Efficiency Evaluation of the DISC, DHC, and DI Diesel Engines

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EFFICIENCY EVALUATION OF THE
DIRECT INJECTION STRATIFIED CHARGE (DISC),
DILUTE HOMOGENEOUS CHARGE (DHC),
AND DIRECT INJECTION DIESEL (DI DIESEL)
ENGINES

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PREFACE

This study was completed for the Division of Energy Conversion and Utilization Technologies (ECUT) in the Department of Energy. The division's mission is to identify and research long-range technology concepts that are attractive for more efficient energy use. To meet its goals, the ECUT staff established a planning and systems analysis project that was responsible for conducting this study.

This report is one of a series of studies in support of the ECUT research planning effort. Other documents in the series contain assessments of energy conservation technology areas, methods to appraise research projects for support, and data reference sources. Publications from this project include the following:

Abarcar, R. and D. Johnson. 1983. ECUT Data Reference Series: Lightweight Materials for Ground Transportation. Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. and D. Johnson. 1983. ECUT Data Reference Series: Materials for Advanced Heat Engines. Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. et al. 1983. An Evaluation of Stationary Combustion Research Needs. Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. and D. Johnson. 1983. ECUT Data Reference Series: Stationary Combustion Systems. Pacific Northwest Laboratory, Richland, Washington.

Hane, G. and D. Johnson. 1983. ECUT Data Reference Series: Otto Cycle Engines in Transportation. Pacific Northwest Laboratory, Richland, Washington.

Hane, G. et al. 1983. Energy Conservation Research and Development Needs: A Review and Synthesis of the Literature, Phase II. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.

Hane, G. et al. 1983. A Preliminary Overview of Innovative Industrial Materials Processes. PNL-4505, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W. et al. 1981. An Overview of Energy Conservation Research Opportunities - Executive Summary. PNL-3944Ex.Sum., Pacific Northwest Laboratory, Richland, Washington.

Hopp, W. et al. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1981. The 1981 ECUT Work Element Appraisal. DOE/CE-0024, U.S. Department of Energy, Washington, D.C.

U.S. Department of Energy. 1983. Energy Conversion and Utilization Technologies Program Report, 1981-1982. U.S. Department of Energy, Washington, D.C.

Young, J. and D. Johnson. 1983. ECUT Data Reference Series: Ammonia Synthesis. Pacific Northwest Laboratory, Richland, Washington.

W.B. Ashton
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SUMMARY

Understanding the impacts of directed basic research is an important concern when determining primary research needs. The Energy Conversion and Utilization Technologies Division of the U.S. Department of Energy (DOE) contracted with the Pacific Northwest Laboratory (PNL) to study the relationships between the potential gains in energy efficiency of advanced internal combustion engines and fundamental research being conducted in combustion and thermodynamics. The engines investigated are the Direct Injection Stratified Charge (DISC), Dilute Homogeneous Charge (DHC), and Direct Injection Diesel (DI diesel). The theory of operation is introduced and the energy losses that limit the efficiencies of conventional engines are discussed. The efficiency gains achievable through the advanced engines are then described, along with the technical barriers to achieving those gains. These linkages between combustion and thermodynamic research and the efficiency characteristics are then illustrated via the technical barriers.

The primary technical barriers to each of these engine concepts encompass many specific problems, each of which must be addressed through applied research. In broad terms, however, these technical barriers provide a useful focus for research. The primary barrier to the DISC engines is developing the capability to operate the engine over a wide range of loads and speeds. The major technical problem that must be overcome is controlling the transition from slow to fast mixing in the cylinder to ensure complete combustion. For the DHC engine, combustion control schemes such as enhanced ignition must be developed to overcome the ignition and flame propagation limits caused by lean mixtures. Efficient operation over a wide range of engine loads and speeds also poses a major question. The primary barrier to the DI diesel engine stems from the need to control the large amount of pollutants generated from diffusion combustion.

In the literature, estimates of efficiency gains possible through advanced Otto cycle engines typically range around 25% (American Institute of Physics 1975; Grey 1978). This is likely a result of eliminating throttling losses anticipated through the DISC and DHC alternatives.

Comparing the brake specific fuel consumption and brake thermal efficiency of the conventional Otto cycle engine with the ideal, fuel-air cycle efficiency reveals that a significant potential for improvement exists. When losses not being actively pursued by combustion and thermodynamic research are factored in, a notable efficiency improvement potential remains. For the conditions selected in the sample calculation in Chapter 2, the maximum improvement in fuel consumption for the fuel-air cycle engine varies with load from 70% at part load to 55% at much higher loads. This translates to efficiency gains of 220 to 140%. Efficiency improvements for the hypothesized engine under the same conditions ranged from 80 to 70%. These figures provide some perspective of the upper bounds for engine efficiency gains.

Imposing a limit of a minimum equivalence ratio significantly reduces these theoretical gains at light loads. Such a minimum is likely to be required in the DHC concept. Using a minimum ratio of 0.4 and requiring throttling for load control results in maximum theoretical efficiencies ranging from 39 to 56% over the loads analyzed. This translates to efficiency improvements of 105 to 140% over the current conventional Otto cycle engine.

The primary efficiency gain attributed to the potential development of a light-duty direct injection diesel engine arises from eliminating the pre-chamber. Data from AVL of Austria indicate that the gain is about 15 to 20%. Additional gains are thermodynamically possible but are not the focus of current research; therefore, they were not investigated further.

The engine efficiencies discussed in this study are summarized in Table S.1. The efficiency gains over the conventional Otto and diesel cycle engines are shown in Table S.2. Although these figures are only meant to show the potential gains, they reveal that substantial efficiency improvements in the operation of Otto and diesel cycle engines are still possible.

Obtaining a more precise understanding of the various contributors to engine inefficiency at varying loads and engine speeds will require additional computer modeling. Such modeling would be valuable in helping to prioritize areas of research, and the development of such a model is highly recommended.

TABLE S.1. Summary of Engine Efficiencies (percent)^(a)
(delivered or brake thermal efficiencies)

	<u>Conventional Otto Engine</u>	<u>DISC</u>	<u>DHC</u>	<u>Conventional Diesel Engine</u>	<u>DI Diesel</u>
Current Engine	19-23	--	--	22-26	--
Improved Engine (Engineering Judgment-Literature)	--	25-30	25-30	--	26-31
Hypothetical Engine	--	34-39	--	--	--
Maximum Theoretical	--	61-56	39-56 ^(b)	--	--

(a) Engine efficiency ranges from light to heavy loads. Nominal MEP load ranges from 30 to 100 psi.

(b) Very sensitive to assumed ignition limits. Here advanced ignition schemes are assumed to reduce this limit to an equivalence ratio of 0.4.

TABLE S.2. Summary of Potential Engine Efficiency Improvements (percent)^(a)

	<u>DISC</u>	<u>DHC</u>	<u>DI Diesel</u>
Improved Engine (Engineering Judgment-Literature)	30	30	18-19
Hypothetical Engine	80-70	--	--
Maximum Theoretical	220-140	105-140 ^(b)	--

(a) Efficiency improvement over the conventional Otto and diesel engines. Nominal MEP load ranges from 30 to 100 psi.

(b) Very sensitive to assumed ignition limits. Here advanced ignition schemes are assumed to reduce this limit to an equivalence ratio of 0.4.

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1.0 INTRODUCTION

The overall objective of this study is to investigate the relationships between the potential gains in energy efficiency of advanced internal combustion engines and "directed" basic research being performed in combustion and thermodynamics. Directed basic research is defined as long-term, fundamental research that is applied to an end use. The end use considered in this study is advanced automobile engine technology. The engines considered are the Direct Injection Stratified Charge (DISC), Dilute Homogeneous Charge (DHC), and Direct Injection Diesel (DI diesel).

The overall objective is composed of the following three elements:

1. identify and discuss the energy loss mechanisms that cause inefficient fuel conversion in current Otto and diesel cycle engines
2. describe the technical barriers or problems that currently impede continued development of the DISC, DHC, and DI diesel engines
3. identify the general linkages between current research work addressing these technical barriers in combustion and thermodynamics and the potential efficiency improvements toward which the research work is directed.

To accomplish the study's goals, two primary sources of information were used: published literature and conversations with members of the engine combustion research community. These experts provided valuable insight into the barriers inhibiting the engines' development and the complexities of attributing energy efficiency figures to each research project. The researchers contacted are listed in the appendix.

To understand the potential for efficiency improvements in Otto and diesel cycle engines, the thermodynamic laws that govern their operation should be reviewed first. These laws define the maximum efficiency benefit that might be achieved. Once this limit is defined, the causes of departures from the optimal efficiency can be investigated, and research to mitigate these losses can be discussed. Using this approach, the following outline was developed. Chapter 2.0 discusses the thermodynamic laws governing these engines and

possible approaches that might be taken to increase the delivered efficiency of the reciprocating piston engine. In Chapter 3.0 the generic aspects of current research are discussed and typical links between research and the technical barriers to the engines' development are shown. General examples of basic research directed toward Otto and diesel engines are also given to show the basic character of needed research.

In Chapter 4.0 through 6.0, the advanced engines are discussed individually. After a brief description of each engine and its advantages, the major technical barriers to their development are discussed. Also included for each engine is a discussion of examples of the linkages between these barriers and current combustion and thermodynamic research. Again, note that the focus of this study is on the linkages between research in combustion and thermodynamics and engine efficiency. Although other aspects such as engine dynamics and control may also offer important contributions to efficiency, these issues were outside this study's scope. Finally, for each engine a list of questions is presented that have yet to be resolved and could not be resolved within the scope of this study. These questions partially indicate the limit to the state of knowledge regarding efficiency characteristics of the advanced engine concepts. Chapter 7.0 contains a summary of the major technical barriers to each of the engines and their ranges of efficiency improvement.

2.0 GENERAL THERMODYNAMICS

The DISC and DHC engines are often referred to by the generic title "lean burn" engines because both engines have the potential for operating with significantly leaner fuel-air mixtures than current Otto cycle engines. In this section these two Otto cycle engines will be discussed as versions of the same thermodynamic concept. This is possible because the important efficiency variables will be shown to be the same in both designs. Although the diesel engine operates with a slightly different cycle, the limited-pressure cycle, it can also be included in this discussion because the primary factors contributing to its efficiency are the same as in the Otto cycle.

The theoretical efficiency of both the Otto cycle and the diesel cycle are primarily functions of two variables: the compression ratio and the ratio of specific heats. The compression ratio is defined as the ratio of the maximum cylinder volume to the clearance volume or volume of compressed gases. The ratio of specific heats is a thermodynamic property of the fuel-air mixture that is influenced by both the mixture's composition and temperature. The composition of the fuel-air mixture is normally defined by the equivalence ratio, which is the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. In the case of the Otto cycle, this relationship can be expressed by the simple equation

$$\eta = 1 - \frac{1}{CR^\gamma} \quad (1)$$

where CR is defined as the compression ratio and γ is the ratio of specific heats. At a given fuel-air mixture and compression ratio, this equation therefore can be used to define the maximum theoretical efficiency of an Otto cycle engine. This limit is normally called the fuel-air cycle efficiency. Other common terms are the thermodynamic efficiency and the theoretical efficiency. The implications of this important relation will be expanded upon later in this chapter.

Generally, two approaches can be used to improve the thermodynamic efficiency of Otto and diesel cycle engines. One approach involves addressing the nonidealities that reduce the amount of useful work that can be retrieved

from each cycle. An alternative approach involves increasing the amount of work that is theoretically available from each cycle. Although the two paths are certainly not mutually exclusive, they will be discussed separately for clarity.

In this section, the engine efficiency characteristics and losses will be discussed first. Then, the potential efficiency improvements from reducing these losses will be analyzed. This will be followed by a discussion of the improvements possible through increasing the fuel-air cycle efficiency.

EFFICIENCY LOSSES IN A CONVENTIONAL ENGINE

Table 1 shows the major contributors to engine inefficiency and typical values for the indicated efficiency and the delivered, or brake efficiency.

The maximum work available from the fuel is larger than the fuel energy (lower heat of combustion) because of entropic contributions from the combustion of reactants to products. The ceiling chosen for this definition does not, however, consider the additional work available from diffusion. Because retrieving contributions to work from diffusion would take a significant amount of time to capture, this factor is typically neglected in computing total available work for most processes.

TABLE 1. Factors that Contribute to Engine Efficiency Losses

<u>Efficiency Losses</u>	<u>Engine Efficiency, %</u>
Fuel available work	100
Fuel energy (commonly used lower heat of combustion)	96
Fuel-air cycle efficiency, CR = 8.5, stoichometric	44
Heat Loss	39
Finite speed loss	37
Blowdown loss	36
Indicated efficiency	36
Friction loss	29
Pumping loss (throttling, valves, etc.)	23
Brake efficiency	23

The amount of fuel energy available is typically defined by the lower heat of combustion. The lower heat of combustion is defined with the water product in a vapor state. Condensation of the water vapor would liberate additional energy, yielding the higher heat of combustion.

The third value shown, the fuel-air cycle efficiency, is a typical value for the maximum theoretical efficiency of a reciprocating piston automobile engine. The fuel-air cycle efficiency is described by Equation 1. Recall that the equation shows this efficiency to be a function of two parameters, the compression ratio and the ratio of specific heats. As either parameter increases, the theoretical fuel-air cycle efficiency also increases. The value shown in Table 1 stems from the typical conditions of a conventional automobile engine operation with a compression ratio of 8.5:1 and a stoichiometric fuel-air mixture.

In Figure 1 a pressure-volume (p-v) diagram is used to show typical losses that cause departures from the ideal cycle in a real engine. Figure 1A shows that the ideal fuel-air cycle efficiency is actually less than the air cycle efficiency. Progressively leaning the fuel-air mixture would increase the theoretical efficiency up to that of the air cycle. The importance of this feature will be expanded upon later in this section.

Departures from the theoretical fuel-air cycle efficiency in conventional engines are attributed to four loss mechanisms: heat loss through the cylinder walls, finite speed (timing) loss, blowdown loss, and frictional loss. The first three losses are responsible for the difference between the fuel-air cycle efficiency and the indicated efficiency of the engine. These losses are not explicitly mentioned in general discussions of automobile engines very frequently. In some cases they are defined in broader terms such as "burning and cylinder wall losses" and in other cases they are combined with general exhaust system losses and losses to the cooling system. Frictional losses, which comprise both pumping losses and mechanical frictional effects, account for the difference between the indicated efficiency and the delivered, or brake thermal efficiency.

DEPARTURE OF THE FUEL-AIR CYCLE
EFFICIENCY FROM THE IDEAL AIR
CYCLE EFFICIENCY

EFFICIENCY LOSSES DUE TO HEAT,
FRICTION, AND VALVE EFFECTS

EFFICIENCY LOSSES DUE TO TIME
AND BLOWDOWN EFFECTS

EFFICIENCY LOSS DUE TO THROTTLING
AND RESULTANT INDICATED WORK

FIGURE 1. Typical Otto Cycle Engine Efficiency Losses
(p = pressure; v = volume)

Heat loss in this instance is the loss of work due to heat flow during the compression and expansion strokes. The effect of this loss on the p-v cycle diagram is shown in Figure 1B. The heat lost during compression up to the ignition of the fuel-air mixture typically is negligible (Taylor 1966).

The finite speed loss, or time loss, occurs because the combustion process takes a finite amount of time, and because the piston is in motion during combustion. The loss thus causes departures from the ideal assumption of constant volume combustion. This effect is responsible for the "rounding" at the top of the p-v cycle diagram, as shown in Figure 1C.

Exhaust blowdown losses, also shown in Figure 1C, occur because the exhaust valve is designed to open before bottom dead center to minimize the exhaust stroke loss in four-stroke engines. This loss occurs in the exhaust stroke when the cylinder pressure falls to the value of the exhaust system pressure. A large part of this process is often in the "critical range" during which the gas velocity through the smallest cross section of the exhaust port is sonic. Since the speed of the gases through the exhaust valve is independent of piston speed during the critical part of blowdown, this process occupies an increasing number of crank degrees as piston speed increases (Taylor 1966).

As a general "rule-of-thumb" the actual indicated efficiency is typically 80% of the theoretical fuel-air cycle efficiency. Experiments by Taylor (1966) indicate that heat loss typically accounts for 60% of the difference between ideal fuel-air cycle efficiency and indicated efficiency. Time loss accounts for 30% of the difference and blowdown loss 10%. In terms of the absolute values of efficiency shown in Table 1, these losses translate to a 5% reduction from heat loss, a 2% reduction from time loss, and a 1% reduction from exhaust blowdown loss. However, because heat losses increase with increasing compression ratio, this difference between the ideal and actual indicated efficiencies varies. Experimentally determined differences between the indicated and fuel-air cycle efficiencies at various compression ratios have yielded the following relationships (Jet Propulsion Laboratory 1975):

<u>Compression Ratio</u>	<u>Indicated Efficiency as a Percent of Fuel-Air Cycle Efficiency</u>
4	85
8	78
10	75

Unfortunately, data were not taken at higher compression ratios or with lean charges. Because of the lower temperatures of lean mixtures, the figures above are likely low when applied to the DISC or DHC engine.

Time losses and exhaust blowdown losses are not expected to be very different in the advanced engines, and although heat loss may change, the degree of change is uncertain. Higher compression ratios increase the amount of heat lost, as does the degree of swirl in the cylinder. However, the leaner mixture results in a lower combustion temperature, which would decrease the amount of heat lost. This trade-off has not been calculated to date and the computation is not a straightforward one (Woschni 1967).

F. Bracco, a professor of combustion sciences and editor of Combustion Science and Technology, confirms that benefits from reduced heat loss are uncertain and would really be considered "frosting on the cake". Reducing the non-ideality of heat loss is not a major goal in current combustion and thermodynamic research.

In addition to the losses mentioned above, other effects can potentially contribute to the discrepancy between the fuel-air cycle and indicated efficiencies. The specific heat of the mixture increases with higher temperatures, which indicates the desirability of operating at the lowest possible maximum temperatures. Secondly, chemical dissociation of molecules occurs at high temperatures with a consequent large absorption of heat, thus lowering temperature and pressure and inducing another nonideality. Thirdly, the product mole yield for real fuel-air systems is not unity but slightly greater and increases as the mixture gets richer. This slightly improves both the efficiency and power output of the engine.

Other losses have been considered and have been determined to have a negligible effect upon the engine's thermal efficiency. These include leakage losses caused by blowby past the piston or valves and incomplete combustion. This latter loss is negligible in both spark ignition and diesel engines, as can be evidenced by the low quantity of unburned hydrocarbons in the exhaust of current engines.

BRAKE THERMAL EFFICIENCY

The losses mentioned above are responsible for the differences between the fuel-air cycle efficiency and the actual indicated engine efficiency. However, further losses are encountered before the value of the delivered or brake thermal efficiency can be determined. This second tier of losses is generally called frictional losses and includes both the losses due to engine friction and pumping. Approximately 40% of the engine friction loss is due to piston ring friction, with the remaining 60% due to other engine friction (Pinkus and Wilcox 1977).

In conventional uniform charge engines, the pumping losses can become significant. The two primary contributors to the pumping loss arise from throttling and valve flow. Throttling losses result from the work required to overcome inlet and outlet pressure throttling. Valve flow losses result from the work required to move the gases past the valves of the combustion chamber. The effect of the throttling loss is shown in Figure 1D.

A plot of the pumping mean effective pressure (mep) versus the indicated mep is shown in Figure 2. Also shown are the contributions to the total pumping loss from the throttling loss and the valve flow loss. The figure shows that the throttling loss dominates the overall pumping loss. The pumping loss typically varies from about 3.5% of the indicated mep at wide-open throttle to nearly 100% of the indicated mep for a fully throttled idling engine (Blackmore and Thomas 1978). In a typical compact U.S. car operating with a 10:1 compression ratio and cruising at 40 miles per hour, the thermal efficiency decreases by 5.5% absolute due to pumping losses. The valve flow loss is insignificant at low loads and only begins to contribute to the overall pumping loss at high loads. However, at high loads the value of the overall pumping loss becomes insignificant. The efficiency losses are summarized in Figure 3.

FIGURE 2. Pumping Loss at Valve Flow Loss as a Function of Indicated Mean Effective Pressure (Blackmore and Thomas 1978)

APPROACH ONE: REDUCED LOSSES

One approach to improving the efficiency in conventional engines is to reduce the magnitude of the losses shown in Table 1 and Figure 3. Using this approach, the compression ratio and equivalence ratio are held constant thus leaving the fuel-air cycle efficiency relatively unchanged. The component losses account for the 21% efficiency difference between the fuel-air cycle efficiency and the brake thermal efficiency that are addressed.

The loss due to heat transfer from the cylinder walls is partially recoverable by eliminating this heat transfer. If the goal of engine re-design were to eliminate heat loss, the maximum amount of heat loss that is recoverable has been estimated to be only 37.5% of the difference between

FIGURE 3. Typical Efficiency Losses in a Conventional Spark Ignition Engine

the fuel-air cycle efficiency and the indicated efficiency rather than the full 60% of the difference that is attributed to heat loss (Blackmore and Thomas 1978). This would occur because the higher temperature would increase the specific heat of the gases and increase dissociation losses. Thus, a 3% absolute efficiency gain is possible. Time and blowdown losses are expected to be similar in advanced Otto or diesel cycle engines and neither loss is the object of current research.

Combining these three elements, heat loss, time loss and blowdown loss, shows that the indicated efficiency may potentially increase from 36 to 39% in this example engine.

Reducing engine friction is possible through tribological developments such as improved lubricants and xylan coatings. Grey, Sutton and Zlotnick (1978) have estimated that engine friction could be reduced by 25% through improved lubricants and up to 50% by the application of xylan coatings. These measures translate to absolute efficiency improvements of approximately 2 to 3.5%.

Methods of reducing the pumping loss include resizing the valves and eliminating the throttling plate. Figure 2 shows that any benefits from valve resizing would only be measurable at high engine loads, and that even then, the gains would be minimal.

Eliminating the throttling plate would result in a significant reduction in the pumping loss but would require that an alternate method of load control be developed. Controlling the engine load by varying the fuel-air ratio has the added advantage of operating the engine at progressively leaner charge mixtures at lighter loads. As will be discussed in Approach Two, Increasing Theoretical Efficiency, leaning the air-fuel mixture increases the theoretical efficiency of the engine.

Summing the potential efficiency improvements for an engine operating at relatively constant compression and equivalence ratios, typical of conventional engines, shows that a 5 to 6.5% absolute increase in brake thermal efficiency might be achieved. This translates to a 22 to 28% relative increase in efficiency. The gain from eliminating the throttling plate will be considered in Approach Two because the alternative scheme for load control would require varying the fuel-air ratio significantly.

APPROACH TWO: INCREASING THEORETICAL EFFICIENCY

An alternative approach to increasing engine efficiency can be developed by noting that additional efficiency gains are possible by increasing the theoretical efficiency of the engine cycle. The aim of this approach is to increase the maximum size of the p-v loop rather than to increase the "fit" of the actual cycle.

As discussed, the relations for efficiency for both the Otto cycle (Equation 1) and limited pressure diesel cycle engines were primarily a function of the compression ratio and the ratio of specific heats of the fuel/air mixture. To increase the fuel-air cycle efficiency shown in Table 1, the aim is to increase the compression ratio, increase the ratio of specific heats, or do both.

Fuel-Air Ratio

By decreasing the fuel-air ratio and thereby increasing the ratio of specific heats of the charge, Equation 1 shows that the fuel-air cycle efficiency of the engine will increase. In the limit, the maximum theoretical efficiency is that of an air cycle. The variation in fuel-air cycle efficiency relative to air cycle efficiency as a function of the equivalence ratio is shown in Figure 4.

Compression Ratio

Equation 1 also shows that the fuel-air cycle increases with increasing compression ratio. The effect of varying both the fuel-air mixture (varying the ratio of specific heats) and the compression ratio is clearly shown in Figures 5 and 6. With one caveat, these graphs represent a primary motivation for developing the advanced engines. Because the advanced engines can operate at lean equivalence ratios and higher compression ratios, significant potential efficiency gains are possible.

The caveat to this conclusion is that in a real engine, frictional effects limit the maximum value of the compression ratio. Figure 7 shows that the optimal efficiency for an automobile-size engine occurs at a compression ratio of approximately 16:1. Conversations with researchers have indicated that a compression ratio of 16:1 is likely to be an upper bound for maximum engine efficiency. W. Tierney from Texaco has indicated that their tests show the optimum compression ratio to be in the range of 12:1-14:1. F. Bracco from Princeton University indicated that their information showed the optimal compression ratio to be in the range of 12:1 to 16:1. The Office of Technology Assessment (OTA) (1979) has also estimated that the optimal range of compression ratios is 12:1 to 14:1, and the Jet Propulsion Laboratory (1975) cites an optimal range of 11:1 to 15:1.

FIGURE 4. Ratio of Fuel-Air-Cycle to Air-Cycle Efficiencies
 ($\eta_{\text{Fuel-Air}}/\eta_{\text{Air}}$) at Various Equivalence Ratios (ϕR)
 (Taylor 1966)

FIGURE 5. The Effects of Compression Ratio and Equivalence Ratio on the Otto Fuel-Air Cycle Efficiency (Dale and Oppenheim 1981)

With the value of the compression ratio constrained to an optimum range, the remaining free variable is the fuel-air or equivalence ratio. The object of research is therefore to enable an engine to operate with a compression ratio of between 12:1 to 16:1 at as lean a fuel/air mixture as possible.

Load Control

The problem posed thus far is fairly straightforward, involving a single value or small range of values for the leanest combustible mixture (with

FIGURE 6. The Effects of Compression Ratio and Equivalence Ratio on the Diesel Fuel-Air Cycle Efficiency (Dale and Oppenheim, 1981)

acceptable emissions, etc...). Recall, however, that a major attractive feature of the DISC and DHC engines is that both maintain load control without throttling the fuel-air mixture. By eliminating throttling, the average brake thermal efficiency would increase by 6% absolute or by a relative increase of 24%. Load control is maintained by varying the amount of fuel injected with a constant air charge. That is, load control is maintained by varying the equivalence ratio. The required equivalence ratio at light load is consequently notably smaller than that required at high loads. Figure 8 shows an

FIGURE 7. The Effects of Compression Ratio on Brake Specific Fuel Consumption (Obert 1973)

ideal variation of equivalence ratio with engine load. The engine load is displayed in the figure as the ratio of mean effective pressure to inlet pressure. Therefore, the maximum efficiency of the lean burn engines highly depends upon the driving conditions.

EFFICIENCY GAINS: SAMPLE CALCULATION

To provide some indication of the levels of fuel consumption and efficiency improvement that can be achieved, a comparison with the conventional engine was made using a calculated fuel-air cycle efficiency, a calculated hypothetical engine efficiency, and the Texaco Controlled Combustion System (TCCS) DISC engine efficiency. The results of these calculations are shown in

FIGURE 8. The Effect of Load Upon Minimum Equivalence Ratio

Figures 9 through 12. Data for the TCCS engine and the conventional engine were taken from Lewis and Tierney (1980), and the dimensions of the fuel-air cycle engine and hypothetical engine are identical to the 292 in.³ TCCS engine.

The fuel-air cycle efficiency is the maximum efficiency possible for any engine's operating condition. Calculations were made for both the fuel consumption, shown in Figure 9, and the brake thermal engine efficiency, shown in Figure 11, as a function of load at a selected compression ratio of 13:1. This compression ratio was selected because it is in the range for optimal efficiency and because it is the same as that currently used in Texaco's TCCS DISC engine. The efficiency figures were taken from Figure 5.

Figures 10 and 12 show the relative improvement in fuel consumption and engine efficiency of the fuel-air cycle engine over a conventional engine. Figure 10 shows that the fuel-air cycle engine possesses a fuel consumption improvement that ranges from approximately 70 to 55% over the loads shown. Figure 12 shows that this translates to an efficiency improvement that loads ranges from 220 to 140%.

Also shown in Figures 9 and 11 are the fuel consumption and engine efficiency curves for a hypothetical engine. These curves were derived by including typical losses between the fuel-air cycle efficiency and the indicated efficiency of the engine as well as frictional losses. The losses included are heat loss through the cylinder wall during compression and expansion, finite speed loss, and blowdown loss. These losses have been included with this hypothetical engine because they are not being directly addressed by current combustion and thermodynamic research in the advanced engines. In this way the hypothetical engine provides some measure of the potential for improvement achievable through DISC and DHC engine development.

Figures 10 and 12 also show the relative improvement in fuel economy and engine efficiency over the conventional engine of the hypothetical engine. The fuel consumption is reduced between 48% and 36% with a consequent increase in brake thermal efficiency of 80% to 70%. The curves describing the performance of the TCCS engine will be explored further in the Chapter 4 discussion of DISC engines.

FIGURE 9. Fuel Consumption Characteristics at Various Loads

FIGURE 10. Reduction in Fuel Consumption When Compared with the Carbureted Engine

FIGURE 11. Efficiency Characteristics at Various Loads

FIGURE 12. Efficiency Improvement Over the Carbureted Engine

Calculating a maximum efficiency over a reference driving cycle, such as the EPA cycle for city driving, would require computer modeling of the engine's interdependent parameters. Such an effort would probably be the next step in approximating efficiency gains, but it was not undertaken here.

3.0 RESEARCH PROJECTS

The purpose of this chapter is to show that the relationship among research projects, research questions, technical barriers, and efficiency characteristics is an interdependent one that does not allow for the direct correlation of research projects with efficiency numbers. Because of the broad applicability of the research tools and techniques being developed, the strategy for linking research with efficiency characteristics will be developed separately. Examples of basic research needs that were identified in previous work will also be presented. These examples illustrate the fundamental character of the needed research.

Although the development of engine designs has historically been an iterative hardware design process, advances in basic and applied research have permitted an alternative engine design strategy. This strategy involves designing engines by accommodating the physical and thermodynamic processes that determine the engine's performance. This analytical approach to design involves two important elements: simulation and experimental verification. Recent developments in measurement technologies have permitted more precise experimental verification of model predictions than has been possible in the past. As a result, optimal engine performance is becoming possible by manipulating the generic combustion processes that occur in a common reciprocating piston engine geometry.

Figure 13 is being used by the Sandia National Laboratories in their engine combustion technology program to display the approach used in linking research activities with the development of the advanced engines. As the figure shows, distinct linkages were not made among the research tools, research questions, and the advanced engine concepts. These linkages were not made because the basic questions and the applicability of the research tools are generic to many combustion processes. For example, molecular species measurements by Raman spectroscopy can be employed toward all three engine concepts.

The analytical approach thus involves specific linkages between the research techniques and the physical and thermodynamic processes that

FIGURE 13. An Approach in Engine Combustion Research
(Sandia National Laboratory 1980)

contribute toward the combustion of a leaner mixture that, in turn, contributes toward greater efficiency. Technical problems inhibiting the realization of these efficiency gains are termed technical barriers. A technical barrier is defined as a known technical hardware difficulty or lack of knowledge that must be overcome before the continued development of an advanced engine system concept toward commercial operating conditions can occur. The barriers alone, however, will not describe efficiency numbers. For example, reducing emissions alone has little efficiency value.

Gaps in current knowledge and uncertainties also inhibit the development and evaluation of these engine concepts. The uncertainties of each engine concept will be discussed in the following sections.

An example of a technical barrier being addressed by various research tools is the formation of pollutant emissions that must be resolved to safely increase efficiency. Determining species concentrations after ignition in the postflame zone is investigated through laser Raman spectroscopy to measure species concentrations, laser velocimetry to quantify flow field speeds, Schlieren movies to visualize the flow field, and computer simulation to predict species concentration as a function of time

and the various parameters. Understanding the processes involved thus points to mitigating measures that would permit leaner combustion and thus greater efficiency. These relationships are depicted in Figure 14.

In 1979 the Secretary of the U.S. Department of Transportation requested the National Science Foundation (NSF) to consider the opportunities possible through a national program of basic research in automobile technology. As a result of this request, the NSF assembled prominent researchers who drafted a technical framework for a Cooperative Automotive Research Program (CARP). This draft, which appears in the Congressional Record of September 18, 1980, discusses specific basic research needs and opportunities in many areas of automobile technology, including combustion, thermal, and fluid sciences.

Because such research was considered with automotive technology in mind, a more precise definition of this area is "directed" basic research. The research suggested by the NSF advisory groups was directed toward general engine types, such as Otto, diesel, or Brayton cycle engines, rather than purely generic combustion and fluid phenomena. However, their study did not specifically address advanced engine types, such as the DISC, DHC, or DI diesel engines. As the preceding discussions of each of these engine types indicate, the problems addressed by directed basic research can be valuable in overcoming technical barriers particular to each engine type.

FIGURE 14. An Example of Linkages Between Research and Efficiency

Table 2 summarizes the categories of research suggested in the CARP document, along with examples of research needs and opportunities. The following chapters discuss research that more specifically addresses particular advanced engines.

TABLE 2. Categories of Research

I. CHEMISTRY AND KINETICS		RESEARCH NEEDS	EXAMPLES OF RESEARCH
Small Molecules	Nitrogen Chemistry	Reactions involving fuel-bound nitrogen and n-hydrocarbon reactions Rates of elementary reactions involving nitrogen-containing compounds and carbonaceous species, especially in the quantitative chemistry of the hydrocarbon species involved	Experimental and theoretical determination of the kinetics of selected elementary reactions of CH _n , NH, CN-X, NO _x species Experimental studies of premixed flames and post-flame zones with sufficient measurement of kinetically important species to allow model validation Development of useful kinetic models giving net production (and destruction) of fixed nitrogen species in the presence of flame-generated carbonaceous species
	Oxidation and Pyrolysis	Quantitative treatment of the oxidation and pyrolysis of 1-2 carbon atoms for the modeling of reactive flows	Experimental and theoretical determination of the kinetics of selected elementary reactions Experimental studies of oxidation, pyrolysis and combustion reactions of 1-2 carbon fuels Kinetic models of pyrolysis, preflame reactions, knock, lean and rich flames and post-flame reactions Development of research mechanisms to facilitate modeling
Large Molecules	Pre-Ignition Chemistry	Determine contributions to knock, ignition delay, deposits, exhaust odor and hydrocarbon pollutants	Experimental and theoretical studies of the early stages of oxidation and pyrolysis Studies of reactions leading to ignition over a wide range of conditions
	Flame Zone Chemistry	Rates and mechanisms of conversion to small species Formation of intermediate-size compounds that cause deposits or polymerize to form aromatic molecules or soot Chemistry leading to soot Role of flame generated ions	Experimental measurement of the rate of conversion to small molecules Identification and chemistry of complex intermediates, especially those that survive to form deposits or post-flame zone hydrocarbons Polymerization and growth to high molecular weight hydrocarbons and particles under diffusion and premixed flame conditions
	Post-Flame Zone Chemistry	Changes in the quantity and composition of hydrocarbons and soot; important for their environmental and health effects	Experimental studies of the chemistry of flame-generated polynuclear aromatics at high temperature but very low oxygen concentrations Studies of the chemistry of polynuclear aromatics and other exhaust components in the presence of oxygen but at temperatures where reaction rates are slow enough to be limiting Studies of the chemistry and physics of growth and oxidation of soot over the entire range of temperature and oxygen concentrations

TABLE 2. (contd)

RESEARCH NEEDS		EXAMPLES OF RESEARCH
II. FLUID MECHANICS, THERMODYNAMICS, HEAT AND MASS TRANSFER		
Turbulent Flow Modeling	<p>Details of fuel-air mixing</p> <p>Details of transient flows</p> <p>Effects of compression on turbulence</p>	<p>Turbulent unsteady flows in ducts, through valves and ports, and within engine cylinders</p> <p>The effects of compression and expansion through boundary displacement of combustion on relevant turbulent flow fields within cylinders</p> <p>Flows in small-sized turbomachinery components relevant to automotive engine systems</p> <p>Development of appropriate calculation techniques for these flows, with special emphasis on flows with moving boundaries and where small regions of flow are critical</p>
Two-Phase Flows and Mass Transfer	<p>Details of transient droplet heating and vaporization, secondary atomizations (including microexplosions), near critical and supercritical vaporization</p>	<p>Experimental and theoretical research on fuel atomization and on the subsequent transport of droplets and air</p> <p>Fuel vaporization involving multicomponent mixtures with a wide range of volatility and two-phase mixtures such as oil-water emulsions</p> <p>Development of predictive models which can be coupled with combustion and emission formation models</p>
Heat Transfer	<p>Details of convective and radiative heat transfer processes</p>	<p>Experimental and theoretical research in simpler-geometry simulations of engine components, as well as in real engines, aimed at developing a fundamental data base on engine heat and mass transfer processes</p> <p>Application of fundamental data to modeling of the actual engine heat transfer processes</p>
III. COMBUSTION AND REACTIVE FLOWS		
Preignition and Post-Flame Reactive Flows	<p>Pre-Ignition Reactions</p> <p>Details of complex fuel composition, chemistry and flow-related interactions</p>	<p>Interaction effects involving fuel composition as related to spontaneous ignition and to exhaust emissions</p> <p>Composition changes prior to ignition in diffusion flames are important. These gradients can involve vaporized fuel or can also include vaporizing droplets.</p>

TABLE 2. (contd)

	RESEARCH NEEDS	EXAMPLES OF RESEARCH
	Post-Flame Reactive Flows	Details of unburned hydrocarbons in fuel-rich or fuel-lean conditions Details of reactions in post-flame zones; advances will help eliminate undesirable exhaust components
		The reaction-flow interactions of fuel and fuel fragments that have bypassed active combustion under circumstances typical of the expansion stroke in reciprocating engines The unburned hydrocarbon and soot composition changes in the exhaust system of all classes of automotive engines (including the effect of increasing temperature, oxygen mol fraction in the exhaust, etc.)
	Reactions Near Cold Boundaries	Details of the chemistry and physics of deposit formation which contributes to premature ignition and knock
Ignition	Spon- taneous Ignition	Quantitatively understand fuel chemistry and fluid mechanics Ignition of fuel vapor of fuel droplets, injected into hot gases The compression ignition of fuel-air mixtures as related to knock The fluid mechanics and physical effects of the pressure wave resulting from knock
	Ignition by External Energy Sources	Ignition of fuel-lean mixtures by jets and hot combustion products Interaction of turbulence with ignition and the effects on cycle-to-cycle variation and misfire Spark ignition of turbulent fuel-air mixture. Basic understanding of ignition energy requirements as related to fluctuations in mixture composition and velocity, shear, etc. Ignition of lean mixtures by hot jets of burned gases
Flame Propagation	Laminar Flames	Validation of chemical kinetic treatments Understanding of flow in which the predominant turbulent scale is large Laminar premixed flames at high preheat temperatures, high pressure and high rate of flame surface extension Small, high pressure laminar diffusion flames involving either vaporized fuel or droplets as the fuel source. Effects of ambient temperature and composition are important. Diagnostics for determining the role of laminar flame properties in automotive combustion systems
	Turbulent Flames	Details of chemistry and fluid mechanics Models to quantify the relative importance of the many processes UNSTEADY-FLOW PREMIXED SYSTEMS Experimental and modeling studies of combustion rates as a function of time for homogeneous charge systems, with emphasis on flame structure relationships to turbulent flame propagation, knock and completeness of combustion near the lean inflammability limit Experimental and modeling studies of premixed stratified charge systems with emphasis on turbulent mixing as related to NO _x formation, completeness of combustion, particulates formation and knock

TABLE 2. (contd)

	RESEARCH NEEDS	EXAMPLES OF RESEARCH
IV. EXPERIMENTAL METHODS	Research Engine and Engine Simulator Measurements Examine details of engine subprocesses and the synthesis of subprocesses Diagnostics for research engine analysis	UNSTEADY-FLOW HETEROGENEOUS SYSTEMS Observations of flow patterns, flame structure and composition, and development of appropriate models for prediction of combustion rate, NO _x formation and particulate formation Detailed study and analyses of specific features of the combustion process to aid in overall model development, to provide guidance on needed detailed mechanistic studies and to make use of the basic information gained in study of simpler systems
		Visualization of engine fuel flow and combustion processes Determination of flow and combustion temperatures in engines Measurement of major and minor species concentrations in engine combustion systems Characterization of droplets and particulates in engine environments
Fundamental Laboratory Experiments	Isolate individual chemical and physical processes in combustion Details of turbulent fluid mechanics	Determine species concentrations and temperature in laminar flows -- Raman scattering, laser fluorescence, tunable laser absorption Determine species concentrations and temperature in turbulent flows -- laser Rayleigh scattering for temperature and density fluctuations -- pulsed Raman scattering for species fluctuation measurements Measurement of submicron particulates, and their precursors

4.0 DIRECT INJECTION STRATIFIED CHARGE (DISC) ENGINE

The primary difference between the DISC engine and conventional automobile engines is in the direct injection of the fuel. Combustion of the fuel occurs as it is injected, with ignition taking place in a stoichiometric or fuel-rich mixture. Combustion is then completed in the remainder of the cylinder, which contains a lean fuel-air mixture, or simply air. The resultant overall mixture is therefore lean. Combusting the fuel as it is injected has the added advantages of removing the knock and pre-ignition limitations in current engines and creating a multifuel capability.

The combination of charge stratification and spark ignition allows for some degree of combustion control and eliminates the diesel engine problems of random ignition and diffusion combustion, which cause noise, high NO_x , smoke and odor. Further, as mentioned in the discussion of common engine characteristics, load control is maintained without throttling by varying the equivalence ratio of the fuel-air mixture.

The main contributions to the higher efficiency of the DISC engine are the absence of throttling, the ability to operate with lean fuel-air mixtures, and the ability to operate with higher compression ratios.

ADVANTAGES

The primary advantages of the DISC engine over the conventional engine can be summarized as follows:

- higher thermodynamic efficiency from lean operation
- higher thermodynamic efficiency from higher compression ratios
- higher brake thermal efficiency at low and medium loads due to the absence of throttling
- multifuel capability
- absence of a preignition or knock limitation
- potentially lower emissions of NO_x , CO , and unburned hydrocarbons.

TECHNICAL BARRIERS

The primary technical barrier to successfully developing an automotive DISC engine stems from the current inability to control combustion over a wide range of loads and speeds. The major contribution to this barrier is the required transition from slow to fast mixing during combustion. When the fuel is injected, slow mixing is desired to ensure charge stratification. Immediately after ignition, a transition to fast mixing is desired to mix the combustion products, CO, and unburned hydrocarbons with the air in the remainder of the chamber to complete oxidation. This transition from slow to fast mixing has been viewed as a possible inherent limitation of this engine concept (Bracco 1976). Fortunately, combustion introduces large gas velocities that create a different flow field and may aid in the transition.

A second barrier is that the mixing and the completion of combustion should occur early in the expansion stroke rather than before expansion occurs. In this latter case, high combustion temperatures, dissociation and variable specific heats occur prior to mixing and result in a process that is not as thermodynamically efficient as homogeneous lean combustion. If, on the other hand, mixing occurs early in the expansion stroke, most of the efficiency benefits of a lean mixture are achieved.

Slow combustion rates create another technical problem in the development of this engine. This characteristic compounds the problem of operating with a wide range of loads and speeds. Slow combustion also contributes toward the particulate emission problem, which accompanies heterogeneous combustion.

A characteristic of the engine that creates inefficiencies, yet does not quite form a technical barrier, is the high swirl used. This swirl increases convective heat transfer to the cylinder walls, hence heat loss, and also tends to lower the volumetric efficiency of the engine, thus decreasing specific power.

RESEARCH EXAMPLES

Although the technical barriers described in the preceding section are specific to the engine concept, the components of the technical barriers that

are addressed by applied research are fundamental issues. That is, the research questions that are posed by these features of the technical barriers are generic.

In the case of transition from slow to fast mixing during combustion, research is directed at the contributions to this process. Issues that need to be understood include molecular species concentration, flow velocity, turbulence, reactive flow, 3-dimensional asymmetrical flow, 2-phase flow, and processes in which the characteristic time is millisecond.

The four processes shown in Figure 13, intake fluid mechanics, fuel preparation, combustion phenomena, and emission formation all play a role in this transitional event. Each is an important issue in better understanding this technical barrier.

Organizations performing research in this area include Princeton University, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratory (Sandia National Laboratory 1980). Research at Princeton is directed at understanding and modeling several of the physical and thermodynamic components, including fuel sprays, intake processes, and flame propagation. At Los Alamos, code development is aimed at modeling coupled fluid dynamics, heat transfer, chemical reactions, and fuel spray dynamics. At Lawrence Livermore, global kinetics equations are being developed to describe engine environmental behavior. Finally, Sandia is developing diagnostic techniques to measure velocities, temperatures, and species concentrations. The tools used by Sandia include laser velocimetry, laser shadowgraph visualization, and Raman spectroscopy.

Each laboratory is investigating one or several aspects of the technical barriers to the development of the engine. The linkage among these examples of current research, important technical questions, and efficiency characteristics is shown graphically in Figure 15.

UNCERTAINTIES

Although the DISC engine has been extensively studied, several important questions were not answered by the researchers contacted and cannot be solved by simple analysis:

FIGURE 15. Examples of DISC Engine Research Linkages

1. Texaco is currently field testing its TCCS DISC engine in United Parcel Service (UPS) vans. Although these engines are designed for these larger vehicles, they are operable from idle to full load with acceptable emissions for light trucks. How extrapolative are these engines to automobile engines?
2. F. Bracco from Princeton University states that the TCCS engine is not optimal and that efficiency falls off significantly as operation deviates from the design point. What is the extent of this deviation?
3. How well can combustion be controlled as load and speed vary?
4. What is the leanest ignitable mixture as a function of operating conditions?
5. To what degree will swirl increase heat loss and decrease efficiency?
6. To what degree do the leaning of the fuel-air mixture and the spatial distribution of the charge affect heat loss and efficiency?
7. When combustion is complete before much expansion occurs, how much does the efficiency decrease as a result of chemical dissociation, high temperatures, and changes in specific heat?

DISCUSSION

Texaco has developed a 292 in.³ DISC engine, called the TCCS, that is currently being fleet tested in UPS vans. Tests indicate that these retrofitted vans will meet current state regulations and inspections for exhaust emissions from trucks. However, when the stricter standard for heavy duty gasoline engines is applied, a catalyst, exhaust gas recirculation (EGR), and some throttling are required. Performance tests also indicate that significant efficiency can be gained when compared with a conventional engine of equivalent displacement. The question of how extrapolative this engine is to an automotive engine is a major unresolved question.

In 1978 Texaco tested a smaller TCCS engine, 163 in.³, in a 2750 lb jeep. The measured emissions, with diesel fuel and without a catalyst, were

1.5 gm/mile of unburned hydrocarbons, 13.2 gm/mile of CO, and 1.3 gm/mile of NO_x, all within the federal standards for light duty vehicles at that time. Currently (1982), the federal standards for light duty vehicles are .41 gm/mile for unburned hydrocarbons, 3.4 gm/mile for CO, and 1.0 gm/mile for NO_x.

F. Bracco at Princeton feels that significant efficiency improvements can still be achieved through more precise control of the combustion process. However, the amount of additional gain is difficult to estimate without a more intimate knowledge of the combustion limits at varying loads and speeds.

Figures 9 through 12 show the TCCS brake fuel consumption, engine efficiency, and relative improvements of both over a conventional engine at an engine speed of 2000 rpm. Note that, as expected, the greatest efficiency improvement is achieved at part loads due to the throttling used in conventional engines and absent in the TCCS. Figure 10 shows that the fuel consumption advantage of the TCCS ranges from 30 to 11% over the load shown with a consequent improvement in brake thermal efficiency ranging from 45 to 13%, as shown in Figure 12.

Figures 10 and 12 also show that a moderate amount of room for improvement does exist between the TCCS engine and the hypothetical and fuel-air cycle engines. An additional 20 to 30% reduction in fuel consumption (relative to the conventional engine) is calculated with the hypothetical engine, whereas an additional 40 to 50% reduction is calculated with the fuel-air cycle engine.

Although direct links between research projects and efficiency numbers have been shown to be difficult, if not impossible, to ascertain, the most important technical barriers nonetheless should receive the focus. In the case of the DISC engine, this technical barrier is the transition from slow to fast mixing to complete combustion.

5.0 DILUTE HOMOGENEOUS CHARGE (DHC) ENGINE

The term DHC applies to two similar models of engine operation: 1) the use of a homogeneous lean fuel-air mixture via dilution with air, and 2) near stoichiometric operation, $\phi=1$, with high levels of exhaust gas recirculation. Both concepts reduce flame temperatures and NO_x emissions and both possess efficiency advantages. However, because of the large potential for efficiency improvements through leaner fuel-air mixtures, this discussion will focus on the first mode of operation.

Conventional automobile engines use a homogeneous fuel-air charge. However, misfire typically limits lean operation to equivalence ratios of about 0.8. To take advantage of the efficiency gains possible through leaner operation, alternative methods of combustion control must be employed.

Dale and Oppenheim (1981) propose the concept of controlled combustion to achieve optimal performance in a homogeneous charge engine. Controlled combustion could serve the same functions as electronic controls and catalytic converters in minimizing pollutant emissions and maximizing engine efficiency. The principle way to achieve such control is through the use of distributed, enhanced ignition schemes. The two primary categories of such advanced combustion control are enhanced autocatalysis and enhanced ignition. Both use multiple ignition point combustion to combust lean mixtures.

Enhanced autocatalysis is primarily achieved chemically. The fuel/air mixture is provided with catalysts that reduce the activation energy of the combustible charge. This can be achieved through active radicals provided by the igniter or derived from catalytic surfaces around the combustion chamber. Enhanced ignition is primarily achieved through some physical means. Ignition is facilitated by jets of active radicals or by flame jets that establish multiple ignition points in the main chamber, thereby accelerating complete combustion. Systems that use this technique include plasma jet ignition [Oppenheim (1978), the LAG process (avalanche-activated combustion)], and torch ignition. Plasma jet and LAG ignition use active radicals to establish multiple ignition points in the main chamber, thereby accelerating complete

combustion. In torch ignition, the torch mixture is ignited in a prechamber and the flame shoots into the main chamber. This process is aided by the fact that flame propagation from a rich mixture into a leaner mixture continues to propagate into the lean mixture with a considerably higher than normal flame speed.

Another possible ignition scheme is the use of specific fields of energy to facilitate combustion. One such technique is the use of specific wavelengths of energy generated by a laser. Early experiments by J.D. Dale et al. (1978) succeeded in extending the lean limit to an air/fuel ratio of 27.8 (equivalence ratio of 0.54), an improvement of 5 air-fuel ratios over the standard engine, without laser ignition. The use of the laser to assist ignition resulted in a more rapid rise in cylinder pressure, leading to better performance, better fuel economy, and higher NO_x emissions than with convention engines. The minimum laser pulse required for steady engine operation appeared to be dictated by the minimum energy required to achieve breakdown of the laser pulse in air at the same pressure.

The homogeneous combustion process also tends to be more efficient than the heterogeneous combustion process because less disassociation occurs due to lower peak temperatures and because the specific heat ratio of the gas tends to be lower. The absence of diffusion combustion also may reduce the particulate emission problem of the DISC or diesel engine.

ADVANTAGES

The primary efficiency advantages of the DHC engine over the conventional engine are largely the same as those of the DISC engine:

- higher thermodynamic efficiency from a leaner mixture
- higher efficiency from a higher compression ratio
- higher efficiency from the absence of throttling for load control
- potentially lower emissions of NO_x , CO, and unburned hydrocarbons
- absence of a particulate emissions problem.

TECHNICAL BARRIERS

The two primary technical barriers that limit the efficiency gains possible through this engine are ignition and flame quenching. The inability to ignite the fuel-air charge is commonly referred to as misfire. Both problems are induced by excessive leaning of the fuel-air charge. The onset of misfire or flame quenching in lean mixtures results in degraded performance and a notable rise in unburned hydrocarbon emissions. As mentioned earlier, the misfire limit in conventional automobile engines is typically around an equivalence ratio of 0.8. In general, the factors that favor ignition include a high charge temperature, low mixture velocity, low turbulence, a hotter spark, and greater ignition system energy.

The other limit, bulk quenching, occurs from partial burn of the mixture due to slower flame speeds in the leaner mixture. Variables that reduce partial burn of the mixture include decreased charge dilution, decreased propagation distance, increased mixture temperature, and increased turbulence.

A factor which influences both the partial burn and misfire limits is the ignition timing. Figure 16 shows the effects of ignition timing upon both limits. Note that in the regimes of highly advanced timing, which reduces the equivalence ratio of the misfire limit, infinite ignition system energy will still not prevent degraded performance because of the partial burn limitation.

FIGURE 16. Zones of Stable and Unstable Combustion (Quader 1976)

The emission of unburned hydrocarbons is another limitation resulting from partial burn and lean misfire. In addition, a third contribution to the emission of unburned hydrocarbons is quenching inside the engine crevice volumes or absorption by the oil film layers on the engine cylinder wall. Finally, it should be noted that unlike the DISC concept, knock is still an issue at high loads. Thus, as in the conventional engine, fuel sensitivity may be a limitation.

RESEARCH EXAMPLES

Research into the DHC concept, as in the DISC engine concept, is directed at various components of the technical barriers. The four generic processes outlined by Sandia all contribute to understanding the character of the technical barriers: intake fluid mechanics, fuel preparation, combustion phenomena, and emission formation.

Questions being addressed include the following posed by Sandia (Sandia 1982). The first two address ignition and the third addresses propagation.

- What are the relative influences of radicals, ions, and temperature in the ignition process?
- Is it possible to vary the controlling parameters to achieve more reliable and, perhaps more global, ignition?
- What is the structure, speed, and mechanisms of freely propagating flames and how do these processes affect pollutant formation?

Research into the DHC concept is being performed at the University of California at Berkeley, the Massachusetts Institute of Technology, the University of Michigan, Ford's Science Application Laboratory, and TRW. At the University of California at Berkeley, a square piston visualization engine is being used to understand flame propagation, space and time resolved heat transfer rates, and hydrocarbon oxidation and quenching processes. At MIT, flow visualization using a water model and a combustion bomb is being used to characterize turbulent fluid mechanics and turbulence ahead of a compression wave, and to correlate turbulent flame speed with theory. In addition to the work at Berkeley, factors contributing to the problem of unburned hydrocarbon emissions

are being researched by the University of Michigan, the Science Application Laboratory at Ford, and TRW. The University of Michigan and Ford are involved in a joint effort to determine the contribution of crevice volumes, oil layer absorption, and wall quench layers on the mechanisms of hydrocarbon emissions. Schlieren movies and gas chromatography measurements are being applied to combustion bombs to aid in producing a theoretical model of the unburned hydrocarbon formation processes. Efforts at TRW center around the wall quenching process and attempt to assess generation via numerical simulation and laser Raman spectroscopy.

The links among these example research activities, technical barriers, and efficiency characteristics are shown graphically in Figure 17.

UNCERTAINTIES

In attempting to gauge the effect of various parameters upon efficiency, several important issues must be resolved. These questions include the leanest combustible mixture, the effect of changing operating conditions, and changes in heat transfer losses.

A major uncertainty is the minimum equivalence ratio at which acceptable combustion can be achieved via the various ignition schemes. The ideal limits shown in the general discussion and mentioned in the DISC engine section provide limits on the efficiency gains, but the degree to which these gains can be achieved is an open question.

Another uncertainty in judging the efficiency gains possible through this concept is the effect of varying operating conditions, loads, and speeds, upon the performance of the engine. That is, even if successful operation could be achieved at a design operating condition, whether the efficiency advantages can be maintained as operation varies from that design point has not been resolved. The effect of ignition process and the lean mixture upon heat transfer losses is also an unresolved question.

DISCUSSION

In the preceeding discussion, the importance of the ignition process was highlighted because of the central role ignition plays in determining misfire and quenching limits. Research directed at understanding these limits is

FIGURE 17. Examples of DHC Engine Research Linkages

clearly underway in current projects. In addition, however, research into possible ignition schemes is an important area that may warrant greater attention.

Because of the limits imposed by lean ignition and flame quenching, the combustion of very dilute homogeneous mixtures is extremely difficult to achieve. Even with enhanced ignition or autocatalytic ignition schemes, it is unlikely that ignition of mixtures with equivalence ratios of less than 0.4 can be achieved.^(a) Maintaining this ratio at light loads will require some form of load control such as throttling. However, as discussed earlier, throttling causes significant efficiency penalties. Using the conditions discussed in Chapter 2, the effect of throttling on engine efficiency at various loads and with a mixture of 0.4 equivalence ratio is shown in Figure 18. Figure 19 shows

(a) Conversation with F. Bracco, Princeton University, 1982.

FIGURE 18. Percent of Work Lost Due to Throttling
 $\phi = 0.4$

FIGURE 19. Effect on Efficiency of Imposing a Lean Limit

the departure from the fuel-air cycle efficiency at various loads for mixtures of various equivalence ratios.

As the figures show, the need for throttling causes dramatic theoretical efficiency penalties at light loads. Although the maximum efficiency at high loads is the same as in the DISC engine, about 56%, the efficiency at lighter

loads decreases to less than 40%, whereas that of the DISC engine increases to above 60%.

The opportunity for efficiency improvement is still substantial, ranging from absolute gains over the conventional engine of 21 to 32%. These translate to relative efficiency improvements of 116 to 135%. To achieve a practical estimate of the gains that are possible through the DHC concept, a more detailed model of engine losses is necessary. Such a model would provide valuable quantification of the specific paths of inefficiency and would assist in guiding research priorities.

6.0 DIRECT INJECTION (DI) DIESEL ENGINE

Although 5% of the new cars sold in the U.S. possess diesel engines, all current engines involve a divided chamber geometry. That is, ignition is initiated in a small prechamber and then jets into the main chamber. This arrangement has been favored to date because of its high speed, high specific power and low exhaust emissions. However, the high-surface-area-to-volume ratio of the prechamber and the pressure drop induced by the orifice connecting the two chambers result in losses in efficiency. By contrast, the DI diesel engine delivers the fuel directly to the main chamber. This single chamber design circumvents these loss mechanisms and therefore possesses the potential for higher efficiencies.

Eliminating the prechamber is the immediate problem being addressed by researchers. These losses were not previously discussed in Chapter 2 because they are specific to the prechamber diesel engine. Additional efficiency gains are still possible by leaning the fuel-air mixture and by optimizing the compression ratio, but these issues have yet to be addressed in detail for the direct injection configuration.

The DI diesel engine typically uses some degree of swirl to facilitate complete combustion. The quiescent or low swirl design is favored by domestic manufacturers and typically operates leaner than the higher swirl design. The low air swirl generally limits engine speeds to low values. However, the lean operation minimizes heat losses through the cylinder wall and head. The medium swirl or deep bowl design is favored in Europe and is primarily used in medium size applications. In general, this engine exhibits good fuel economy and low heat losses to the cooling system. Thirdly, the high swirl design uses a cork-screw type intake port and squish action of the piston to induce fluid motion. The primary advantage of this concept is its multifuel capability.

ADVANTAGES

Immediate efficiency advantages over the conventional automotive diesel engines are achievable in the DI diesel by eliminating the prechamber. This

would eliminate the heat loss and pressure drop loss caused by the prechamber. Test data from AVL of Austria indicate that a 15 to 20% efficiency gain in brake thermal efficiency can be achieved by eliminating the prechamber.^(a) As shown in Figure 6, additional gains are possible by leaning the charge mixture in the engine. However, this advantage is not a motivating reason behind the development of the DI diesel engine.

Efficiency improvements can also be achieved by optimizing the compression ratio. Due to cold starting limitations, current light-duty diesel engines operate with compression ratios above 20:1. Reducing the compression ratio would reduce both the friction and heat transfer losses. F. Bracco related that reducing this compression ratio to 14 to 16:1 would increase the relative efficiency by 20 to 30%.^(b)

TECHNICAL BARRIERS

The diffusion combustion occurring in the diesel engine results in levels of pollutant emissions that are the primary technical barriers to this engine. When compared with the prechamber engine performance, the level of unburned hydrocarbon emissions is eight times higher and the level of NO_x emissions is three times higher. Excessive particulate emissions and excessive odor are also issues that must be overcome.

The performance of the DI diesel is also less attractive than that of the indirect injection version. The DI engine suffers from a limited speed range and lower power output per unit displacement. The DI engine is also heavier and noisier due to the higher pressure rises that occur during combustion.

RESEARCH EXAMPLES

Research into this technology includes the areas of computer modeling, flow field measurements, and soot concentration measurements.

(a) Conversation with W. Roessler, Aerospace Corp., 1982.

(b) Conversation with F. Bracco, Princeton University, 1982.

Organizations involved in DI Diesel research efforts include S-Cubed, the United Technologies Research Center, the Imperial College, and Purdue University (Sandia National Laboratory 1980). S-Cubed is developing a code to model the induction and exhaust processes in the direct injection geometry. Components of the model include heat transfer, flame propagation, and valve flow. Turbulence modeling of 2-D time dependent flow is a second task of their project. At the United Technologies Research Center, applications of Coherent Anti-Stokes Raman Spectroscopy (CARS) for thermometry and concentration measurement in diesel engines is being explored. Extinct/Mie scattering diagnostics are also being used to attempt to measure soot in diesel engine environments. At the Imperial College in London laser doppler velocimetry is being employed to measure flow velocities and turbulence levels. They are also using the TEACH code to analyze the flows numerically. Finally, Purdue is using laser doppler velocimetry (LDV) and flow visualization in a combustion bomb to characterize velocity distributions in a diesel fuel spray. The relationship between these example research projects, technical barriers, and efficiency characteristics is summarized in Figure 20.

UNCERTAINTIES

A primary uncertainty is the question of whether the direct injection engine geometry can be manipulated to take advantage of the efficiency gains possible through leaner operation and an optimized compression ratio. If this is possible, as many in the field feel it is, the question arises as to the degree of improvement that could be achieved. Limiting factors will most likely include exhaust emissions, especially particulate emissions, and startability.

DISCUSSION

Unlike the DISC and DHC engines, which possess efficiency advantages by eliminating or reducing throttling and by operating at higher compression ratios and leaner mixtures, the efficiency advantages of the DI diesel are being addressed by eliminating the prechamber. As previously noted,

FIGURE 20. Examples of DI Diesel Research Linkages

efficiency gains of 15 to 20% have been measured by AVL of Austria. AVL is planning to penetrate the market with an automotive-sized DI diesel engine in 1983 or 1984. Information on their near commercialization activities should be considered in the design of research into this technology.

REFERENCES

- Amann, C. A. 1980. "Why Not a New Engine?" SAE Paper 801428, Society of Automotive Engineers, Warrendale, Pennsylvania.
- American Institute of Physics. 1975. Efficient Use of Energy. American Institute of Physics, New York, New York.
- Blackmore, D. R. and A. Thomas. 1978. Fuel Economy of the Gasoline Engine. MacMillan, London, England.
- Bracco, F. 1976. "Toward an Optimal Power Plant." Combustion Science and Technology. Vol. 12.
- Dale, J. D. and A. K. Oppenheim. 1981. A Rationale For Advances in the Technology of I. C. Engines. LBL-13179, Lawrence Berkeley Laboratory, Berkeley, California.
- Congressional Record -- Senate. 1980. "Department of Transportation and Related Agencies Appropriations, 1981." September 18, 1980. U.S. Congress, Washington, D.C.
- Dale, J. D. et al. 1978. "Laser Ignited Internal Combustion Engine -- An Experimental Study." SAE Paper 780329, American Society of Automotive Engineers, Warrendale, Pennsylvania.
- Dowdy, M. et al. 1978. Automotive Technology Status and Projections Volume 1: Executive Summary. N78-31428, Jet Propulsion Laboratory, Pasadena, California.
- Grey, J., G. W. Sutton, and M. Zlotnick. 1978. "Fuel Conservation and Applied Research." Science. 200(4338):135-142.
- Harrow, G. A. 1968. "Some Applications of Basic Combustion Research to Gasoline Engine Development Problems." SAE Paper 680765, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Heywood, J. B. and P. A. Watts. 1979. "Parametric Studies of Fuel Consumption and No Emissions of Dilute Spark-Ignition Engine Operating Using a Cycle Simulation,": In Fuel Economy and Emissions of Lean Burn Engines. The Institute of Mechanical Engineers, London, England.
- Hopp, W. J. et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.
- Jet Propulsion Laboratory. 1975. Should We Have a New Engine? Volume 2: Technical Reports. JPL SP 43-17, Jet Propulsion Laboratory, Pasadena, California.

- Lewis, J. M. and W. T. Tierney. 1980. "United Parcel Service Applies Texaco Stratified Charge Engine Technology to Power Parcel Delivery Vans - Progress Report." SAE Paper 801429, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania.
- Lewis, J. M. and W. T. Tierney. 1979. "Stratified Charge Engine Development with Broad Fuel Tolerance." Presented at the SAE National Truck Meeting, Fort Wayne, Indiana, November 8-9, 1979.
- Lyn, W. T. 1978. "Optimization of Diesel Combustion Research." SAE Paper SP-433, Society of Automotive Engineers, Warrendale, Pennsylvania.
- May, M. G. 1979. "The High Compression Lean Burn Spark Ignited 4-Stroke Engine." In Fuel Economy and Emissions of Lean Burn Engines. The Institute of Mechanical Engineers, London, England.
- Newhall, H. K. 1975. "Combustion Process Fundamentals and Combustion Chamber Design for Low Emissions." SAE Paper 751001, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Obert, E. F. 1973. Internal Combustion Engines and Air Pollution. Harper and Row, New York, New York.
- Office of Technology Assessment (OTA). 1979. Automobile Transportation System, Vol. II, Technical Report. Office of Technology Assessment, Washington, D.C.
- Oppenheim, A. K. 1978. "Prospects for Internal Combustion Engines Among Advanced Energy Conservation Systems." SAE Paper 789652, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Oppenheim, A. K. et al. 1978. "Jet Ignition of an Ultra-Lean Mixture." SAE Paper 780637. Presented at the Passenger Car Meeting, June 5-9, 1978, Troy, Michigan.
- Pinkus, O. and D. F. Wilcox. 1977. Strategy for Energy Conservation Through Tribology. American Society of Mechanical Engineers, New York, New York.
- Quader, A. A. 1976. "What Limits Lean Operation in Spark Ignition Engines - Flame Initiation or Propagation?" SAE Paper 760760, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Roessler, W. U. et al. (Aerospace Corporation). 1980. Light-Duty-Diesel Engine Development Status and Research Needs. ATR-80(7753)-2, The Aerospace Corporation, El Segundo, California.
- Sandia National Laboratory. 1980. Engine Combustion Technology Work Package Description. Sandia National Laboratory, Livermore, California.
- Sandia National Laboratory. 1982. Application of New Diagnostic Techniques to Combustion Studies in Engines. SAND 81-8831, Sandia National Laboratory, Livermore, California.

- Segaser, C. L. (ORNL). 1977. Internal Combustion Piston Engines. ANL/CES/TE 77-1, Argonne National Laboratory, Argonne, Illinois.
- Shiomoto, G. H., R. F. Sawyer, and B. D. Kelly. 1978. "Characterization of the Lean Misfire Limit." SAE Paper 780235, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Taylor, C. F. 1966. The Internal Combustion Engine in Theory and Practice, Volume 1: Thermodynamics, Fluid Flow, Performance. MIT Press, Cambridge, Massachusetts.
- Taylor, C. F. 1968. The Internal Combustion Engine in Theory and Practice, Volume 2: Combustion, Fuels, Materials, Design. MIT Press, Cambridge, Massachusetts.
- TRW. 1977. Program Plan Report for Applied Research in Road Vehicles. TRW, McLean, Virginia.
- Turkish, M. C. 1974. "3-Valve Stratified Charge Engines: Evolvment, Analysis and Progression." SAE Paper 741163, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Wood, C. D. 1978. "Unthrottled Open-Chamber Stratified Charge Engines." SAE Paper 780341, Society of Automotive Engineers, Warrendale, Pennsylvania.
- Woschni, G. 1967. "A University Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine," SAE Paper 670931, Society of Automotive Engineers, Warrendale, Pennsylvania.

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