THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report

ROTATING COMBUSTION CHAMBER ENGINE HYDROCARBON EMISSIONS

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NOMENCLATURE

A/F - air/fuel ratio

CFM - cubic feet per minute

CID - cubic inches displacement

CO - carbon monoxide

F/A - Fuel/air ratio

ft - feet

^{o}F - degrees Fahrenheit

G.E. - General Electric

HC - hydrocarbons

Hg - Mercury (in. Hg.—measurement of pressure)

HP - horsepower

Hr. - hour

in., " - inches

lbs. - pounds

M_T - Total mass flow rate of fuel and air

M_A - Mass air flow rate

MBT - mean best torque

mph - miles per hour

mv - millivolts

NDIR - non-dispersive infrared

n-hexane - normal hexane, C_6H_{14}

No. - number

NOMENCLATURE (Concluded)

N_2 - nitrogen

ppm - parts per million (volume)

psi - pounds per square inch

RC - Rotating combustion chamber

rpm - revolutions per minute (crankshaft)

sec. - second

WAD - Wright Aeronautical Division

ϕ - equivalence ratio

I. INTRODUCTION

A. GENERAL

The purpose of this research project was to investigate the exhaust hydrocarbon emissions from the Curtiss-Wright RC2-60-U5 engine. The results of a year and four month test program demonstrated that this engine can achieve a steady-state emission level of less than 75 ppm (n-hexane) with the proper control of engine operating variables and the addition of an exhaust reaction device. Thus, it is expected that the RC engine should conceivably be able to meet and surpass all existing Federal exhaust hydrocarbon emission standards.

In the past few years with the rapid growth of atmospheric air pollution problems on both the local and national levels, the internal combustion engine has received increasing criticism for its suspected contribution to the problem. In some special cases, notably Los Angeles with its photochemical smog, the automotive spark-ignition engine has been blamed for the greatest proportion of the problem.

California was the first state to legislate for control of engine exhaust emissions, doing such in 1961. They developed a seven-mode chassis dynamometer driving schedule designed to simulate typical driving conditions and specified a nondispersive infared technique for exhaust emission analysis. In 1967, California modified their earlier specifications and established a composite average maximum standard for unburned hydrocarbons and carbon monoxide emissions of 275 ppm and 1.5%, respectively, for reciprocating engines with greater than 140 CID. The federal government following California's direction has adopted a "Clean Air Act"[1] covering the continental United States. Currently the Federal standards, which also use the California simulated driving cycle, are also established at 275 ppm as n-hexane (HC) and 1.5% CO. In 1970 this will be lowered to 170 ppm as n-hexane (HC) and 1% CO. However, there is a distinct possibility that the 1970 standards will be modified and put on a mass flow basis (pounds per hour). A standard of this nature could penalize the large displacement engines with their greater air and fuel consumption.

Considering the great national interest in this problem it is apparent that a new parameter has been thrust at the engine designer. In the past, performance and economy were of utmost importance, and because of their often conflicting nature many compromises were in order. Today a third parameter, exhaust emissions, has assumed equal if not greater importance. This additional consideration has greatly complicated the already formidable task facing our highway transportation industry. Our spark-ignition engines must at least meet the Federal standards before thought can be given to production for the consumer market.

Looking into the future it is conceivable that the eventual emissions standards will be as low as 25 ppm as n-hexane (HC) and .25% CO. This most certainly will provide a monumental challenge to our powerplant designers and could signal an end to our fossil fuel prime movers. However, they most certainly will be in the picture for many years to come.

B. TEST PROGRAM

The RC engine was installed on a dynamometer test stand in the Automotive Engineering Laboratory. This was done in lieu of a chassis dynamometer vehicular test installation for several important reasons:

1. It is difficult to precisely control the engine operating variables on the chassis dynamometer.
2. More convenient access is provided to the engine for development purposes.
3. Steady-state data is easier to obtain and was believed to be sufficient for development work.

The exhaust sampling and analyzing system which was designed and built in our laboratory, was based on the Beckman non-dispersive infared analyzer to provide compatibility with current instrumentation practice in the automotive industry and government laboratories. To minimize cost and decrease the installation time, the system was designed to analyze only one class of exhaust gas pollutants, the unburned hydrocarbons. Another consideration in this decision was that it was believed that the carbon monoxide emissions would follow the same general pattern as the hydrocarbon emissions and would therefore not be of significant value.

The actual test schedule was divided into two separate phases:

1. Tests of the basic engine with the standard exhaust manifold.
2. Tests of the engine with the Curtiss-Wright exhaust reactor manifold.

Prior to development work in each phase, an important series of tests was conducted on the engine to obtain the baseline emission characteristics; these to be used for comparative purposes. This data was examined statistically to gain an understanding of data reproducibility.

In both phases of the test program certain engine operating parameters, which had been found in previous research[2] on reciprocating engines to have significant effect on emissions, were modified to measure their effect on the RC engine hydrocarbon emissions. These variables were fuel/air ratio, spark-advance, and coolant temperature.

The engine with the WAD exhaust reactor was also tested with an exhaust port air injection system to measure air injection effectiveness in reducing emissions.

Several other tests were run incidentally to the primary test program:

1. The RC engine was operated on a propane-air mixture to measure the relative effectiveness of the standard engine's carburetor and induction system in obtaining a homogeneous gasoline and air mixture.

2. A static leak test was conducted to obtain an indication of the raw mixture leakage past the leading apex seal and its contribution to the overall hydrocarbon emissions.

3. A 1965 Chevrolet 283 CID engine was tested to obtain a steady-state emission comparison with the RC engine.

All testing was done under steady-state conditions at one of four engine speeds—1000, 1500, 2000, or 3000 rpm.

II. SUMMARY OF RESULTS, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

1. The exhaust hydrocarbon emissions from the baseline engine without the WAD reactor or air injection are summarized in the following table:

AVERAGE HYDROCARBON CONCENTRATIONS (ppm n-hexane)

Speed (rpm)	Intake Manifold Vacuums (in.Hg.)			
	20	15	10	5
1000	1100	950		
2000	450	400	300	250
3000	225	175	150	140

Note: these data are with #365-129 Champion Spark Plugs.

It was observed that generally the emissions decreased with both an increase in speed and load.

2. Approximately a 15% decrease in emissions was obtained with a 10° retardation of the spark from the MBT setting.

3. Variation in air-fuel ratio had a very significant effect on the emissions. A 25% reduction in the hydrocarbon emissions was observed with optimization (for minimum emissions) of the fuel/air ratio in the engine without reactor and from 75% to 90% reduction in the engine with the exhaust reactor and no air injection.

4. The hydrocarbon emissions decreased slightly with an increase in engine coolant temperature.

5. Operation of the engine with a propane and air mixture showed that the minimum emission equivalence ratio was lower than that with operation on gasoline. No direct comparison of exhaust emissions could be made between the two fuels because the exhaust gases have different compositions.

6. The WAD exhaust manifold reactor, alone, added to the standard engine accounted for approximately a 50% reduction in the hydrocarbon emissions.

7. In the engine at 2000 and 3000 rpm with the exhaust reactor and no air injection, the hydrocarbon emissions ranged from 40 to 70 ppm and less than .06 lb/hr for the minimum emission fuel/air ratio. The equivalent results with the minimum emission fuel/air ratio and spark advance combination were 30 to 50 ppm and less than .05 lb/hr.

8. The exhaust back pressure attained a value of over 12 in. Hg. at 3000 rpm and high load conditions with the reactor on the engine.

9. Temperature increases of 100 to 200°F were measured from the engine exhaust port to the internal core of the reactor.

10. At an idle condition (1000 rpm, no load), the exhaust reactor attained 90% of its steady-state effectiveness (140 ppm n-hexane), 2 min. after a cold start. The emissions were extremely sensitive to the idle screw adjustment; thus, fuel/air ratio.

11. In the standard engine with the exhaust reactor and air injection it was not possible to decrease the exhaust hydrocarbon emissions below 70 ppm at 2000 rpm and 50 ppm at 3000 rpm by varying the exhaust port air injection rate.

12. Generally, minimum emissions from the exhaust reactor-air injection combination were obtained with an injected air rate of 10 to 15% of the engine air at 2000 rpm and 5 to 10% at 3000 rpm.

13. Several signs of wear and deterioration were observed in the WAD exhaust reactor:

a. Erosion of the baffle plates in the inner core.

b. Thermal stress cracking on the middle insulating cylinder at the welds.

c. Warpage of the inner core about its longitudinal axis.

14. During the study the engine was run approximately 250 hours with no failures other than of one spark plug. The spark plugs, however, needed cleaning periodically (every 10 hours).

15. The WAD exhaust manifold reactor was tested for approximately 100 hours.

16. Oil consumption averaged 15-20 hours per quart, or in terms of mileage, 700-1100 miles per quart.

B. CONCLUSIONS

1. The steady-state hydrocarbon emissions of the base RC engine are high, substantially above the road load emissions of an engine capable of meeting the Federal exhaust emission standards.

2. Fuel/air ratio is the engine variable which has the greatest single effect on emissions. Therefore, development of a low emission carburetion system should occupy a position of primary importance in the RC engine research program.

3. It is imperative to utilize a retarded spark for operation at high intake manifold vacuums which correspond to both idle and deceleration conditions.

4. The mixing of the fuel and air and/or the distribution of the mixture to the rotors could be improved as demonstrated by the propane study.

5. An exhaust manifold reactor of the type used in this study appears to hold the greatest promise for successful exhaust emission control.

6. The use of the exhaust reactor without air injection combined with a fuel/air ratio adjustment for minimum emissions provides very efficient emission control, at least under steady-state conditions. This combination demonstrates the greatest promise for a marketable package when compared to an automotive reciprocating engine which may require both air injection and rich mixture ratios to obtain equivalent emission control.

7. The use of air injection does not appear to improve the emissions over those from the engine-reactor combination with the fuel/air ratio adjusted for minimum emissions.

8. In all of the tests the exhaust port temperatures were high enough to initiate a self-sustaining reaction in the exhaust manifold reactor.

C. RECOMMENDATIONS

1. The induction system should be studied extensively to gain improvement in rotor-to-rotor fuel-air distribution and mixture homogeneity. Possibly, increased manifold heat, a dual manifold system such as used on the new Volvo or fuel injection would improve the situation.

2. A number of combustion chamber modifications should be considered to minimize regions of fuel-air mixture through which the flame might not propagate. These could include a decrease of the dead volume above the rotor side seals and between the rotor and rotor side housing, and relieving the rotor surface near the leading and trailing apex seals.

3. The use of multiple ignition sources should be explored, perhaps with phased firing.

4. The size and shape of the WAD exhaust reactor manifold should be modified to obtain an optimum configuration. The current design, however, appeared to be extremely effective.

5. The use of nonmetallic materials should be explored for reactor construction.

6. The exhaust ports could be redesigned to provide for an increased portion of the "after engine" reaction zone within the ports themselves. This is an approach currently being followed in the automotive industry.

7. It would be desirable to measure CO under steady-state conditions to verify the hypothesis that its concentration is directly related to the unburned hydrocarbons.

8. A chromatographic analysis should be made of the RC engine exhaust to establish its composition. This may become an increasingly important factor with respect to the emission control specifications of the Federal Government if, as has been suggested, the standards begin to incorporate regulations of the individual constituents of the exhaust on a reactivity basis.

9. Serious consideration should be given to making a feasibility study of a hybrid combination of the RC engine and an electric generator as a possible powerplant for the small car, urban market.

10. The starter motor capacity should be increased to permit easier starting with a decreased current draw on the battery.

III. TEST EQUIPMENT AND INSTALLATION

A. DYNAMOMETER INSTALLATION

The RC engine was installed initially in test cell 242 of the Automotive Engineering Laboratory at The University of Michigan. It was connected to a Mid-West 300 hp, eddy current dynamometer through a 1964 Dodge Dart automatic transmission, which was used to minimize a torsional vibration problem that could occur with a more conventional dynamometer coupling. The Curtiss-Wright Preliminary Data Compilation Booklet[3] was used, with several modifications, as a guide for installation of the engine. The test installation is shown in Figs. 1, 2, and 3. Note particularly Fig. 3 which shows the engine with the exhaust reactor installed.

Pertinent information regarding the dynamometer, the control instrumentation and comments on the installation are given in Appendix A.

One serious deficiency of the Mid-West dynamometer was the lack of an amplidyne speed control system. This required the dynamometer operator to control both the engine load and speed to maintain a given test condition which proved to be very time consuming both from the standpoint of establishing the test condition and maintaining it.

Consequently, when a dynamometer (G.E. 125 hp) with speed control became available, the RC engine was moved into test cell 244 at the Automotive laboratory. It was believed that the time saved in establishing and maintaining the test points fully justified the switch.

B. TEMPERATURE MEASUREMENT

All temperatures of less than 1000°F, with the exception of the rotor housing temperature, were measured with copper-constantan thermocouples used in conjunction with a Brown continuous indicating potentiometer.

The rotor housing temperature was obtained with iron-constantan thermocouples and indicated on a Leeds and Northrup potentiometer.

All high temperatures, those above 1000°F, were measured with the aid of chromel-alumel thermocouples used with either the Brown potentiometer or a second Leeds and Northrup potentiometer.

C. FLOW MEASUREMENT

Engine air-flow data was required for several parts of the experimental work. It was measured using a specially constructed air cart with rounded-approach circular orifices.

The mass rate of air-flow was measured at the three engine speeds (1000, 2000, and 3000 rpm) as a function of intake manifold vacuum. Test results are

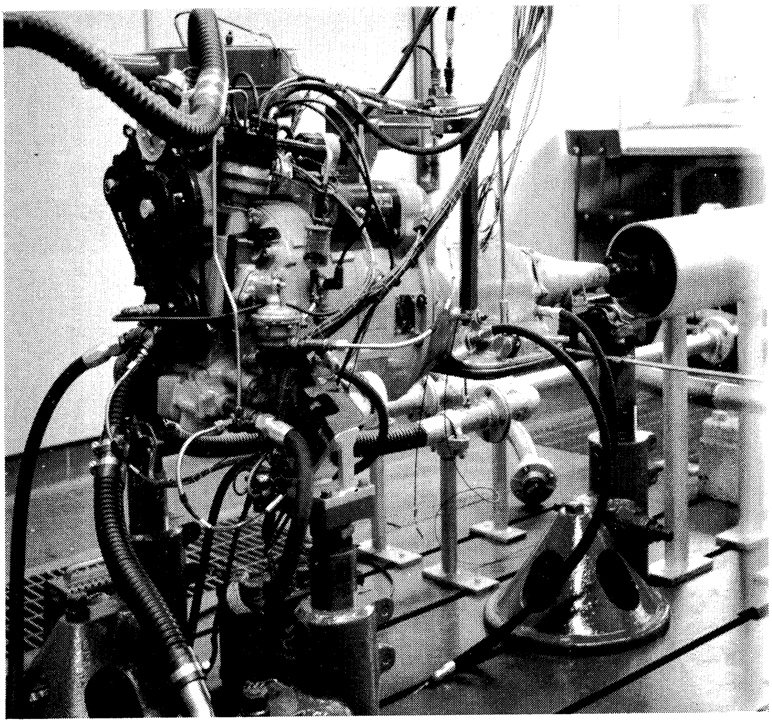

Fig. 1. RC engine dynamometer installation—front quartering view.

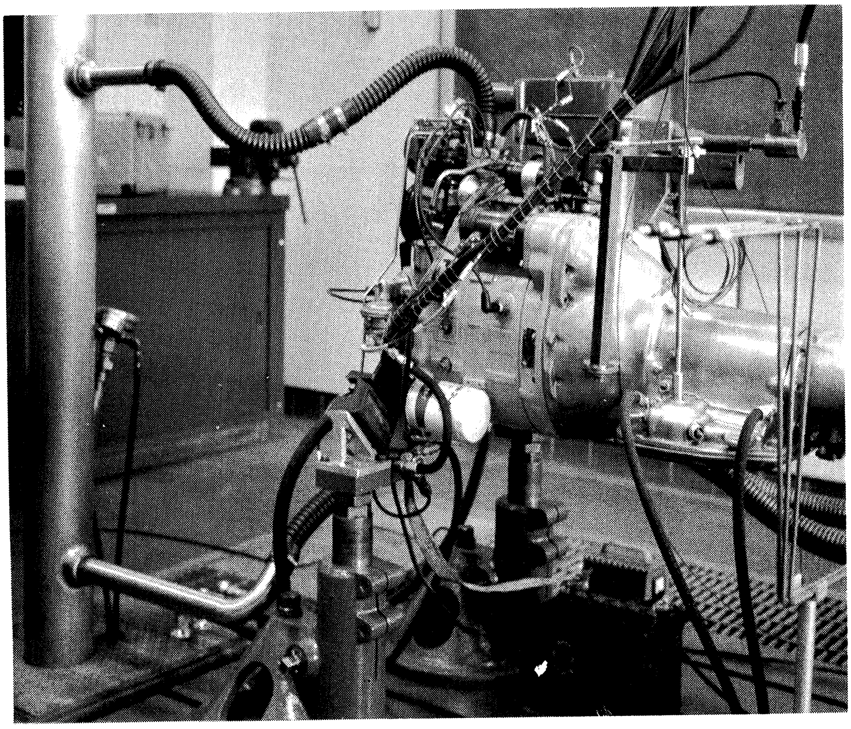

Fig. 2. RC engine dynamometer installation—rear quartering view.

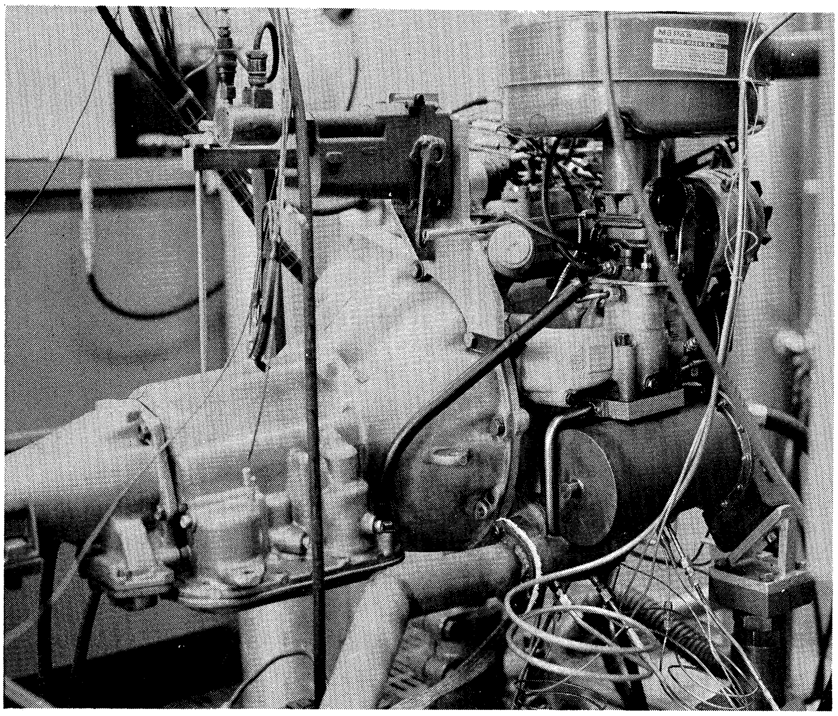

Fig. 3. Instrumented RC engine showing the WAD exhaust reactor.

plotted in Appendix B. As expected the flow rate was almost linear with respect to manifold vacuum at each speed. Thus, knowing the manifold vacuum at any of the three speeds it was possible to obtain the approximate air rate.

Brooks rotometers were utilized in measuring the propane flow rate in the carburetor mixing and distribution studies, and the air injection rate in the exhaust reactor air-injection experiments. These units were calibrated individually with a positive displacement air bell.

D. SPEED MEASUREMENT

Both the RC engine crankshaft speed and the dynamometer speed were measured with Hewlett-Packard electronic counters. It was necessary to measure both speeds because of transmission slippage which is an inherent property of conventional automatic transmissions.

E. FUEL/AIR RATIO MEASUREMENT

All measurements of gasoline fuel/air ratio were made with the well known Orsat technique which involves measurement of the volume percentage of carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2) in the exhaust gas. The calibration curve[4] of fuel/air ratio as a function of exhaust gas composition for gasoline is shown in Appendix C.

F. EXHAUST HYDROCARBON MEASUREMENT

Perhaps the single most important measurement made in this research program was the concentration of unburned hydrocarbons in the exhaust gas. To accomplish this end an exhaust hydrocarbon sampling and analyzing system was designed with the aid of Refs. 5-9 and built into a large, fully enclosed bench. The complete installation is shown in the photographs of Figs. 4 and 5. Note: Beckman NDIR analyzer is not shown in Fig. 5.

The system is shown schematically in Fig. 6. The normal path of the exhaust gas sample is shown by the heavy black line. A viton-diaphragm, Air Shield Pump was used to draw the sample from the specially constructed stainless steel exhaust pipe probe which is shown in Fig. 7, into an ice bath which was used to condense most of the water vapor from the exhaust sample. The condensation step was necessary because the analyzer used was responsive to water and would thus given an erroneous hydrocarbon concentration measurement if the water vapor was not removed. Following the trap, a 2-in. paper element filter made by Gelman Instrument Company removed particulate matter from the sample. The flow rate through the system was regulated by a Hoke needle valve and measured with a Fischer and Porter rotameter. A Beckman model 315[10] nondispersive infrared (NDIR) analyzer was used to measure the hydrocarbon concentration in the exhaust sample. Initially the Beckman instrument was equipped with a 5-1/4 in. sample cell which provided accurate hydrocarbon measurements in the range from 100 to 1500 parts per million (ppm). Due to consistently low hydrocarbon readings in the latter stages of the test program the 5-1/4 in. sample cell was replaced with a much more sensitive 13-1/2 in. cell which permitted accurate measurement of hydrocarbon concentration in the range from 20-500 ppm.

Stainless steel tubing was used from the exhaust probe to the paper filter to prevent corrosion and contamination by reactive material in the high temperature exhaust gas. Copper tubing was used in the remainder of the system.

A stainless steel sample tank was incorporated in the system to collect an exhaust gas sample which could then be analyzed by the Perkin-Elmer flame ionization analyzer available in the Combustion Laboratory of the Automotive Laboratory. This provided a periodic check on the continuous sampling Beckman analyzer. The sample tank and copper manifolding were evacuated by a Cenco vacuum pump prior to obtaining a sample.

To insure accurate analyses with the Beckman instrument periodic calibration was required. Six different concentrations of normal hexane* (n-hexane) in nitrogen from 25 to 1200 ppm were used as the standard reference gases. These gases were purchased from Matheson in No. 2 high pressure gas cylinders. A sample calibration curve for the Beckman analyzer is shown in Appendix D.

Nitrogen was used to purge the system after sampling of the exhaust and to establish a zero reference in the Beckman analyzer.

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*Normal hexane (n-hexane-C_6H_{14}) is specified by current government standards as being representative of the average composition of the unburned hydrocarbons in the exhaust gas and therefore, is used as the standard reference gas.

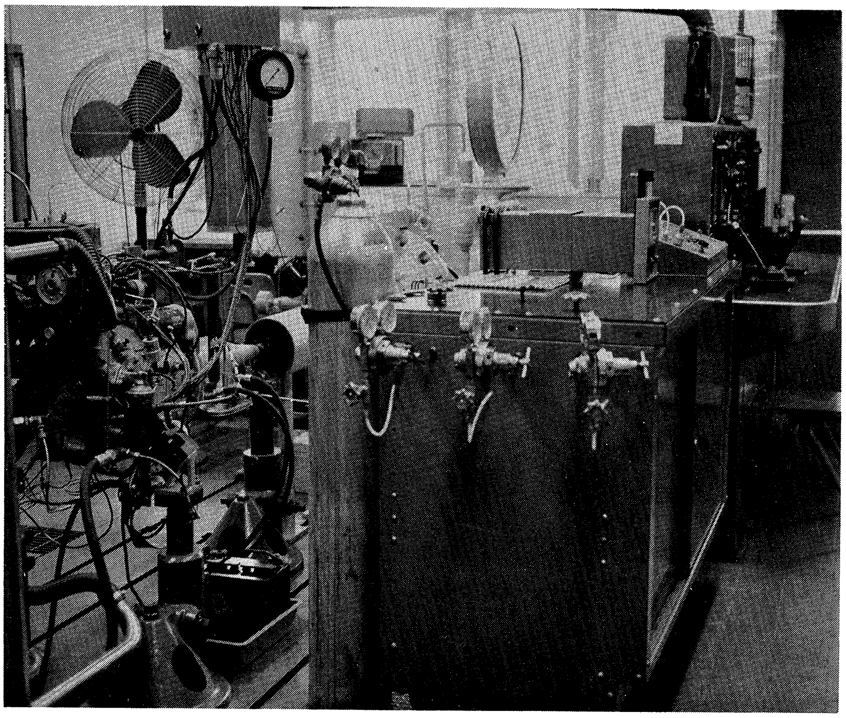

Fig. 4. Exhaust gas hydrocarbon sampling and analyzing cart—side view.

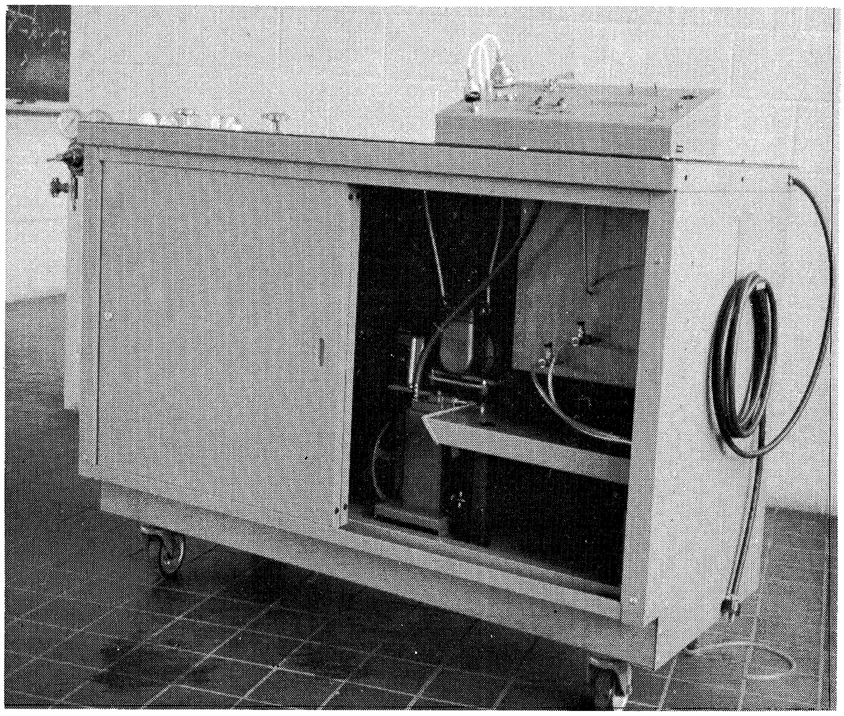

Fig. 5. Exhaust gas hydrocarbon sampling and analyzing cart—interior view showing water trap, and diaphragm and vaccum pumps.

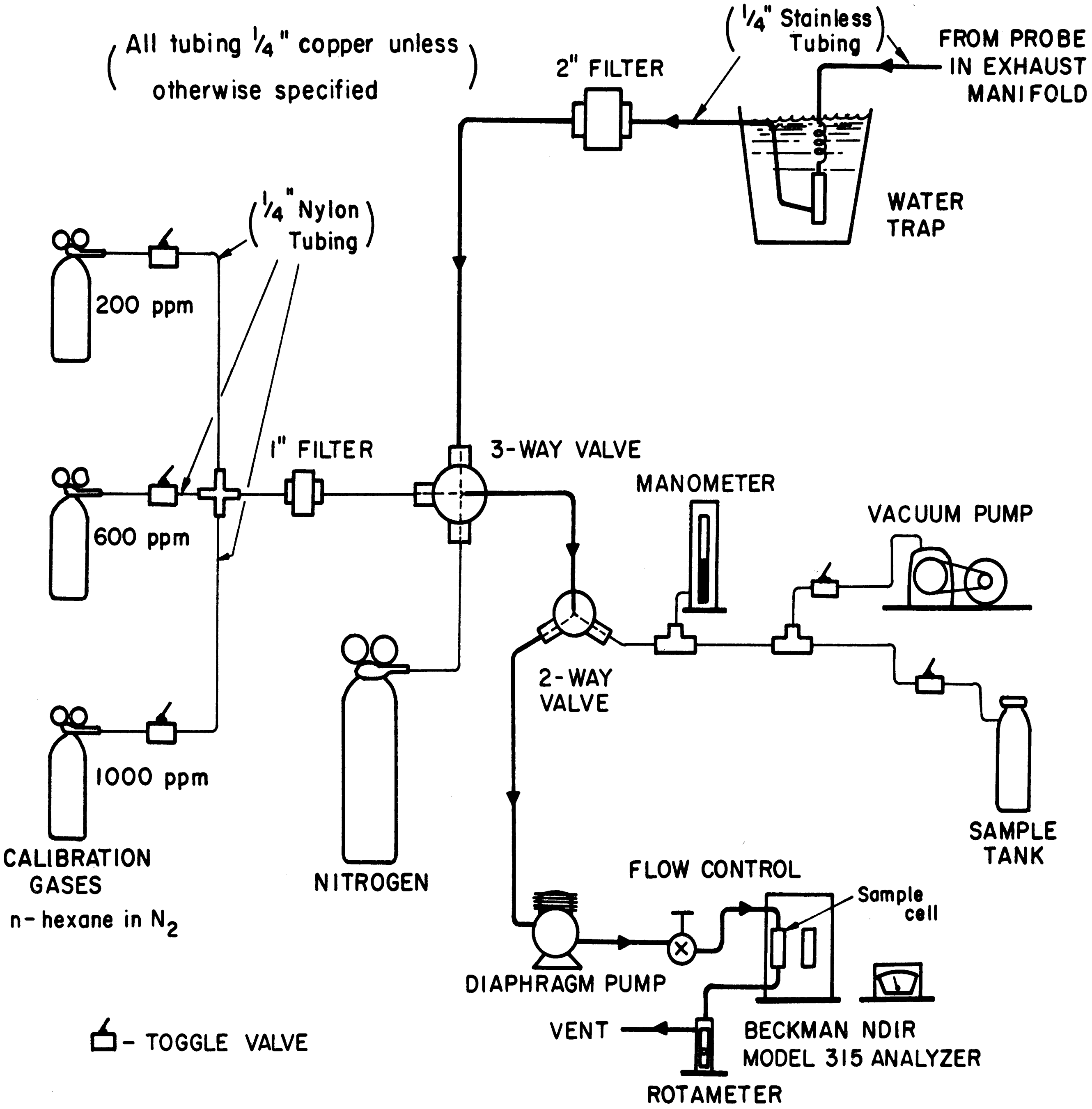

Fig. 6. Exhaust gas hydrocarbon analysis system—schematic diagram.

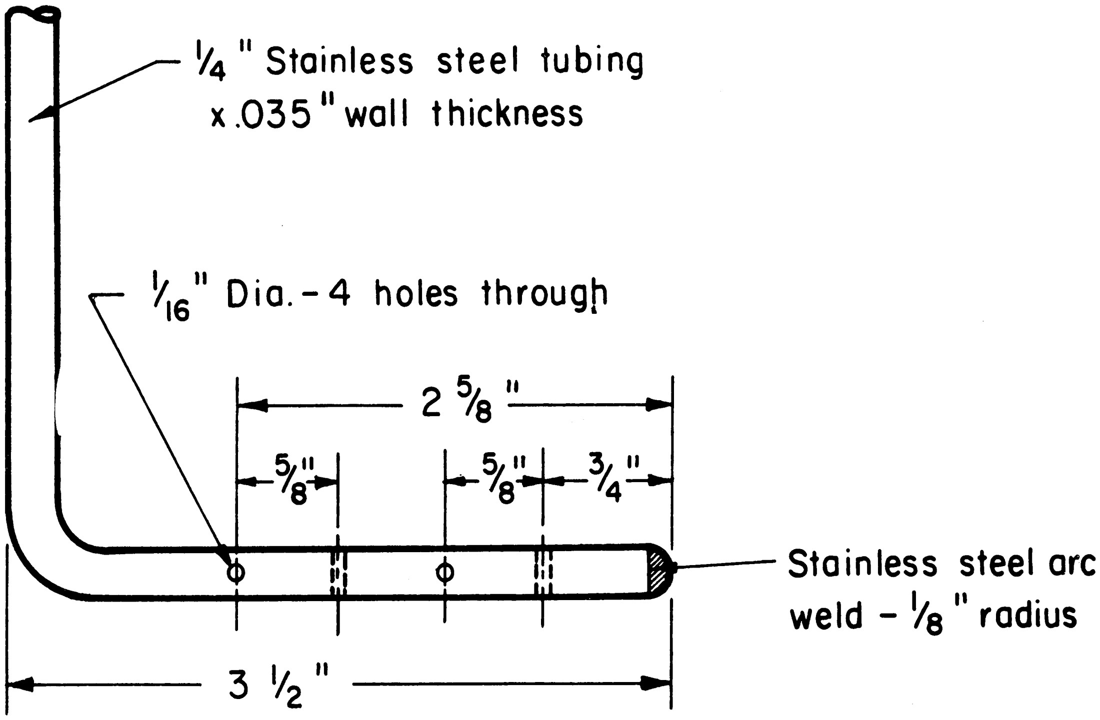

Fig. 7. Exhaust gas sampling probe.

The output of the Beckman analyzer, which was proportional to the hydrocarbon concentration, was read directly from a microampere meter on the amplifier section of the analyzer. This was done in lieu of using a pen recorder, such as Texas Instruments servo/riter II because of the recorder's initial expense ($1,000-$1,500) and more significantly, the long time delay for delivery (6-9 months).

G. PROPANE-AIR MIXING SYSTEM

A propane-air carburetion and mixing system was designed[11,12,13] and built to furnish a homogeneous fuel/air mixture to the engine. The engine operation with the gasoline-air mixture furnished by the standard carburetor could then be compared to that with the propane system to obtain a measure of the standard systems effectiveness.

A schematic diagram of the apparatus is shown in Fig. 8. Important components of the system are labeled. A Century gaseous fuel carburetor was used to obtain proper metering of the propane into the air. The fuel/air ratio was varied by changing the fuel supply pressure.

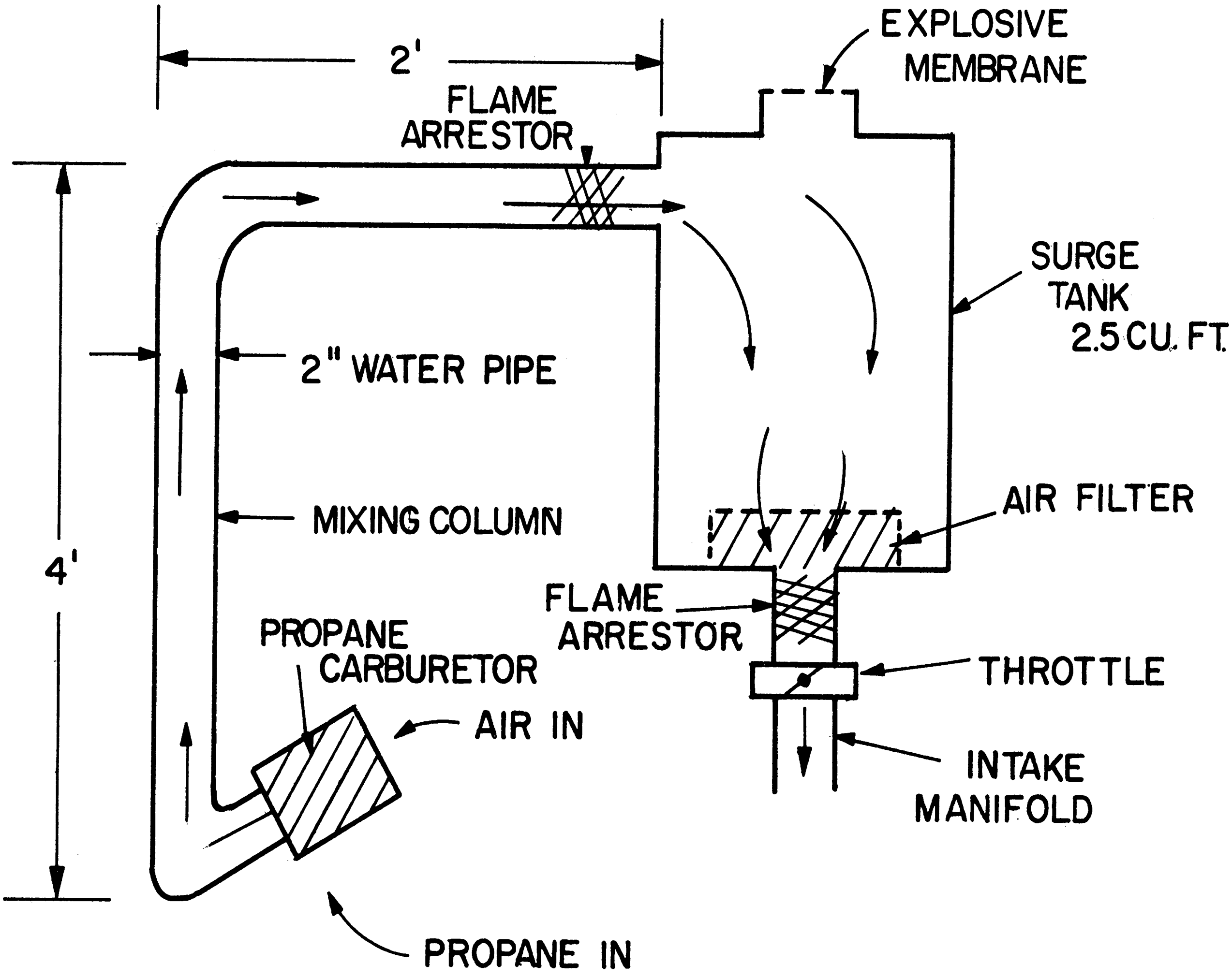

Fig. 8. Propane and air mixing system—schematic diagram.

H. AIR INJECTION SYSTEM

For part of the experimental work on the engine-exhaust reactor combination an exhaust port air injection system[14] was required. A rather simple system was devised which used shop air as the high pressure supply. The injection pressure was controlled with a conventional 0-50 psi regulator and the flow rate measured with a Brooks rotometer which was calibrated in CFM. A flow balanced, air manifold was constructed which proportioned equally the air to the two ports.

The position of the air injection nozzles and also the bayonent type exhaust thermocouples in the exhaust ports is shown in Fig. 9. In this particular figure the air injection nozzles are shown at the right side of each port. All air injection testing was done, however, with the air nozzles in the central position, not in the location shown in the photograph.

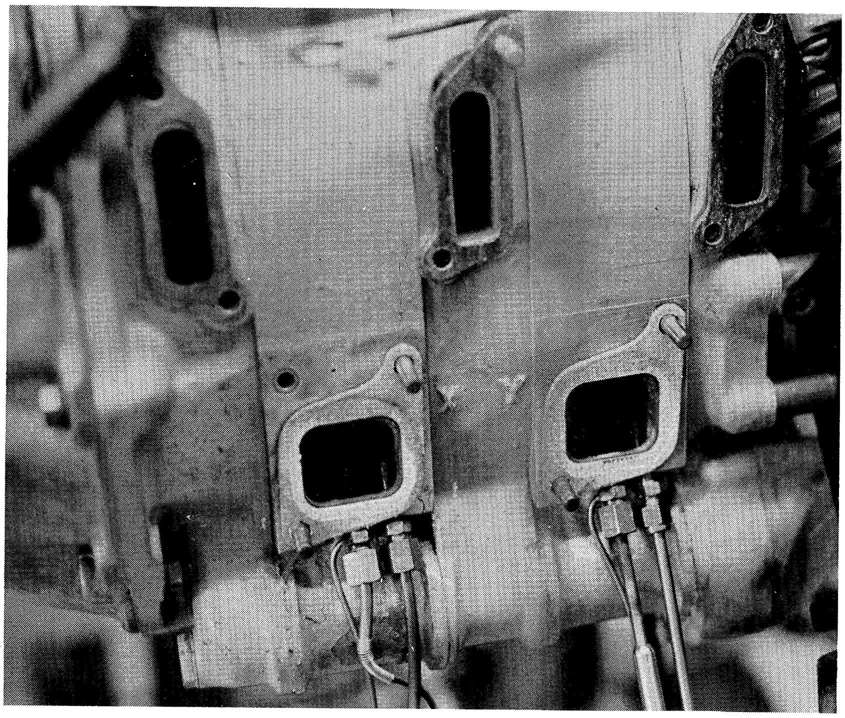

Fig. 9. RC engine exhaust ports showing the air injection tubes, and pressure and temperature instrumentation.

Each injection nozzle was made from stainless steel tubing. Air was injected from eight equally spaced holes in the tubing wall which provided good mixing of the air with the hot exhaust gases.

IV. RESULTS AND ANALYSIS

The results of the experimental work are presented and discussed in the chronological order that they were performed.

A. Base Engine without the WAD exhaust reactor or air injection.
B. Engine with the WAD reactor and without air injection.
C. Engine with the WAD reactor and air injection.

Also included in this section of the report is:

D. Discussion of the exhaust reactor system.
E. General analysis of the sources of exhaust emissions from the RC engine.

A. BASE ENGINE WITHOUT EXHAUST REACTOR

The initial and one of the most important phases of testing was the measurement of the base-line emission characteristics of the "as received" RC engine. This was necessary to firmly establish a basis of comparison for all development work on the engine to minimize the exhaust hydrocarbon emissions. The results of this study are shown in Fig. 10 where the hydrocarbon emissions measured as parts per million (ppm)of n-hexane are plotted as a function of the intake manifold vacuum (in. Hg.) at three engine speeds (1,000, 2,000, and 3,000 rpm). Several important conclusions can be drawn from this data:

1. The hydrocarbon emissions decrease with an increase in speed.
2. The emissions decrease with an increase in load.

At 1000 rpm, which closely corresponds to an idle condition, a sharp increase in emissions was observed at intake manifold vacuums greater than 19 in. Hg. This undoubtedly was caused by misfiring brought on by excessive dilution of the intake charge with exhaust residual. In reciprocating engines this same effect is observed but it generally occurs at a higher intake manifold vacuum.

An interesting feature of the 2000 and 3000 rpm curves was the apparent effect of spark-plug heat on the emissions. At both speeds a hotter plug (Champion #365-129) resulted in a slight decrease in emissions. This may have resulted from poorer combustion initiation with the cold plugs (Champion #365-127) caused by cooler electrodes or a deposit formation on the electrodes. It was necessary to clean the cooler plugs every 3 or 4 hours to maintain smooth engine operation.

A full range of engine loads was not investigated at 1000 rpm because of a conflict with the automatic transmission shift points.

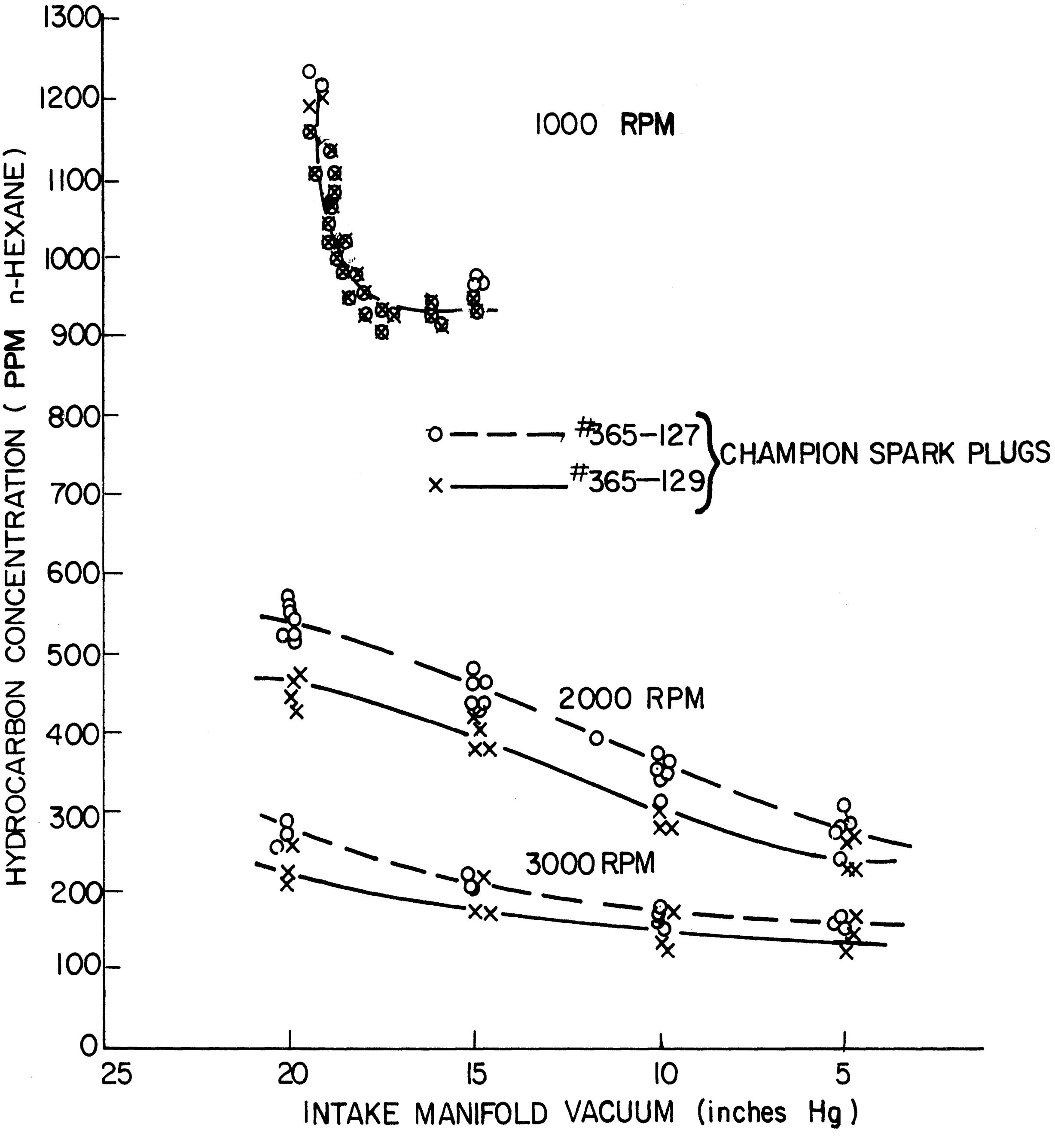

Fig. 10. Baseline hydrocarbon emissions as a function of intake manifold vacuum—standard RC engine without WAD reactor.

The concentation emissions from the individual rotors and the average total of both rotors for the base engine are shown in Fig. 11 for 2000 and 3000 rpm. Notice that there is a significant spread, up to 50 ppm, in the emissions from the two rotors. At 2000 rpm the hydrocarbon concentrations from the two rotors cross at 13 in. Hg. intake manifold vacuum with the front rotor (#1) initially having higher emissions and then, at a load greater than 13 in. Hg;. lower emissions.

The total exhaust was sampled at a point about 3-1/2 ft. downstream from where the exhaust from the individual rotors was sampled. Generally the hydrocarbon concentration in the total exhaust was approximately the average of that from the two rotors considered individually. There was one exception though, at 2000 rpm and 12 in. Hg. gage pressure. Here the total was somewhat lower which was probably caused by slight oxidation of unburned hydrocarbones in the exhaust system between the sampling probe locations.

Figure 12 shows the influence of spark-advance on the hydrocarbon emissions in the standard engine at 2000 rpm and 10, 15, and 20 in. Hg. manifold vacuum. The emissions were found to decrease with retardation of the spark which is consistent with the findings in reciprocating engine studies. The retardation generally leads to somewhat slower combustion and higher average temperatures—both of which promote more complete oxidation of the unburned reactants. The results are shown as a band to cover the range of emission values observed in the testing. This practice was followed in most of the following figures where it could be accomplished without excessive confusion. It must be noted that all experimental data is not absolutely reproducible and thus, a spread of data occurs at every test point.

In the next series of tests a variable fuel/air ratio carburetor was installed on the RC engine. This carburetor used an external control on the enrichment valve which permitted the main metering systems' fuel jet area to be varied by the operator. The results are shown in Fig. 13 for the engine at 2000 rpm and 10, 15 and 20 in. Hg manifold vacuum.

Variation of the air/fuel ratio had a very significant effect on the hydrocarbon emissions. Approximately a 25% decrease in hydrocarbon emissions was observed with the minimum emission air/fuel ratio. The minimum emission air/fuel ratio was approximately 2-1/2 ratios leaner than stoichiometric at 10 and 15 in Hg. manifold vacuum and 1/2 ratio leaner at 20 Hg. manifold vacuum.

The curves appear to have the same characteristic shape as those from automotive type reciprocating engines. One point must be made with respect to the use of the air/fuel ratio data as a measurement of the absolute air/fuel ratio furnished to the engine. The Orsat technique, which was used to measure air/fuel ratio in the research program, is not considered to be an accurate quantitative device. It is, however, adequate for relative measurements of air/fuel ratio.

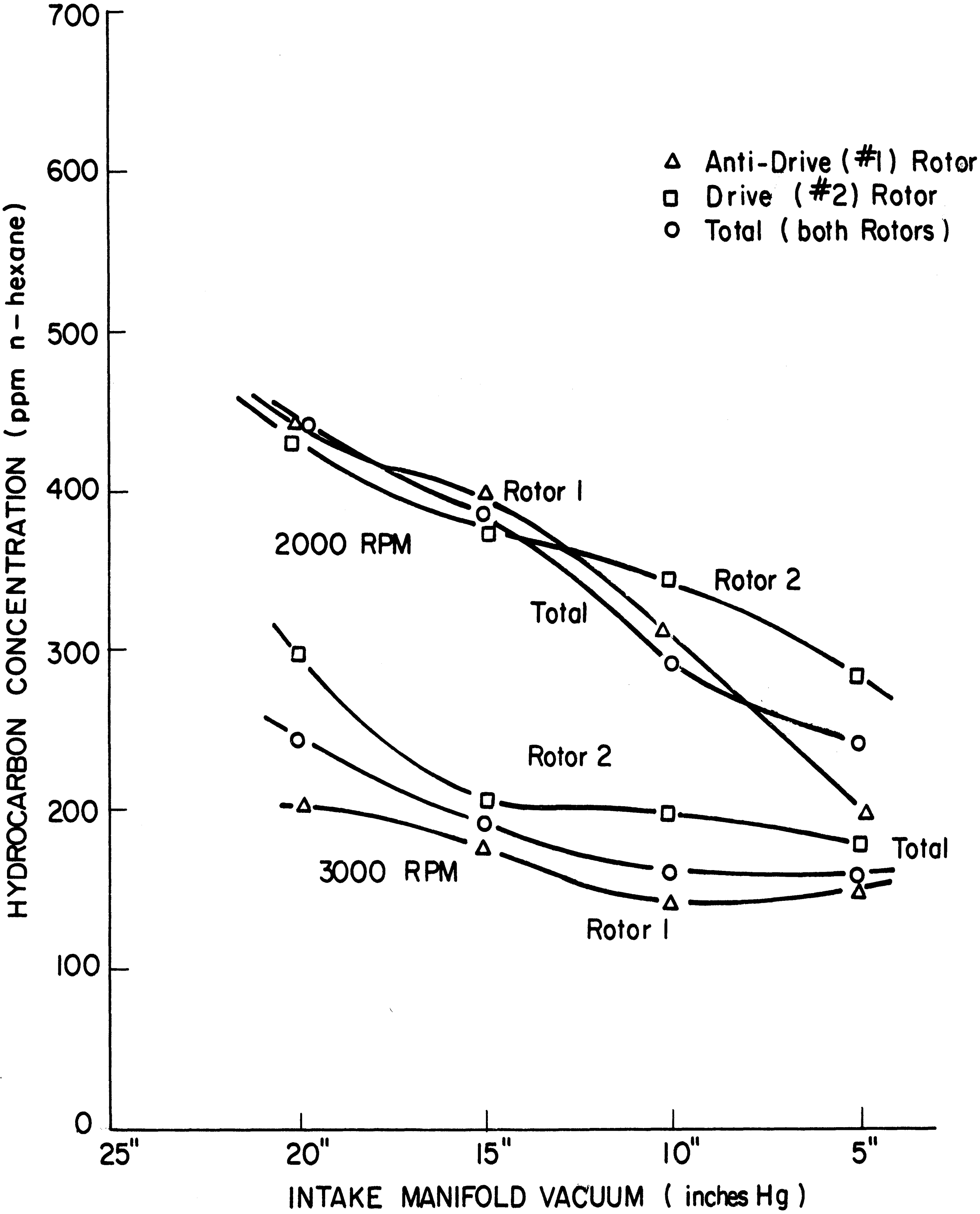

Fig. 11. Baseline hydrocarbon emissions from the exhaust of individual rotors and the combined exhaust—standard RC engine without reactor.

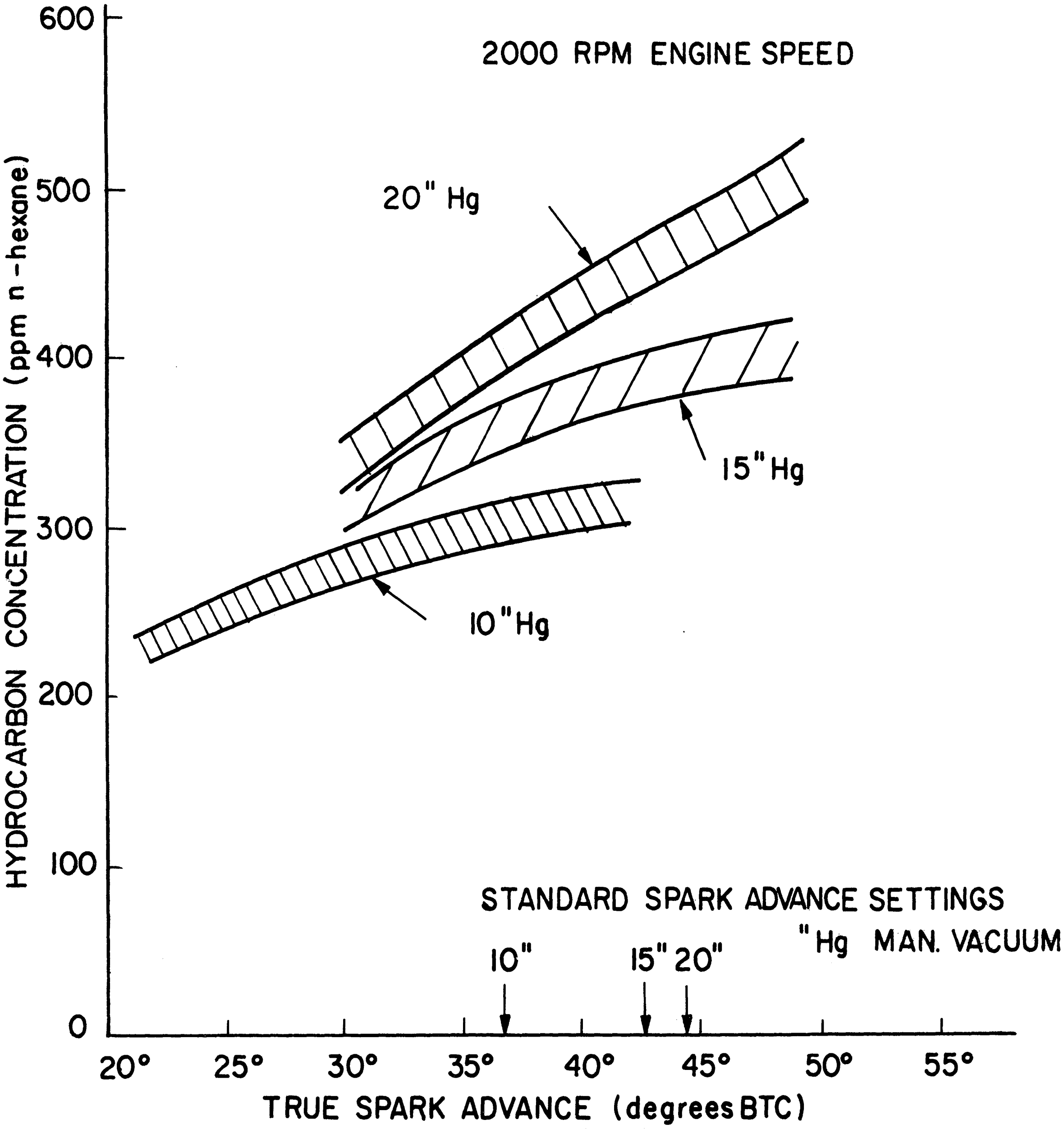

Fig. 12. The effect of spark advance on the hydrocarbon emissions—RC engine without reactor.

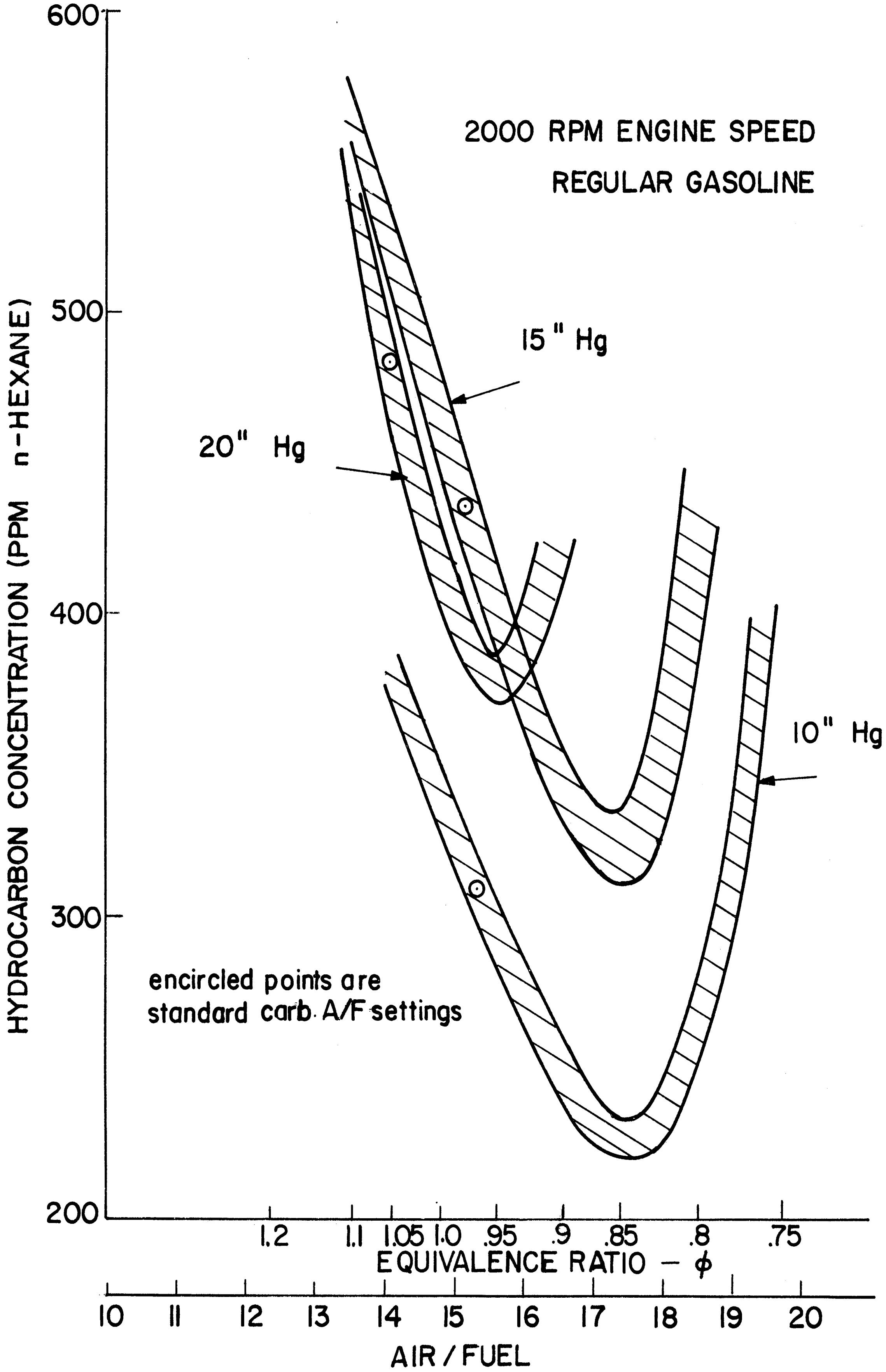

Fig. 13. Hydrocarbon emissions as a function of air/fuel ratio with regular gasoline at 2000 rpm and several intake manifold vacuums—RC engine without reactor, MBT spark advance.

At mixture ratios leaner than the minimum emission air/fuel ratio a very sharp rise was noticed in the unburned hydrocarbons. This was caused by the misfiring which occured as the lean combustability limit was approached.

Most of the air/fuel ratio and spark-advance testing was done at 2000 rpm. It was believed that this speed with variable loads was representative of most engine conditions and would suffice to show the effect of the stated variables on the exhaust emissions.

The next series of tests were intended to measure how effective the induction system was at providing an equally distributed, homogeneous air/fuel mixture to the two rotors. To do this a propane-air carburetor and manifold system was designed and built which would essentially provide a single phase, homogeneous mixture to the engine. It is reasonable to expect that this was effectively accomplished in the propane-air system because propane is in the superheat region at room temperature and atmospheric pressure, and a large mixing volume was provided prior to induction into the engine.

The results are plotted in Fig. 14 for the engine at 2000 rpm with three different loads and show the same characteristic shape as the hydrocarbon emission—air/fuel ratio curves for gasoline. The only significant variation is that the minimum concentration point for 20 in. Hg. manifold vacuum occurs at a leaner mixture ratio than those of the 10 and 15-in. curves. Generally this minimum point would be expected to both increase in mangitude and occur at higher mixture ratios with an increase in intake manifold vacuum due to greater exhaust dilution and decreased absolute pressure which cause increased time losses.

The gasoline and propane data is compared in Fig. 15 which shows that the minimum emission point occurs at lower equivalence ratios (leaner mixtures) with the propane fuel. Several points must be brought out about this comparison.

1. The only significant information is that the gasoline fueled engine can not operate as lean as the propane fueled engine and still achieve minimum emissions.
2. The absolute emission levels cannot be directly compared because the use of propane and gasoline as fuels result in different exhaust gas compositions which may cause the Beckman NDIR analyzer to respond nonlinearly with respect to concentrations from the two exhaust samples.
3. The results are plotted against equivalence ratio (relative fuel/air ratio) because the gasoline-air and propane-air chemical reactions have different stoichiometric air/fuel ratios, (14.8 for gasoline, 15.7 for propane).

Figure 16 shows the results of operating the RC engine at several water inlet temperatures and demonstrates that high coolant temperatures are desirable to minimize the hydrocarbon concentrations. The testing was done at 1500 and 2000 rpm with 5, 10, 15, and 20 in. Hg. intake manifold vacuum. The hydrocarbon emissions are about 10% higher with a 140°F water inlet temperature

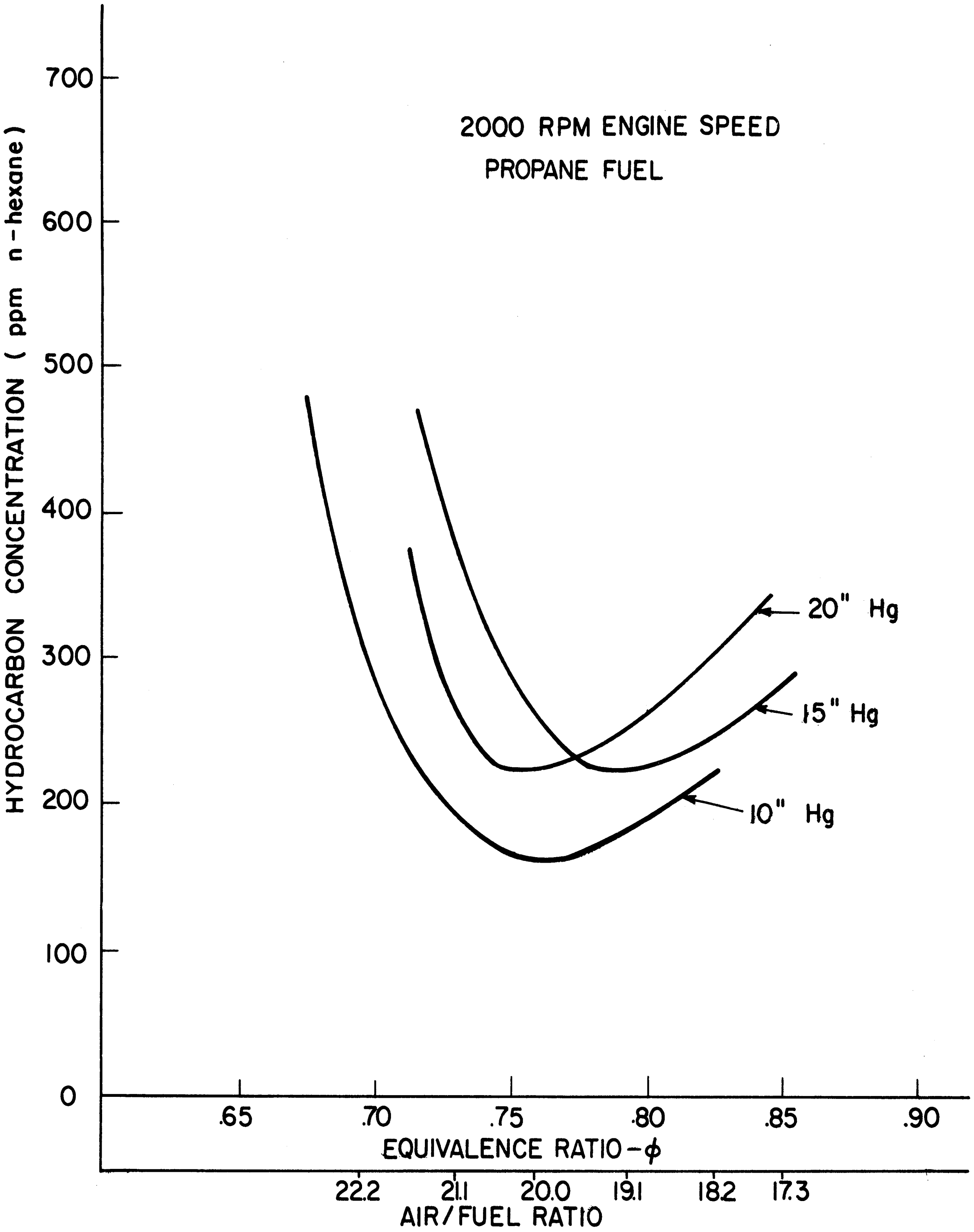

Fig. 14. Hydrocarbon emissions as a function of air/fuel ratios with propane fuel at 2000 rpm and several intake manifold vacuums—RC engine without reactor, MBT spark advance.

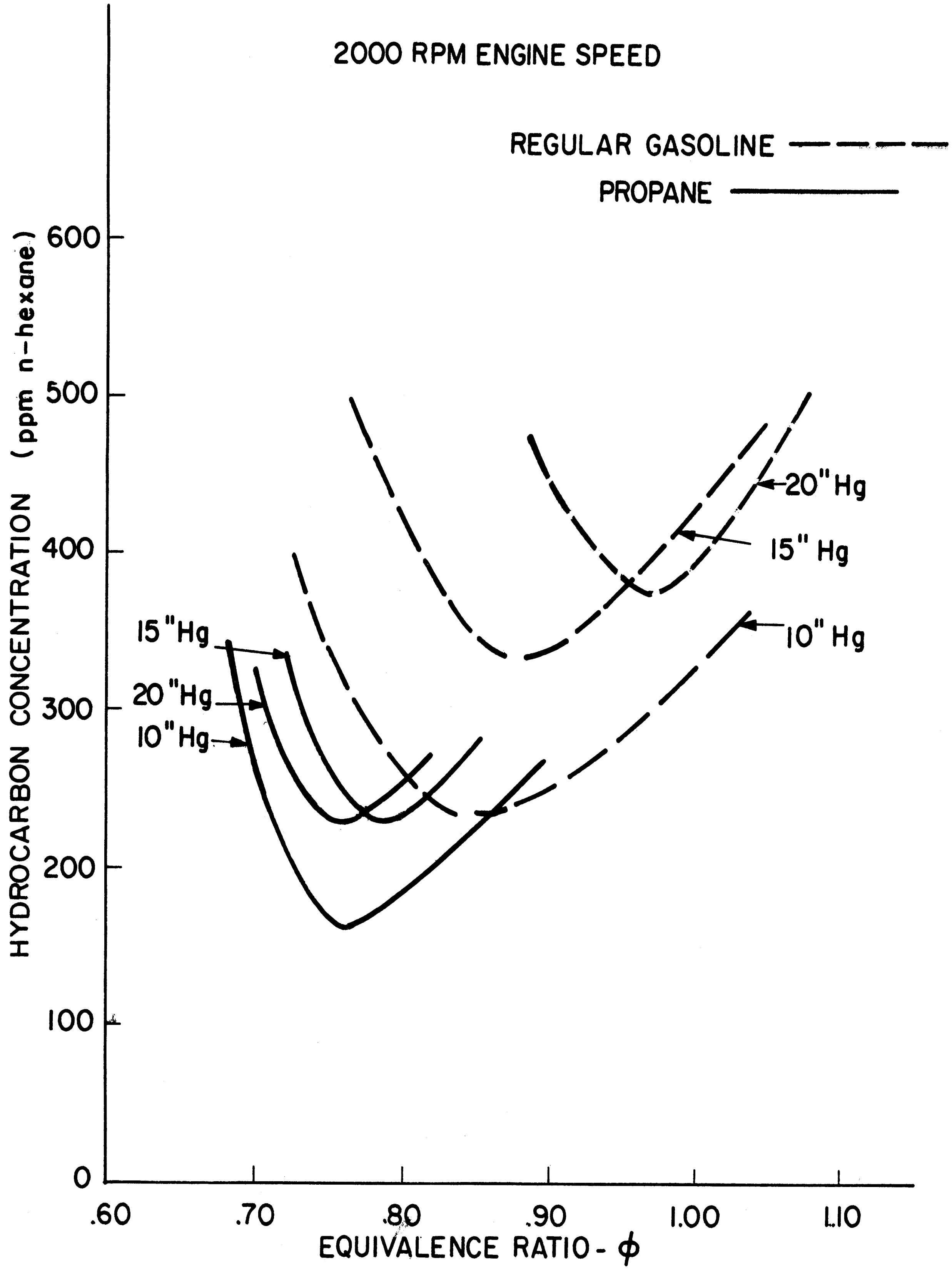

Fig. 15. Hydrocarbon emissions as a function of equivalence ratio with both regular gasoline and propane fuel—RC engine without reactor, MBT spark advance.

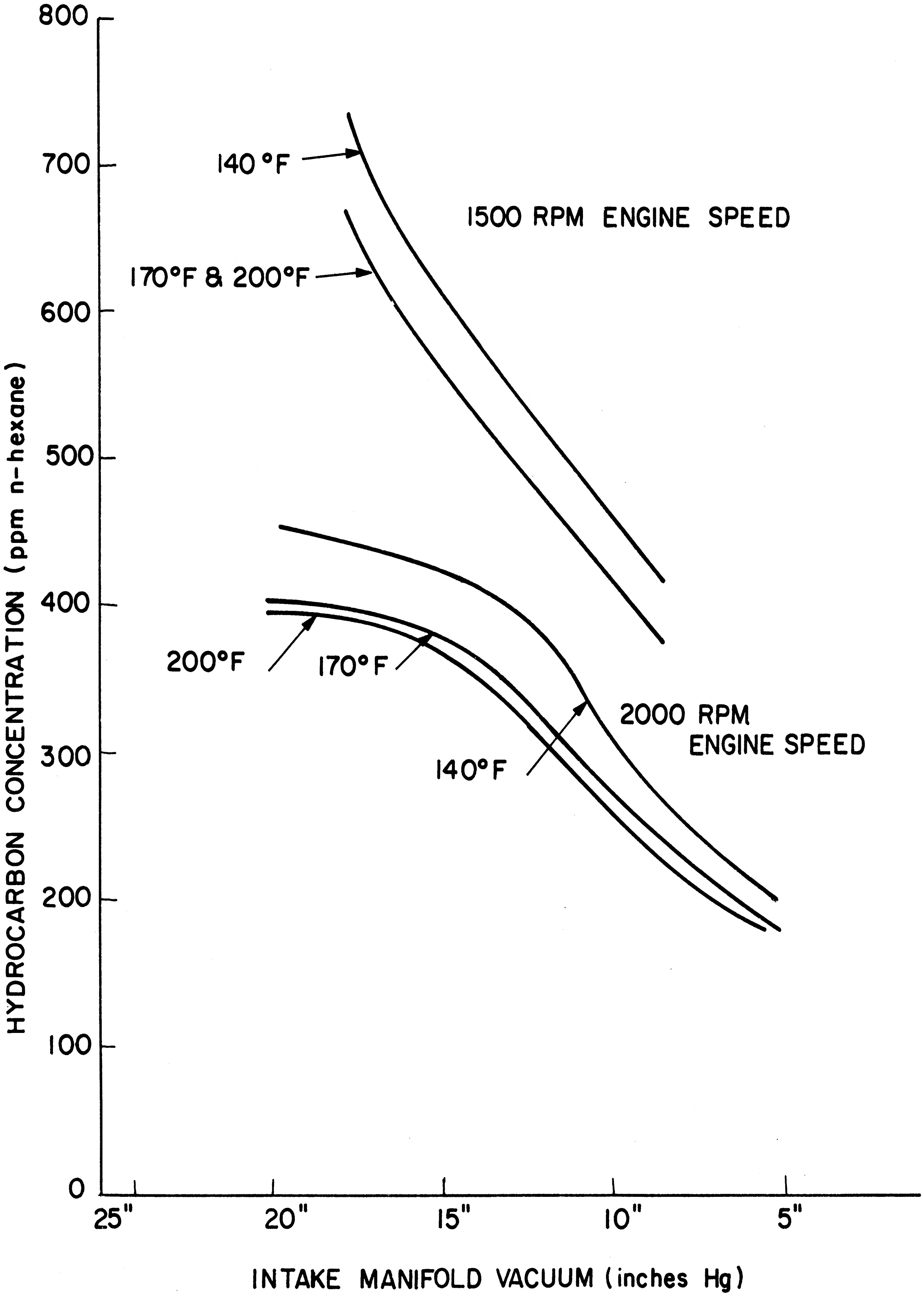

Fig. 16. Effect of coolant temperature on hydrocarbon emissions—RC engine without reactor.

than at a 170°F temperature. Beyond 170°F little reduction in concentration was observed with increasing engine coolant temperature.

During the context of the RC engine test program it became of interest to measure the exhaust gas hydrocarbon content of a conventional automotive reciprocating engine for comparative purposes. A 1965 model Chevrolet 283 CID engine was selected for this test since it was available in the Automotive Laboratory and had approximately the same power rating as the RC engine. The results of this test are shown in Fig. 17.

The same general trend of hydrocarbon emissions with speed and load that occurred in the RC engine was observed in the Cheverolet engine. The RC engine, however, demonstrated a greater range of emission levels, being much higher at low speeds (under 2000 rpm) and moderately lower at high speeds (greater than 2000 rpm). The emissions from the Chevrolet engine increased at high loads due to the functioning of the enrichment valve in the carburetor. The current automotive engines exhibit much lower emissions at steady state than this engine because of the addition of the so-called "Smog Package." This suggests that the RC engine, with the proper modifications, could also be built to satisfy current Federal exhaust emission standards.

B. BASE ENGINE WITH THE EXHAUST REACTOR

As with the initial study of the RC engine without the exhaust reactor the first experimental study with the reactor was the establishment of baseline exhaust hydrocarbon emission and other pertinent data with standard operating conditions. This base line information is shown in Figs. 18 through 24.

The first of these figures, Fig. 18, indicates the exhaust hydrocarbon emissions at 2000 and 3000 rpm as a function of load (intake manifold vacuum). In addition to the previous practice of reporting the results on a concentration basis, the mass hydrocarbon emissions per unit time (lb/hr) are also shown. A computer program was developed which utilized hydrocarbon concentration data along with engine air flow and fuel/air ratio data to compute the mass emissions. Details of this procedure are shown in Appendix E. The mass emission calculations were stimulated by the fact that the Federal government is giving serious consideration to a total mass rather then concentration standard in 1970.

Perhaps the most significant conclusion which may be drawn from this figure, with reference to Fig. 1, is that merely by the addition of the reactor approximately a 50% reduction in the hydrocarbon emissions is affected. The hydrocarbon concentration is almost constant at 75-100 ppm at 3000 rpm and decreases almost linearly from 275 to 100 ppm with increasing load at 2000 rpm.

Because of the fact that the air flow rate changes with both speed and manifold vacuum the mass emission data in the upper curves of Fig. 18 does

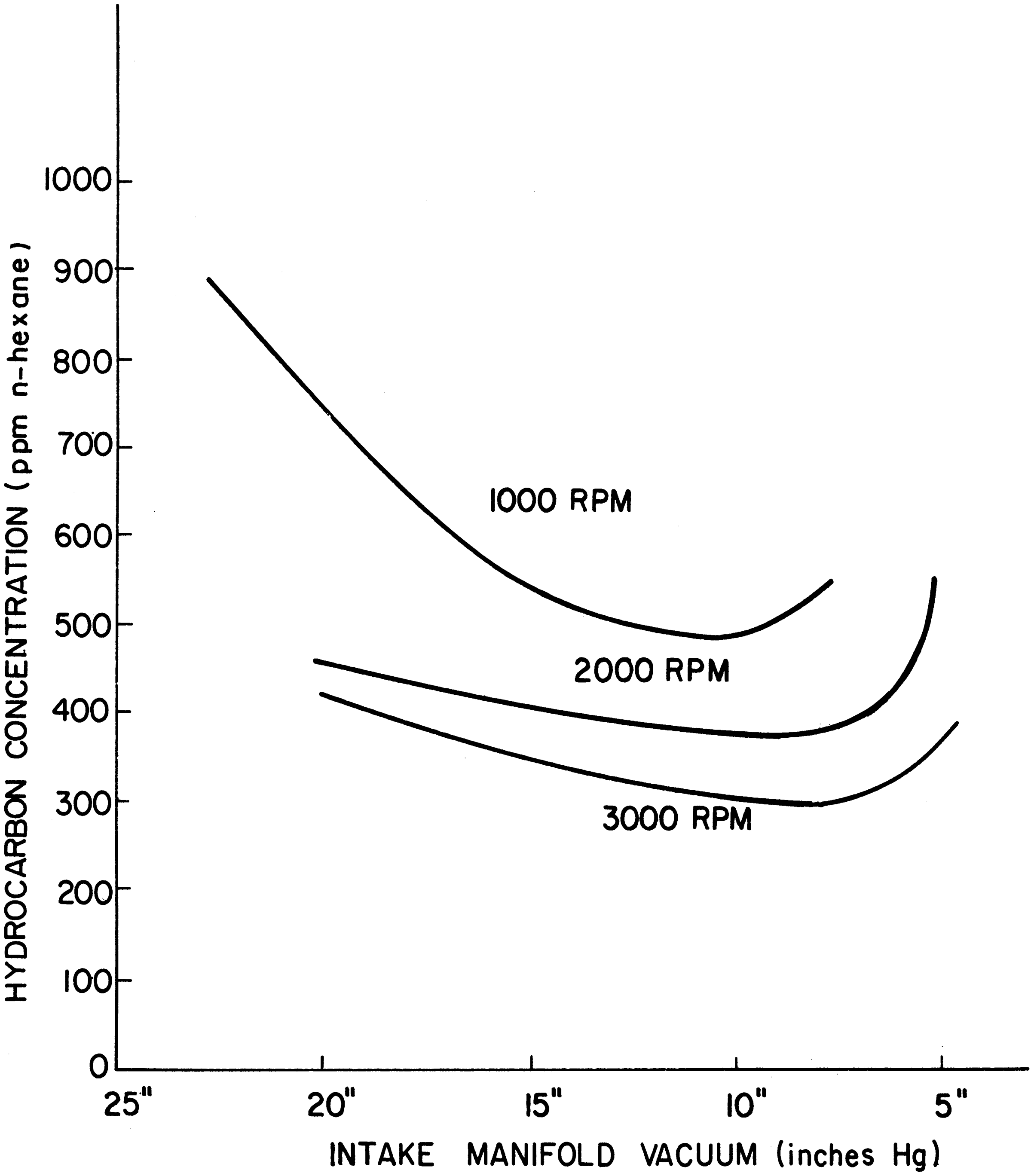

Fig. 17. Steady state hydrocarbon emissions from a 1965 Chevrolet (283 CID) engine.

not follow the same pattern as the volume concentration data. Here it can be seen that even though the air flow rate is higher for a given manifold vacuum at 3000 rpm than 2000 rpm, the mass emissions are still higher at 2000 rpm except at high loads.

The RC engine horsepower and torque data is shown in Fig. 19 as a matter of interest. Also included are curves of the dynamometer rpm, which is different than the engine speed because of transmission slippage. Note that this slippage, as expected, increases with load.

An important variable with the addition of the somewhat restrictive exhaust manifold reactor was the back pressure at the exhaust ports. These data for 2000 and 3000 rpm are shown in Fig. 20. The system seems to become quite restrictive (12 in. Hg. gage pressure) at moderate speeds and high loads. One can speculate that this back pressure might be a limiting factor in the design of a reactor, considering that the engine should function efficiently at speeds up to 6000 rpm and loads of 2-3 in. Hg. manifold vacuum. Test data was not obtained at these high speeds and loads because of an imbalance in the dynamometer coupling which caused excessive vibration above 3000 rpm.

Contrary to the adverse effect on engine power, the higher the exhaust back pressure the greater is the exhaust reactor's effectiveness. The reactivity of the unburned hydrocarbons increases functionally with pressure. A variable exhaust restriction device which would increase the back pressure at low loads and speeds, and relieve back pressure at high loads and speeds could offer additional emission control.

Figures 21 and 23 indicate the pertinent low termperature data from the engine at 2000 and 3000 rpm, respectively. Included are the oil in and out, water in and the air inlet temperatures. Generally, these temperatures remaim almost constant throughout the range of loads.

High temperature exhaust gas data is shown in Figs 22 and 24 also for 2000 and 3000 rpm. Relative to functioning of the reactor as an exhaust gas combustion chamber this information is of critical importance. It has been shown[15] that in the temperature range of approximately 1400°F-2000°F for every 40°F increase in temperature there is a corresponding doubling of the reactivity of the unburned constituents in the exhaust gas. Thus, it is imperative to maintain the temperatures before and in the reactor at the highest possible and/or practical values to achieve the maximum reaction in a minimum reactor volume.

The RC engine appears to be particularly adaptable to the type of exhaust reactor used in this study for a number of reasons:

1. An exhaust process occurs every crankshaft revolution in each exhaust port rather than every other revolution as in the case of the 4-stroke cycle reciprocating engine.

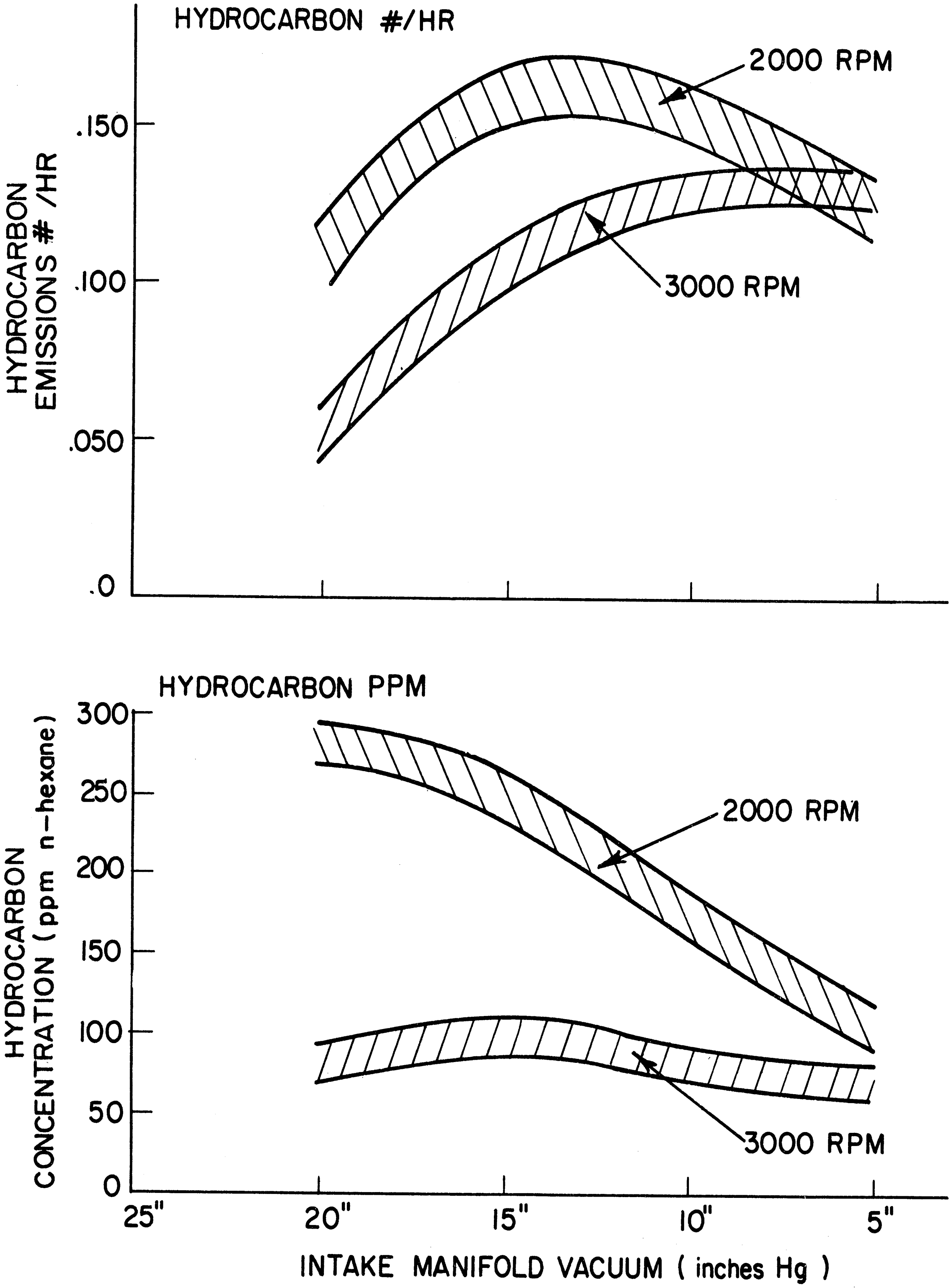

Fig. 18. Baseline hydrocarbon emissions as a function of intake manifold vacuum—standard RC engine with WAD reactor, no air injection.

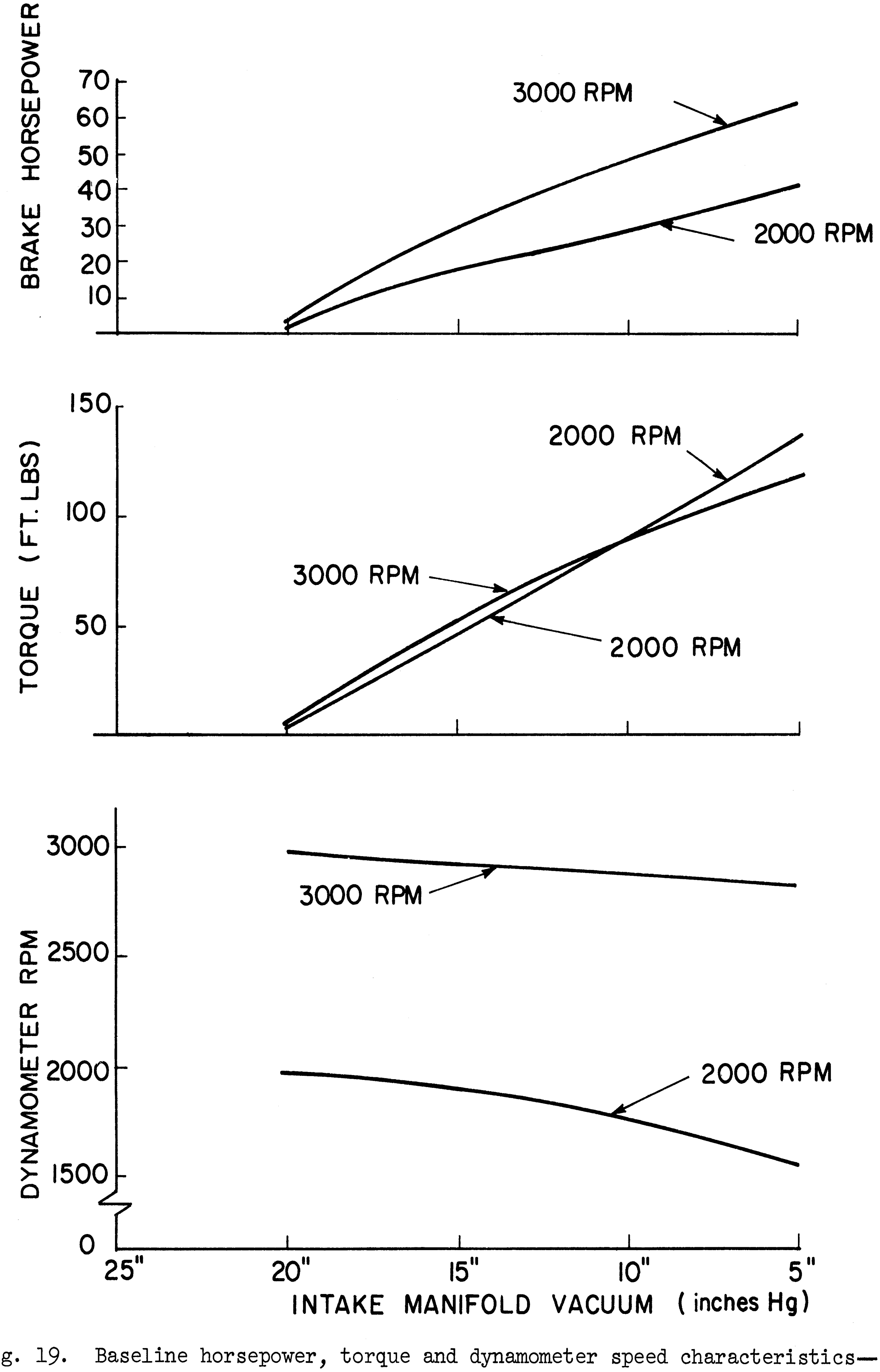

Fig. 19. Baseline horsepower, torque and dynamometer speed characteristics—standard RC engine with WAD reactor, no air injection.

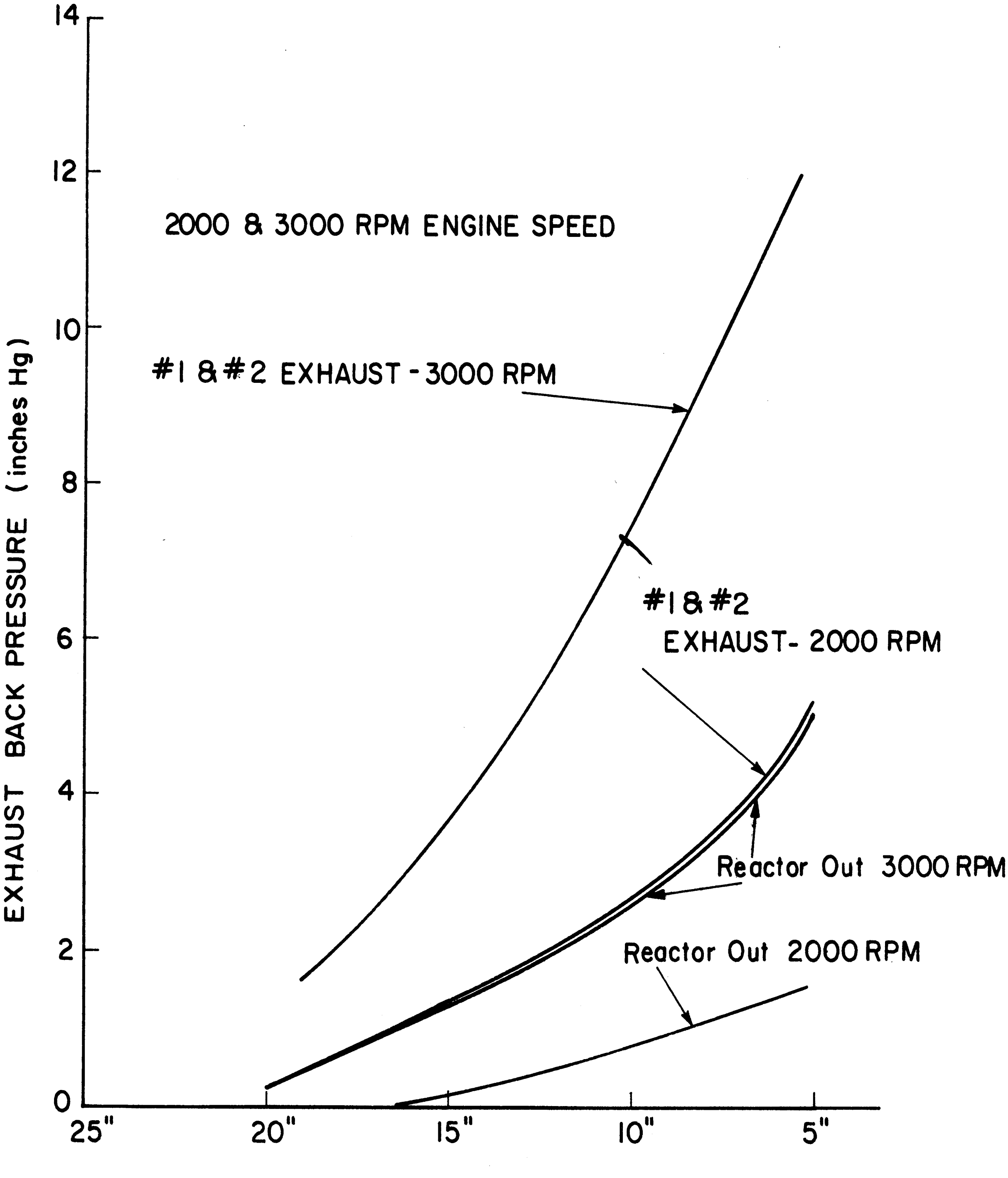

Fig. 20. Exhaust back pressure in engine exhaust ports and at the exhaust manifold reactor outlet—RC engine with WAD reactor, no air injection.

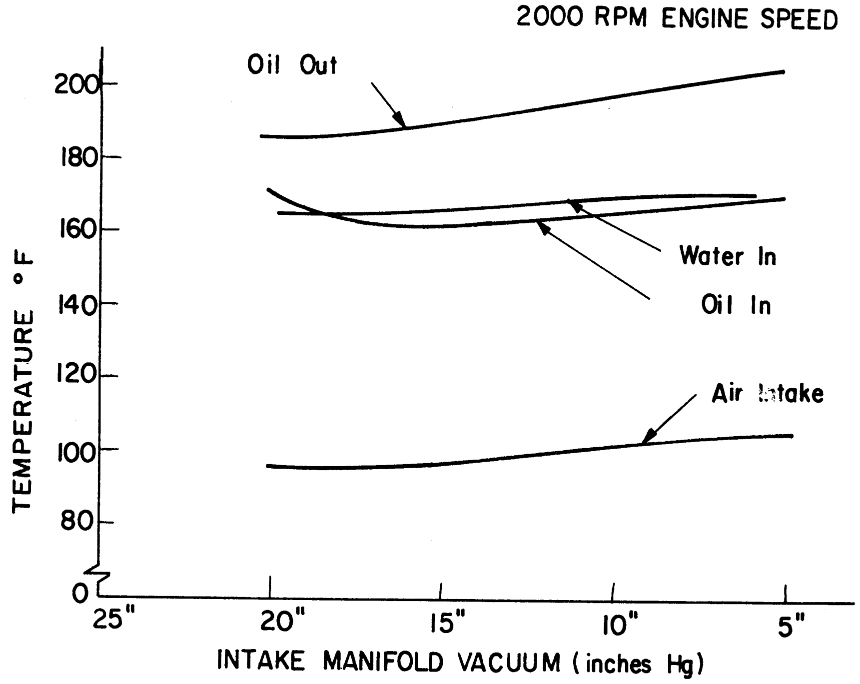

Fig. 21. Engine oil, water, and air temperatures at 2000 rpm—standard RC engine with WAD reactor, no air injection.

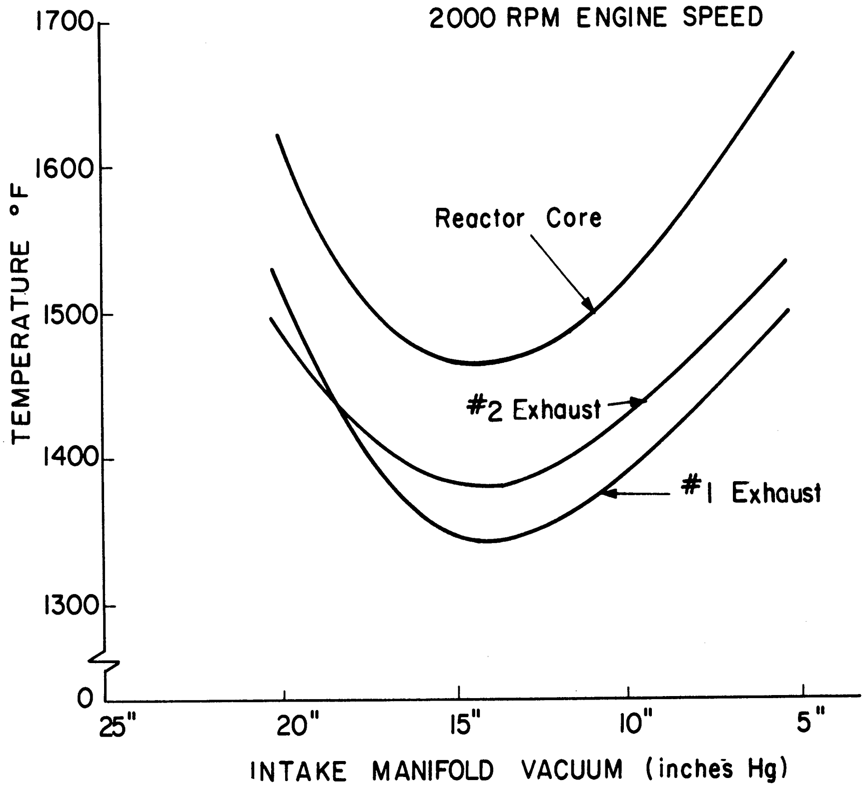

Fig. 22. Exhaust port and reactor core temperatures at 2000 rpm—standard RC engine with WAD reactor, no air injection.

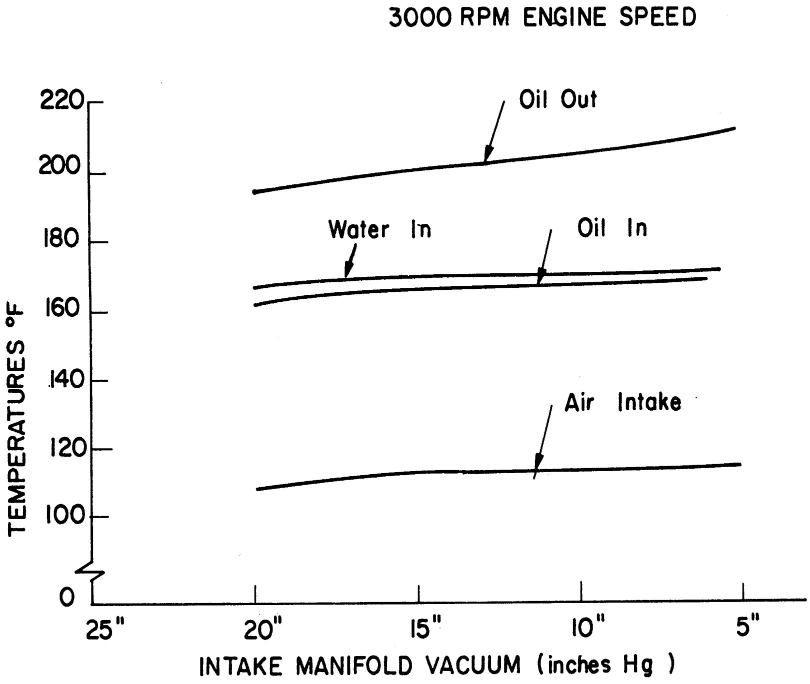

Fig. 23. Engine oil, water, and air temperatures at 3000 rpm—standard RC engine with WAD reactor, no air injection.

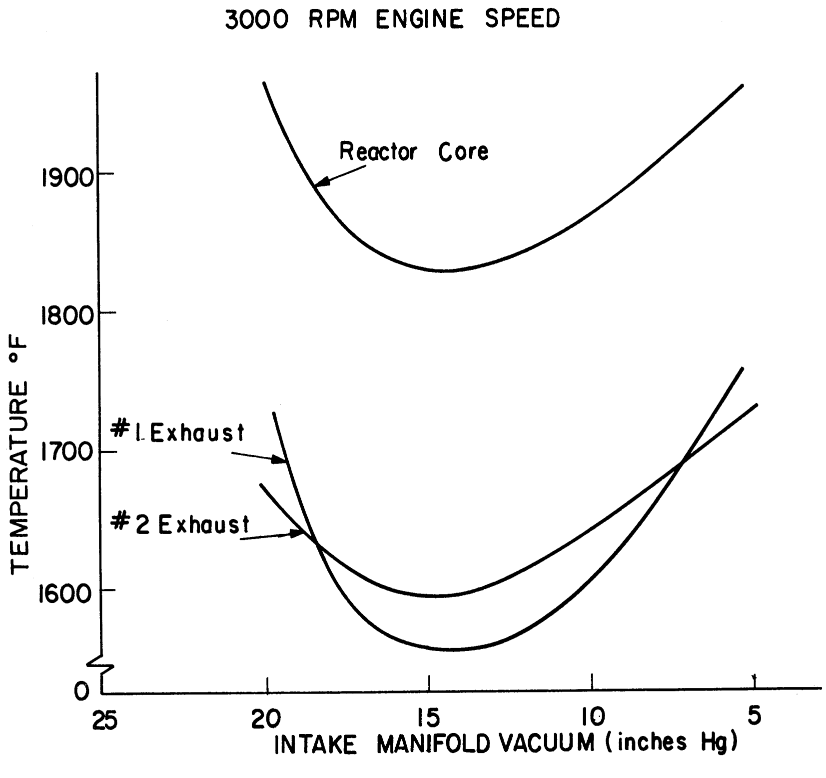

Fig. 24. Exhaust port and reactor core temperatures at 3000 rpm—standard RC engine with WAD reactor, no air injection.

2. The higher emissions of the RC engine are benefical in obtaining high combustion temperatures during a self-sustaining reaction in the exhaust system.

3. The exhaust ports are in close proximity to one another which permits the use of a small size exhaust collector with a low surface-to-volume ratio which minimizes heat transfer.

4. There is a minimum length exhaust passage with a relatively low surface-to-volume ratio from the engine combustion chamber to the exhaust reactor. This minimizes heat transfer through the port walls into the engine collant.

It is interesting to note that the exhaust port and core temperatures are higher at the lightest measured load conditions than at 15 in. Hg. manifold vacuum. This is probably caused by a combination of two factors:

1. Fuel/air ratio enrichment; at very light loads the carburetor idle system is functioning and supplying a relatively richer mixture than the lean, cruising mixture ratio to the engine.
2. Spark retardation; since the intake manifold vacuum sensing port for the vacuum spark-advance system is located above the throttle valve at its closed position, spark retardation probably occurs with light loads.

Ramifications of this can be seen in the emission data in Figs. 10 and 18 which show that there was a less than expected decrease in the hydrocarbon emissions at 15 in. Hg. manifold vacuum compared to the other engine loads.

Also note that there was a temperature increase of about 150°F from the exhaust port to the reactor core for all cases. Several comments can be made about this measured temperature increase:

1. A major portion of this temperature increase was probably due to the energy release from the reaction of previously unburned carbon monoxide and hydrocarbons with oxygen in the reactor.
2. It is unlikely that the measured core temperature was the maximum exhaust reactor temperature since the measurement was made at the outside surface of the internal chamber. The maximum temperature probably occurs at the baffle surface on which the exhaust gases impinge or in the interior of the inner-cylinder.
3. Radiation losses from the bayonet type thermocouple to the relatively cool exhaust port walls may have caused some error in the measurement of the exhaust port temperatures.
4. It is not possible to predict the temperature increase theoretically with the data observed in this study because the carbon monoxide concentration reduction in the reactor was not measured. The CO may not be an important factor, however, with lean mixtures since its concentration in the exhaust should be quite low, less than 1%.

Another exhaust reactor parameter, one that is particularily important with respect to a vehicular installation is the region of maximum temperature and the maximum temperature at the outside surface of the reactor. It was found to occur at the 90° bend in the outlet pipe of the reactor and to attain a maximum temperature of 1525°F at 3000 rpm and 5 in. Hg. manifold vacuum. This data is not shown in any of the figures.

Base line data was not studied for the light load, 1000 rpm condition because of the uncertainty in the idle mixture settings which have predominant effect on the overall mixture ratio at this state. In all subsequent work the idle screws in both the standard and variable fuel/air ratio carburetor were adjusted for minimum hydrocarbon emissions (approximately 1 turn from fully closed). The engine appeared to still operate smoothly with this somewhat leaner than standard idle mixture ratio. No quantitative measurement of fuel/air ratio was made, however.

This idle study gave the first indication of the engine-reactor combinations' extreme sensitivity to mixture ratio. At 1000 rpm and 20 in. Hg. manifold vacuum the hydrocarbon effluent decreased from about 1200 ppm for the engine without the reactor and with the Curtiss-Wright specified idle setting to approximately 150 ppm for the engine with the reactor and minimum emission idle adjustment, a reduction of 90%.

An important aspect of any exhaust emission control device is that it must rapidly attain a satisfactory operating condition after a "cold start." This "cold start" data for the RC engine is presented graphically in Figs. 25 and 26. The engine was started and run at 1000 rpm for the duration of the test, with the transmission in neutral and the vacuum spark advance line disconnected and plugged. A 50% reduction in hydrocarbon emissions was observed after 30 seconds and a 95% reduction after two minutes. The warm-up appears to be very rapid. Thus, the reactor should be near its optimum operating temperature for all "test points" of the "California Cycle."

The dependence of the emissions on temperature in the reactor is quite evident with hydrocarbon concentration being inversely proportional to core temperature. Note that the engine coolant has not attained its steady-state operating temperature at the completion of the test (10 minutes after starting).

The great effect of fuel air ratio on the emissions is shown in Figs. 27 and 28 for the engine-reactor combination with the fuel/air ratio set for minimum emissions. It was consistently possible to obtain hydrocarbon concentrations of less than 75 ppm, the lowest observed value being 30 ppm at 3000 rpm and 10 in. Hg. manifold vacuum. High loads at 3000 rpm were not investigated because the emissions were already low and the high reactor temperatures, which occurred at these conditions, could have caused a serious metallurgical failure. This test program modification was followed throughout the remaining studies.

Due to erratic behavior of the Orsat apparatus which was used to measure the air/fuel ratio, it was not possible to determine the air/fuel ratio accurately. However, it appeared to be in the range of 15.5:1 to 16.5:1. Quite obviously the mixture ratio must be leaner than stoichiometric to provide excess air which can react with the unburned pollutants in the reactor.

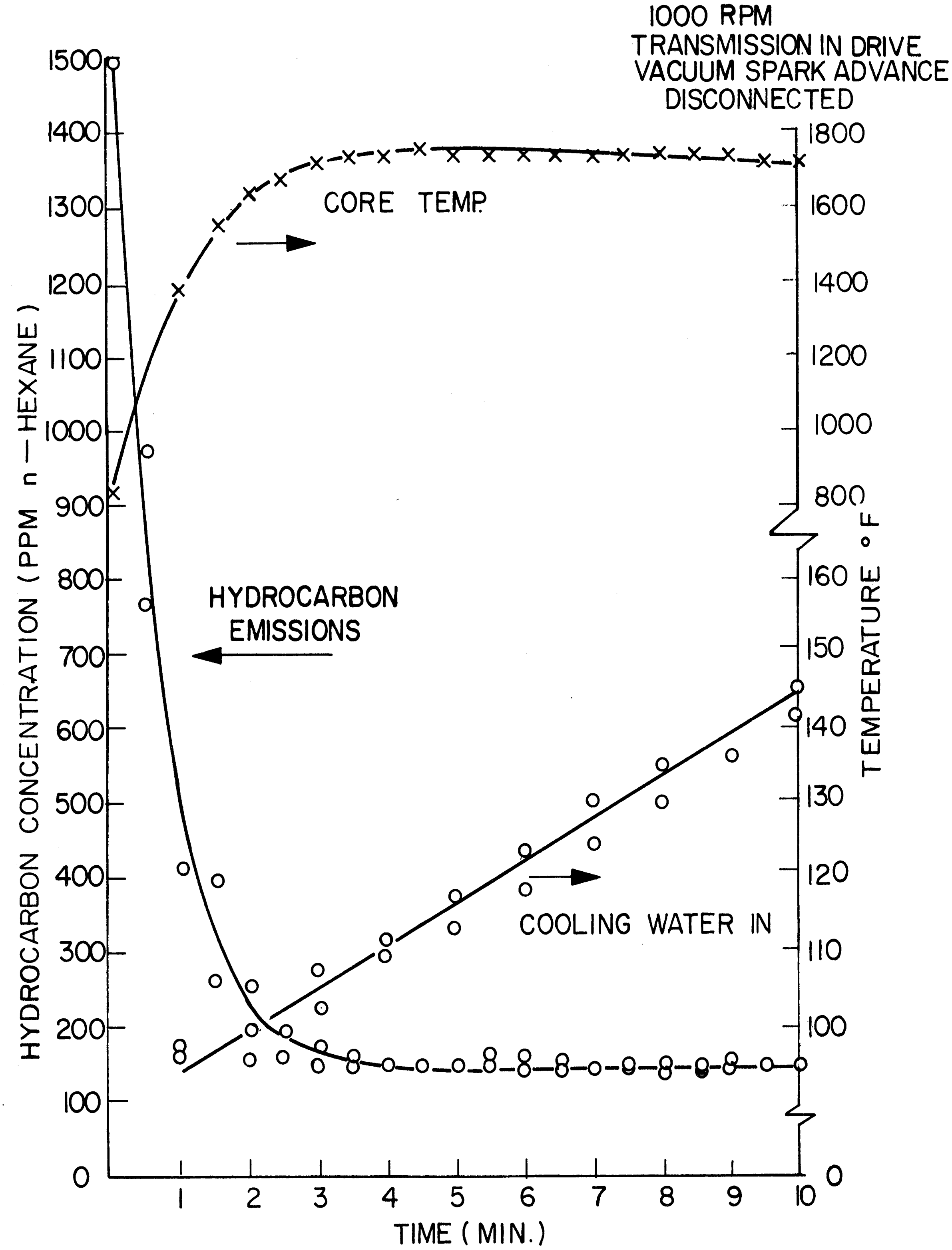

Fig. 25. Cold start, warm-up test—hydrocarbon emissions, and reactor core and engine cooling water temperatures as a function of time—RC engine with WAD reactor, no air injection.

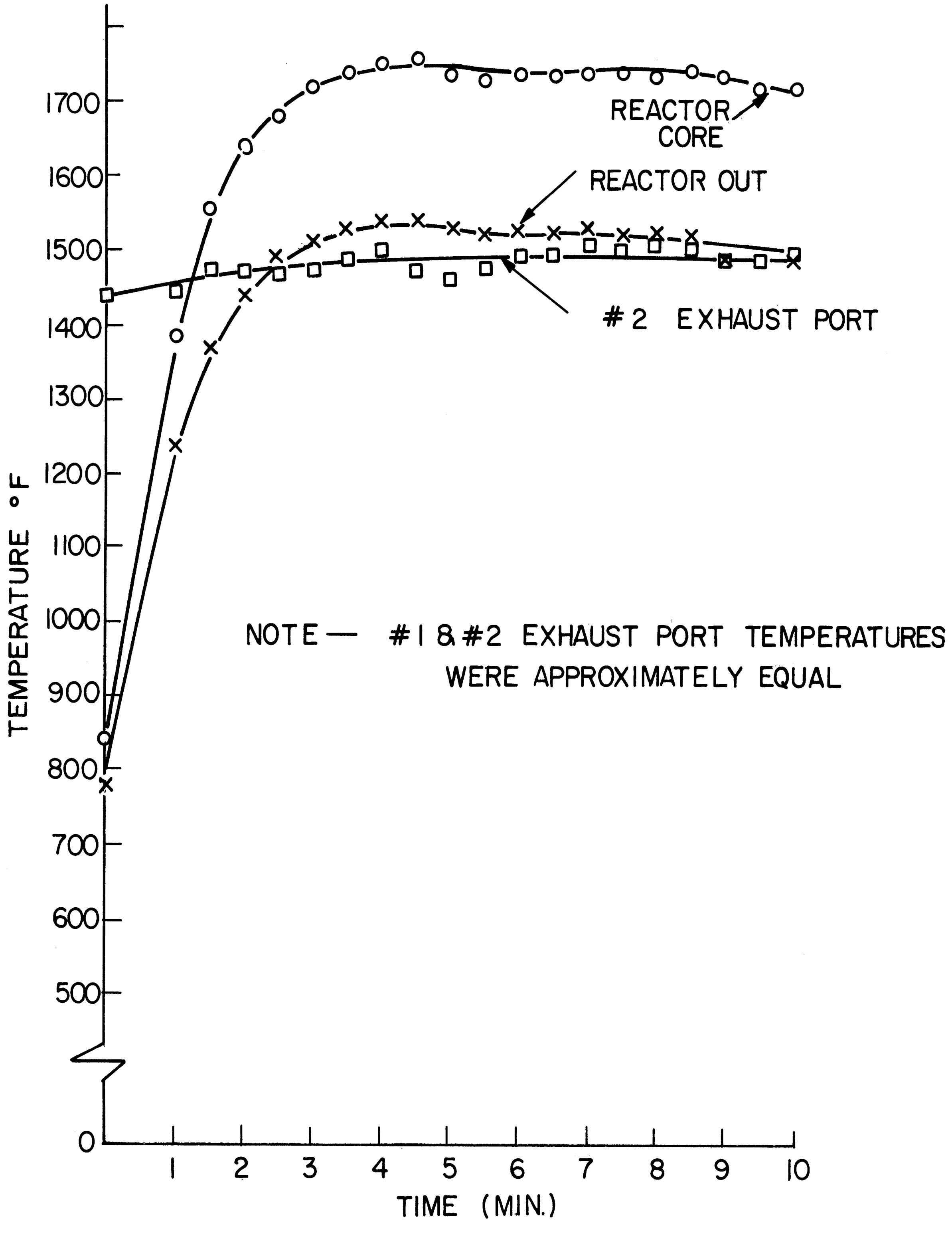

Fig. 26. Cold start, warm-up test—exhaust port, reactor outlet and reactor core temperatures as a function of time—RC engine with WAD reactor, no air injection.

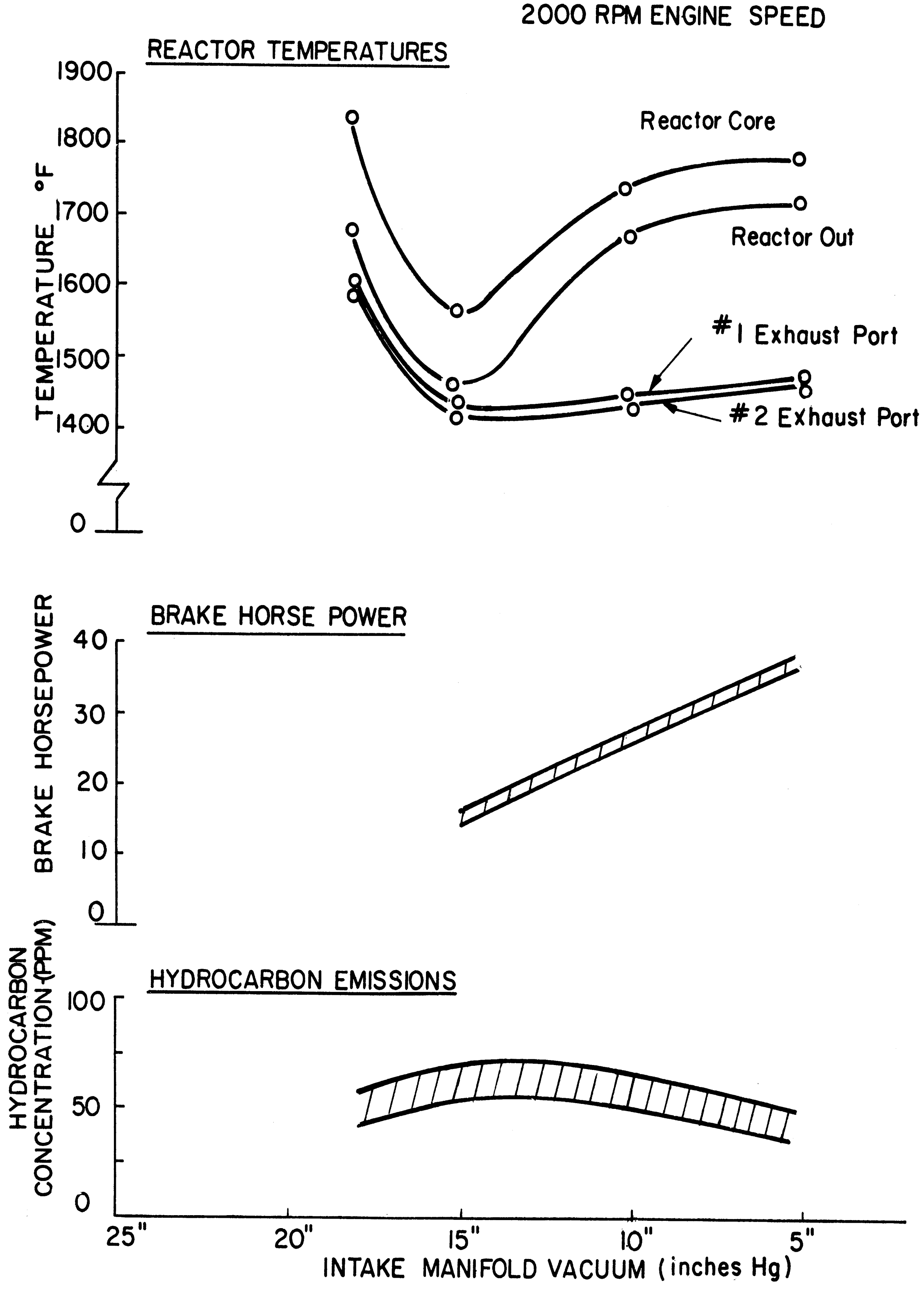

Fig. 27. RC engine performance at 2000 rpm with the fuel/air ratio adjusted for minimum emissions—MBT spark advance, WAD reactor, no air injection.

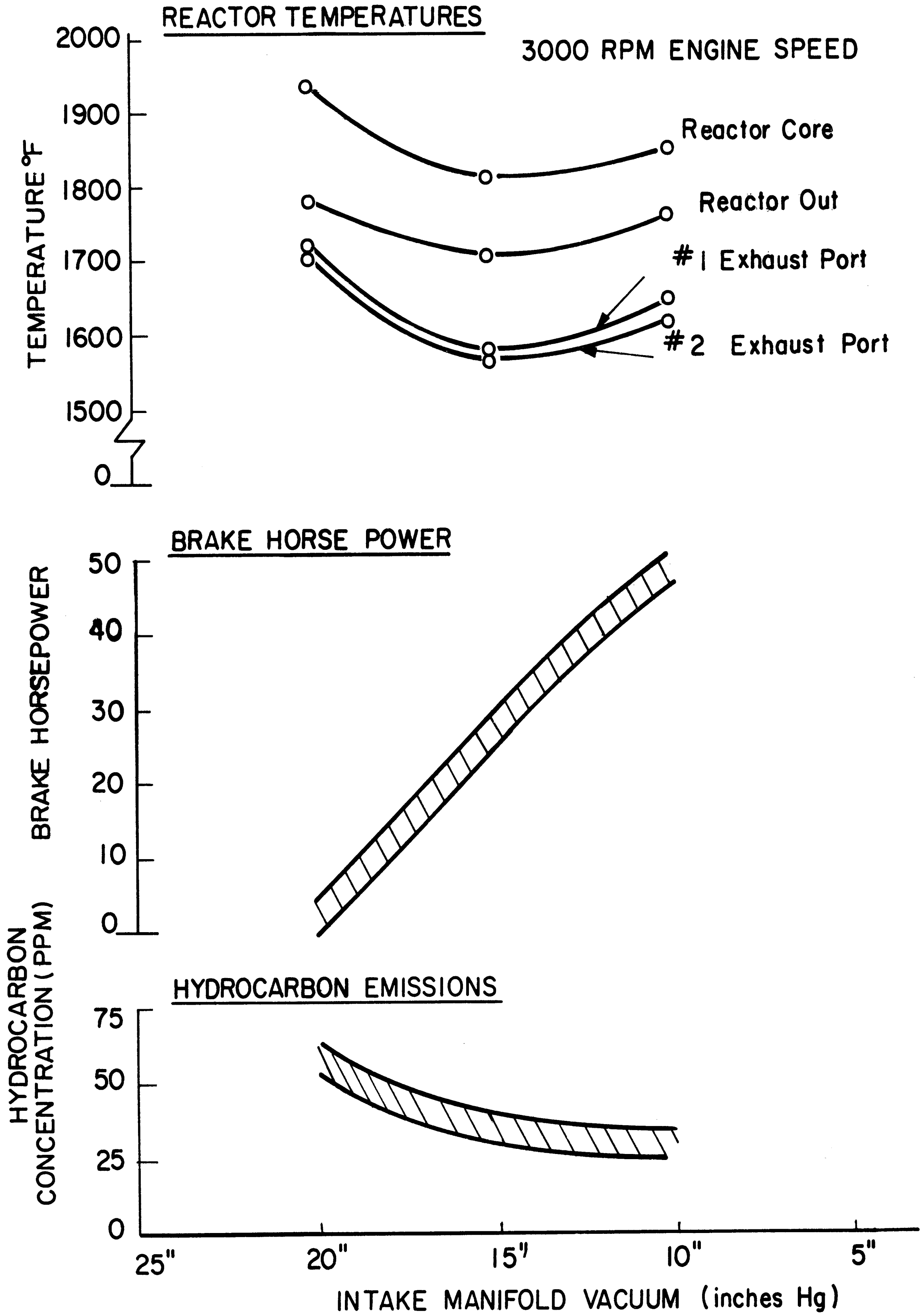

Fig. 28. RC engine performance at 3000 rpm with the fuel/air ratio adjusted for minimum emissions—MBT spark advance, WAD reactor, no air injection.

It is interesting to note that the minimum emission air/fuel ratio was greater for the engine without the reactor than for the engine with the reactor. This is caused at least partially by a temperature phenomena. The highest exhaust temperatures are found with close to stoichiometric mixtures ratios. Thus, the combination of air/fuel ratio and high exhaust temperature must be considered rather than predominatly air/fuel ratio as is the case in the engine without the reactor. There is a distinct advantage to operation with the richer minimum emission mixture ratio of the engine-reactor combination, drivability. In a vehicle the richer mixture should provide smoother operation.

Important data from Figs. 27 and 28 is replotted in Figs. 29 and 30 together with equivalent data for the standard engine-reactor combination to show directly how they compare. Notice that a great reduction was found in the unburned hydrocarbons but only a slight decrease in brake horsepower was observed with the relatively lean mixtures used. The reactor core temperatures are also somewhat greater for the lean mixture operation even though the exhaust port temperatures are lower.

It can be hypothesized that if the mixing of the fuel and air is improved in the carburetor and induction system an even greater decrease in exhaust emissions might be achieved with perhaps an increase in the drivability of the engine. This might be accomplished by using increased intake manifold heating,* a smaller venturi carburetor, dual runner manifold, fuel injection or other such modifications.

The fact that the engine responds so well to lean mixture operation could be a major factor in gaining acceptance for the RC engine in an automotive application.

The minimum emission air/fuel ratio hydrocarbon concentration data was converted to a mass base (lb/hr) and was plotted against intake manifold vacuum in Fig. 31. Here also can be seen the magnitude of the reduction with a controlled mixture ratio. The observed hydrocarbon emission level of about .06 lb/hr. is quite low, based on experience with current automotive engines.

The following figure, Fig. 32, shows the before mentioned mass emissions plotted against brake horsepower. This figure is particularly important with respect to a vehicular requirement. A given automobile requires "x" horsepower to propel it along the highway at "y" mph or "P" horsepower to give it an acceleration rate of "q" ft/sec.^{2}. Thus, if a modification is made to the engine which affects a decrease in emissions, the power gain or more commonly loss must be considered. If, as is the case with lean mixture ratios, the power is decreased, something must be done to increase the power back to the vehicle required power. Generally, this is accomplished in an engine by in-

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*The heat riser was disconnected in all of the engine-exhaust reactor research so that a direct comparison could be made with earlier work on the base engine which, because of a special exhaust manifold, did not employ intake manifold heating.

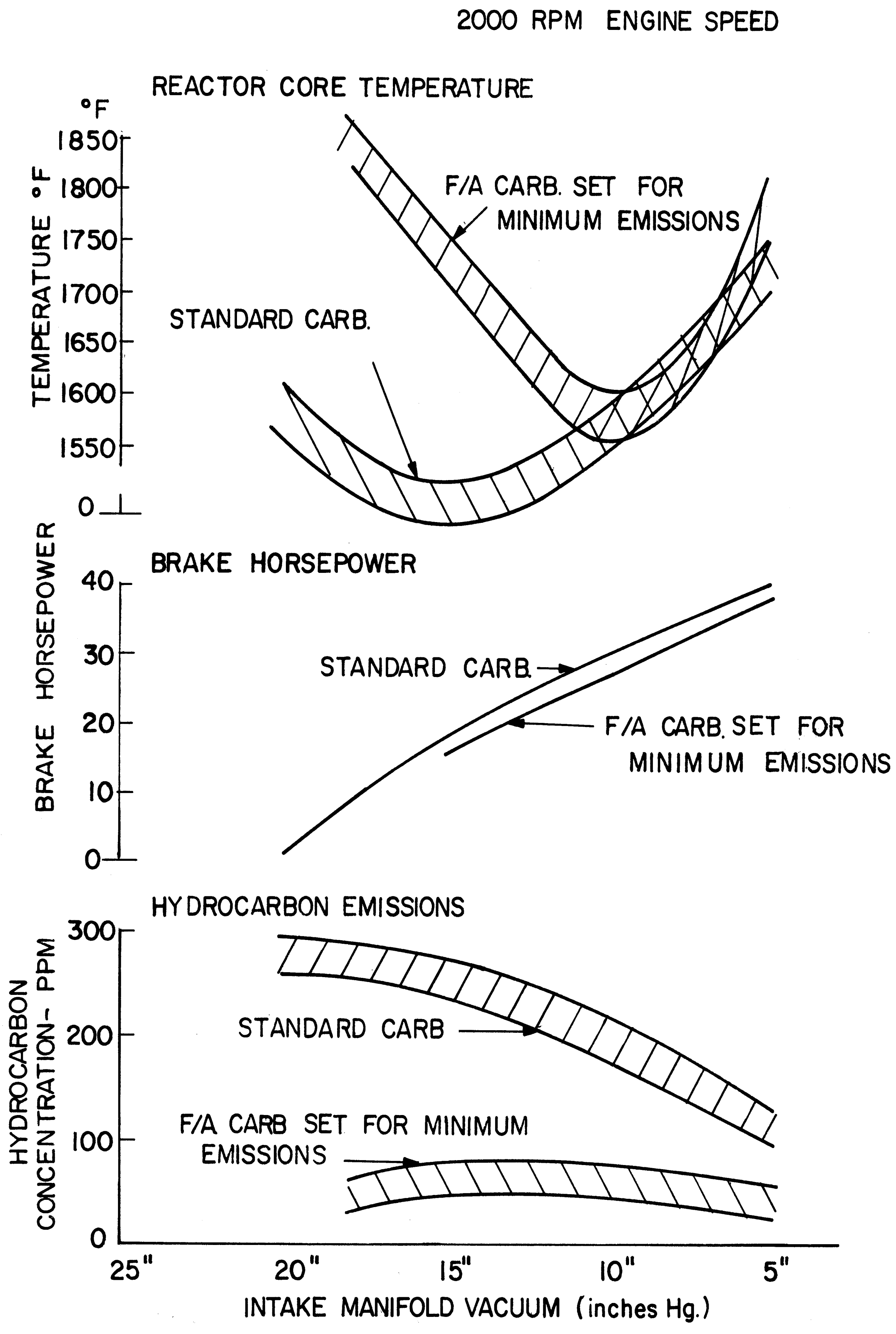

Fig. 29. Comparison of the RC engine performance data at 2000 rpm—minimum emission F/A ratio and standard F/A ratio—MBT spark advance, WAD reactor, no air injection.

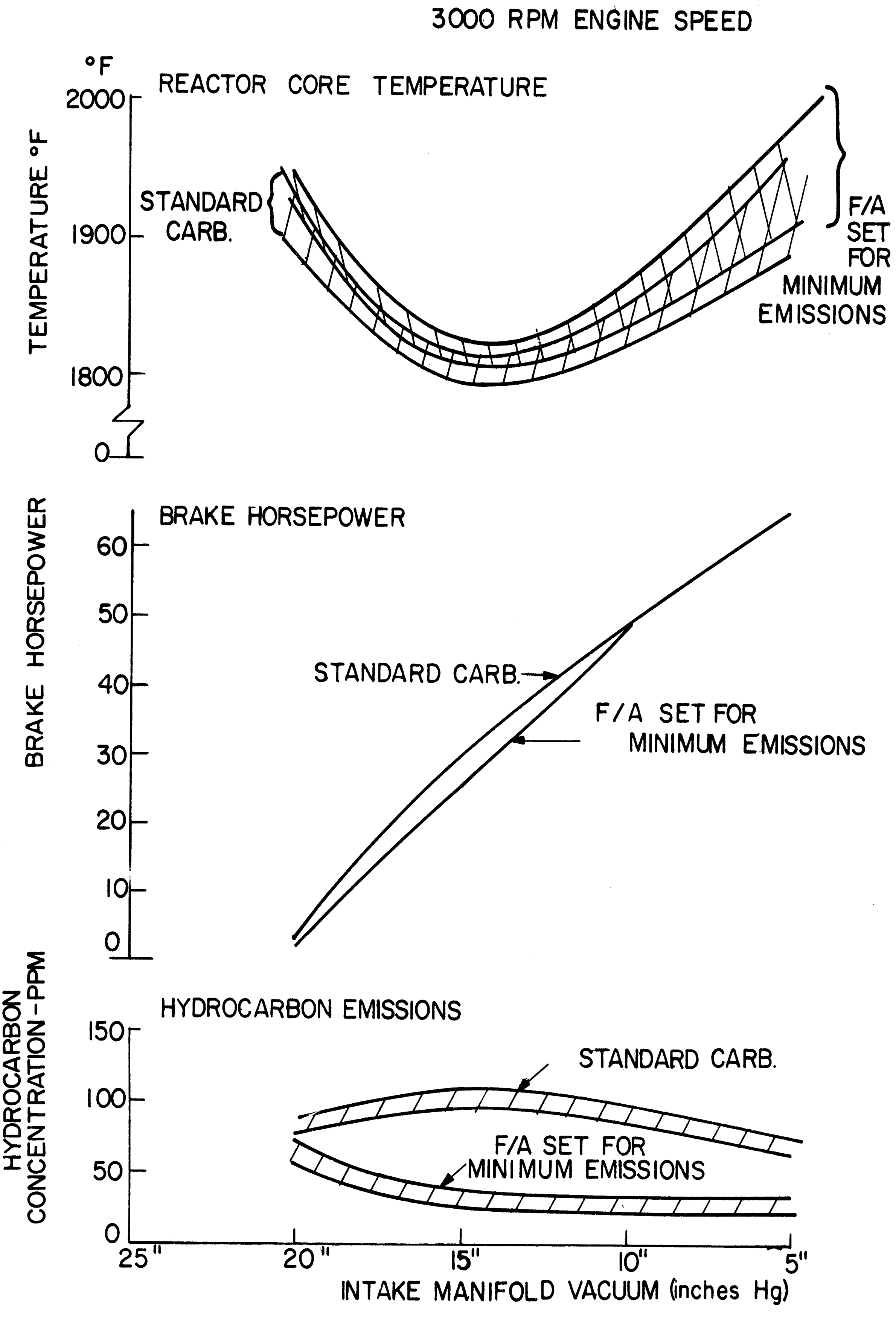

Fig. 30. Comparison of the RC engine performance data at 3000 rpm—minimum emission F/A ratio and standard F/A ratio—MBT spark advance, WAD reactor, no air injection.

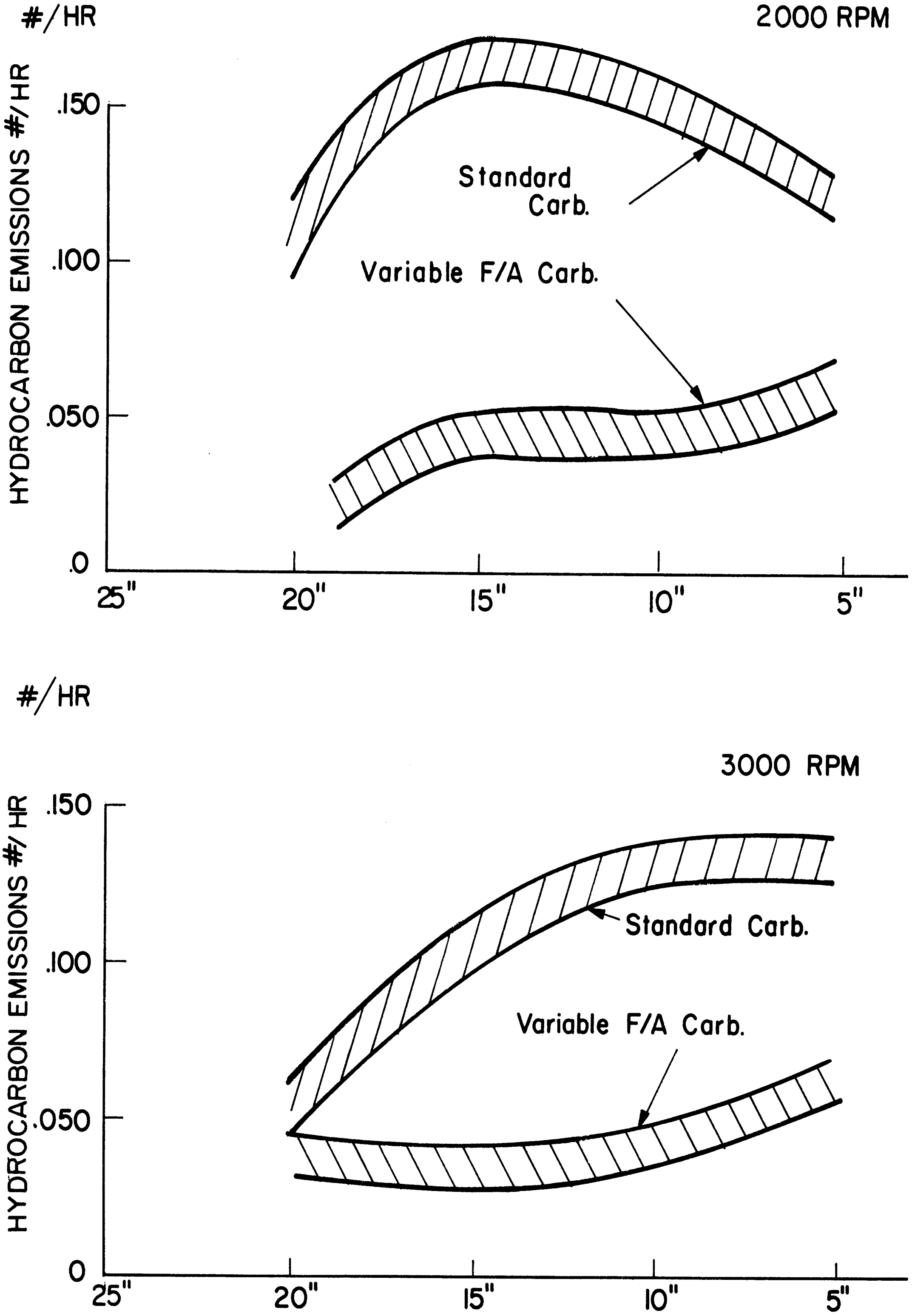

Fig. 31. Mass rate of hydrocarbon emissions with the standard carburetor and the variable fuel/air ratio carburetor adjusted for minimum emissions RC engine with WAD reactor, no air injection.

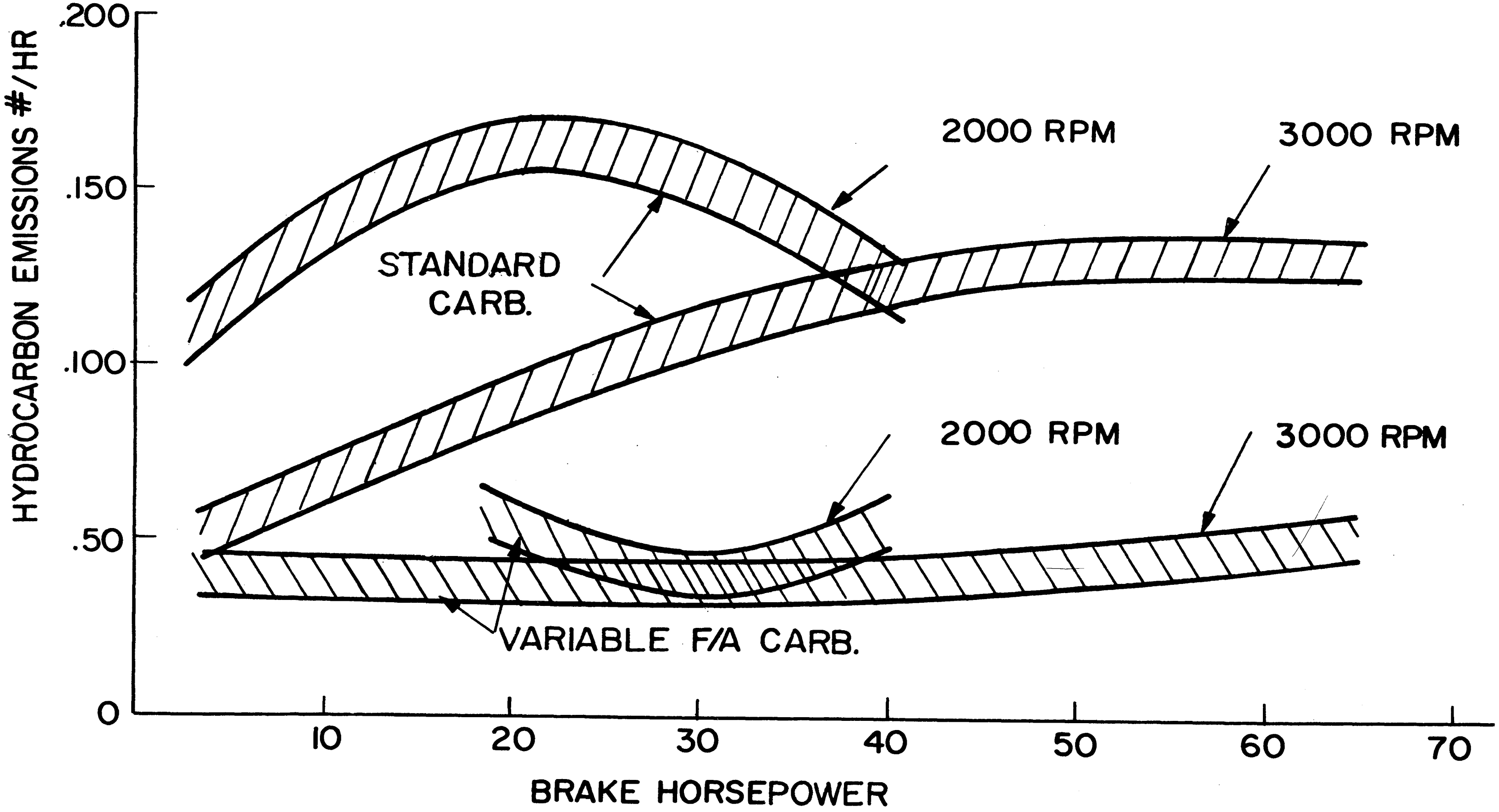

Fig. 32. Mass rate of hydrocarbon emissions as a function of brake horsepower with the standard carburetor and variable fuel/air ratio carburetor adjusted for minimum emissions—RC engine with WAD reactor, no air injection.

creasing the throttle opening which in turn increases the mass flow of air and fuel to the engine. Therefore, even though the modification may cause a reduction in pollutant concentration, the increase in mass flow may nullify the gain if the mass effluent (lb/hr) of the emissions were considered. Hence, the critical importance of data such as that shown in Fig. 32.

Spark-advance as demonstrated on the RC engine without the exhaust reactor has significant effect on emissions. The same relative effect was observed in the engine-reactor combination and therefore, the results are not plotted. Instead, both the fuel/air ratio and spark-advance were varied together. At each spark-advance setting the fuel/air ratio was adjusted to obtain minimum hydrocarbon emissions. These results are plotted in Figs. 33 through 37 which show important reactor temperatures, brake horsepower, and hydrocarbon concentration plotted as a function of spark-advance at 2000 and 3000 rpm and several intake manifold vacuums. Generally, the emissions decreased with retardation of the spark but not as much on percentage basis as those observed from the engine-reactor combination with the standard carburetor.

All observed emissions were quite low, less than 75 ppm. The horsepower curves behave in a somewhat unpredictable manner, in some cases even showing a horsepower increase with spark retardation. This is not totally unexpected though, since both the spark advance and air/fuel ratio affect power and different fuel/air ratios were probably required to obtain minimum emissions at each spark advance.

The reactor core temperature generally followed the pattern observed in the early studies being inversely proportional to the hydrocarbon concentration though several exceptions were observed. Light loads at both 2000 and 3000 rpm exhibited core temperatures in excess of 1800°F, certainly an indication of a high quality reaction. This reactor core temperature cannot, however, be used as a quantitative measure of the hydrocarbon emission concentration because the increase in temperature from the exhaust port to the core is a function of both the mass of reactants which are oxidized in the device and the mass rate of flow through it. For a given reactor temperature is a greater emission reduction would be expected at 2000 rpm and light load, for example, than at 3000 rpm and the same load since the exhaust gases are exposed to the high temperature region for a greater period of time.

The variable fuel/air ratio and spark advance data is summarized in Fig. 38. Mass hydrocarbon emissions based on the minimum hydrocarbon concentration from the full range of spark advances examined and reactor core temperature are plotted against brake horsepower and thus relate to a vehicular requirement. Also shown is similar data for the base engine with the reactor. Througout the power range observed in this test the mass emissions were from 50% to 75% less than those of the base-engine-reactor combination and from 75% to 90% less than those from the base engine alone, certainly a significant improvement.

One point of significant interest is the comparison of the mass emissions observed in this test to those from the test where only the fuel/air ratio was

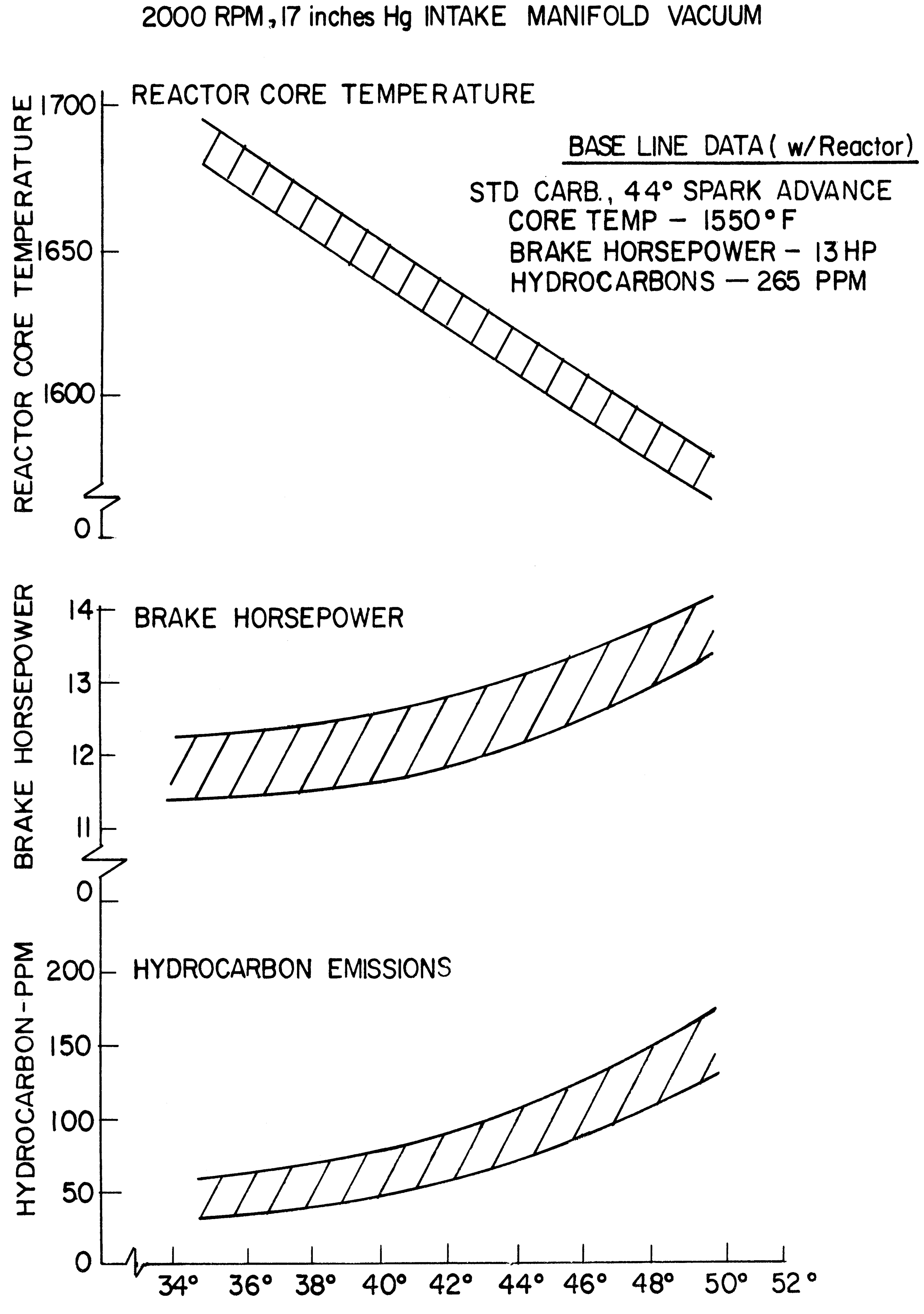

Fig. 33. The effect of spark advance on performance with the F/A ratio adjusted for minimum emissions; 2000 rpm, 17 in. Hg.—RC engine with WAD reactor, no air injection.

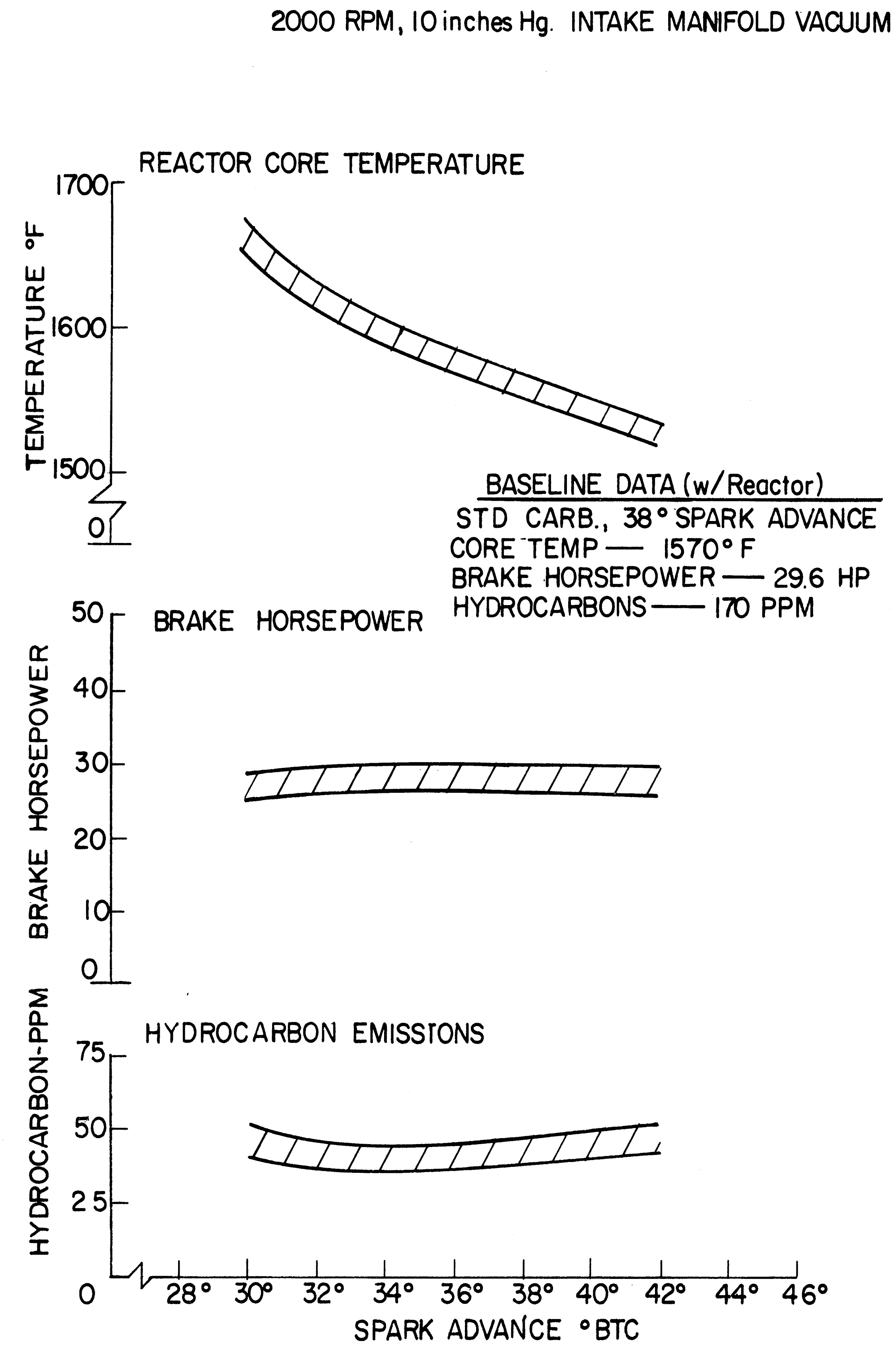

Fig. 34. The effect of spark advance on performance with the F/A ratio adjusted for minimum emissions; 2000 rpm, 10 in. Hg.—RC engine with WAD reactor, no air injection.

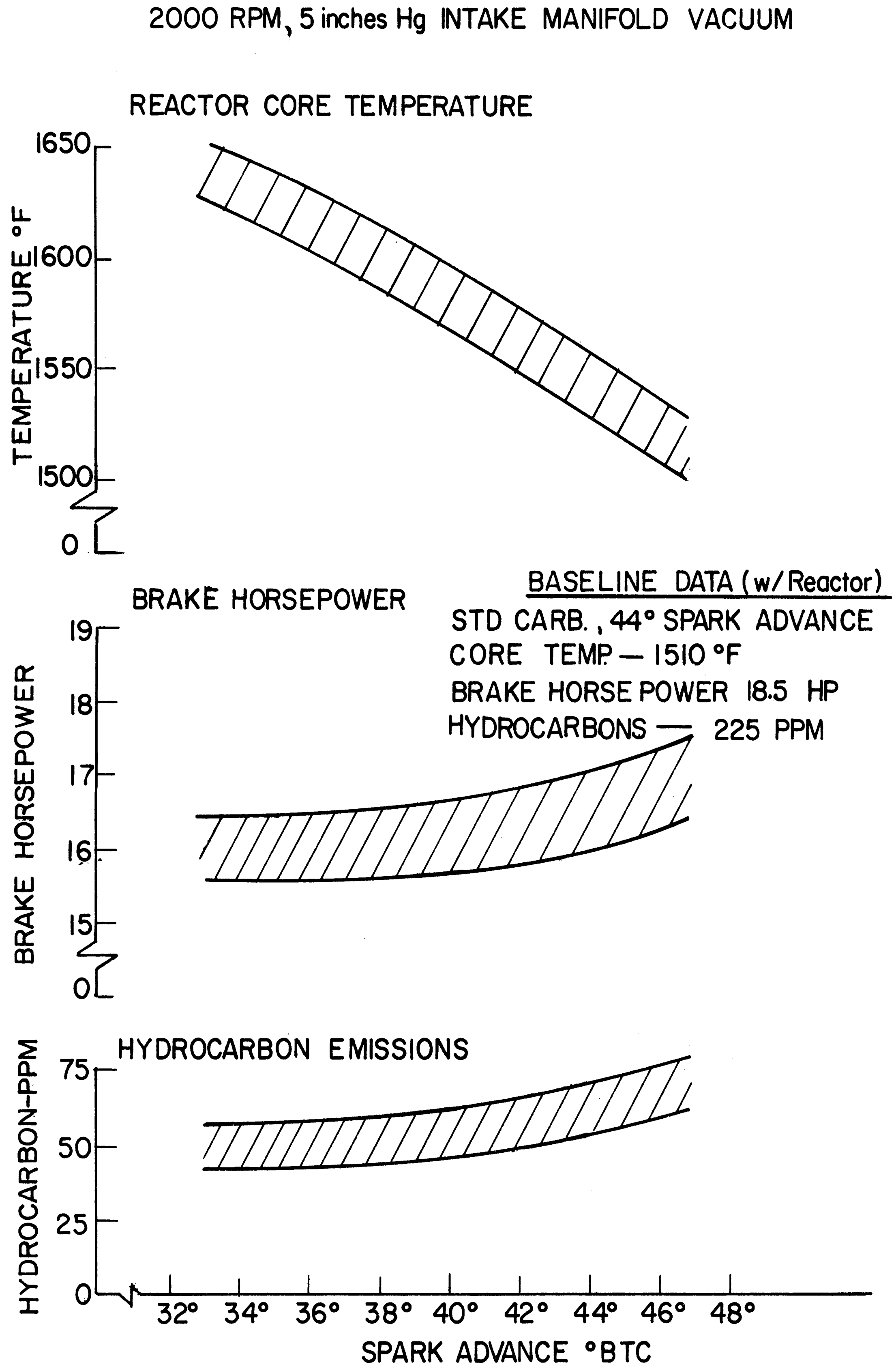

Fig. 35. The effect of spark advance on performance with the F/A ratio adjusted for minimum emissions; 2000 rpm, 5 in. Hg.—RC engine with WAD reactor, no air injection.

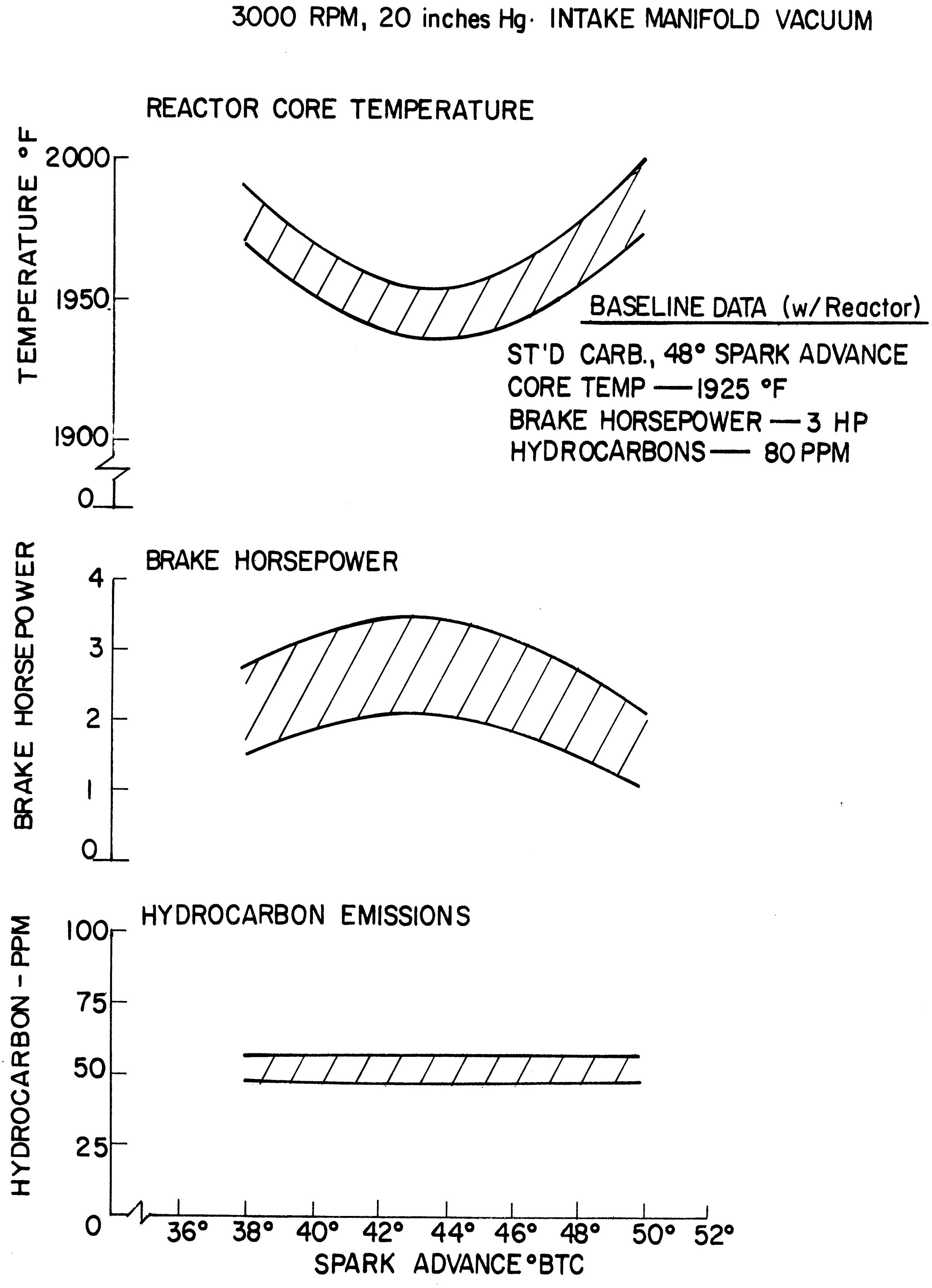

Fig. 36. The effect of spark advance on performance with the F/A ratio adjusted for minimum emissions; 3000 rpm, 20 in. Hg.—RC engine with WAD reactor, no air injection.

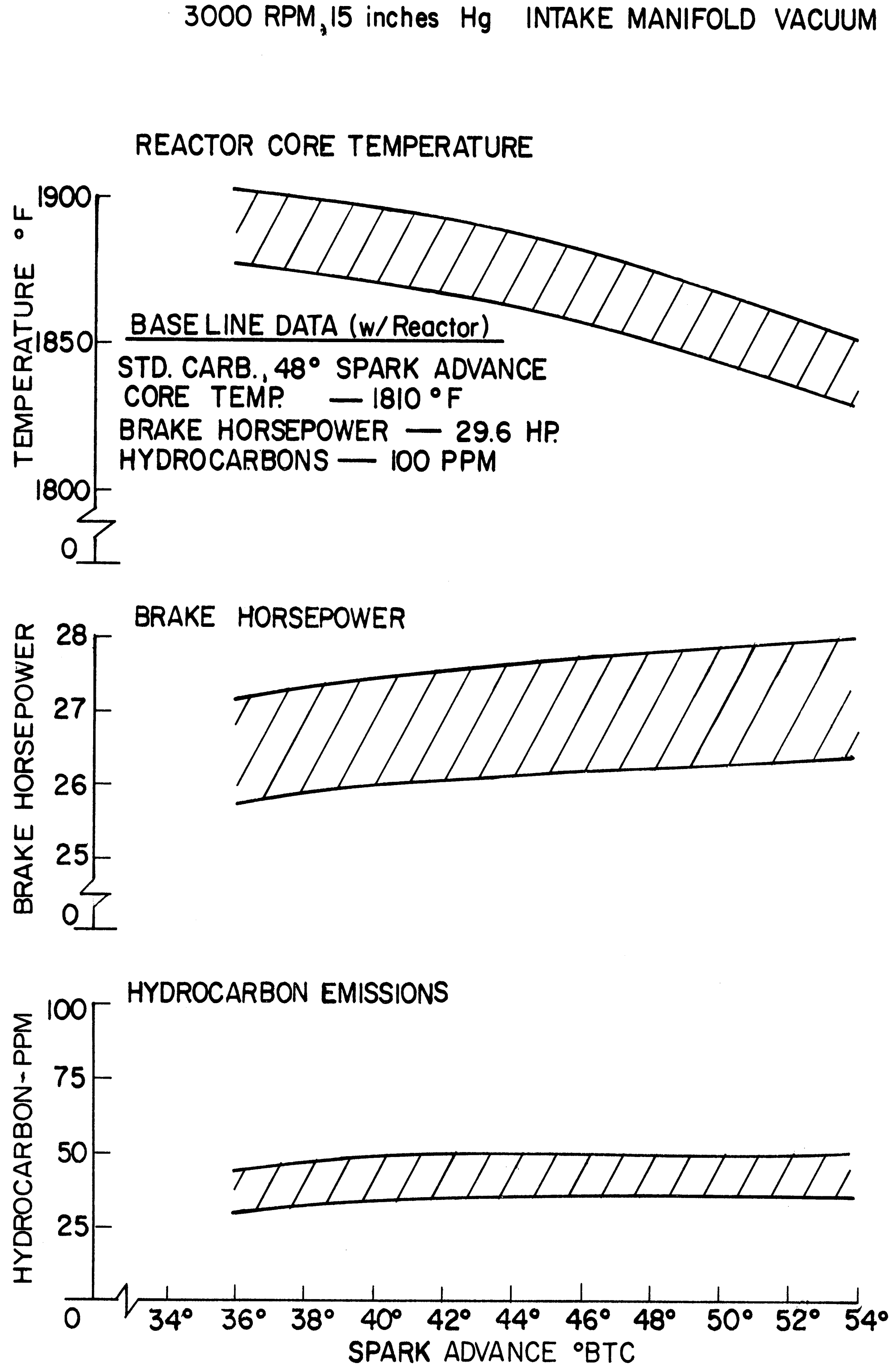

Fig. 37. The effect of spark advance on performance with the F/A ratio adjusted for minimum emissions; 3000 rpm, 15 in. Hg.—RC engine with WAD reactor, no air injection.

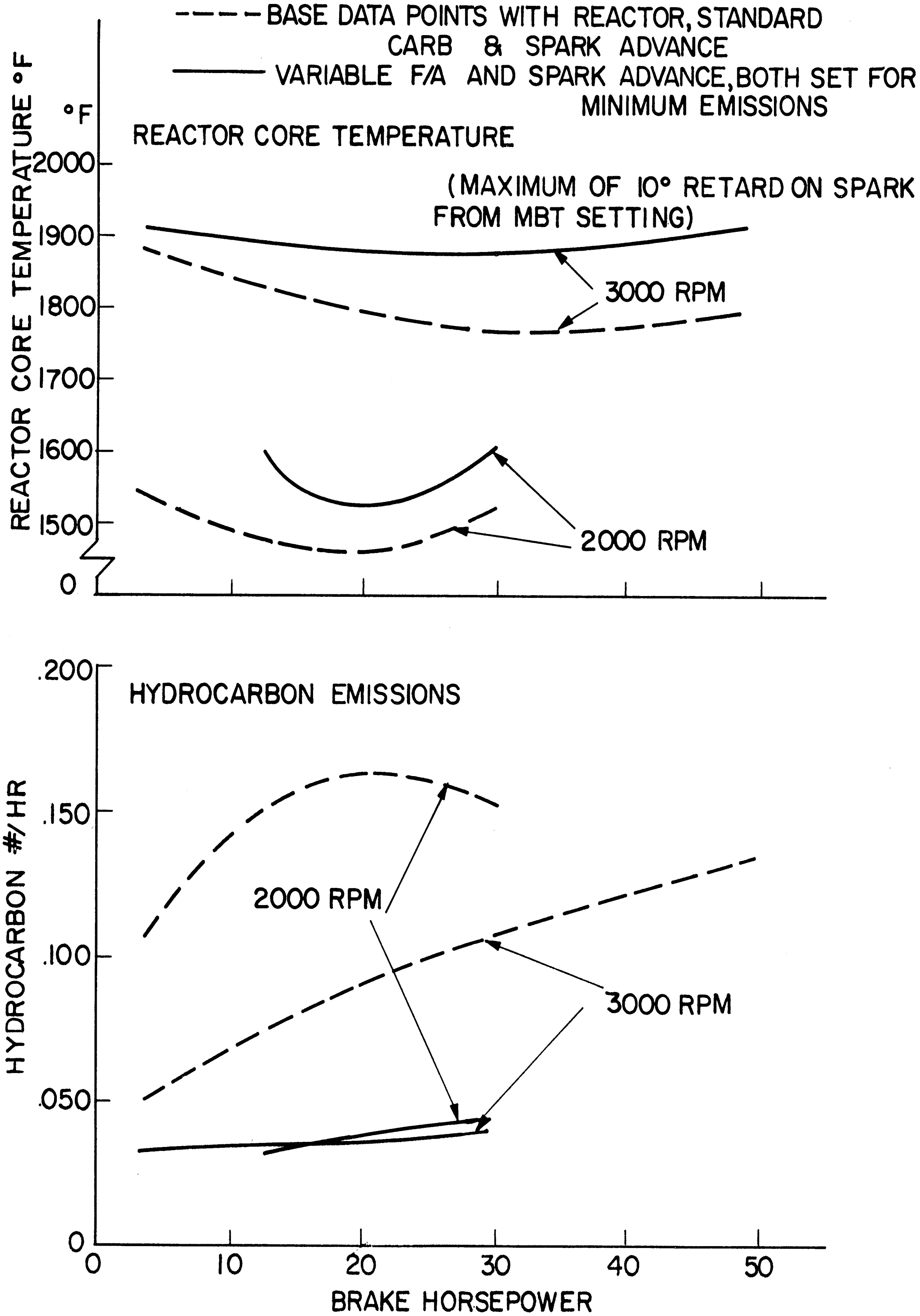

Fig. 38. Hydrocarbon emissions and reactor core temperature as a function of brake horsepower with both spark advance and F/A ratio optimized for minimum emissions—RC engine with WAD reactor, no air injection.

varied. Only slight improvement can be seen which demonstrates the powerful effect of optimizing just the fuel/air ratio.

C. RC ENGINE WITH EXHAUST REACTOR AND AIR INJECTION

The final phase of the experimental study involved the measurement of the hydrocarbon emissions from the RC engine with both the exhaust manifold reactor, and air injection in the engine exhaust ports. Due to the limited time available for this part of the work, quantitative measurements were made only for the engine with the standard carburetor and spark advance. Data was taken at a full range of loads at 2000 rpm and only light loads (15 and 20 in. Hg. manifold vacuum) at 3000 rpm because at higher loads the emissions were already low and reactor temperatures excessive.

The results are plotted in Figures 39, 40, and 41 which show the corrected hydrocarbon emission concentration as a function of air injected, measured in per cent of engine combustion air. All concentration measurements made with the Beckman NDIR analyzer were corrected to compensate for dilution caused by the added air.

Generally, the emissions decreased with an increase in air-injection rate up to 10-15% of engine air after which the concentrations became almost constant. At all test points but one, emissions of less than 100 ppm were observed. The only exception was at 2000 rpm, 15 in. Hg. manifold vacuum where the hydrocarbon concentration was somewhat greater. Also, the leveling off of the curve at high air injection flow rates was not observed at this test condition. Apparently this behavior was caused by the lack of proper operating conditions (air/fuel ratio and spark advance) for an efficient reaction with low injection rates.

Qualitatively data was observed for several combinations of air/fuel ratio and air-injection rate at the test points. The results demonstrated that only a slight improvement in the air-injected, standard engine emissions could be made.

Perhaps the most interesting result of this phase of the study was that the RC engine with the reactor, no air-injection and optimized fuel/air ratio performed better than the RC engine with the reactor and air injection. This fact is very important when considering a possible production application for the engine. The advantages are threefold if the emissions can be controlled without using rich mixture ratios and air injection:

1. Decreased initial cost
2. Better economy (due to the use of lean mixtures)
3. Decreased complexity

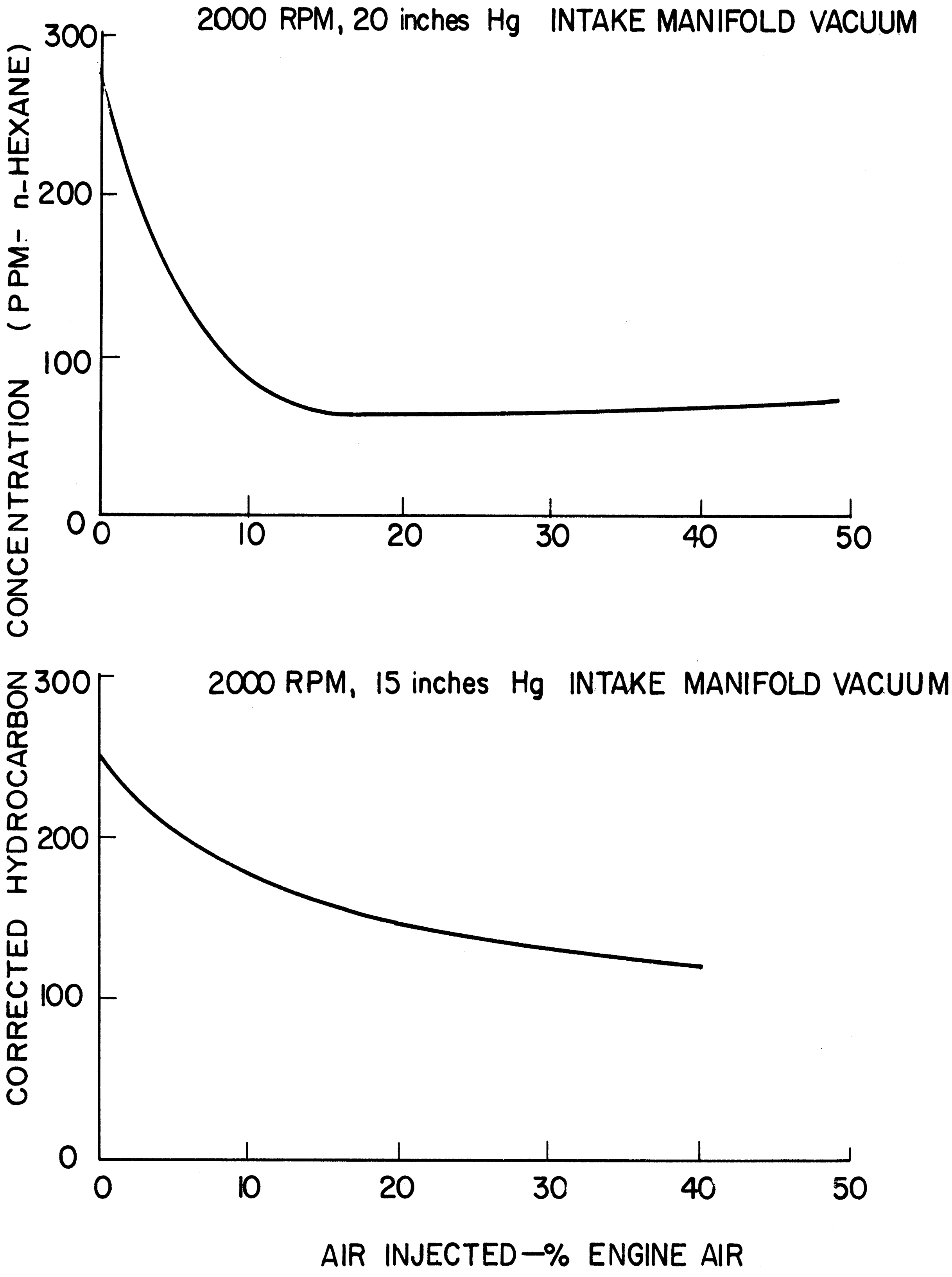

Fig. 39. The effect of exhaust port air injection on the hydrocarbon emissions; 2000 rpm, 15 and 20 in. Hg.—RC engine with WAD reactor.

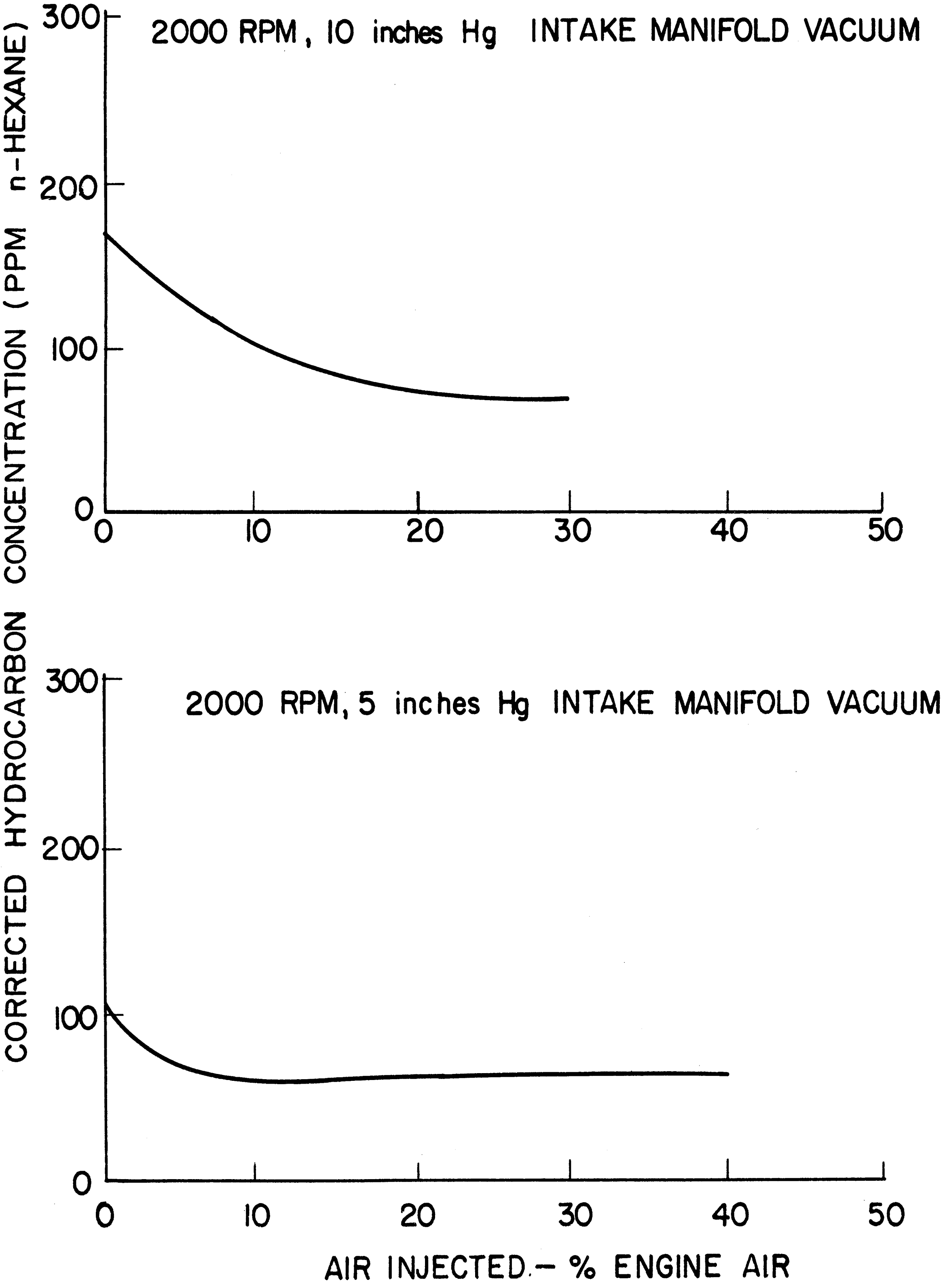

Fig. 40. The effect of exhaust port air injection on the hydrocarbon emissions; 2000 rpm, 5 and 10 in. Hg.—RC engine with WAD reactor.

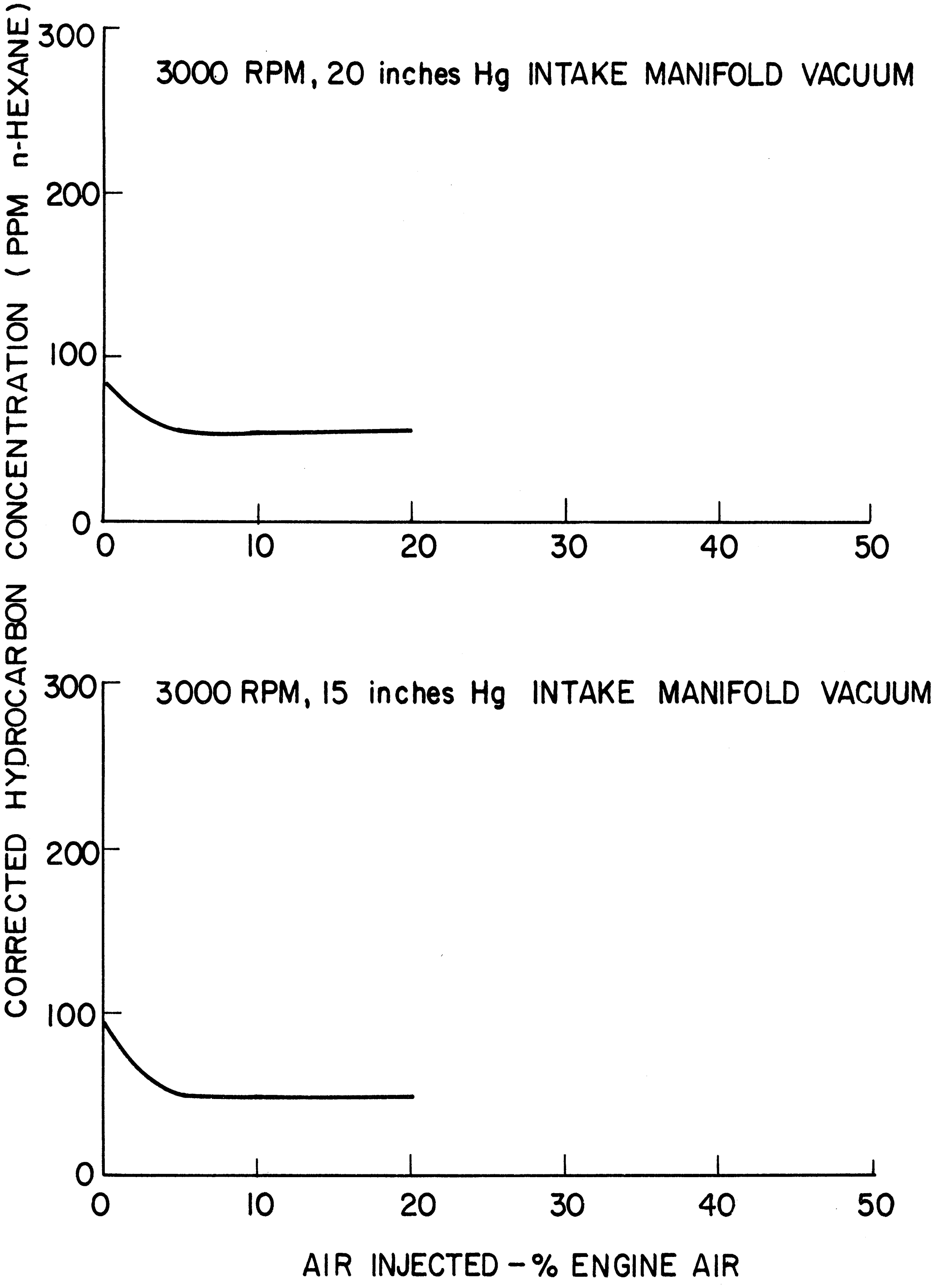

Fig. 41. The effect of exhaust port air injection on the hydrocarbon emissions; 3000 rpm, 15 and 20 in. Hg.—RC engine with WAD reactor.

D. DISCUSSION OF THE CURTISS—WRIGHT EXHAUST MANIFOLD REACTOR

The exhaust manifold reactor used in the second phase of the experimental study was designed by the Curtiss-Wright Corporation specifically for the RC 2-60 engine. As demonstrated by the results of the emission studies this reactor performed extraordinarily well in its role as an after engine, combustion chamber. However, even though the reactor was made of a high quality turbine alloy, Hastelloy X, several failures did occur which cast some doubt on the design. Perhaps a ceramic material of some type would be as effective and undoubtedly, much less expensive.

The reactor assembly is shown in Fig. 42 viewed from the side which attaches to the engine exhaust ports.

In Fig. 43 it is shown disassembled (note this is after 100 hours of use). Located in the center of the photograph is a shell consisting of two concentric cylinders of Hastelloy X which enclose an insulating material. Several failures occurred in the welds at the end of this shell caused by excessive grinding of the original welds, stress risers due to the welding, and high thermal stresses. These failures were noticed on disassembly after approximately 30 and 60 hours of running. Repairs were made by Saffran Engineering Company in Detroit. The cylinder at the lower part of the picture is the reactor core into which the hot exhaust gases are directed from the engine. This core is subjected to the highest temperatures. The core is shown in more detail in Figs. 44 and 45. In Fig. 44 the baffle plates in the core interior can be seen. These eroded substantially during the test program demonstrating the highly corrosive nature of the high temperature exhaust gases. The effect of this high temperature and the significant temperature gradients within the reactor is shown in the end view of the core in Fig. 45. The originally circular cross-section has deformed into a noticeably elliptical shape.

It is possible to generalize somewhat with respect to the design of any exhaust reactor and say that there are several factors which work together to determine its effectiveness. These factors are:

1. Temperature
2. Volume
3. Pressure
4. Time
5. Excess oxygen
6. Mass flow Rate
7. Specific reaction rate of the unburned components

If, for example, the reactor temperature could be increased both its volume and/or the dwell time of the gases in the reactor could be decreased. Excess oxygen, however, must always be present and well mixed with the exhaust to achieve a more complete reaction. Unfortunately, the increased temperature would probably cause severe metallurgical problems, and more than likely increase the cost and decrease the expected life of the reactor.

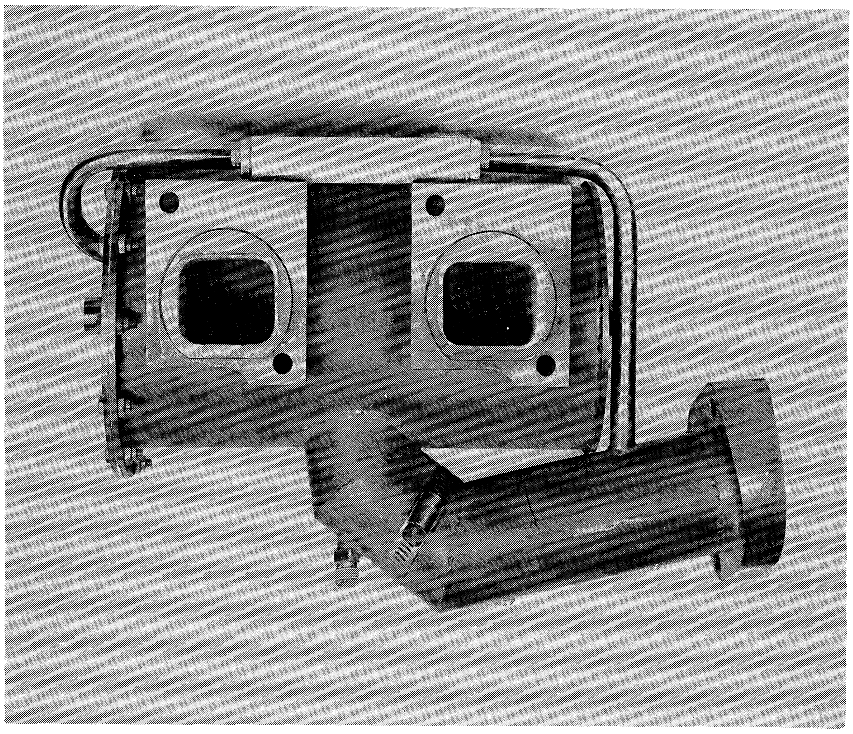

Fig. 42. WAD reactor assembly—viewed exhaust port side.

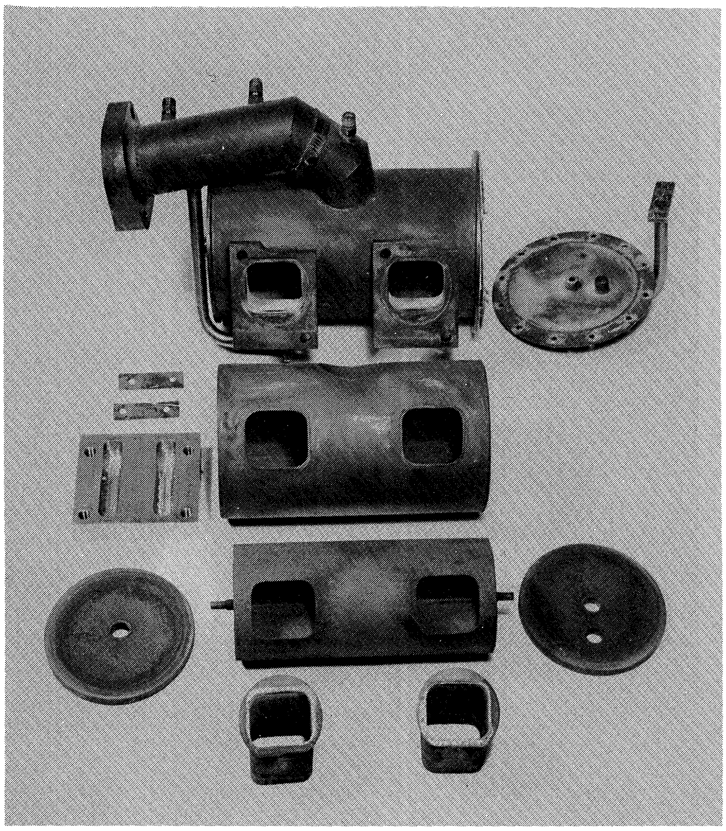

Fig. 43. WAD reactor disassembly—after 97-1/2 hours of testing.

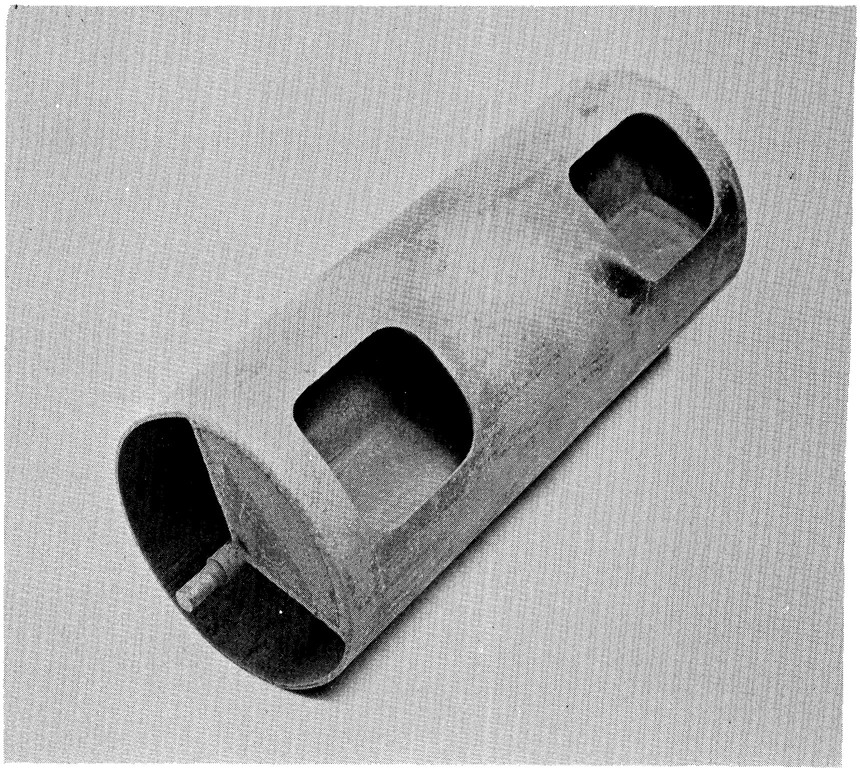

Fig. 44. WAD reactor inner core—after 97-1/2 hours testing.

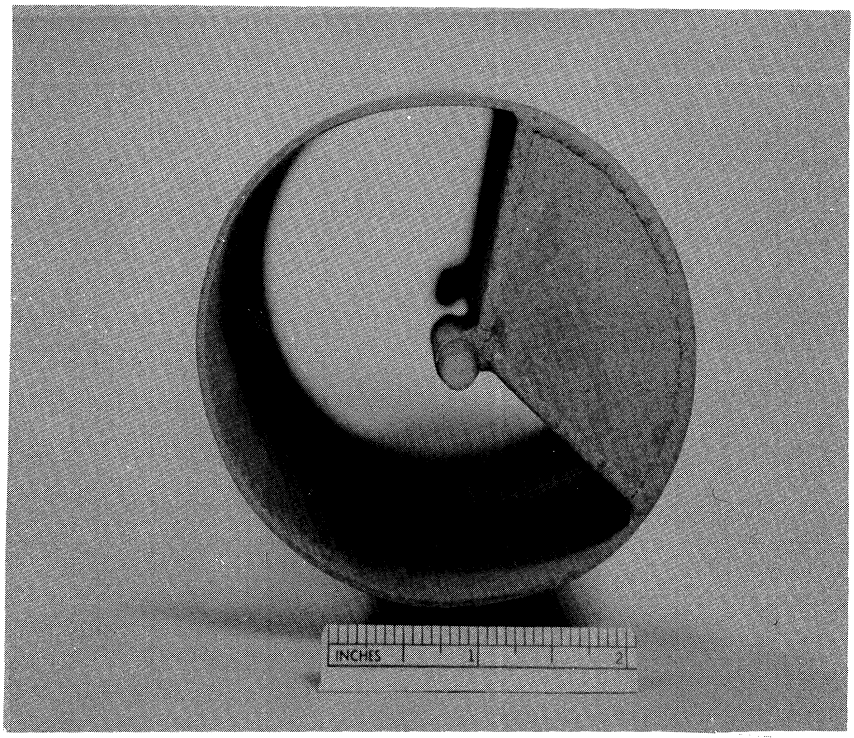

Fig. 45. WAD reactor inner core—end view showing heat distortion after 97-1/2 hours testing.

E. ANALYSIS OF THE RC ENGINE EXHAUST EMISSIONS

The RC engine presents a difficult analysis problem to one concerned with explaining the whys and wherefores of its exhaust emissions.

The exhaust emissions from the combustion chamber of the RC engine as well as other spark-ignition engines are a result of several processes.

1. Perhaps the most important emission source results from the well known but little understood wall quenching phenomena. As the propagating flame front approaches the relatively cool chamber wall, it is extinguished or quenched a finite distance from the wall. Remaining in this so-called "quench zone" is raw fuel/air mixture, partially burned and/or cracked fuel, carbon monoxide, and other less noxious products. There is apparently little tendency to form oxides of nitrogen, however, in this relatively low temperature region. During the exhaust process some of these "quench zone" products are scavenged from the chamber walls and released to the atmosphere, and some are retained and partially burned on the succeeding cycle.

This emission source is particularly significant in the RC engine for two basic reasons:

a. The RC engine has a high surface/volume ratio in the combustion chamber and thus, a large quench zone volume.

b. The trailing apex seal of a given rotating combustion chamber "scrapes" the quench layer off the rotor housing and into the peripheral exhaust port.

2. The second possible source arises from another quench process. In this case if two relatively cool surfaces enclosing a mixture are brought progressively together, a certain separation distance (quench distance) will be reached where a flame will not propagate between them. The volume contained in these quenched regions is filled primarily with unburned fuel/air mixture which has an extremely high concentration of unburned hydrocarbons. If this volume is relatively large and is vented unburned to the atmosphere during the engine cycle the overall hydrocarbon emissions may be greatly affected.

The RC engine in its present form has substantial combustion chamber volume contained between surfaces in closer proximity than this "quench distance." These regions include:

a. The volume above the side seal and between the rotor and rotor housing.

b. The leading and trailing portions of the rotor surface which are close to the rotor housing.

c. The elevated rib bordering the rotor cut-out may also be too close to the housing.

3. Leakage of unburned mixture to the atmosphere can affect the emissions significantly. Raw fuel/air mixture when considered alone has an unburned

hydrocarbon concentration of from 17,000 to 25,000 ppm. Thus, even a small percentage loss of mixture can have a great effect on the overall concentration of hydrocarbons in the exhaust.

A conventional four-stroke cycle automotive engine loses only a very small portion of unburned mixture past the closed exhaust valve. The blowby is not considered because it is rebreathed with current emission controls. The RC engine, however, shows significant leakage of raw mixture past the leading apex seal, which is lost directly through the exhaust port to the atmosphere.

4. Incomplete combustion in the reaction zone can result in emissions, particularly with rich fuel/air mixtures and/or poor mixing of the fuel and air.

The RC engine would appear to have a minimum problem from this source because it operates well on lean mixtures and has intense combustion chamber turbulence which promotes homogeneity and complete combustion.

APPENDIX A. COMMENTS ON THE RC ENGINE INSTALLATION

1. A 1964 Dodge Dart automatic transmission P/N 2466092 and torque converter P/N 2204403 were connected to the engine as safety devices to prevent starter motor overload due to the large rotor inertia of the Mid-West dynamometer and to minimize a possible torsional vibration problem.

2. A spicer coupling, which is used on most of the dynamometers in the Automotive Lab, was welded to a Dodge universal joint to connect the transmission to the dynamometer. This was done in lieu of machining the Thomas coupling specified by Curtiss-Wright.

3. Lake Shore engine stands were used with rubber motor mounts in place of the pedestal mounts indicated by blueprints Nos. 318118 and 319423.

4. All of the iron-constantan thermocouples, except for the one mounted in the skin of the combustion chamber of the anti-drive rotor, were replaced with copper-constantan and chromel-alumel thermocouples which matched the reference junctions of the Brown potentiometer in the dynamometer console.

5. In the experimental studies without the WAD exhaust reactor the exhaust manifold supplied with the engine was replaced with individual steel pipes which were attached directly to the exhaust ports. Several feet downstream from the ports the pipes were brought together into a single exhaust pipe. This system permitted either individual sampling of the exhaust gases from each rotor, or sampling of the total engine exhaust.

APPENDIX B. RC ENGINE COMBUSTION AIR FLOW MEASUREMENTS

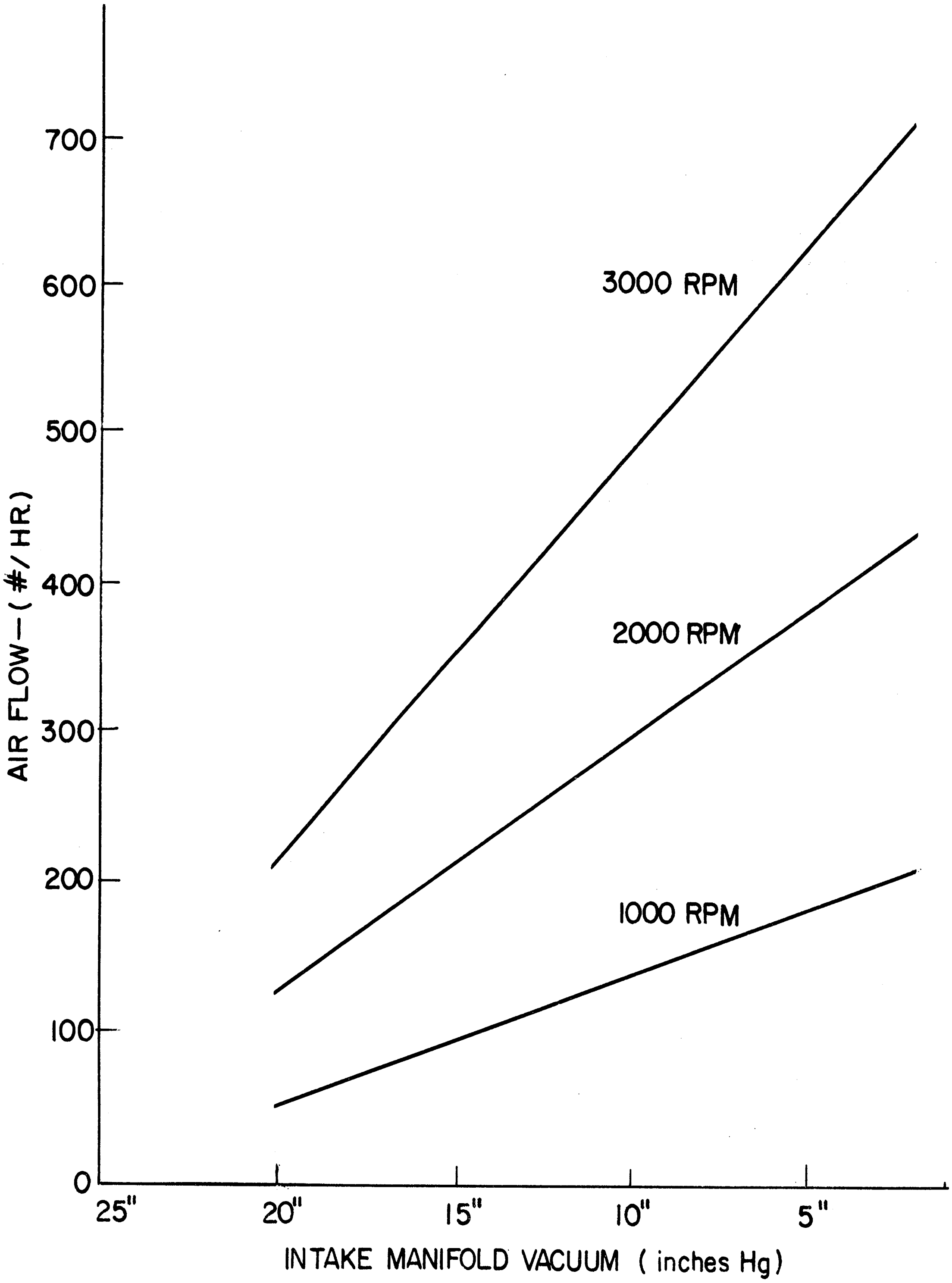

Fig. 46. RC engine mass rate of air flow as a function of intake manifold vacuum.

APPENDIX C. ORSAT CALIBRATION CURVES

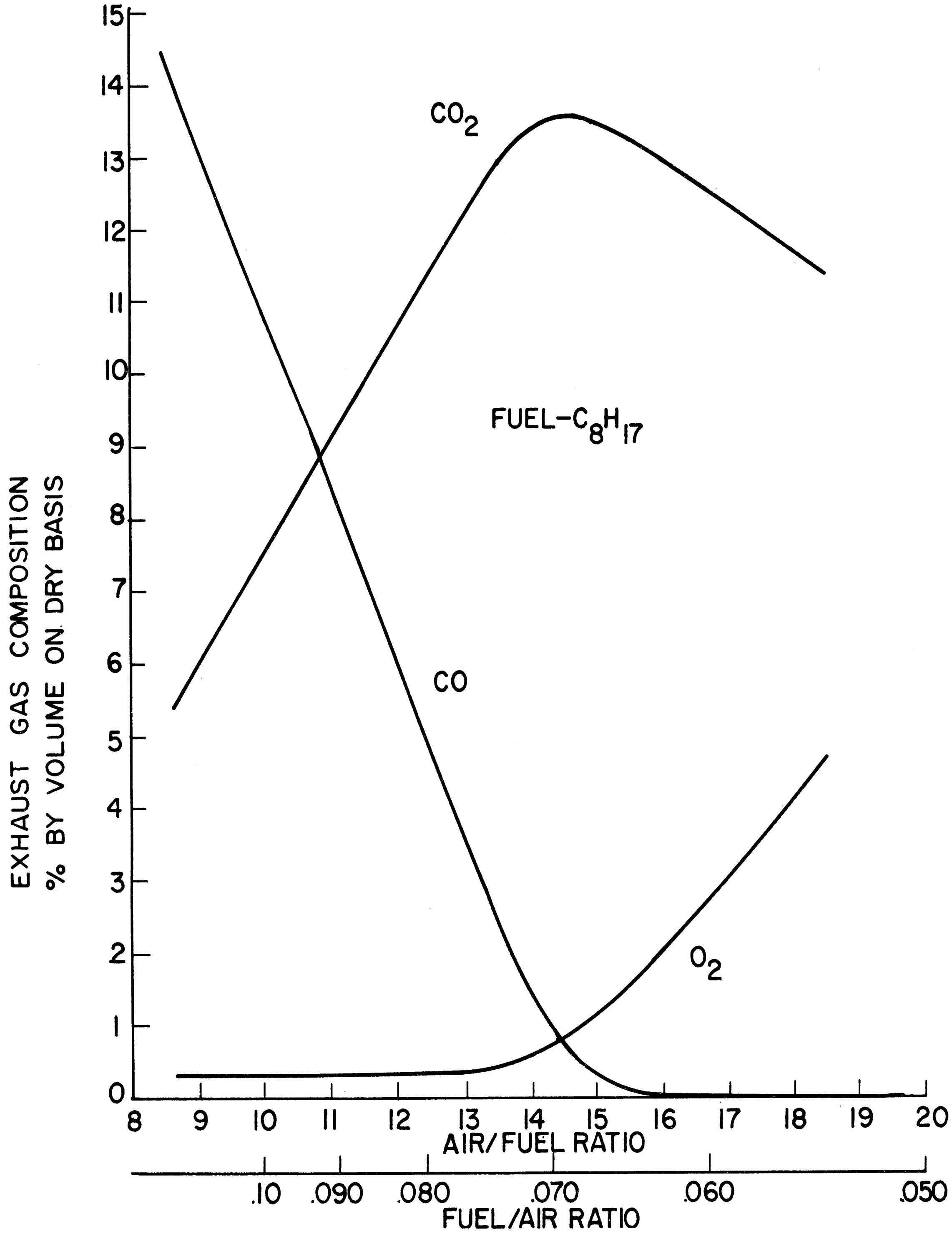

Fig. 47. Exhaust gas composition as a function of air/fuel ratio.

APPENDIX D. BECKMAN NDIR CALIBRATION CURVE

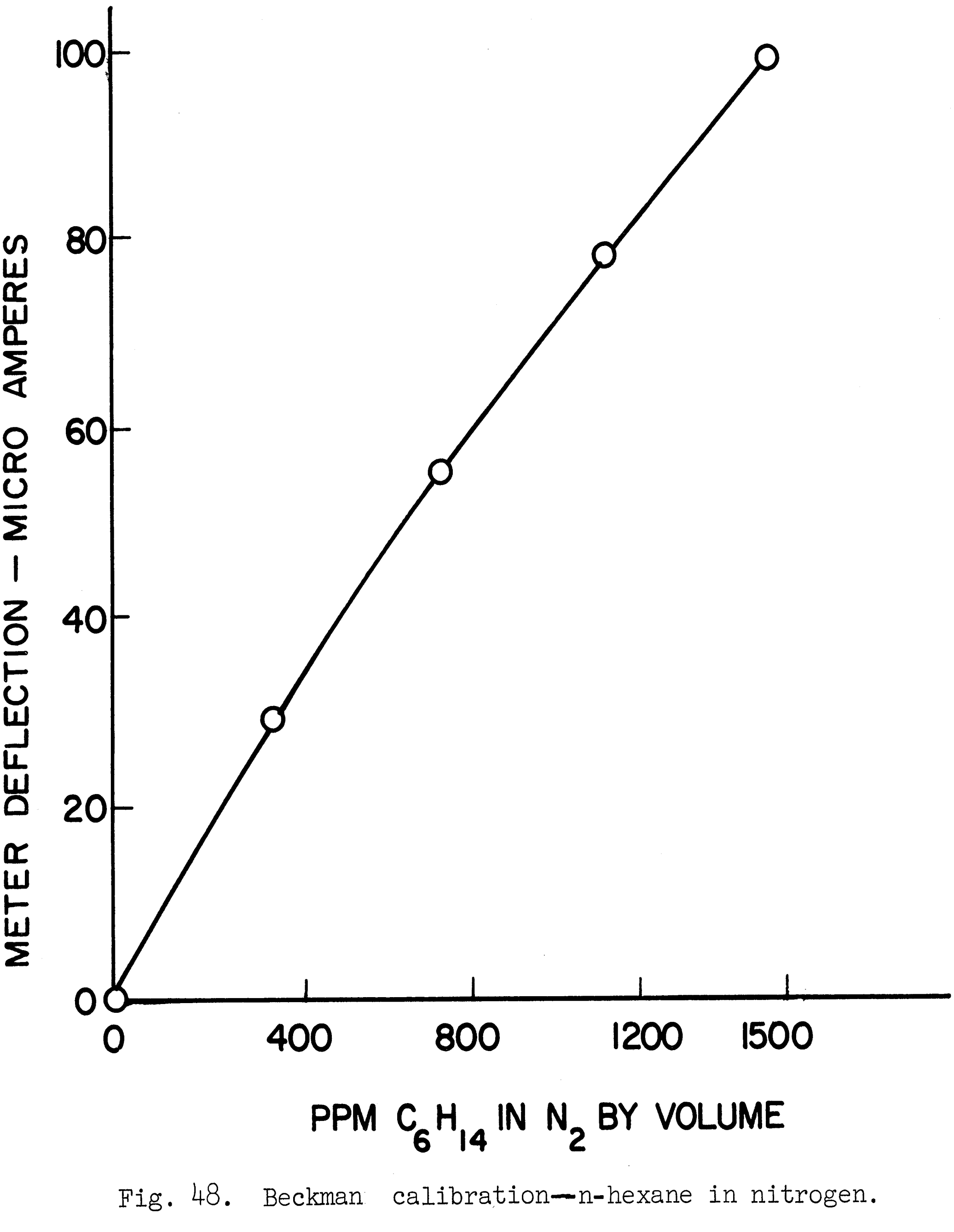

Fig. 48. Beckman calibration—n-hexane in nitrogen.

APPENDIX E. CONVERSION OF CONCENTRATION HYDROCARBON EMISSIONS TO MASS EMISSIONS PER UNIT TIME

Assume the dry exhaust gas is composed only of these components with their respective molecular weights; CO_2 - 44, N_2 - 28, and C_6H_{14} - 86. For each mole of CO_2 there are approximately 6 moles of N_2.

$$\text{Molecular weight of } CO_2 \text{ and } N_2 \text{ mixture} = \frac{(1x44) + (6x28)}{7} = 30.3 \qquad \text{(E-1)}$$

If x = ppm C_6H_{14} (n-hexane), then 86x is proportional to the mass of C_6H_{14}, and 30.3 (10^6-x) is proportional to the mass of $CO_2 + N_2$,

$$\frac{\text{Mass } C_6H_{14}}{\text{Total mass}} = \frac{86\ x}{30.3(10^6-x)+86\ x} \qquad \text{(E-2)}$$

if x < 1000 ppm, less than a .5% error will be introduced if the above relation is simplified to;

$$\frac{\text{Mass } C_6H_{14}}{\text{Total Mass}} \cong \frac{86\ x}{30.3 \times 10^6} \qquad \text{(E-3)}$$

Engine air flow + fuel flow is;

$$\dot{M}_T = \dot{M}_A + F/A\ \dot{M}_A = (1+F/A)\ \dot{M}_A$$

where:

$$\dot{M}_T = \text{total mass flow rate} \qquad \text{(E-4)}$$

and

$$\dot{M}_A = \text{air flow rate}$$

$$M_T = (1+F/A)\ \dot{M}_A$$

Thus, the mass rate of hydrocarbon emissions is

$$\dot{M}_{C_6H_{14}} = \dot{M}_A(1+F/A)(\frac{86\ x}{30.3x10^6})$$

x = ppm n-hexane (measured)

$\dot{M}_{C_6H_{14}}$ -#/hr. n-hexane (E-5)

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