 5 | 3 | 3 | 3 | 3 | 3 | 7 | 7 | 7 | 7 | 2 |
| 3 | Odour | 6 | 6 | 6 | 6 | 6 | 4 5 | 4 5 | 4 | 4 5 | 3 | 5 | 5 | 6 | 6 | 4 |
| 4 | NO | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 7 | 5 | 7 | 7 | 5 | 5 | 5 | 5 |
| 5 | HC | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 6 | CO | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 |
| 7 | SO | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 2 |
| 8 | HC Reactivity | 5 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 5 | 5 | 7 |
| 9 | Evap Emissions | 5 | 5 5 | 5 5 | 5 5 | 5 6 | 5 5 | 5 6 | 5 5 | 5 5 | 5 6 | 5 6 | 5 5 | 5 | 5 | 7 |
| 10 | Misc Emissions | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 11 | Noise (Drive-by) | 7 | 6 5 | 7 | 5 | 6 5 | 7 5 | 7 | 7 | 6 5 | 7 | 6 5 | 6 5 | 6 5 | 6 5 | 5 5 |
| 12 | Package Volume | 7 | 7 | 7 | 5 | 6 | 5 | 4 | 9 | 4 5 | 6 | 7 | 7 | 6 | 4 5 | 5 5 |
| 13 | Package Weight | 6 | 7 | 6 | 6 | 6 | 5 6 | 6 | 8 | 5 | 5 | 6 | 6 | 6 | 5 5 | 4 5 |
| 14 | Fuel Economy | 6 5 | 7 | 7 5 | 6 5 | 7 | 7 | 5 5 | 5 5 | 7 5 | 6 5 | 6 | 6 5 | 6 | 8 5 | |
| 15 | Fuel Cost | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 |
| 16 | Vehicle First Cost | 6 | 6 | 4 5 | 5 5 | 4 | 4 | 4 | 5 | 2 5 | 4 5 | 3 5 | 3 | 6 | 5 | 5 |
| 17 | Maintenance Cost | 5 | 5 | 4 5 | 4 5 | 3 | 3 | 3 | 2 5 | 3 | 4 | 4 | 3 | 6 | 5 5 | 6 |
| 18 | Startability | 7 | 7 | 7 | 7 | 7 | 8 | 8 | 5 | 8 | 7 | 6 | 6 | 6 5 | 6 5 | 5 |
| 19 | Hot Driveability | 8 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 7 | 8 | 8 | 8 | 7 | 5 | 7 |
| 20 | Cold Driveability | 4 | 6 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 7 | 7 | 7 | 4 | 4 | 7 |
| 21 | Torque Back-up | 7 | 6 5 | 6 5 | 7 | 5 | 7 | 5 5 | 6 | 6 5 | 7 | 4 | 4 | 7 | 6 5 | 7 |
| 22 | Durability | 5 | 5 | 4 5 | 4 5 | 3 | 3 | 3 | 2 5 | 2 5 | 4 5 | 4 | 3 | 7 | 6 5 | 7 |
| 23 | Heat Loss | 7 | 7 | 7 | 7 | 7 | 5 | 5 | 6 | 7 | 5 | 7 | 7 | 6 | 6 | 5 |
| 24 | Fire Risk | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4.5 | 4.5 | 6 |
| 25 | Idling Noise | 8 | 8 | 5 5 | 5 | 5 | 5 | 5 | 7 | 4 5 | 5 | 6 | 6 | 8 | 8 | 4 |
| 26 | Torque Recoil | 8 | 7 5 | 6 5 | 6 | 6.5 | 8 | 5 5 | 7 5 | 8 | 5 | 8 | 8 | 8 | 8 | 6 |

FINAL RATINGS FOR EACH ASPECT

## TECHNICAL REPORT DATA

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| 4. TITLE AND SUBTITLE A STUDY OF STRATIFIED CHARGE FOR LIGHT DUTY POWER PLANTS - VOLUME 3. EXECUTIVE SUMMARY | | 5. REPORT DATE OCTOBER 1975 |
| | | 6. PERFORMING ORGANIZATION CODE |
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15. SUPPLEMENTARY NOTES

Pick up from Volume 1

16. ABSTRACT

The objectives of this project were to determine the acceptability of various types of stratified charge engines as potential power plants for light duty vehicles and motorcycles in America. The light duty vehicle considered was a 4/5 seat compact sedan with good acceleration capabilities and exhaust emissions below a primary target of 0 41 g/mile HC, 3.4 g/mile CO, 1.5 g/mile $NO_x$. A secondary target of 0 41 g/mile HC, 3.4 g/mile CO and 0.4 g/mile $NO_x$ was also considered.

A literature survey was undertaken, comparing stratified charge engines with examples of good conventional gasoline and diesel engines. While some stratified charge engines had exhaust emission or fuel economy advantages, there were always sacrifices in other areas.

Eleven engines were configured, four of which were specifically directed towards the secondary emission targets. A method of rating the engines was derived, and the design concepts were compared with two gasoline engines by a jury panel. The overall result was that the Ford PROCO and Honda CVCC combustion processes were serious contenders to the gasoline engine at the primary emission target, and that both of these systems, together with the VW combustion process, might be suitable at the secondary targets.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| EXHAUST EMISSIONS<br>STRATIFIED CHARGE ENGINES<br>POWER PLANT RATING METHODOLOGY<br>ENGINE DESIGN<br>LITERATURE REVIEW | LIGHT DUTY VEHICLES<br>LIGHT DUTY ENGINE<br>GASOLINE/STRATIFIED CHARGE COMPARISON<br>EMISSION CONTROLS<br>FUEL ECONOMY | |

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