COMBUSTION EFFICIENCY
IN INTERNAL COMBUSTION ENGINES

by

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ABSTRACT

Exhaust gas analysis can be used to determine combustion efficiencies and equivalence ratios in internal combustion engines. The exhaust emissions and combustion efficiencies are functions of the fuel-air mixture entering the engine. Plotting the combustion efficiency and the mole fractions of each of the exhaust constituents against the equivalence ratio will show their relationship to the equivalence ratio.

Exhaust gas data was collected by two methods. Experimental data was collected from a fully instrumented Ricardo Hydra MK III engine connected to a gas cart. The second method of data acquisition was research of work done previously by others in this area. The collection of data included results from both spark-ignition and diesel engines, and involved four different fuels. Graphical superposition of all results formed single curves, indicating that combustion efficiencies and exhaust emissions are functions only of the fuel-air mixtures, not of the engine or fuel type.

Thesis Supervisor: John B. Heywood

Title: Professor of Mechanical Engineering

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

CHAPTER ONE

INTRODUCTION

The combustion efficiency and exhaust emissions of an internal combustion engine are functions of the fuel-air mixture entering the combustion chamber. The combustion efficiency characteristics are known to be quite different for fuel-air mixtures of excess fuel and of excess air. Since most engines are normally operated in the range where there is just enough air to fully burn the fuel, or slightly more air than needed, the efficiency and emission characteristics in this operating range are well known. A study examining these characteristics over a very wide operating range, involving different fuel and engine types, would be beneficial in verifying the expected trends and in examining the dependence of these characteristics on fuel or engine type.

Exhaust gas data was collected both experimentally and through research of work done by others in this area. Combustion efficiencies and equivalence ratios are determined from exhaust gas analysis. The equivalence ratio is the ratio of the actual fuel-air ratio to the chemically correct fuel-air ratio. Combustion efficiencies and mole fractions of exhaust constituents are plotted against the equivalence ratio to show their characteristics over the range of the fuel-air mixture.

This work deals with three main areas. The first area is the theoretical analysis of the principles involved in determining combustion efficiencies and equivalence ratios from exhaust gas analysis. Second, the sources of data and the analysis methods are discussed. Third, analysis of the data and graphical representation of the results are presented and discussed.

CHAPTER TWO

THEORETICAL BACKGROUND

The equivalence ratio, ϕ, is defined as the actual fuel-air ratio entering a combustion chamber divided by the stoichiometric fuel-air ratio, the stoichiometric ratio being the case where there is just enough air to fully burn the fuel.

$$\phi = \frac{(F/A)_{ACTUAL}}{(F/A)_{STOICH.}}$$

The equivalence ratio is useful in showing that for the case of the equivalence ratio being greater than one, rich operation, and that in the case of the equivalence ratio being less than one, lean operation, the combustion products have substantially different composition. This is because the two cases have excess fuel and excess air, respectively.

The equivalence ratio can be found by two methods; by measuring the air and fuel flow rates into the engine and calculating the metered equivalence ratio, ϕ_m, and by analyzing the exhaust gas and calculating the exhaust equivalence ratio, ϕ_e. Theoretically, if no error is introduced in the flow rate measurements and the exhaust gas analysis, the metered equivalence ratio should be equal to the exhaust equivalence ratio.

2.1 METERED EQUIVALENCE RATIO

In order to find the metered equivalence ratio, one must measure the fuel and air flow rates into the engine. The actual fuel-air ratio is the ratio of the mass flow rates of the fuel to the air.

The stoichiometric fuel-air ratio is a function of the hydrogen to carbon ratio in a molecule of the fuel used. This ratio can be found from an element balance for carbon and oxygen and is given as:

$$(\dot{m}_A/\dot{m}_F)_s = (A/F)_s = (F/A)_s^{-1}$$

$$= (1 + y/4)(32 + 3.773x28.16)/(12.011 + 1.008y)$$

$$= 34.56(4 + y)/(12.011 + 1.008y)$$

In this equation, y is the hydrogen to carbon ratio, 32 is the molecular weight of oxygen, 28.16 is the molecular weight of atmospheric nitrogen, 12.011 is the molecular weight of atomic carbon, and 1.008 is the molecular weight of atomic hydrogen.[1]

In order to determine the metered equivalence ratio, therefore, three things are needed: the mass flow rate of the fuel, the mass flow rate of the air, and the hydrogen to carbon ratio of the fuel being used. From this information, the metered equivalence ratio is found:

$$\phi_m = \frac{(\dot{m}_F/\dot{m}_A)_{ACTUAL}}{(\dot{m}_F/\dot{m}_A)_{STOICH.}}$$

2.2 EXHAUST EQUIVALENCE RATIO

The exhaust equivalence ratio is found through exhaust gas analysis. Mole fractions of hydrocarbons, carbon monoxide, carbon dioxide, oxygen, and nitrogen oxides are measured in the exhaust gas. The various components of the exhaust gas are measured in percent or parts per million (ppm), then converted to mole fractions. The hydrocarbon measurement is on a wet mole fraction basis (i.e. water vapor present in the exhaust gas), each of the others measured dry (i.e. no water vapor present). This information, along with the number of oxygen molecules needed for complete combustion, is used to compute the exhaust equivalence ratio, ϕ_e, as follows:

$$\phi_e = 2(n_{O_2})/(n_p(x_{H_2O}(1 - x^*_{CO} - 2x^*_{CO_2} - 2x^*_{O_2} - x^*_{NO}) + (x^*_{CO} + 2x^*_{CO_2} + 2x^*_{O_2} + x^*_{NO})))$$

In this equation, x_i is the wet mole fraction of the component i, x^*_i is the dry mole fraction of the component i, n_p is the total number of moles of exhaust products, and n_{O_2} is the number of oxygen molecules needed for complete combustion.[2]

In practice, the above equation is implemented in a different manner. The concentrations of the exhaust components are used to calculate the air-fuel ratio. The inverse of this is divided by the stoichiometric fuel-air ratio to find the exhaust equivalence ratio in the same manner that the metered equivalence ratio is found. The air-fuel ratio is found from exhaust gas analysis as follows:

$$A/F = \frac{f}{f + (HC)_w} \left[\frac{9.67(1 + .5b + g)}{1 + b} + \frac{19.06}{3.5 + b} \right]$$

where:

$()$ = dry concentration

$()_w$ = wet concentration

$a = (CO) + (CO_2)$

$b = (CO)/(CO_2)$

$c = 0.258b + 0.888$

$d = H_2O = \frac{a}{c + a}$

$e = 1 - d$

$f = a \times e$

$g = (O_2)/(CO_2)$

The exhaust equivalence ratio is obtained by dividing $(A/F)_s$ by (A/F).[1]

2.3 COMBUSTION EFFICIENCY

The combustion efficiency, η_c, is the fraction of the chemical energy supplied by the fuel which is released in the combustion process. It is found by computing the combustion inefficiency (energy not released) from the energy in the combustible constituents of the exhaust, and subtracting from 1. The inefficiency is the ratio of the energy flow out of the combustion chamber to the energy flow in, as shown below:

$$\text{Combustion Inefficiency} = 1 - \eta_c$$

$$= \frac{\dot{m}_{HC} Q_{HV(HC)} + \dot{m}_{CO} Q_{HV(CO)} + m_{H_2} Q_{HV(H_2)}}{\dot{m}_F Q_{HV(F)}}$$

In this equation, $\dot{m}_i$ is the mass flow rate of the constituent i (F is the fuel), and $Q_{HV(i)}$ is the lower heating value of i.[1]

CHAPTER THREE

DATA ACQUISITION AND REDUCTION

Exhaust gas data was acquired from a variety of sources. Much of the data was collected experimentally by myself and other students in the Sloan Automotive Laboratory at M.I.T. Additional data was collected through research of past work done by others in this area of study. The data was subsequently grouped by fuel type.

The Sloan Laboratory computer system was used for the reduction of all exhaust data. A program called Acart was used to compute equivalence ratios and combustion efficiencies from the data. Since the program required information on the mass flow rates of the fuel and air entering the engine, both exhaust equivalence ratios and measured equivalence ratios were calculated. In addition to this information, the mole fractions of the various exhaust constituents were printed out.

The results given by Acart were entered into data files in the form of combustion efficiency versus exhaust equivalence ratio or mole fraction of (constituent) versus exhaust equivalence ratio. These data files were used in conjunction with a second program, called Pointplot (pntplt), which graphically represented the data through the use of computer plotting and a laser printer.

3.1 INDOLENE

All data for Indolene fuel (H/C = 1.69) was collected experimentally in the Sloan Automotive Laboratory. A fully instrumented Ricardo Hydra MK III single cylinder spark-ignition engine was used in conjunction with a gas cart in order to collect exhaust gas data. The gas cart showed readings for exhaust by-products. The hydrocarbons were given on a wet basis, in parts per million (ppm). The readings for carbon monoxide, carbon dioxide, and oxygen were given on a dry basis, in percent. The nitrogen oxides were also given dry, but on a parts-per-million scale. The mass flow rates of the fuel and air entering the engine were metered. This information was fed into Acart and Pointplot for data reduction and representation.

Previous to my own experiments, exhaust gas data had been collected from this engine by two M.I.T. graduate students, Kwang-Min Chun and Fred Nelson. Their data, made available for my use, was focused around the stoichiometric equivalence ratio ($\phi_e = 1$). My own data included a much wider range of equivalence ratio values.

In my own experiments, the main objective was to collect exhaust gas data over as wide a range of the equivalence ratio as possible. The engine was run at a moderate speed, 2500 rpm at wide open throttle. Data was collected over a range of equivalence ratios from 0.65 to 1.15. The same procedure was followed with the engine at half throttle (air-flow reduced by fifty percent). Under these conditions, data was collected over a range of equivalence ratios from 0.88 to 1.17. In all, data was taken at fifteen operating points. All data was entered into the Acart program for combustion efficiency and equivalence ratio computations. Additional details of the experimental set-up can be found in Nelson's work.[3]

3.2 ISO-OCTANE

Exhaust gas data for iso-octane fuel (H/C=2.25) was collected from three sources. One major source was documentation of work done by Donald L. Stivender of General Motors' Research Labs.[4] His work, given in two tables of data, gave dry exhaust concentrations of hydrocarbons, carbon monoxide, carbon dioxide, and oxygen, as well as the measured air-fuel ratio. In order to use his data in the Sloan Lab Acart program, some revisions had to be made.

Stivender's hydrocarbons were given in terms of dry hexane; Acart uses hydrocarbons on a wet "per carbon atom" basis. In order to be usable data, the hydrocarbon values were multiplied by six to reduce the data from C_6 to C_1. In order to change from a dry to a wet basis, his hydrocarbons were also multiplied by 0.89. This value was used because it was an average of the values of the ratio of wet mole fraction HC to dry mole fraction HC in the data that I had experimentally collected. In effect, Stivender's hydrocarbon values were multiplied by 5.34 to fit our computer program.

The second problem with Stivender's data was that it lacked information on the nitrogen oxide emissions. Since the nitrogen oxide had no effect on the combustion efficiency and very little effect on the exhaust equivalence ratio, the value of zero was used when entering this data in Acart.

These two revisions to Stivender's data allowed the use of the Acart program to calculate the combustion efficiency and both the metered and the exhaust equivalence ratios.

A discrepancy arose with Stivender's first table of data. The information stated that the fuel was Indolene-30. The hydrogen-carbon ratio was given as 2.25, however, the same as iso-octane. Since the hydrogen-carbon ratio is a crucial part of the equivalence ratio calculation, this fuel was grouped with the iso-octane fuel data.

Another source of iso-octane exhaust gas data was work done by R. S. Spindt of Gulf Research and Development Co.[5] His work gave dry exhaust concentrations of hydrocarbons, carbon monoxide, carbon dioxide and oxygen by percent. Again, the lack of nitrogen oxide data was overcome by using the value of zero.

The hydrocarbon data, given on a dry "per carbon atom" basis, needed only to be multiplied by 0.89 to convert to a wet basis and to be converted from percent to parts-per-million in order to become usable data. These revisions again allowed the use of the Acart program for data reduction and computation.

Since Spindt's work had been referenced by Stivender, it does not appear separately, but is included in Stivender's data.

The third source of exhaust gas data for iso-octane fuel was work done by J. A. Harrington and R. C. Shishu of Ford Motor Co.[6] Their work showed graphically the variation of exhaust emissions with the air-fuel ratio. Carbon monoxide, carbon dioxide and oxygen emissions were given as percents, while the hydrocarbons and nitrogen oxides were given in parts-per-million. All emissions were shown on a dry basis.

To use this data in the Acart program, the values of each emission were taken from the graph at a given air-fuel ratio. The hydrocarbons, given in terms of hexane, were multiplied by 5.34 to convert to a wet "per carbon atom" basis as Stivender's data had been. The revised data was fed into Acart for data reduction.

3.3 TEST FUEL

Harrington and Shishu's work also included data from a standard test fuel (H/C=2.01). Since the data was given in the same format as their iso-octane data, it was revised and used in the same manner.

3.4 DIESEL FUEL

Exhaust gas data from diesel fuel was taken from two sources, a paper by E. D. Petrow and others from Drexel University,[7] and from a United States Department of Energy report.[8]

Petrow's work included emissions data for oxygen, carbon dioxide, and carbon monoxide on a dry basis and hydrocarbons on a wet basis. The data was from a single-cylinder test engine and was given graphically as a function of the air-fuel ratio. Since the hydrocarbon values were given in terms of propane, they were multiplied by three to convert them to a per carbon atom basis. The value of zero was used for nitrogen oxide values, since no data was given. This revised data was used in Acart for data reduction and computation of combustion efficiency and equivalence ratios.

The other source of diesel emission data was a United States Department of Energy report on emissions characteristics of diesel engines. Six different four, five, and six cylinder engines were tested, representative of those commonly found in automobiles, light trucks, or marine use.

Exhaust composition for each of the six engines was shown for a given speed over a varying load range. Carbon dioxide data was given dry, as percent. Carbon monoxide and nitrogen oxides were given dry, as parts-per-million. The hydrocarbons were given wet, on a parts-per-million, per carbon basis, so no revision was necessary. What the report lacked was information on oxygen data, however, which is an important part of the calculations.

The solution to this problem was found in a report on diesel exhaust gas analysis by John C. Holtz and M. A. Elliott.[9] Their report showed graphically a chart of oxygen and carbon dioxide emissions from diesel fuel as a function of the air-fuel ratio. This chart was used to find the percentage of oxygen in the emissions that corresponded to a given percentage of carbon dioxide.

The Department of Energy report, in conjunction with the graph from Holtz and Elliott, provided data that was usable in the Acart program.

CHAPTER FOUR

ANALYSIS, RESULTS, DISCUSSION

4.1 SAMPLE SET OF GRAPHS

A sample set of the graphs produced from exhaust gas analysis is shown in figures 1 through 6. These plots were created using the data collected through my own experiments.

Figure 1 shows the agreement between the metered equivalence ratio and the exhaust equivalence ratio. Had no error been introduced, they would be equal. As the graph shows, they are within a few percent of each other, favorable agreement considering the error introduced.

Error in these values can most likely be attributed to error in reading the gages on the exhaust cart as well as the metered values of the flow rates of the fuel and air. Inexperience in using this equipment was probably an additional factor.

Figures 2 and 3 show the combustion efficiency plotted as a function of the metered equivalence ratio and the exhaust equivalence ratio. As they show, combustion efficiency is highest at slightly lean conditions. During rich engine operation, the combustion efficiency drops off. Since the mixture is oxygen deficient under these conditions, some of the fuel will not burn. As the equivalence ratio increases, greater amounts of fuel will not burn, thereby decreasing the combustion efficiency.

Under very lean conditions, the combustion efficiency also drops. Here, the mixture is too lean for stable combustion and won't burn easily enough. The combustion becomes more incomplete, increasing the inefficiency, thereby decreasing the combustion efficiency.

Figures 4 and 5 show the dry mole fractions of carbon monoxide, carbon dioxide, and oxygen in the exhaust emissions plotted as a function of the metered equivalence ratio and the exhaust equivalence ratio. The mole fraction of carbon dioxide rises with the equivalence ratio and peaks at just about the stoichiometric point, after which it begins to fall.

The mole fraction of oxygen is highest at lean conditions and falls as the equivalence ratio rises. At the stoichiometric point, the oxygen approaches zero and stays there. This is from the definition of the stoichiometric point. As the equivalence ratio increases past 1, there is not enough oxygen to burn all of the fuel, so theoretically all oxygen should be used up.

The mole fraction of carbon monoxide is very low under lean operating conditions and begins to rise after the stoichiometric point. This is also a result of greater amounts of unburned fuel as the equivalence ratio increases past the stoichiometric point.

The dry mole fraction of hydrocarbons, shown as a function of the exhaust equivalence ratio, is shown in figure 6. The hydrocarbons tend to increase with the equivalence ratio. Since the hydrocarbons are a major factor in the combustion efficiency, this suggests that higher fractions of hydrocarbons would correspond to lower combustion efficiencies.

The scatter found in all of these curves can again be attributed to error in reading the gages on the exhaust cart or in their calibration.

The sample set of graphs included plots as a function of the metered equivalence ratio only to show the agreement between the metered equivalence ratio and the exhaust equivalence ratio. Further data will be shown only in plots as a function of the equivalence ratio found through exhaust gas analysis.

4.2 M.I.T. INDOLENE

Figures 7 and 8 show data collected at M.I.T. using Indolene fuel in the Ricardo test engine. These figures give the same information as figures 3 and 5 in the sample set of data plots. In addition to my data, these figures show the data collected by Chun and Nelson. Since their data is shown over a very narrow range of equivalence ratios (focused around the stoichiometric point), it does not significantly add to the information shown in the plots of my data.

4.3 HARRINGTON AND SHISHU

Graphs of Harrington and Shishu's data are shown in figures 9 and 10. These graphs show results from two fuels, iso-octane (H/C=2.25), and a standard test fuel (H/C=2.01). The data follows the patterns established in the sample set of plots: combustion efficiency falls off just before the stoichiometric point, carbon dioxide emissions rise with the equivalence ratio to a peak at the stoichiometric point and then fall off, oxygen emissions fall as the equivalence ratio rises to stoichiometric, staying near zero from this point on, and the carbon monoxide emissions stay near zero until just before the stoichiometric point, rising with the equivalence ratio after this point.

An important observation of this data is that the curves are slightly shifted for the two fuels. Figure 9 clearly shows that for lean mixtures the combustion efficiency is slightly higher for the fuel with the higher hydrogen to carbon ratio, the iso-octane. Figure 10 shows that the emissions also differ in the two fuels. The carbon dioxide emissions are lower over the full range of the equivalence ratio, and the oxygen and carbon monoxide emissions are lower on the lean side of the stoichiometric point. The two graphs together suggest that a fuel with a higher hydrogen to carbon ratio will produce higher combustion efficiencies and lower exhaust emissions under slightly lean conditions.

4.4 ISO-OCTANE

Iso-octane data is shown graphically in figures 11 and 12. These figures include the iso-octane data from Harrington and Shishu that was just examined, as well as the data from Stivender. The combustion efficiency plot, figure 11, shows that the two sets of data follow the same curve. In the lean operating range, Harrington and Shishu's combustion efficiencies are slightly higher, but they are along the same curve during rich operation. The Harrington and Shishu data is not consistently above or below Stivender's, as it was in figure 9 with the two different fuels.

The same observation can be made about the emissions data shown in figure 12. Though some scatter is visible in the curves, both sets of data form a single curve for each of the emissions. The scattered points are not the result of a shift in the curve of one set of data.

In general, these two figures show that the combustion efficiency and exhaust emission characteristics do not vary significantly for different sources of data using a fuel with the same hydrogen to carbon ratio.

4.5 ALL SPARK-IGNITION ENGINE DATA

Figures 13 through 17 show the results of all data collected from spark-ignition engine exhaust gas analysis. Figures 13 through 15 show this data by fuel type, figures 16 and 17 show it broken down by source.

Figure 13 shows the combustion efficiency data. This graph shows that the highest efficiencies are reached at slightly lean conditions, where inefficiencies are in the range of 2 to 3 percent. Also, the highest efficiencies are those from the iso-octane fuel data.

Unusually low combustion efficiencies are shown for several points along the slightly lean range. If these points are compared to their respective points on the plot of figure 14, the hydrocarbon plot, it can be seen that they are points of high hydrocarbon emissions. The high hydrocarbons indicate poor combustion, leading to higher inefficiencies.

Examination of the hydrocarbon plot (figure 14) shows that the lowest hydrocarbon emissions are under slightly lean conditions, where the combustion efficiency is highest. In general, the hydrocarbons begin to increase just before the stoichiometric point and continue to rise as the equivalence ratio increases. This is reflected in the lower combustion efficiency under rich conditions. Under very lean conditions, where the mixture is too lean for stable combustion and the inefficiency is higher, the hydrocarbon emissions are also high.

The emissions data for carbon monoxide, carbon dioxide, and oxygen, broken down by fuel type, is shown in figure 15. Though there is quite a bit of scatter, the curves do not seem to shift significantly with each fuel. An exception to this is the carbon dioxide curve for M.I.T. Indolene.

The carbon dioxide curve for Indolene is shifted above the rest, reaching values on the order of sixteen percent around the stoichiometric point. These values are higher than would be expected. This suggests the possibility of error in recording this data. This error could be the result of human error, in reading the scale, but does not seem likely for two reasons: The oxygen and carbon monoxide curves are not shifted as significantly, and these high values were found by different investigators during different runs. (See breakdown in figure 17.) A more likely suggestion is the possibility that the carbon dioxide gage on the gas cart is reading higher than it should, due either to a calibration error or a malfunction of the gage itself.

The scatter in the data shown in figures 13 and 15 can be attributed to many factors. Measurement inaccuracies probably cause a significant amount of the variation. Differences between engines and engine operating conditions are likely to be contributing factors. Atmospheric conditions and variations in load and speed could also cause variation in the emissions data.

4.6 DIESEL ENGINE DATA

As shown by figures 18, 19, and 20, the diesel engines always run on the lean side of the equivalence ratio. Figures 18 and 19 show the mole fractions of the carbon monoxide, carbon dioxide, and oxygen emissions as a function of the exhaust equivalence ratio for the data from both Petrow and the United States Department of Energy, respectively. Figure 20 shows the combustion efficiency plot for the United States Department of Energy data.

The plots of the emissions data follow the same patterns as those of the spark-ignition engine data. The oxygen emissions start high and fall as the equivalence ratio increases. Following this pattern, the curves would reach zero at the stoichiometric point. The carbon monoxide levels are on the order of zero over the whole range of the equivalence ratio and are barely starting to rise as the equivalence ratio nears the stoichiometric point. The carbon dioxide levels start low and increase as the equivalence ratio increases toward the stoichiometric point. Recall that the carbon dioxide levels for spark-ignition engines had also followed this pattern, peaking at the stoichiometric point and then falling as the equivalence ratio increased further.

The combustion efficiency data, shown by figure 20, shows that over the entire operating range the efficiency is high. Under very lean conditions ($\phi_e < 0.3$), the inefficiency is increased due to unstable combustion. As the equivalence ratio nears the stoichiometric point the combustion efficiency begins to fall, as it did in the spark-ignition engines. The highest combustion efficiencies are reached over an equivalence ratio range of roughly 0.4 to 0.65.

This scatter in the graph of Petrow's data is much more noticeable than the scatter in the United States Department of Energy data. This is most likely due to error in interpreting Petrow's data for my use. His data was shown graphically, rather than in tabulated form. In taking this data off the graphs, error was introduced that shows up as inconsistencies in the plot.

The fact that the curves of figure 19 are so well behaved is very interesting. Scatter in these curves is virtually non-existent. This is important because the data was taken from six diesel engines of different size and manufacture. This information shows that the exhaust emissions are a function of the equivalence ratio, rather than of the engine itself.

The well behaved nature of the oxygen curve of this data is somewhat deceiving, however, since no oxygen emission data was given for these engines. As previously discussed, a curve relating oxygen emissions to carbon dioxide emissions in diesel engines was used to obtain this information. Had the carbon dioxide curve not been so well behaved, the oxygen curve would have had more inconsistencies.

The combustion efficiency curve (figure 20) does show variation overall, but no scatter in each individual curve. The curves for each of the six engines are well behaved, showing that the variation in the overall graph is due to the differences in combustion efficiencies between the six engines.

4.7 SPARK-IGNITION AND DIESEL ENGINE DATA

Figures 21 and 22 show the superposition of the diesel data on the plots of the spark-ignition data. These plots show that the diesel engines always operate lean, while the spark-ignition engines operate over both the lean and the rich range of the equivalence ratio. The emissions characteristics of the two types of engines follow the same pattern, tending to form a single curve for each constituent, indicating that the emissions are based only on the equivalence ratio, not the engine type. The combustion efficiencies are in general higher for the diesel engines than for the spark-ignition engines. Superposition of all combustion efficiency data also forms a single curve, with some scattering at the very lean edge of the spark-ignition data, where these engines are running poorly. This plot shows that each engine type has an optimum operating range, an equivalence ratio range of 0.4 to 0.65 for diesel engines and 0.8 to 0.95 for spark-ignition engines, and that as a spark-ignition engine's operations moves into the rich range its combustion efficiency drops dramatically.

CHAPTER FIVE

SUMMARY AND CONCLUSION

The equivalence ratio can be determined by two methods, measurement of fuel and air mass flow rates into the engine, or by exhaust gas analysis. The metered equivalence ratio is found by dividing the actual fuel-air ratio by the stoichiometric fuel-air ratio. The exhaust equivalence ratio is determined by calculating the air-fuel ratio from the concentrations of carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons, and oxygen in the exhaust gas. The inverse of this ratio is divided by the stoichiometric fuel-air ratio to get the exhaust equivalence ratio.

Exhaust data was collected through both experimentation and research. Experimental data was collected in the Sloan Automotive Laboratory at M.I.T. using an instrumented Ricardo Hydra MK III test engine and a gas cart. Other data was collected through research of work done by others in this field. All data was subsequently used in the calculation of both the metered and exhaust equivalence ratios, combustion efficiencies, and mole fractions of the emissions constituents. This information was then compiled by fuel type and engine type and shown graphically in order to show the characteristics of combustion efficiencies and exhaust emissions over a wide range of equivalence ratios.

Superposition of all data produced curves that were continuous over the range of equivalence ratios. Although there was some scatter due to error, different engines, operating conditions, and other factors, each of the curves was well defined. With the exception of the different operating ranges, the curves did not vary significantly for data collected from either spark-ignition or diesel engines. Fuel type also caused very minor variation in the curves. The stoichiometric equivalence ratio ($\phi = 1$), defined to be the boundary between lean operation and rich operation, was also shown to be the boundary between quite different compositions of exhaust products and combustion efficiency levels. Highest combustion efficiency levels were reached under slightly lean conditions. As the equivalence ratio reached the stoichiometric point, the combustion efficiency began to decrease, falling dramatically under rich operating conditions.

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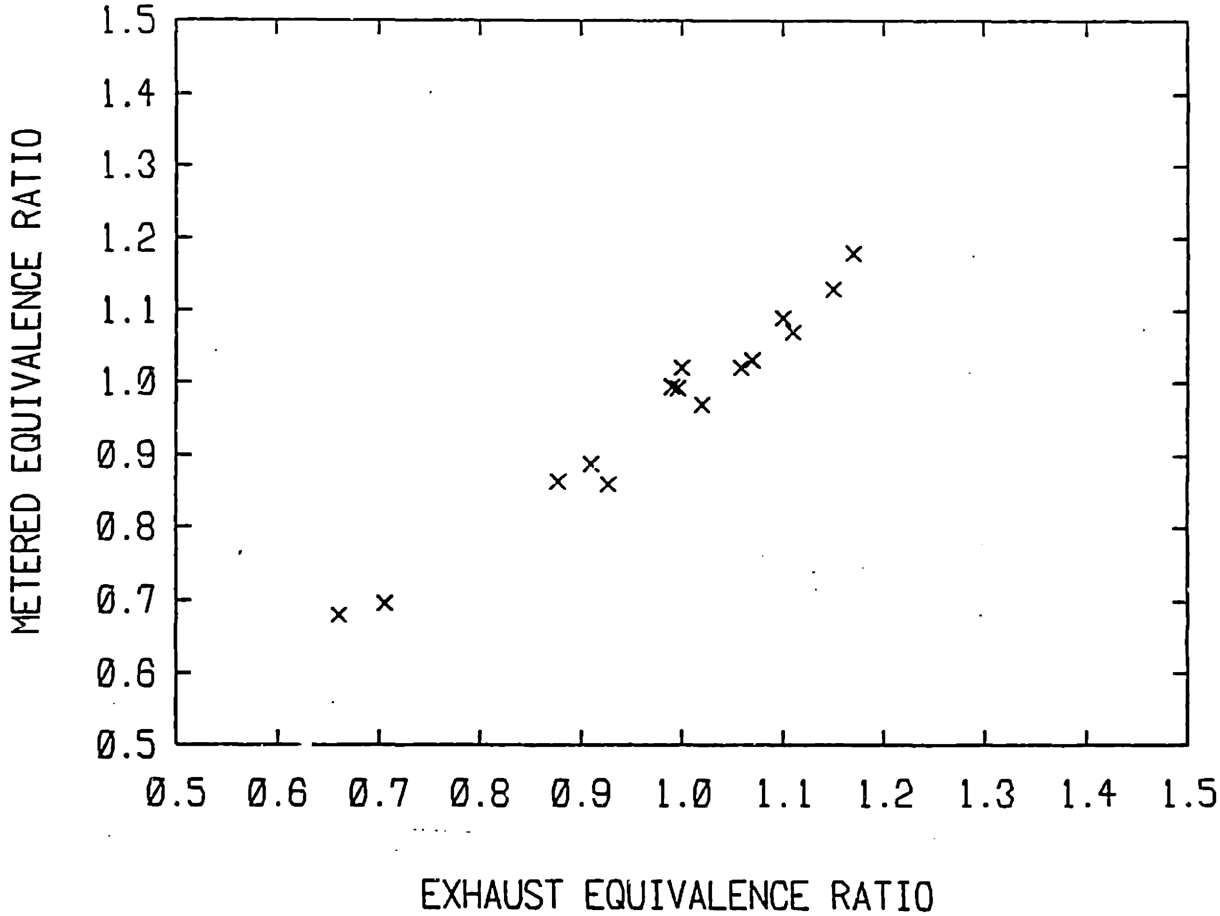


Figure 1. Agreement between metered equivalence ratio and exhaust equivalence ratio in Bishop's experiments.

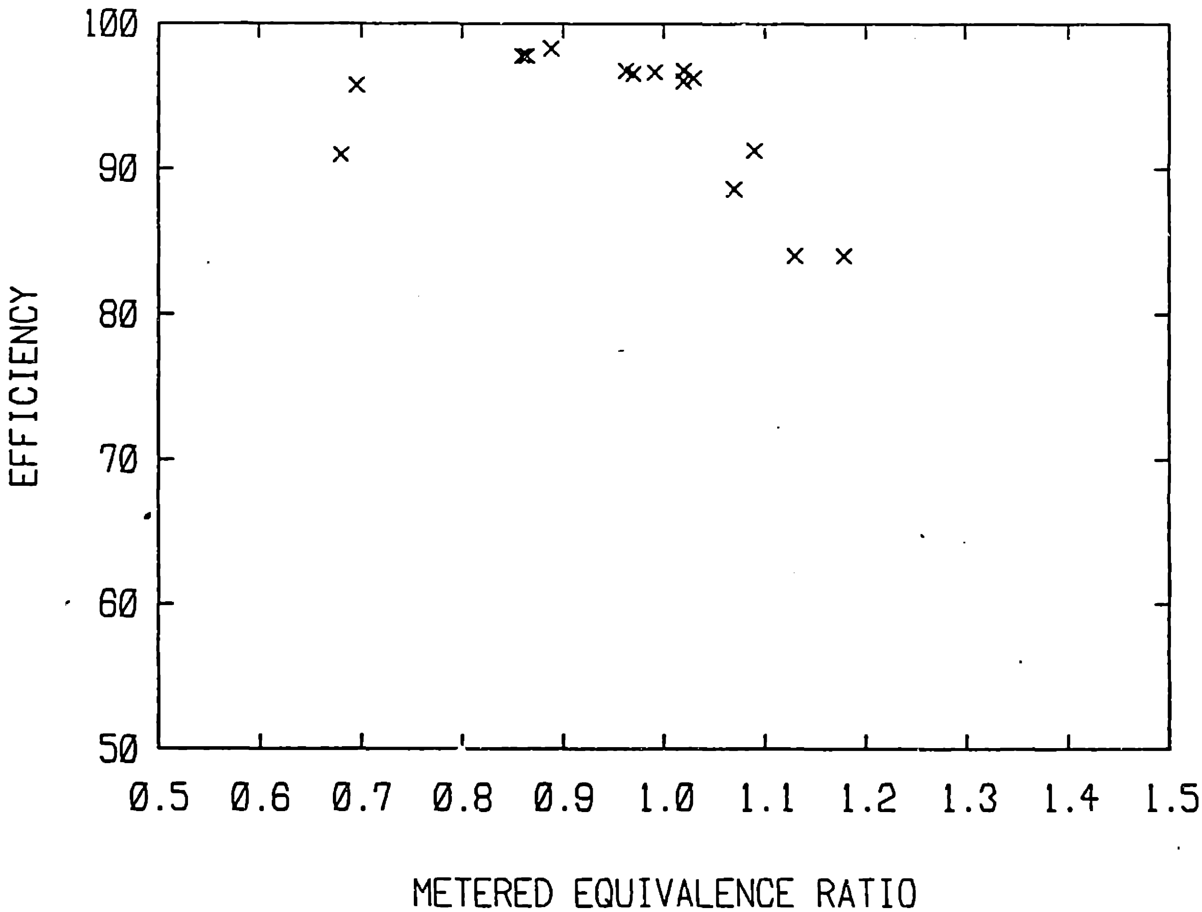


Figure 2. Combustion efficiency versus metered equivalence ratio, Bishop's data.

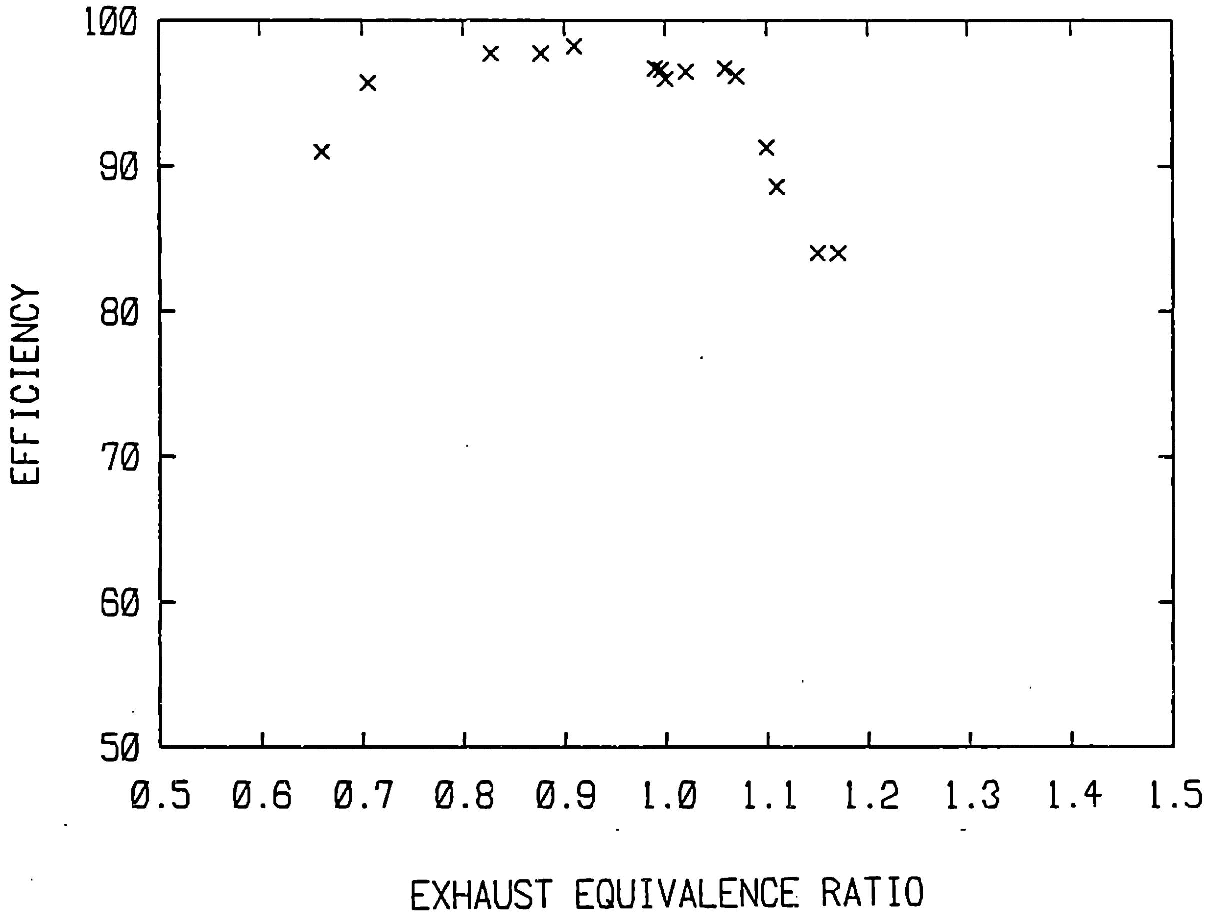
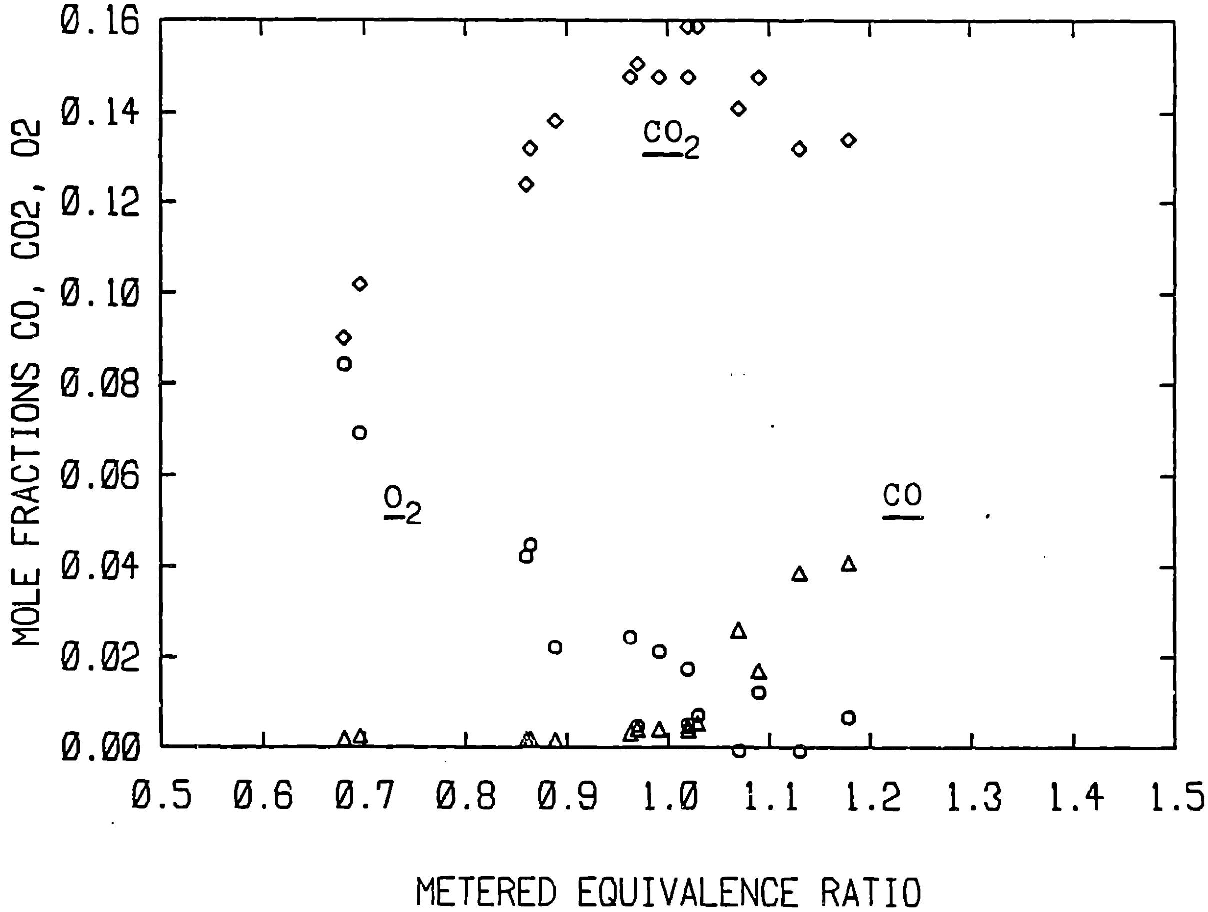
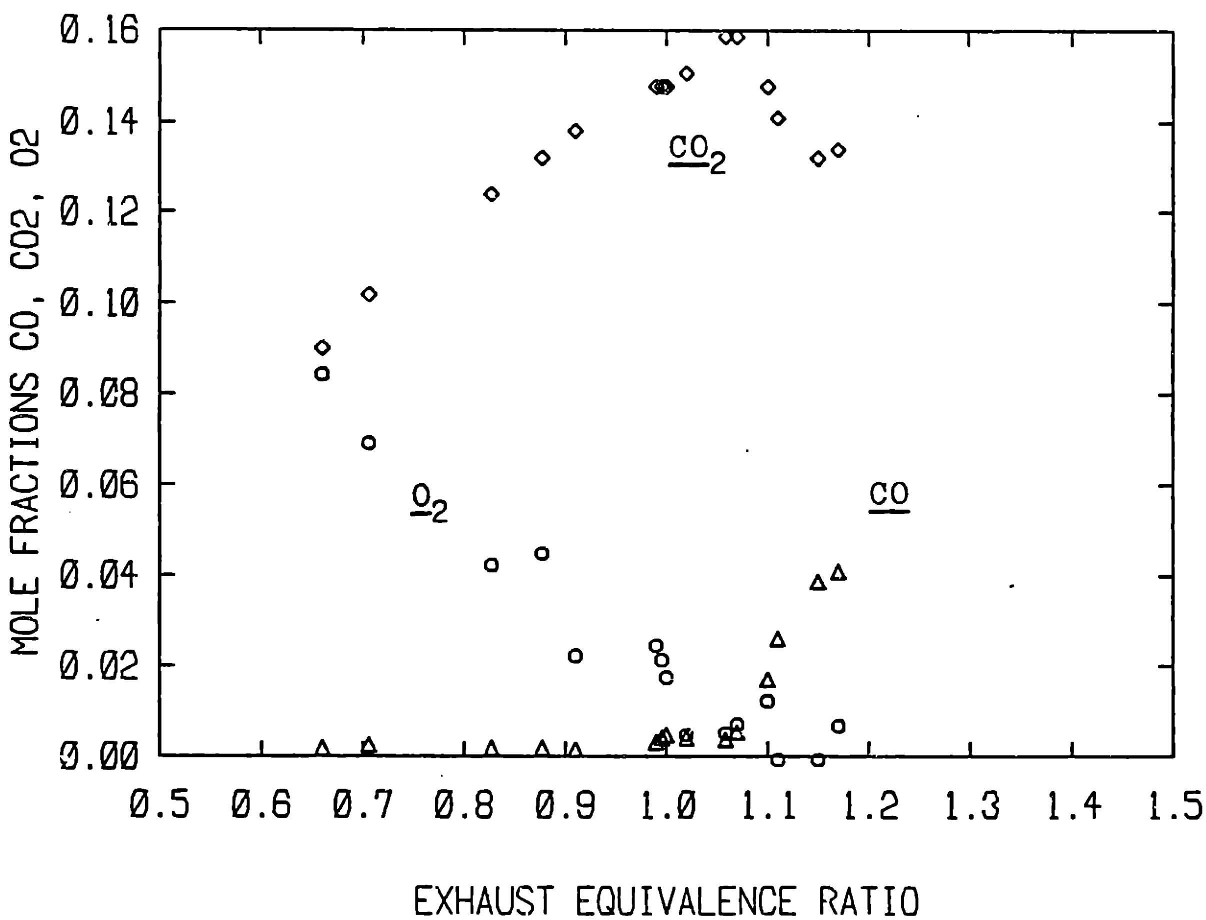


Figure 3. Combustion efficiency versus exhaust equivalence ratio, Bishop's data.



△ : Carbon Monoxide
◇ : Carbon Dioxide
○ : Oxygen

Figure 4. Dry mole fractions of exhaust emissions versus metered equivalence ratio, Bishop's data.



△ : Carbon Monoxide
◇ : Carbon Dioxide
○ : Oxygen

Figure 5. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio, Bishop's data.

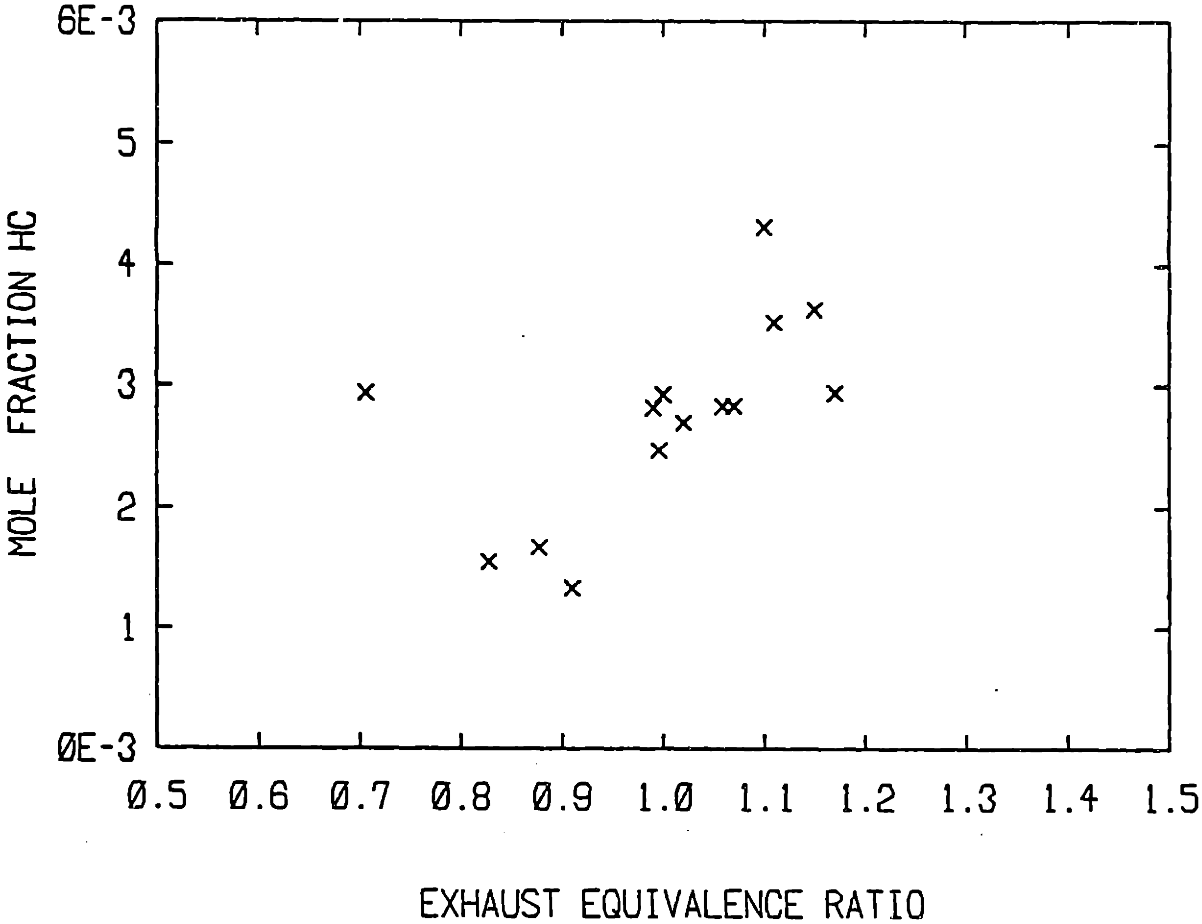


Figure 6. Dry mole fraction of hydrocarbon emissions versus exhaust equivalence ratio, Bishop's data.

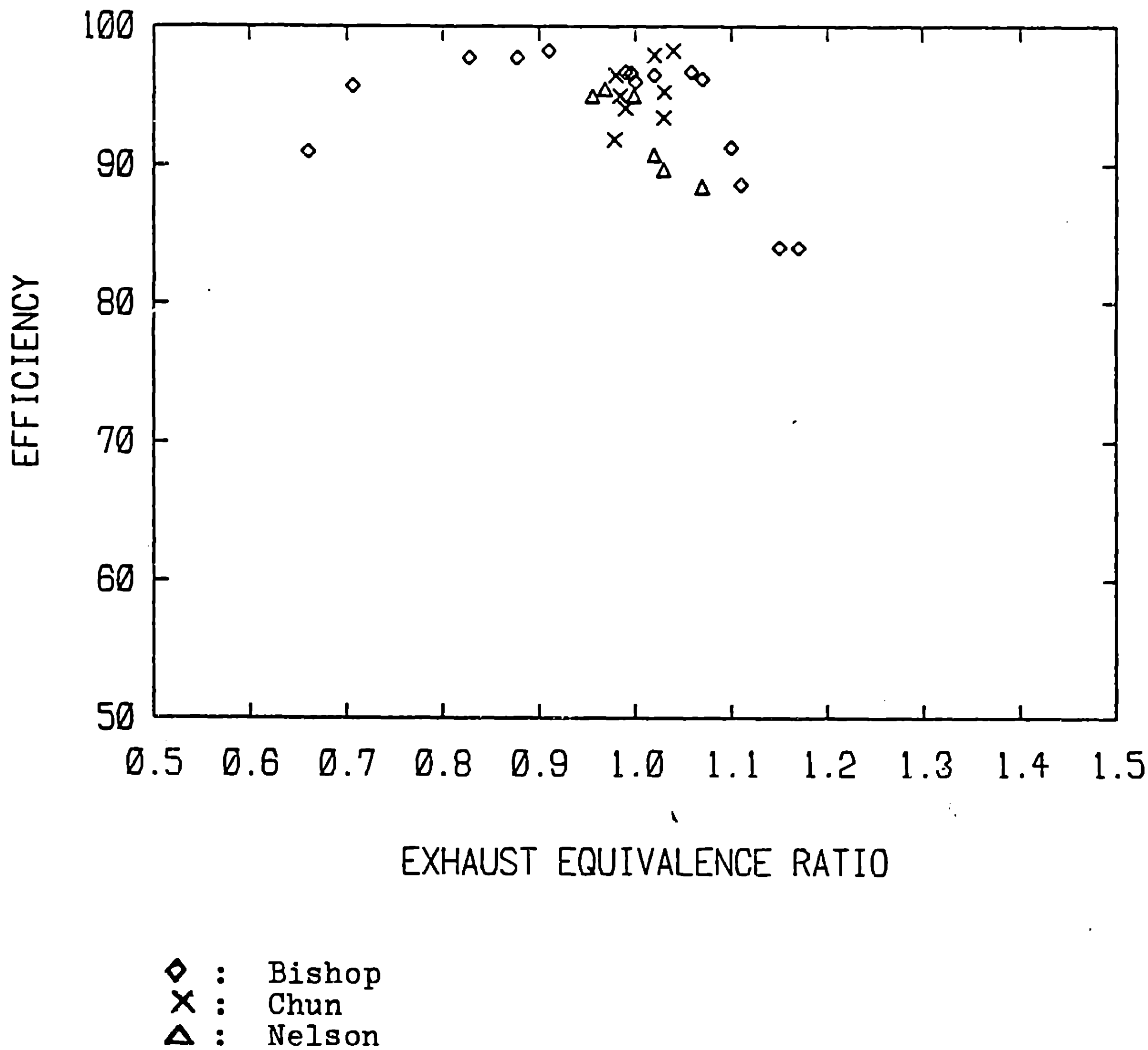
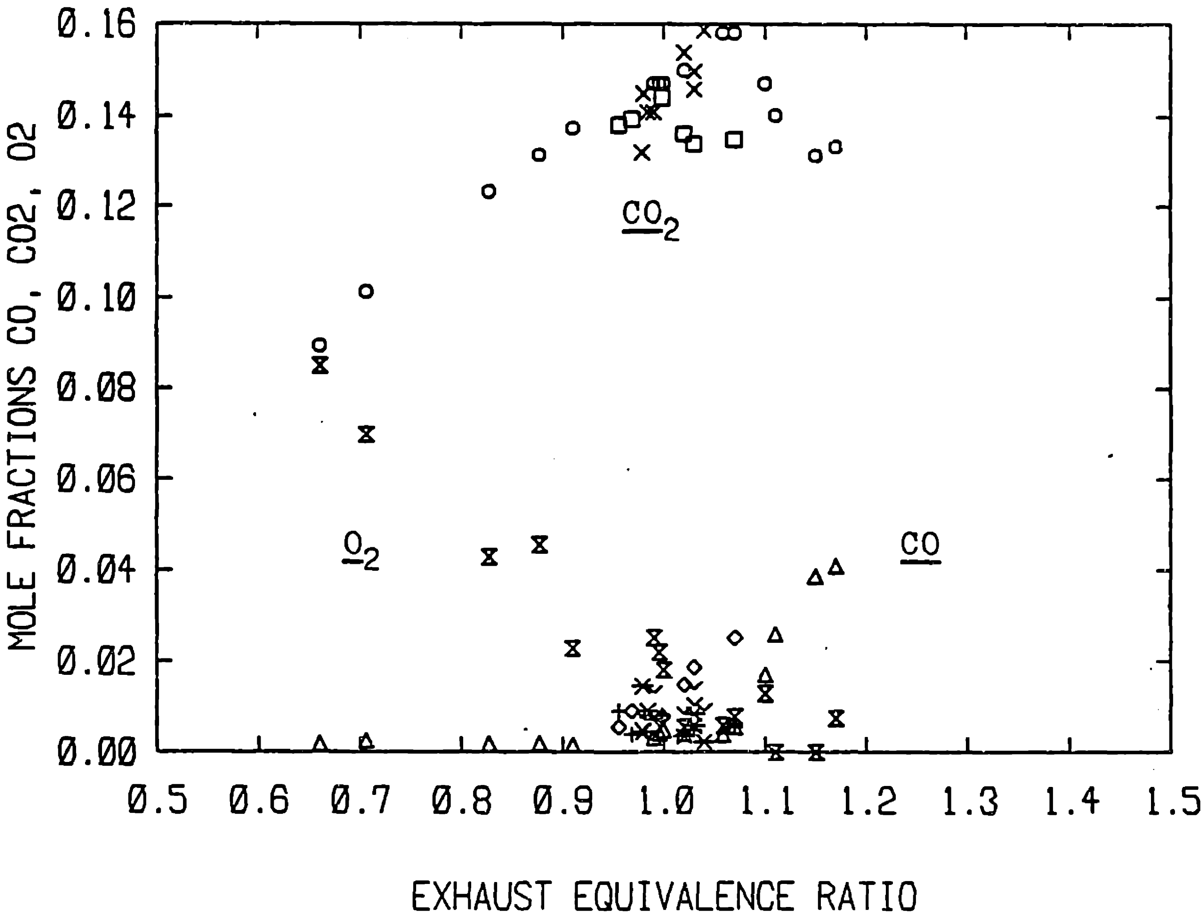


Figure 7. Combustion efficiency versus exhaust equivalence ratio for M.I.T. Indolene.



○, ⧗, △ : Bishop
×, ✱, ∨ : Chun
□, ◇, + : Nelson

Figure 8. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio for M.I.T. Indolene.

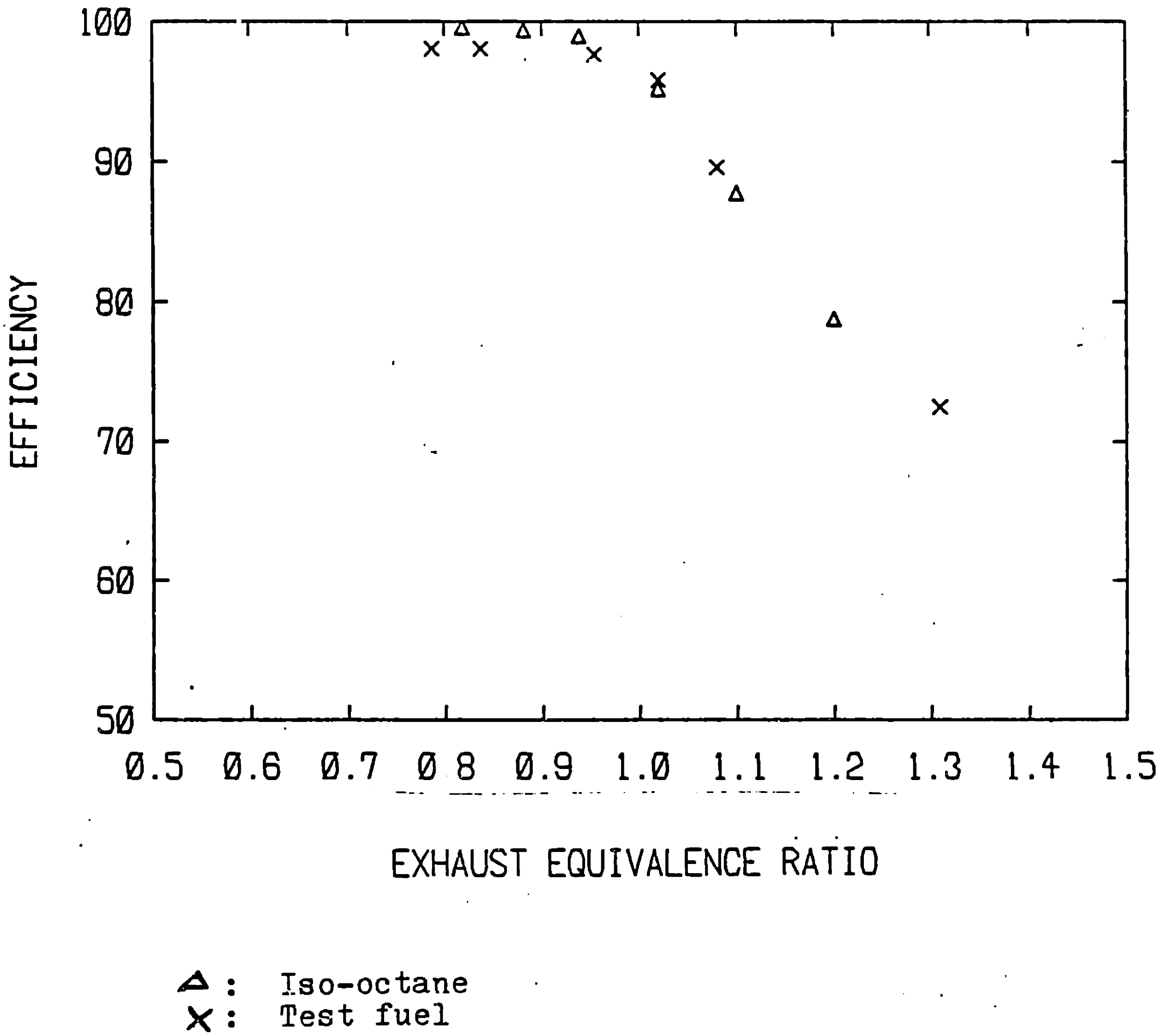
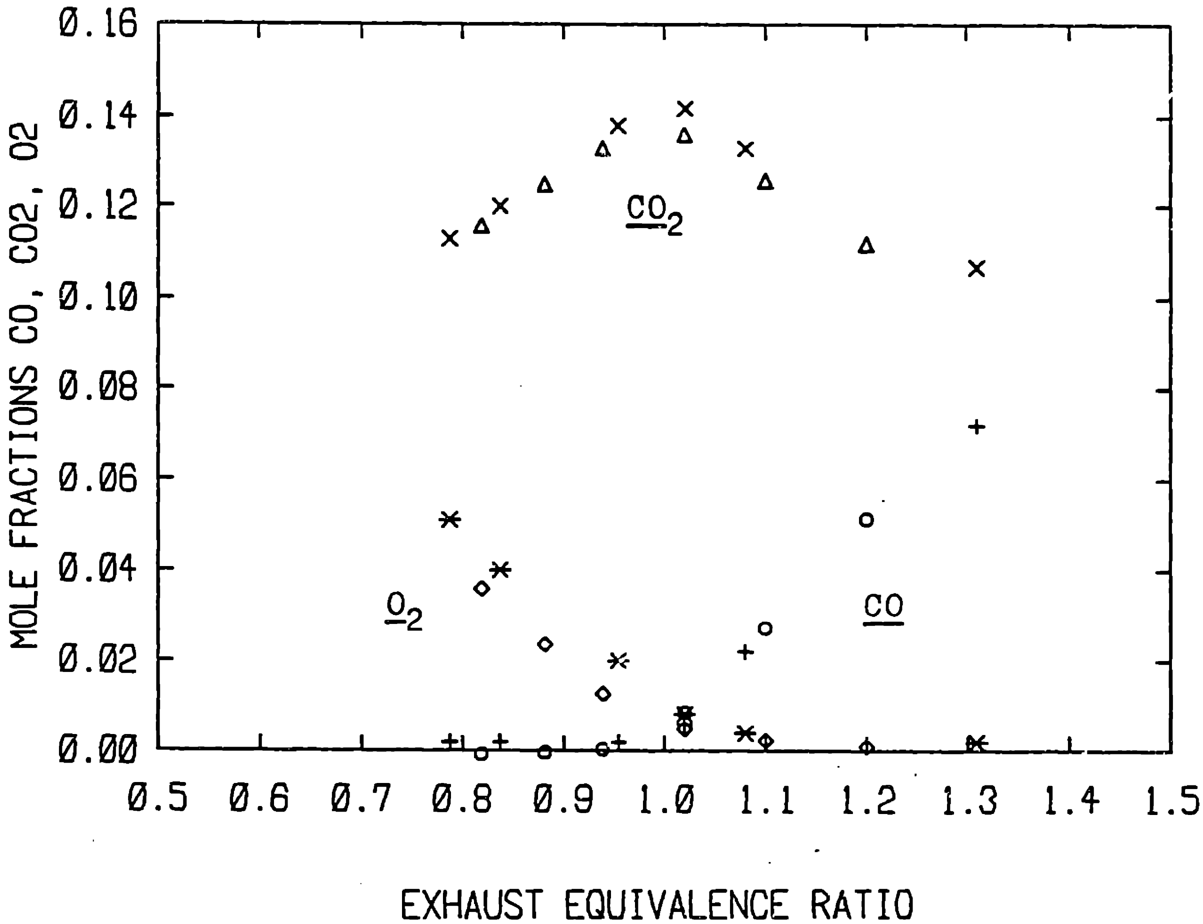


Figure 9. Combustion efficiency versus exhaust equivalence ratio for Harrington and Shishu's data.



△,◇,○: Iso-octane
×,✳,+: Test fuel

Figure 10. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio for Harrington and Shishu's data.

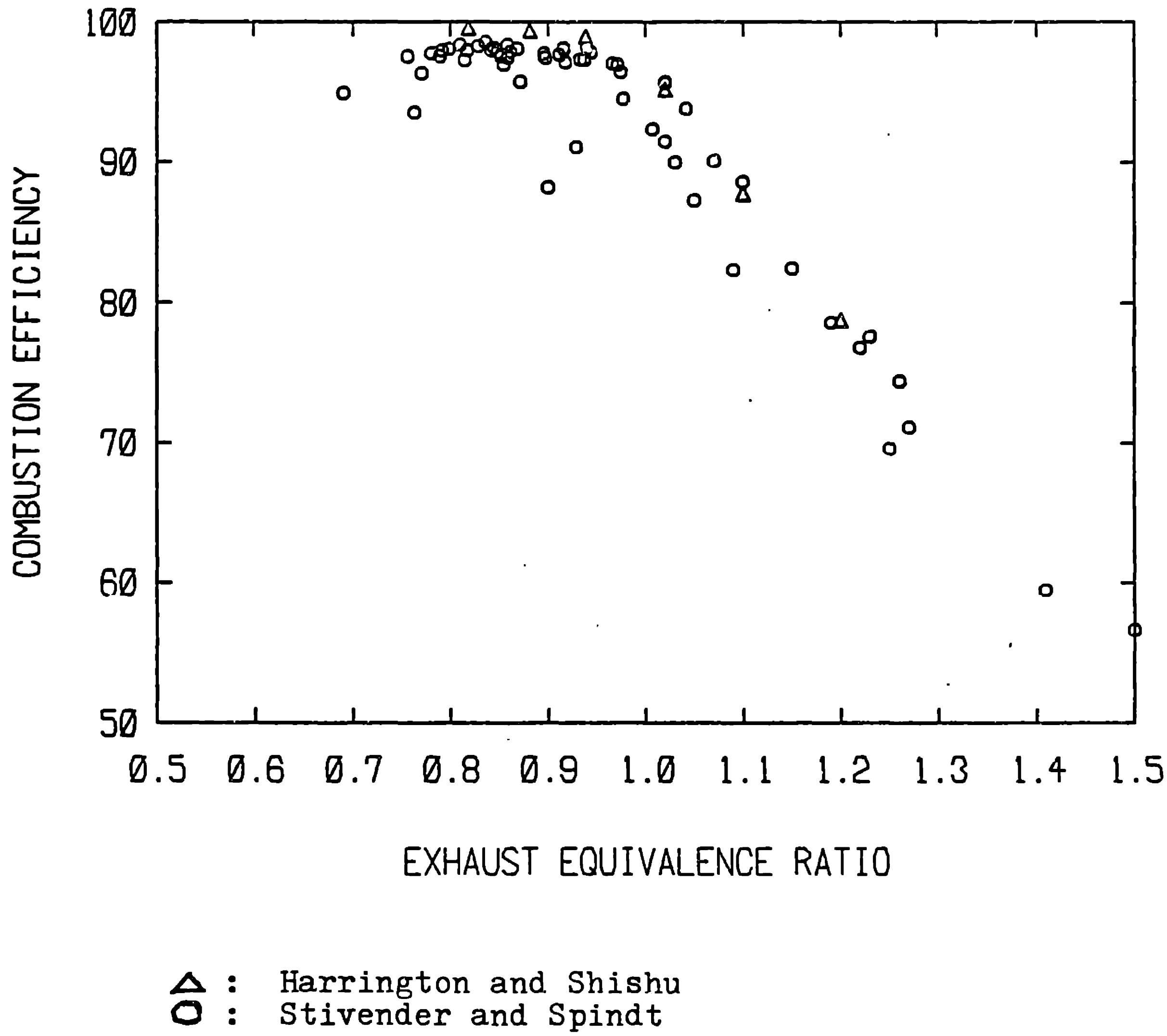


Figure 11. Combustion efficiency versus exhaust equivalence ratio for iso-octane fuel.

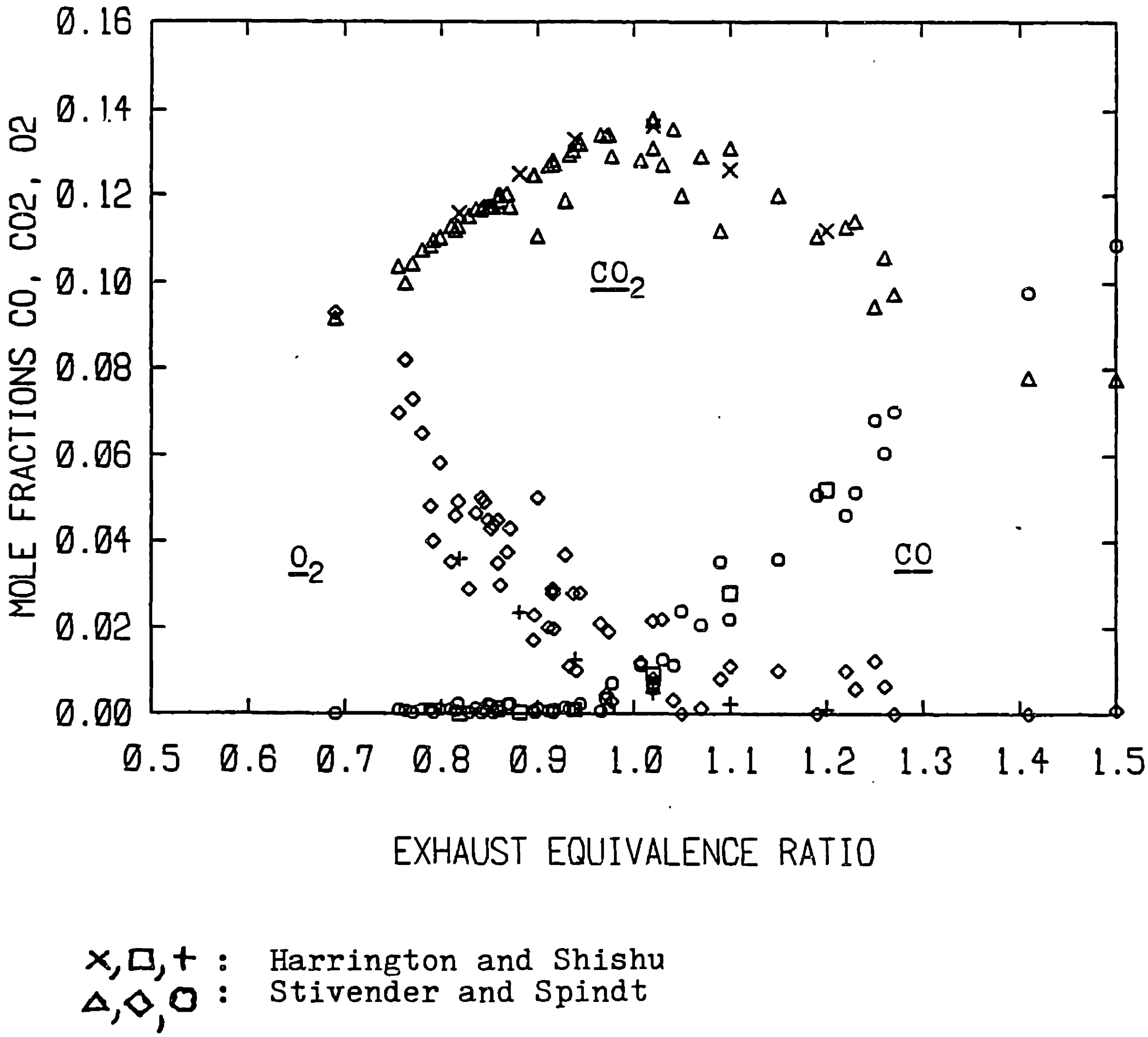
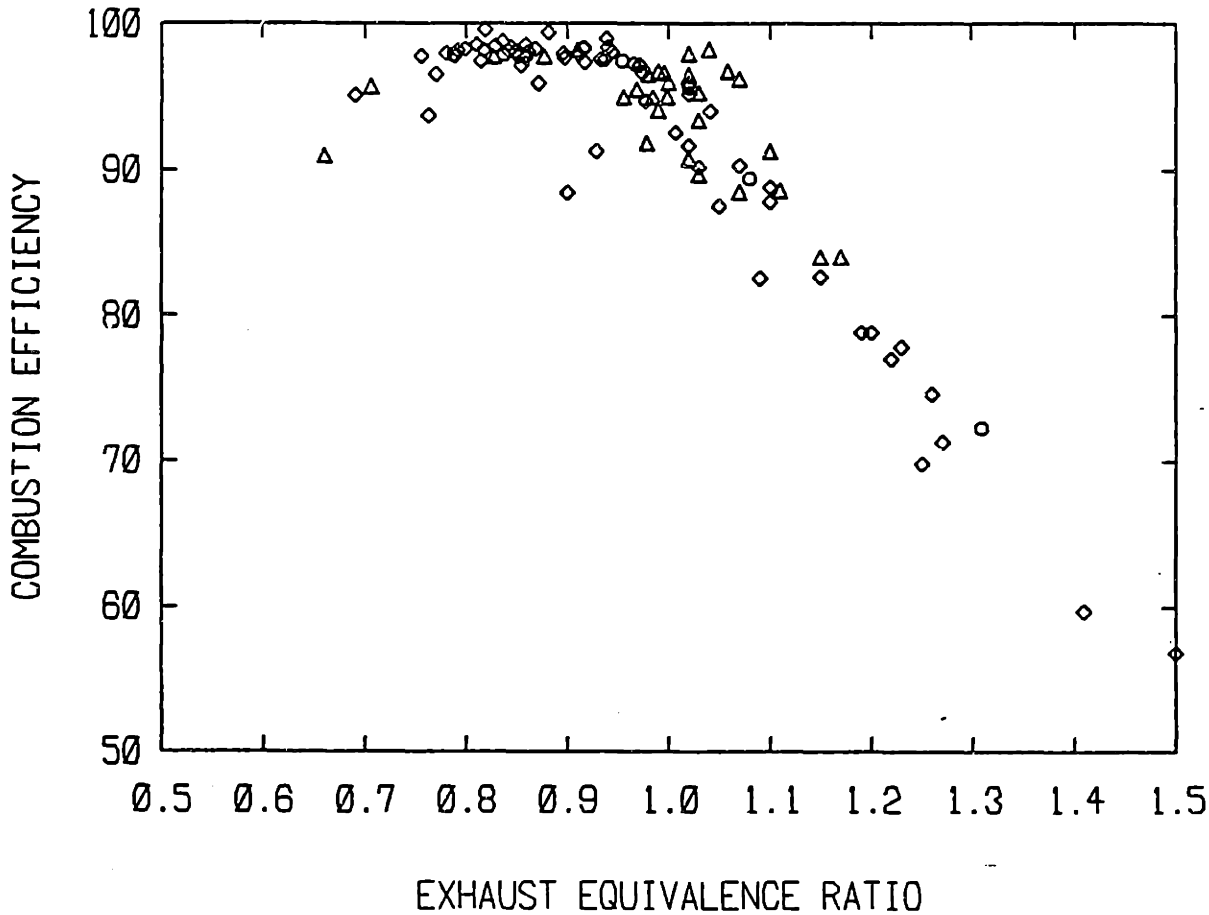


Figure 12. Dry mole fractions of exhaust emissions versus equivalence ratio for iso-octane fuel.



△ : M.I.T. Indolene
◇ : Iso-octane
○ : Test fuel

Figure 13. Combustion efficiency versus exhaust equivalence ratio for all spark-ignition engine data.

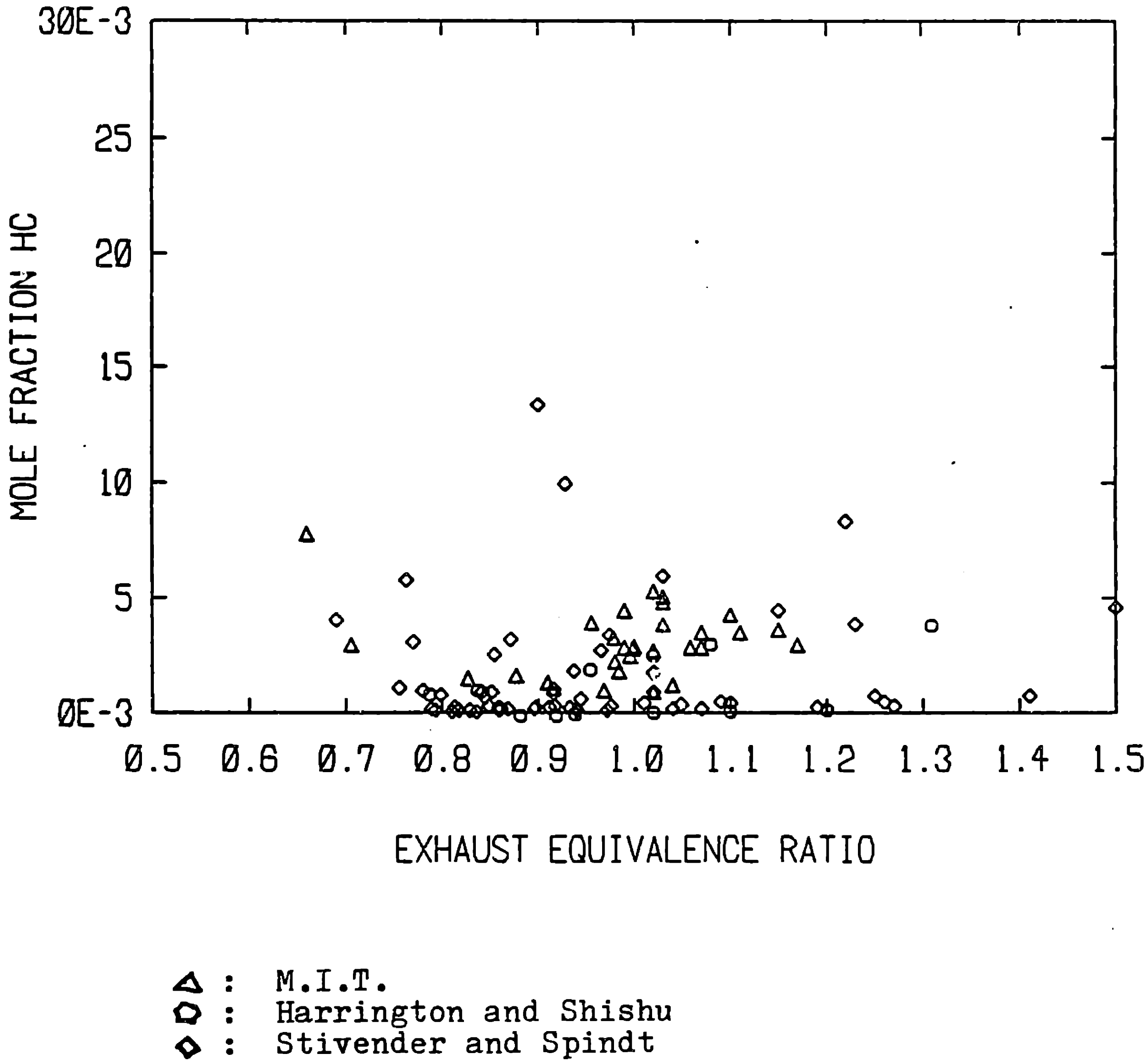


Figure 14. Dry mole fraction of hydrocarbon emissions versus exhaust equivalence ratio for all spark-ignition engine data, by investigator.

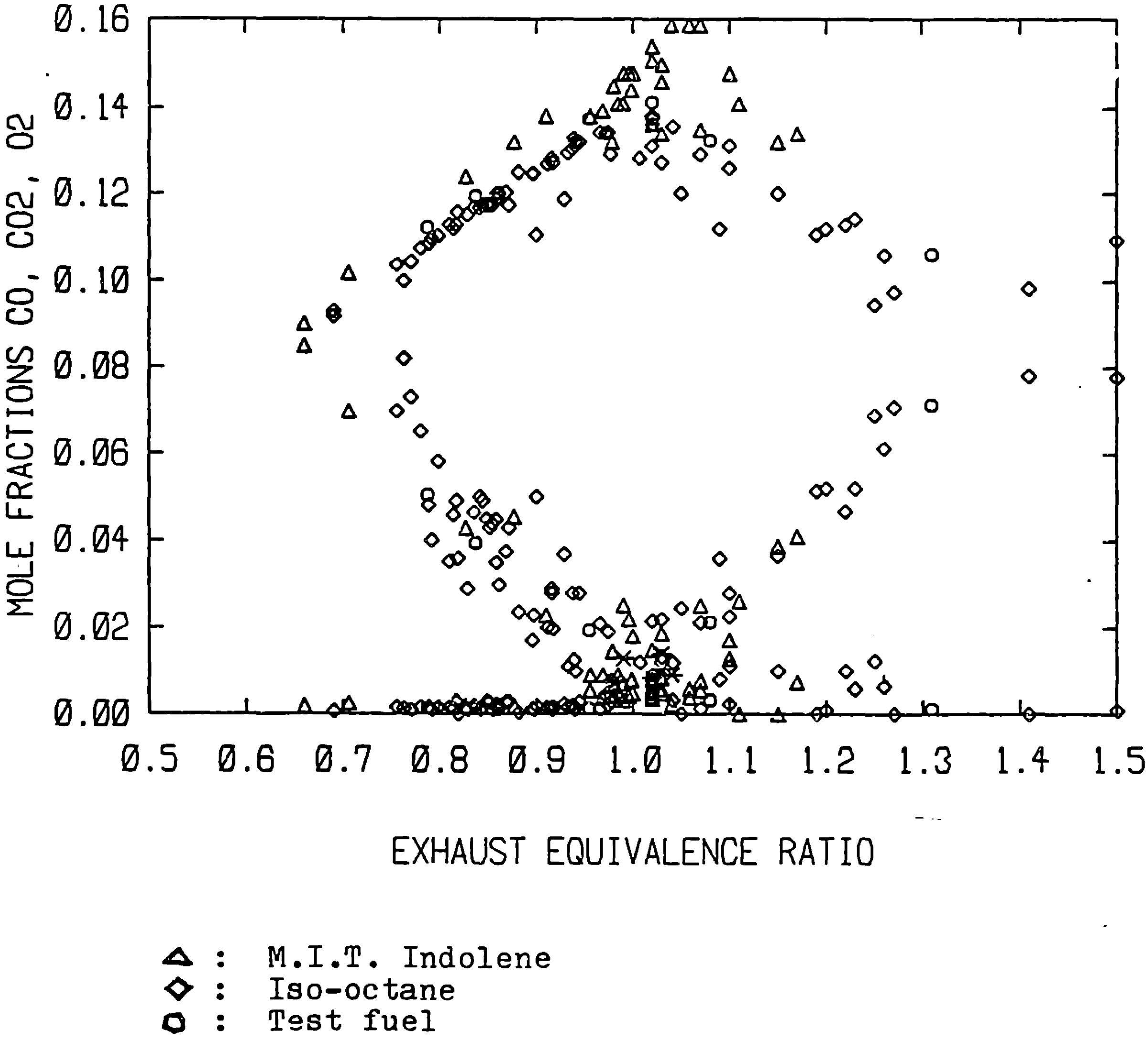
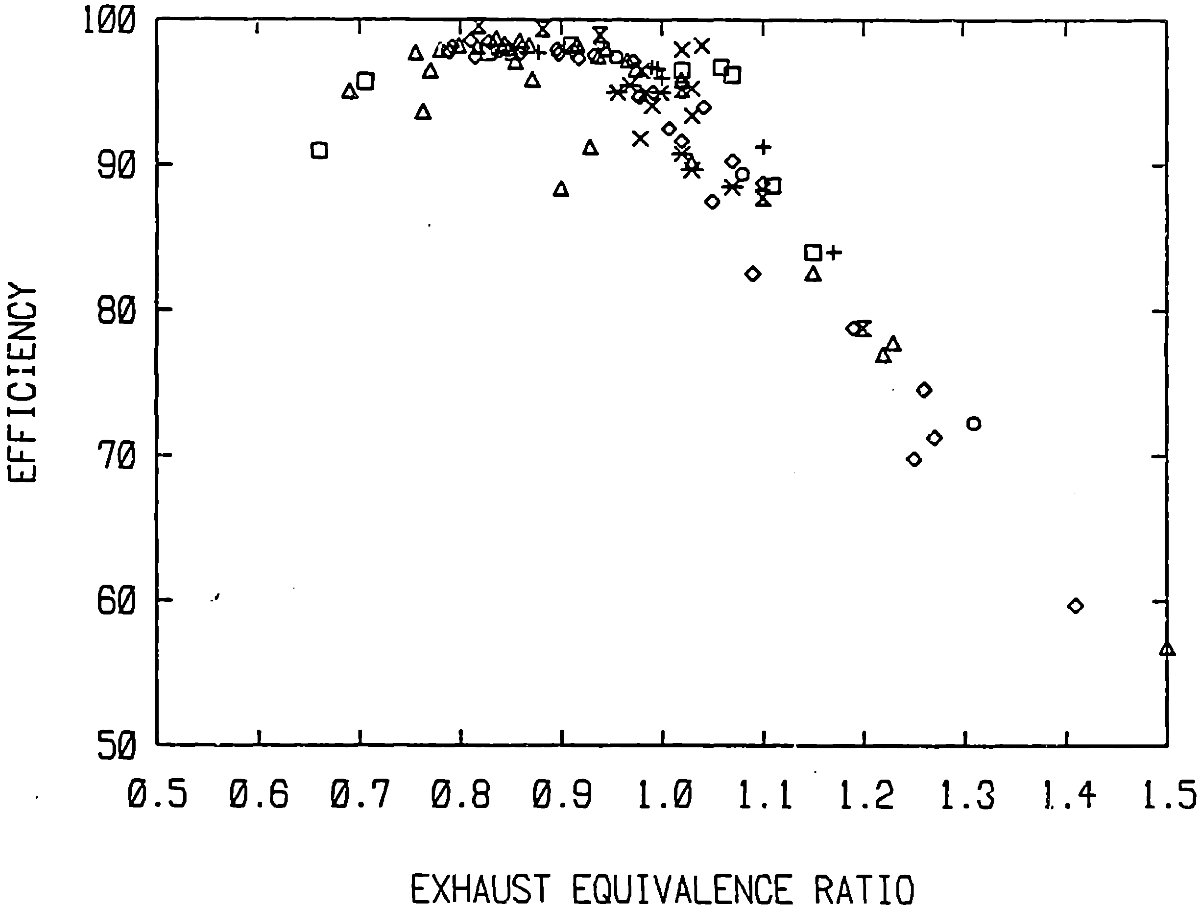
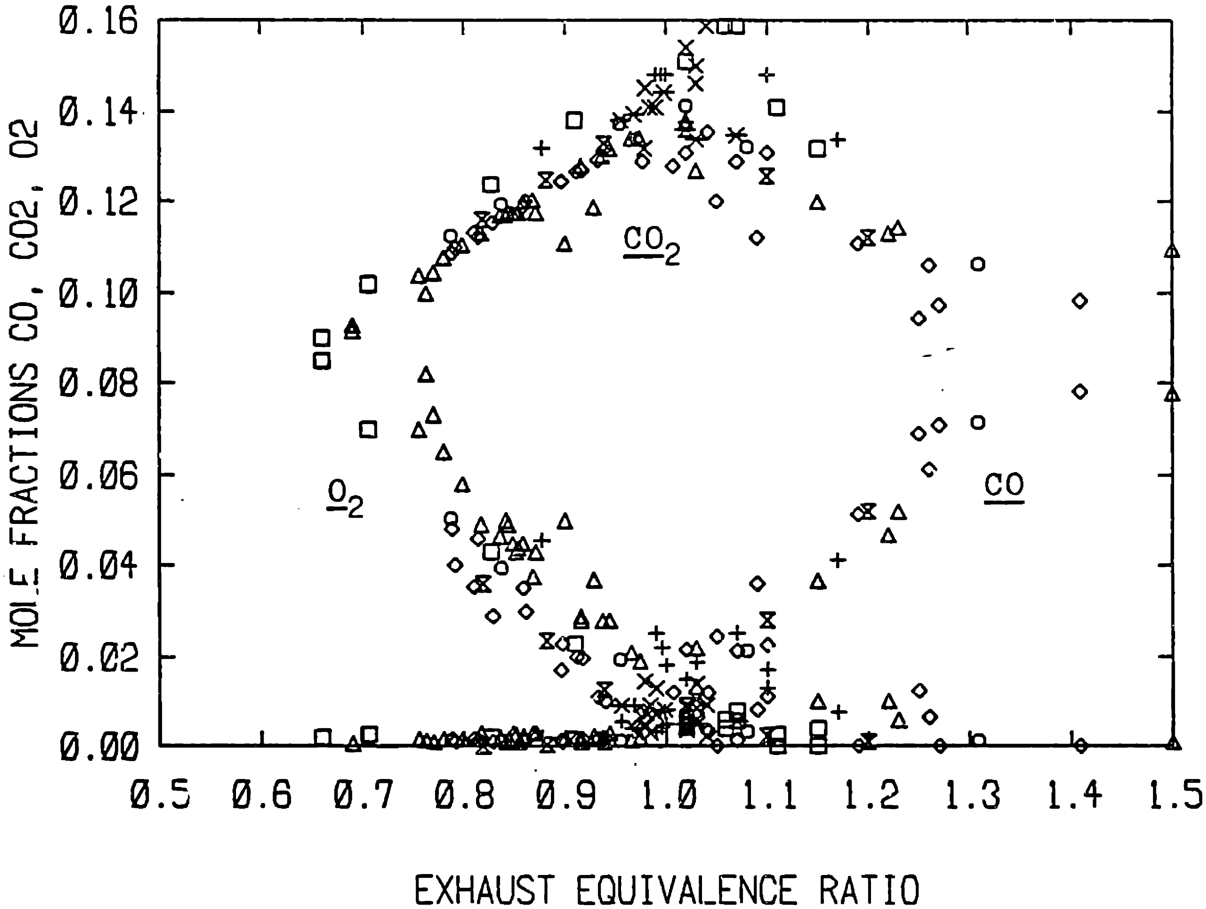


Figure 15. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio for all spark-ignition engine data.



+, □ : Bishop
× : Chun
⧖, ○ : Harrington and Shishu
✳ : Nelson
△, ◇ : Stivender and Spindt

<u>Figure 16.</u> Combustion efficiency versus exhaust equivalence ratio for all spark-ignition engine data, by investigator.



+, □ : Bishop
× : Chun
⧖, ○ : Harrington and Shishu
⋇ : Nelson
△, ◇ : Stivender and Spindt

Figure 17. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio for all spark-ignition engine data, by investigator.

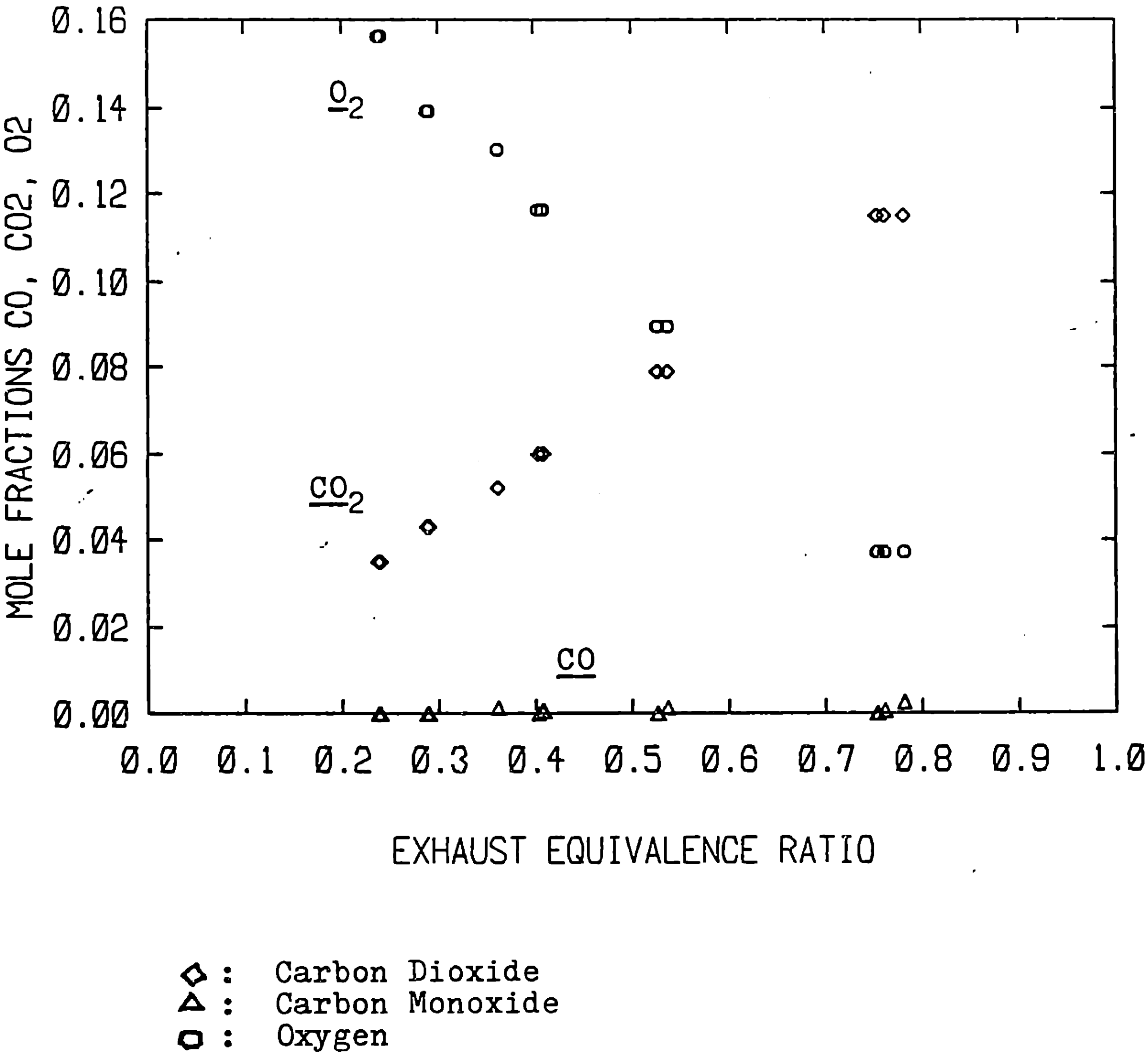
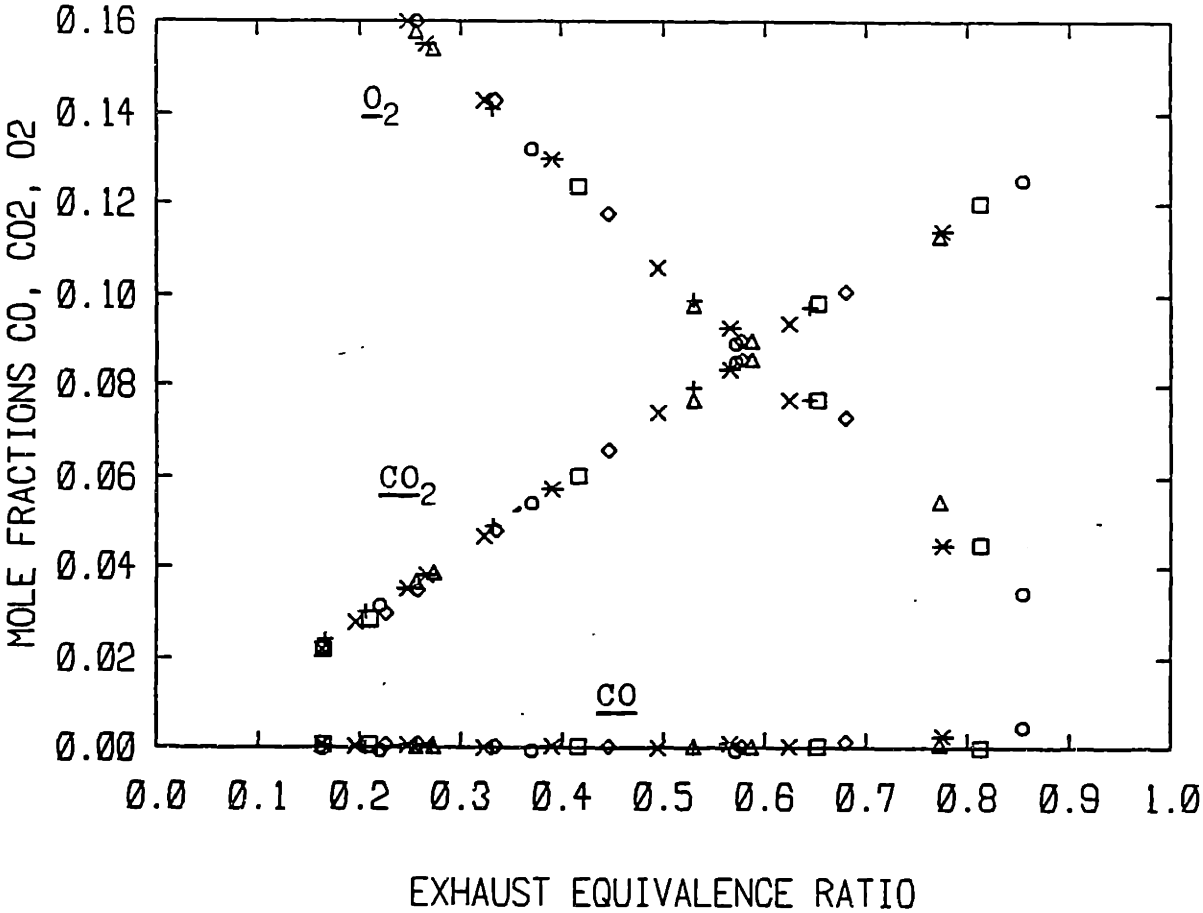
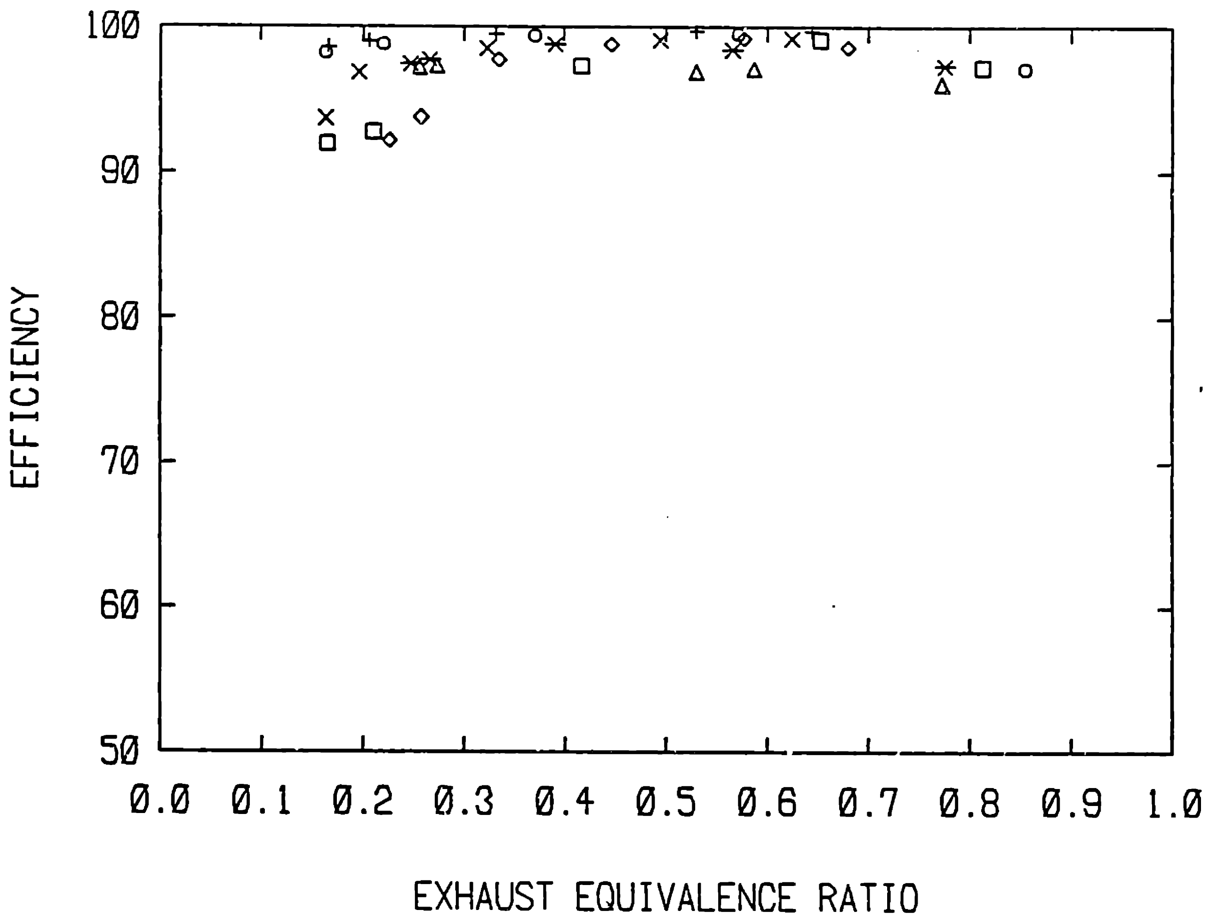


Figure 18. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio, data from diesel engine, Petrow et. al.



∗, ×: Volkswagen engine, 1978, 4 cylinders
+: Mercedes engine, 1975, 5 cylinders
△: Nissan engine, 1976, 6 cylinders
□: Nissan engine, 1975, 6 cylinders
◇: Perkins engine, 1975, 6 cylinders
○: Mitsubishi engine, 1975, 6 cylinders

Figure 19. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio, diesel engines, U.S. Dept. of Energy.



ж × : Volkswagen engine, 1978, 4 cylinders
\+ : Mercedes engine, 1975, 5 cylinders
△ : Nissan engine, 1976, 6 cylinders
□ : Nissan engine, 1975, 6 cylinders
◇ : Perkins engine, 1975, 6 cylinders
○ : Mitsubishi engine, 1975, 6 cylinders

Figure 20. Combustion efficiency versus exhaust equivalence ratio, diesel engines, U.S. Dept. of Energy

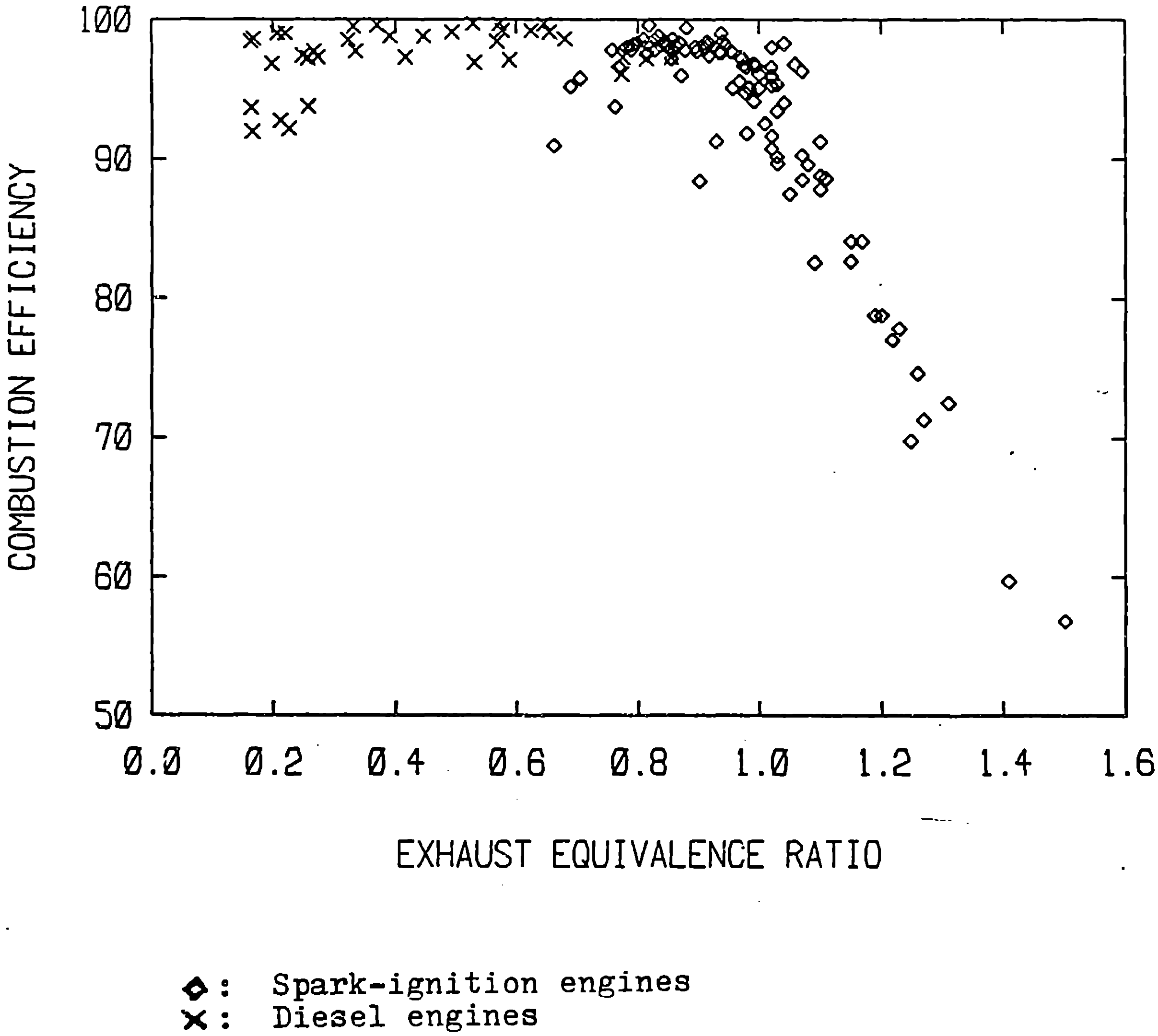
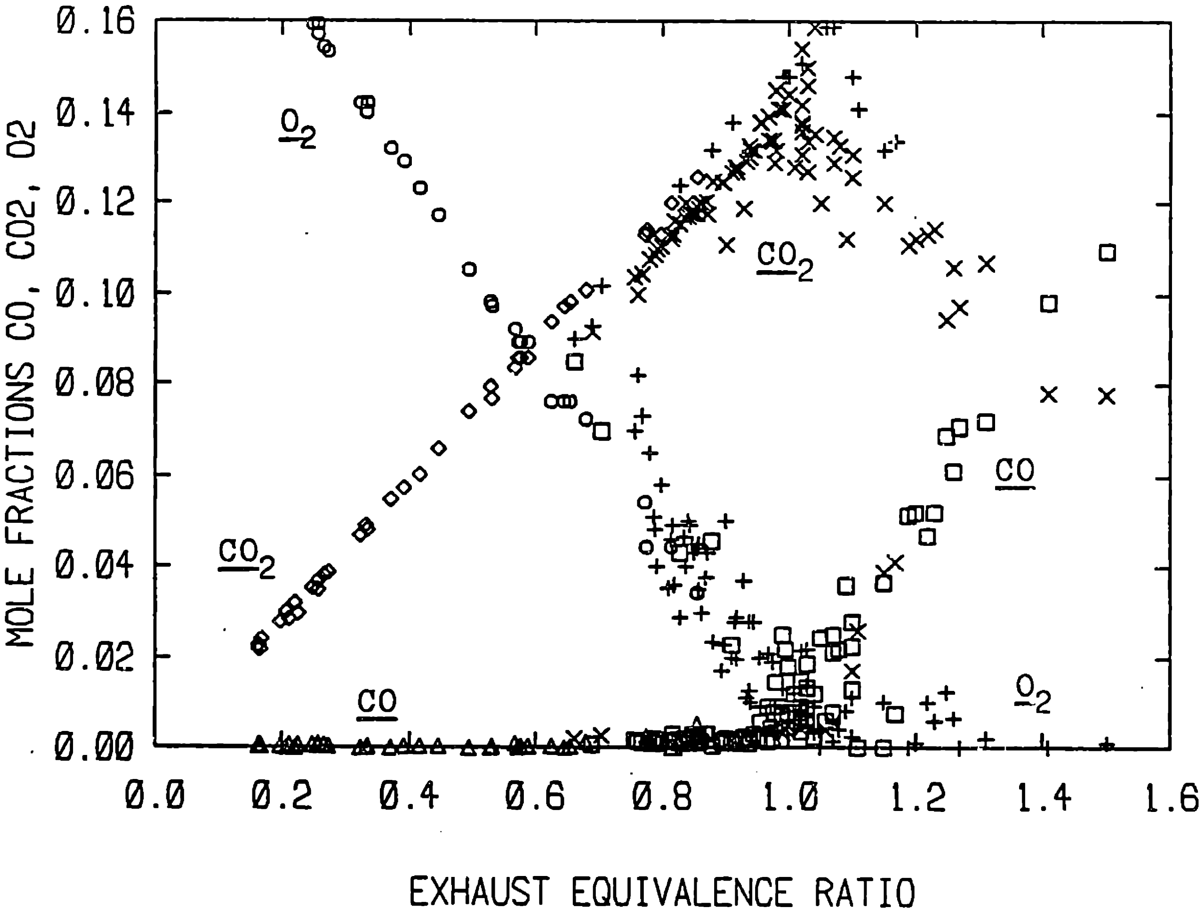


Figure 21. Combustion efficiency versus exhaust equivalence ratio, superposition of all data.



×, □, + : Spark-ignition engines
○, △, ◇ : Diesel engines

Figure 22. Dry mole fractions of exhaust emissions versus exhaust equivalence ratio, superposition of all data.

APPENDIX A

FUEL SUMMARY SHEET

Fuel	(H/C)	$(A/F)_s$
Indolene	1.69	14.34
Iso-octane	2.25	15.13
Test fuel	2.01	14.80
Diesel fuel	1.73	14.40

APPENDIX B

DATA FROM REFERENCE SOURCES

Air-Fuel Ratios and Combustion Efficiency; Indolene-30 Fuel, H/C = 2.25, N/O = 3.76, $(CO \cdot H_2O/CO_2 \cdot H_2) = 3.8$

HC	CO	CO2	O2	MEAS. A/F	CARBON BAL. A/F	OXYGEN BAL. A/F	SPINDT A/F *	COMB. EFF.
281.3	.678	13.8	.7	14.94	15.12	14.52	14.54	96.32
171.8	.164	12.83	2.9	16.91	16.85	16.5	16.51	98.45
152.8	.184	11.7	5	18.58	18.36	18.45	18.46	98.4
164.5	.19	10.76	6.5	20.05	19.82	20.12	20.13	98.17
188.4	.19	10.39	7	20.64	20.45	20.75	20.76	97.98
750.3	10.95	7.78	.1	10.46	10.46	10.16	10.18	62.66
288.4	.658	13.73	.8	15.08	15.2	14.59	14.61	96.34
140.9	.184	12.83	2.8	16.87	16.87	16.45	16.46	98.59
117.3	.19	11.77	4.9	18.41	18.29	18.38	18.38	98.56
136.2	.177	11.07	5.8	19.34	19.36	19.4	19.4	98.43
1337.	4.7	11.32	1	12.24	12.74	12.54	12.6	79.37
971.6	1.33	12.71	2.2	14.86	15.01	14.82	14.86	91.02
1637.	.228	11.89	3.7	16.61	16.76	16.04	16.13	91.56
2222.	.196	11.09	5	17.25	17.32	16.7	16.83	88.59
720.6	3.65	12	1	12.78	13.46	13.26	13.29	84.56
548.7	.196	13.43	1.9	15.6	15.87	15.41	15.44	96.88
524.4	.228	11.77	4.3	17.54	17.85	17.47	17.5	96.44
971.6	.133	10.01	8.2	18.58	20.33	21.18	21.25	93.89
622.	5.21	11.43	.6	12.5	12.58	12.52	12.55	80.33
444.5	.152	13.43	2.1	16.2	15.99	15.65	15.68	97.48
425.2	.12	11.77	4.4	18.21	18.11	17.73	17.75	97.36
514.7	.101	10.46	7.3	20.53	20.12	20.69	20.72	96.65
683.5	.0948	9.179	9.3	22.98	22.45	23.34	23.39	95.23
58	.3	11.75	4.5	17.69	18.2	18.02	18.02	98.36
25	.239	12	4.5	17.57	17.97	18.03	18.03	98.81
150	.27	11.75	4.3	17.25	18.16	17.79	17.8	98.04
300	.209	13.03	2.8	15.9	16.48	16.28	16.3	97.81
10.5	.209	11.69	4.65	18.3	18.47	18.28	18.28	98.99
30	.3	12.06	3.75	17.32	17.79	17.36	17.36	98.53
27.5	.3	11.3	4.9	18.65	18.89	18.53	18.53	98.45
100	.3	13.19	2.8	16.15	16.33	16.36	16.37	98.35

* REFERENCE (18)

Figure B-1. Table of Stivender's data. Fuel considered to be iso-octane due to H/C ratio.

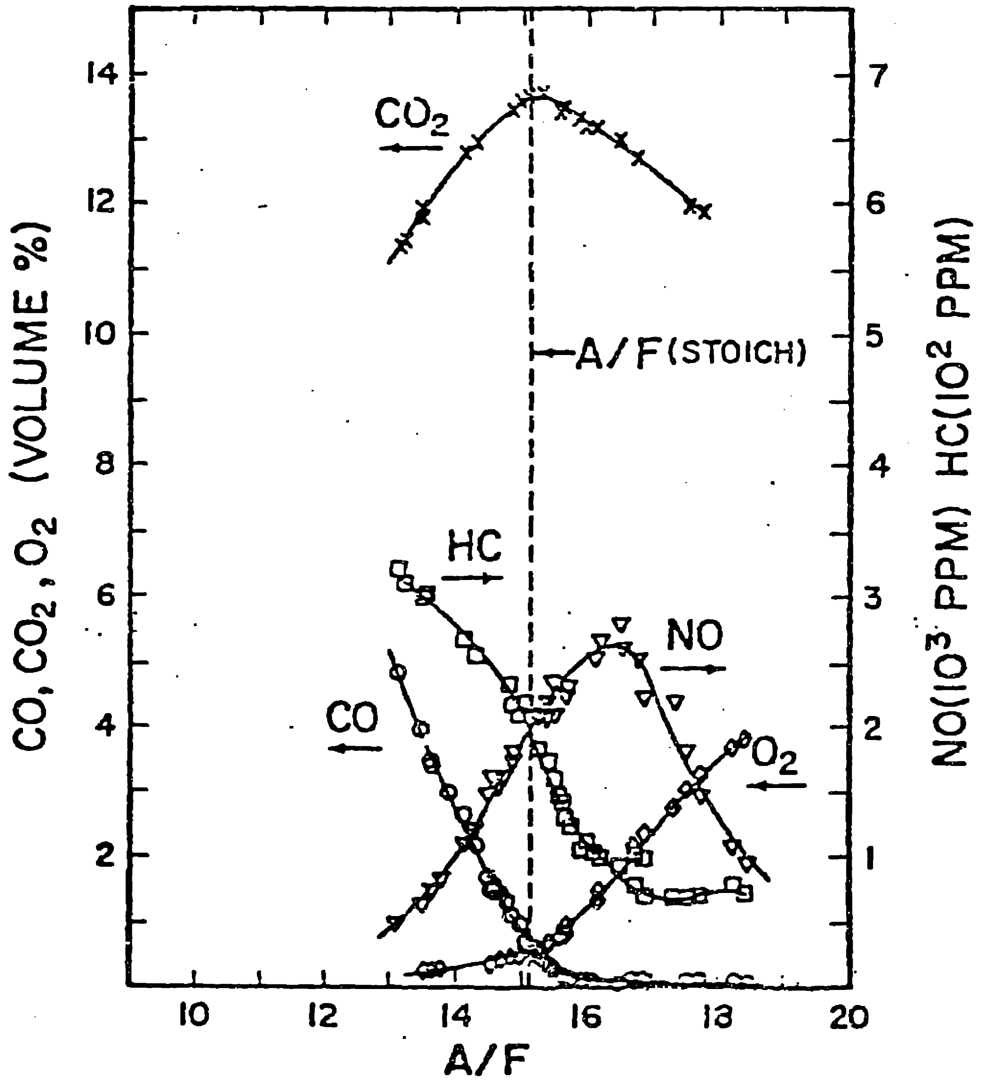
- Air-Fuel Ratios and Combustion Efficiency; Iso-octane Fuel, H/C = 2.25, N/O = 3.76, $(CO \cdot H_2O / CO_2 \cdot H_2) = 3.8$

HC	CO	CO2	O2	MEAS. A/F	CARBON BAL. A/F	OXYGEN BAL. A/F	SPINDT A/F *	COMB. EFF.
259.2	1.187	13.56	.35	14.43	14.58	14.65	14.65	94.41
543.7	1.19	12.83	1.2	14.87	15.08	15.02	15.02	92.96
367.4	.12	12.47	2.3	16.58	16.93	16.5	16.5	97.75
403.5	.16	12.71	1.96	16.4	16.56	16.17	16.17	97.46
331.5	.13	11.89	3.5	17.5	17.7	17.54	17.54	97.77
319.5	.15	11.21	4.6	18.44	18.65	18.59	18.6	97.61
658.8	3.59	11.21	.8	13.6	13.95	13.64	13.65	83.49
403.6	.777	12.9	.3	15.04	15.58	14.67	14.68	95.08
283.7	.133	12.47	1.7	16.34	16.98	16.1	16.1	98.08
193.1	.101	11.55	2.9	17.66	18.35	17.26	17.26	98.53
224.1	.101	10.98	4	18.41	19.19	18.29	18.29	98.29
236.	.164	10.87	4.8	18.98	19.24	18.95	18.95	97.9
331.5	.196	12.95	1.1	15.98	16.29	15.56	15.56	97.68
536.6	2.46	12	0	14	14.49	13.68	13.68	88.16
946.2	9.85	7.82	0	10.91	10.84	10.69	10.7	62.14
236.	.133	12	3	17.36	17.63	17.2	17.2	98.23
307.6	.133	12.71	2	16.46	16.67	16.29	16.29	98.01
188.5	.164	13.19	1	16.13	16.17	15.6	15.6	98.47

Figure B-2. Table of Stivender's data.

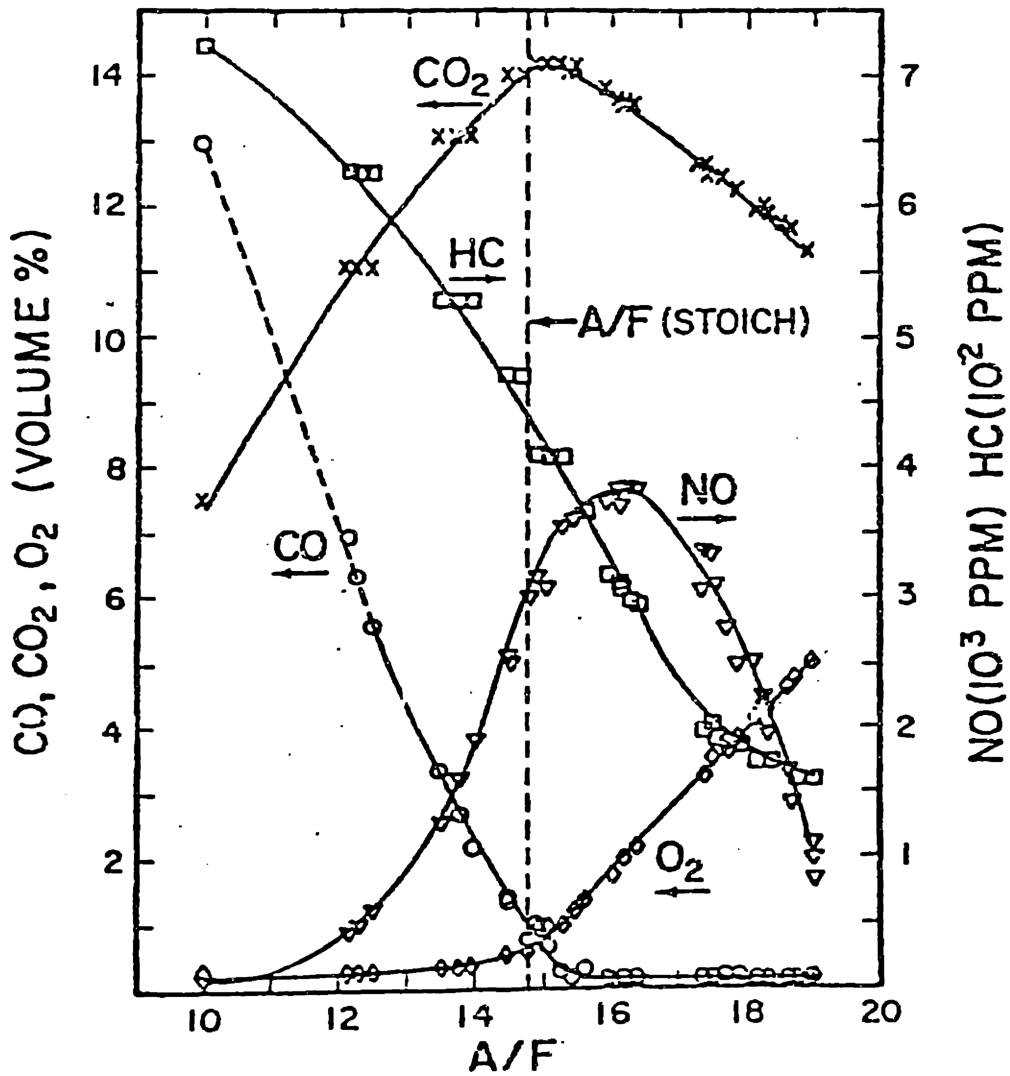
Per Cent					Air-Fuel Ratio	
CO_2	CO	Hydro-carbon	O_2	$100F_u$	Calc.	Meas-ured
Fuel: Isooctane - MAP 12 in. Hg						
9.44	6.88	0.587	1.22	3.47	12.39	11.61
10.64	6.13	0.408	0.65	2.37	12.62	12.36
13.06	2.26	0.366	1.11	2.33	14.47	14.06
13.06	0.77	0.719	2.17	4.94	15.44	14.82
Fuel: Isooctane - MAP 20 in. Hg						
9.75	7.09	0.250	0.0	1.46	11.94	12.39
11.06	5.13	0.210	0.0	1.28	12.76	13.33
12.87	2.14	0.158	0.15	1.04	14.10	14.41
13.36	0.44	0.116	0.45	0.83	15.07	15.44
11.28	0.16	0.060	3.54	0.53	17.88	17.98

Figure B-3. Table of Spindt's data. Referenced by Stivender, grouped with his data from table in figure B-2.



· Variation of exhaust emissions with A/F for a single-cylinder engine using isooctane fuel (No. 11)

Figure B-4. Graph given by Harrington and Shishu, iso-octane fuel.



· Variation of exhaust emissions with A/F for a single-cylinder engine using fuel No. 1

Figure B-5. Graph given by Harrington and Shishu, standard test fuel.

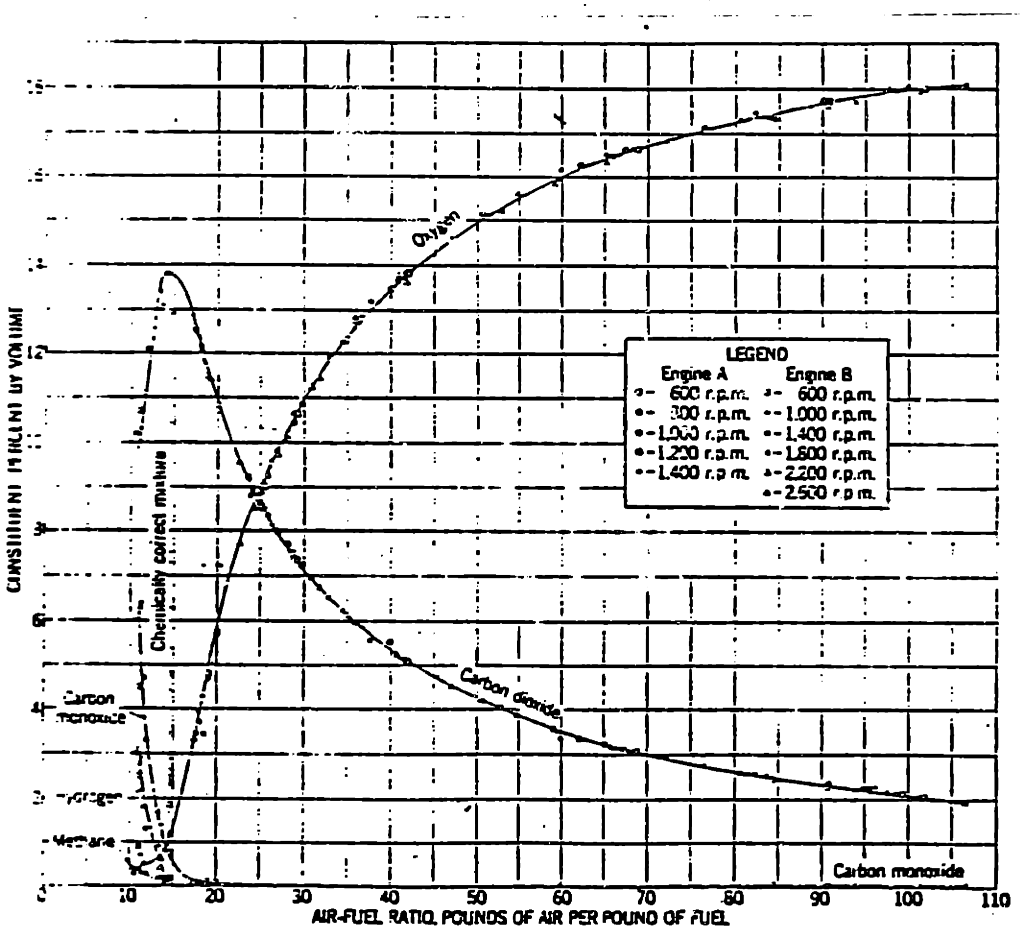


Figure B-6. Graph of diesel engine emissions given by Holtz and Elliot, used to determine Oxygen emissions corresponding to given Carbon Dioxide emissions in order to utilize U.S. Dept. of Energy data.