NACA RM E53A27

RM E53A27

RESEARCH MEMORANDUM

EFFECT OF INLET OXYGEN CONCENTRATION ON COMBUSTION EFFICIENCY OF J33 SINGLE COMBUSTOR OPERATING WITH GASEOUS PROPANE

By Charles C. Graves

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

March 31, 1953
Declassified February 10, 1956.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF INLET OXYGEN CONCENTRATION ON COMBUSTION EFFICIENCY OF J33 SINGLE COMBUSTOR OPERATING WITH GASEOUS PROPANE

By Charles C. Graves

SUMMARY

An investigation was conducted to determine the effect of oxygen concentration of the inlet oxygen-nitrogen mixture on the combustion efficiency of a J33 single combustor operating with gaseous propane fuel. Combustion efficiency data were obtained at combustor-inlet total pressures from 10.0 to 30.0 inches of mercury absolute, fuel flow rates from 0.008 to 0.016 pound per second, and inlet oxygen concentrations from approximately 14 to 46 percent by volume. The combustor-inlet temperature and weight flow rate of the oxygen-nitrogen mixture were held constant at 40° F and 1.0 pound per second, respectively. Attempts were made to correlate combustion efficiency with selected fundamental combustion properties and with a simplified reaction kinetics equation. The results were compared with those obtained from a similar previous investigation conducted with liquid isooctane fuel.

At a given fuel flow rate, combustion efficiency obtained with propane increased with oxygen concentration. The rate of increase was appreciably greater at the lower oxygen concentrations and combustion efficiencies. Change in fuel flow rate had a small effect on combustion efficiency over the major portion of the conditions investigated. At a given fuel flow rate, satisfactory correlations were obtained between combustion efficiency and parameters based on (1) a simplified reaction kinetics equation and (2) a flame-speed mechanism. No satisfactory correlation was obtained between combustion efficiency and a parameter involving minimum spark-ignition energy. In a previous investigation in which liquid isooctane fuel was used, satisfactory correlations were obtained with all the parameters. For the same inlet conditions, the combustion efficiencies for the combustor operating with propane fuel were appreciably higher than those obtained for the combustor operating with isooctane fuel. The relative effects of inlet pressure and oxygen concentration on combustion efficiency were approximately the same for both fuels.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to study the relative importance of the basic processes involved in the over-all turbojet combustion mechanism. In a recent report (ref. 1) oxygen concentration of the inlet oxygen-nitrogen mixture was used as a combustor-inlet variable in an attempt to separate the molecular from the grosser scale processes and to relate changes in combustion efficiency to possible controlling individual processes in the over-all combustion mechanism. The combustion efficiency of a J33 single combustor operating with a liquid fuel (isooctane) was determined over a range of inlet pressures, oxygen concentrations, and fuel flow rates. The temperature and weight flow rate of the inlet oxygen-nitrogen mixture were held constant throughout the test program. At a constant fuel flow rate, combustion efficiency was related to selected fundamental combustion properties of vaporized isooctane-oxygen-nitrogen mixtures and to a simplified reaction kinetics equation. In this treatment of the combustion efficiency data, it was assumed that the fraction of the reaction zone required for the fuel evaporation and mixing steps was small and essentially constant with changes in inlet pressure and oxygen concentration.

Over the range of conditions investigated in reference 1, combustion efficiency increased with fuel flow rate. This effect might be tentatively attributed to the reduction in average drop size at the higher fuel pressures associated with the higher fuel flow rates, either in terms of reduction of fuel evaporation time or change in the fraction of the fuel deposited on the liner walls. Since the fuel evaporation step can have a significant effect on combustor performance, it would be desirable to determine the effect of this step on the correlations obtained in reference 1. A possible method would involve duplication of the tests of reference 1 with the fuel evaporation step eliminated through the use of a gaseous or vaporized fuel. Comparison of the two sets of data may indicate the effect of the fuel evaporation step on the applicability of the several correlations developed in reference 1.

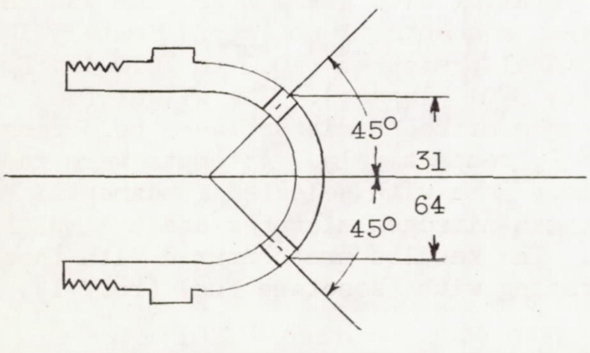
Considerable fundamental data were available for propane-oxygen-nitrogen mixtures. Accordingly, the combustion efficiency of a J33 single combustor operating with gaseous propane was determined over a range of inlet oxygen concentrations (approximately 14 to 46 percent by volume), inlet total pressures (10.0 to 30.0 in. Hg abs.), and fuel flow rates (0.008 to 0.016 lb/sec). The weight flow rate and inlet temperature of the oxygen-nitrogen mixture were held constant at 1.0 pound per second and 40° F, respectively. Attempts were made to correlate the combustion-efficiency data with selected fundamental combustion properties of propane-oxygen-nitrogen mixtures and a simplified reaction kinetics equation. The results are compared with those obtained for the J33 combustor operating with isooctane fuel (ref. 1).

APPARATUS AND PROCEDURE

The single J33 combustor installation is shown diagrammatically in figure 1. The test facility was supplied with refrigerated air at 48 inches of mercury absolute and -40° F and was connected to the laboratory low-pressure exhaust system. The air flow and inlet pressure in the combustor were controlled by valves located upstream and downstream of the combustor. Combustor-inlet-air temperature was regulated by valves proportioning the amount of air passing through a steam-fed heat exchanger. Oxygen concentration was varied by metering quantities of pure oxygen or nitrogen into the inlet-air system. Air flow rates were measured by means of a square-edged orifice installed according to A.S.M.E. specifications and located upstream of the regulating valves; oxygen (or nitrogen) flow rates were measured by calibrated critical flow orifices. Additional details of the oxygen (or nitrogen) system are given in reference 1.

The fuel system was connected to the laboratory gaseous propane supply line (fig. 1). Propane flow rates were measured with a square-edged orifice installed according to A.S.M.E. specifications and located upstream of the flow-regulating valve. The propane orifice upstream temperature was controlled by a valve proportioning the amount of propane passing through a hot-water heat exchanger. Fuel-nozzle-discharge pressure was measured with a calibrated Bourdon gage. Commercially supplied propane (approximately 97 mole percent purity) was used throughout the program.

A cross-sectional view of the combustor is shown in figure 2. The hollow-cone spray nozzle used in reference 1 (45° cone angle, 10.5 gal/hr capacity) was replaced with the modified commercial hollow-cone spray nozzle tip illustrated below. The normal discharge orifice was blocked and the swirl chamber and retaining plug removed. Six $\frac{1}{16}$-inch diameter holes, equally spaced around the nozzle tip, were drilled at a 45° angle from the nozzle axis.



Cross-sectional views of the combustor instrument stations are also presented in figure 2. At each station the thermocouples and total-pressure tubes were located at the centers of equal annular areas. Design details of the total-pressure rakes and thermocouple rakes are presented in reference 2. Exhaust thermocouples with single cylindrical shields were connected in a parallel circuit to give an instantaneous average temperature reading. All thermocouples were connected through multiple switches to a dual-range, self-balancing potentiometer.

Combustion efficiency was determined at combustor-inlet total pressures of 10.0, 14.3, 21.4, and 30.0 inches of mercury absolute, inlet oxygen concentrations from approximately 14 to 46 percent by volume, and fuel flow rates of 0.008, 0.012, and 0.016 pound per second. The inlet temperature and weight flow rate of the oxygen-nitrogen mixture were held constant at 40° F and 1.0 pound per second, respectively.

Combustion efficiency, defined as the ratio of the actual to the theoretical increase in enthalpy across the combustor, was computed by means of the equations and charts presented in reference 3. The enthalpy rise of the oxygen-nitrogen mixture was computed from enthalpy values of oxygen and nitrogen tabulated in reference 4. The combustor reference velocities presented herein were computed from the maximum cross-sectional area of the combustor flow passage (0.267 sq ft), the inlet oxygen-nitrogen mixture density, and the oxygen-nitrogen mixture flow rate. Indicated thermocouple readings were not corrected for radiation, conduction, or stagnation effects.

RESULTS AND DISCUSSION

Combustor Data

The data obtained in the investigation to determine the effect of inlet oxygen concentration on the combustion efficiency of a J33 combustor operating with propane fuel are presented in table I. In figure 3, combustion efficiency is plotted against inlet oxygen concentration (volume percent) at the various inlet pressures and fuel flow rates investigated. It is noted that combustion efficiency increased with inlet oxygen concentration and that the rate of increase was more pronounced at the lower values of oxygen concentration. Combustion efficiency increased with pressure, as would be expected.

The faired curves of figure 3 are combined in figure 4 to show the effect of fuel flow rate on combustion efficiency. Except at low values of oxygen concentration, fuel flow rate had a relatively small effect on combustion efficiency. Although no attempt was made to determine exact blow-out limits, it was observed that blow-out generally occurred at lower values of oxygen concentration with the lower fuel flow rates.

Application of Fundamental Combustion Properties to Combustor Data

In reference 1 the variation in combustion efficiency with inlet pressure and oxygen concentration was related to minimum spark-ignition energy, quenching distance, and laminar flame speed of isooctane-oxygen-nitrogen mixtures. The same fundamental combustion properties were considered in the present investigation.

Minimum spark-ignition energy and quenching distance. - Curves of minimum spark-ignition energy and quenching distance for propane-oxygen-nitrogen mixtures at various fuel concentrations are presented in reference 5 for oxygen concentrations from 21 to 100 percent by volume and for total pressures from 0.2 to 1.0 atmosphere. There was no consistent relation between combustion efficiency and values of minimum spark-ignition energy obtained from reference 5 either at a stoichiometric fuel-oxygen ratio or at a fuel-oxygen ratio giving the lowest value of minimum spark-ignition energy at a given pressure and oxygen concentration. The inability to obtain a satisfactory correlation between minimum spark-ignition energy and combustion efficiency, as obtained in reference 1, possibly may be due to large errors arising from the cross-plotting and extrapolation required in the application of the data of reference 5 to the low oxygen concentrations tested in the present investigation. Since similar errors could arise in the use of the quenching distance data of reference 5, no attempt was made to relate combustion efficiency to quenching distance.

Laminar flame speed. - In reference 1 a parameter based on a flame-speed mechanism was derived which satisfactorily correlated the effect of inlet pressure and oxygen concentration on combustion efficiency for the conditions of constant inlet temperature and weight flow rate of the oxygen-nitrogen mixture. This relation is of the form

$$\eta_b = f\left(\frac{P_i^{1/3}\, u_f}{V_r}\right) \tag{1}$$

where

η_b combustion efficiency

P_i combustor-inlet pressure

u_f laminar flame speed based on combustor-inlet conditions

V_r reference velocity

Equation (1) was applied to the data of reference 1 by assuming laminar flame speed to be independent of pressure and by using the results of reference 6 in which the maximum flame speed of isooctane-oxygen-nitrogen mixtures was found to be proportional to the term $(\alpha - 12)$. Here α is the volume percent inlet oxygen concentration and the maximum flame speed is defined as the maximum point of the curve of flame speed against equivalence ratio at a given temperature and oxygen concentration. The resulting correlation equation was

$$\eta_b = f\left[\frac{P_i^{1/3}}{V_r}(\alpha - 12)\right] \tag{2}$$

In reference 7 the flame speeds of propane-oxygen-nitrogen mixtures at atmospheric pressure and various equivalence ratios were determined for laminar Bunsen flames by the area method. Flame speeds were measured for oxygen concentrations from 16.6 to 49.6 percent by volume and for inlet temperatures of 311° and 422° K. The effect of inlet temperature and oxygen concentration on maximum flame speed for the entire range of conditions investigated was correlated by the relation

$$u_f = KT_i^a(\alpha - b) \tag{3}$$

where K, a, and b are constants and T_i is the inlet temperature. A similar correlation was applied to the data of reference 7 for oxygen concentrations of 30 percent by volume and below in order to provide a more accurate representation of the flame speeds at the low oxygen concentrations used in the present investigation. For this range the constant b in equation 3 has an average value of 11.5. It is noted that this value of b, which represents the extrapolated value of oxygen concentration for zero flame speed, is in agreement with the value of 11.6 cited in reference 8 (pp. 58-59) as the oxygen concentration below which no propane-oxygen-nitrogen mixture can propagate flame at room temperature and pressure. For constant inlet temperature T_i, the maximum flame speed of propane is proportional to the term $(\alpha - 11.5)$. Thus, if the laminar flame speed is assumed independent of pressure, equation (1) becomes

$$\eta_b = f\left[\frac{P_i^{1/3}}{V_r}(\alpha - 11.5)\right] \tag{4}$$

for propane combustion.

In figure 5 combustion efficiency is plotted against the parameter of equation (4) for the three fuel flow rates investigated. It is seen that the parameter of equation (4) satisfactorily correlates the combustion-efficiency data of figure 3. However, there is some increase in scatter in the data at the low values of combustion efficiency with the fuel flow rate of 0.008 pound per second. It is noted that this parameter is approximately the same as that used to correlate the combustion-efficiency data of reference 1.

Application of Simplified Reaction Kinetics Equation to Combustor Data

In reference 1, the combustion efficiency data at a given fuel flow rate were also correlated by a simplified reaction kinetics equation given by

$$\eta_b = f\left[\frac{\alpha P_i\ T_i}{V_r}\left(\frac{e^{-E/RT_{eq}}}{T_{eq}^{3/2}}\right)\right] \qquad (4)$$

where

E apparent energy of activation

R gas constant

T_{eq} stoichiometric adiabatic equilibrium temperature

Details of the derivation and assumptions involved in the application of this equation to turbojet combustor data are presented in references 1 and 9. The equilibrium temperatures at the various oxygen concentration and pressures covered in this investigation were computed according to the methods and charts of reference 10. Values of E were obtained from cross plots of the faired curves of figure 3 by determining the slope of the best straight line through the plotted points of $1/T_{eq}$ against

$$\ln\left(\frac{T_{eq}^{-3/2}\ \alpha P_i\ T_i}{V_r}\right)$$

at a constant value of combustion efficiency. The values of E determined by this method varied from approximately 27,000 calories per gram-mole in the low combustion-efficiency range to approximately

33,000 calories per gram-mole in the high combustion-efficiency range. Since the slope of the curve of

$$\frac{\alpha P_i \, T_i}{V_r}\left(\frac{e^{-E/RT_{eq}}}{T_{eq}^{3/2}}\right)$$

against combustion efficiency is quite steep in the low combustion-efficiency range, the scatter of the correlation in this range will be very sensitive to the choice of E. In figure 6 the data of table I are plotted against the reciprocal of the combustion efficiency parameter of equation (4) for a value of E/R of 14,000° K (E = 27,818 cal/g mole). This choice of E results in a satisfactory correlation of the combustion data. Use of a higher value of E would result in some decrease in scatter of the correlation at the higher values of combustion efficiency and an appreciable increase in scatter of the correlation at the low values of combustion efficiency. However, in view of the sensitivity of the correlation parameter at the low efficiency range to the accuracy of the measurement of combustor-inlet oxygen concentration, determination of an exact value of E between 27,000 and 33,000 calories per gram-mole for a minimum scatter of the correlation was not warranted. The range of values of E is in reasonable agreement with those cited for propane in the literature. In reference 11 a value of 38,000 calories per gram-mole is given. This value was used in reference 7 in the application of the Semenov thermal theory of flame propagation to the flame speed data of propane-oxygen-nitrogen mixtures. Unpublished observations by the authors of reference 7 indicated that a value of 34,000 calories per gram-mole resulted in an improvement between experimental and predicted values of flame speed.

Comparison of Liquid and Gaseous Fuel Data

In reference 1, similar data were obtained with liquid isooctane fuel for the same combustor but a different fuel-injection nozzle. Comparisons of the combustion efficiencies obtained with propane and with isooctane, for the same operating conditions, are presented in figure 7. Over the entire range of conditions compared, the combustion efficiencies obtained with propane were appreciably higher than those obtained with isooctane; the differences were more pronounced at the lower oxygen concentrations. The relative effects of inlet oxygen concentration and pressure on combustion efficiency, however, were approximately the same for both fuels.

Combustion efficiency increased with fuel flow rate for isooctane. This trend would be expected as a result of the smaller average fuel-spray drop size and hence decreased evaporation time at the higher fuel flow rates. With propane, no evaporation step was required, and fuel flow rate had a small effect on combustion efficiency over the major portion of conditions investigated (fig. 4).

A correlation between combustion efficiency and minimum spark-ignition energy, such as was found in reference 1 with liquid isooctane, was not obtained with propane. The simplified reaction kinetics equation parameter and flame-speed parameter correlated the data obtained for both propane and isooctane. The values of the apparent energy of activation required in the second-order reaction equation parameter were in reasonable agreement with those expected for the two fuels.

The data obtained in these investigations also indicate that the reduction in combustor-inlet oxygen concentration resulting from the use of supply air heated by the addition of exhaust gases may result in an appreciable lowering of combustion efficiency.

Limitations of Correlation Parameters

The relative effects of inlet pressure and velocity on combustion efficiency predicted by the flame speed parameter differ appreciably from those predicted by the second-order reaction equation parameter. In the present investigation, conducted at constant weight flow rate of the oxygen-nitrogen mixture, it was not possible to determine relative effects of inlet pressure and velocity on combustion efficiency and, hence, to distinguish between parameters. Determination of the ability of either parameter to correlate combustion efficiency at conditions other than those investigated will require additional tests involving independent variation of combustor-inlet pressure, temperature, velocity, and fuel flow.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of inlet oxygen concentration on the combustion efficiency of a J33 combustor operating with gaseous propane fuel and from comparison with data from a previous similar investigation conducted with liquid isooctane fuel:

1. At a given fuel flow rate, combustion efficiency increased with oxygen concentration; the rate of increase was appreciably greater at the lower oxygen concentrations and combustion efficiencies. Variations in fuel flow rate had a small effect on combustion efficiency at most conditions investigated.

2. At a given fuel flow rate, satisfactory correlations between combustion efficiency and minimum spark-ignition energy, laminar flame speed, or a simplified reaction kinetics equation were obtained in a previous investigation conducted with liquid isooctane; however, with gaseous propane fuel a satisfactory correlation was obtained only with the simplified reaction kinetics equation and flame-speed parameter.

3. For the same inlet conditions, combustion efficiencies obtained with propane were appreciably higher than those obtained with isooctane; the relative effects of pressure and oxygen concentration on combustion efficiency were approximately the same for both fuels.

4. The reduced oxygen concentration of combustion-inlet air resulting from the use of supply air heated by the addition of exhaust gases may result in appreciable lowering in combustion efficiency obtained with gaseous propane or liquid isooctane fuel.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

REFERENCES

1. Graves, Charles C.: Effect of Oxygen Concentration of the Inlet Oxygen-Nitrogen Mixture on the Combustion Efficiency of a Single J33 Turbojet Combustor. NACA RM E52F13, 1952.

2. Dittrich, Ralph T., and Jackson, Joseph L.: Altitude Performance of AN-F-58 Fuels in J33-A-21 Single Combustor. NACA RM E8L24, 1949.

3. Turner, L. Richard, and Bogart, Donald: Constant-Pressure Combustion Charts Including Effects of Diluent Addition. NACA Rep. 937, 1949. (Supersedes NACA TN's 1086 and 1655.)

4. Anon.: Tables of Thermal Properties of Gases. Nat. Bur. Standards, July 1949.

5. Lewis, Bernard, and von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Academic Press, Inc., 1951.

6. Dugger, Gordon L., and Graab, Dorothy D.: Flame Speeds of 2,2,4-Trimethylpentane-Oxygen-Nitrogen Mixtures. NACA TN 2680, 1952.

7. Dugger, Gordon L., and Graab, Dorothy D.: Flame Velocities of Propane- and Ethylene-Oxygen-Nitrogen Mixtures. NACA RM E52J24, 1953.

8. Coward, H. F., and Jones, G. W.: Limits of Flammability of Gases and Vapors. Bull. 503, Bur. Mines, 1952.

9. Childs, J. Howard: Preliminary Correlation of Efficiency of Aircraft Gas-Turbine Combustors for Different Operating Conditions. NACA RM E50F15, 1950.

10. Hottel, H. C., Williams, G. C., and Satterfield, C. N.: Thermodynamic Charts for Combustion Processes, Parts I and II. John Wiley & Sons, Inc., 1949.

11. Jost, Wilhelm: Explosion and Combustion Processes in Gases. McGraw-Hill Book Co., Inc., 1946, p. 437.

TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE

(a) Fuel flow rate, 0.008 pound per second

Point	Combustor inlet total pressure, P_1, in. Hg abs	Combustor inlet temperature, T_1, °R	Combustor inlet oxygen-nitrogen mixture flow, lb/sec	Combustor inlet oxygen concentration, α vol. percent	Combustor reference velocity V_r, ft/sec	Fuel flow, lb/sec	Fuel-nozzle pressure drop, lb/sq in.	Mean combustor outlet temperature, °R	Mean temperature rise through combustor, °F	Combustion efficiency, percent
52	10.0	502	1.01	20.1	144	0.0081	13.2	732	230	35.5
39	10.0	495	1.00	20.9	141	.0080	12.8	790	295	45.6
3	10.0	498	1.00	20.9	141	.0080	12.8	800	302	46.2
64	10.0	499	1.00	20.9	142	.0081	13.3	795	296	45.5
46	10.0	502	1.00	24.2	142	.0081	13.5	960	458	70.7
166	10.0	500	1.00	24.2	141	.0080	12.9	945	445	69.4
161	10.0	499	1.00	25.1	141	.0080	12.9	970	471	73.5
141	10.0	500	1.00	26.0	142	.0080	12.9	995	495	77.0
155	10.0	500	1.00	26.0	141	.0081	13.2	1005	505	78.4
40	10.0	500	1.00	26.2	141	.0080	12.8	1002	502	78.0
34	10.0	504	1.00	28.4	142	.0081	13.1	1050	546	84.7
37	10.0	502	1.01	28.4	142	.0080	13.3	1047	545	85.0
142	10.0	502	1.00	30.0	141	.0080	13.2	1070	568	88.3
31	10.0	503	1.01	30.4	142	.0081	13.3	1065	562	87.3
28	10.0	503	1.01	32.5	142	.0081	13.3	1075	572	88.9
22	10.0	503	1.00	46.3	138	.0081	13.3	1140	637	97.7
117	14.4	500	1.00	18.2	99	.0081	11.1	935	435	67.3
131	14.3	502	1.00	18.6	100	.0080	11.1	962	460	72.1
119	14.3	500	1.00	19.2	99	.0081	11.3	985	485	74.8
126	14.3	502	1.00	20.1	100	.0080	10.8	1010	508	79.9
114	14.3	499	1.00	20.9	99	.0080	11.0	1018	519	81.0
105	14.2	502	1.01	20.9	101	.0081	11.2	1013	511	80.1
121	14.3	499	1.00	20.9	99	.0080	11.1	1018	519	81.0
147	14.3	498	1.00	20.9	99	.0080	11.1	1020	522	81.6
132	14.3	501	1.00	24.2	99	.0080	11.1	1075	574	90.1
167	14.3	500	1.00	24.2	99	.0080	10.8	1070	570	89.5
160	14.3	500	1.01	25.0	99	.0080	10.8	1075	575	90.8
138	14.3	502	1.00	26.0	99	.0080	11.1	1110	608	95.7
154	14.3	500	1.00	26.0	98	.0080	11.1	1100	600	93.8
112	14.3	500	1.00	28.0	98	.0081	10.8	1117	617	95.9
109	14.3	506	1.00	30.2	99	.0081	10.8	1130	624	96.7
106	14.3	504	1.00	32.2	98	.0081	11.3	1130	626	97.2
104	21.3	504	.99	14.2	67	.0080	8.3	840	336	51.8
103	21.5	504	1.00	14.4	67	.0080	8.2	855	351	54.6
76	21.5	497	1.00	15.1	66	.0082	8.3	917	420	64.6
75	21.4	500	.99	15.2	66	.0081	8.1	908	408	62.7
86	21.5	501	1.00	16.2	67	.0081	8.2	982	481	74.7
98	21.4	502	1.00	17.3	67	.0081	8.3	1045	543	84.5
61	21.4	504	1.01	18.2	67	.0081	8.0	1072	568	89.0
90	21.3	505	1.00	18.2	68	.0082	8.3	1075	570	88.5
53	21.4	502	1.02	20.1	68	.0081	8.0	1077	575	91.0
49	21.4	502	1.00	20.9	67	.0082	8.3	1095	593	91.7
65	21.4	498	1.00	20.9	66	.0081	7.9	1098	600	93.7
78	21.5	502	1.00	20.9	66	.0081	8.0	1102	600	93.4
87	21.4	503	1.00	20.9	67	.0082	8.1	1105	602	92.9
113	21.4	496	1.00	20.9	66	.0080	7.8	1095	599	93.8
43	21.5	500	1.01	26.3	66	.0081	8.1	1125	625	97.6
73	30.0	498	1.00	14.3	48	.0081	6.4	925	427	66.3
71	30.1	500	1.00	15.3	47	.0080	6.0	1027	527	83.3
84	30.0	501	1.00	16.2	48	.0081	6.2	1058	557	87.3
96	30.0	503	1.00	17.2	48	.0081	5.5	1095	592	91.7
93	30.1	500	1.00	18.2	47	.0081	6.0	1110	610	95.0
59	30.2	505	1.00	19.2	48	.0081	6.2	1130	625	98.3
58	30.1	503	1.02	20.1	48	.0081	6.3	1125	622	99.1
13	30.1	502	.99	20.9	47	.0081	5.9	1135	633	98.1
70	30.0	497	1.00	20.9	47	.0081	7.0	1135	638	99.9

TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE - Continued

(b) Fuel flow rate, 0.012 pound per second

Point	Combustor inlet total pressure, P_1, in. Hg abs	Combustor inlet temperature, T_1, ^oR	Combustor inlet oxygen-nitrogen mixture flow, lb/sec	Combustor inlet oxygen concentration, α vol. percent	Combustor reference velocity V_r, ft/sec	Fuel flow, lb/sec	Fuel-nozzle pressure drop, $\frac{lb}{sq\ in.}$	Mean combustor outlet temperature, ^oR	Mean temperature rise through combustor, ^oF	Combustion efficiency, percent
47	10.0	502	1.00	24.3	142	0.0121	22.1	1137	635	66.8
163	10.0	501	1.01	25.1	142	.0120	21.9	1183	682	73.0
145	10.0	502	1.00	26.0	142	.0119	21.9	1242	740	79.7
156	10.1	500	1.00	26.0	140	.0119	21.7	1235	735	78.7
41	10.1	500	1.01	26.4	141	.0120	22.0	1243	743	79.4
38	10.0	503	1.00	28.4	142	.0121	22.3	1295	792	84.1
35	10.0	503	1.01	28.7	142	.0120	22.1	1293	790	84.5
143	10.0	502	1.00	30.0	141	.0119	21.8	1325	823	88.4
32	10.0	502	1.01	30.7	143	.0120	22.1	1305	803	86.4
29	10.0	501	1.01	32.8	142	.0121	22.3	1337	836	89.3
26	10.1	502	1.01	35.9	139	.0121	22.1	1367	865	91.8
23	10.0	500	1.01	46.2	139	.0120	22.1	1385	885	94.8
118	14.3	500	1.00	18.1	100	.0120	19.8	1120	620	65.9
130	14.3	502	1.00	18.7	100	.0119	20.1	1162	660	70.6
120	14.3	500	1.01	19.2	100	.0120	19.8	1195	695	74.2
127	14.3	500	1.00	20.1	99	.0119	19.8	1247	747	80.3
122	14.3	498	1.00	20.9	99	.0119	19.8	1268	770	83.0
115	14.4	500	1.00	20.9	99	.0120	19.6	1272	772	83.2
133	14.3	502	1.00	24.2	100	.0119	19.8	1340	838	91.0
168	14.3	501	1.00	24.2	99	.0119	19.8	1345	844	91.2
169	14.3	501	1.00	24.2	99	.0119	19.8	1352	851	91.9
134	14.3	502	1.00	24.3	99	.0119	19.8	1350	848	91.9
162	14.4	500	1.00	25.1	98	.0119	19.8	1355	855	92.5
139	14.4	502	1.00	26.1	98	.0119	19.8	1385	883	95.1
157	14.3	500	.99	26.1	98	.0119	19.6	1373	873	93.8
136	14.4	503	1.01	28.1	99	.0119	19.8	1393	890	96.6
110	14.3	500	1.00	30.2	98	.0120	19.8	1400	900	96.6
107	14.3	504	1.00	32.3	99	.0120	19.8	1405	901	96.7
77	21.4	495	1.00	15.1	66	.0122	16.6	1103	608	64.0
97	21.5	502	1.00	16.3	66	.0120	16.7	1265	763	81.6
83	21.4	506	1.01	17.2	68	.0121	16.6	1310	804	86.4
62	21.5	503	1.01	18.1	67	.0120	16.2	1350	847	91.8
91	21.4	503	1.01	18.2	67	.0121	16.8	1345	842	90.3
54	21.4	502	1.02	20.0	68	.0120	16.6	1360	858	94.0
50	21.5	502	1.01	20.9	67	.0121	16.7	1390	888	95.3
66	21.4	498	1.01	20.9	66	.0120	16.5	1385	887	95.9
88	21.4	502	1.00	20.9	67	.0121	17.0	1395	893	95.6
44	21.4	501	1.01	26.3	67	.0121	16.7	1412	911	98.2
72	29.9	500	1.00	15.2	48	.0120	12.9	1275	775	83.6
85	30.1	502	1.00	16.2	48	.0121	12.5	1345	843	90.7
99	30.0	502	1.00	17.2	48	.0120	13.0	1400	898	96.7
94	30.1	501	1.00	18.1	48	.0121	13.0	1407	906	97.5
60	30.1	505	1.00	19.1	48	.0120	11.5	1427	922	99.1
57	30.1	504	1.02	20.1	48	.0121	13.5	1420	916	100.3
15	30.1	503	1.00	20.9	47	.0121	12.9	1430	927	99.1
69	30.0	498	1.00	20.9	47	.0120	13.5	1427	929	100.2

TABLE I. - PERFORMANCE DATA FOR J33 SINGLE COMBUSTOR OPERATING WITH PROPANE- Concluded

(c) Fuel flow rate, 0.016 pound per second

Point	Combustor inlet total pressure, P_1, in. Hg abs	Combustor inlet temperature, T_1, °R	Combustor inlet oxygen-nitrogen mixture flow, lb/sec	Combustor inlet oxygen concentration, α vol. percent	Combustor reference velocity V_r, ft/sec	Fuel flow, lb/sec	Fuel-nozzle pressure drop, lb/sq in.	Mean combustor outlet temperature, °R	Mean temperature rise through combustor, °F	Combustion efficiency, percent
48	10.0	501	1.00	24.3	142	0.0161	31.1	1205	704	56.4
164	10.0	501	1.01	25.0	143	.0158	30.4	1290	789	65.2
146	10.1	500	1.00	26.1	140	.0159	30.6	1440	940	77.5
159	10.0	500	1.00	26.1	141	.0159	30.9	1425	925	75.9
42	10.0	500	1.01	26.2	143	.0161	30.8	1415	915	75.2
36	10.2	502	1.00	28.3	139	.0160	31.0	1530	1028	84.3
144	10.2	502	1.00	29.9	138	.0159	30.8	1565	1063	87.9
33	10.3	501	1.02	30.6	138	.0160	31.2	1555	1054	87.7
30	10.3	500	1.01	32.9	137	.0160	31.2	1580	1080	89.3
27	10.3	503	1.00	36.0	136	.0161	31.2	1612	1109	90.4
24	10.3	499	1.01	46.4	134	.0161	31.7	1630	1131	92.8
124	14.3	503	1.02	18.7	102	.0159	28.6	1193	690	57.3
129	14.4	502	1.00	18.7	99	.0159	28.6	1240	738	60.1
125	14.3	502	1.00	19.2	100	.0159	28.6	1313	811	66.2
128	14.3	500	.99	20.1	99	.0159	28.6	1435	935	76.9
123	14.3	499	1.00	20.9	99	.0159	28.8	1498	999	82.7
116	14.4	500	1.00	20.9	99	.0160	28.6	1513	1013	83.7
135	14.3	500	1.00	24.3	99	.0159	28.8	1612	1112	92.7
170	14.3	500	1.01	24.3	99	.0158	28.6	1595	1095	91.8
165	14.3	501	1.00	25.1	99	.0158	28.3	1600	1099	92.0
140	14.4	501	1.00	26.1	98	.0159	28.8	1643	1142	95.1
158	14.3	500	1.00	26.1	98	.0159	28.8	1623	1123	93.0
137	14.4	502	1.01	28.2	99	.0159	28.8	1642	1140	95.6
111	14.4	500	1.00	30.2	97	.0160	28.8	1645	1145	94.5
108	14.3	505	1.00	32.2	99	.0160	29.1	1643	1138	94.0
80	21.3	505	1.00	16.2	68	.0161	25.4	1328	823	66.7
82	21.5	505	1.00	17.2	67	.0161	25.3	1528	1023	84.5
63	21.4	503	1.00	18.2	67	.0160	25.8	1615	1112	92.2
92	21.3	500	1.01	18.2	67	.0161	25.8	1605	1105	91.6
55	21.4	503	1.02	20.1	68	.0161	25.6	1625	1122	94.5
51	21.4	502	1.00	20.9	67	.0161	25.8	1650	1148	94.5
67	21.5	497	1.00	20.9	66	.0160	25.2	1635	1138	94.4
89	21.4	502	1.00	20.9	67	.0161	25.8	1647	1145	94.2
45	21.4	502	1.01	26.4	67	.0161	26.2	1645	1143	95.3
102	30.1	504	.99	15.8	47	.0159	21.5	1570	1066	88.3
101	30.0	504	1.00	15.9	48	.0159	22.0	1560	1056	88.5
79	30.0	505	1.00	16.2	48	.0162	21.6	1569	1064	87.1
81	30.0	505	1.00	17.2	48	.0161	21.1	1645	1140	94.3
95	30.0	502	1.01	18.1	48	.0161	21.7	1652	1150	95.8
56	30.1	504	1.02	20.0	49	.0160	21.5	1668	1164	98.4
68	30.1	497	1.00	20.9	47	.0160	21.2	1675	1178	97.8
17	29.9	502	1.00	20.9	48	.0160	21.5	1675	1173	97.8

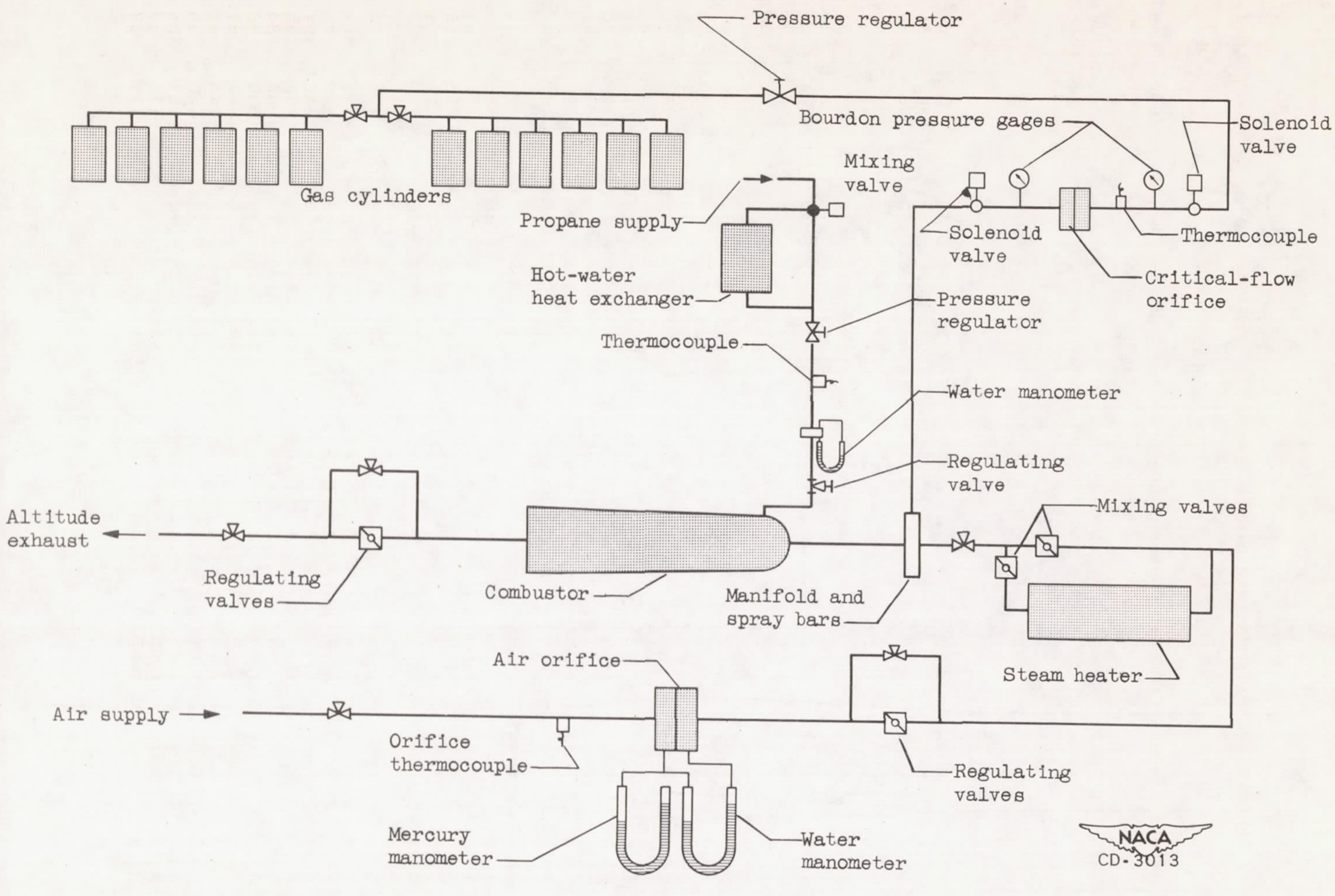


Figure 1. - Schematic sketch of J33-combustor experimental apparatus.

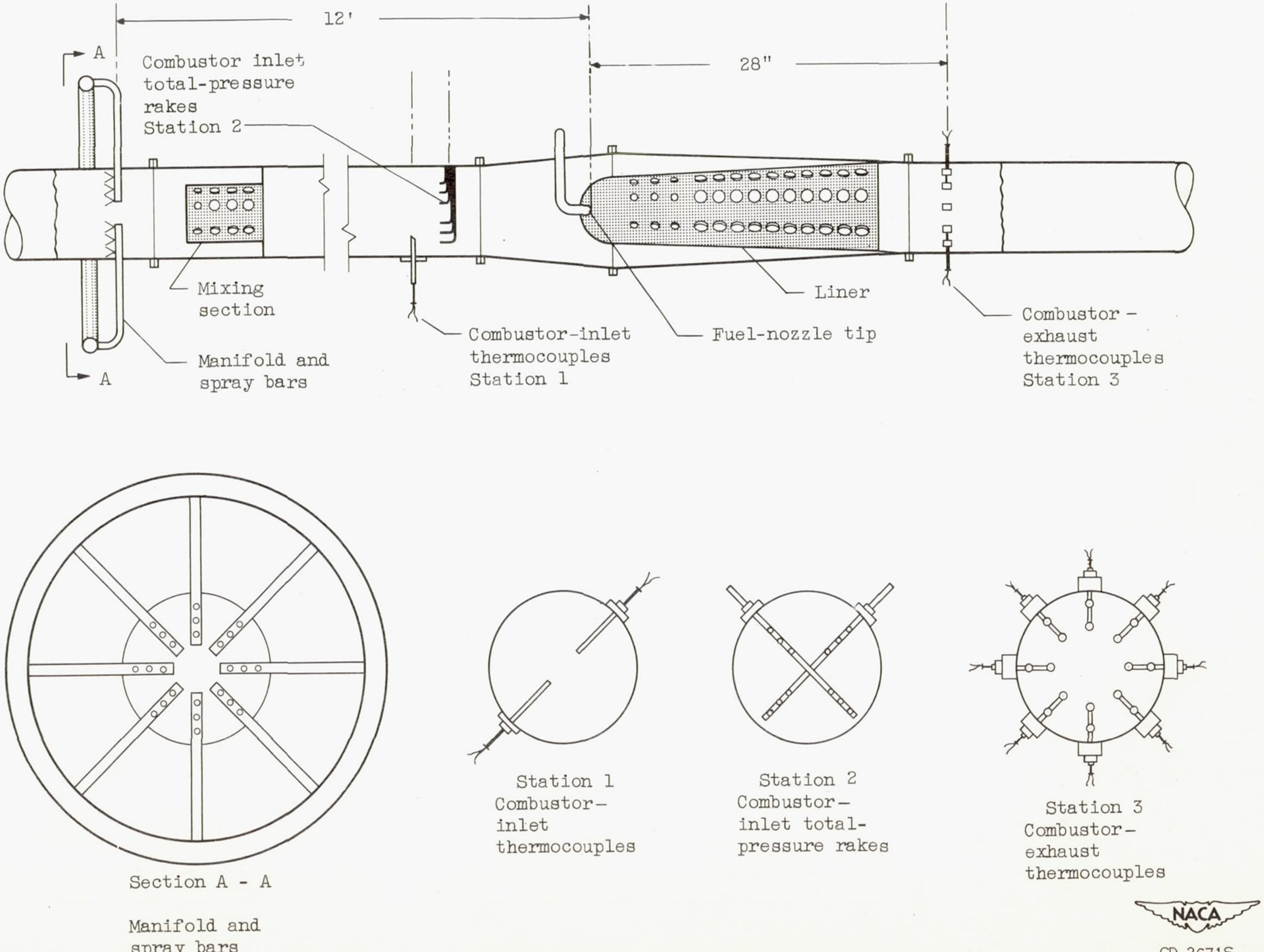
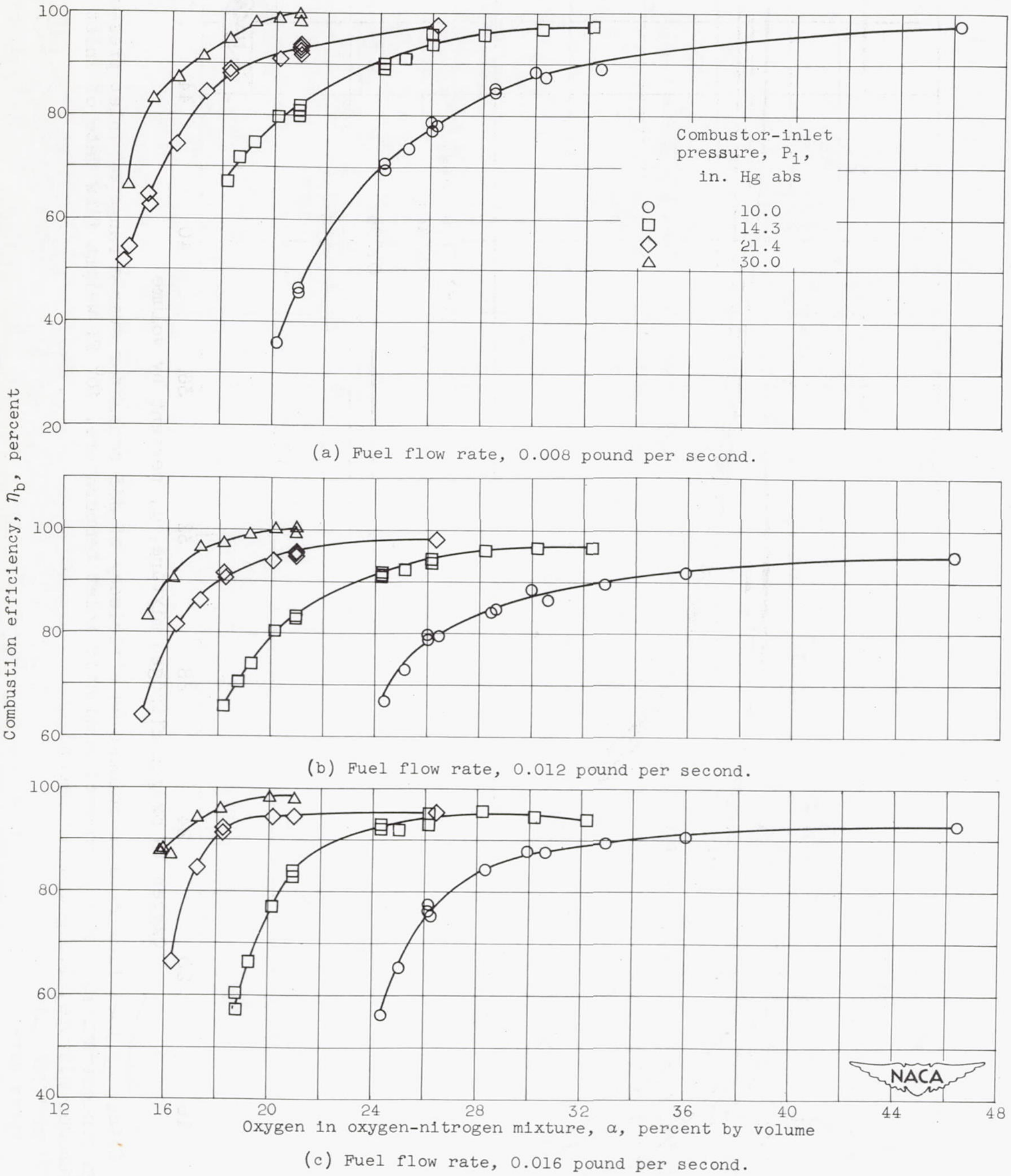


Figure 2. - Sketch of single J33 combustor and instrumentation.



(c) Fuel flow rate, 0.016 pound per second.

Figure 3. - Effect of oxygen concentration of inlet oxygen-nitrogen mixture on combustion efficiency of single J33 combustor over a range of inlet pressures and fuel flow rates. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.

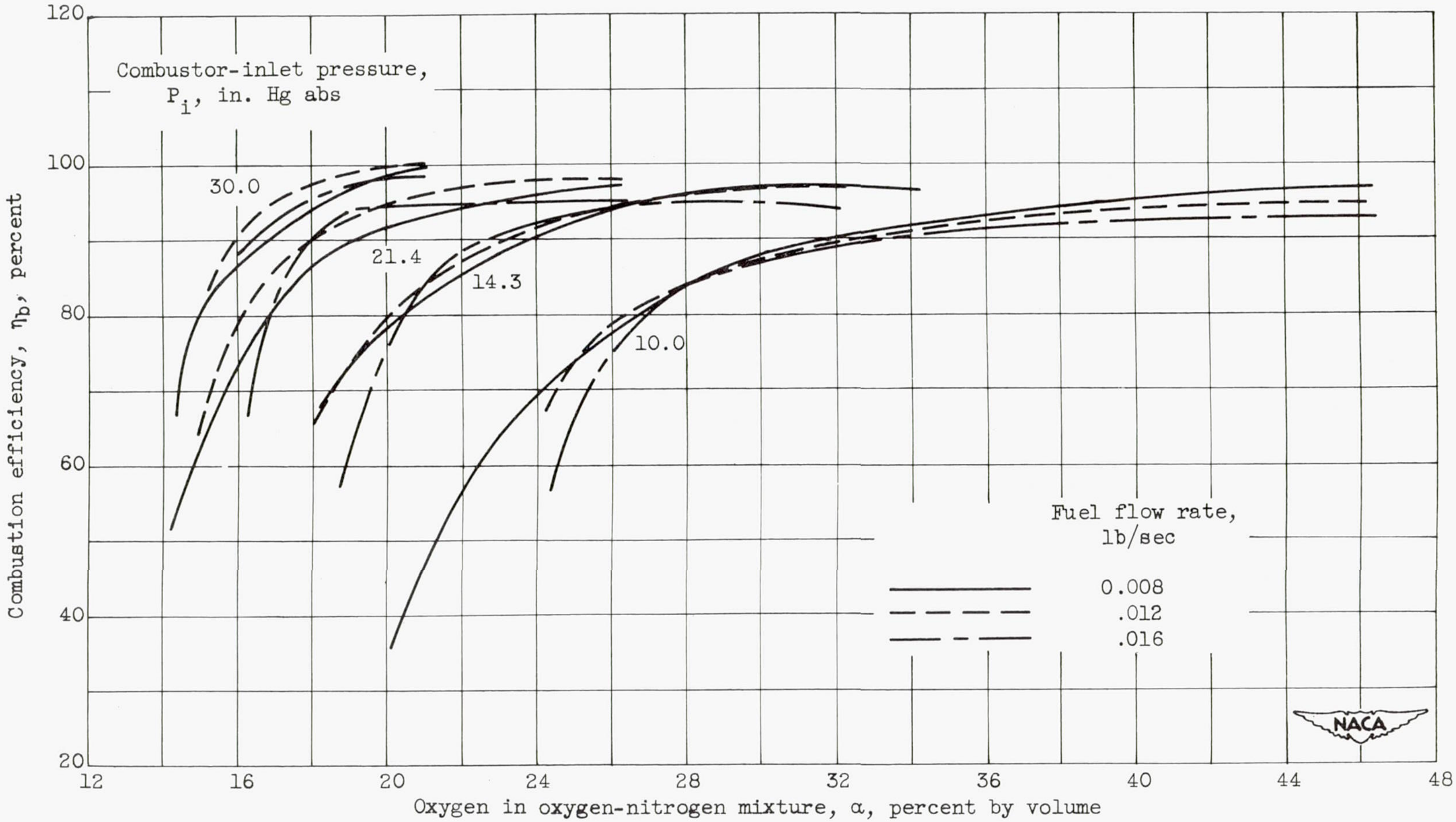
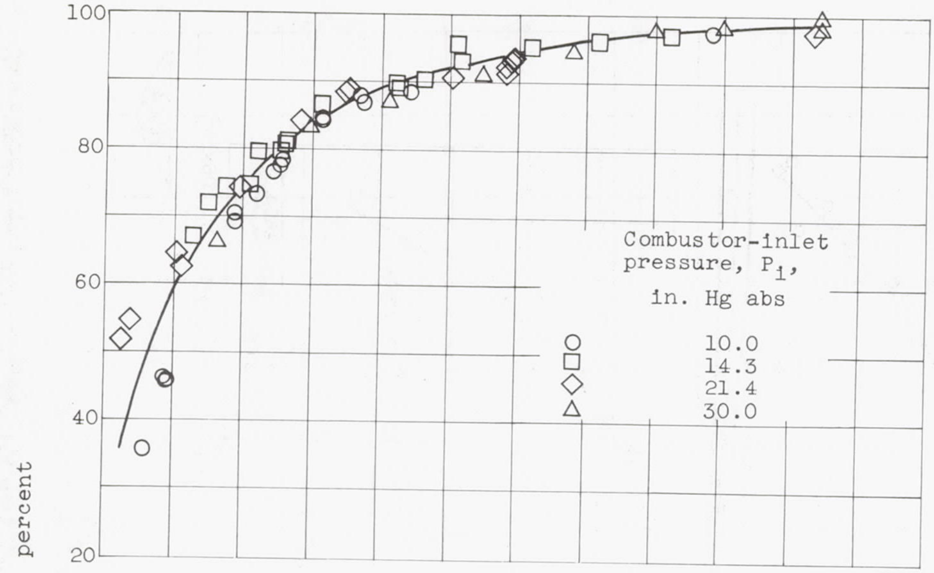
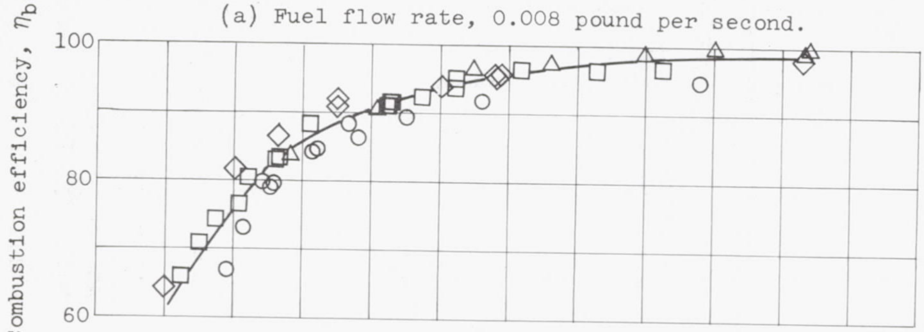


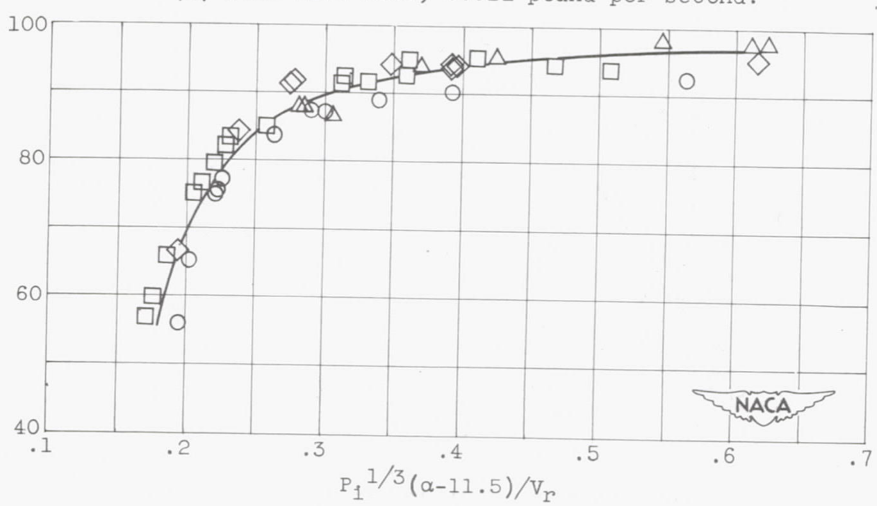
Figure 4. - Effect of fuel flow rate on combustion efficiency of J33 combustor over a range of inlet pressures and oxygen concentrations. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.



(a) Fuel flow rate, 0.008 pound per second.

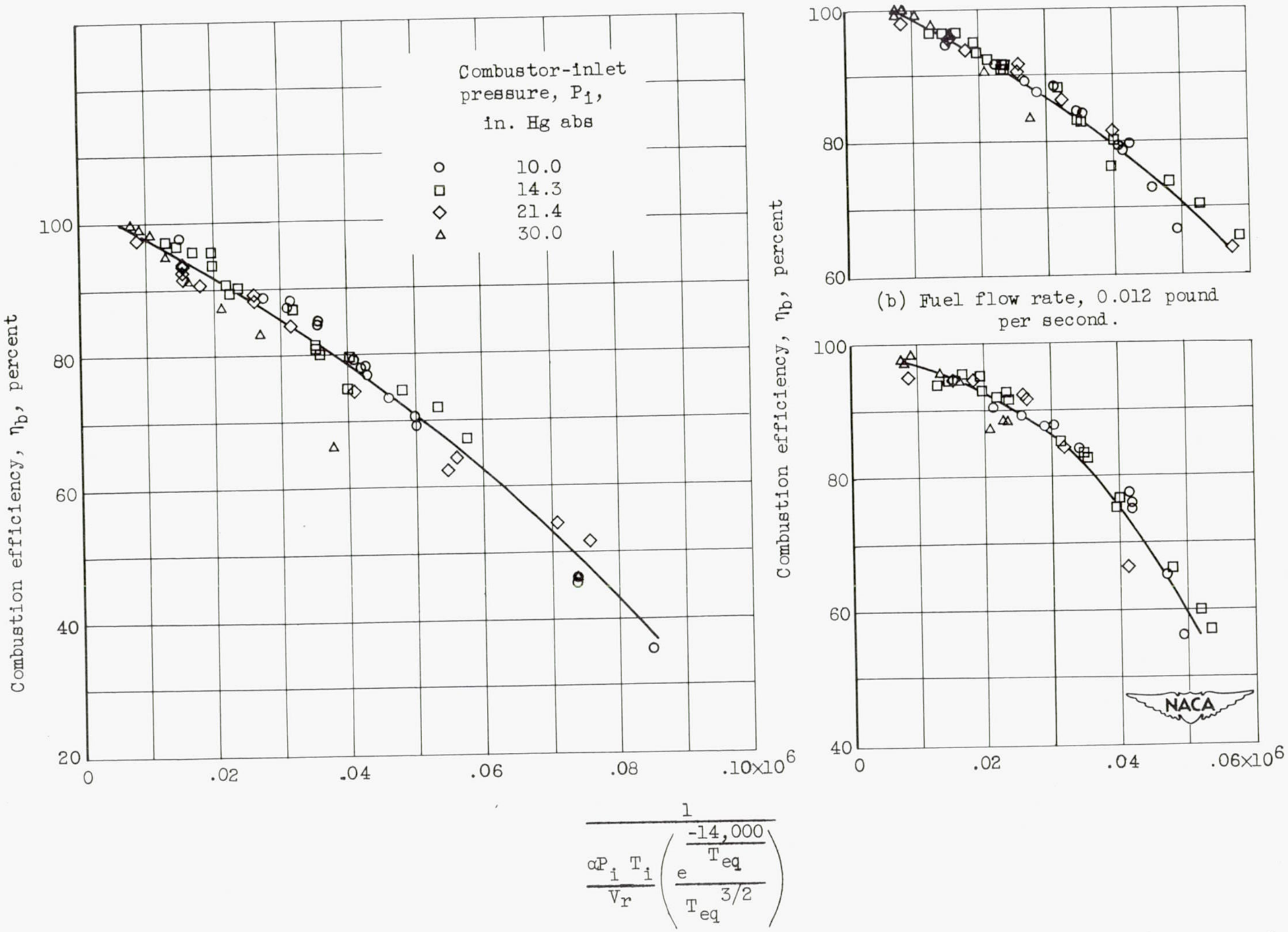


(b) Fuel flow rate, 0.012 pound per second.



(c) Fuel flow rate, 0.016 pound per second.

Figure 5. - Correlation of combustion efficiency of single J33 combustor with flame speed parameter. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.

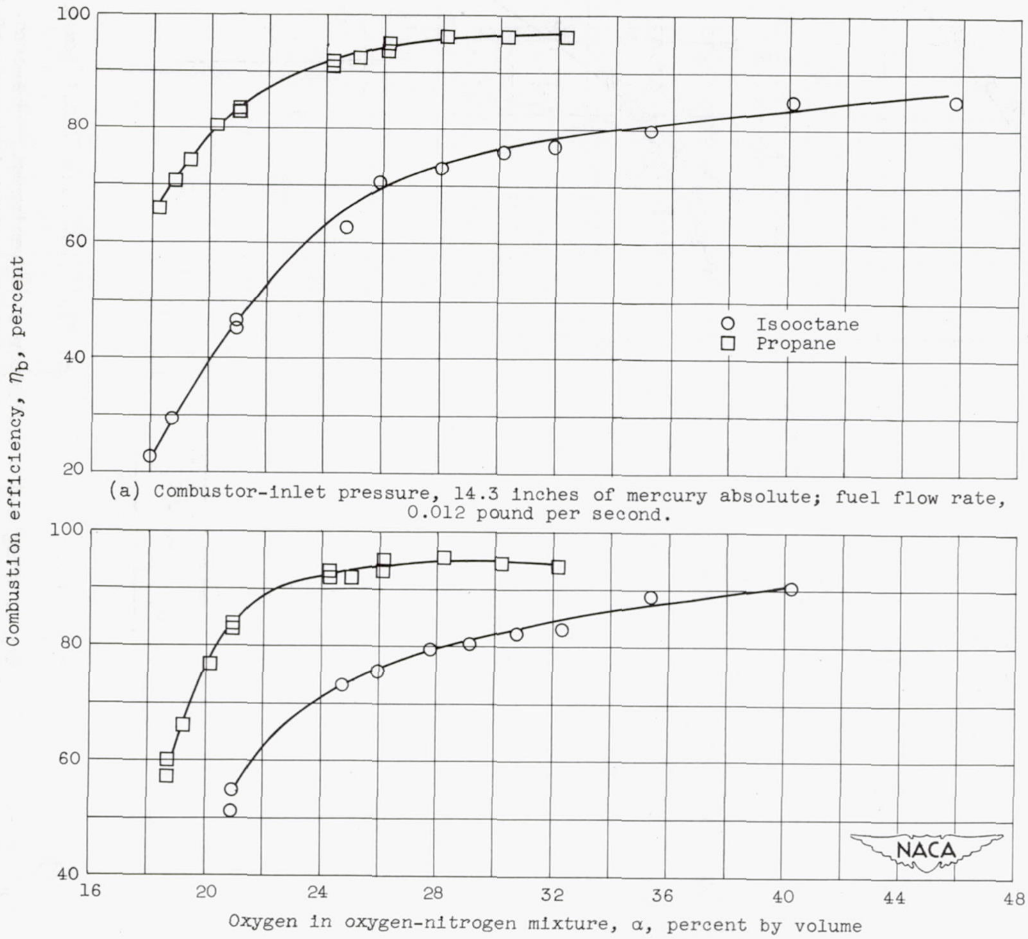


(a) Fuel-flow rate, 0.008 pound per second.

(b) Fuel flow rate, 0.012 pound per second.

(c) Fuel flow rate, 0.016 pound per second.

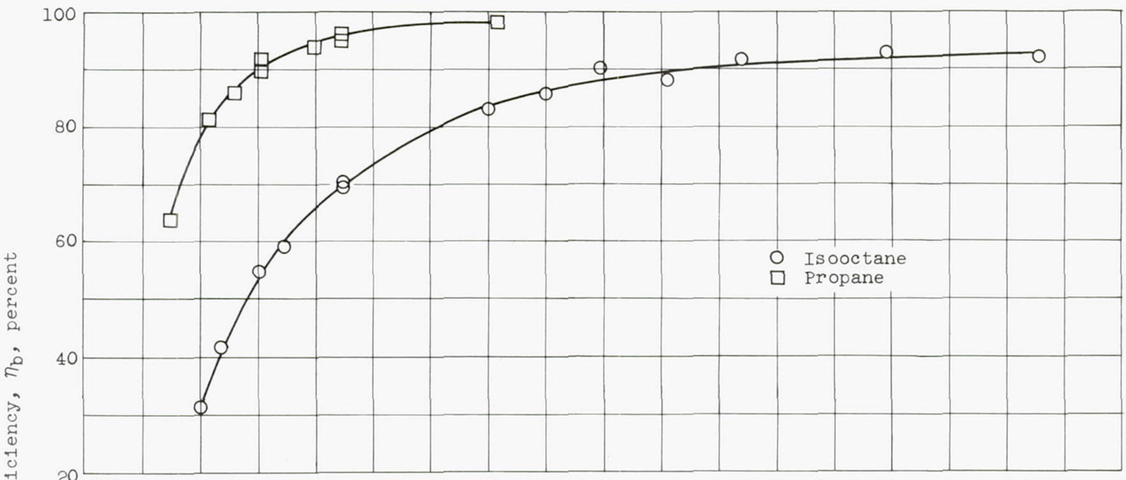
Figure 6. - Correlation of combustion efficiency of single J33 combustor with reciprocal of second-order reaction equation parameter. Fuel, propane; combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.



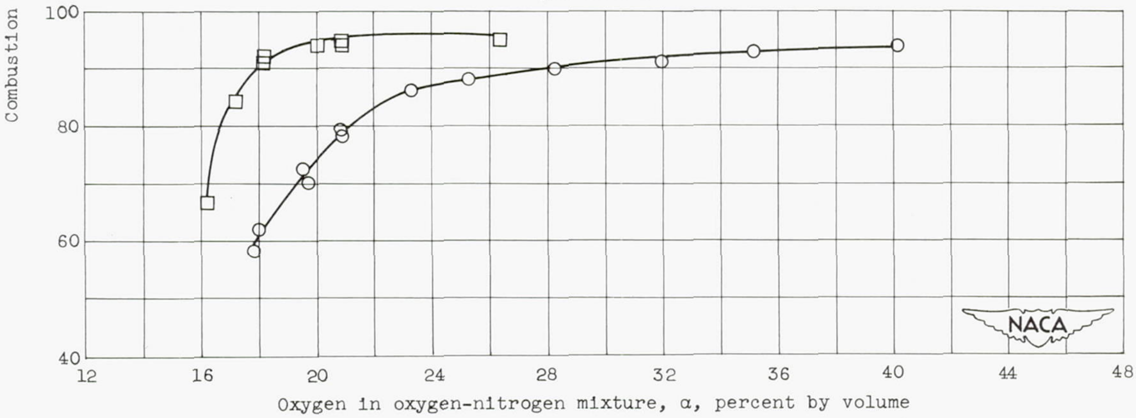
(a) Combustor-inlet pressure, 14.3 inches of mercury absolute; fuel flow rate, 0.012 pound per second.

(b) Combustor-inlet pressure, 14.3 inches of mercury absolute; fuel flow rate, 0.016 pound per second.

Figure 7. - Comparison of combustion efficiency of single J33 combustor operating with propane and isooctane fuels. Combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.



(c) Combustor-inlet pressure, 21.4 inches of mercury absolute; fuel flow rate, 0.012 pound per second.



(d) Combustor-inlet pressure, 21.4 inches of mercury absolute; fuel flow rate, 0.016 pound per second.

Figure 7. - Concluded. Comparison of combustion efficiency of single J33 combustor operating with propane and isooctane fuels. Combustor-inlet temperature, 40° F; weight flow rate of inlet oxygen-nitrogen mixture, 1.0 pound per second.