THE HEAD GASKET IONIZATION PROBE AS A COMBUSTION DIAGNOSTIC FOR SPARK IGNITION ENGINES

by

Adelbert S. Cheng

B.S., Mechanical Engineering
University of California at Los Angeles, 1991

Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

and

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February 1994

Signature of Author ______________________
Department of Mechanical Engineering
January 14, 1994

Certified by ______________________
Wai K. Cheng
Associate Professor, Department of Mechanical Engineering
Thesis Advisor

Accepted by ______________________
Ain A. Sonin
Chairman, Department Graduate Committee

Accepted by ______________________
Richard de Neufville
Chairman, Technology and Policy Program

THE HEAD GASKET IONIZATION PROBE AS A COMBUSTION DIAGNOSTIC FOR SPARK IGNITION ENGINES

by

Adelbert S. Cheng

Submitted to the Department of Mechanical Engineering on January 14, 1994
in partial fulfillment of the requirements for the degrees of Master of Science in
Mechanical Engineering and Master of Science in Technology and Policy

ABSTRACT

Recent proposals to increase Corporate Average Fuel Economy (CAFE) levels combined with the legislation of tightening passenger car emissions standards have intensified research into potential areas for automotive technology improvements. Among the recent innovations is the development of the head gasket ionization probe, a diagnostic which allows the investigation of in-cylinder combustion phenomenon in spark ignition engines.

Experiments were conducted at the MIT Sloan Automotive Laboratory in a preliminary investigation of the head gasket ionization probe's capabilities. The probe was manufactured with printed circuit board techniques and recorded the arrival of the propagating flame front at eight symmetrically spaced locations around the cylinder bore. Six different engine operating conditions were selected to determine the response of the flame arrival data to changes in the relative air-fuel ratio and engine speed.

Experimental results indicated that the head gasket ionization probe can provide valuable details regarding the combustion process in SI engines. Averaged flame travel speeds were observed to be longer both during lean engine operation and at higher engine speeds, and distinctive characteristics in the data were associated with poor combustion cycles. Most impressive among the results was the ability of the diagnostic to reveal the existence of in-cylinder charge motion.

While the head gasket probe, and other automotive technologies can potentially lead to substantial improvements in fuel economy and emissions controls, alternative strategies are also discussed as means for achieving the goals of the technology forcing standards. Because CAFE and emissions regulations alone have failed to significantly reduce fuel consumption or urban air pollution, these alternative strategies are recommended as important considerations for future strategies to mitigate the problems caused by automobile use.

Thesis advisor: Wai K. Cheng
Title: Associate Professor, Department of Mechanical Engineering

ACKNOWLEDGMENTS

Well, what can I say? It's been two and a half years since I first set foot on the campus of the Massachusetts Institute of Technology, and as my studies draw to a close, I have these brief moments (sandwiched between the final hours of thesis preparation) to reflect upon on my time here.

First and foremost I must thank Professors Wai Cheng and John Heywood for their valuable help and research guidance during my work at the Sloan Auto Lab. Also at the lab, special thanks go out to Don Fitzgerald and Brian Corkum for their technical support; to Kyoung-Doug Min, who assisted my research in innumerable ways; to Olivier Salvat for helping in many of the experiments; to Jonathan Fox for his sharing his knowledge on vehicle emissions, as well as his eye-opening perspectives on life; to Jean-Charles Brossert, the "French Texan" (or is that the "Texas Frenchman?") for his taxi services and for being a fellow sufferer of thesis woes (misery indeed loves company); and to Joan "Santa" Kenney for her administrative support and for supplying those gifts which injected a light-hearted atmosphere into an otherwise stressful time. Many other students, too numerous to mention, also contributed to my overall positive experience at the Sloan Lab.

Outside of the lab, I cannot forget those "engineers with a difference" over at the Technology and Policy Program. They have helped me further realize the importance of understanding the roles, both positive and negative, that technology plays in today's society. Thanks also to all my friends, both in the Boston/Cambridge area and beyond, who helped me to survive the "unique" conditions of life at MIT.

And most of all, my deepest gratitude goes to my parents, Jim and Nancy Cheng, whose direction and support have led me to where I am today. They are truly my most important teachers, and of them I am as proud as they are of me.

The research for this thesis was supported by the Industrial Consortium for Engine Research. Its members are Chrysler Motors Corporation, Ford Motor Company, General Motors Research, Peugeot S.A., Renault, and Volvo Car Corporation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

During the past several decades, concern has grown over the problems caused by automobile use in the United States. Passenger cars and light trucks, for instance, contribute significantly to the nation's dependence on imported petroleum sources. The Energy Information Administration reports that in 1990, petroleum consumption by light-duty vehicles averaged 10 million barrels per day (MMbbl/day) out of a total U.S. consumption of 17 MMbbl/day [1]*. With around half of the demand being met by foreign resources, issues of both national and economic security clearly exist.

In an attempt to reduce the United States' dependence on imported oil, Congress passed the Energy Policy and Conservation Act in 1975. Prompted largely by the 1973 OPEC oil embargo, it established corporate average fuel economy (CAFE) requirements for both domestic and imported vehicles. Manufacturers faced a mandated fleet average of their new car fleets of 18 mpg in model year 1978, rising to 27.5 mpg for model years 1985 and beyond. For light trucks, the corresponding requirement is set at 20.2 mpg. In the time since the passage of the bill, the legislated standards have been achieved and significant strides have been made in improving fuel economy. Yet these improvements

* Numbers in brackets denote references at the end of the thesis.

have been outpaced by both the growth of the vehicle fleet as well as the growth in vehicle miles traveled (VMT). As a consequence, the topic of CAFE requirements is being revisited — in fact, the possibility of an increase in the standards emerged as a heated topic of debate during the 1992 presidential campaign.

In addition to the issue of fuel economy, attention has focused on the negative impact of automotive emissions on air quality, especially in metropolitan areas such as Los Angeles and Denver. In Los Angeles, for example, the transportation sector is a substantial contributor to the formation of ground-level ozone, for which National Ambient Air Quality Standards (NAAQS) were exceeded on 104 days in 1990 [2]. The Clean Air Act and its subsequent amendments include provisions to control the amount of airborne pollutants discharged by automobiles through emissions limits on hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_X). The standards have become progressively tighter, and the most recent 1990 Clean Air Act Amendments mandate the phase-in of limits that are 3 to 6 percent of those which were first established. California, because of its severe air quality problems, enforces still stricter requirements. Table 1.1 and Table 1.2 provide a detailed summary of both past and future passenger car emission standards.

While numerous strategies exist to address these tough issues, legislative emphasis will likely continue to focus on the use of mandatory standards which force vehicle technology. To meet the challenges brought forth by the tightening standards, automotive manufacturers must identify potential areas for technology improvements. Techniques such as decreasing aerodynamic drag or improving post-combustion emissions controls are among those receiving attention. In the future, emerging technologies such as battery or fuel cell powered vehicles may prove feasible. In the near term, however, and especially when considering the problem of emissions, understanding and improving the combustion process in current internal combustion engines is of vital importance.

Table 1.1
History of emission standards for light-duty passenger cars. [3]

	Federal			California		
Model Year	HC [g/mile]	CO [g/mile]	NO_X [g/mile]	HC [g/mile]	CO [g/mile]	NO_X [g/mile]
1966				6.30	51.0	
1968	6.30	51.0		6.30	51.0	
1970	4.10	34.0		4.10	34.0	
1971	4.10	34.0		4.10	34.0	4.0
1972	3.00	28.0		2.90	34.0	3.0
1973	3.00	28.0	3.0	2.90	34.0	3.0
1974	3.00	28.0	3.0	2.90	34.0	2.0
1975	1.50	15.0	3.1*	0.90	9.0	2.0
1977	1.50	15.0	2.0	0.41	9.0	1.5
1978	1.50	15.0	2.0	0.41	9.0	1.5
1980	0.41	7.0	2.0	0.39	9.0	1.0
1981	0.41	3.4	1.0	0.39	7.0	0.7
1983	0.41	3.4	1.0	0.39	7.0	0.4
1984	0.41	3.4	1.0	0.39	7.0	0.4
1985	0.41	3.4	1.0	0.39	7.0	0.4
1986	0.41	3.4	1.0	0.39	7.0	0.4
1987	0.41	3.4	1.0	0.39	7.0	0.4
1989	0.41	3.4	1.0	0.39	7.0	0.4
1990	0.41	3.4	1.0	0.39	7.0	0.4
1991	0.41	3.4	1.0	0.39	7.0	0.4
1992	0.41	3.4	1.0	0.39	7.0	0.4
1993	0.41	3.4	1.0	0.25	3.4	0.4

*change in test procedure

1.2 BACKGROUND

An important element in the study of combustion processes is the development of suitable diagnostics for the various physical processes of the vehicle power plant. By far the most widely used is the piezoelectric pressure transducer, which allows instantaneous measurement of in-cylinder pressure. A recent innovation which also shows promise is the head gasket ionization probe. This simple and relatively inexpensive tool allows one to

Table 1.2
Future passenger car emission standards. 50,000 mile standards are listed with 100,000 mile standards in parentheses. [3]

		Federal		
	Effective	HC [g/mile]	CO [g/mile]	NO_X [g/mile]
Current	1993	0.41	3.4	1.0
Tier I	1994	0.25 (0.31)	3.4 (4.2)	0.4 (0.6)
Tier II	2004	(0.125)	(1.7)	(0.2)
		California		
	Effective	HC [g/mile]	CO [g/mile]	NO_X [g/mile]
TLEV*	1995	0.125	3.4 (4.2)	0.4 (0.6)
LEV*	1995	0.075	3.4 (4.2)	0.2 (0.3)
ULEV*	1995	0.040	1.7 (2.1)	0.2 (0.3)
ZEV*	1998	0.000	0.0 (0.0)	0.0 (0.0)

* TLEV = transitional low-emission vehicle; LEV = low-emission vehicle; ULEV = ultra low-emission vehicle; ZEV = zero emission vehicle

investigate the combustion process inside the combustion chamber with little or no modification to the engine. Physically, the diagnostic is packaged as a replacement for an ordinary engine head gasket, and is equipped with a number of ionization probes which provide access to the combustion chamber. Each of the probe electrodes serves as a flame detector, signaling the arrival of flame at a discrete point on the combustion chamber wall. Thus, in contrast to the pressure transducer, an ionization probe allows the collection of spatial data regarding flame shape during the combustion process.

Information gained from this diagnostic may prove beneficial in many ways. Most notably, the head gasket ionization probe might be used to analyze the effects of charge motion on combustion efficiency in the engine development process. Optimal conditions could be better mapped for given engines and then used to guide electronic control systems. Furthermore, the probe allows investigation of the effects of design modifications ranging from changes in engine geometry to the use of variable valve timings. Benefits to engine performance would likely result, and the examination of certain phenomenon could readily lead to improvements in vehicle fuel efficiency or emissions characteristics. For example, the head gasket ionization probe could provide insight into knocking, which limits engine compression ratios and thus fuel economy. Detailed studies might also be conducted to analyze behavior during engine idle, where the flame development is marginal due to the low cylinder pressure and high charge dilution.

1.3 Objectives

The objectives of this thesis are twofold. First, through a set of experiments conducted at the MIT Sloan Automotive Laboratory, an assessment will be made regarding the capabilities of the head gasket ionization probe. Results from the experiments will reveal how data collected with the diagnostic can be used to characterize engine combustion and complement information provided with a pressure transducer. The data analysis technique will investigate the manner in which flame arrival times change with variations in engine operating conditions, and specific focus will be placed on cycles for which poor combustion is evident. These issues related to the experimental work will be handled in Part I of the thesis.

In Part II of the thesis, an attempt will be made to extend the technical results into a discussion which will have particular relevance to policy makers. The preliminary aim will be to examine the potential contribution of the head gasket ionization probe in improving fuel economy and emissions characteristics in automobile engines. Other technologies will also be briefly reviewed so that recommendations about future policies or possible deficiencies in current regulations can be presented. Finally, although a thorough analysis is beyond the scope of this thesis, some solutions which are not technological in nature (e.g., behavioral and societal changes) will be discussed and compared in terms of potential effectiveness and feasibility.

PART I

EXPERIMENTAL STUDIES WITH THE HEAD GASKET IONIZATION PROBE

CHAPTER 2: EXPERIMENTAL FRAMEWORK

2.1 COMBUSTION IN SI ENGINES

Internal combustion engines can be classified into either diesel or spark ignition (SI) engines. In the United States, SI engines tend to dominate in car and light truck applications. Power is delivered in these engines by igniting with a spark plug a mixture of fuel and air inducted into each cylinder. The resulting combustion and flame development process is a crucial factor affecting a vehicle's performance.

Figure 2.1 illustrates the aspects of combustion inside a typical SI engine combustion chamber. As the flame front propagates across the combustion chamber, the in-cylinder pressure rises rapidly and compresses the fuel-air mixture in the unburned end-gas region. This process will differ drastically depending upon speed-load conditions, and even from one cycle to the next. The velocity or direction of flame propagation during each cycle can also have a dramatic affect on combustion efficiency.

Under certain conditions, knocking may take place due to the spontaneous ignition of the end-gas. This phenomenon prevents proper operation of the engine and can damage crucial components such as the piston or cylinder head. To prevent the occurrence of knock, engine designers must limit the compression ratio of engines. However, a price must be paid as lower compression ratios correspond to lower fuel

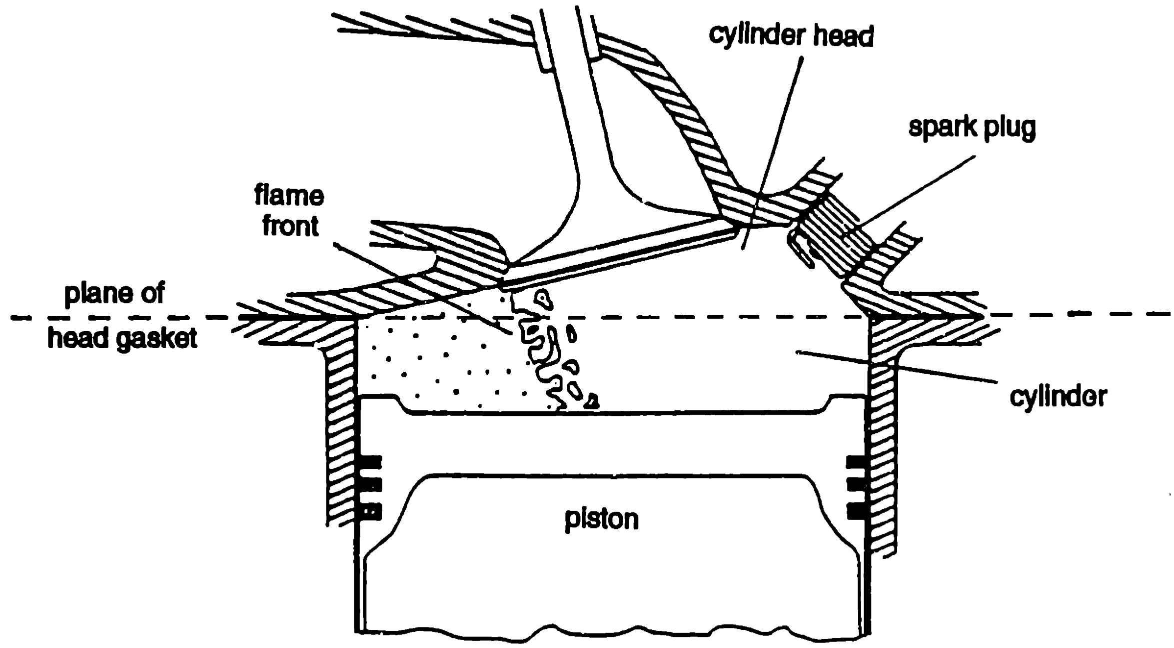


Figure 2.1
Combustion inside a spark ignition engine. The burned gas region is located to the right of the flame front; to the left is the unburned end-gas region. [4]

conversion efficiencies. Consequently, knocking is a critical factor limiting the performance of spark ignition engines.

In terms of the formations of emissions in SI engines, many mechanisms play a role. For example, crevices in the engine, such as those between the head and cylinder or in the spark plug threads, have been identified as an important factor with regards to hydrocarbons [5]. However, one of the most important aspects of automotive combustion which affect emissions is engine behavior during cold start. In this period before the engine and the catalytic converter are warmed up, emissions are high due to the need for enrichment compounded with the inability of the cold catalyst to effectively remove pollutants in the exhaust gas.

2.2 IONIZATION PROBE FUNDAMENTALS

In this study, combustion in an SI engine is examined through the use of a head gasket instrumented with multiple ionization probes. Ionization probe operation is based upon the presence of electrical conductivity in hydrocarbon flames, a fact which has been known since the late 1800's. The use of ionization probes in engine combustion research dates back to 1934 [6], and since that time, they have been utilized for burned gas measurements, in fluid motion studies, and most notably as flame front detectors.

The ionization probe itself is a relatively simple device which consists of an insulated conductor biased at a voltage potential different from ground. In the reaction zone of a flame, and also to a lesser extent in the burned gas region, ionized gases are present and provide free ions and electrons which bridge the ionization gap. This causes a current to be set up in the ionization probe circuit which can produce a signal which a researcher can observe or record. Figure 2.2 illustrates a typical ionization probe circuit, and a sample ionization probe signal trace is provided in Figure 2.3.

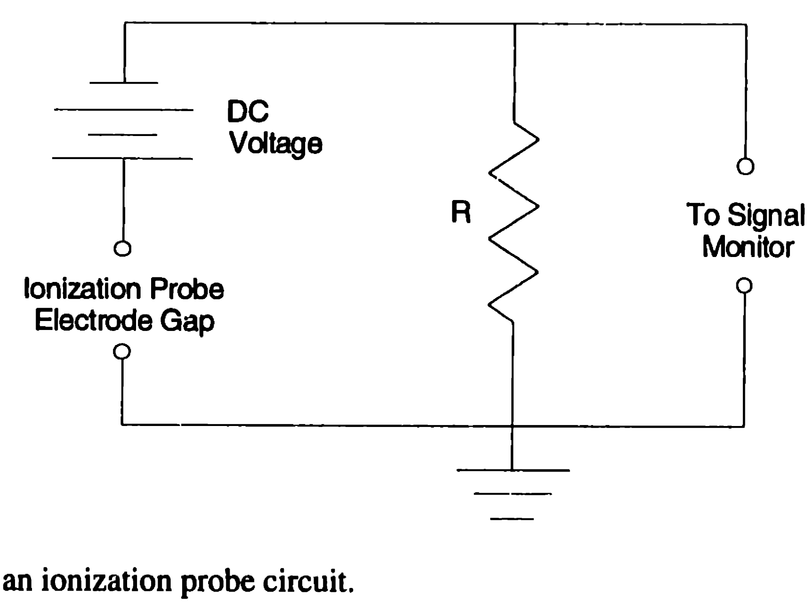


Figure 2.2
Schematic of an ionization probe circuit.

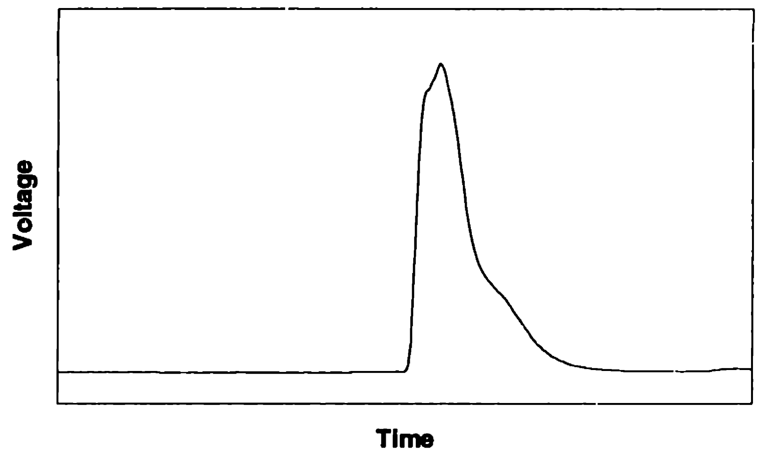


Figure 2.3
Sample ionization probe signal trace. The sharp rise in the signal corresponds to the arrival of the flame front at the ionization probe electrode.

2.3 HISTORICAL DEVELOPMENT OF THE HEAD GASKET IONIZATION PROBE

Until recently, the use of ionization probes typically required complex installation procedures. Significant engine modifications would usually be necessary to gain access to the combustion chamber. At minimum, one access hole would have to be machined for each probe to be installed in an engine. In order to provide the benefits available with ionization probes while avoiding the difficult set-up processes, Müller et al. proposed integrating ionization probes with the head gasket of an engine [7]. This technique would allow installation through simple removal the cylinder head and replacement of the regular engine head gasket. Once in place, the diagnostic could detect the flame front at locations on the plane of the head gasket at the circumference of the engine cylinder (see Figure 2.1).

This idea of a head gasket ionization probe was implemented in several recent studies by Witze at Sandia National Laboratories [8-10]. In his earlier experiments, a probe was manufactured with techniques that were quite labor-intensive and the diagnostic itself appeared to be less robust than was desired. However, in a 1993 SAE paper, Witze reported promising results with a head gasket probe manufactured with printed circuit board techniques [10]. Using this method, numerous diagnostics could be easily constructed after a one time set-up procedure. As will be discussed in the following chapter, the probe used for the experiments at the Sloan Auto Lab were manufactured using similar circuit board techniques.

CHAPTER 3: EXPERIMENTAL APPARATUS

Chapters 3 and 4 provide details concerning the equipment and procedures used during the experiments with the head gasket ionization probe. The information is intended to afford the reader a better understanding of those aspects which may have influenced the collection and interpretation of the experimental data. Future duplication of these experiments, especially with regard to the construction of the head gasket ionization probe itself, would also be aided by the material contained in these chapters.

3.1 ENGINE AND DYNAMOMETER

The engine used for this study was a Ricardo Hydra Mark III single-cylinder research engine. With a few notable exceptions, this engine is representative of modern spark ignition production engines. It utilizes a hemispherical, two-valve combustion chamber with a centrally located spark plug, and opening and closing of the valves is achieved with two separate overhead camshafts. For purposes of this study, the engine was configured for a quiescent flow field inside the combustion chamber. That is, no attempts were made to force a swirl or tumble bulk fluid motion. Table 3.1 provides geometric data for the engine, and valve and spark plug positions inside the combustion chamber are illustrated in Figure 3.2.

Table 3.1
Ricardo Mark III engine geometry.

Bore	86 mm
Stroke	86 mm
Displacement volume	500 cm^3
Compression ratio	8.0
Intake valve:	
open	4° BTC*
close	46° ABC*
lift	10.0 mm
Exhaust valve:	
open	57° BBC*
close	15° ATC*
lift	10.0 mm

* BDC = before top center; ABC = after bottom center; BBC = before bottom center; ATC = after top center

Differences between the Ricardo engine and production automotive engines include a relatively low compression ratio of 8.0, compared with values of around 9 to 11 which are typical in modern spark ignition engines. In addition, many designs now employ more than the single intake and exhaust valves. Three valve (one intake, two exhaust) and four valve (two intake, two exhaust) configurations are becoming increasingly used because of their ability to provide higher volumetric efficiency and flow field control. Production engines used in automotive applications are also invariably multi-cylinder. While these differences are to a certain degree undesirable, their existence does not alter the significance of the experimental results, as the ability of the head gasket ionization probe to characterize the combustion process could be assessed equally well in either research or production engines.

Attached to the Ricardo engine via the crankshaft was an Eaton Dynamatic Model AF 6360 dynamometer. This adjustable frequency regenerative dynamometer utilizes an AC induction motor and is capable of both driving and absorbing power to maintain a specified load or engine speed. In these experiments, the dynamometer was configured for constant engine speed. Torque measurements were provided by a torque arm and load cell connected to the induction motor. In previous studies at the Sloan Automotive Laboratory, researchers reported that at speeds below 1100 RPM and at low loads, the dynamometer failed to maintain precise control of the engine speed [11,12]. Consequently, consideration of this factor was necessary during the interpretation of data collected within this operating regime.

3.2 Spark Plug

In place of an NGK spark plug normally installed in the Ricardo engine, a fiber-optic instrumented spark plug supplied by Southwest Research Institute was used during the course of these experiments. Like the head gasket ionization probe, this diagnostic is also a recent development and is used to determine flame arrival times at the periphery of the spark plug base. Its detailed description can be found elsewhere in the literature [13]. Data was collected with the fiber-optic instrumented spark plug but was done so for use by other researches and will not be presented in this thesis. Of note, however, is the fact that the geometry of the instrumented spark plug differs slightly from that of typical commercial spark plugs.

3.3 Fuel Injection System

A wide variety of injection systems can and have been used with the Ricardo engine to supply fuels to the combustion chamber. However, in these experiments, propane (C_3H_8) was the single fuel used and a only one injection system was required. Because propane is a gaseous fuel, the process for injection was relatively simple. Fuel was supplied in a continuous mode through an orifice in the intake port 30 cm away from the intake valve seat, and a manually operated metering valve was used to adjust the amount of propane injected.

3.4 HEAD GASKET IONIZATION PROBE

For this study, a head gasket ionization probe was manufactured with conventional printed circuit board techniques. Design and construction of the probe took place at MIT, and an attempt was made to employ simple and low-cost production methods. The material used for the probe was a double-sided copper-clad printed circuit board material (FR-4 glass epoxy "G" type laminate) which exhibited favorable characteristics in terms of flame retardancy and dimensional stability. In producing the head gasket probe, a circuit pattern was etched on one side of the board while the full copper layer was left intact on the other side for use as the ground electrode. Appropriate holes were drilled for the bore, head bolts, alignment pins, and a 9-pin connector, and when installed, a thin sheet of teflon was used to insulate the probes from the cylinder head.

An illustration of the head gasket ionization probe is provided in Figure 3.1. As the figure shows, eight ionization probe electrodes were located in a symmetric configuration around the circumference of the cylinder bore. The combined thickness of the circuit board and teflon sheet was approximately 1.7 mm (compressed), and the width of each ionization probe electrode was 3.2 mm. The probe electrodes, numbered 1 through 8, were located in the combustion chamber as represented in Figure 3.2.

During operation of the engine, signals from each ionization electrode were passed through a signal conditioner and fed to a personal computer equipped with a multi-channel counter/timer card (Industrial Computer Source model DCC20/A). A voltage threshold set in the signal electronics translated the analog ionization probe signals into a gate pulses

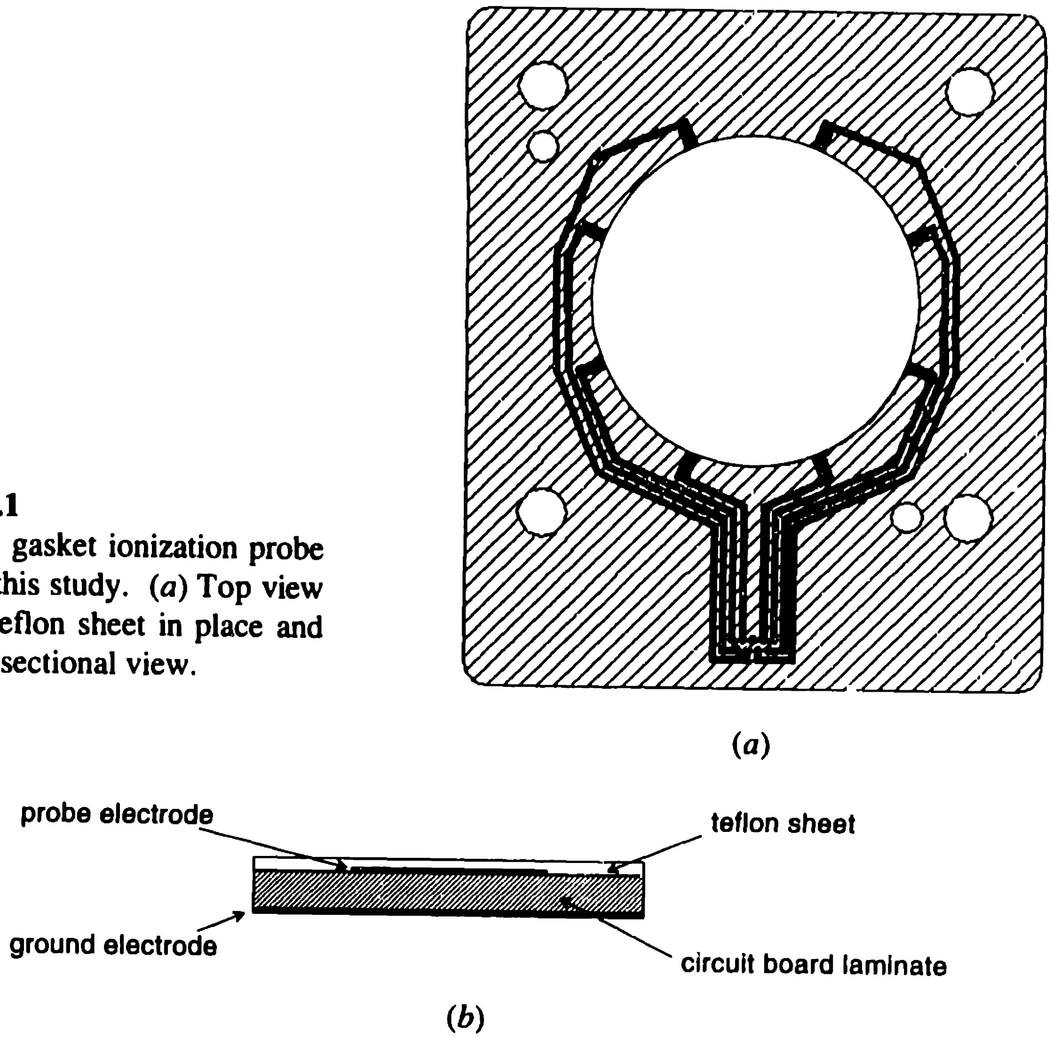


Figure 3.1
The head gasket ionization probe used for this study. (*a*) Top view without teflon sheet in place and (*b*) cross-sectional view.

which were recorded by the counter/timer card. The resulting values stored in the computer reflect the time elapsed between spark plug ignition and flame arrival at each of the ionization probe electrodes.

3.5 Additional Apparatus

Measurement of in-cylinder pressure was accomplished with a Kistler model 7061 water-cooled pressure transducer coupled with a Kistler model 5026 charge amplifier. The output from the pressure transducer was recorded on a personal computer equipped

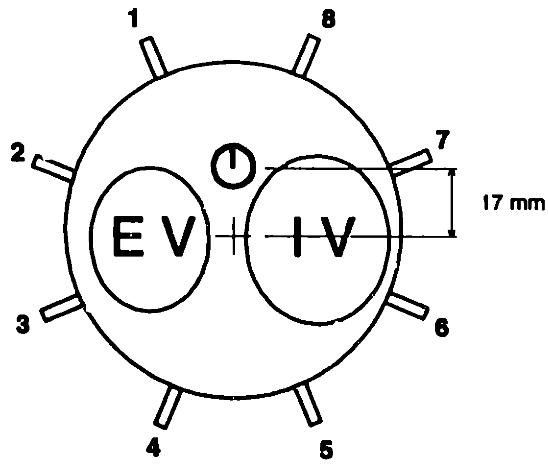


Figure 3.2
Orientation of ionization probe electrodes with respect to the engine head geometry. EV and IV denote respectively the exhaust valve and intake valve, with the spark plug location shown in between.

with a Data Translation DT2828 dual-channel DMA data acquisition board. Use of a shaft encoder allowed collection of pressure data at each crank angle degree (CAD).

Monitoring of the relative air-fuel ratio λ was handled with a NTK model MO-1000 Air Fuel Ratio Meter. Although accurate under most conditions, the lambda meter is prone to inaccurate readings under misfiring conditions. For the purposes of this study, however, this deficiency was not of significant importance.

CHAPTER 4: EXPERIMENTAL PROCEDURES

4.1 DATA COLLECTION PROCEDURE

Data was obtained in this experiment to reveal how flame arrival times at the head gasket ionization probe vary with respect to two engine operating parameters: engine speed and the relative air-fuel ratio λ. While it would have been interesting to investigate the effects of other parameters such as spark timing or inlet pressure, consideration of more than the two factors would have comprised a task too burdensome for this preliminary study.

Table 4.1 lists the six operating conditions selected for data collection. They represent stoichiometric (λ=1.00) and lean (λ=1.25) operating conditions at three different engine speeds. Spark timing was unchanged at each engine speed and was set to the optimal timing which gave maximum brake torque (MBT timing) at the stoichiometric air-fuel equivalence ratio. In each case, 500 consecutive cycles of flame arrival time and pressure data were obtained.

Engine operating parameters not listed in Table 4.1 were held constant to the extent possible. For instance, inlet pressure was adjusted to 0.5 bar in each case. Temperatures of the cylinder head and combustion chamber walls were also controlled by

Table 4.1
Experimental test matrix.

Engine Speed [RPM]	Relative Air-Fuel Ratio (λ)	Spark Timing [CAD BTC]
900	1.00	33†
900	1.25	33
1600	1.00	27†
1600	1.25	27
2500	1.00	29†
2500	1.25	29

†MBT timing

monitoring the engine coolant temperature to ensure the absence of warm-up transients or other undesired variations.

To further reduce any the effects from external variables, an attempt was made to use identical procedures in collecting each data set. After the engine was started and the ignition and fuel injection systems were enabled, the following steps were sequentially carried out:

- setting of desired engine speed
- adjustment of inlet pressure
- adjustment of fuel flow rate to achieve desired air-fuel ratio
- setting of spark timing
- simultaneous collection of pressure data and flame arrival time data

4.2 Data Analysis and Presentation

Interpretation of the experimental data required the results of both flame arrival time and pressure data. However, separate handling of the two types of information was necessary during the conversion from raw data into values or graphs which could be easily interpreted. Each of the data analysis methods will be described briefly in this section. Data presentation methods will also be addressed, although the explanation of some details is deferred until the actual presentation of results Chapter 5.

4.2.1 Flame Arrival Time Data

As mentioned previously, the data acquisition system for the head gasket ionization probe records the elapsed times between ignition and flame arrival at each of the eight individual ionization probe electrodes. A FORTRAN program was created to access this data for any given cycle. For cycle-averaged analyses, the program calculated statistical information about the flame arrival times such as the average values and sample standard deviations. Distributions of the measurements were also computed to allow display of the data in the form of histograms.

Individual and cycle-averaged results of the flame arrival data will be primarily presented in a form introduced by Witze [8] and shown in Figure 4.1. The radial diagram is intended to display in a coordinated manner both spatial and temporal information. Arrows are plotted to show the flame travel times for each of the eight directions (the arrows are not symmetrically spaced due to the offset of the spark plug location), with the solid line connecting the tips of the arrows representing a spline contour fit to the eight data points. For cycle-averaged results, dot-dashed lines are also included and correspond to spline fits for the average arrival times plus and minus one standard deviation. The methodology for computing the spline fit is relatively straightforward and is documented elsewhere [14].

4.2.2 Pressure Data

For each experimental case, pressure data was collected at every crank angle degree over the 500 cycle duration. However, output from the pressure transducer was recorded in voltage and required conversion into units of pressure. This computation was carried out with a suitably written FORTRAN program. In addition to providing the pressure trace (pressure as a function of crank angle degree), the program determined the crank angle degree at which the maximum pressure in each cycle was observed. For this parameter, results for the average, standard deviation, and the distribution of data were also computed. A separate program was written to make calculations of indicated mean effective pressure (IMEP), a measure of an engine's ability to do work.

When combined with other inputs, pressure data can also be used to calculate the mass fraction of fuel burned in each cycle. The technique which was used in this thesis involves a single zone burn rate analysis proposed by Gutowski et al. [15] and implemented for use at the Sloan Automotive Laboratory by Cheung [16]. This method can provide a more complete analysis than the traditional Rassweiler and Withrow model [17] while avoiding the time-consuming computations required of a more complex two zone combustion analysis.

CHAPTER 5: EXPERIMENTAL RESULTS AND DISCUSSION

5.1 PRIMARY RESULTS

Figures 5.1 to 5.6* present the primary results for the six operating conditions of Table 4.1. Corresponding graphs in each of the six figures retain the same scales in order to facilitate easy comparison. Flame arrival time information is displayed in the first part of each figure, where the radial plot described in Chapter 4 for the mean arrival times plus and minus one standard deviation is shown along with histograms of the arrival times at the eight ionization probe electrodes. The results comprise 500 cycles of data.

In the second part of the figures, the in-cylinder pressure data is displayed. The plots show the cycle-averaged pressure trace, with dot-dashed lines representing the average pressure plus and minus one standard deviation at each crank angle degree. Histograms are also provided for the crank angle degree at which the maximum pressure in each cycle is recorded. Two numbers, listed in all of the histograms, represent averages and sample standard deviations for the data.

In the final part of each figure, the cycle-averaged mass fraction burned profile is shown. Averages and sample standard deviations for both the 0 to 10 percent and 10 to 90 percent burn durations are included in the upper left hand corner of the plots. One may

* Figures and tables for Chapter 5 have been grouped together and placed at the end of the chapter.

note that the burn rate profiles extend beyond unity for the 900 RPM cases (Figures 5.1*c* and 5.2*c*). This can be explained by an apparent leak in the intake system which caused the recorded value of inlet air mass flow to be substantially lower than the value read by the air flow meter (located at the entrance of the intake system). As a consequence, the burn rate program, which calculates the mass of fuel based upon the mass of air and the relative air-fuel ratio, underestimated the amount of fuel supplied to the combustion chamber. The result was an upwards scaling of the burn rate profile to well above 1.0. This phenomenon was less of a difficulty in the 1600 RPM and 2500 RPM cases due to the more rapid intake processes which occur at these higher engine speeds.

In addition to being displayed within the graphs, flame arrival time results are grouped together and summarized in a tabular form in Table 5.1. The coefficient of variation, which represents the standard deviation as a percentage of the average, has also been included.

5.1.1 General Observations

Several trends can be identified from the cycle-averaged results of the six experimental cases. First of all, although the locations of the ionization probe electrodes are symmetric about a centerline passing through the spark plug position (see Figure 4.2), the experimental data reveals that flame arrival times are consistently shorter for the probe electrodes located on the exhaust valve side of the combustion chamber. This is contrary to what would be expected if a simple spherical flame front model is assumed. In such a model, flame arrival would be detected simultaneously at symmetrically located ionization probe positions. The absence of this result presumably indicates the presence of a discernible bulk fluid motion — perhaps a small degree of tumble — which causes the developing flame kernel to be convected away from spark plug location towards the exhaust valve side during combustion.

Another notable observation is the fact that the flame arrival time plots for the four 1600 RPM and 2500 RPM cases all exhibit the sam general shape. The two cases at 900 RPM, on the other hand, exhibit a slightly different shape, but one which is consistent within that grouping. This result can be more readily noticed in Figure 5.7, where average flame arrival times for all the cases are plotted in a single graph. Relatively longer arrival times for ionization probe locations closer to the spark plug are evident at 900 RPM (the cases identified by dotted lines). It appears, therefore, that similar processes affect combustion at the higher 1600 RPM and 2500 RPM engine speeds, while slightly different factors play a role in flame development and propagation at the lower 900 RPM engine speed.

5.1.2 Effect of Relative Air-Fuel Ratio

Evident from Figures 5.1 to 5.6, as well as from Figure 5.7, is the dramatic impact of the relative air-fuel ratio on flame arrival times. For each engine speed, arrival times are substantially longer under lean (λ=1.25) operating conditions than under stoichiometric (λ=1.00) conditions. Correspondingly, the mass fraction burned profiles also exhibit longer burn durations in cases for which the engine was run lean. This is, in fact, consistent with established research data which show that laminar burning velocities decrease when the relative air-fuel ratio moves increases beyond stoichiometric [18]. Again, the two higher engine speed cases showed similar results, with around a 25 to 35 percent increase in flame arrival times associated with lean combustion. For the 900 RPM case, arrival times showed a more marked increased of around 35 to 45 percent in going from stoichiometric to lean.

5.1.2 Effect of Engine Speed

Because faster burn rates are associated with the higher turbulence present at higher engine speeds, the combustion durations, when measured in crank angle degrees, increase only slowly with increasing engine speeds [19]. This is supported by the flame arrival data at the 1600 and 2500 RPM stoichiometric conditions (Figures 5.1*a*, 5.3*a*, and also Figure 5.7). The data at 900 RPM, however, does not follow this trend. A plausible explanation is that at 900 RPM the turbulence level during flame propagation may have fallen to a level such that the increase of real time per crank angle does not compensate for the slow flame speed.

For lean combustion, engine speed also has the anticipated impact on flame arrival times for the 1600 RPM and 2500 RPM cases (Figures 5.4*a* and 5.6*a*). However, as illustrated in Figure 5.2*a*, arrival times are exceedingly long for the 900 RPM case. In this instance, the discrepancy can be explained by the existence of a significant number of misfired and partial burn cycles (apparent, for instance, from the peak pressure histogram in Figure 5.2*b*). As will be discussed later in this chapter, such cycles can usually be associated with slower burn rates and considerably longer flame arrival times.

One remarkable feature which is evident from Figure 5.7 is that the flame arrival pattern at appears to be independent of the equivalence ratio and its pronounced effect on flame speed. However, this observation is consistent with the notion that the flame kernel is convected as a whole in the early stages of flame development. In the later stages, when the flame has become larger, the flame front expands at a uniform velocity while the flame center remains at an approximately fixed location.

If converted from crank angle degrees into absolute time units such as milliseconds, flame arrival times will actually exhibit significant changes with respect to engine speeds. This is consequence of the fact that one crank angle degree encompasses a longer time interval at lower speeds than at higher speeds. In Figure 5.8, averaged flame velocities, calculated by dividing the flame travel distance to each ionization probe electrode by the corresponding flame arrival time (expressed in absolute units), are plotted against engine speeds. The graphs depict the changes in flame travel velocities that occur as a result of the increase in engine speed. Faster flame velocities should be observed anticipated at greater engine speeds due to higher turbulence intensities which allow for a more rapid burn of the mixture in the combustion chamber. As the graphs illustrate, this turbulent burning effect is accurately represented by the data collected with the head gasket probe.

5.2 Individual Cycle Observations

The histograms and standard deviations of the flame arrival times furnished in Figures 5.1 to 5.6 succeed in revealing a certain degree of information about the behavior of the individual cycles. For example, the data shows that flame arrival times at the ionization probe electrodes tend to follow relatively normal distributions around their respective means. The exception is at the 900 RPM lean case (Figure 5.2*a*), where flame arrival times appear to be skewed to the right. As mentioned previously, however, this stems from the fact that this particular case included some misfires and partial burns. Elimination of those "bad" cycles would have likely yielded a variation in data more characteristic to that of a normal distribution.

Yet despite the fact that the histograms and standard deviations provide useful information, such results inherently mask many of the attributes of the individual cycles. For example, nine randomly selected individual cycle plots from the 1600 RPM lean case are shown in Figure 5.9*a*. The plots indicate that significant differences exist in the shapes of the spline fit contours. They are by no means simply scaled up or scaled down versions of the cycle-averaged contour, and in fact particular cycles exhibit some striking peculiarities. In certain instances, the flame front is detected first at an ionization probe which is located relatively far from the spark plug. In other cases, there are indentations in the plots, where flame arrival is recorded for a given probe considerably earlier than for those two probes immediately adjacent to it. In order to identify possible trends or patterns in the individual cycles, a more in depth analysis concerning the nature of the cycle by cycle results was conducted.

5.2.1 Poor Combustion Cycles

Perhaps the most notable trend apparent from the individual cycle data is an association between long flame arrival times and poor combustion cycles (as characterized by a low indicated mean effective pressure, or IMEP). Figure 5.9*b*, which shows flame arrival contours for three low IMEP cycles at the 1600 RPM lean case, illustrates the longer times which are required in such cases for the flame front to reach the circumference of the combustion chamber. In fact, for all six experimental cases, the same phenomenon can be observed. Figure 5.10, in which pressure and mass fraction burned plots are included along with the flame arrival contours, provides a more detailed comparison between a normal burn and a slow burn cycle is provided. The graphs, representing data at the 2500 RPM lean case, serve also to illustrate agreement between the ionization probe data and the pressure data in identifying the low IMEP cycle.

As can be anticipated, poor combustion cycles are observed more frequently in the lean cases than at stoichiometric conditions. This is due to the fact that, during lean operation, the increased dilution of the fuel-air mixture causes the combustion process to be less stable, leading to a greater occurrence of the slow or partial burning cycles. In fact, at the lowest speed (900 RPM) lean case, combustion was marginal to the extent that many incidents of partial burns and even misfires occurred.

5.2.2 Indications of Fluid Motion

From this previous discussion, one might generalize that, for a given cycle, a late flame arrival at one ionization electrode would be indicative of a slow burn cycle and thus point to corresponding late arrivals at the seven other probe locations. This is indeed true for numerous cases, but it should be emphasized that such a trend does not universally apply. For example, returning to Figure 5.9*a*, certain cycles can be seen to exhibit late flame arrival times at some ionization probes while very early arrival times are recorded at other probe locations (i.e., the second and fifth cycles, counting across and then down). These contours indicate that the flame development for those particular cycles was affected by a strong in-cylinder motion. That is, the flame kernel was likely rapidly convected by a bulk flow towards one side of the combustion chamber, thereby causing the ionization electrodes located in that direction to detect the flame front much earlier than those probes located in the opposite direction. This type of information regarding the nature of fluid motion is possible due to the spatial data provided by the head gasket ionization probe and would certainly be unavailable from pressure data alone.

5.2.2 Cycle to Cycle Analyses

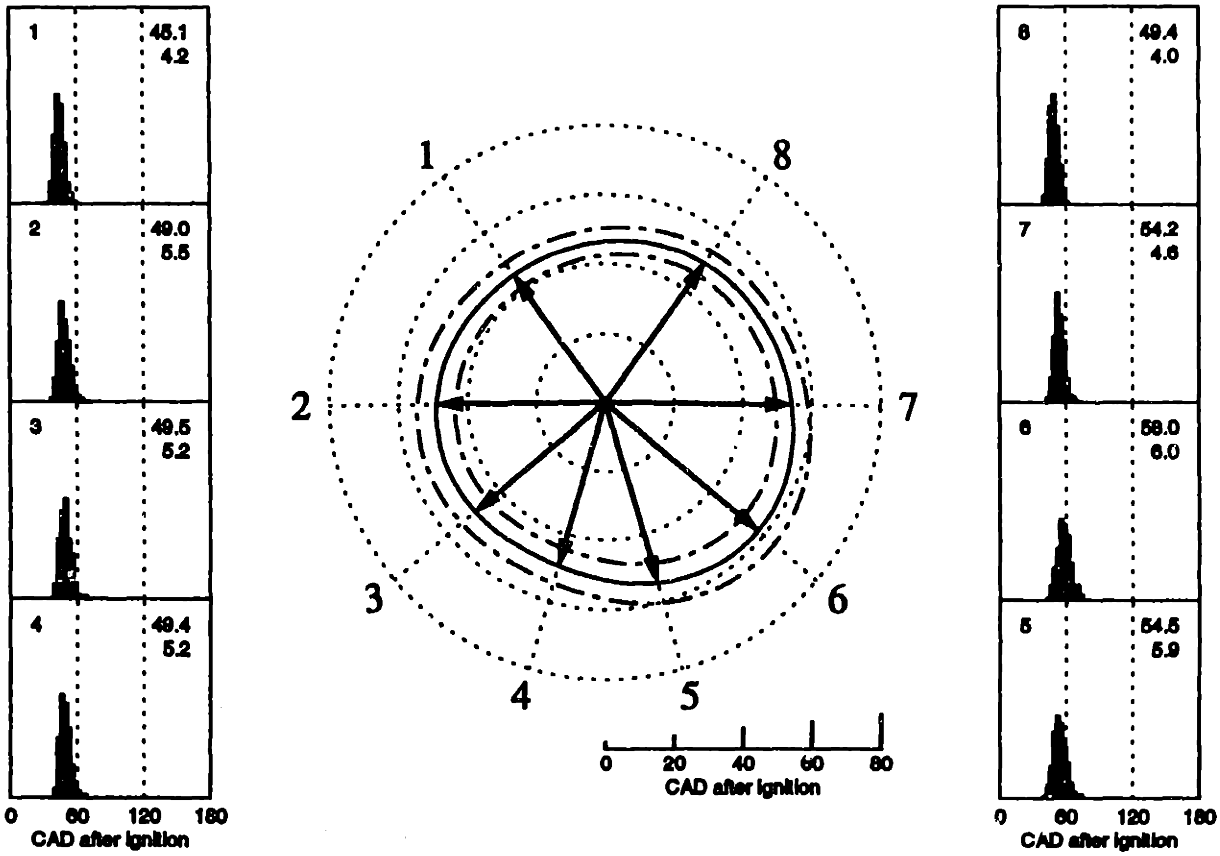
In an attempt to determine if any time or cycle dependent trends were associated with the experimental data, an analysis of the sequential behavior of the individual measurements was conducted. For instance, Figure 5.11 shows the flame arrival times for one probe location plotted by cycle over the entire 500 cycle measurement duration. These types of plots, along with methods such as exponential smoothing, were used for the individual probe arrival times to identify any possible patterns or cyclic trends in the experimental data. Analysis results did not point to any unusual variations or periodic phenomenon that may have affected the flame arrival times. The only notable peculiarities consisted of some large value outliers which were associated with the exceptionally slow burning cycles.

In addition to analyzing the data from individual ionization probe electrodes, an investigation of the cycle to cycle behavior of all eight probe measurements was conducted. For instance, it might be anticipated that a slow burning cycle, in which all probe arrival times are relatively long, would typically be followed by a fast burning cycle with shorter arrival times due to some fuel entrained in the intake port during the slow burn cycle. While this was indeed observed in certain sequences of experimental data, the trend did not occur to an extent that was statistically significant. Figure 5.12 provides an illustration of the cycle to cycle behavior of a subset of the ionization probe measurements.

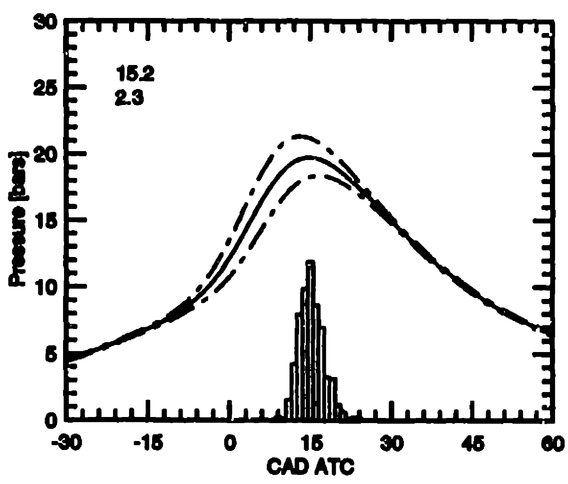
5.3 SUMMARY AND DISCUSSION

The results of this experimental study indicate that a substantial amount of information can be gained through the use of the head gasket ionization probe. It has been demonstrated, for instance, that flame arrival time measurements both verify and compliment results obtained with the pressure transducer. Yet even more notable is the fact that the head gasket probe unveils details regarding the combustion process which are completely hidden in the in-cylinder pressure data. These results, which include indications of bulk flow motion and insight into variations in flame propagation, are dependent upon the spatial information which the flame arrival data is able to provide.

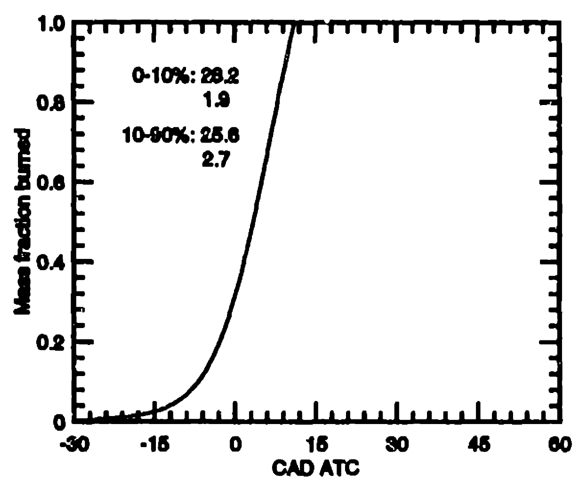
Although admittedly less simple to implement than the pressure transducer, the head gasket ionization probe does require a less burdensome set-up procedure than those which are associated with many other engine research techniques. In addition, the probe has proved quite durable in withstanding over 25 hours of engine operation. These factors, along with the availability of the useful spatial information, suggest that the head gasket ionization probe can indeed find use as a important combustion diagnostic. Of course, further studies will be necessary to fully investigate the abilities of the probe. In addition, improved data processing models, such as the ability to provide actual flame shapes from the flame arrival times, would serve to augment the value of the ionization probe data. With the engagement in such research work continuing — at MIT and at other research facilities — it is likely that the head gasket ionization probe will emerge as an important tool which can provide substantial benefits in both general engine research as well as in the development of future production automobile engines.



(*a*)



(*b*)



(*c*)

Figure 5.1
Results for 900 RPM, $\lambda = 1.00$. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

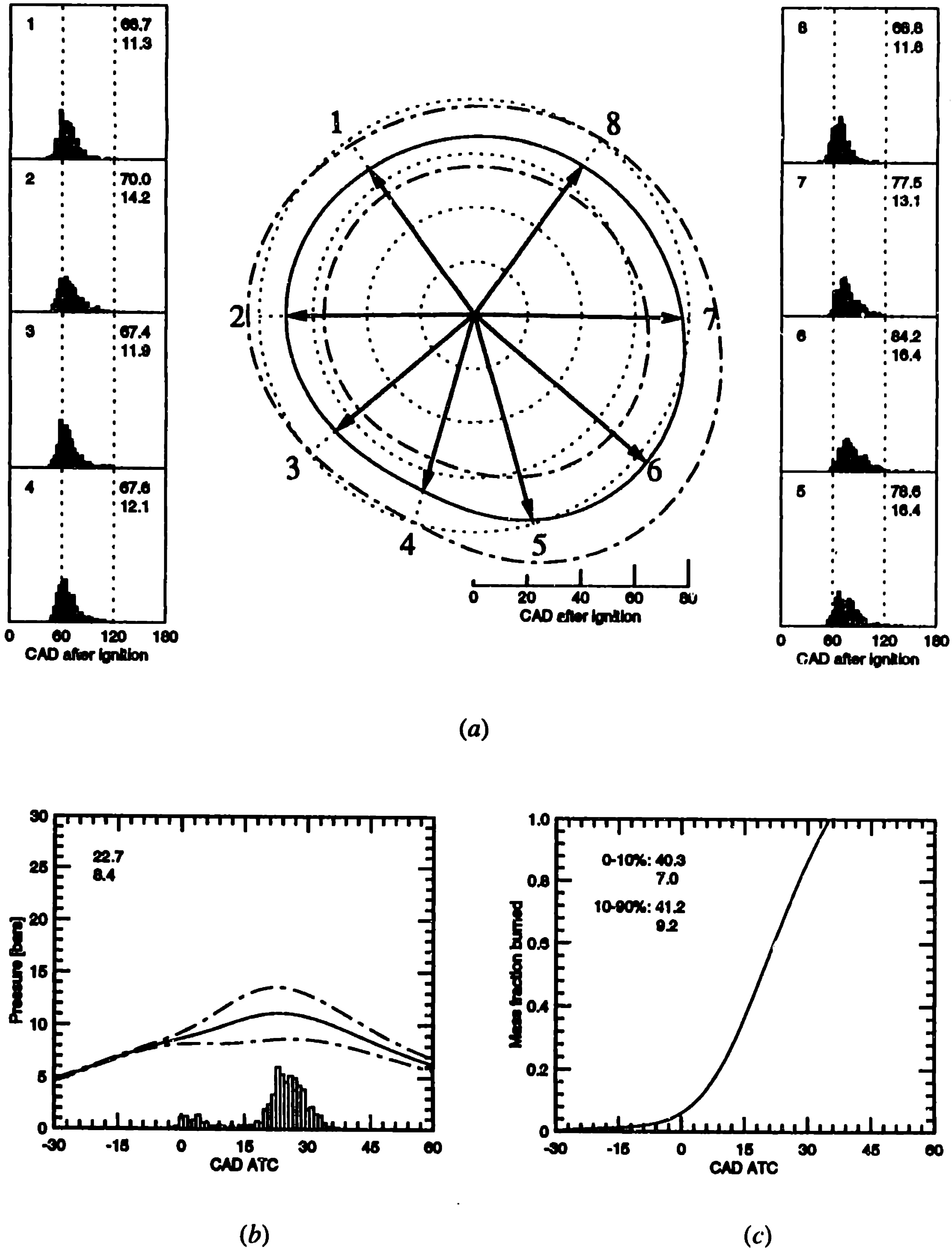


Figure 5.2
Results for 900 RPM, λ = 1.25. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

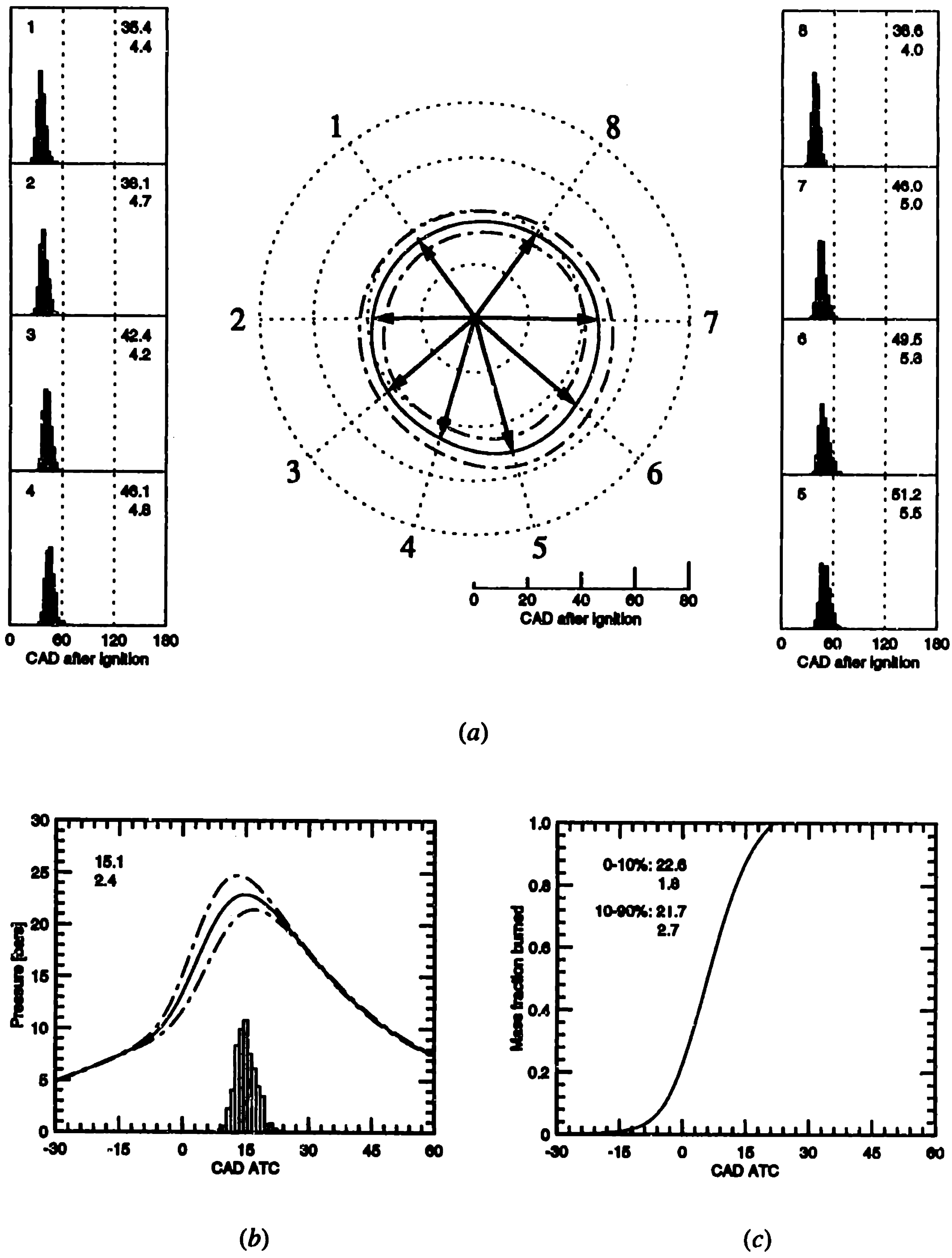


Figure 5.3
Results for 1600 RPM, $\lambda = 1.00$. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

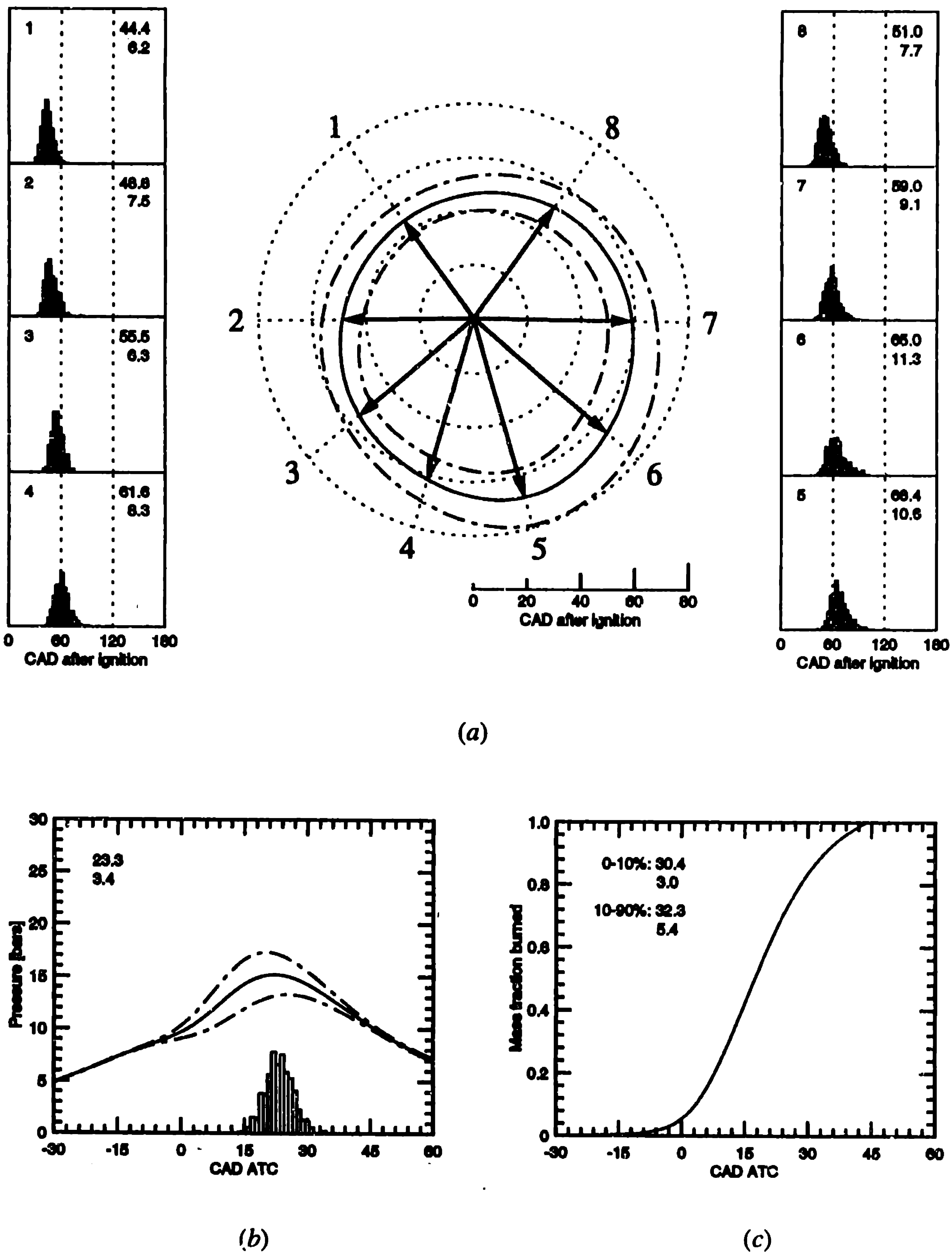


Figure 5.4
Results for 1600 RPM, $\lambda = 1.25$. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

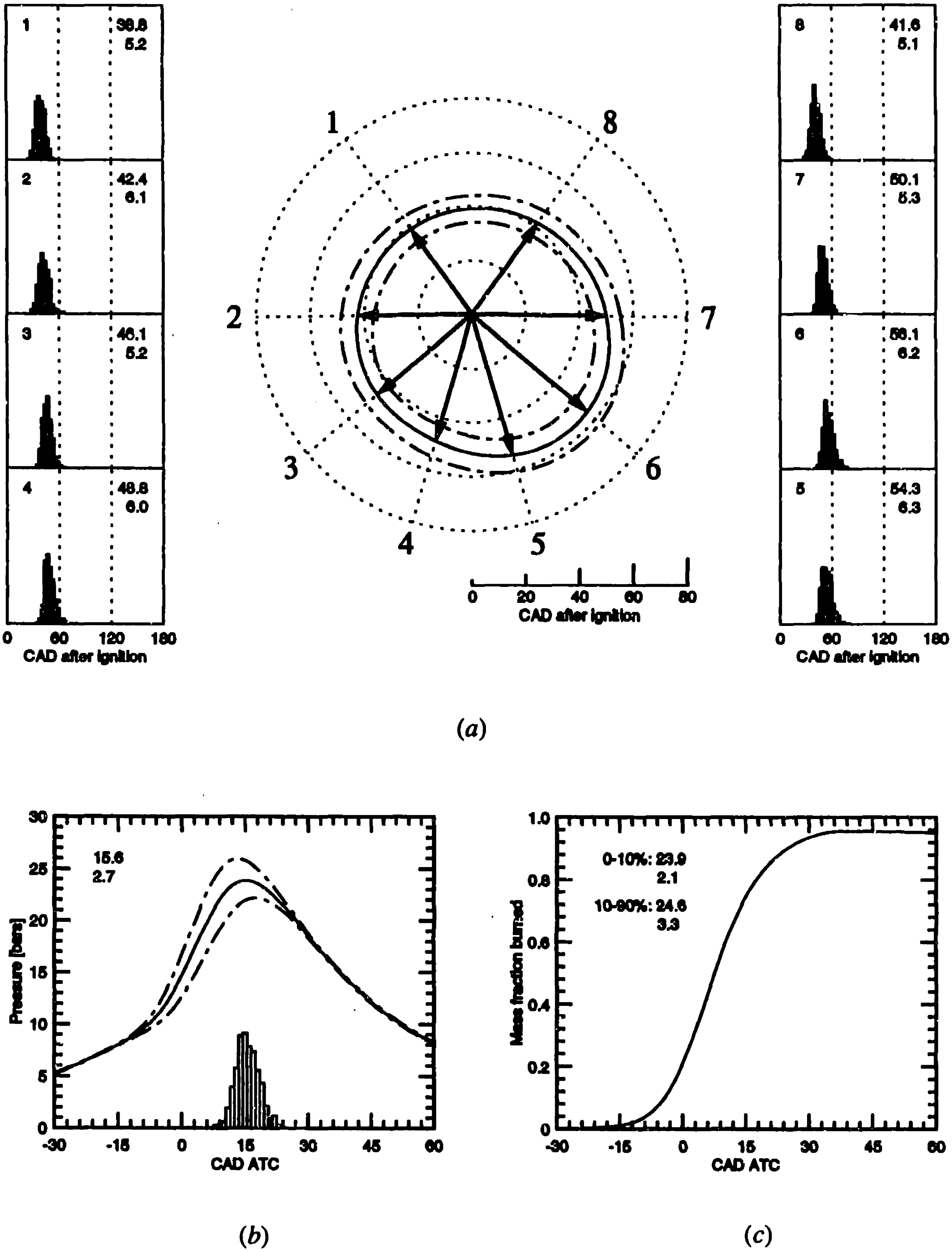


Figure 5.5
Results for 2500 RPM, λ = 1.00. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

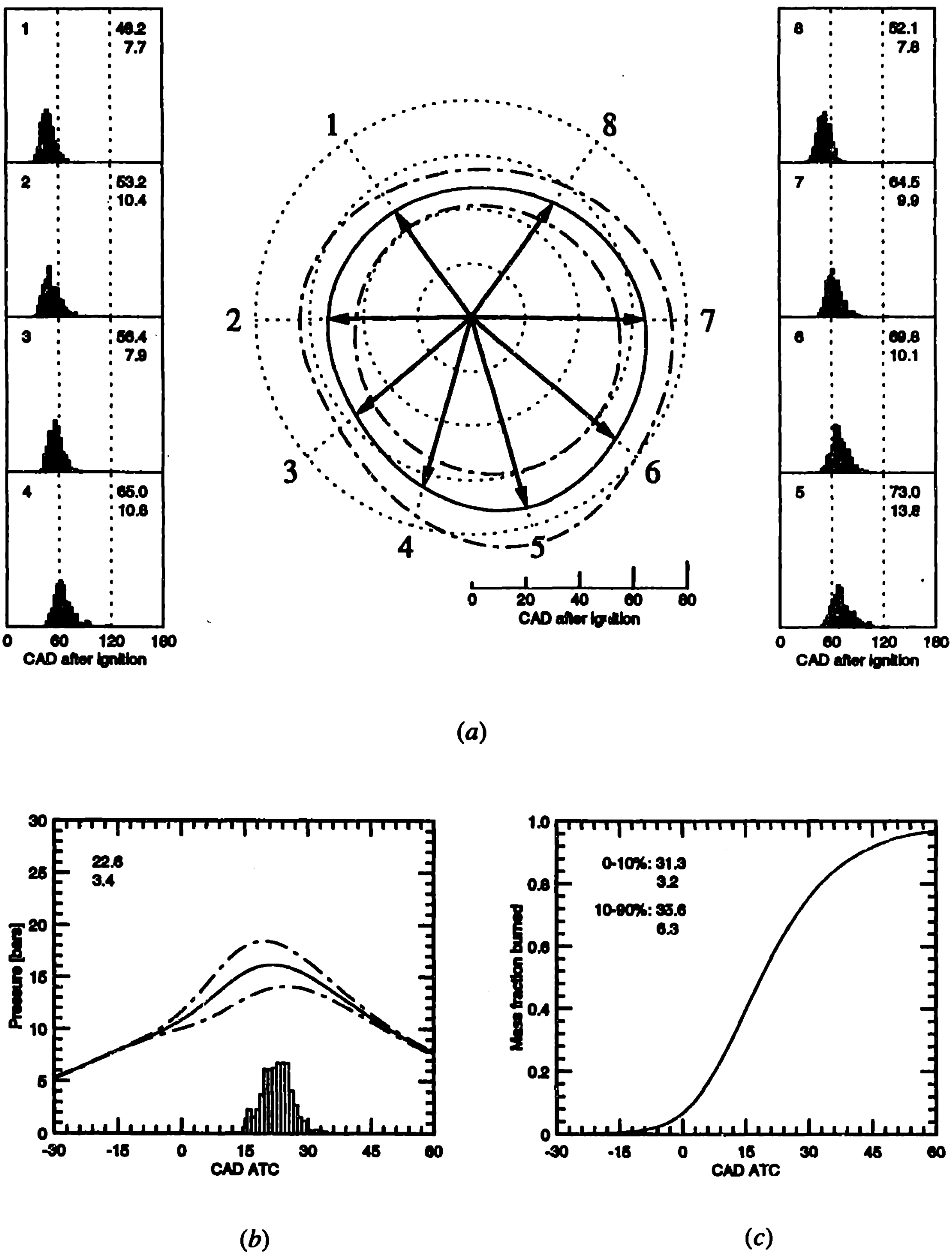


Figure 5.6
Results for 2500 RPM, $\lambda = 1.25$. (a) Flame arrival times, (b) pressure data, and (c) burn rate profile. See Figure 3.2 for relative probe locations within the combustion chamber.

Table 5.1
Summary of numerical results.

	900 RPM $\lambda = 1.00$	900 RPM $\lambda = 1.25$	1600 RPM $\lambda = 1.00$	1600 RPM $\lambda = 1.25$	2500 RPM $\lambda = 1.00$	2500 RPM $\lambda = 1.25$
Probe Number	Average [CAD after ignition]					
1	45.1	66.7	35.4	44.4	38.8	48.2
2	49.0	70.0	38.1	48.8	42.4	53.2
3	49.5	67.4	42.4	55.5	46.1	56.4
4	49.4	67.6	46.1	61.6	48.8	65.0
5	54.5	78.6	51.2	68.4	54.3	73.0
6	58.0	84.2	49.5	65.0	56.1	69.8
7	54.2	77.5	46.0	59.0	50.1	64.5
8	49.4	68.8	38.6	51.0	41.6	52.1
Probe Number	Sample Standard Deviation [CAD after ignition]					
1	4.2	11.3	4.4	6.2	5.2	7.7
2	5.5	14.2	4.7	7.5	6.1	10.4
3	5.2	11.9	4.2	6.3	5.2	7.9
4	5.2	12.1	4.8	8.3	6.0	10.8
5	5.9	16.4	5.5	10.6	6.3	13.8
6	6.0	16.4	5.8	11.3	6.2	10.1
7	4.6	13.1	5.0	9.1	5.3	9.9
8	4.0	11.8	4.0	7.7	5.1	7.8
Probe Number	Coefficient of Variation					
1	9%	17%	12%	14%	13%	16%
2	11%	20%	12%	15%	14%	20%
3	11%	18%	10%	11%	11%	14%
4	11%	18%	10%	13%	12%	17%
5	11%	21%	11%	15%	12%	19%
6	10%	19%	12%	17%	11%	14%
7	8%	17%	11%	15%	11%	15%
8	8%	17%	10%	15%	12%	15%

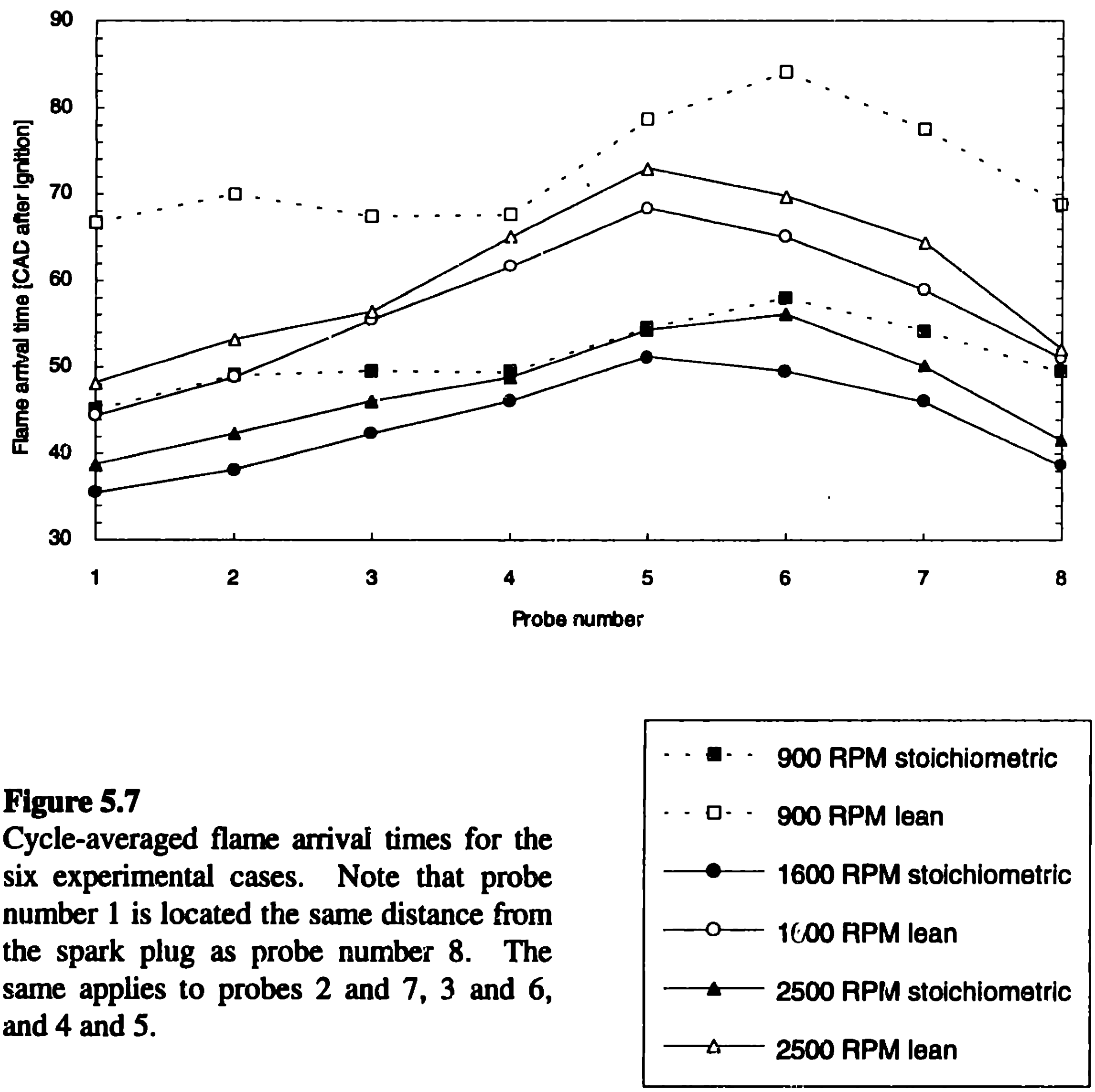
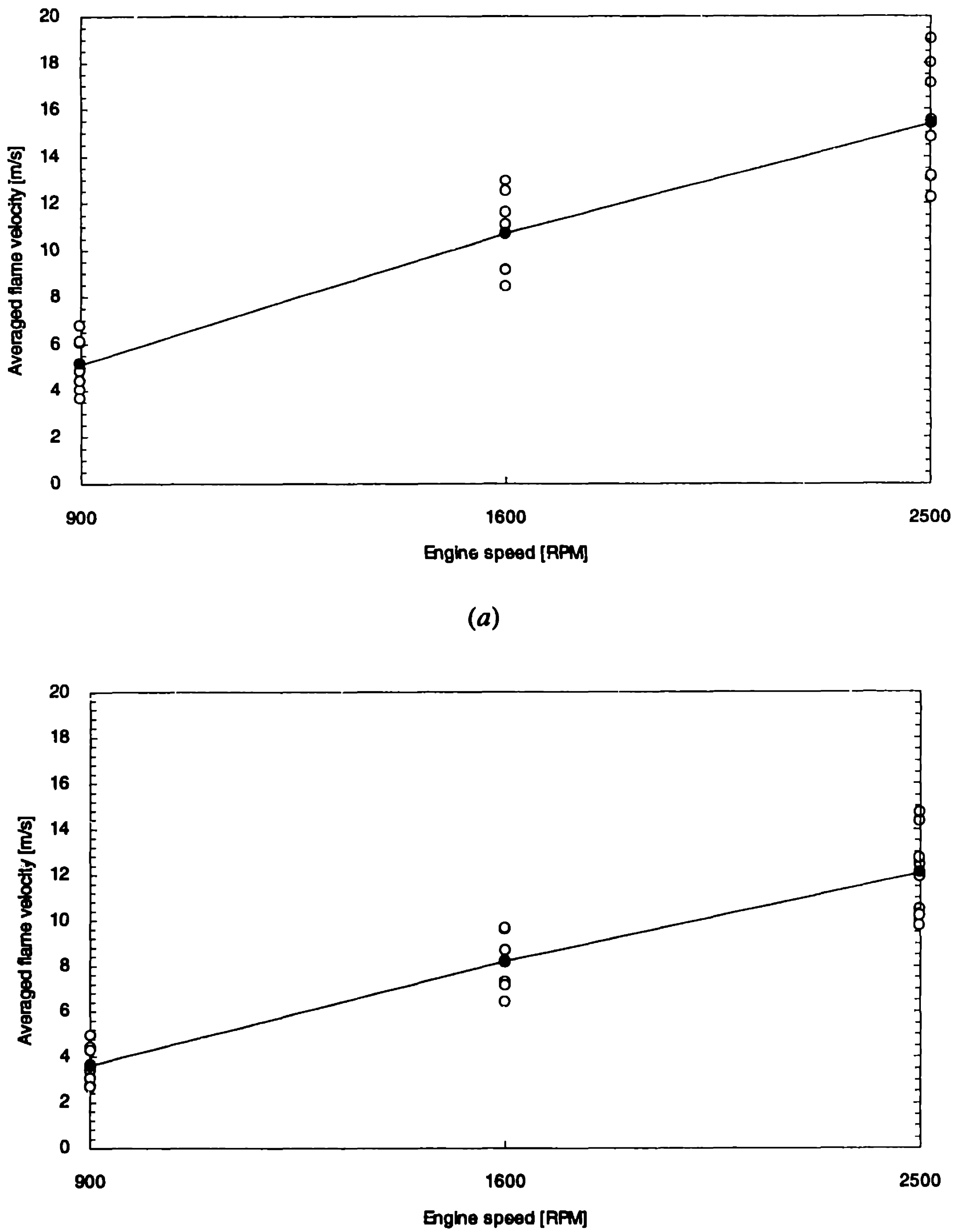


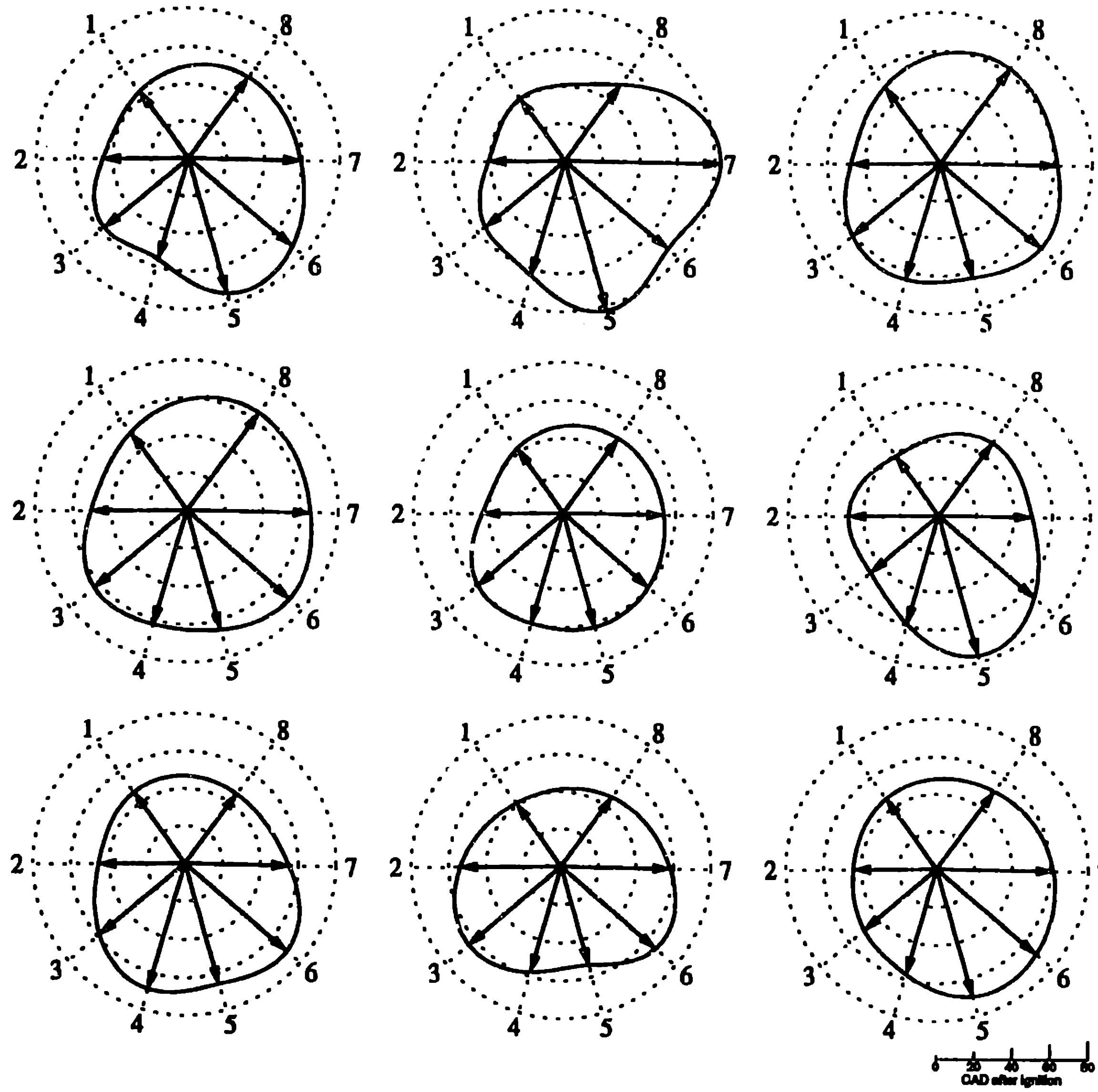
Figure 5.7
Cycle-averaged flame arrival times for the six experimental cases. Note that probe number 1 is located the same distance from the spark plug as probe number 8. The same applies to probes 2 and 7, 3 and 6, and 4 and 5.



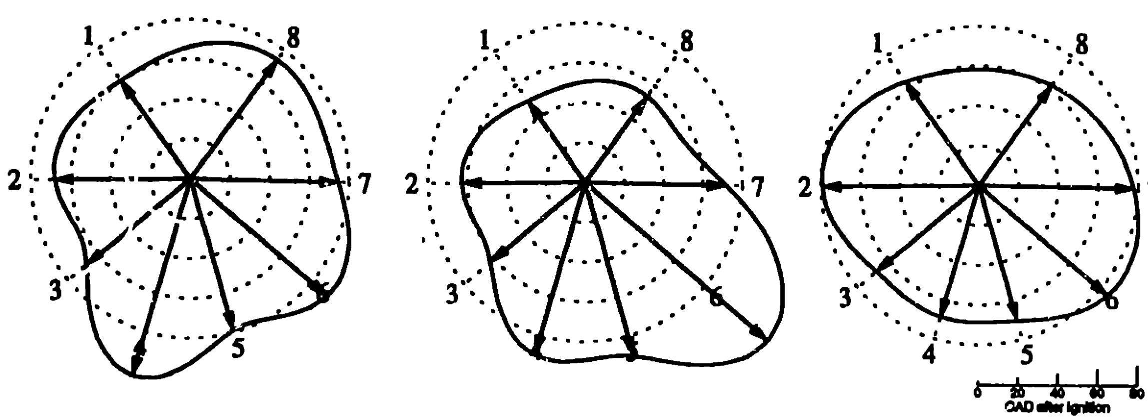
(*a*)

(*b*)

Figure 5.8
Averaged flame velocities plotted against engine speed. (a) λ = 1.00 and (b) λ = 1.25. Open markers in the figures represent cycle-averaged results from the each of the eight ionization probe electrodes, while solid markers represent the averages of those results.



(*a*)



(*b*)

Figure 5.9
Individual cycle plots from the 1600 RPM lean case. (*a*) Randomly selected cycles and (*b*) low IMEP cycles.

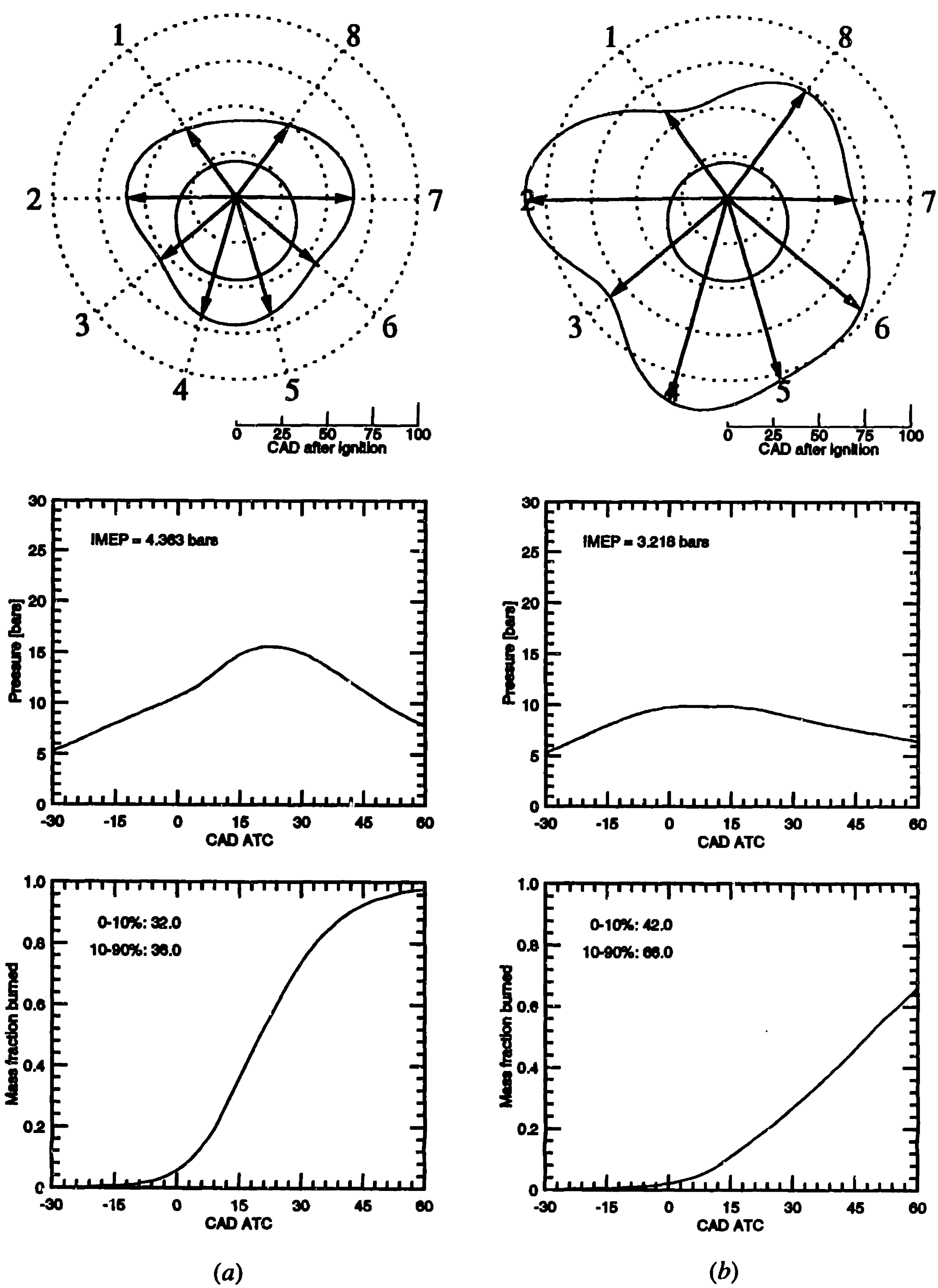


Figure 5.10
Individual cycle results from the 2500 RPM lean case. (a) Cycle with an IMEP equal to the cycle-averaged value and (b) a low IMEP cycle.

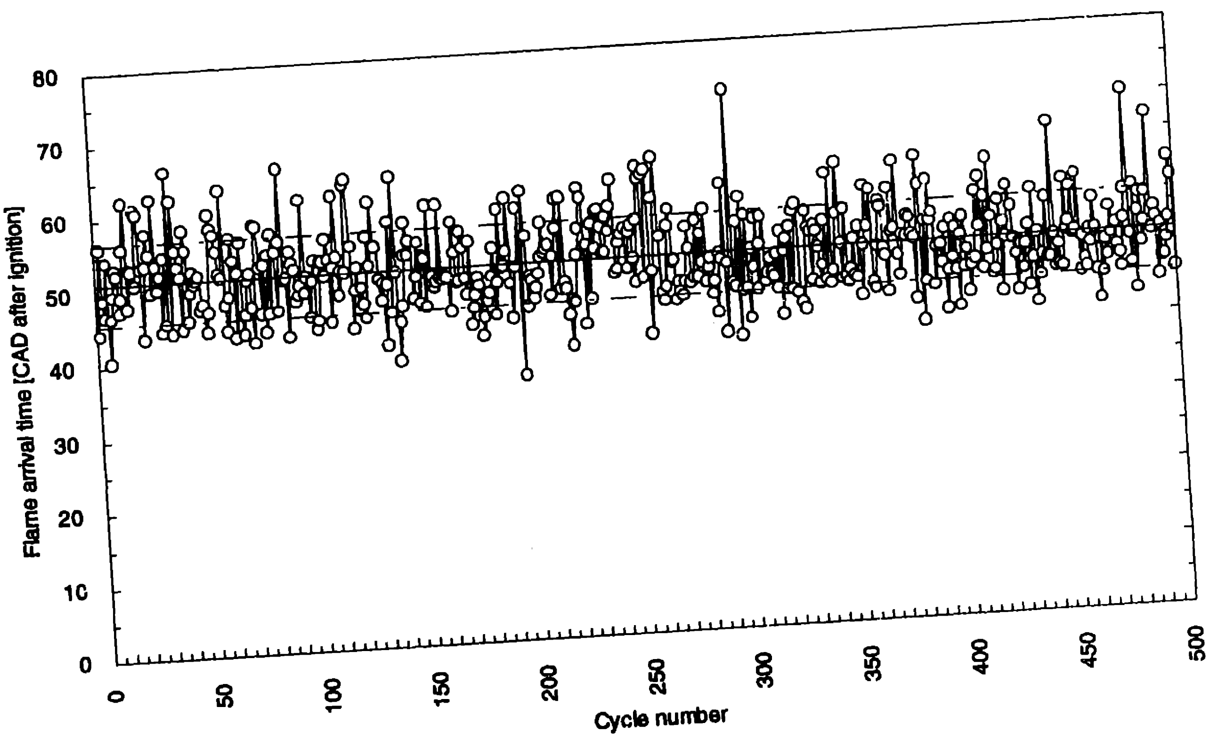
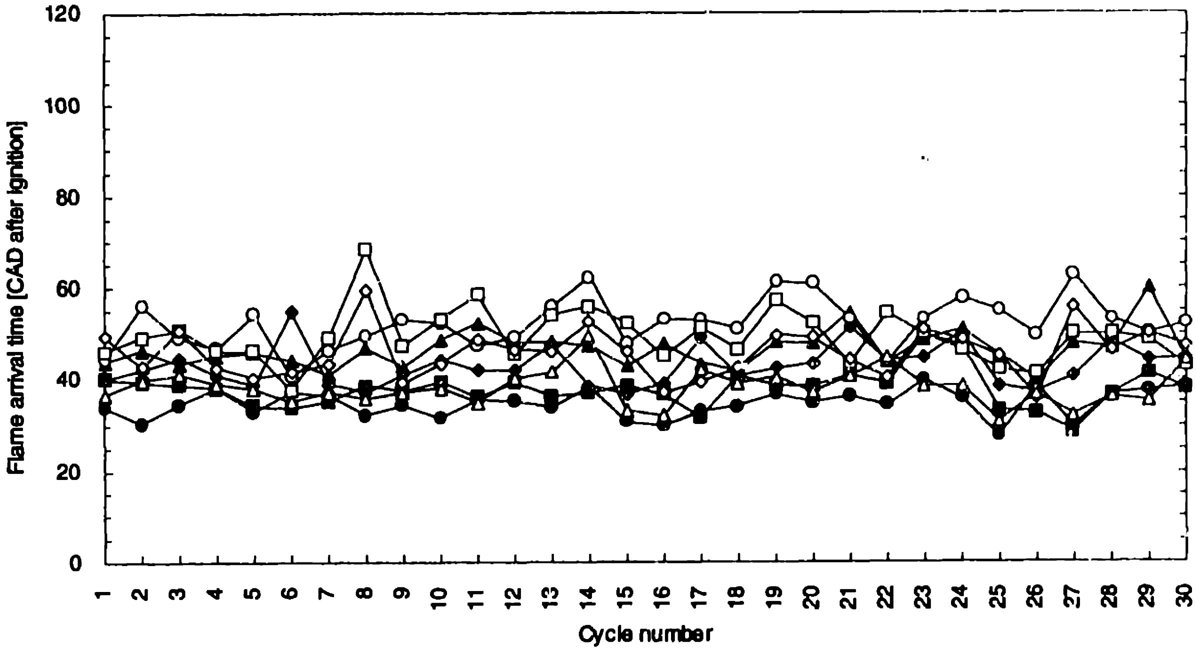
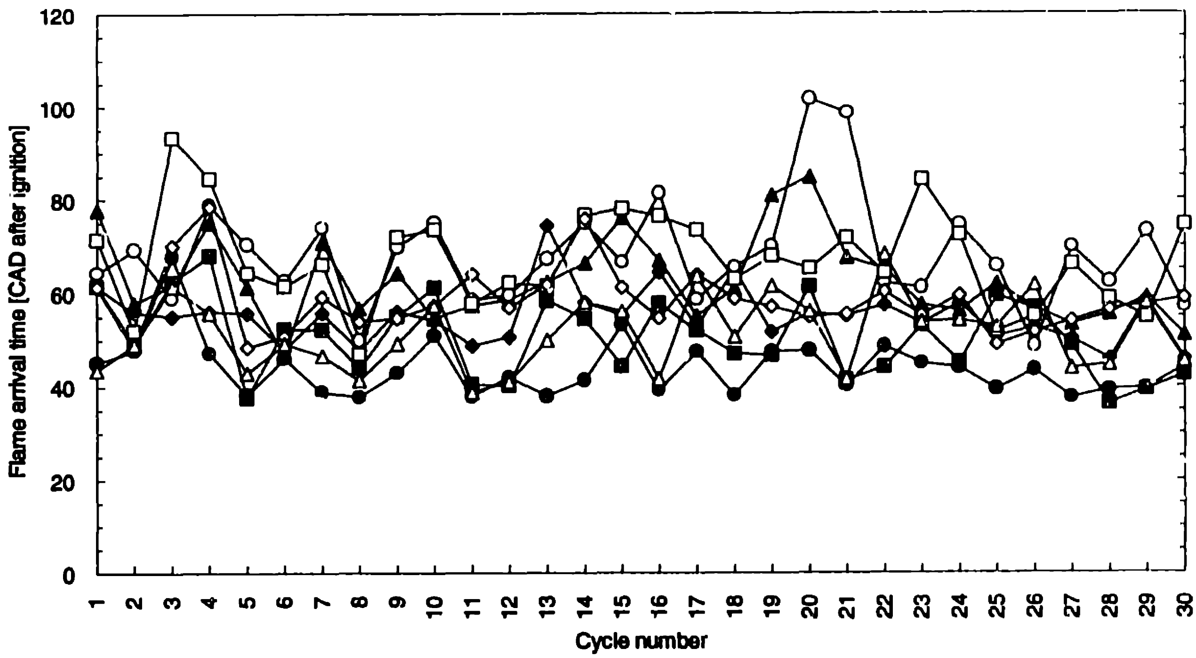


Figure 5.11
Sequence of flame arrival times for probe number 5 at the 1600 RPM stoichiometric condition. A solid line is drawn at the average value with dot-dashed lines representing the average plus and minus one sample standard deviation.



(*a*)



(*b*)

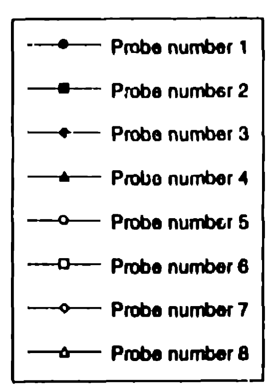


Figure 5.12
Flame arrival times for all eight ionization probes during cycles 1 through 30. (a) 1600 RPM stoichiometric and (b) 1600 RPM lean.

PART II

POLICY CONSIDERATIONS AND RECOMMENDATIONS

CHAPTER 6: FUEL ECONOMY AND EMISSIONS CONTROL TECHNOLOGIES

Experimental work has demonstrated that the head gasket ionization probe can reveal important details regarding the combustion processes which occur inside an automobile engine. The diagnostic, along with numerous other technology advancements, will likely play a crucial role in allowing automotive manufacturers to achieve further improvements in fuel efficiency and emissions controls. Yet one prominent question which arises focuses on the extent to which these vehicle characteristics can be improved. In fact, information regarding "technically feasible" levels of fuel economy or emissions reductions are especially important to policy makers who must determine how far future legislation should force automotive technology. This chapter addresses this issue by presenting an overview of potential technology improvements, along with a discussion of their anticipated benefits. Particular focus will also be given to those areas in which the head gasket ionization probe may find use.

6.1 FUEL ECONOMY

6.1.1 Available Technologies

In 1992, a committee of the National Research Council conducted a study concerning the prospects for increasing the fuel economy levels of automobiles and light trucks [20]. Table 6.1 outlines the technologies which were identified in their report as important factors in fuel economy. They cover a wide range of areas which include engine

Table 6.1
Fuel economy technologies for automobiles and light trucks. [20]

Proven technologies	Proven technologies (continued)
Engine technologies	Accessories
Roller cam followers	Accessories
General friction reduction	Electric power steering
Deceleration fuel restriction	
Compression ratio increase	Rolling resistance
Throttle-body fuel injection	Advanced tires
Multipoint fuel injection	
Overhead camshaft	Inertia
Four valves/cylinder	Weight reduction
Variable valve timing	Front-wheel drive
Four-cylinder engines	
Six-cylinder engines	Aerodynamic drag
Advanced lubricants	Aerodynamics
Turbo/supercharging*	
Diesel†	
Transmission technologies	
Torque converter lockup	Emerging technologies
Electronic control	
Four-speed automatic	Lean-burn engine
Five-speed automatic	Two-stroke engine
Continuously variable transmission	Active noise control
Five-speed manual	Lean NO_x catalyst

* Currently used primarily to enhance performance
† Light trucks only

technologies, transmission technologies, accessories, rolling resistance, inertia, and aerodynamic drag.

In broader terms, these technologies can be separated by their focus on one of two separate goals: 1) increasing the energy conversion efficiency of the fuel, or 2) reducing the loads place on the engine during the driving cycle. It should be noted that within the first category are the areas where the head gasket ionization probe can contribute. For instance, by providing insight into the combustion process, and especially into the phenomenon of knocking, the diagnostic would aid in the design of production automobile engines with increased compression ratios. Furthermore, contributions might be made towards developing lean-burn engines, which run at relative air-fuel ratios slightly lean of stoichiometric. Effects of other changes in engine design, such as the implementation of variable valve timings or of additional valves per cylinder, also invite investigation with the head gasket ionization probe.

Within a separate category of fuel economy strategies are those which concentrate upon reducing engine driving loads. They focus on facilitating a better transfer of power to the wheels through transmission improvements, or on reducing excessive loads which are needed to drive accessories or to overcome rolling, inertial, and aerodynamic resistances. Although these areas will not be directly influenced by the use of ionization probes, they remain important technologies which should be addressed in the attempt to design more fuel efficient automobiles.

6.1.2 Potential Benefits

The extent to which the technologies of Table 6.1 can improve vehicle fuel economy is inherently uncertain. However, since legislative standards can be formulated based largely upon such information, much effort has gone into developing estimates which are as accurate as possible. Table 6.2 summarizes some specific percentage improvement figures which result from studies conducted by both the automotive industry

Table 6.2

Estimates of fuel economy improvement potential of various technologies. All values in percent. [20]

Technology	Baseline	EEA	SRI	BSA	Ford	GM	Chrysler	Toyota	Honda	Nissan	Mitsubishi
Engine technologies											
General											
Roller cam followers	Flat followers	2.0	1.7	0.3	3.0	1.5	2.4	0.8	1.0	1.4	1.3
Friction reduction, -10%	Base 1987	2.0	2.0		2.0	1.0	0.5	0.8	1.0	1.4	
Accessory improvement	Conventional	0.5	0.7		0.7	0.0	1.4	0.5		0.2	0.8
Deceleration fuel restriction	None	1.0	1.0		1.0						
Compression ratio increase, +0.5	9:1 (EEA 4-V only)	*	2.0		1.5	1.0		1.3			1.0
Fuel systems											
Throttle-body fuel injection	Carburetor	3.0	2.6	3.0	3.0	2.5	3.4	0.8	1.0	3.3	
Multipoint fuel injection	Carburetor	5.0†	4.6	3.1	6.0	1.0	4.9	2.5	3.5	4.3	
Valve train											
Overhead camshaft	Overhead valve	3.0	2.5	1.2	3.5	1.5	2.0		0.8	2.0	
4 valves per cylinder	2 valves	5.0	3.0	2.1	3.5	3.0	3.5	4.5	2.0	3.4	
Variable valve timing	Fixed timing	6.0	2.6		3.0	2.0	1.5	2.0	2.5‡	2.7	
Reduced number of cylinders											
4-cylinder	6-cylinder	3.0	0.0	1.2	-3.0	0.0	0.0	0.0	0.0	0.0	
6-cylinder	8-cylinder	3.0	1.0	-0.9	0.0	0.0	0.0	0.0	0.0	0.0	
Transmission technologies											
Torque converter lock-up	Open converter	3.0	2.0	2.8	2.0	3.0	3.0	2.5	3.0	3.2	
Electric transmission control	Hydraulic	0.5	0.5	0.5	0.5	0.0	0.5	0.5	0.5	0.6	
4-speed automatic	3-speed auto	4.5	2.8	2.9	3.0	4.0	2.0	2.3	1.8	3.0	
5-speed automatic	3-speed auto	7.0	3.3		5.0	4.5	3.0	3.5	3.3	4.0	
Continuously variable transmission	3-speed auto	8.0	4.8		5.5	4.5	3.0		3.8	5.5	
5-speed manual**	3-speed auto	8.0	4.8	0.0	5.5	0.0	0.0	0.0	0.0	0.0	
Rolling resistance, aerodynamics, and weight											
Front wheel drive	Rear wheel drive	10.0	0.5	0.8	1.0	0.0			1.1	3.0	
Aerodynamics	Base	2.3	2.4	2.7	2.0	3.1	2.0	2.0	1.5	1.2	1.7
Weight reduction, -10%	Base	6.6	5.0	9.1	5.5	8.0	5.0	5.5	5.0	6.0	
Electric power steering	Conventional	1.0	1.4		1.5	0.5	1.0	1.0	1.0	1.0	
Advanced tires, -10%	Base	1.0	1.0	0.6	1.0	0.5	0.5			1.0	1.0
Advance lubricants	Conventional	0.5	0.3		0.2			0.5	0.5		

* Fuel economy benefit for EEA incorporated into 4-valve engine

† Apportioned to account for incorporation of limited deceleration fuel restriction in multipoint fuel injection

‡ A savings as large as 12.5 percent can be inferred

** Fuel economy benefit assumed same as that of CVT over 3-speed automatic transmission as well as the U.S. Department of Energy and its contractors. While many of the technologies can indeed lead to incremental increases, it is apparent that no one measure is associated with a tremendous benefit in fuel economy. Such data should perhaps be anticipated, as the fuel efficiency characteristics of internal combustion engines have been undergoing continual refinements for many decades.

With regards to the technically feasible levels of fuel economy, studies have yielded widely varying results. For example, SRI International has projected a fleet averaged fuel economy level of 28.7 to 30 MPG in model year 2001 [21]. For that same model year, however, analysts at the American Council for an Energy Efficient Economy (ACEEE) argue that a goal of 45 MPG is attainable [22]. Yet most would agree that a MPG estimate in the low to mid 30's is appropriate. Estimates which are widely divergent from those values must therefore be viewed in the light of any political agendas which might have influenced them.

6.2 EMISSIONS CONTROL

6.2.1 Available Technologies

In terms engine design strategies, a certain degree of overlap exists between technologies which can improve automotive fuel economy and those that reduce engine-out emissions. This is because, given a fixed emissions rate per unit mass of fuel consumed, reducing the quantity of fuel used by an automobile will also contribute to reducing the emissions in the exhaust gas. There do exist certain instances in which fuel economy technologies may detrimentally affect CO and NO_x emissions, and thus engine designers must carefully investigate all the potential impacts of proposed design changes.

Table 6.3 outlines some of the areas which are known to be significant factors affecting the emissions of automobiles and light trucks. They are grouped into the

Table 6.3
Emission control strategies for spark ignition engines. [25]

Engine design measures	Exhaust gas aftertreatment
Fuel metering	Thermal afterburning
Mixture preparation	Catalytic afterburning
Uniform air and fuel distribution	Oxidation catalysts
Exhaust gas recirculation (EGR)	Reduction catalysts
Valve timing	Dual-bed catalyst system
Compression ratio	Three-way or selective catalyst
Combustion chamber design	
Ignition system design	
Crankcase ventilation/blowby	
Fuel evaporation	

categories of engine design measures and exhaust gas aftertreatment. Again, the head gasket ionization probe will find use in the areas which directly concern combustion and the emissions formations mechanisms inside the engine. One specific problem, that of engine behavior during cold start and cold idle conditions, is in fact the focus of an ongoing study at Southwest Research Institute which utilizes the head gasket ionization probe [23]. The subject is of particular interest to automotive manufacturers as approximately 80 percent of the emissions produced during the Federal Test Procedure (FTP) cycle can be attributed to the cold start segment [24].

Post combustion technologies, namely the introduction and continuing development of catalytic converters, must certainly not be overiooked in a summary of emissions control strategies. These devices, which are comprised of an active catalytic material enclosed in a vibration-proof and heat-insulated casing, can typically remove up to 90 percent of engine-out emissions when warmed up [26]. Catalytic converter technologies therefore play an essential role in reducing the quantities of HC, CO, and NO_x in the exhaust gas.

6.2.2 Potential Benefits

In order to comply with the 1990 Clean Air Act Amendments, as well as with the recent regulations imposed by the California Air Resources Board (Table 1.2), automotive manufacturers will need to further develop and utilize many of the technologies which are listed in Table 6.3. As is the case with fuel economy technologies, the incremental benefits associated with individual emissions control measures will be modest. Some experts predict that a combination of efforts in the areas of engine combustion, control systems, and exhaust aftertreatment may over the next decade lead to exhaust emissions reductions of a factor of two to three [27]. However, if in fact achievable, such improvements will often be accompanied by increasing design complexity and costs. For example, implementation of an electrically heated catalyst would, according to one estimate, add 40 pounds and cost $822 to $1045 per car [28]. While the emissions reductions associated with this technology would be substantial, more simple and cost-effective approaches should first be investigated and developed.

6.3 Summary and Discussion

Numerous technologies to improve vehicle fuel economy and reduce vehicle emissions have been discussed in this chapter. If implemented, these technologies could, by model year 2001, lead to fuel economy levels approximately 5 MPG higher than those of the current new car fleet. Furthermore, significant improvements in automotive emissions characteristics may also result as manufacturers actively pursue methods to meet impending standards. Yet while considerable improvements in both of these areas may be technically feasible, policy makers should recognize that the major developments will in many cases impose tremendous costs on both consumers and automotive manufacturers. In fact, if viewed in light of the benefits which have been achieved, many would contend that both the CAFE and emissions standards are ill-formulated mechanisms for achieving their intended societal goals. Consequently, additional methods for reducing petroleum dependence and the production of airborne pollutants should also be examined in the development of future legislation. Such approaches, which look beyond the regulation of automotive technology itself, will be the focus of discussion in the following chapter.

CHAPTER 7: ALTERNATIVE POLICY SOLUTIONS

As noted earlier, policies addressing the problems caused by automobile use have historically focused on technology based standards for the new vehicle fleet. If these policies are to be evaluated based upon the improvements which have resulted in automotive fuel economy and emissions controls, they might indeed be judged as a resounding success. However, if evaluated based upon their impact on U.S. petroleum consumption or upon the improvements realized in air quality, praise would be considerably more reserved. For instance, the National Research Council recently concluded that "despite the major regulatory and pollution control programs of the past 20 years, efforts to attain the National Ambient Air Quality Standard for ozone largely have failed" [29]. Such discouraging appraisals stem from the fact that increases in population, the vehicle fleet, and ultimately vehicle miles traveled have served to wipe out many of the strides made in automotive technology. Additional measures must therefore be examined to achieve the original goals of both the CAFE and emissions standards.

7.1 Overview of Policy Options

A wealth of options are in fact available to policy makers who must endeavor to meet society's overall transportation demands while minimizing the associated economic and social costs. Table 7.1, for instance, provides a list of important areas identified by Weiss and Heywood towards which future research might directed [30]. The options cover the wide variety of issues which can affect and shape the transportation sector's impact on both petroleum dependence and air quality in the United States. Naturally, individual policies cannot be all-encompassing and will focus on certain specifics. However, a thorough understanding of the interdependence of all these issues must exist if future legislation is to be adequately formulated.

Very recently, efforts to address transportation problems have indeed begun to extend beyond an emphasis on automotive technology standards. The 1990 Clean Air Act Amendments and the State of California, for instance, have imposed separate measures which require environmentally safer fuels to be introduced. In addition, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 provides a generous allocation of funds to further advance Intelligent Vehicle Highway Systems (IVHS), a development which promises to tackle many of the inefficiencies which exist in the transportation system. Yet the focus of these policies continues to concentrate upon technology as the means for curing societal ills. It is curious to note the avoidance of alternative approaches which can manage the demand of transportation services.

7.2 Market Incentives

One particular type of strategy which has been actively discussed is the use of market or pricing mechanisms to reduce the consumption of petroleum and curb the growth in vehicle miles traveled. With regards to the price of fuel, for instance, it has been well publicized that the cost of gasoline is considerably lower in the U.S. than in other industrialized nations. Figure 7.1 illustrates this difference, which results not from discrepancies in production costs but from dissimilarities in the levels of imposed taxes.

Table 7.1
Strategic options for meeting societal objectives in transportation. [30]

---

1. Modify or manage demand for transportation
    - 1.1 Encourage land-use planning to reduce transportation needs
        - 1.1.1 Shorten commuting distances
        - 1.1.2 Increase provision of local services
        - 1.1.3 Plan work/residential/service clusters that justify public transport
    - 1.2 Substitute communications services for transportation needs
        - 1.2.1 Encourage remote work (telecommuting)
        - 1.2.2 Encourage remote services (telebanking, teleshopping, teleteaching, etc.)
        - 1.2.3 Encourage remote business activity (teleconferencing)
    - 1.3 Reduce the desire for transportation services
        - 1.3.1 Make selected transportation alternatives expensive and/or inconvenient
        - 1.3.2 Encourage a travel-conservation ethic and human-powered options

2. Provide a larger share of transportation services to modes with higher efficiency or lower emissions
    - 2.1 Shift transportation services to modes with higher efficiency or lower emissions
        - 2.1.1 Shift services up the efficiency/emissions hierarchy: water, rail, highway, air
        - 2.1.2 Shift services into non-fossil modes
    - 2.2 Improve operating practices for given modes
        - 2.2.1 Increase load factors and backhauling
        - 2.2.2 Establish shortest routes and optimum speeds
        - 2.2.3 Implement procedures which promote improved in-use vehicle performance (e.g., inspection/maintenance programs, retirement of older vehicles)

3. Increase the inherent system energy efficiency, and/or decrease the inherent system energy-related emissions for all modes of transportation services
    - 3.1 Improve energy supply systems (from resource to vehicle tank or motor)
        - 3.1.1 Recover, refine, and transport fuels with lower consumption of fossil resources
        - 3.1.2 Provide fuels that burn with lower emissions
        - 3.1.3 Provide a larger share of fuels from lower-carbon fossil resources
        - 3.1.4 Provide transportation energy from non-fossil resources
    - 3.2 Improve vehicle technology (reduced vehicle emissions and increased conversion of consumed energy to motion)
        - 3.2.1 More effective and durable emissions control systems
        - 3.2.2 Increase efficiency of conventional types of propulsion systems, petroleum-based and alternative fuels
        - 3.2.3 Reduce vehicle weight, improve vehicle aerodynamics and rolling friction
        - 3.2.4 Introduce alternative propulsion systems (e.g., electric, fuel-cell-based) which reduce environmental impact

---

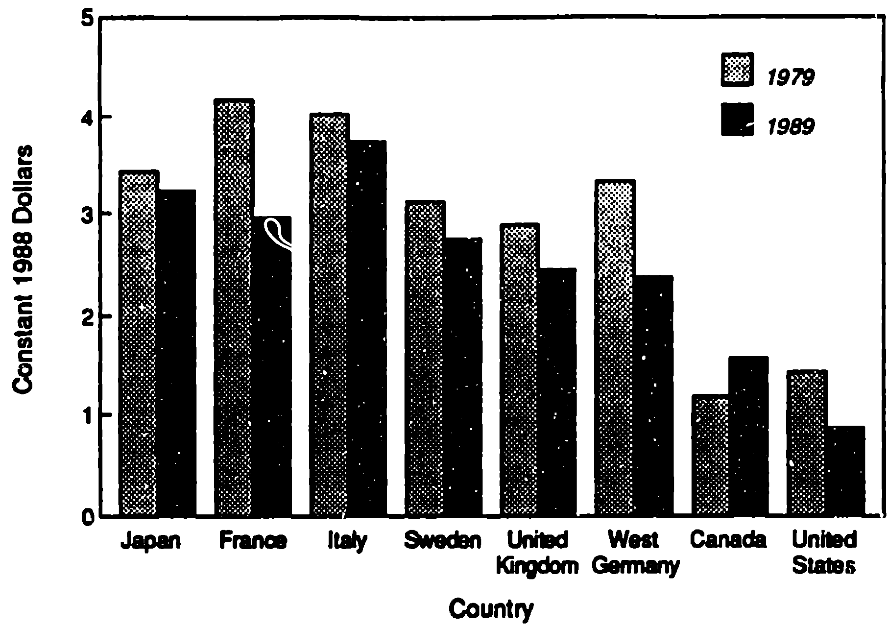


Figure 7.1
Gasoline prices for selected countries in 1979 and 1989. [33]

Since observations have indicated that the higher fuel prices have been absorbed in other nations without significant adverse effects, a similar pricing strategy for the United States warrants serious consideration. Studies to precisely determine the relation of fuel pricing to the CAFE standards have yielded varying results. Crandall et al. have argued that the miles per gallon characteristics of automobiles are the natural response to the price of fuel in the market [31]. Others, such as Greene, feel that fuel pricing strategies have less prominent of an effect compared to the fuel economy standards [32]. However, few would argue against the general notion that an increase in gasoline prices would tend to reduce petroleum consumption and help to better align consumer behavior with overall societal goals.

Rebates for more fuel efficient or reduced emission vehicles exists as another market-based strategy for forwarding environmental objectives. If combined with fees on gas-guzzling or high-polluting vehicles, a policy could be implemented that would be, on the whole, revenue neutral. Developing the precise structure of the rebates and fees would of course require significant analysis. Yet if properly designed, such an approach could emerge as an important addition to both the CAFE and emissions regulations.

While such market incentives would indeed carry significant benefits and would be relatively easy to implement, disadvantages can also emerge. Beyond the predictable outcries against market interference, equity problems such as the regressive nature of a gasoline tax do exist. Furthermore, pricing strategies which increase the costs of transportation may have the unintended effect of discouraging the retirement of older cars, which tend to possess low fuel efficiencies and inadequate emissions controls. Programs to provide subsidies for low income individuals or to set up incentives to replace older vehicles could be implemented to address much of the criticism. However, it is questionable whether the political hurdles and public opposition which tend accompany these market-based policy proposals can ultimately be overcome.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

In addressing U.S. transportation needs in the face of national and societal goals, legislative solutions have been seen to focus primarily on technology forcing measures. CAFE standards emerged in 1978 to increase automotive fuel efficiency and limit the nation's dependence on foreign oil, and vehicle emissions limits were likewise enacted to combat the persistent problem of urban air pollution. While the standards have indeed influenced the pace of automotive technology, future advancements will likely be associated with continually increasing design complexities and costs. Therefore, although substantial areas for improvements have indeed been identified for automotive fuel efficiency and emissions characteristics, it should be questioned whether policies to force changes which are technically feasible are at the same time practically sound.

Moreover, despite tightening automobile regulations, evidence has indicated that the emphasis on standards has largely failed to reduce the nation's aggregate petroleum consumption or to significantly improve ambient air quality. Mounting concerns about greenhouse gases, notably CO_2, serve to further sound the alarm. In order to effectively tackle all of these difficult problems, policy makers must look towards additional means to supplement existing legislative efforts. A wealth of options have been identified in Chapter 7, and the several market incentives specifically discussed should be seriously considered in designing future policy solutions. Unfortunately, Congressional members have typically been unwilling to direct such an influence on the behavior of their constituents, as the American public is uniquely demanding with regard to their attachment to personal freedom and mobility. While many may support the overriding societal objectives, individuals tend to view their contribution to petroleum dependence and air pollution as insignificant, and are thus unwilling to pay the costs — whether in the form of increased taxes or in modifications to their behavior — of mitigating the problems. As a result, it has been politically easier to place the burden of environmental protection and petroleum conservation on a few large car manufactures than to require a contribution from the population as a whole. Yet if such societal goals are indeed desirable, policy makers must attempt to consider the more difficult options in creating an effective federal strategy for dealing with the problems caused by automobile use in the United States.

REFERENCES

1. U.S. Department of Energy, Energy Information Administration. *Annual Energy Outlook,* Washington D.C., 1991.

2. U.S. Bureau of the Census. *Statistical Abstract of the United States,* Washington D.C., 1992.

3. Fox, J., J. Heywood, and G. McRae. "Aggregate Vehicle Emissions Estimates for Evaluating Control Strategies," SAE Paper 940303, 1994.

4. Chen, C. and A. Veshagh. "A Refinement of Flame Propagation Combustion Model for Spark-Ignition Engines," SAE Paper 920679, 1992.

5. Min, K. "The Effects of Crevices on the Engine-Out Hydrocarbon Emissions in Spark Ignition Engines," Ph.D. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1994.

6. Schnauffer, K. "Engine-Cylinder Flame-Propagation Studied by New Methods," SAE Transactions, Vol. 34, 1934.

7. Müller, K., E. Linder, and H. Maurer. U.S. Patent 4,393,687, 1983.

8. Witze, P. "Cycle-Resolved Multipoint Ionization Probe Measurements in a Spark Ignition Engine," SAE Paper 892099, 1989.

9. Witze, P. and S. Bopp. "Investigation of In-cylinder Fluid Motion Using a Head Gasket Instrumented with Ionization Probes," SAE Paper 910719, 1991.

10. Nicholson, D. and P. Witze. "Flame Location Measurements in a Production Engine Using Ionization Probes Embodied in a Printed-Circuit-Board Head Gasket," SAE Paper 930390, 1993.

11. Stenderowitcz, M. "Mixture Nonuniformity and Combustion Variability in Spark Ignition Engines," Ph.D. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1989.

12. Fox, J. "Effects of Fuel Injection Strategy on HC Emissions During SI Engine Start-Up," S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1992.

13. Witze, P., M. Hall, and J. Wallace. "Fiber-Optic Instrumented Spark Plug for Measuring Early Flame Development in Spark Ignition Engines," SAE Paper 881638, 1988.

14. Bianco, Y., W. Cheng, and J. Heywood. "The Effects of Initial Flame Kernel Conditions on Flame Development in SI Engine," SAE Paper 912402, 1991.

15. Gutowski, J., E. Balles, K. Chun, F. Nelson, J. Ekchian and J. Heywood. "Heat Release Analysis of Engine Pressure Data," SAE Paper 841359, 1984.

16. Cheung, H. "A Practical Burn Rate Analysis for Use in Engine Development and Design," S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1993.

17. Rassweiler, G. and L. Withrow. "Motion Pictures of Engine Flames Correlated with Pressure Cards," SAE Transactions, Vol. 83, 1938.

18. Metghalchi, M., and Keck, J. "Laminar Burning Velocity of Propane-Air Mixtures at High Temperature and Pressure," *Combustion Flame*, vol. 38, pp. 143-154, 1980.

19. Taylor, C. *The Internal Combustion Engine in Theory and Practice, Volume 2: Combustion, Fuels, Materials, Design*, MIT Press, Cambridge, 1968.

20. National Research Council, Committee on Fuel Economy of Automobiles and Light Trucks. *Automotive Fuel Economy: How Far Should We Go?*, National Academy Press, Washington D.C., 1992.

21. SRI International. *Potential for Improved Fuel Economy in Passenger Cars and Light Trucks,* Prepared for Motor Vehicle Manufacturers Association, Menlo Park, 1991.

22. Chandler, W., H. Geller, and M. Ledbetter. *Energy Efficiency: A New Agenda,* American Council for an Energy-Efficient Economy, Washington, D.C., 1988.

23. Meyer, R., J. Kubesh, and S. Shahed. "Simultaneous Application of Optical Spark Plug Probe and Head Gasket Ionization Probe to a Production Engine," SAE Paper 930464, 1993.

24. Gallopoulos, N., "Bridging the Present to the Future in Personal Transportation - The Role of the Internal Combustion Engine," SAE Paper 920721, 1992.

25. Adler, U., ed. *Bosch Automotive Handbook,* Robert Bosch GmbH, Stuttgart, 1986.

26. Heywood, J. *Internal Combustion Engine Fundamentals,* McGraw-Hill, Inc., New York, 1988.

27. Calvert, J., J. Heywood, R. Sawyer, and J. Seinfeld. "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions," *Science,* Vol. 261, July 2, 1993.

28. The Automotive Consulting Group, Inc. *The Electrically Heated Catalyst: A "Systems" Cost Analysis,* 1991.

29. National Research Council, *Rethinking the Ozone Problem in Urban and Regional Air Pollution,* National Academy Press, Washington, D.C., 1991.

30. Weiss, M. and J. Heywood. "Energy and the Environment: A Framework for Evaluating Research Needs in the Transportation Sector," Proceedings of the Conference, Energy and the Environment in the 21st Century, held at the Massachusetts Institute of Technology, March 26-28, 1990.

31. Crandall, R., H. Gruenspecht, T. Keeler, and L. Lave. *Regulating the Automobile,* The Brookings Institution, Washington D.C., 1986.

32. Greene, D. "CAFE or Price?: An Analysis of the Effects of Federal Fuel Economy Regulations and Gasoline Price on New Car MPG, 1978-89," *The Energy Journal,* Vol. 11, July 1990.

33. Oak Ridge National Laboratory. *Transportation Energy Data Book, 11th ed.,* 1991.