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RESEARCH MEMORANDUM

EFFECT OF OXYGEN CONCENTRATION OF THE INLET OXYGEN-NITROGEN MIXTURE ON THE COMBUSTION EFFICIENCY OF A SINGLE J33 TURBOJET COMBUSTOR

By Charles C. Graves

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the importance of molecular-scale processes in the over-all turbojet combustion process. The effect of oxygen concentration of the inlet oxygen-nitrogen mixture on the combustion efficiency of a single J33 combustor was determined for combustor-inlet pressures from 12.0 to 21.4 inches of mercury absolute and a range of fuel-flow rates. 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.

At a given fuel-flow rate, combustion efficiency decreased at an increasing rate with reduction in oxygen concentration. For the pressures and oxygen concentrations tested, combustion efficiency decreased with a decrease in fuel-flow rate. At a given fuel-flow rate, combustion efficiency correlated with minimum spark-ignition energy, flame speed, and a simplified reaction-kinetics equation. A greater range of combustor-inlet conditions or other types of combustor test will be required to distinguish the most significant correlation.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to formulate design parameters for improving the performance of turbojet combustors. One of the important problems in combustor design is that of maintaining high combustion efficiency at altitude. As shown in reference 1, both the low pressure and low temperature encountered at altitude result in reduced combustion efficiency. An explanation of this effect in terms of basic processes is one of the goals of fundamental combustion research.

The conversion of fuel and oxygen to end products in a turbojet combustor is extremely complex, involving such gross and molecular-scale processes as evaporation of the fuel spray, turbulent mixing, and diffusion, ignition, and oxidation of the fuel. If the rate of one of these steps can be considered as controlling the over-all conversion rate, the problem of treating the combustion process analytically is considerably simplified. In a theoretical analysis of the turbojet combustion process (reference 2), the controlling step was assumed to be the chemical reaction (oxidation of the fuel). This analysis resulted in the P_iT_i/V_r parameter (where P_i, T_i, and V_r are the combustor-inlet pressure, temperature, and reference velocity respectively), which has been used with varying success to correlate the combustion efficiency of a number of turbojet combustors over their operating range. The encouraging results obtained in this investigation warrant further study of the role of molecular-scale processes in the over-all turbojet combustion mechanism. 2599

In view of the complexity of the turbojet combustion process, a possible method of separating molecular-scale processes from grosser physical processes would be to compare the effect of selected variables both on combustion efficiency and on certain fundamental combustion properties of premixed fuel-oxygen-nitrogen mixtures. Any relations found may (1) indicate the importance of molecular-scale processes in the turbojet combustion mechanism and (2) suggest possible combustion mechanisms which can be treated analytically.

The combustion efficiency of a ram-jet operating with premixed, vaporized fuel-air mixtures has been correlated with fundamental combustion properties (reference 3); but the problem in a turbojet is much more difficult, because comparisons cannot be made at definite fuel-air ratios. While the typical over-all fuel-air ratio in the turbojet combustor is outside the lean flammability limit, the distribution of the total air flow can result in fuel-air ratios near stoichiometric in various portions of the combustor. In addition, little is known of the effects of turbulent mixing, fuel atomization, and fuel evaporation on the fraction of fuel available for reaction.

Investigations of gaseous fuel-oxygen-nitrogen mixtures have shown the marked effect of oxygen concentration on minimum spark-ignition energy, quenching distance, and flame speed (reference 4). Oxygen concentration appreciably affects equilibrium temperature (stoichiometric or richer fuel-oxygen ratios) and is therefore a means of varying the kinetics term in equations based on bimolecular chemical reactions. In combustor tests, variations in oxygen concentration should affect the rate of combustion without appreciably changing such factors as inlet velocity, turbulent mixing as associated with inlet conditions, and fuel-spray characteristics. Thus, oxygen concentration, as a combustor-inlet variable, offers a possible means of relating combustor performance characteristics to fundamental combustion properties and of separating molecular-scale processes from grosser physical processes associated with inlet conditions.

Accordingly, a program was conducted to determine the effect of oxygen concentration of the inlet oxygen-nitrogen mixture on the combustion efficiency of a J33 single combustor. The combustor, installed in the laboratory air and exhaust supply system, was operated over a range of inlet pressures (12.0 to 21.4 in. Hg absolute) and fuel-flow rates (0.010 to 0.0157 lb/sec). The oxygen concentration of the inlet oxygen-nitrogen mixture was varied from approximately 16 to 48 volume percent by the introduction of metered quantities of pure oxygen or nitrogen into the combustor-inlet air system. 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. Isooctane was used throughout the program, since considerable fundamental combustion data were available for this fuel. Possible correlations of combustor data with fundamental combustion properties (minimum spark-ignition energy, quenching distance, flame speed) and a simplified reaction-kinetics equation are presented. The material presented in this report is part of a dissertation presented for the degree of Doctor of Engineering in the Yale School of Engineering.

APPARATUS AND PROCEDURE

Combustor. - The single J33 combustor installation is shown diagrammatically in figure 1. The combustor was connected to the laboratory system which provided refrigerated air at -40° F, 48 inches of mercury absolute, and low-pressure altitude exhaust. The air flow and pressure in the combustor were regulated by remote-controlled valves located upstream and downstream of the combustor. The inlet temperature was controlled by valves proportioning the amount of air passing through a steam-fed heat exchanger. The exhaust gases were cooled by means of a water spray located upstream of the exhaust regulating valve.

The shell, liner, and dome of a production-model J33 combustor were used in the investigation. A conical diffuser was used at the combustor inlet; the combustor outlet was attached directly to a 6-inch-diameter exhaust-instrumentation section. In order to obtain fully developed fuel sprays at the low fuel-flow rates required in this investigation, the standard nozzle was replaced with a hollow-cone nozzle having a 45° spray angle and a nominal rating of 10.5 gallons per hour. A sketch of the combustor is shown in figure 2.

Oxygen-nitrogen supply system. - Oxygen (or nitrogen) was added to the combustor-inlet air from 12 cylinders manifolded as shown in figure 1. The gas-flow rate was determined by measuring the pressure and temperature upstream of a calibrated critical-flow orifice. To cover the range of flow rates required, two such orifices, having nominal diameters of 0.20 and 0.30 inches, were used. The pressure upstream of the critical-flow orifices could be maintained at any value between 30 and 200 pounds per square inch gage by means of a remote-controlled pressure regulator. The gas was brought into the air duct at a point approximately 12 feet upstream of the combustor inlet through a spray bar (see fig. 2) consisting of eight spokes, each having three 3/32-inch holes pointed upstream and located at centers of equal areas of the 6-inch-diameter duct. A mixing section was installed downstream of the spray bar to ensure complete mixing of the gas-air mixture at the combustor inlet.

Instrumentation. - Cross-sectional views of the combustor instrumentation stations are shown in figure 2. At each station, the instruments were located at centers of equal areas. Design details of the total-pressure rakes and thermocouple rakes are presented in reference 5. 2599
Exhaust thermocouples were arranged in a parallel circuit to give an instantaneous average-temperature reading. This method has been found to give average-temperature readings which are accurate within the limits of the other instrumentation. Thermocouples were connected through multiple switches to a dual-range, self-balancing potentiometer. The fuel-flow rate was measured with a calibrated rotameter; fuel nozzle discharge pressure, with a calibrated Bourdon gage. Air flow was metered by a square-edged orifice installed according to A.S.M.E. specifications and located upstream of the inlet-air regulating valve (fig. 1).

Procedure. - Combustion efficiency was measured over a range of combustor-inlet pressures from 12.0 to 21.4 inches of mercury absolute, inlet oxygen concentrations from approximately 16 to 48 percent (by volume), and fuel-flow rates from 0.010 to 0.0157 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. A.S.T.M. certified isooctane (purity 99.6 mole percent) was used throughout the program.

Combustion efficiency was computed in accordance with the equations and charts given in reference 6. The enthalpy rise of the oxygen-nitrogen mixture was computed from enthalpy values of oxygen and nitrogen tabulated in reference 7. 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 total oxygen-nitrogen mixture flow rate. No corrections for radiation, conduction, or stagnation effects on the thermocouple readings were made.

RESULTS AND DISCUSSION

Combustor Tests

Reproducibility of data. - Throughout the test program, daily checks on the performance of the combustor were made at 17.3 inches of mercury absolute, 0.0157 pound per second fuel-flow rate, and normal air-oxygen concentration. The deviation in combustion efficiency at this operating condition is shown in figure 3. A possible upward drift in combustion efficiency with time is indicated, with a maximum spread in combustion efficiency of approximately 5 percent. This variation may be due to slight warpage of the combustor liner resulting from above-normal liner temperatures which were reached with the high oxygen concentrations. These check data were obtained at a combustor operating condition of average severity for the range of inlet conditions covered. Greater day-to-day deviations might be expected at less favorable operating conditions.

Combustion-efficiency data. - The data obtained in the investigation of the effect of oxygen concentration on combustion efficiency are presented in table I. In figure 4, combustion efficiency is plotted against oxygen concentration (volume percent) at the various combustor-inlet pressures investigated. The effect of oxygen concentration on combustion efficiency was more pronounced at the lower values of oxygen concentration and combustion efficiency. At approximately 21 percent oxygen (air) a 1-percent increase in oxygen concentration increased combustion efficiency approximately 9 percent. At constant fuel-flow rate and oxygen concentration, combustion efficiency increased with increase in inlet air pressure. Comparison of the curves of figure 4 indicates that, at constant inlet pressure and oxygen concentration, combustion efficiency increased with an increase in fuel-flow rate over the range of inlet conditions investigated. A slight increase in scatter of the data is indicated at the lower fuel-flow rates.

Correlation of Data with Fundamental Combustion Properties

In order to study the importance of molecular-scale processes in limiting the completeness of combustion in the turbojet combustor, attempts were made to correlate combustion efficiency with fundamental combustion properties of isooctane fuel. The fundamental combustion properties considered in this investigation were minimum spark-ignition energy, quenching distance, and flame speed.

Minimum spark-ignition energy. - Minimum spark-ignition energies of isooctane-oxygen-nitrogen mixtures as a function of equivalence ratio for various pressures and oxygen-nitrogen mixtures were obtained from a commercial laboratory. The equivalence ratios in the reaction zone of the turbojet combustor are not known. Accordingly, a comparison of the effect of pressure and oxygen concentration on minimum spark-ignition energy and combustion efficiency was made using values of minimum spark-ignition energy arbitrarily taken at the equivalence ratios giving the lowest value of minimum spark-ignition energy for each pressure and oxygen concentration. These values are shown in table II.

From cross plots of these data and the combustion-efficiency data of table I, an approximate relation between combustion efficiency η_b, combustor inlet pressure P_i, and minimum spark-ignition energy E_m was obtained as shown in figure 5. This correlation is of the form

$$\eta_b = f(P_i^2/E_m) \tag{1}$$

(All symbols are defined in appendix A.) The exponent in the inlet pressure term, determined from the data for the 0.0157 pound per second fuel-flow rate, represents an approximate average value of the slopes obtained by plotting minimum spark-ignition energy against burner-inlet pressure on logarithmic paper at various values of combustion efficiency. The scatter in the correlation increased somewhat at the lower fuel-flow rates. 2599

The faired curves of figure 5 are combined in figure 6 to indicate the effect of fuel-flow rate on the form of the correlation curve. Similar trends are shown for all fuel-flow rates. Combustion efficiency increased with fuel-flow rate for the range of inlet conditions investigated.

Quenching distance. - The quenching distance d and minimum spark-ignition energy E_m of isooctane-oxygen-nitrogen mixtures are approximately related by the expression $E_m = kd^2$ over a wide range of pressure and oxygen concentration. A similar relation exists for methane, ethane, and propane (reference 4). Substitution of the previously mentioned relation into equation (1) results in the following approximate relation between combustion efficiency, burner-inlet pressure, and quenching distance:

$$\eta_b = f(P_i/d) \tag{2}$$

The change in low-pressure propagation limits with tube diameter for various isooctane-oxygen-nitrogen mixtures was investigated in reference 8. Since the minimum tube diameter for flame propagation has been shown to be proportional to quenching distance (reference 9), no attempt was made to use these data. In a recent theoretical analysis (reference 10) based on an active-radical-diffusion mechanism, the proportionality constant is related to changes in geometry of the test equipment. The relation between minimum tube diameter and combustion efficiency would be of the same form as equation (2).

Flame speed. - The laminar flame speeds of isooctane-oxygen-nitrogen mixtures at atmospheric pressure and various equivalence ratios were determined in reference 11 from schlieren photographs of Bunsen-type flames. For a range of initial mixture temperatures T_i from 560° to 760° R and for oxygen concentrations α from 21 to 49.6 percent (volume), an empirical equation of the following form was obtained, relating the combined effect of these variables to the maximum flame speed u_f:

$$u_f = KT_i^{1.4}\ (\alpha-12) \qquad (3)$$

Maximum flame speed is defined as the maximum point of the curve of
2599 flame speed against equivalence ratio at a given temperature and oxygen concentration.

The effect of variation in pressure on the flame speeds of hydrocarbon fuel-air mixtures has not been definitely established. The effect, if any, is small and appears to vary with fuel type (references 12 to 17). Gaydon and Wolfhard (reference 18) concluded that the flame speed of hydrocarbon fuel-air mixtures is independent of pressure, provided that the apparatus dimensions are large enough to prevent surface effects from becoming important. The flame speeds of isooctane-oxygen-nitrogen mixtures were assumed to be independent of pressure in the present investigation.

Since flame speed is one of the fundamental properties which can readily fit into a physical picture of the combustion process, an attempt was made to derive a combustion-efficiency parameter based on a flame-speed mechanism (appendix B). The final equation presented in appendix B for conditions of constant inlet temperature and weight-flow rate of the fuel and the oxygen-nitrogen mixture is

$$\eta_b = f(P_i^{1/3}\ u_f/V_r) \qquad (B9)$$

For a constant inlet temperature, assuming flame speed to be independent of pressure, the maximum flame speed of isooctane-oxygen-nitrogen mixtures is proportional to the term $(\alpha-12)$ of equation (3). Substituting this term in equation (3) gives the following relation between combustion efficiency, inlet pressure, reference velocity, and oxygen concentration:

$$\eta_b = f\left[P_i^{1/3}\ (\alpha-12)/V_r\right] \qquad (4)$$

As shown in figure 7, the flame-speed parameter of equation (4) satisfactorily correlates the combustion-efficiency data of table I. The faired curves of figure 7 are combined in figure 8 and are shown to be similar for each fuel-flow rate.

Application of Simplified Reaction-Kinetics Equation to Data

In the analysis of reference 2, it is assumed that the step controlling the over-all conversion rate of fuel in the turbojet combustion process is the chemical reaction (oxidation of the fuel). The chemical reaction was considered to be governed by the effective collision rate between two reactants A and B in one slowly occurring step in the oxidation chain. In the derivation of the $P_i T_i / V_r$ parameter, the following equation relating combustion efficiency to inlet variables and conditions in the burning zone was obtained: 2599

$$\ln\left(\frac{1 - \frac{N_A}{N_B}\eta_b}{1 - \eta_b}\right) + K_6 = K_3 \frac{\left(\sigma_A + \sigma_B\right)^2}{R^{1/2}} \left(\frac{e^{\frac{-E}{RT_c}}}{T_c^{3/2}}\right) \frac{P_i T_i}{V_r} \tag{5}$$

In this equation N_A and N_B are the concentrations of the two reactants, σ_A and σ_B are the molecular diameters of the two reactants, R is the gas constant, E is the apparent energy of activation, T_c is the burning-zone temperature, and K_6 and K_3 are constants. Equation (5) applies for a given combustor, fuel, and fuel-air ratio when combustion occurs in zones where N_A is less than N_B. If the burning-zone temperature T_c is considered to be independent of changes in combustor-inlet conditions, the right side of the equation reduces to a constant times the $P_i T_i / V_r$ parameter. For the case where oxygen concentration is a combustor-inlet variable, T_c can no longer be considered constant. Variations in oxygen concentration result in appreciable changes in the flame temperature of stoichiometric or richer fuel-oxygen-nitrogen mixtures. In the application of equation (3) to the data obtained in the present investigation, the burning-zone temperature was arbitrarily taken as the stoichiometric adiabatic equilibrium temperature, and the concentration of reactant B was considered proportional to the oxygen concentration α of the combustor-inlet oxygen-nitrogen mixture. Under these conditions, the ratio N_A/N_B can be assumed constant, and equation (5) can be expressed in the form

$$\eta_b = f\left[\frac{\alpha\, P_i T_i}{V_r}\left(\frac{e^{-\frac{E}{RT_{eq}}}}{T_{eq}^{3/2}}\right)\right] \tag{6}$$

where T_{eq} is the stoichiometric adiabatic equilibrium temperature.

The application of equation (6) to the data of table I is shown in figure 9. The equilibrium temperatures at the various combustor-inlet pressures and oxygen concentrations were computed by the methods and charts of reference 19. It was found that, for an activation energy of approximately 37,000 calories per gram mole, the data were satisfactorily correlated. (This value is in reasonable agreement with the apparent activation energy of 32,000 calories per gram mole obtained from adiabatic compression data for isooctane-air mixtures (reference 4). In reference 20, a value of 40,000 calories per gram mole was used in the application of a thermal theory of flame propagation to the flame speeds of a number of hydrocarbons. In the application of the Semenov thermal-theory flame-propagation equation (reference 21) to the flame-speed data of isooctane-oxygen-nitrogen mixtures, reference 11 found that the value of 40,000 gave closer agreement between experimental and predicted flame speeds than did the 32,000 value.) In figure 10, the faired curves of figure 9 are combined to show the change in the form of the correlation curve with change in fuel-flow rate.

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Equation (6) was applied to the case of constant fuel-oxygen-nitrogen mixture ratio by correlating the effect of pressure and oxygen concentration at constant fuel-flow rate. For the case of constant fuel-oxygen ratio, a slightly higher value of apparent activation energy would be required to correlate the data.

The correlation of combustion-efficiency data for combustors following normal operating conditions will not be appreciably affected if equation (6) is used in place of the $P_i T_i / V_r$ parameter, which was obtained by assuming reaction-zone temperature to be constant with inlet conditions. While the kinetics term $\frac{e^{-\frac{E}{RT_{eq}}}}{T_{eq}^{3/2}}$ can be appreciably affected by T_{eq}, typical changes in combustor-inlet pressure and temperature result in relatively small percentage changes in T_{eq}.

General Discussion

Over the range of inlet conditions investigated, correlations of combustion efficiency were obtained with certain fundamental combustion properties - minimum spark-ignition energy, quenching distance, flame speed - and with a simplified reaction-kinetics equation. In general, the fundamental combustion properties of hydrocarbon fuels are interrelated (reference 4). Consequently, correlation of the combustor data with all of these properties would be expected if a correlation were obtained with any one of the properties. The flame-speed parameter predicts a relation between inlet pressure and velocity which is appreciably different from that of the second-order reaction-equation parameter. Since pressure and velocity were not varied independently, it was not possible to distinguish the significant correlation. Additional tests involving independent variations of combustor-inlet pressure, temperature, and velocity will be required to determine the applicability of the parameters used in the present investigation.

The correlations do not take into consideration fuel-spray effects. As seen in figures 5, 7, and 9, the data scatter as the correlations increased with decreased fuel-flow rate. Part of this increase can be attributed to the increase in scatter of the basic data shown in figure 4. Increase in relative importance of the fuel-spray vaporization time, resulting from increase in mean drop diameter at the lower fuel-flow rates, may also be a contributing factor. Since fuel vaporization time should be affected by changes in primary-zone temperature with oxygen concentration, an increase in the scatter of the correlations might be expected at the lower fuel-flow rates.

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The data obtained in this investigation indicate the magnitude of the effect of reduction in combustor-inlet oxygen concentration on combustion efficiency when combustor-inlet air temperature is raised by the addition of preheater exhaust gases. For a 200° F temperature rise across the preheater, the oxygen concentration would be reduced to approximately 20 percent (volume). At high combustion efficiencies, the effect would be small; however, at moderate to severe operating conditions, combustion efficiency may be reduced approximately 10 percent, assuming the effect of oxygen concentration to be the same as obtained in this investigation. The beneficial effect of increase in combustor-inlet temperature on combustion efficiency would therefore tend to be offset by the reduction in oxygen concentration. The data may also indicate trends to be expected in turbojet engine afterburners where oxygen concentrations have been reduced considerably (to approximately 16 percent) by the primary combustors.

SUMMARY OF RESULTS

In an investigation to determine the effects of oxygen concentration of the inlet oxygen-nitrogen mixture on the combustion efficiency of a single J33 combustor the following results were obtained:

1. At a given fuel-flow rate, combustion efficiency decreased with reduction in oxygen concentration; the rate of decrease in combustion efficiency increased with a decrease in oxygen concentration.

2. At a given fuel-flow rate, the combustion efficiency could be correlated with (a) minimum spark-ignition energy, (b) flame speed, or (c) a simplified reaction-kinetics equation. A greater range of inlet conditions or other types of combustor test will be required to distinguish the most significant correlation.

3. Combustion efficiency decreased with a decrease in fuel-flow rate over the range of pressures and oxygen concentrations investigated. No attempt was made to correlate fuel-spray characteristics with combustion efficiency.

4. The combustion efficiency of turbojet afterburners and of combustors supplied with air heated by the addition of exhaust gases may be substantially reduced by the decreased oxygen concentration.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A_f total flame-surface area in combustor

A'_f flame-surface area per unit volume 2599

A'_{fi} initial flame surface per unit volume

A_r combustor reference cross-sectional area

D dimension of combustor

d quenching distance

E energy of activation

E_m minimum spark-ignition energy

f over-all fuel-oxygen-nitrogen mixture ratio

f_m fuel-oxygen-nitrogen mixture ratio of unburned mixture

K_f proportionality constant

m_a molecular weight of oxygen-nitrogen mixture

m_f molecular weight of fuel

N_A concentration of reactant A

N_B concentration of reactant B

P_m pressure of unburned mixture

P_1 combustor-inlet pressure

Pr Prandtl number

R gas constant

Re Reynolds number

T_c burning-zone temperature

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T_{eq} stoichiometric adiabatic equilibrium temperature

T_m temperature of unburned mixture

T_1 combustor-inlet temperature

u_f maximum flame speed

V_c total combustor volume

V_r reference velocity, based on A_r and ρ_a

W_a weight-flow rate of inlet oxygen-nitrogen mixture

W_f weight-flow rate of fuel

α oxygen concentration

η_b combustion efficiency

ρ_a inlet density

ρ_{fm} weight of fuel per unit volume of unburned mixture

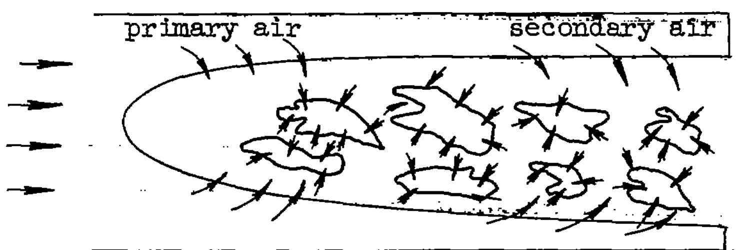
σ_A molecular diameter of reactant A

σ_B molecular diameter of reactant B

APPENDIX B

DERIVATION OF FLAME-SPEED CORRELATING PARAMETER

The combustion process was visualized as the burning of fuel-oxygen-nitrogen mixture zones of random size and shape which are surrounded by a flame surface and which are consumed as they pass through the combustor. The temperature and fuel-oxygen-nitrogen mixture ratio of all unburned zones are considered to have the same value. The flame surface advances 2599
into the adjacent unburned mixture at a rate determined by the physical conditions of the unburned mixture. The effect of turbulence on rate of combustion is considered in terms of its effect on the flame surface area. This picture of the turbojet combustion process was suggested by the analysis of Wohlenberg (reference 22), in which the concept of reaction interface extension was introduced in a detailed study of the combined effects of diffusion and chemical reaction in gaseous fuel combustion.



If the preceding figure represents conditions in the combustor at a given instant of time, the combustion efficiency η_b can be expressed by the relation

$$\eta_b = \frac{\rho_{fm} A_f u_f}{W_f} \qquad \text{(B1)}$$

where ρ_{fm} is the fuel per unit volume of the unburned mixture, A_f is the total flame-surface area in the combustor at the instant considered, and u_f is the flame speed as determined by the physical conditions of the unburned mixture. The numerator represents the pounds of fuel burned per unit time in the combustor; the denominator W_f, the pounds of fuel supplied per unit time to the combustor.

If f is the over-all fuel-oxygen-nitrogen mixture ratio, W_a and ρ_a are the weight-flow rate and density of the inlet oxygen-nitrogen mixture, respectively, and V_r is the reference velocity based on the combustor reference cross-sectional area A_r, then

$$W_f = f\,W_a = f\,\rho_a A_r V_r \tag{B2}$$

It may be shown that

$$\rho_{fm} = \frac{f_m m_a P_m}{RT_m}\left[\frac{1}{1 + \frac{m_a}{m_f} f_m}\right]$$

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where m_f and m_a are the molecular weights of the oxygen-nitrogen mixture and fuel, respectively; R is the gas constant; and f_m, P_m, and T_m are the fuel-oxygen-nitrogen mixture ratio, pressure, and temperature of the unburned mixture, respectively. Since the term in the brackets is very close to unity

$$\rho_{fm} \approx \frac{f_m m_a P_m}{RT_m} \tag{B3}$$

For a low pressure drop across the combustor, P_m may be considered to equal the combustor inlet pressure P_i. Also, if the effects of radiant heat transfer are neglected, T_m can be considered constant along the combustor. In the case of the turbojet combustor, in which fuel is vaporized and mixed with air in the primary zone, T_m may be much higher than T_i. Assuming that T_m is proportional to T_i, the relationship ρ_{fm} becomes

$$\rho_{fm} = \frac{f_m m_a P_i}{K_f R T_i} = \frac{f_m}{K_f}\,\rho_a \tag{B4}$$

where K_f is the proportionality constant relating combustor-inlet temperature to the temperature of the unburned mixture in the reaction zone. When equations (B2) and (B4) are substituted in equation (B1), the expression for combustion efficiency becomes

$$\eta_b = \left(\frac{1}{K_f}\right)\left(\frac{f_m}{f}\right)\left(\frac{A_f}{A_r}\right)\left(\frac{u_f}{V_r}\right) \tag{B5}$$

The total flame-surface area A_f represents an integration of the flame-surface area per unit volume A_f' over the total combustor volume V_c. The mean value of A_f' at any point in the combustion path will be a function of A_f' at the start of the combustion path and the change in

[redacted]

A_f' as combustion progresses. In the absence of additional sources of turbulence along the combustor, the change in A_f' can be associated with (a) the tendency of the initial turbulence to decay with time, (b) the change in turbulence accompanying the energy release along the combustor, and (c) the change in volume of the unburned mixture. The latter two factors should account for the major change in flame-surface area along the combustor. For a given fuel, the energy released is proportional to the over-all fuel-air ratio and the change in combustion efficiency along the combustor length. 2599 The fractional volume occupied by the unburned mixture is a function of the over-all fuel-air ratio, combustion efficiency, and inlet temperature. Accordingly, it is possible that A_f can be expressed in the form

$$A_f = A_{fi}' \; \varphi(f,\eta_b,T_i)V_c \tag{B6}$$

where A_{fi}' is the initial flame-surface area per unit volume of combustor reaction zone, and $\varphi(f,\eta_b,T_i)$ accounts for the effect of energy-release rate and reduction in volume of the unburned mixture on A_f. The area A_{fi}' will be a function of the over-all fuel-air ratio and of the combustor geometry and inlet aerodynamics. As shown in reference 22, A_{fi}', as affected by combustor-inlet density alone, is proportional to $P_i/T_i^{1/3}$. The area A_{fi}' is a measure of the average hydraulic radius of the unburned-mixture zones, or the average distance through which the flame must travel to complete the combustion process. As suggested in reference 22, a dimensional analysis relating A_{fi}' to combustor-inlet conditions would involve such dimensionless groups as Reynolds and Prandtl numbers. If it is assumed that

$$A_{fi}' = DK(P_i/T_i)^{1/3}(Re)^a(Pr)^b$$

then

$$A_f = DKV_c(P_i/T_i)^{1/3}(Re)^a(Pr)^b \, \varphi(f,\eta_b,T_i) \tag{B7}$$

In these expressions, K is a constant and D is a characteristic dimension of the combustor. Substitution for A_f in equation (B5) gives

$$\frac{\eta_b}{\varphi(f,\eta_b,T_i)} = \frac{DKV_c}{K_f f A}\left(\frac{P_i^{1/3}(Re)^a(Pr)^b}{T_i^{1/3}V_r}\right)u_f \tag{B8}$$

For the combustor data obtained in the present investigation, in which combustor-inlet temperature and weight-flow rate of the inlet oxygen-nitrogen mixture and fuel were held constant, equation (B8) reduces to

$$\eta_b = f\left(P_i^{1/3} u_f / V_r\right) \tag{B9}$$

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if the slight change in Reynolds number resulting from the change in viscosity of the inlet mixture with oxygen concentration is neglected.

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TABLE I - PERFORMANCE DATA FROM COMBUSTOR OPERATING WITH VARIOUS INLET OXYGEN-NITROGEN MIXTURES

(a) Nominal fuel-flow rate, 0.0157 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 (volume 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)
71	12.0	500	1.00	20.9	118	0.0156	74	937	437	36.2
192	12.0	496	1.00	20.9	117	.0157	77	912	416	34.6
72	12.0	500	1.00	23.3	118	.0156	74	1135	635	52.8
73	12.0	500	1.00	24.8	118	.0156	73	1225	725	60.9
85	12.0	499	1.00	24.7	118	.0157	72	1247	748	62.7
80	12.0	499	1.00	26.2	117	.0158	77	1315	816	68.0
88	12.0	497	1.00	27.8	116	.0157	71	1370	873	72.9
87	12.0	497	1.01	30.8	117	.0157	71	1412	915	77.4
81	12.0	495	1.01	32.6	116	.0157	73	1407	912	76.9
84	12.0	496	1.00	33.3	115	.0157	72	1472	976	81.8
83	12.0	494	.99	33.7	114	.0157	72	1492	998	83.5
255	12.0	503	1.01	35.4	117	.0157	77	1480	977	84.0
248	12.0	501	1.01	40.4	116	.0157	78	1505	1004	86.2
49	14.3	499	1.00	20.9	99	.0157	73	1118	619	51.5
284	14.3	502	1.00	20.9	100	.0157	78	1147	645	54.9
65	14.3	501	1.00	24.7	99	.0157	74	1363	862	73.0
74	14.3	500	1.00	25.9	99	.0157	74	1390	890	75.5
55	14.3	498	1.00	27.7	98	.0157	74	1440	942	79.6
52	14.3	499	1.00	29.1	97	.0157	73	1460	961	80.6
51	14.3	499	1.00	30.7	98	.0157	73	1477	978	82.6
50	14.3	498	1.01	32.3	98	.0157	73	1487	989	83.2
254	14.3	503	1.00	35.4	98	.0157	78	1537	1034	88.9
248	14.3	501	1.01	40.3	97	.0157	77	1555	1054	90.5
88	14.3	498	1.01	40.3	97	.0157	72	1547	1049	90.1
180	17.3	498	1.00	20.9	82	.0157	76	1287	789	67.3
26	17.3	498	1.00	18.0	82	.0157	73	1040	542	45.1
67	17.3	502	.99	18.9	82	.0156	74	1160	658	55.0
20	17.3	502	1.00	19.0	81	.0157	73	1165	663	54.1
9	17.2	502	1.00	23.3	82	.0157	73	1460	958	80.8
33	17.3	500	1.01	25.2	82	.0157	72	1460	960	81.6
44	17.3	500	.99	27.7	80	.0157	73	1520	1020	85.5
38	17.3	500	1.00	28.3	82	.0157	72	1505	1005	85.3
45	17.3	501	1.00	28.6	81	.0157	73	1518	1017	86.4
43	17.3	500	1.00	28.7	81	.0157	73	1510	1010	85.6
39	17.3	500	.99	30.2	80	.0157	72	1550	1050	88.3
36	17.3	504	.99	32.0	81	.0157	72	1550	1046	88.0
31	17.3	502	1.00	32.0	81	.0157	72	1555	1053	88.6
149	17.3	494	1.01	32.3	81	.0157	76	1540	1046	90.5
93	17.4	497	1.00	40.0	79	.0157	71	1550	1053	90.2
112	17.2	504	1.00	43.2	81	.0158	72	1590	1086	92.8
11	21.4	500	1.00	20.9	66	.0157	72	1430	930	78.4
276	21.4	501	1.00	20.9	67	.0157	78	1420	919	79.4
28	21.4	500	1.00	17.8	67	.0157	73	1198	698	58.4
297	21.4	503	1.00	18.0	67	.0158	78	1233	730	62.1
23	21.4	504	1.00	19.5	67	.0157	74	1370	866	72.9
24	21.4	499	1.00	19.7	66	.0157	73	1335	836	70.2
15	21.4	500	.99	23.3	66	.0157	73	1525	1025	86.2
14	21.4	500	1.01	25.3	66	.0157	73	1530	1030	88.2
13	21.4	500	1.00	28.3	65	.0157	73	1565	1065	90.0
12	21.4	500	.99	32.0	65	.0157	72	1583	1083	91.4
256	21.4	503	1.00	35.2	65	.0157	77	1586	1083	93.1
249	21.4	502	1.01	40.2	65	.0157	77	1590	1088	93.8

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TABLE I - PERFORMANCE DATA FROM COMBUSTOR OPERATING WITH VARIOUS INLET OXYGEN-NITROGEN MIXTURES - Continued

(b) Nominal fuel-flow rate, 0.014 pound per second

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Point	Combustor-inlet total pressure P_i (in. Hg abs)	Combustor inlet temperature T_i (°R)	Combustor-inlet oxygen-nitrogen mixture flow (lb/sec)	Combustor-inlet oxygen concentration α (volume 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)
191	12.0	497	1.00	20.9	117	0.0140	59	850	353	32.7
211	12.0	499	1.00	26.0	117	.0139	58	1205	706	66.9
79	12.0	500	1.00	26.2	117	.0138	57	1160	660	62.1
221	12.0	500	1.01	28.1	118	.0139	58	1242	742	71.0
232	12.0	502	1.00	32.0	117	.0139	59	1295	793	75.4
250	12.0	505	1.00	32.0	118	.0140	59	1307	801	75.9
257	12.0	504	1.00	34.9	117	.0139	59	1345	841	80.1
159	12.0	502	1.00	40.0	116	.0141	56	1360	858	81.0
177	11.9	494	1.01	45.4	115	.0140	58	1375	881	84.1
194	14.3	500	1.00	20.9	99	.0140	59	1040	540	50.6
283	14.3	500	1.00	20.9	99	.0140	60	1035	535	50.3
270	14.3	498	1.00	18.7	99	.0139	59	832	334	31.3
210	14.3	499	1.00	26.0	96	.0139	58	1282	783	74.7
218	14.3	501	1.01	28.0	99	.0139	58	1315	814	78.0
199	14.3	504	.99	30.0	98	.0140	59	1370	866	81.7
231	14.3	502	1.00	32.0	98	.0139	59	1370	868	82.5
172	14.3	499	1.01	32.1	98	.0140	59	1350	851	81.3
253	14.3	503	1.00	35.2	98	.0139	59	1395	892	85.2
246	14.3	502	1.00	40.2	97	.0140	59	1425	923	87.8
239	14.3	500	1.00	45.0	96	.0140	59	1435	935	88.3
57	17.3	500	1.00	20.9	82	.0143	60	1190	690	63.6
143	17.3	497	1.00	20.9	82	.0140	59	1177	680	64.4
185	17.4	498	1.01	18.0	83	.0140	59	960	462	43.8
265	17.3	498	1.01	18.6	83	.0140	60	1008	510	48.4
233	17.3	503	1.00	26.0	82	.0139	60	1352	849	81.1
225	17.3	502	1.00	26.1	82	.0140	59	1362	860	82.3
217	17.3	501	1.01	28.0	82	.0139	58	1373	872	84.0
207	17.3	500	1.00	30.0	81	.0139	58	1408	908	87.1
148	17.3	495	1.00	32.1	80	.0140	58	1410	915	87.3
161	17.4	503	1.00	35.0	81	.0140	58	1440	937	89.2
145	17.4	495	1.01	35.0	81	.0140	58	1430	935	90.1
158	17.3	502	1.00	40.3	81	.0140	58	1430	928	87.9
128	17.3	508	1.00	40.3	81	.0140	57	1450	942	89.3
154	17.3	502	1.00	45.4	80	.0141	58	1460	958	90.6
168	17.3	498	1.01	45.5	80	.0140	58	1430	932	89.2
3	21.5	500	1.00	20.9	66	.0138	60	1285	785	74.8
275	21.4	500	1.00	20.9	66	.0140	60	1282	782	74.5
183	21.4	497	1.02	16.6	68	.0140	59	965	468	44.9
296	21.4	503	.99	18.0	67	.0140	60	1120	617	58.2
262	21.4	498	1.00	18.7	66	.0140	60	1168	670	63.6
224	21.4	502	1.00	26.0	66	.0139	58	1403	901	86.6
212	21.4	501	1.01	27.9	66	.0139	58	1410	909	87.9
204	21.4	501	.99	30.0	65	.0139	59	1460	959	91.6
171	21.4	500	1.00	32.2	66	.0140	59	1437	937	90.1
236	21.4	505	1.00	34.9	65	.0139	59	1465	960	91.6
290	21.4	505	1.00	40.0	65	.0140	60	1485	980	93.0
176	21.3	495	1.01	45.3	64	.0140	58	1460	965	91.9

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TABLE I - PERFORMANCE DATA FROM COMBUSTOR OPERATING WITH VARIOUS INLET OXYGEN-NITROGEN MIXTURES - Continued

(c) Nominal fuel-flow rate, 0.012 pound per second

Point	Combustor-inlet total pressure P_i (in. Hg abs)	Combustor-inlet temperature T_i (°R)	Combustor-inlet oxygen-nitrogen mixture flow (lb/sec)	Combustor-inlet oxygen concentration α (volume 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)
97	12.1	499	1.00	20.9	117	0.0120	40	807	308	33.2
190	12.1	497	1.00	20.9	117	.0120	44	797	300	32.3
78	12.0	501	1.00	26.1	117	.0120	43	1047	546	58.5
103	12.0	504	1.02	28.0	121	.0120	41	1092	588	65.3
108	12.0	503	1.00	29.3	117	.0121	42	1155	652	70.5
101	12.0	503	1.00	32.1	117	.0120	41	1175	672	73.2
98	12.0	501	1.00	36.0	116	.0120	41	1215	714	77.3
106	12.1	498	1.00	48.9	113	.0120	40	1253	755	81.5
62	14.3	500	1.00	20.9	99	.0121	43	927	427	45.3
282	14.3	501	1.00	20.9	100	.0120	44	927	426	46.6
188	14.4	498	1.02	18.0	101	.0120	44	705	207	22.7
269	14.3	498	1.00	18.7	100	.0120	44	770	272	29.6
64	14.3	500	1.00	24.7	99	.0117	39	1067	567	62.9
209	14.3	500	1.00	25.9	98	.0119	43	1145	645	70.8
219	14.3	501	1.00	28.0	99	.0120	44	1167	666	73.2
200	14.3	502	.99	30.1	97	.0119	44	1203	701	76.4
230	14.4	503	.99	31.9	98	.0120	44	1210	707	77.2
252	14.3	504	1.00	35.2	99	.0119	44	1230	726	80.0
245	14.3	503	1.00	40.1	97	.0119	44	1277	774	85.0
240	14.3	500	1.00	45.8	96	.0120	44	1283	783	85.3
58	17.3	500	1.00	20.9	82	.0121	43	1043	543	58.4
279	17.3	500	1.01	20.9	82	.0120	43	1037	537	59.1
184	17.4	498	1.01	18.1	82	.0120	44	872	374	40.8
68	17.3	501	1.00	18.9	82	.0122	44	943	442	46.2
234	17.3	503	1.00	26.0	82	.0120	44	1190	687	75.5
226	17.4	501	1.00	26.1	81	.0120	45	1213	712	78.4
216	17.4	500	1.01	28.1	82	.0119	44	1217	717	79.5
206	17.4	500	1.00	29.9	81	.0119	43	1265	765	84.4
163	17.4	502	1.00	30.1	81	.0121	43	1245	743	81.4
147	17.3	494	1.01	32.0	81	.0120	43	1255	761	83.9
160	17.4	502	1.00	34.9	81	.0120	43	1300	798	87.5
127	17.3	508	1.00	40.2	81	.0120	43	1305	797	86.9
157	17.4	502	1.00	40.3	80	.0121	43	1275	773	83.6
134	17.3	505	1.00	45.2	80	.0120	43	1322	817	89.3
153	17.4	502	1.00	45.4	79	.0120	42	1305	803	87.3
274	21.4	499	1.00	20.9	66	.0120	45	1133	634	69.5
299	21.4	498	1.00	20.9	66	.0120	45	1140	642	70.4
293	21.3	508	.99	16.0	68	.0120	44	798	290	31.2
182	21.5	497	1.02	16.7	67	.0120	44	875	378	41.7
295	21.4	502	1.00	18.0	67	.0120	44	998	496	55.0
69	21.4	500	.99	18.9	66	.0120	43	1055	555	59.4
223	21.4	502	1.00	26.0	66	.0120	43	1258	756	83.3
213	21.4	500	1.01	28.0	66	.0120	44	1275	775	86.0
203	21.5	500	1.00	29.9	65	.0119	43	1320	820	90.6
170	21.5	500	1.00	32.2	65	.0120	44	1303	803	88.2
237	21.4	503	1.01	34.8	66	.0120	44	1330	827	91.7
288	21.4	505	1.01	39.8	66	.0121	44	1355	850	93.2
175	21.4	496	1.00	45.1	64	.0120	44	1343	847	92.3

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TABLE I - PERFORMANCE DATA FROM COMBUSTOR OPERATING WITH VARIOUS INLET OXYGEN-NITROGEN MIXTURES - Concluded

(d) Nominal fuel-flow rate, 0.010 pound per second

NACA

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 (volume 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)
76	12.0	500	1.00	20.9	118	0.0101	30	750	250	31.4
96	12.0	499	1.00	20.9	119	.0100	27	748	249	32.1
77	12.0	500	1.00	26.1	118	.0101	29	933	433	54.5
102	12.0	505	1.02	27.8	121	.0100	28	967	462	60.7
109	12.0	502	1.00	29.3	117	.0100	28	1000	498	64.3
100	12.0	504	1.00	32.0	118	.0100	28	1020	516	66.6
99	12.0	502	1.00	36.2	116	.0100	28	1055	553	71.5
107	12.0	502	.99	43.1	115	.0100	28	1105	603	76.6
105	12.0	498	1.00	48.7	114	.0100	28	1105	607	77.6
61	14.3	499	1.00	20.9	99	.0099	27	815	316	40.7
196	14.3	501	1.00	20.9	100	.0100	30	833	332	42.7
187	14.3	499	1.01	18.0	101	.0100	30	672	173	22.6
268	14.3	498	1.00	18.7	99	.0101	31	727	229	29.3
208	14.3	500	.99	25.9	98	.0101	30	997	497	63.8
220	14.3	500	1.01	28.0	99	.0100	30	1005	505	65.6
201	14.3	503	.99	30.2	98	.0100	30	1035	532	68.3
229	14.3	504	1.00	31.8	98	.0100	30	1045	541	69.6
251	14.3	504	1.00	35.1	98	.0100	30	1062	558	71.9
241	14.3	498	1.01	45.9	97	.0100	30	1120	622	80.7
59	17.3	500	1.00	20.9	82	.0100	29	900	400	51.4
138	17.3	499	.99	20.9	81	.0101	30	910	411	52.6
186	17.4	498	1.01	18.0	83	.0100	30	772	274	35.7
267	17.3	499	1.01	18.5	83	.0100	30	795	296	38.5
235	17.3	503	1.00	26.0	82	.0101	31	1020	517	66.2
215	17.3	500	1.01	28.1	82	.0100	30	1048	548	71.3
205	17.3	500	1.00	29.9	81	.0100	30	1080	580	74.9
162	17.3	502	1.00	30.0	81	.0100	29	1065	563	73.0
146	17.3	495	1.00	31.9	80	.0100	30	1077	582	75.3
155	17.3	503	1.01	34.7	81	.0100	29	1133	630	82.5
144	17.3	497	1.00	34.9	80	.0100	30	1120	623	80.8
156	17.3	503	1.00	40.1	80	.0100	29	1110	607	78.3
132	17.3	511	1.00	45.0	81	.0101	30	1160	649	82.9
166	17.3	499	1.01	45.2	80	.0100	29	1125	626	80.4
273	21.4	497	1.00	20.9	66	.0100	31	965	468	60.8
298	21.4	497	1.00	20.9	66	.0101	31	997	500	64.3
292	21.3	508	1.00	16.0	68	.0101	30	742	234	30.0
181	21.4	498	1.01	16.7	67	.0100	30	780	282	37.0
294	21.5	502	1.00	18.0	66	.0100	30	878	376	48.6
271	21.4	499	1.00	18.7	66	.0100	30	880	381	49.3
222	21.4	500	1.00	25.9	66	.0100	29	1080	580	75.2
214	21.4	502	1.01	28.1	66	.0100	30	1107	605	79.1
202	21.5	502	.99	30.0	65	.0100	30	1163	661	85.4
178	21.4	500	1.01	31.1	66	.0100	30	1132	632	82.9
169	21.5	500	1.00	32.0	65	.0101	30	1130	630	81.1
238	21.4	503	1.01	34.9	66	.0100	30	1147	644	84.3
287	21.4	505	1.01	39.8	66	.0101	30	1200	695	90.0
174	21.5	498	1.00	45.0	64	.0101	30	1197	699	90.3

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TABLE II - MINIMUM SPARK-IGNITION ENERGIES OF ISOOCTANE-OXYGEN-NITROGEN MIXTURES

Pressure (in. Hg abs)	Oxygen concentration (volume percent)	Minimum spark-ignition energy (joules) (a)
29.92	15	32.0×10^{-4}
29.92	21	5.7
29.92	25	1.67
29.92	30	.68
29.92	35	.40
29.92	50	.133
22.44	15	49.0
22.44	21	8.3
22.44	25	2.5
22.44	30	1.15
22.44	35	.7
22.44	50	.24
14.96	15	107.0
14.96	21	14.7
14.96	25	4.4
14.96	30	2.55
14.96	35	1.7
14.96	50	.62
7.48	15	388.0
7.48	21	77.0
7.48	25	15.9
7.48	30	8.2
7.48	35	5.4
7.48	50	2.4

[a]Values taken from minimum points of curves of minimum spark-ignition energy against equivalence ratio at various pressures and oxygen concentrations. Data obtained from a commercial laboratory.

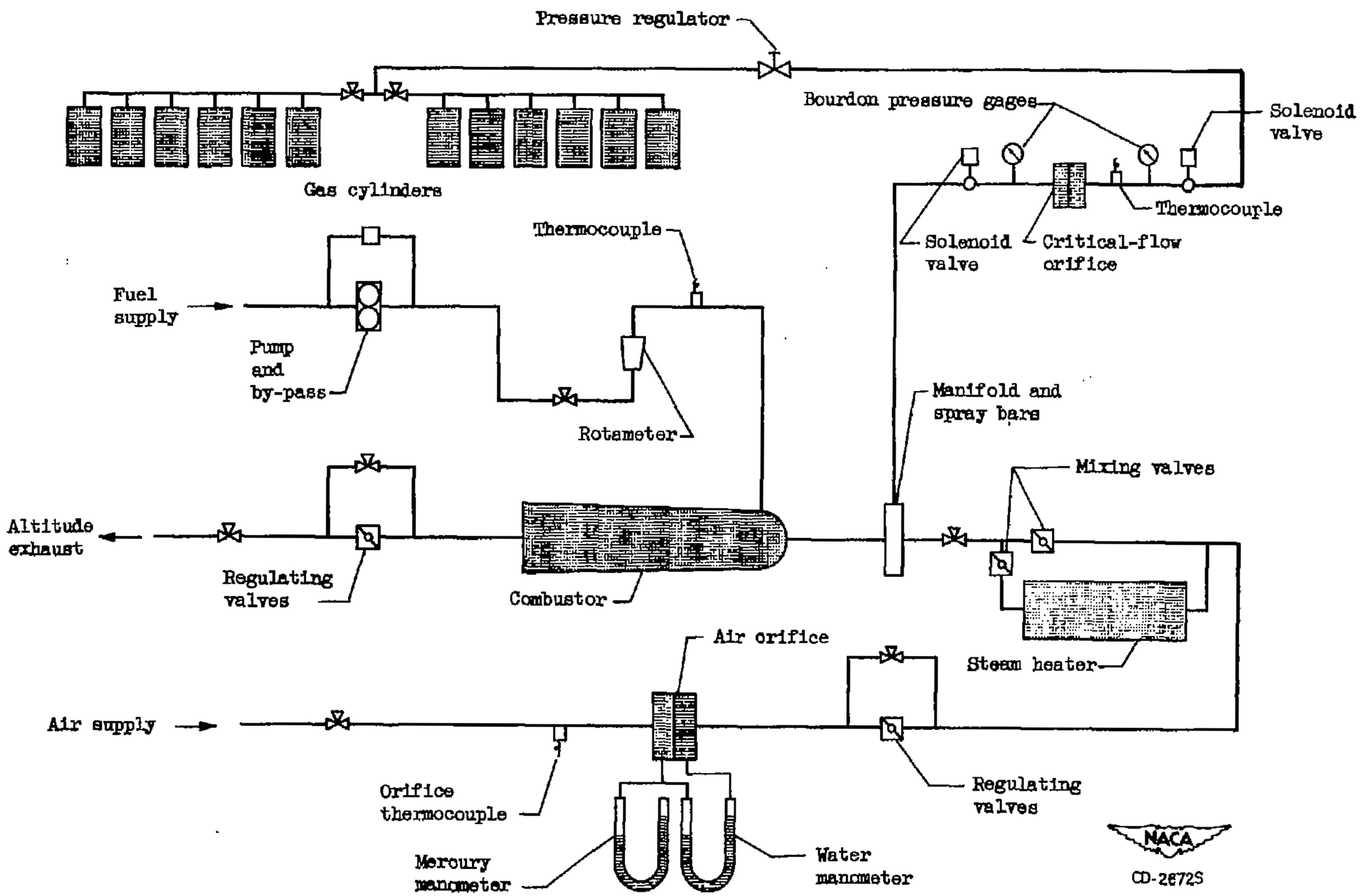

Figure 1. - Schematic sketch of J33-combustor experimental apparatus.

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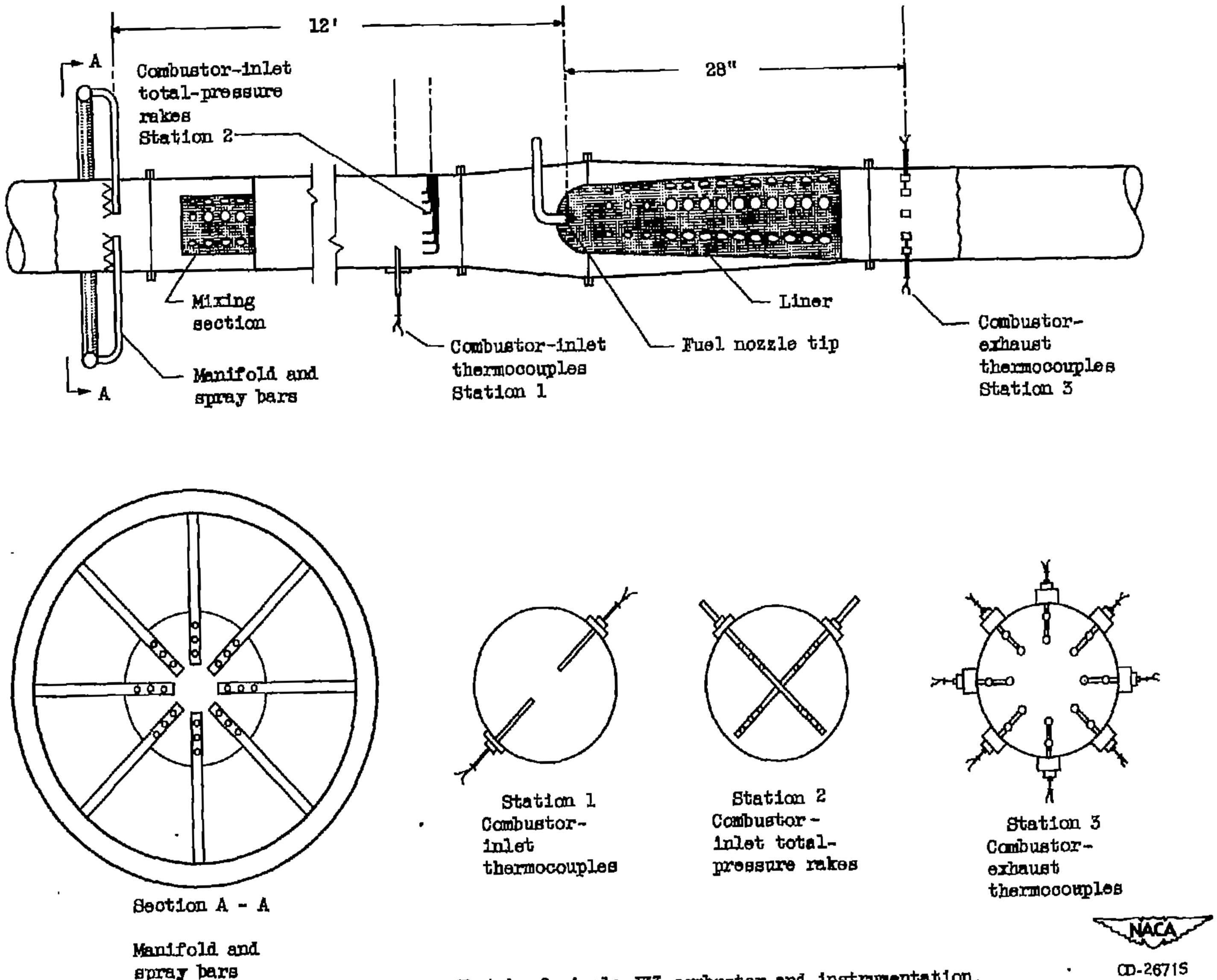

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Figure 2. - Sketch of single J33 combustor and instrumentation.

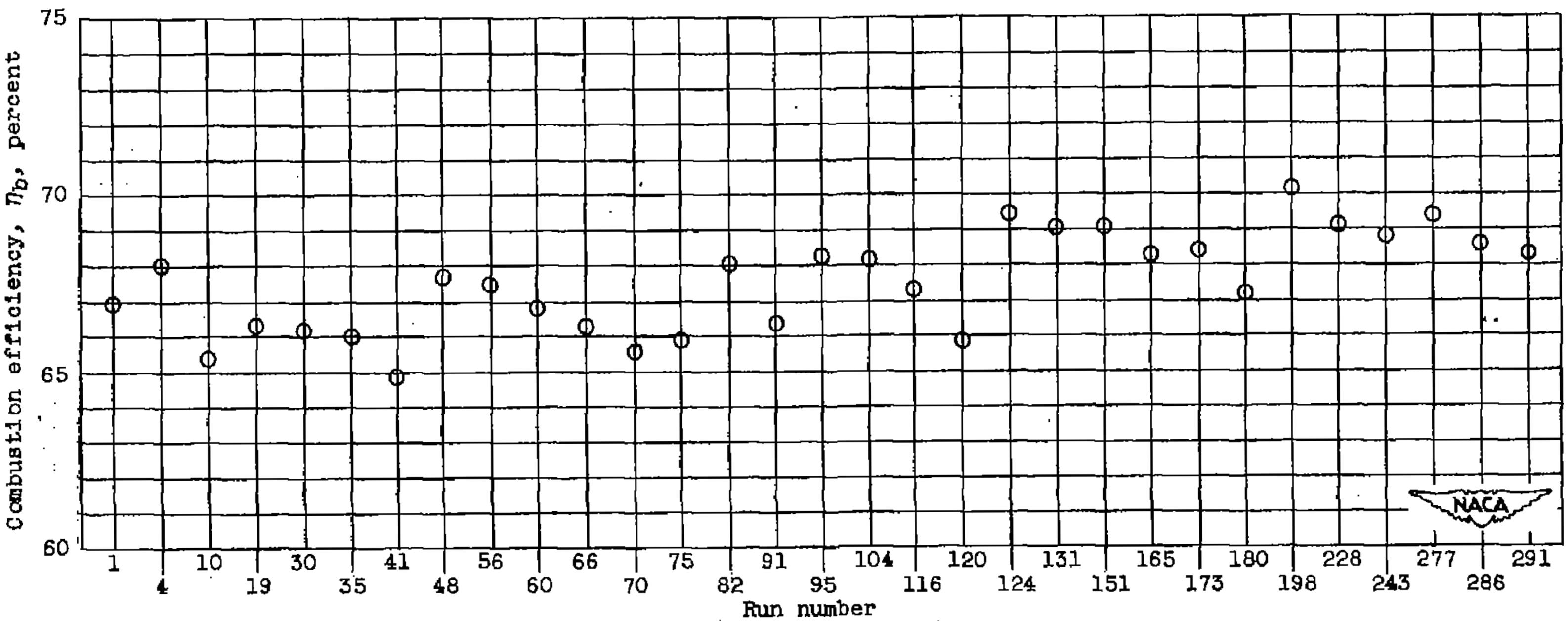

Figure 3. - Reproducibility of combustion efficiency at check point. Combustor-inlet pressure, 17.3 inches of mercury absolute; nominal fuel-flow rate, 0.0157 pound per second; oxygen concentration, 20.9 percent by volume; oxygen-nitrogen-mixture flow rate, 1.0 pound per second.

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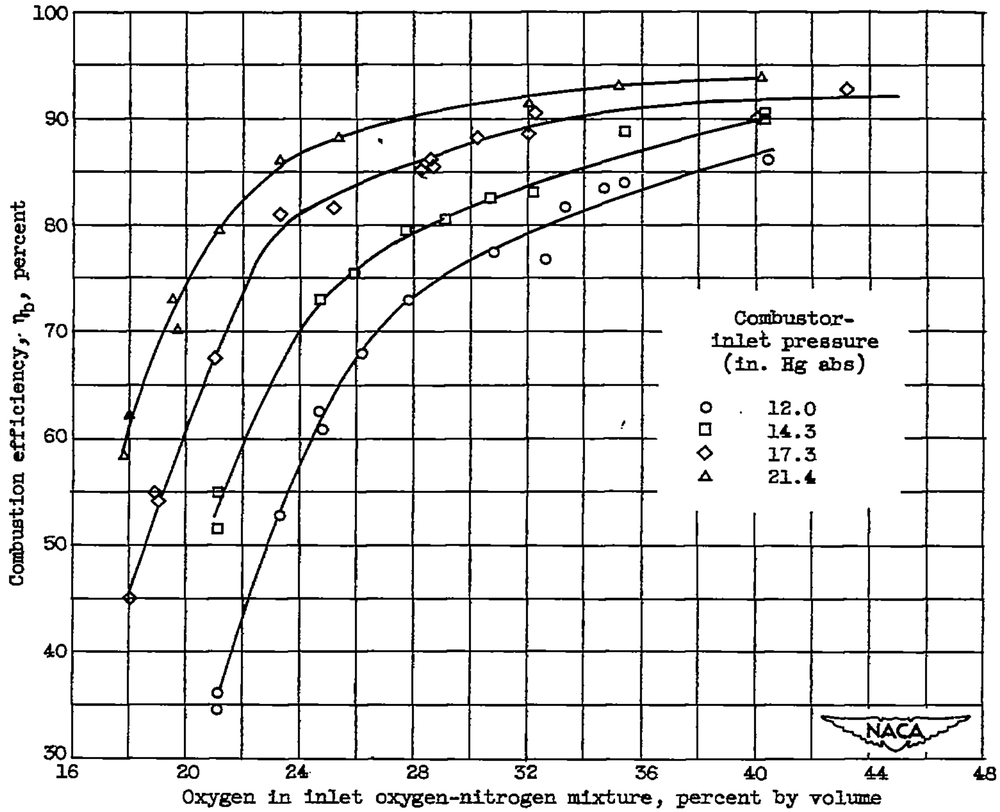

(a) Nominal fuel-flow rate, 0.0157 pound per second.

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

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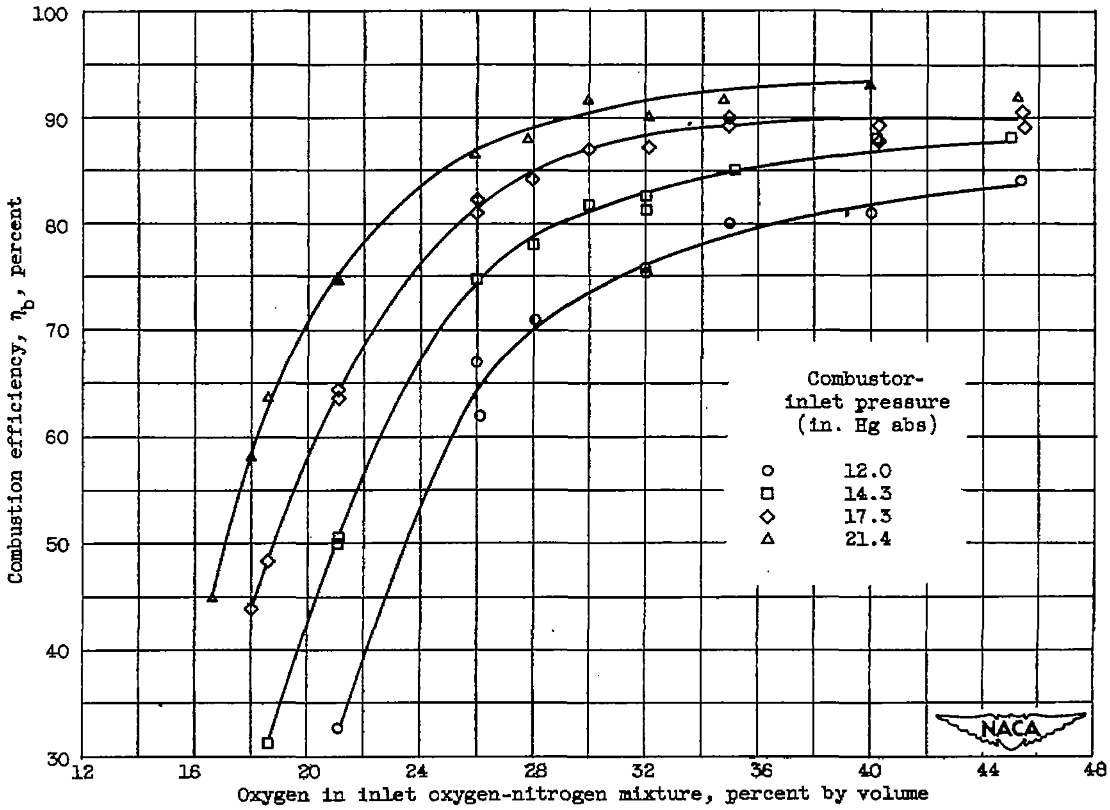
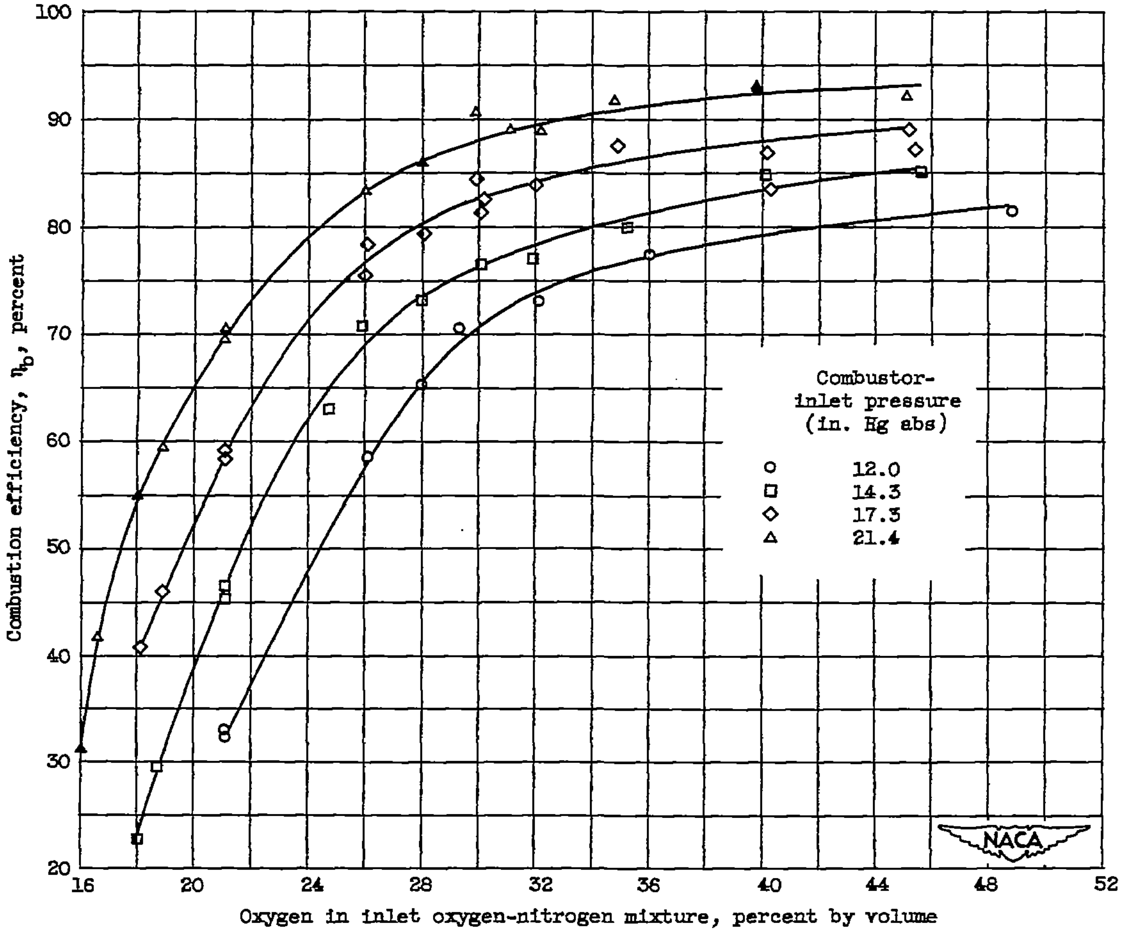


(b) Nominal fuel-flow rate, 0.014 pound per second.

Figure 4. - Continued. Effect of oxygen concentration of inlet oxygen-nitrogen mixture on combustion efficiency of a single J33 combustor over a range of inlet pressures and fuel-flow rates. Combustor inlet temperature, 40° F; oxygen-nitrogen mixture flow rate, 1.0 pound per second.



(c) Nominal fuel-flow rate, 0.012 pound per second.

Figure 4. - Continued. Effect of oxygen concentration of inlet oxygen-nitrogen mixture on combustion efficiency of a single J33 combustor over a range of inlet pressures and fuel-flow rates. Combustor inlet temperature, 40° F; oxygen-nitrogen mixture flow rate, 1.0 pound per second.

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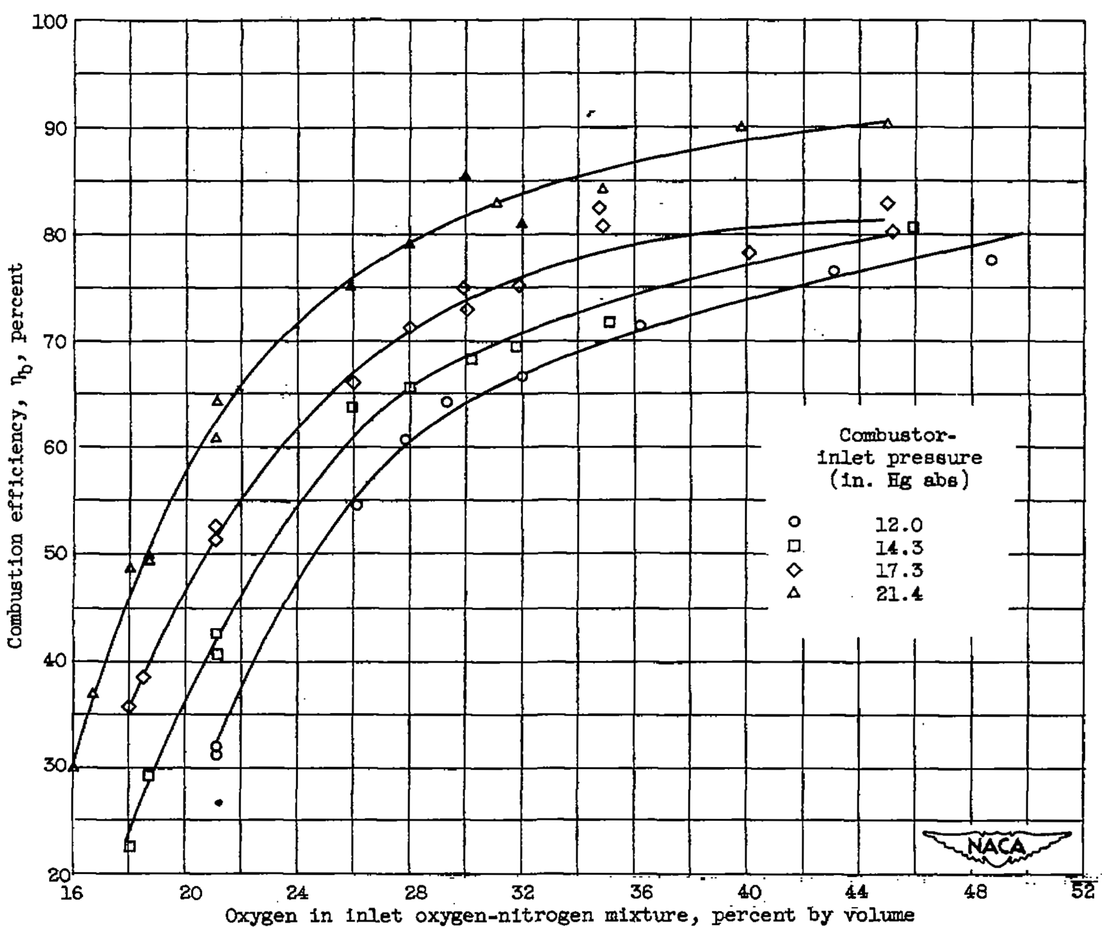
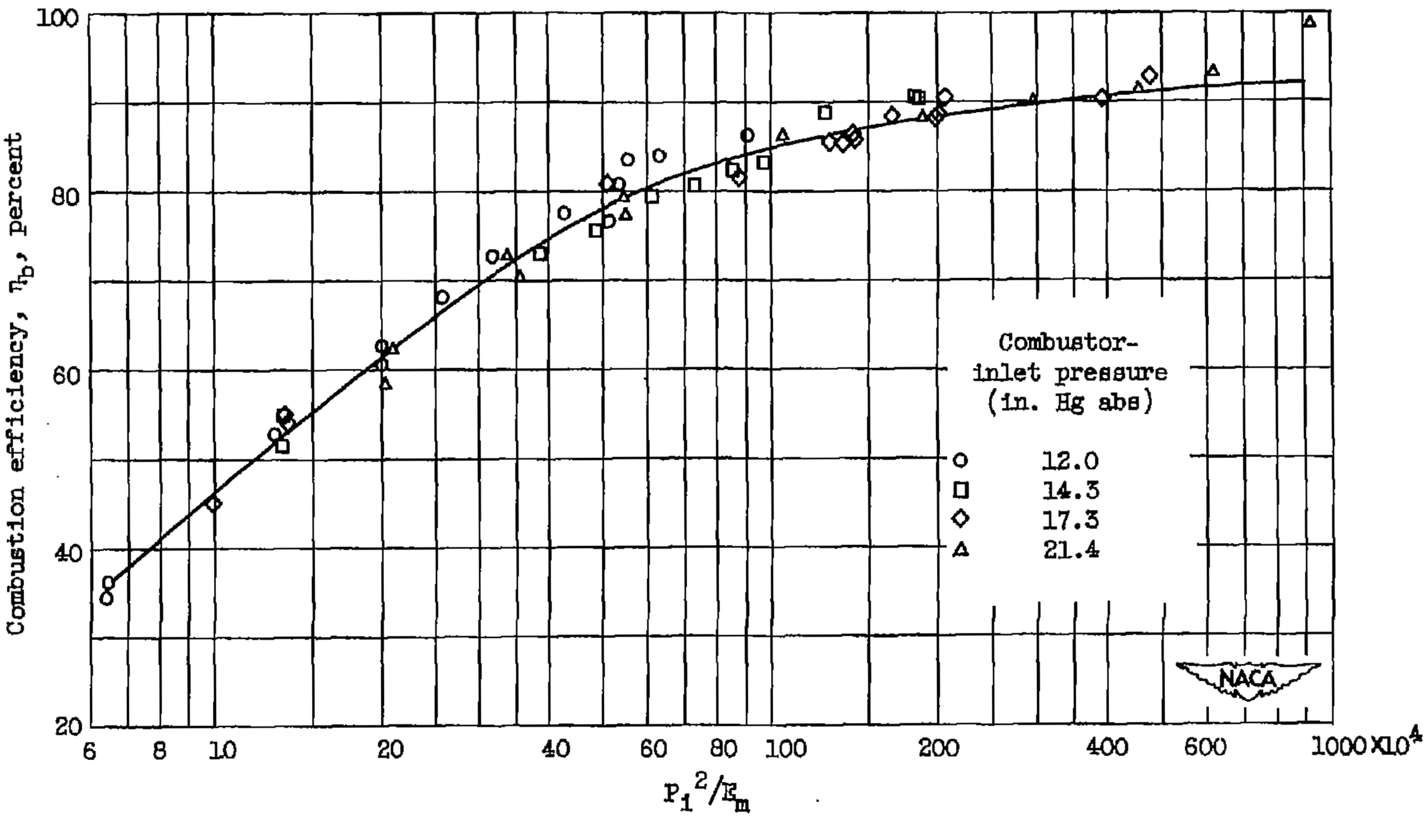


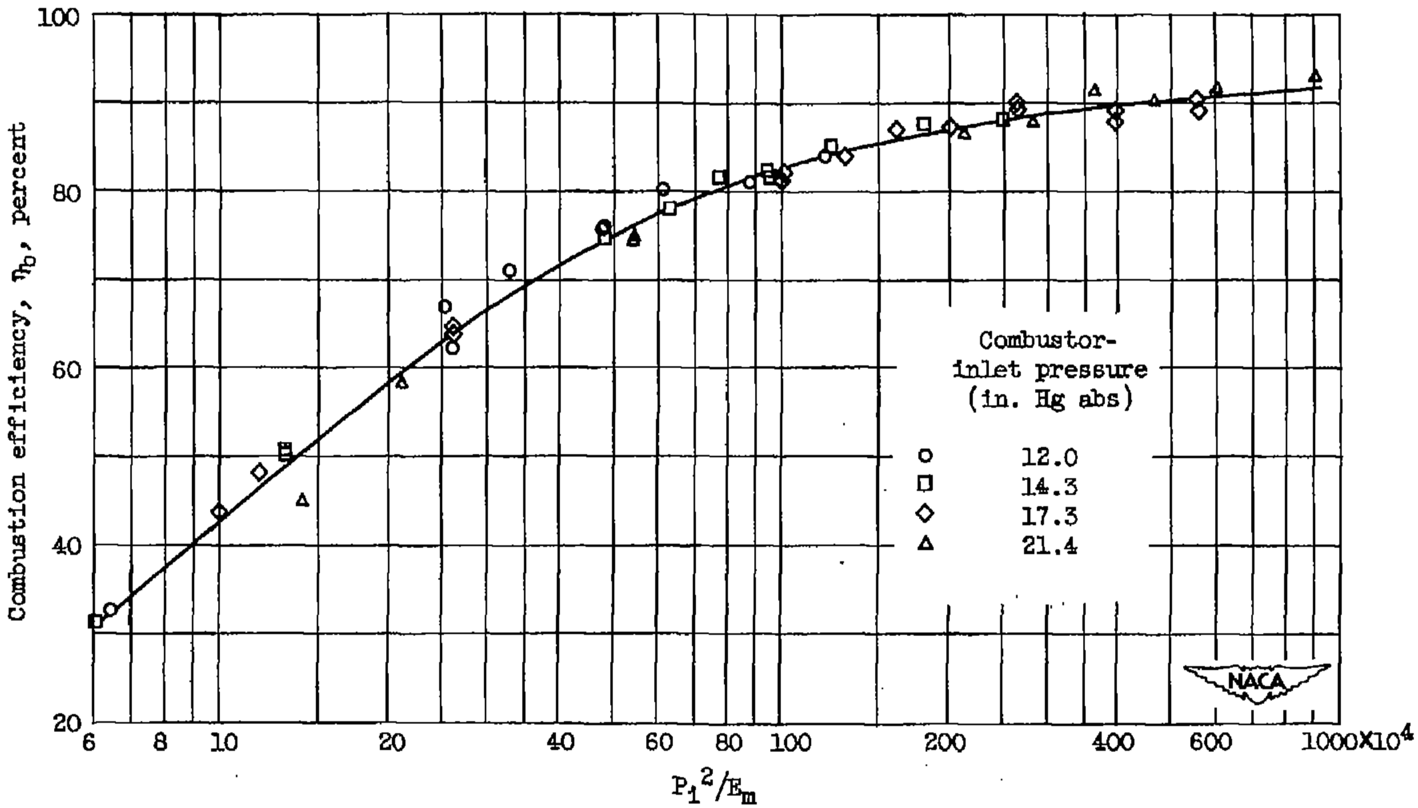
(d) Nominal fuel-flow rate, 0.010 pound per second.

Figure 4. - Concluded. Effect of oxygen concentration of inlet oxygen-nitrogen mixture on combustion efficiency of a single J33 combustor over a range of inlet pressures and fuel-flow rates. Combustor inlet temperature, 40° F; oxygen-nitrogen mixture flow rate, 1.0 pound per second.



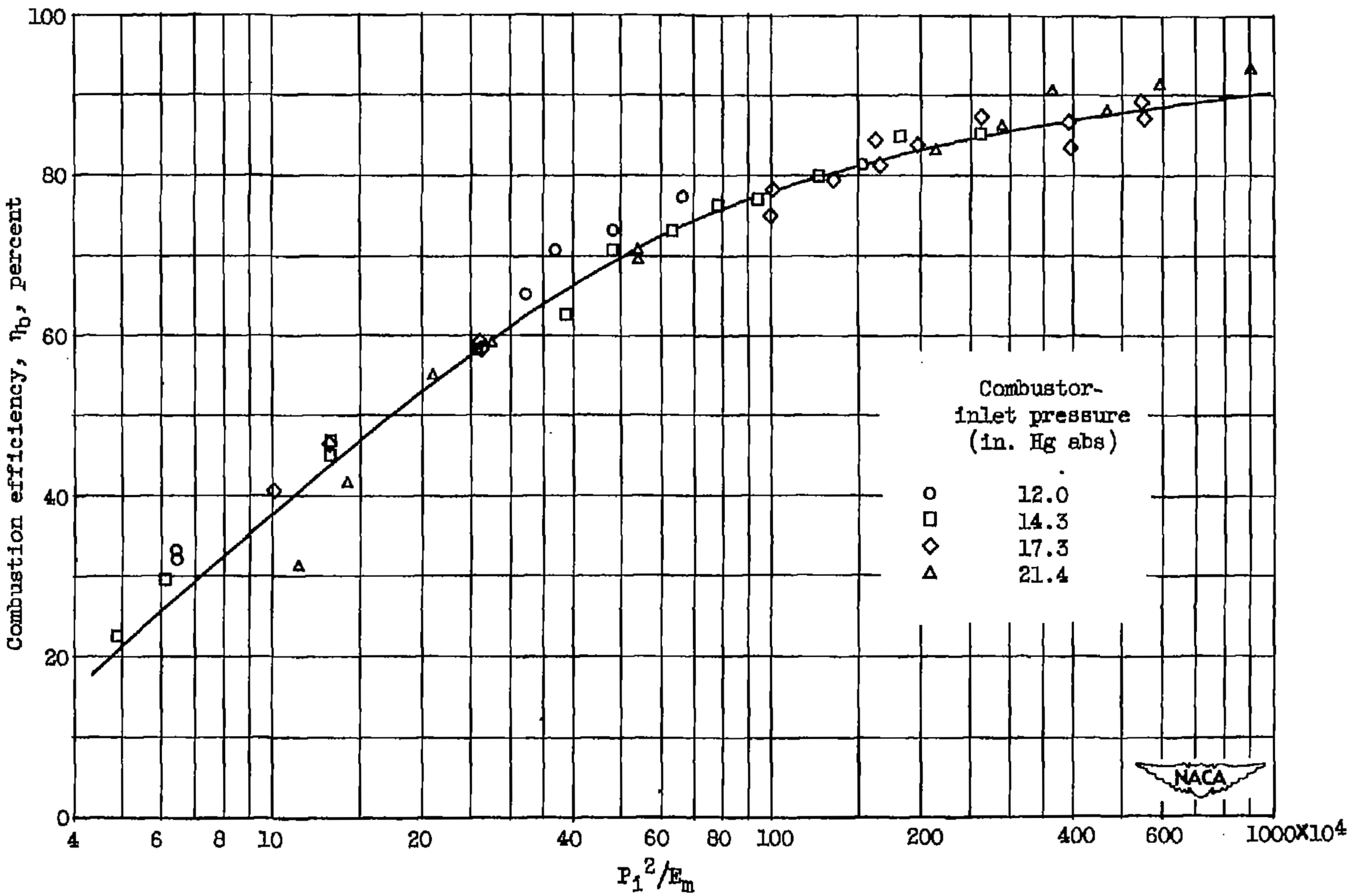
(a) Nominal fuel-flow rate, 0.0157 pound per second.

Figure 5. - Correlation of combustion efficiency of a single J33 combustor with a function of minimum spark-ignition energy and combustor-inlet pressure.



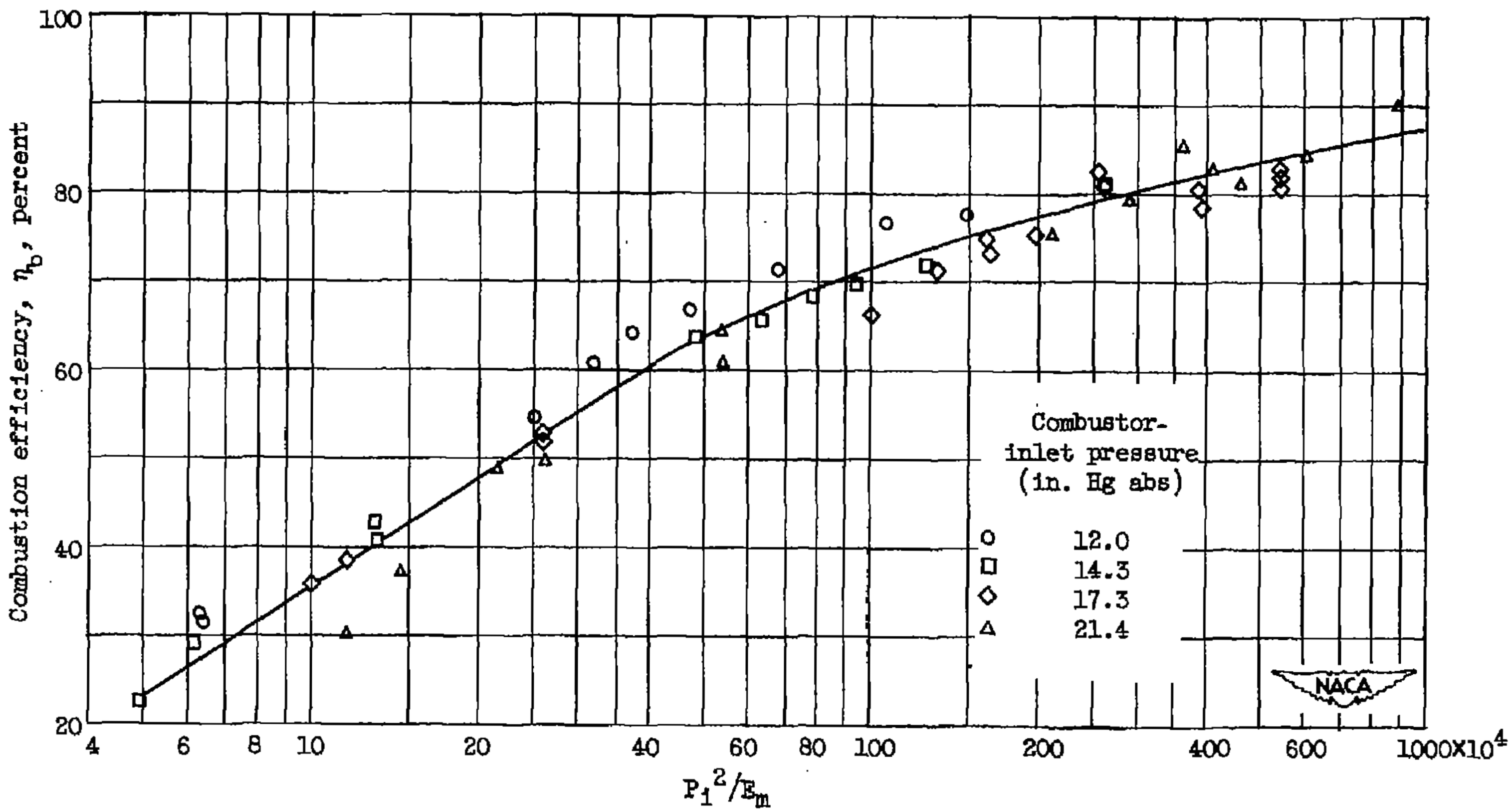
(b) Nominal fuel-flow rate, 0.014 pound per second.

Figure 5. - Continued. Correlation of combustion efficiency of a single J33 combustor with a function of minimum spark-ignition energy and combustor-inlet pressure.



(c) Nominal fuel-flow rate, 0.012 pound per second.

Figure 5. - Continued. Correlation of combustion efficiency of a single J33 combustor with a function of minimum spark-ignition energy and combustor-inlet pressure.



(d) Nominal fuel-flow rate, 0.010 pound per second.

Figure 5. - Concluded. Correlation of combustion efficiency of a single J33 combustor with a function of minimum spark-ignition energy and combustor-inlet pressure.

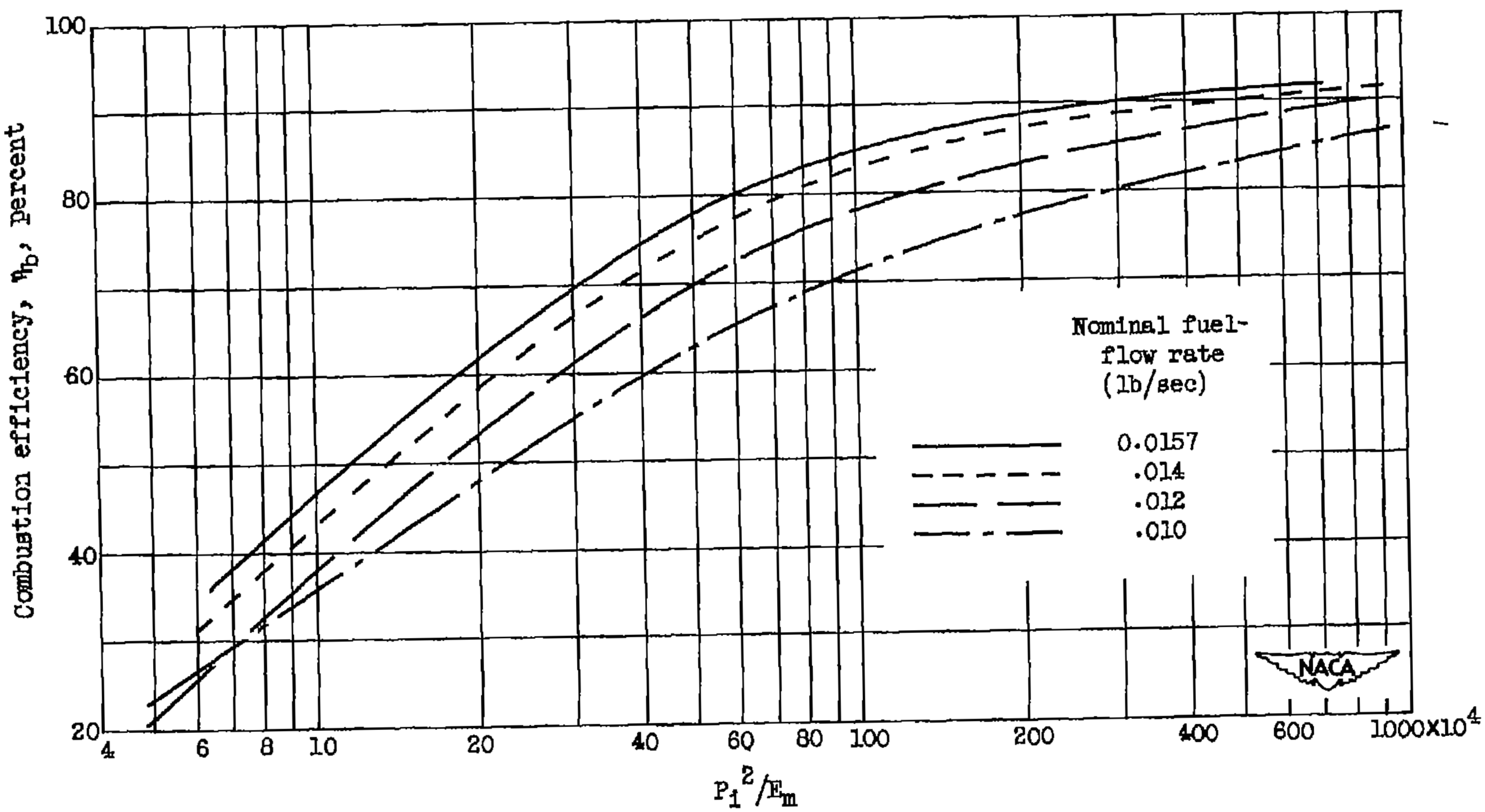
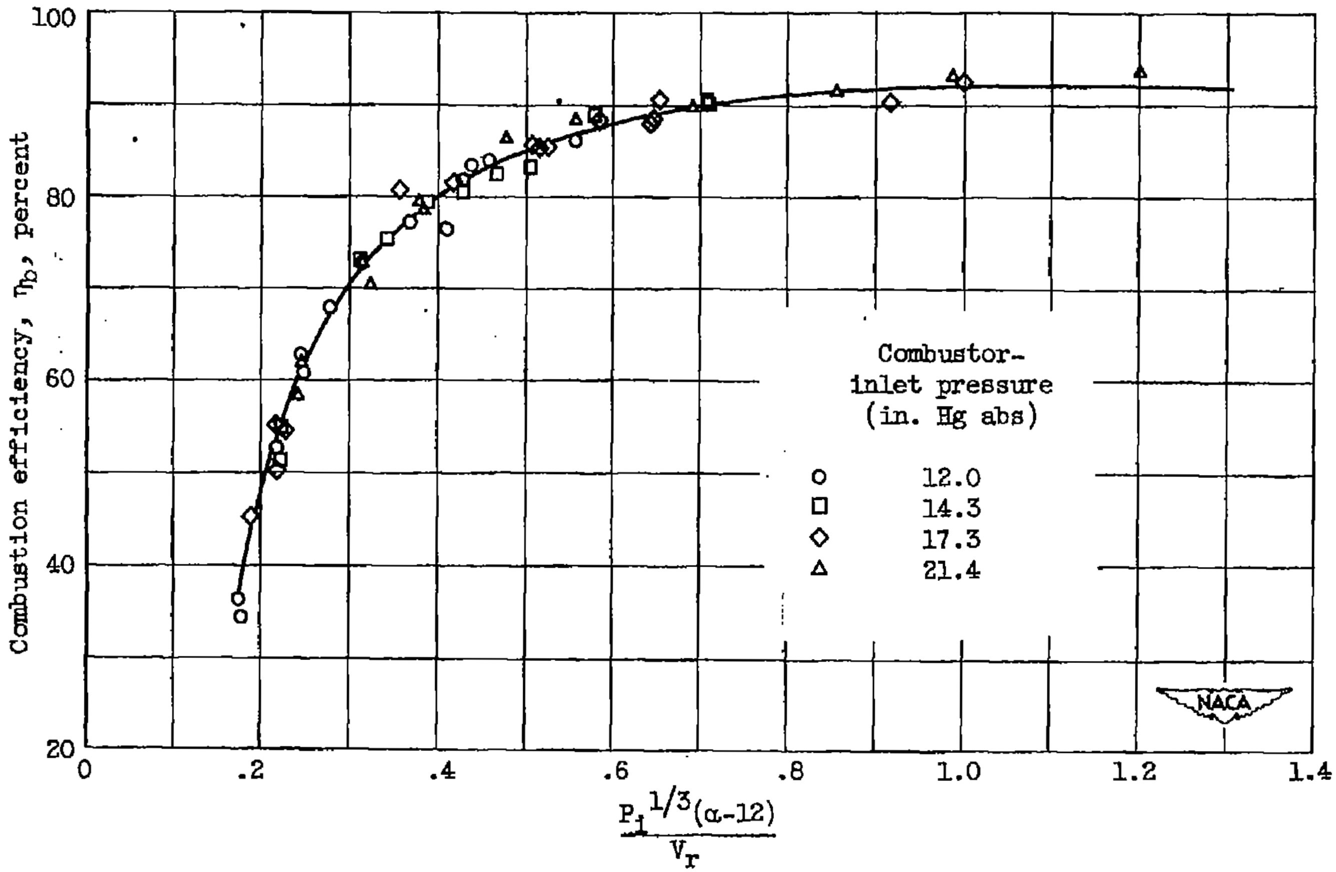
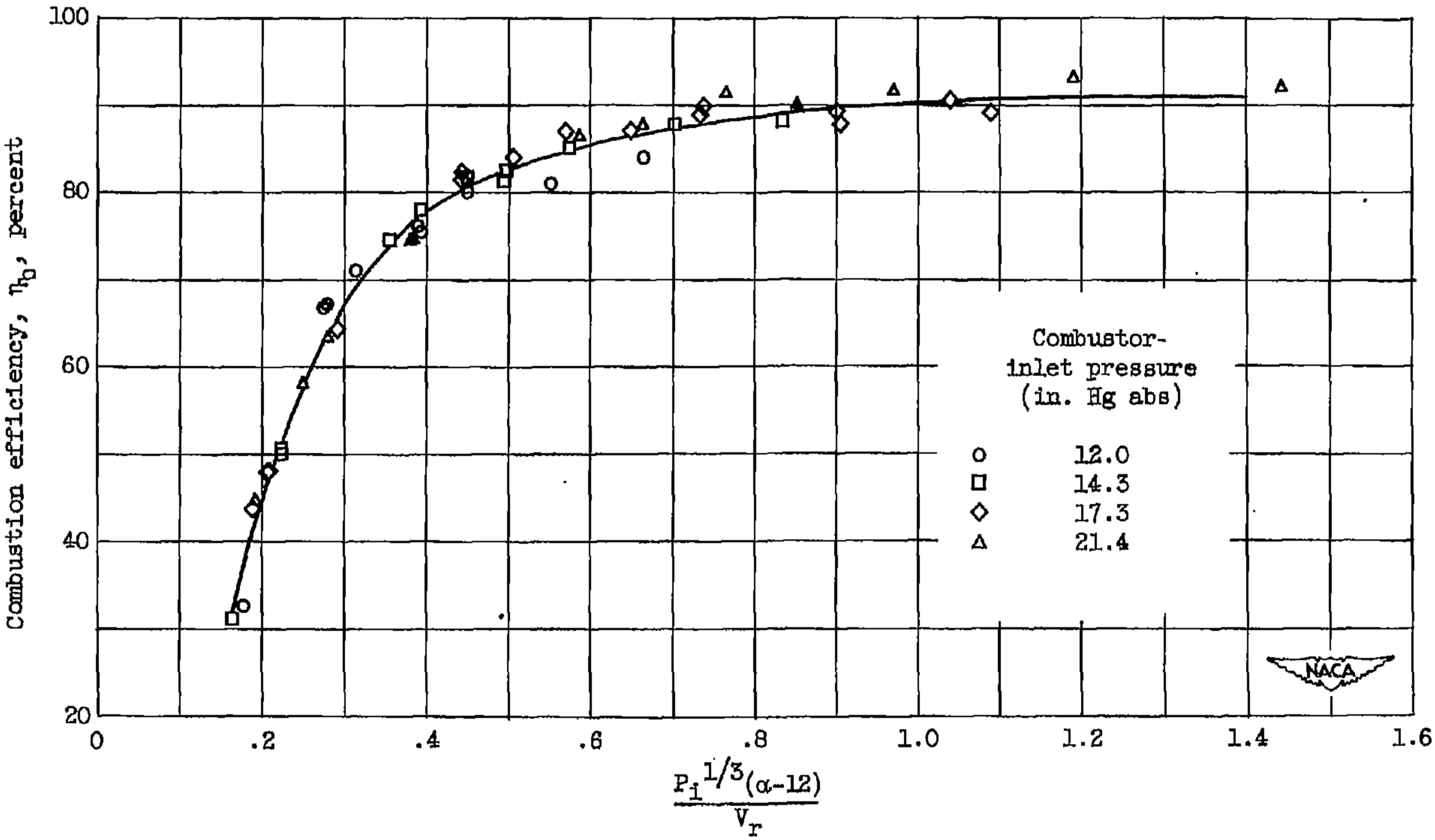


Figure 6. - Effect of fuel-flow rate on form of correlation curves. Correlation of combustion efficiency with function of minimum spark-ignition energy and combustor-inlet pressure.



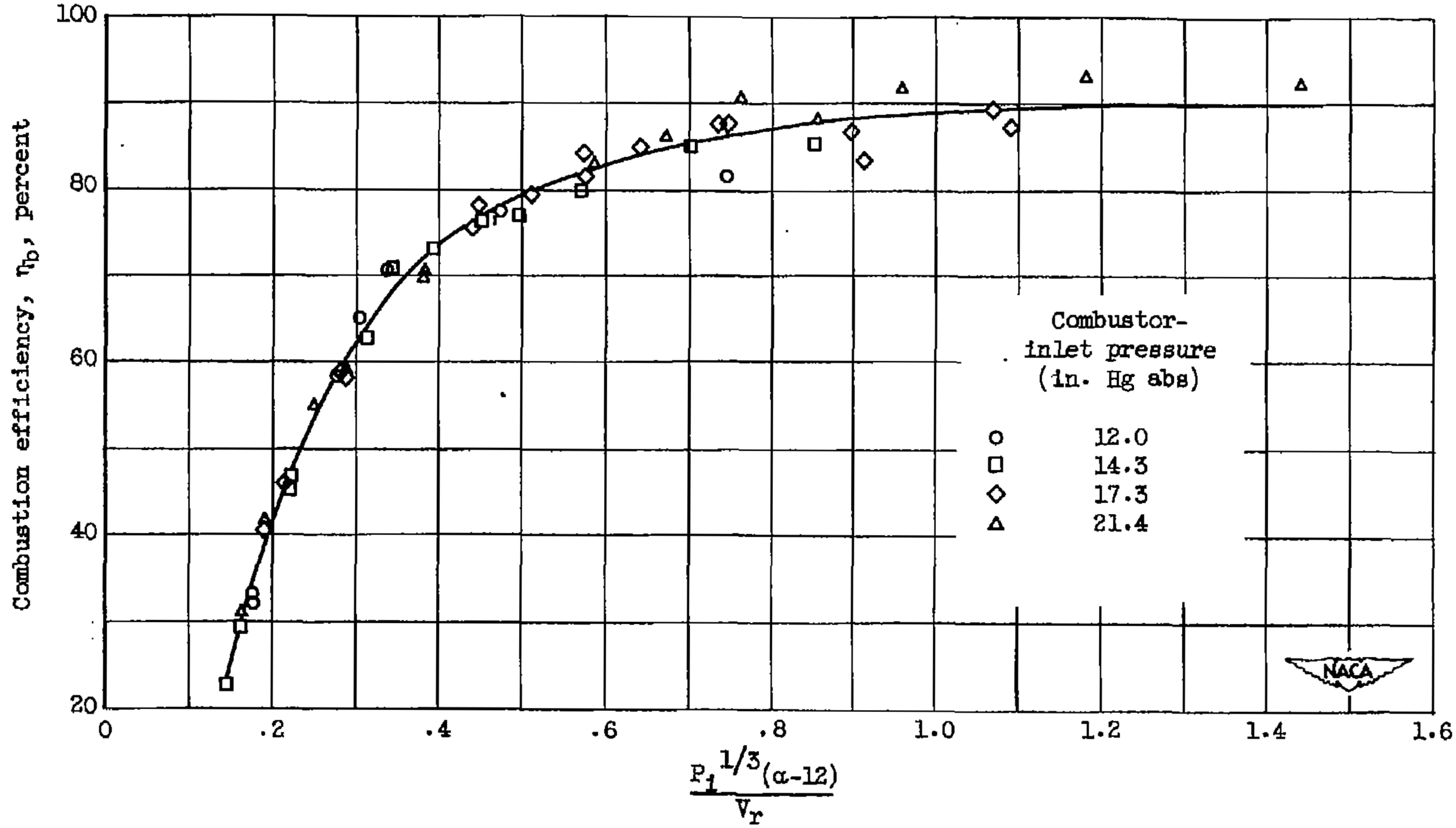
(a) Nominal fuel-flow rate, 0.0157 pound per second.

Figure 7. - Correlation of combustion efficiency of a single J33 combustor with flame-speed parameter.



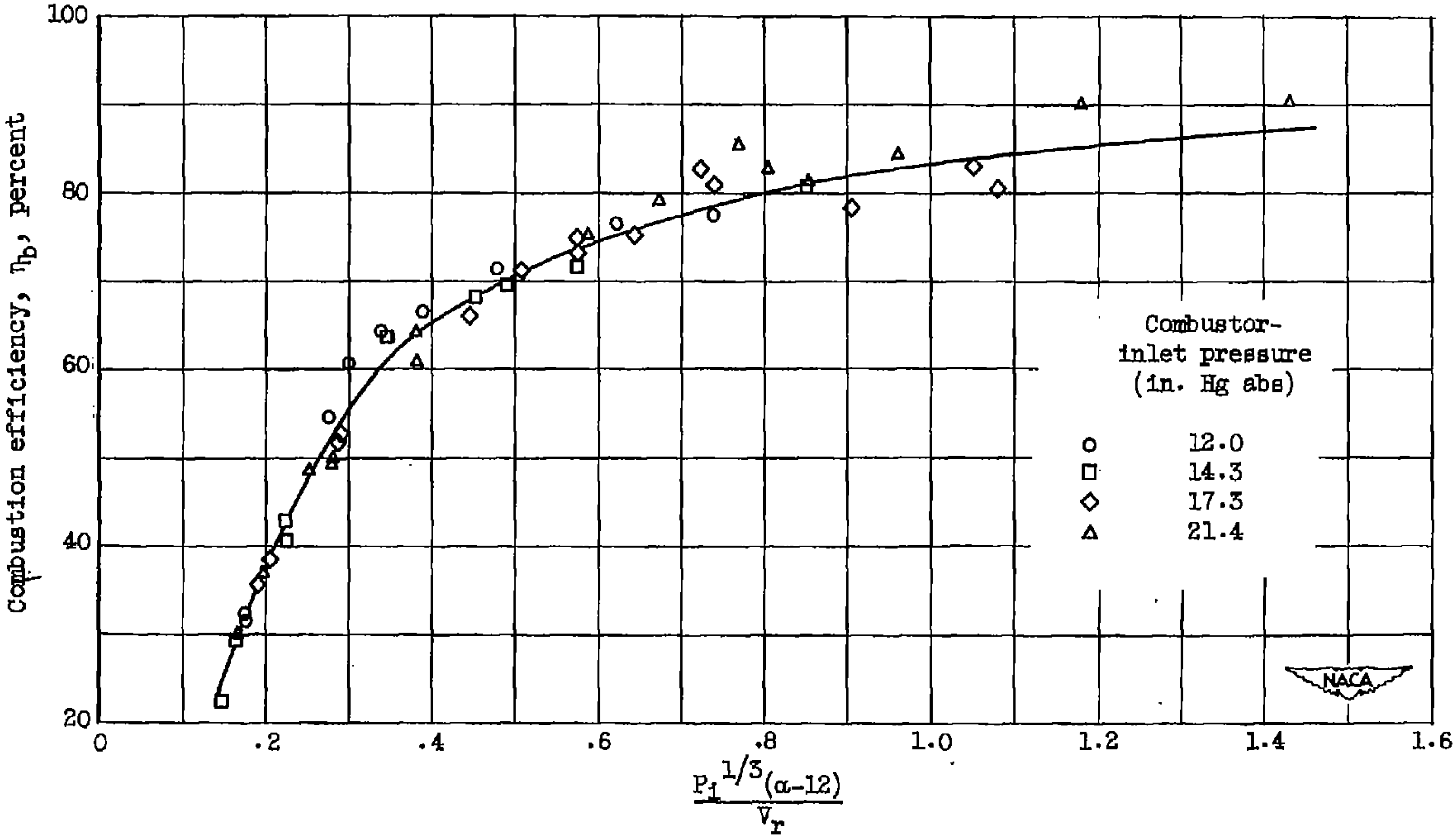
(b) Nominal fuel-flow rate, 0.014 pound per second.

Figure 7. - Continued. Correlation of combustion efficiency of a single J33 combustor with flame-speed parameter.



(c) Nominal fuel-flow rate, 0.012 pound per second.

Figure 7. - Continued. Correlation of combustion efficiency of a single J33 combustor with flame-speed parameter.



(d) Nominal fuel-flow rate, 0.010 pound per second.

Figure 7. - Concluded. Correlation of combustion efficiency of a single J33 combustor with flame-speed parameter.

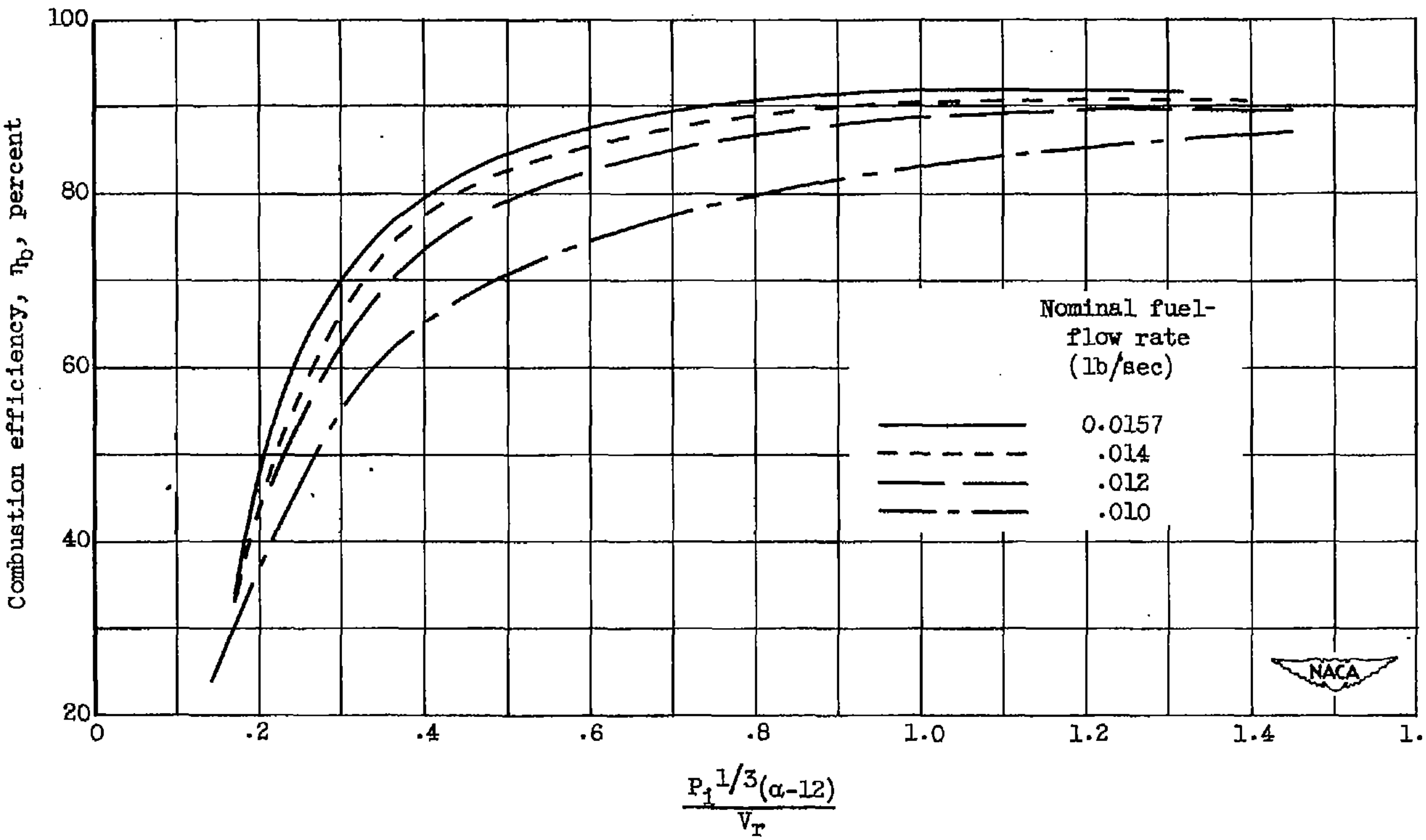
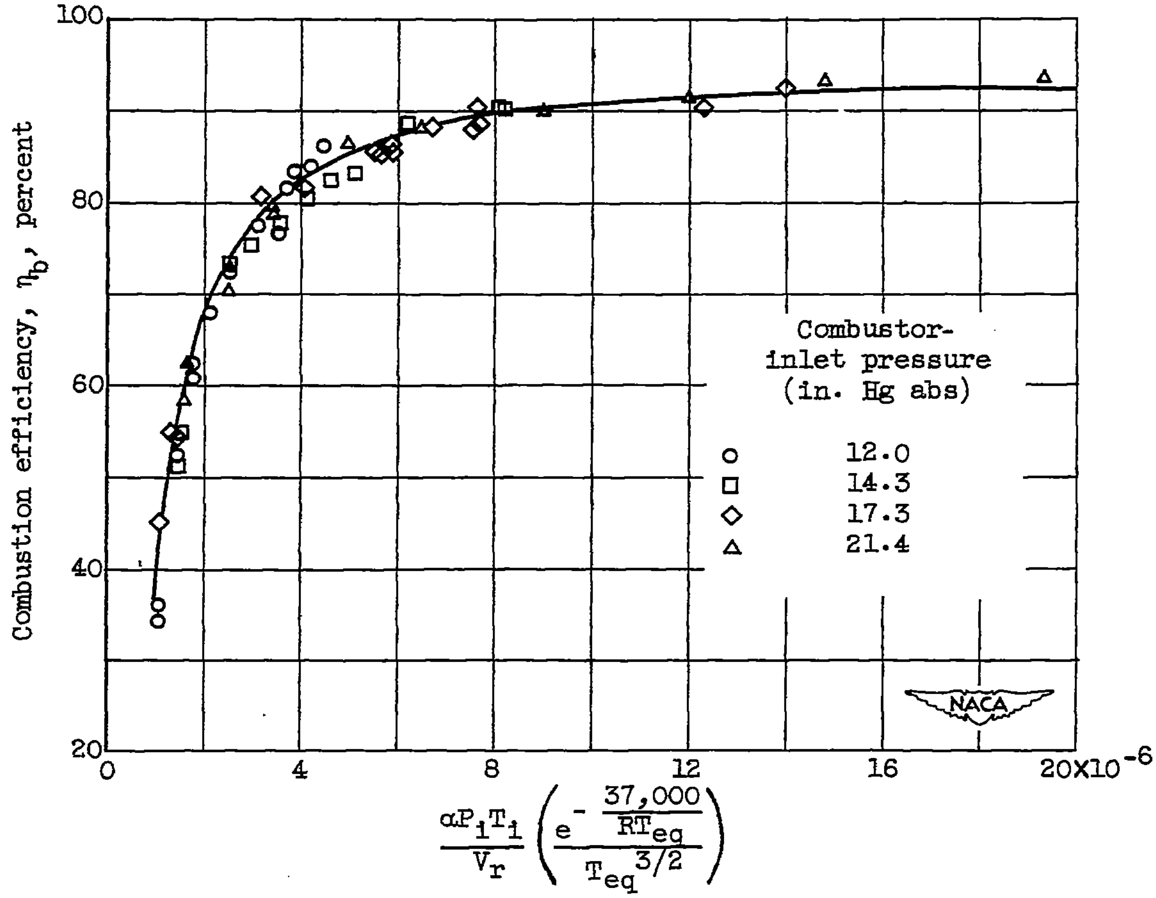
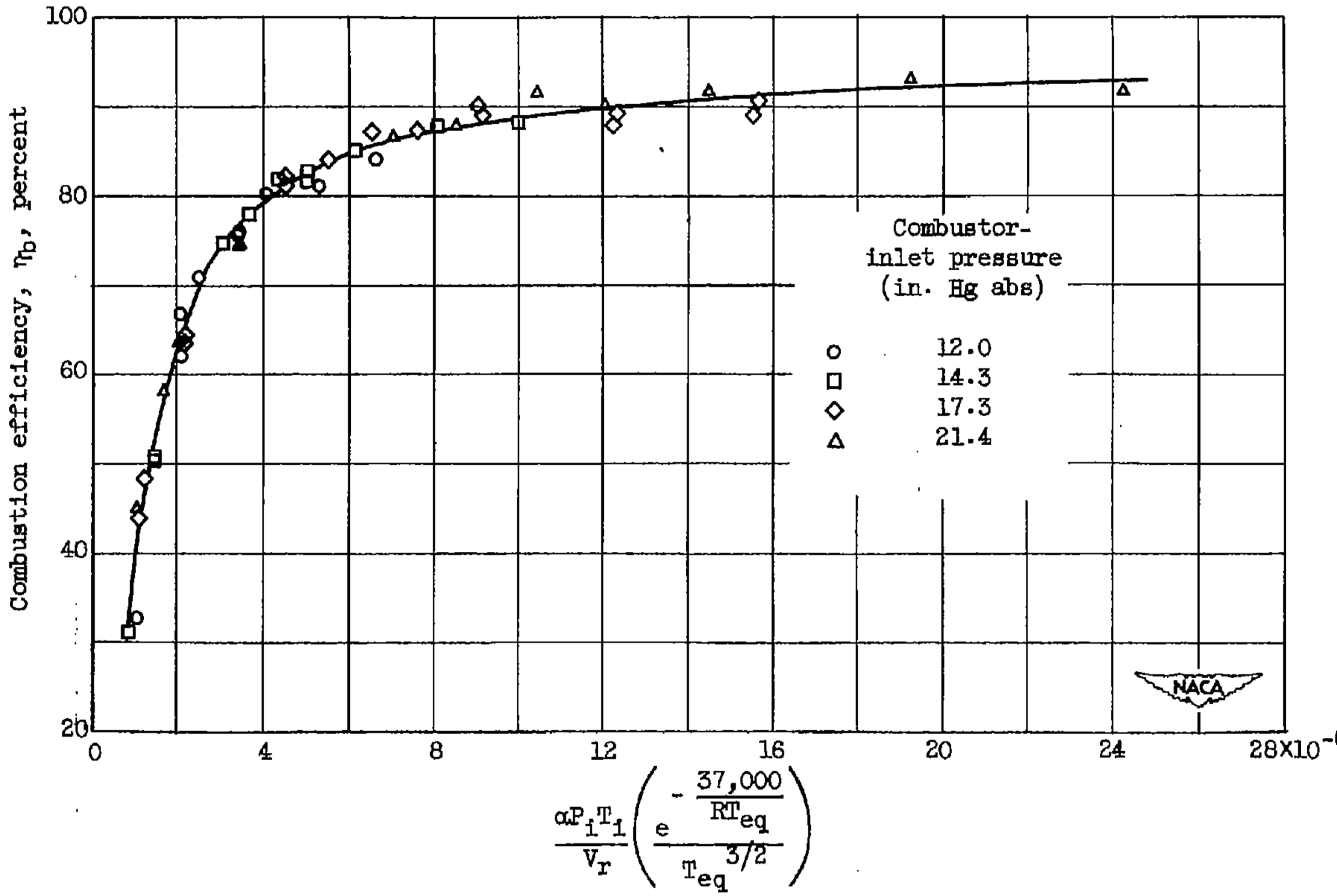


Figure 8. - Effect of fuel-flow rate on form of correlation curves. Correlation of combustion efficiency with flame-speed parameter.



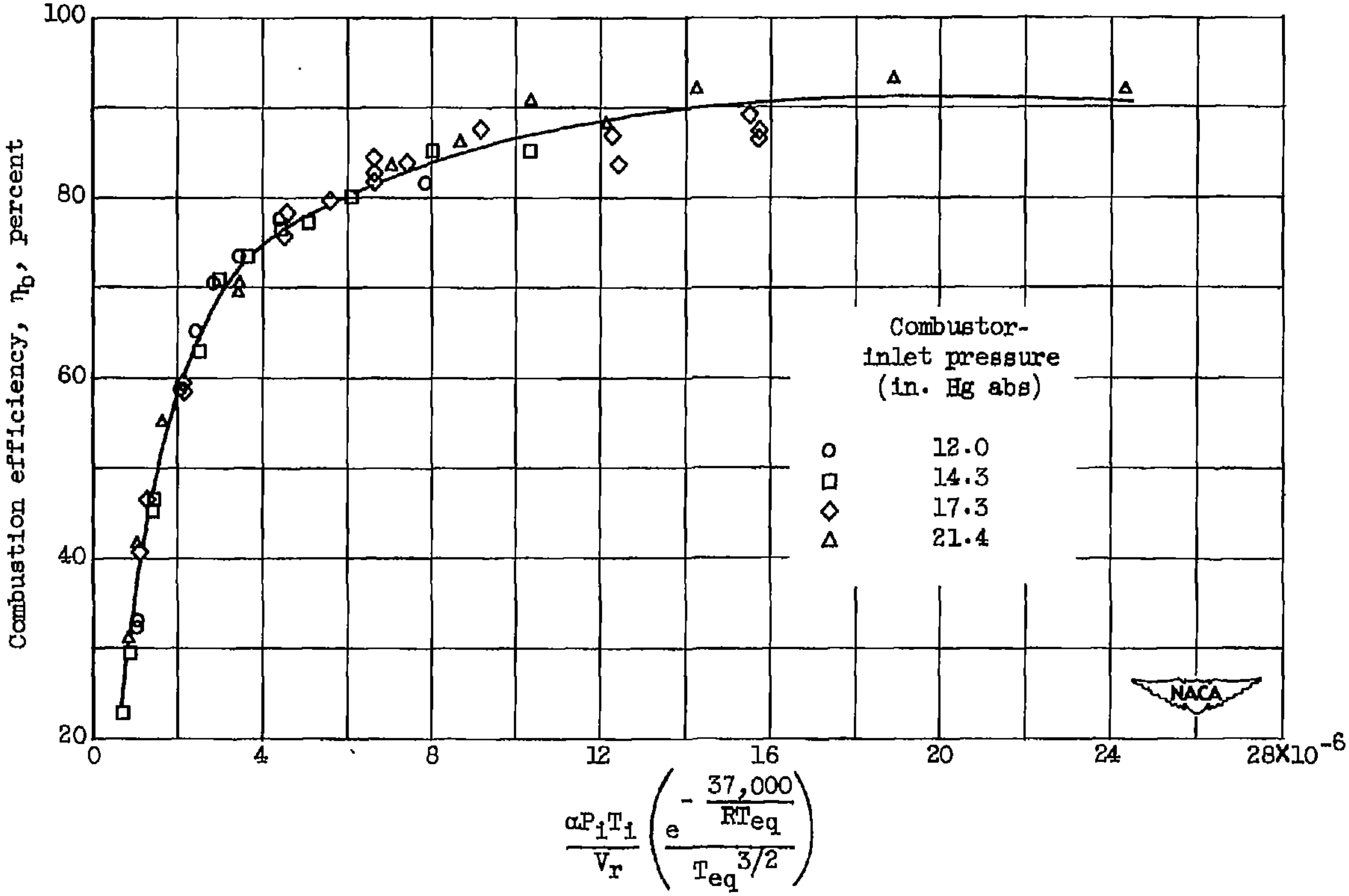
(a) Nominal fuel-flow rate, 0.0157 pound per second.

Figure 9. - Correlation of combustion efficiency of a single J33 combustor with second-order reaction-equation parameter.



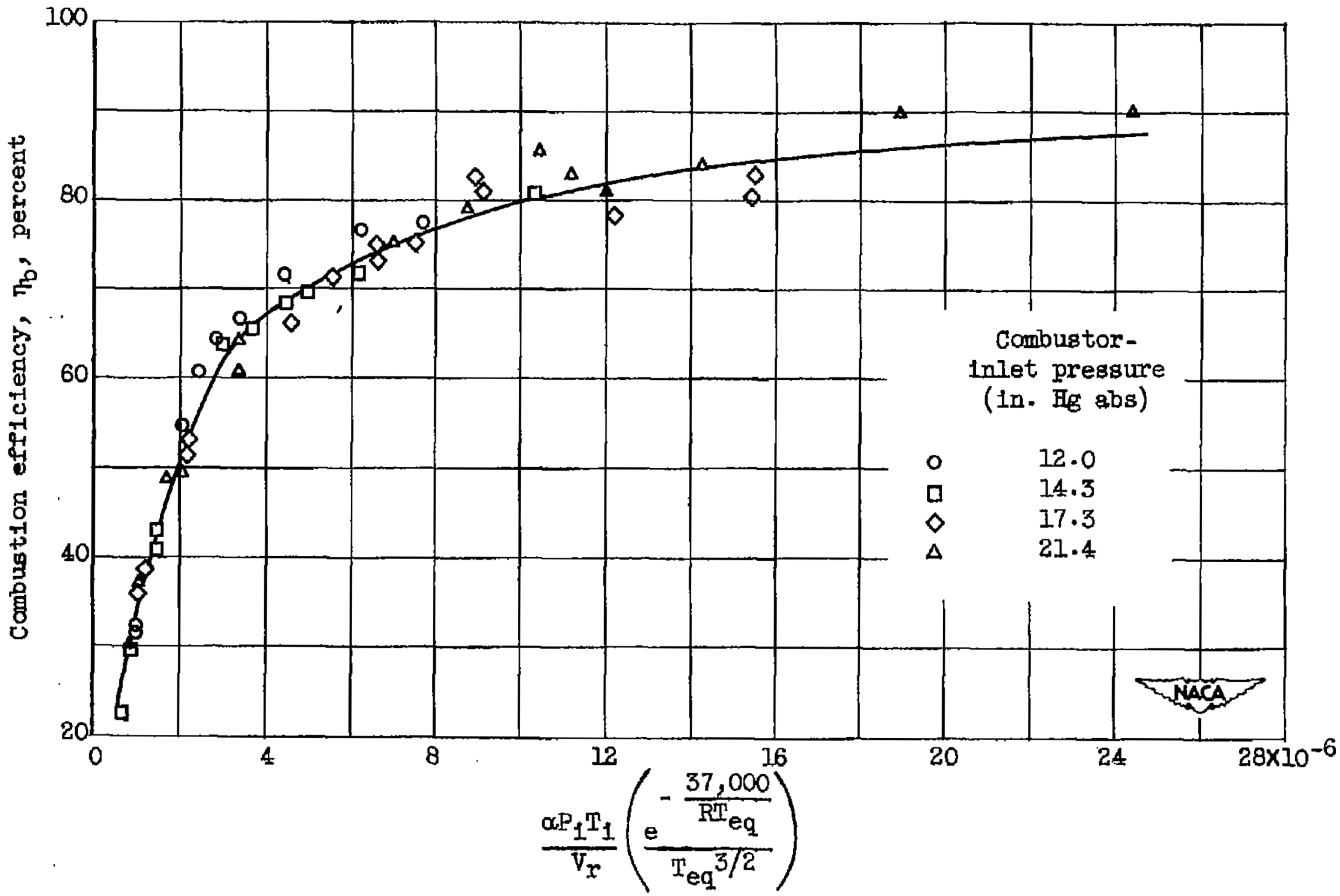
(b) Nominal fuel-flow rate, 0.014 pound per second.

Figure 9. - Continued. Correlation of combustion efficiency of a single J33 combustor with second-order reaction-equation parameter.



(c) Nominal fuel-flow rate, 0.012 pound per second.

Figure 9. - Continued. Correlation of combustion efficiency of a single J33 combustor with second-order reaction-equation parameter.



(d) Nominal fuel-flow rate, 0.010 pound per second.

Figure 9. - Concluded. Correlation of combustion efficiency of a single J33 combustor with second-order reaction-equation parameter.

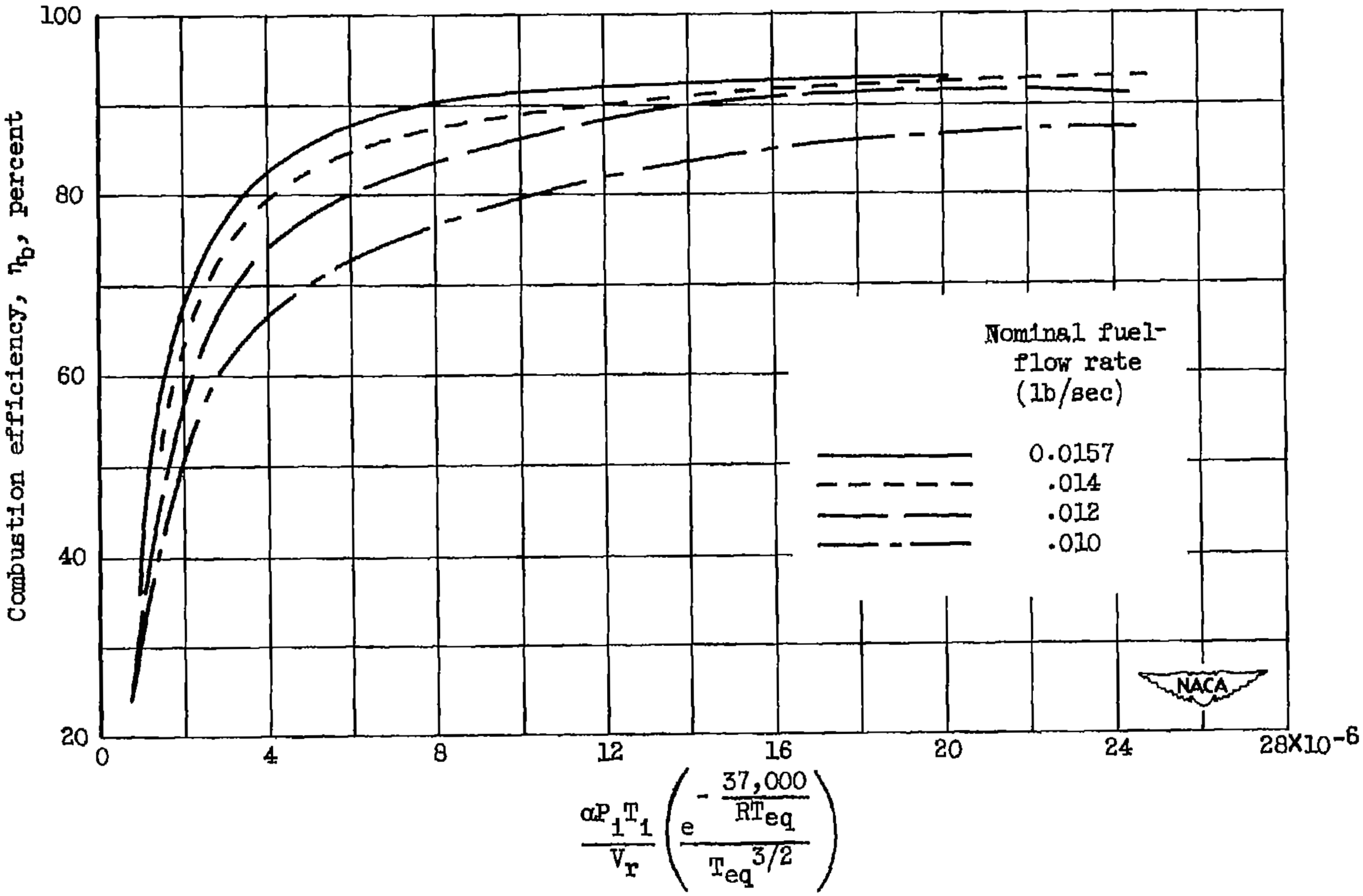


Figure 10. - Effect of fuel-flow rate on form of correlation curves. Correlation of combustion efficiency with second-order reaction-equation parameter.

SECURITY INFORMATION

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