NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 757

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THE MEASUREMENT OF FUEL-AIR RATIO BY ANALYSIS OF THE OXIDIZED EXHAUST GAS

By HAROLD C. GERRISH and J. LAWRENCE MEEM, Jr.

1943

AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length_____	l	meter_____	m	foot (or mile)_____	ft (or mi)
Time_____	t	second_____	s	second (or hour)_____	sec (or hr)
Force_____	F	weight of 1 kilogram_____	kg	weight of 1 pound_____	lb
Power_____	P	horsepower (metric)_____	_____	horsepower_____	hp
Speed_____	V	{kilometers per hour_____	kph	miles per hour_____	mph
		{meters per second_____	mps	feet per second_____	fps

2. GENERAL SYMBOLS

W Weight=mg

g Standard acceleration of gravity=9.80665 m/s^2 or 32.1740 ft/sec^2

m Mass=$\dfrac{W}{g}$

I Moment of inertia=mk^2. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\dfrac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\dfrac{L}{qS}$

D Drag, absolute coefficient $C_D=\dfrac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D0}=\dfrac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{Di}=\dfrac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{Dp}=\dfrac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\dfrac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\dfrac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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Cleveland, Ohio

I

National Advisory Committee for Aeronautics

Headquarters, 1500 New Hampshire Avenue NW., Washington 25, D. C.

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By Harold C. Gerrish and J. Lawrence Meem, Jr.

SUMMARY

An investigation was made to determine a method of measuring fuel-air ratio that could be used for test purposes in flight and for checking conventional equipment in the laboratory.

Two single-cylinder test engines equipped with typical commercial engine cylinders were used. The fuel-air ratio of the mixture delivered to the engines was determined by direct measurement of the quantity of air and of fuel supplied and also by analysis of the oxidized exhaust gas and of the normal exhaust gas. Five fuels were used: gasoline that complied with Army-Navy Fuel Specification No. AN–VV–F–781 and four mixtures of this gasoline with toluene, benzene, and xylene.

The method of determining the fuel-air ratio described in this report involves the measurement of the carbon-dioxide content of the oxidized exhaust gas and the use of graphs or the presented equation. This method is considered useful in aircraft, in the field, or in the laboratory for a range of fuel-air ratios from 0.047 to 0.124.

INTRODUCTION

Measurement of the fuel-air ratio of the combustible mixture supplied to internal-combustion engines has received considerable attention during the past few years. This interest has been accentuated by investigations that have shown the limitation of the allowable range of fuel-air ratios in full-scale engines when compared with the range in a single-cylinder engine. The fuel-air ratio at which an internal-combustion engine operates is of paramount importance not only because it is a factor in the correlation of all engine-performance data but also because it affects the temperature of the engine cylinders, the specific fuel consumption, the range, and the useful carrying capacity of aircraft.

Knowledge of the fuel-air ratio at which internal-combustion engines are operated and the control of this ratio in flight is essential for the following reasons: (1) to avoid possibility of engine failure due to high temperature or to knock caused by unfavorable mixtures, (2) to assure optimum power when required, (3) to achieve maximum economy, and (4) to make possible the correlation of engine-performance data.

An analysis of the exhaust gas from each cylinder can be used to determine the mixture strength of the charge to the cylinders of a multicylinder engine in flight, in the field, or in the laboratory. This method would also be useful in checking the accuracy of conventional methods in the laboratory.

The determination of the fuel-air ratio in the laboratory is usually made by employing gasometers, venturi meters, orifice plates, fuel-weighing devices, and flow meters in various combinations to measure separately the air and the fuel supplied to the engine intake. In flight, the accurate determination of fuel and air quantities with such devices is difficult and, in some cases, impossible. Automatic instruments that are actuated by the thermal conductivity of the products of combustion in the exhaust gases have been used in flight for indicating the fuel-air ratio. The extension of the operating range of the engine to lean-mixture operation (mixtures leaner than the theoretical), however, causes reversal of the usual type of indicator making it show a rich mixture when the engine is operating on a lean mixture. For these reasons and because a simple fundamental standard is required to measure the fuel-air ratio of the mixture supplied to the engine as well as that supplied to the separate cylinders in flight, this investigation was undertaken.

This report presents an accurate method of determining the fuel-air ratio of the mixture supplied to the cylinders of an internal-combustion engine and also presents data correlating the results obtained by this method with those obtained by the usual method for fuels having hydrogen-carbon ratios between 0.115 and 0.188 and for mixture strengths covering the entire range of possible engine operation.

ENGINE CONDITIONS

Two single-cylinder test units, designated engine A and engine B, were equipped with typical commercial engine cylinders. Figure 1 shows the setup of engine A and of the auxiliary equipment. The setup of engine B was similar. Both units had dual-ignition and modified carburetor fuel systems and were air-cooled. Characteristics of the engines and the test conditions are given in the following table:

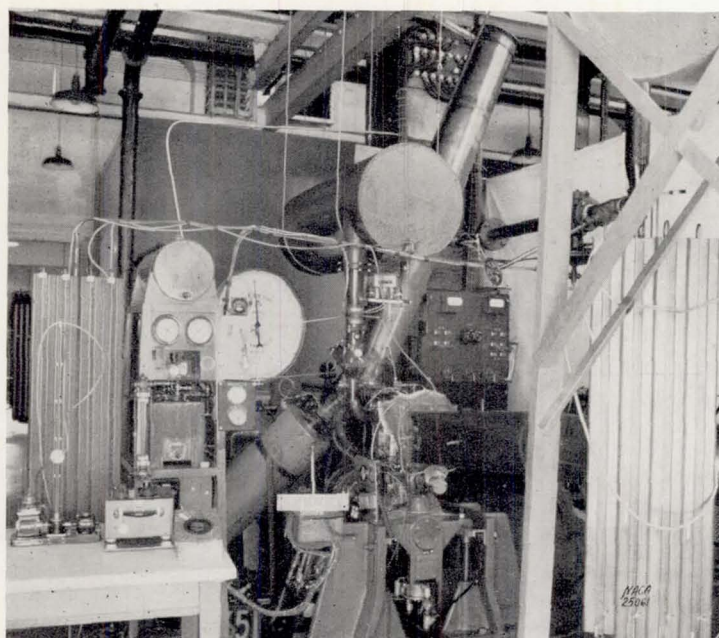| Engine	Type of cylinder	Displacement (cu in.)	Compression ratio	Engine speed (rpm)	Valve timing (deg overlap)	Manifold pressure (in. Hg)
A	G200	206	6.99 6.7	2000	44	32
B	G	202	6.4	2000	47	29.5

1

FIGURE 1.—Setup engine A and auxiliary equipment.

The engine speed was manually controlled within ±10 rpm of the standard speed by stroboscopic observation of marks on the flywheels. Rotameters were used to make preliminary adjustments of the fuel going to the engines. The weight of fuel used was determined by weighing tanks electrically synchronized with the engine revolution counters and stop watches. The air entering the engine cylinders passed through sharp-edged orifices where the pressure drop was measured. It then passed through surge tanks and to modified carburetors in which only the fuel jets and the venturi passages were used. The quantity of fuel flowing to the jets was controlled by an adjustable needle valve.

The fuels used in this investigation were obtained by adding aromatic fuels to 100-octane gasoline that complied with Army-Navy Fuel Specification No. AN–VV–F–781. Characteristics of these fuels are shown in the following table:

En-gine	Fuel	Composition by volume (percent)				Tetra-ethyl lead (ml/gal)	Hydro-gen-carbon ratio, H/C	Heat of combustion (Btu/lb)	
		100-octane gasoline	Tol-uene	Ben-zene	Xy-lene			Gross	Net
B	A	100	---	---	---	3	0.188	20,420	18,935
A	A	100	---	---	---	3	.188	20,420	18,935
A	B	85	15	---	---	3	.168	20,060	18,705
A	C	60	20	5	15	3	.147	19,650	18,445
A	D	50	---	50	---	3	.125	19,030	17,885
A	E	37.2	---	62.8	---	3	.115	18,625	17,656

The hydrogen-carbon ratios of the fuels were determined in this laboratory by the usual combustion method. The aircraft-engine lubricating oil was Navy 1120 with a hydrogen-carbon ratio of 0.156 and a specific gravity of 0.881 at 25° C (77° F).

METHOD

Exhaust gas was obtained by inserting a ¼-inch tube of stainless steel into the center of the exhaust stack approximately 1½ inches from the exhaust port. The length of the gas-sampling tube varied from 4 to 20 feet depending on the setup. Experiments with many engines during the past several years have shown that this method is satisfactory provided that a positive pressure exists at the gas entrance of the tube and that no air leaks are present. The gas-entrance end of the tube was pointed upstream to increase the positive pressure of the gas by the dynamic pressure. The gas was passed through the tubing to an oxidizer, through a desiccator, and then to a gas-analysis apparatus in which the carbon dioxide (CO_2) content of the oxidized exhaust gas was determined. The oxidizer was made of 1-inch tubing of stainless steel and filled with cupric-oxide wire 0.020 inch in diameter. In flight, the oxidizer would be located in the exhaust stack or the collector ring of the engine at a position where the temperature is not less than 1000° F and not more than 1600° F but, for the purpose of simplicity of installation in these tests, the oxidizer was located in an electric furnace maintained at a temperature of approximately 1200° F. A connection was provided in the tubing between the oxidizer and the exhaust stack in order that samples of the normal exhaust gas could be taken for each engine-operating condition. These samples were taken by mercury displacement in glass sampling tubes and completely analyzed in a modified gas-analysis apparatus developed at the National Bureau of Standards. (See reference 1.)

The desiccator, containing calcium chloride, was not required for the work described in this report but concurrent tests of an indicating device, which is to replace the gas-analysis apparatus and required dry gas for its operation, made the inclusion of the desiccator necessary.

Engine data for the computation of the fuel-air ratio of the mixture in the engine cylinder, samples of the normal exhaust gas, and the CO_2 content of the oxidized exhaust gas were obtained for each engine-operating condition covering a range of mixture strengths from full lean to full rich, fuel-air ratios from 0.047 to 0.124.

Two fundamental methods for the determination of the fuel-air ratio were thus made available. First, the usual laboratory method in which the rate of fuel supply is divided by the rate of air supply and, second, the method in which the normal exhaust gas is chemically analyzed. In the second method the fuel-air ratio is calculated by stoichiometric equations and oxygen and nitrogen balances.

Because these basic methods provide a standard for comparison, it will be shown that the relation between the fuel-air ratio and the CO_2 content of the oxidized exhaust gas can be expressed by an equation and shown graphically for convenience in application. A similar use can be made of the percentages of CO_2 and oxygen (O_2) found in the normal exhaust gas by correlating them with the fuel-air ratio.

RESULTS AND DISCUSSION

Figure 2 shows the relation of CO_2 to fuel-air ratio in dry oxidized exhaust gas for the five fuels used. The relation has been computed on a dry basis because the method used in gas analysis gives the composition on a dry basis. The
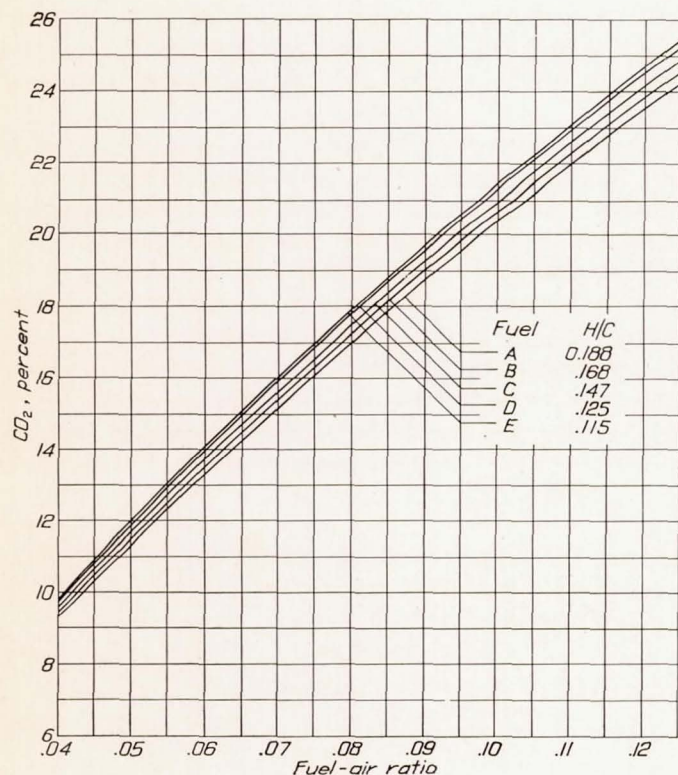

FIGURE 2.—Calculated relation of percentage carbon dioxide in dried oxidized exhaust gas to fuel-air ratio. Fuel-air ratio computed from equation (1).

symbols CO_2 and N_2 represent the volume percentage as well as the mole percentage of carbon dioxide and nitrogen, respectively, in the completely dried, oxidized exhaust gas; F/A, the weight ratio of fuel and air entering the engine cylinder; and H/C, the weight ratio of hydrogen and carbon in the fuel. In the analysis from which figure 2 was prepared, the weights of the various constituents involved in the formation of 1 mole of oxidized exhaust gas are:

$$\text{Weight of carbon} = 12\ CO_2$$

$$\text{Weight of hydrogen} = 12\ CO_2\left(\frac{H}{C}\right)$$

$$\text{Weight of fuel} = 12\ CO_2\left(1+\frac{H}{C}\right)$$

$$\text{Weight of air} = \frac{28}{0.767}N_2$$

but

$$N_2 = 100 - CO_2$$

therefore

$$\text{Weight of air} = \frac{28}{0.767}(100 - CO_2)$$

and

$$\frac{F}{A} = \frac{0.329\ CO_2\left(1+\dfrac{H}{C}\right)}{100 - CO_2} \tag{1}$$

With a given CO_2 content in the oxidized exhaust gas, the fuel-air ratio is not critically dependent upon the hydrogen-carbon ratio of the fuel. With a CO_2 content of 17 percent in the oxidized exhaust gas, which is approximately that for maximum power, equation (1) shows that, in an extreme case, a change from 0.188 to 0.115 in the hydrogen-carbon ratio of the fuel results in a change in the fuel-air ratio from 0.080 to 0.075.

The hydrogen-carbon ratios of aviation gasoline available in this country and those of aviation petrols used in Great Britain may be assumed, with negligible error in the fuel-air ratio, to have a value of 0.188.
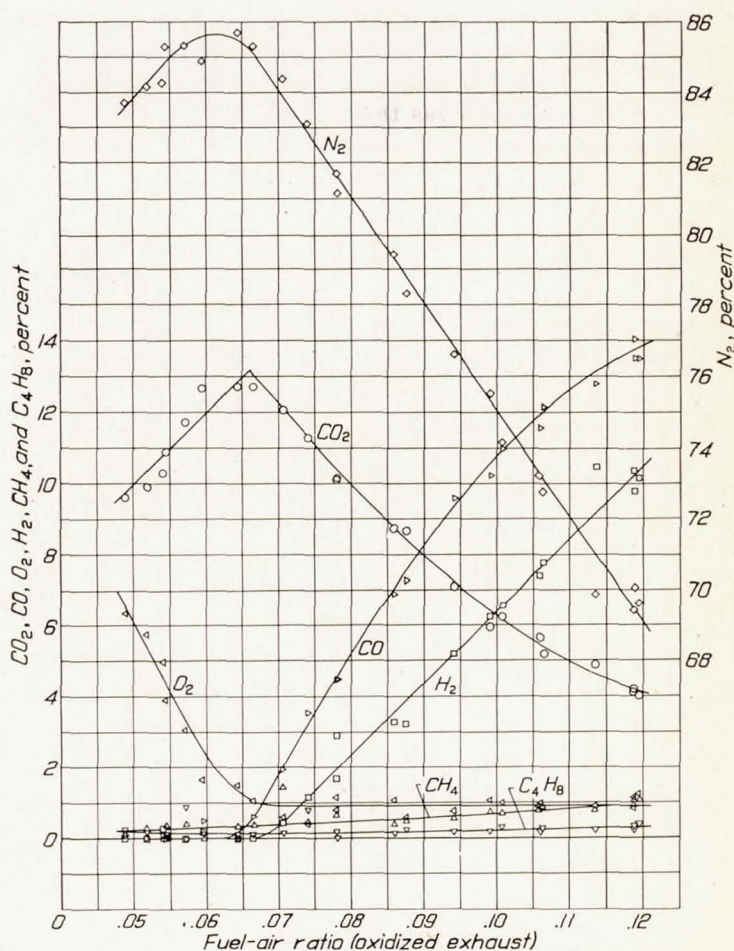

FIGURE 3.—Relation of constituents in normal exhaust gas to fuel-air ratio. Fuel A, Army 100-octane; aromatics, 0 percent; hydrogen-carbon ratio, 0.188; tetraethyl lead, 3 ml per gallon.

Figure 3 shows the relation of the constituents in the normal exhaust gas of an engine using fuel A to fuel-air ratio determined from the CO_2 in the oxidized exhaust gas and from figure 2. The quantity of unsaturated hydrocarbons is determined by passing the exhaust gases through fuming sulfuric acid. Slow-combustion experiments indicate that these hydrocarbon molecules have an average of four carbon atoms; the hydrocarbon was therefore assumed to be butene (C_4H_8).

The experimental results of the effect of fuel-air ratio on the CO_2 content in normal and in oxidized exhaust gas and on the O_2 content in normal exhaust gas for fuels A, B, C, D, and E are shown in figure 4. The line showing the relation of CO_2 in the oxidized exhaust gas to fuel-air ratio was calculated from equation (1). The test points near the calculated curve show the relation between the measured CO_2 content of the oxidized exhaust gas and the fuel-air ratio determined by the measured intake. No oxygen was detected in the oxidized exhaust gas. The lines for CO_2 and O_2 in the normal exhaust gas were faired through the experimental points. The peak of the curve of normal CO_2 exhaust was located at the theoretically correct mixture.

It will be noted that, for all five fuels tested, the calculated relation of CO_2 to fuel-air ratio is in excellent agreement with the experimentally measured intake values except for the slight scatter of a few test points, which is probably due to the difficulty in maintaining constant engine conditions during the time required to make the observations. Considerably more experimental points are plotted for the CO_2 in the oxidized exhaust gas than for the CO_2 in the normal exhaust gas because the number of samples of the normal exhaust was limited by the time required to analyze completely each sample.

The agreement between the fuel-air ratio determined from the volume percentage of CO_2 in dried oxidized exhaust gas and from figure 2 and the fuel-air ratio determined from the measured intake is shown by figure 5 for the five fuels tested and for the two test engines. The excellent agreement indicates that the simple method of measuring the CO_2 content of the oxidized exhaust gas and of using the relations shown in figure 2 is satisfactory for indicating the fuel-air ratio.

After this agreement is noted, the question naturally arises: What happened to the lubricating oil consumed by the engine? If the lubricating oil burned, it would increase the CO_2 content of the oxidized exhaust gas and thus give a richer mixture than shown by the measured intake, which does not take into consideration the consumption of lubricating oil. If the lubricating-oil consumption is assumed to be 5 percent of the specific fuel consumption and this oil is considered to be burned completely at an intake fuel-air ratio of 0.060, then the fuel-air ratio determined from the CO_2 in the oxidized exhaust gas and in figure 2 would be
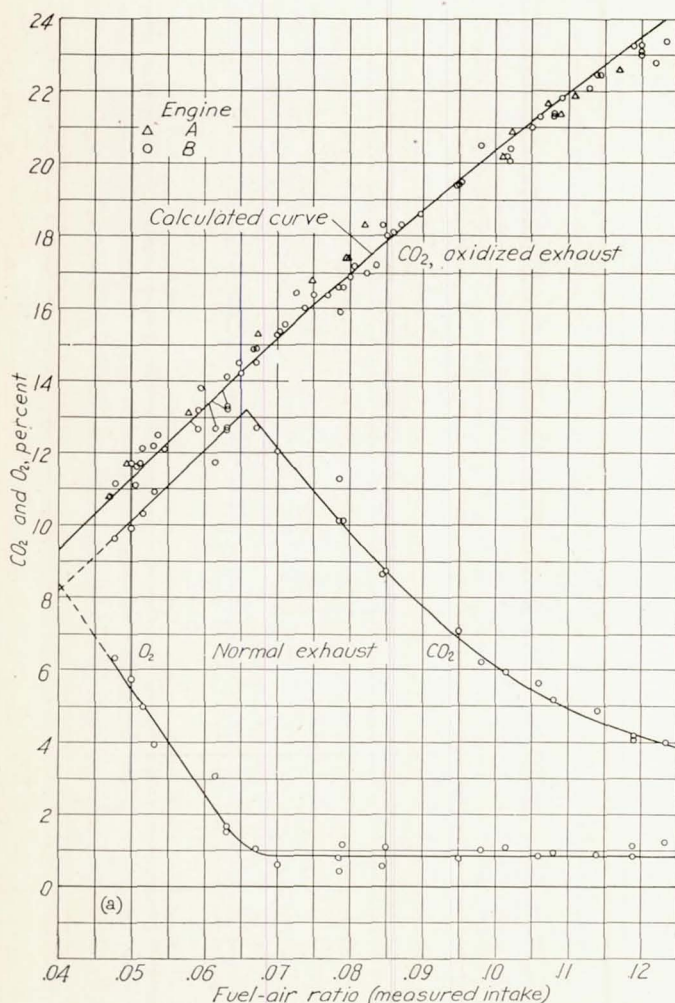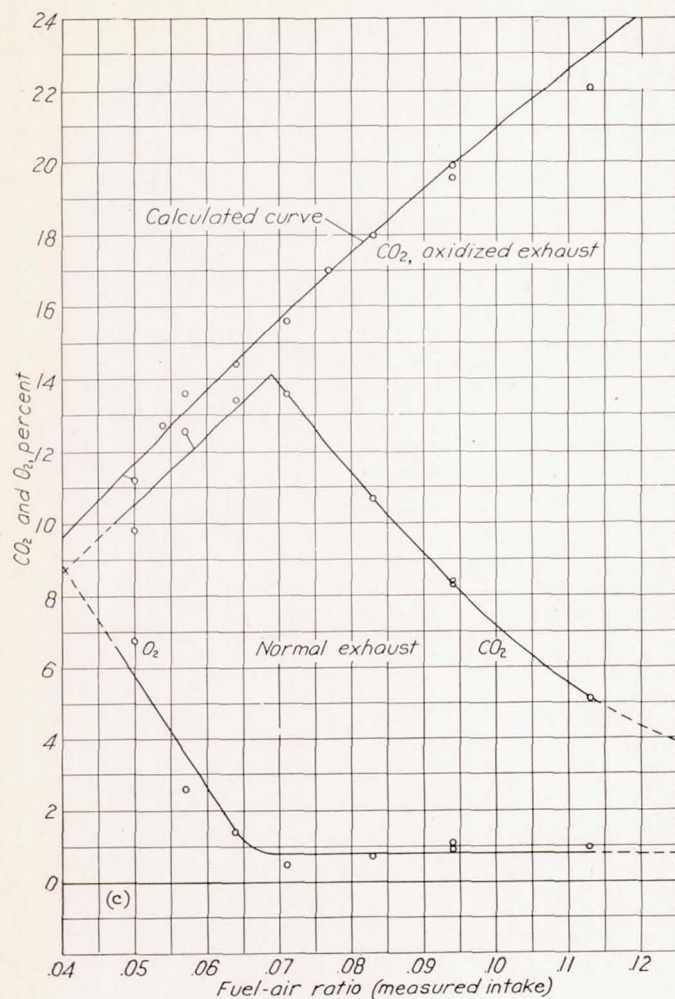

(a) Fuel A, Army 100-octane; aromatics, 0 percent; hydrogen-carbon ratio, 0.188; tetraethyl lead, 3 ml per gallon.
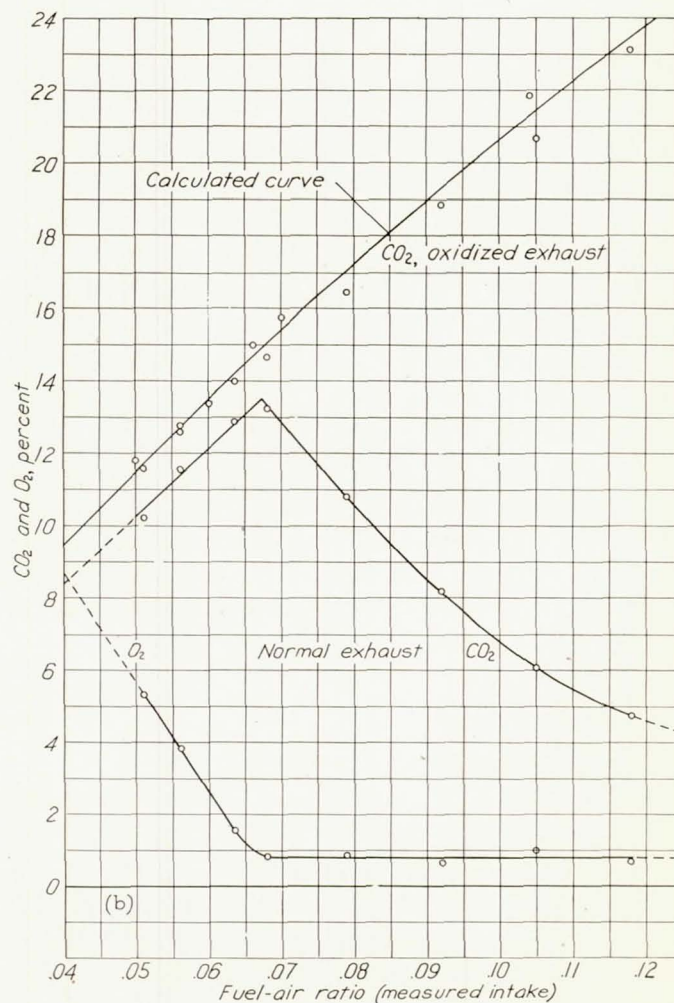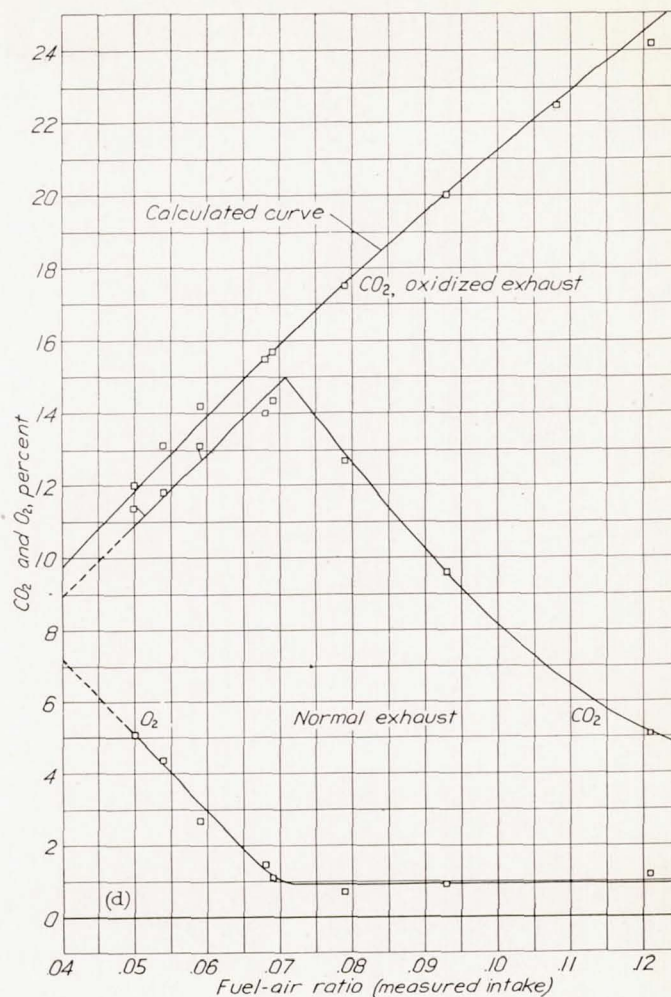
(b) Fuel B, Army 100-octane plus 15-percent toluene; hydrogen-carbon ratio, 0.168; tetraethyl lead, 3 ml per gallon.

FIGURE 4.—Effect of fuel-air ratio on carbon dioxide content in normal and oxidized exhaust gas and on oxygen content of normal exhaust gas.

(c) Fuel C, Army 100-octane plus 20-percent toluene plus 5-percent benzene plus 15-percent xylene; hydrogen-carbon ratio, 0.147; tetraethyl lead, 3 ml per gallon.

(d) Fuel D, Army 100-octane plus 50-percent benzene hydrogen-carbon ratio, 0.125; tetraethyl lead, 3 ml per gallon.

FIGURE 4.—Continued.   Effect of fuel-air ratio on carbon dioxide content in normal and oxidized exhaust gas and on oxygen content of normal exhaust gas.

0.063.   Although figure 5 shows some scatter of the data, there is no evidence of such a displacement of the curve, indicating that the lubricating oil actually burned was small.

Figure 6 shows the correlation between the possible CO_2 that may be obtained stoichiometrically from the constituents in the normal exhaust gas and the actual CO_2 in the oxidized exhaust gas for the five fuels tested. It will be seen that the agreement between the two methods in the range of normal engine operation is excellent, whereas in the case of ultrarich mixtures the possible CO_2 is insufficient. This condition is to be expected because, in the complete chemical analysis of the products of combustion, the solid carbon does not enter into the analysis.

The results obtained by various methods of determining the fuel-air ratio are compared in figures 7 (a) and 7 (b). Figure 7 (b) shows the agreement of the oxidized-exhaust-gas, the normal-exhaust-gas, and the chemical-analysis methods with the measured-intake method. The agreement of the measured-intake, the normal-exhaust-gas, and the chemical-analysis methods with the fuel-air ratio of the oxidized

exhaust is presented in figure 7 (b). It will be seen that any one of the four methods is satisfactory for measuring the fuel-air ratio. The greater simplicity of determining the fuel-air ratio by measuring the CO_2 content of the oxidized exhaust gas, however, and the fact that by this method the probability of error is reduced make it the preferred method and it is therefore recommended for use on all carburetor engines. Valve overlap and resulting discharge of unburned fuel or incomplete combustion due to slow-burning mixtures would have no effect because the method depends upon complete combustion in the oxidizer. The method may also be used in engines having direct cylinder injection with no scavenging air. In direct-injection engines that employ scavenging air, a timed sampling valve would be required.

Although the results were obtained at sea level, they are applicable to aircraft in flight because the analysis results do not depend upon pressure as long as it remains constant. Variations in pressure or changes in altitude of the airplane between the beginning and the end of the analysis will cause considerable error in the results. Calculations show that,
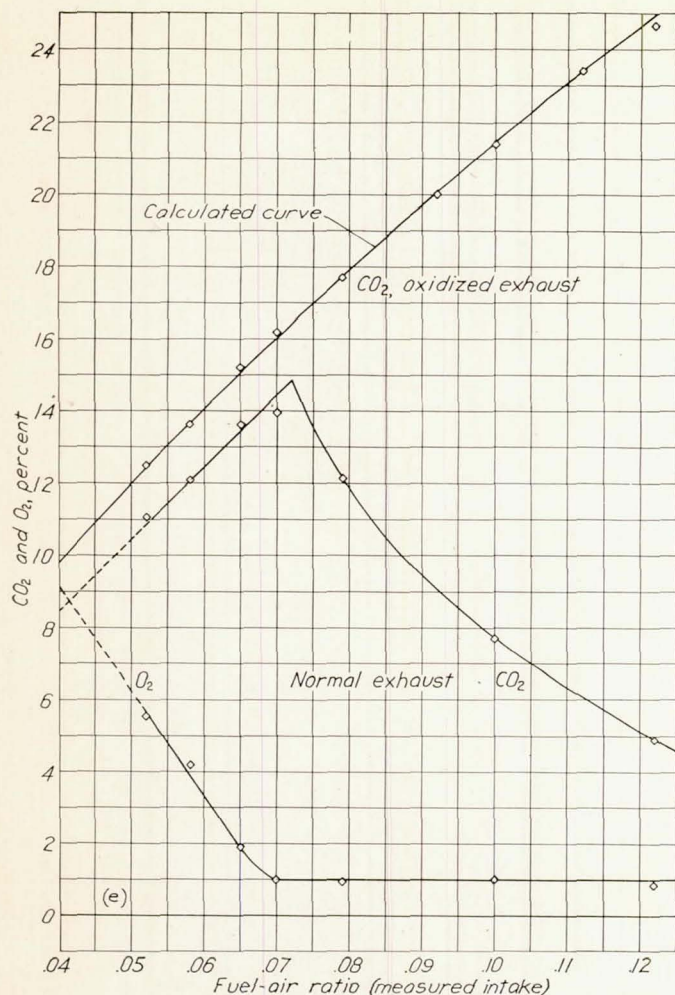
(e) Fuel E, Army 100-octane plus 62.8-percent benzene; hydrogen-carbon ratio, 0.115; tetraethyl lead, 3 ml per gallon.

FIGURE 4.—Concluded. Effect of fuel-air ratio on carbon dioxide content in normal and oxidized exhaust gas and on oxygen content of normal exhaust gas.

if the airplane is maintained within ±50 feet of the stipulated altitude during the test runs, the error in the analyses will be inappreciable, ±0.3 percent.

The method has been applied to a large airplane operating at various altitudes from sea level to 15,000 feet. The oxidizer was located in the collector ring and samples of the oxidized exhaust gas were satisfactorily obtained and analyzed. These tests covered a period of several weeks.

The method has also been used in the laboratory for obtaining the distribution of the mixture among the cylinders of a two-row radial engine equipped with short stacks. The same technique for obtaining, oxidizing, and analyzing the samples as described in this report were used on each cylinder.

It is realized that taking gas samples in a pursuit airplane and analyzing them in flight is not practical. In large airplanes such as bombers or transports, the method men-
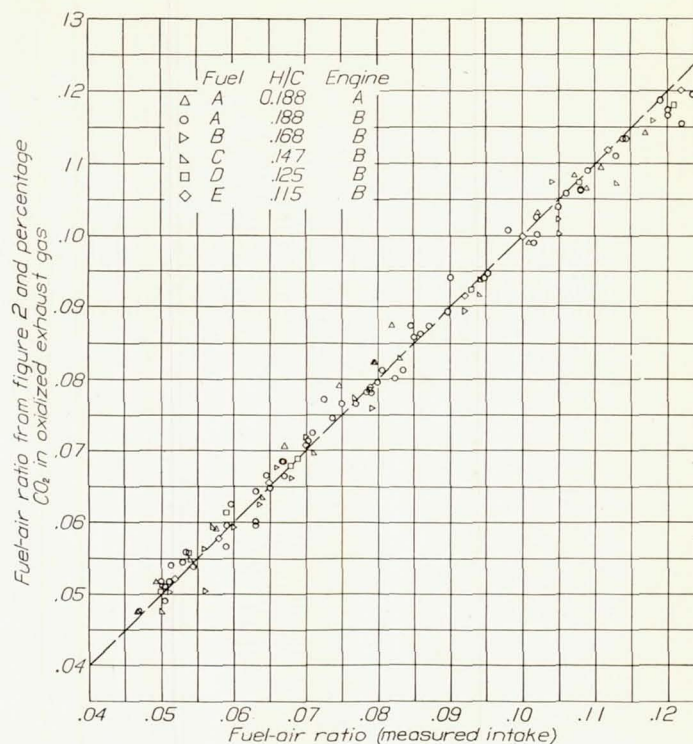

FIGURE 5.—Agreement between fuel-air ratio determined from volume percentage of carbon dioxide in dried oxidized exhaust gas and from figure 2 and fuel-air ratio determined from measured intake.

tioned is entirely feasible. The application of electrical means instead of absorption means for determining the carbon-dioxide content, however, is possible for all classes of airplanes. The electrical means could consist of a thermal-conductivity bridge wherein the thermal conductivity of the oxidized exhaust gas could be compared with that of a standard gas and the unbalance of the bridge shown on a galvanometer calibrated in carbon dioxide or preferably in fuel-air ratio.

The method should be of considerable help in the laboratory for checking the accuracy of installed equipment used to measure fuel-air ratio and should be especially valuable in the field where it would be impracticable to have the conventional measuring equipment. The cost of the necessary portable apparatus including a simple Orsat apparatus, a single-pass oxidizer, and the necessary tubing and chemicals would be nominal.

CONCLUSIONS

Tests of two single-cylinder engines using five fuels with hydrogen-carbon ratios between 0.115 and 0.188 over a range of fuel-air ratios from 0.047 to 0.124 resulted in the following conclusions:

1. The proposed method of determining the fuel-air ratio of the mixture supplied to internal-combustion engines by analysis of the oxidized exhaust gas for its CO_2 content and by use of the graphs presented is simple and precise and may be used in flight, in the field, and in laboratory tests.
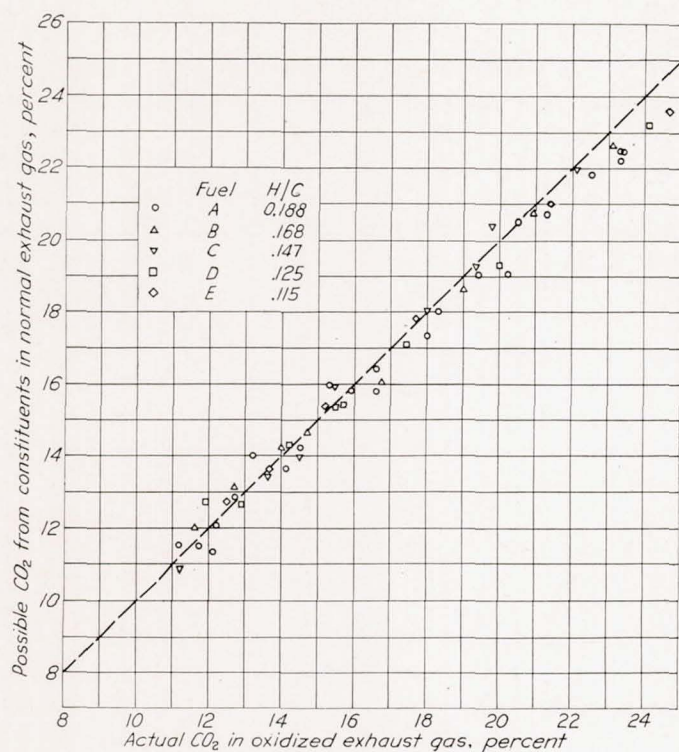
FIGURE 6.—Agreement between possible carbon dioxide from constituents in normal exhaust gas and actual carbon dioxide in oxidized exhaust gas.

2. The proposed method may be used for an exact survey of the mixture distribution among the cylinders of a multicylinder carburetor engine in flight, in the field, and in the laboratory.

3. Sampling of the exhaust gas through a ¼-inch tube of stainless steel located in the center of the exhaust stack and within 1½ inches of the exhaust valve resulted in securing satisfactorily representative samples of the gas.

4. The fuel-air ratio was not critically dependent upon the hydrogen-carbon ratio of the fuel; negligible error in the fuel-air ratio resulted when a hydrogen-carbon ratio of 0.188 was assumed for aviation gasoline.

AIRCRAFT ENGINE RESEARCH LABORATORY,
    NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
        CLEVELAND, OHIO, *October 1, 1943.*

REFERENCE

1. Shepherd, Martin: An Improved Apparatus and Method for the Analysis of Gas Mixtures by Combustion and Absorption. Res. Paper 266, Bur. Standards Jour. Res., vol. 6, no. 1, Jan. 1931, pp. 121–167.

(a) Fuel-air ratio (measured intake).
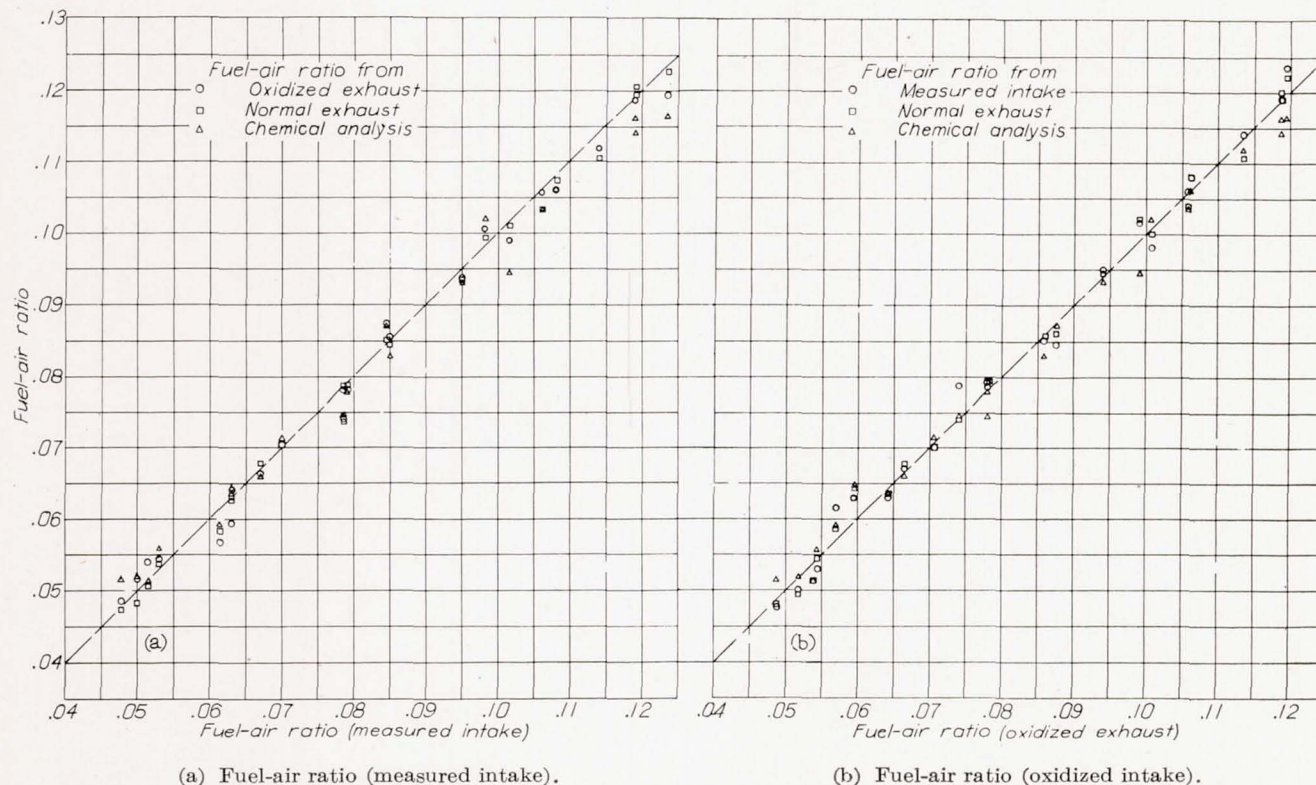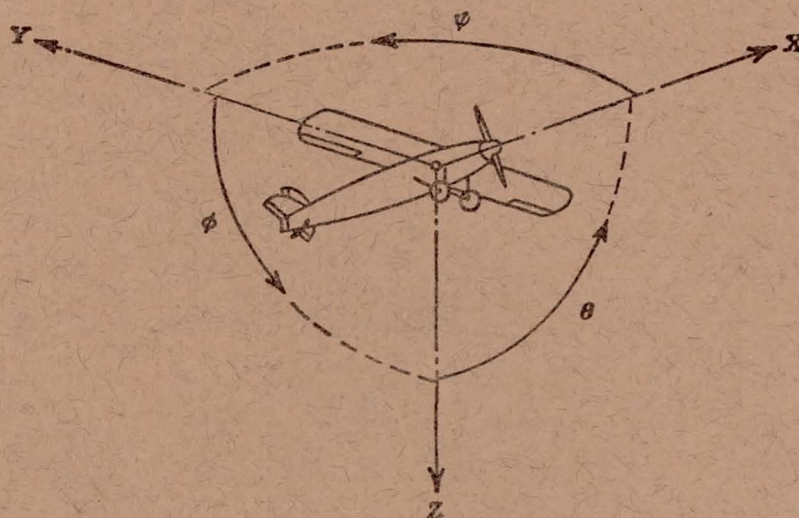
(b) Fuel-air ratio (oxidized intake).

FIGURE 7.—Comparison of various methods of determining fuel-air ratio. Fuel A, Army 100-octane; aromatics, 0 percent; hydrogen-carbon ratio, 0.188; tetraethyl lead, 3 ml per gallon.

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	φ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$
$$\text{(rolling)} \qquad \text{(pitching)} \qquad \text{(yawing)}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter
p Geometric pitch
p/D Pitch ratio
V' Inflow velocity
V_s Slipstream velocity

T Thrust, absolute coefficient $C_T = \dfrac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q = \dfrac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P = \dfrac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $= \sqrt[5]{\dfrac{\rho V^5}{P n^2}}$

η Efficiency
n Revolutions per second, rps

Φ Effective helix angle $= \tan^{-1}\left(\dfrac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg-m/s = 550 ft-lb/sec
1 metric horsepower = 0.9863 hp
1 mph = 0.4470 mps
1 mps = 2.2369 mph

1 lb = 0.4536 kg
1 kg = 2.2046 lb
1 mi = 1,609.35 m = 5,280 ft
1 m = 3.2808 ft