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RESEARCH MEMORANDUM

ANALYSIS AND EXPERIMENTAL OBSERVATION OF PRESSURE LOSSES

IN RAM-JET COMBUSTION CHAMBERS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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ANALYSIS AND EXPERIMENTAL OBSERVATION OF PRESSURE LOSSES

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SUMMARY

Analyses were made to determine the effect of primary variables on pressure losses resulting from flame-holder drag and from heat addition in a ram-jet combustion chamber. A sudden-expansion flow-area theory for flame holders composed of a system of elements arranged approximately in a single plane is presented. From this theory, a reasonably accurate estimate of flame-holder pressure-drop coefficient was made that may be used in the design or estimation of performance of ram jets.

Experimental data on pressure losses resulting from the addition of heat in combustion chambers were obtained from wall-static-pressure measurements and indicate an appreciable deviation from the one-dimensional theoretical value of static-pressure-drop coefficient. A ratio of experimental to theoretical value of pressure-drop coefficient as large as 1.31 was obtained. The percentage difference between theoretical and experimental data varied with flame-holder design and combustion-chamber conditions.

INTRODUCTION

Knowledge of pressure losses within combustion chambers of ram jets is required in at least two important applications: (1) design and estimation of ram-jet performance; and (2) determination of combustion-gas temperature rise from a measurement of the drop in combustion-chamber static pressure, if direct temperature measurements are not feasible. The pressure losses in combustion chambers result primarily from the aerodynamic drag of flame holders and from the addition of heat to the gases.

Some experimental data on flame-holder pressure losses have been presented (references 1 to 4). A theoretical analysis that assumes a sudden enlargement of flow area was made at the NACA Lewis laboratory to determine the effect of flame-holder open area and

combustion-chamber-inlet Mach number on the pressure losses across
flame holders. The results of this analysis were then compared
with experimental data obtained with several different flame-holder
designs.

Theoretical analyses of pressure losses and velocity changes
due to heat addition in constant-area combustion chambers by assum-
ing one-dimensional frictionless flow are described in reference 5.
In order to determine the agreement of the results of the one-
dimensional theory (reference 5) with the results of experimental
ram-jet data, a comparison was made of the pressure-loss results of
this theory with pressure-loss data obtained from ram-jet-wall
static-pressure measurements.

SYMBOLS

The following symbols are used in this report:

A   cross-sectional area, square feet

C   total-pressure-drop coefficient

K   area-contraction coefficient

M   Mach number

m   mass flow rate, slugs per second

P   total pressure, pounds per square foot absolute

p   static pressure, pounds per square foot absolute

q   dynamic pressure, pounds per square foot

R   gas constant, foot-pounds per $^{\circ}F$ per pound

T   total temperature, $^{\circ}R$

t   static temperature, $^{\circ}R$

V   velocity, feet per second

γ ratio of specific heat at constant pressure to specific
        heat at constant volume

1187

ρ   density, slugs per cubic foot

Subscripts:

1   combustion-chamber inlet

2   combustion-chamber outlet

f   flame-holder station

v   vena-contracta station

PRESSURE LOSSES DUE TO FLAME-HOLDER DRAG

Theoretical Analysis

Flame holders used in ram-jet combustion chambers are designed to create turbulent and eddying motions in the gas stream. This condition is generally accomplished by a device such as a system of gutters, flat plates, cones, and similar elements that provide a sudden enlargement of flow area into which the air stream expands.

An idealized concept of the flow conditions about flame holders composed of elements approximately in a single plane is shown in figure 1. The area of the vena contracta (station v) is the product of the flame-holder open area A_f and the area-contraction coefficient K. This coefficient is primarily dependent on the shape of the approach to the enlargement section (stations 1 to f). In general, a decrease in the value of the contraction coefficient is obtained with an increase in the abruptness of the area contraction from stations 1 to f.

In this analysis, the method of calculating pressure losses resulting from sudden expansion of flow area has been applied. From the considerations of conservation of mass, energy, and momentum, the following equations (derived in the appendix) can be stated, which relate the total-pressure ratio across a flame holder to the effective open-area of the flame holder $K(A_f/A_1)$ and the combustion-chamber-inlet Mach number M_1. The friction losses along the surfaces of the flame holder are small and have been neglected.

The following expression, derived in the appendix as equation (A3), is obtained from the conservation of mass and energy between stations v and 2:

$$\frac{P_2}{P_1} = K \frac{A_f}{A_1} \frac{M_v}{M_2} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_v^2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

where KA_f equals A_v.

A second expression describing the flow conditions about a flame holder, as illustrated in figure 1, is furnished from the conservation of momentum assuming A_2 equal to A_1 and from the conservation of mass and energy. (See equation (A5).) Thus

$$M_2^2 = \frac{P_1}{P_2} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_v^2} \right)^{\frac{\gamma}{\gamma-1}} \left(K \frac{A_f}{A_1} M_v^2 + \frac{1}{\gamma} \right) - \frac{1}{\gamma} \tag{2}$$

Equations (1) and (2) assume the existence of adiabatic flow.

The third expression relating M_v to the combustion-chamber-inlet Mach number M_1 is obtained from a statment of the conservation of mass and energy between stations 1 and v, assuming the existence of isentropic flow. (See equation (A6).) Thus

$$K \frac{A_f}{A_1} = \frac{M_1}{M_v} \left(\frac{1 + \frac{\gamma-1}{2} M_v^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{3}$$

From a graphic simultaneous solution of equations (1), (2), and (3), the total-pressure ratio across the flame holder P_2/P_1 can be solved in terms of the effective open-area ratio of the flame holder $K(A_f/A_1)$ and the combustion-chamber-inlet Mach number M_1. A parameter more commonly used to express the total-pressure drop across a flame holder, however, is the total-pressure-drop coefficient C. A general expression relating C to M_1, in terms of the total-pressure ratio between stations 1 and 2, can be derived from the definition of C. Thus

$$C = \frac{P_1 - P_2}{q_1} \tag{4a}$$

or

$$C = \left(1 - \frac{P_2}{P_1}\right) \frac{\left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma}{\gamma-1}}}{\frac{1}{2} \gamma M_1^2} \tag{4b}$$

The solution of equation (4b) by using values of P_2/P_1 obtained from equations (1), (2), and (3) is plotted in figure 2 as the variation of C with M_1 and $K(A_f/A_1)$ for γ equals 1.4. A plot of equation (4b) is also presented in figure 3 and can be used to determine values of P_2/P_1 for various values of C and M_1.

Experimental Evaluation of Area-Contraction Coefficient

Use of figure 2 requires the selection of a value of the area-contraction coefficient K that can be experimentally determined. The variation of K as a function of M_1 for various flame-holder designs (fig. 4) with elements approximately in a single plane normal to the direction of air flow are presented in figures 5 and 6. The values of K were computed from experimentally determined values of M_1, C, and A_f/A_1 (figs. 5(b) and 6(b)) and the theoretical curves presented in figure 2. The flame holders studied include: (1) designs having approximately the same values of A_f/A_1, but various sizes, shapes, and arrangements of flame-holder elements (figs. 4(a), 4(b), and 4(e) to 4(g)); and (2) designs having the same elements in a similar arrangement but different values of A_f/A_1 (figs. 4(e) and 4(h)). Values of A_f/A_1 range from 0.70 for a cone-type flame holder (fig. 4(c)) to 0.46 for two gutter-grid flame holders (figs. 4(f) and 4(g)).

Experimental data indicated that a reasonably accurate estimate of pressure-drop coefficient could be made from the sudden-expansion flow-area theory if a value of area-contraction coefficient between 0.8 and 0.9 was assumed. Only slight variation of K with M_1 over a range of M_1 from about 0.06 to 0.20 was obtained for the different

flame holders studied (figs. 5(a) and 6(a)). The average value of K for an annular-V-gutter flame holder with a three-row series of 1/4-inch perforations in the annular gutters was about 0.95. This computed value of K is larger than the values obtained for the other flame holders, presumably because the projected open area of the perforations was not included in the measurements of the flame-holder open area A_f.

Another type of flame holder in use consists of a complex arrangement of gutters, plates, cones, and similar elements located in several staggered planes. The pressure-drop coefficient for such flame holders cannot be determined from the theory presented for the single-plane flame holders.

PRESSURE LOSSES DUE TO HEAT ADDITION

Theory

The equations that follow (derived in reference 5) describe the changes in pressure and velocity occurring in a one-dimensional non-viscous gas stream flowing in a constant-area combustion chamber to which heat is added. Heat is first added after station 1 in such a manner that the total temperature of the fluid remains uniform over the cross section of the combustion chamber. In the same manner, additional heat is gradually added as the gas stream flows through the combustion chamber to station 2.

From reference 5, the variation of combustion-chamber-outlet Mach number M_2 with combustion-chamber-inlet Mach number M_1 and total-temperature ratio T_2/T_1 is given by the following expression:

$$\left(\frac{R_2}{R_1}\right)\left(\frac{T_2}{T_1}\right) = \left(\frac{M_2}{M_1}\right)^2\left(\frac{\gamma_2}{\gamma_1}\right)\left(\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2 M_2^2}\right)^2\left(\frac{1 + \frac{\gamma_2-1}{2} M_2^2}{1 + \frac{\gamma_1-1}{2} M_1^2}\right) \quad (5)$$

Equation (5) was derived from equations of the conservation of mass and momentum between stations 1 and 2. The expression for the static-pressure-drop coefficient of the gas stream, given in reference 5 in terms of the combustion-chamber-inlet and outlet Mach numbers and the ratio of the specific heats at the combustion-chamber inlet and outlet, is

$$\frac{p_1 - p_2}{q_1} = 2 \left(\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2 M_2^2} \right) \left(\frac{M_2^2 \gamma_2}{M_1^2 \gamma_1} \right) - 2 \qquad\qquad (6)$$

This expression was derived from the conservation of momentum.

The solution of equation (5) is plotted in figure 7 and gives the graphic variation of M_2 with M_1 and $(R_2/R_1)(T_2/T_1)$ for γ_1 equals 1.4 and γ_2 equals 1.3. When the values of M_2 from figure 7 are substituted in equation (6) and the expression solved, the variation of $(p_1 - p_2)/q_1$ with M_1 and $(R_2/R_1)(T_2/T_1)$ for γ_1 equals 1.4 and γ_2 equals 1.3 can be obtained (fig. 8). A similar curve in terms of the total-pressure loss is given in reference 5.

Although the foregoing equations have assumed a one-dimensional nonviscous gas stream in the combustion chamber, the same variables might describe the pressure losses due to only heat addition in combustion chambers in which the flow is viscous and three dimensional. It should not be expected, however, that the quantitative values predicted by equations (5) and (6) will necessarily apply.

Comparison with Experiment

A comparison of experimental data obtained from a typical 20-inch ram-jet configuration for different burners with the theoretical curves in figure 8 is presented in figure 9. The static-pressure-drop coefficient across the combustion chamber is plotted as a function of the total-temperature ratio across the combustion chamber. In each case, the cold static-pressure-drop coefficient of the flame holder is not included as a portion of the combustion-chamber static-pressure-drop coefficient. The values of the combustion-chamber-inlet Mach number for the data points are also given in figure 9.

The data in figures 9(a) to 9(c) were obtained with a ram jet having a 5-foot combustion chamber and a 2-foot converging exhaust nozzle. Data for a similar ram jet having an 8-foot combustion chamber and a 2-foot converging exhaust nozzle are presented in figure 9(d). The drop in static pressure through the exhaust nozzle was not included in the computation of the static-pressure-drop coefficient.

The experimental data show an appreciable deviation from the theoretical value of pressure-drop coefficient. For example, the

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maximum ratio of experimental to theoretical value of pressure-drop coefficient ranged from 1.15 for a configuration with a flame-holder open-area ratio of 0.64 at T_2/T_1 equals 3.2 and M_1 equals 0.129 to a value of 1.31 for a configuration with a flame-holder open-area ratio of 0.49 at T_2/T_1 equals 5.9 and M_1 equals 0.141 (figs. 9(a) and 9(d)). As indicated in figure 9, the percentage difference between theoretical and experimental data will vary with flame-holder design and combustion-chamber flow conditions. The differences between theoretical and experimental values of $(p_1-p_2)/q_1$ presumably result from: (1) the possible existence of a nonuniform static-pressure profile over the combustion-chamber cross section due to tangential and radial velocity components; (2) the effects of a three-dimensional combustion-chamber-inlet flow pattern introduced primarily by the flame holder; and (3) the effect of the pattern of heat addition throughout the combustion chamber.

Thus, the one-dimensional, compressible, nonviscous flow theory applied to an analysis of combustion-chamber pressure changes result-ing from the addition of heat to the flowing gases gives values of pressure losses that may be sufficiently accurate for use in designing ram-jet combustion chambers. An appreciable error in the determi-nation of T_2/T_1, however, may result if this quantity is obtained from an experimental measurement of the drop in wall static pressures along the combustion chamber as given by this theory. Application of the theoretical analysis to a ram-jet temperature-rise meter or fuel-metering control by proper calibration of the instrument may be accomplished, as shown in reference 4.

SUMMARY OF RESULTS

From a theoretical and experimental study of pressure losses in ram-jet combustion chambers resulting from flame-holder drag and from heat addition, the following results were obtained:

1. A reasonable estimate of flame-holder pressure-drop coefficient for flame holders composed of a system of elements approximately in a single plane was made from the sudden-expansion flow-area theory. Quantities required for the estimate were the flame-holder open-area ratio, the combustion-chamber-inlet Mach number, and a value of area-contraction coefficient experimentally found to be between 0.8 and 0.9.

2. Experimental data on wall-static-pressure losses due to heat addition indicated an appreciable deviation from the theoretical value of pressure-drop coefficient. A ratio of the experimental to the theoretical value of pressure-drop coefficient as large as 1.31 was obtained. The percentage difference between theoretical and experimental data varied with the flame-holder configuration and with combustion-chamber conditions.

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APPENDIX - THEORETICAL ANALYSIS OF FLAME-HOLDER PRESSURE LOSSES

In the following analysis, a one-dimensional, nonviscous, compressible fluid flowing about a flame holder mounted in a constant-area duct is assumed. (See fig. 1.) The first condition that describes the motion of fluid about the flame holder is the equation for the conservation of mass.

$$m = \rho_v K A_f V_v = \rho_2 A_1 V_2 \tag{A1}$$

When equation (A1) is written in terms of Mach number, the following relation is obtained:

$$\frac{p_v}{p_2} = K \frac{A_1}{A_f} \frac{M_2}{M_v} \left(\frac{t_v}{t_2}\right)^{\frac{1}{2}} \tag{A2}$$

Because $T_v = T_2$ and P_v can be assumed equal to P_1 with little error, equation (A2) becomes in terms of total pressures

$$\frac{P_2}{P_1} = K \frac{A_f}{A_1} \frac{M_v}{M_2} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_v^2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{A3}$$

The second condition describing the motion of fluid about the flame holder illustrated in figure 1 is furnished by the conservation of momentum equation

$$m V_v = m V_2 + A_1 (p_2 - p_v) \tag{A4}$$

or, in terms of Mach numbers and total pressures,

$$M_2^2 = \frac{P_1}{P_2} \left(\frac{1 + \frac{\gamma-1}{2} M_2^2}{1 + \frac{\gamma-1}{2} M_v^2}\right)^{\frac{\gamma}{\gamma-1}} \left(K \frac{A_f}{A_1} M_v^2 + \frac{1}{\gamma}\right) - \frac{1}{\gamma} \tag{A5}$$

The final equation is obtained from a statement of equation (A1) in terms of conditions at stations 1 and v.

$$K \frac{A_f}{A_1} = \frac{M_1}{M_v} \left(\frac{1 + \frac{\gamma-1}{2} M_v^2}{1 + \frac{\gamma-1}{2} M_1^2} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{A6}$$

From equations (A3), (A5), and (A6), the total-pressure ratio P_2/P_1 can be graphically solved in terms of $K(A_f/A_1)$ and M_1.

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3. Pinkel, I. Irving, and Shames, Harold: Analysis of Jet-Propulsion Engine Combustion-Chamber Pressure Losses. NACA Rep. 880, 1947.

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5. Hawthorne, W. R., and Cohen, H.: Pressure Losses and Velocity Changes Due to Heat Release and Mixing in Frictionless, Compressible Flow. Rep. No. E.3997, British R.A.E., Jan. 1944.
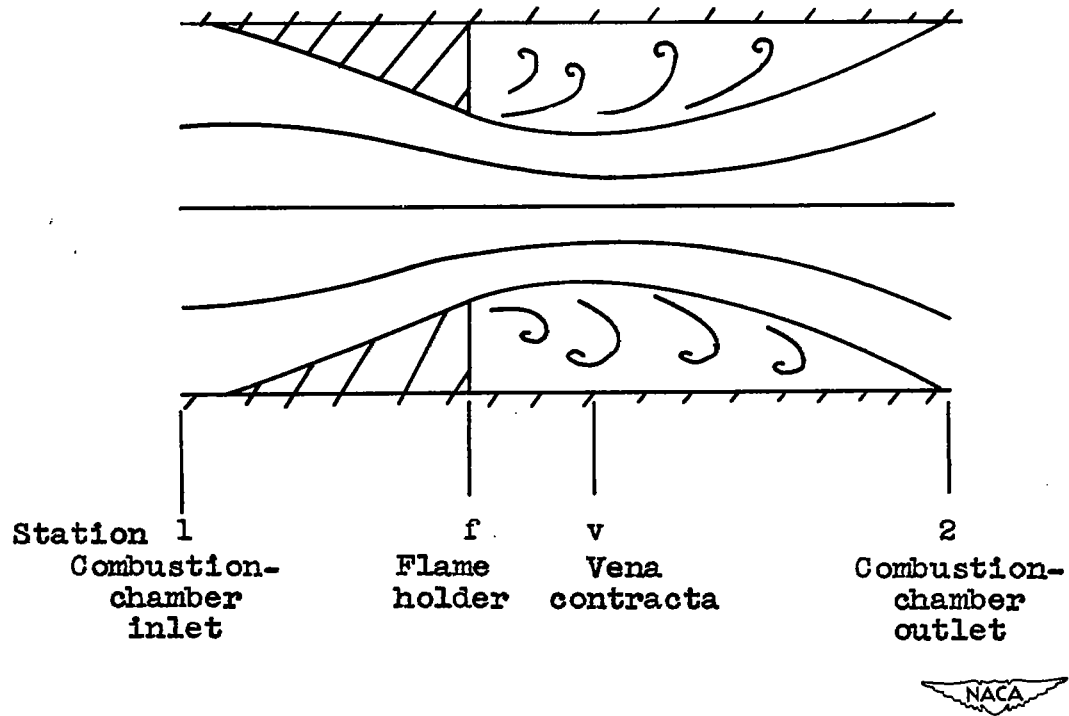
Figure 1. - Idealized concept of flow conditions about flame holders composed of elements approximately in single plane.
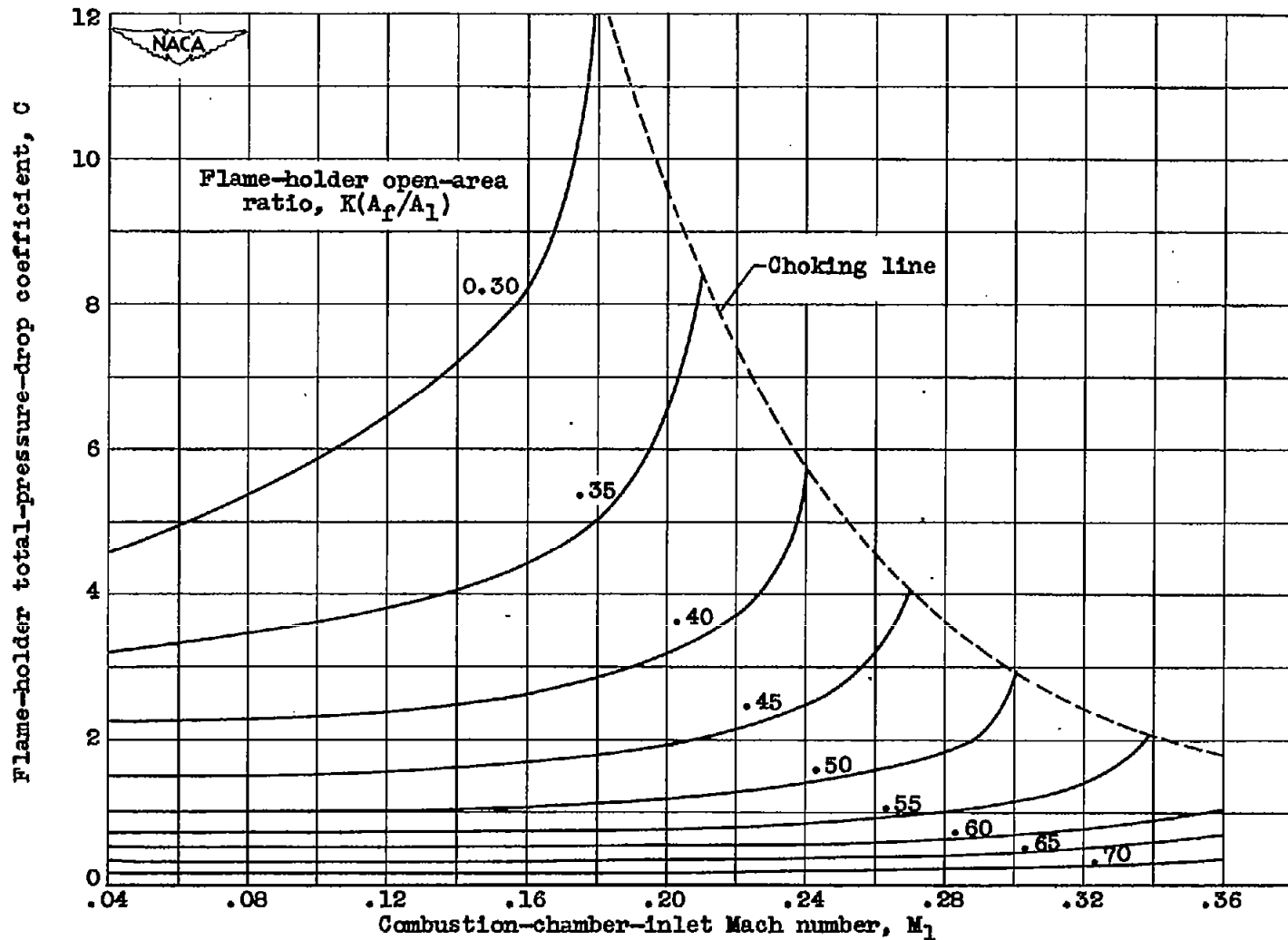
Figure 2. – Theoretical variation of flame-holder total-pressure-drop coefficient with combustion-chamber-inlet Mach number for various values of effective flame-holder open-area ratio. Specific heat ratios, $\gamma_1 = \gamma_2 = 1.4$.
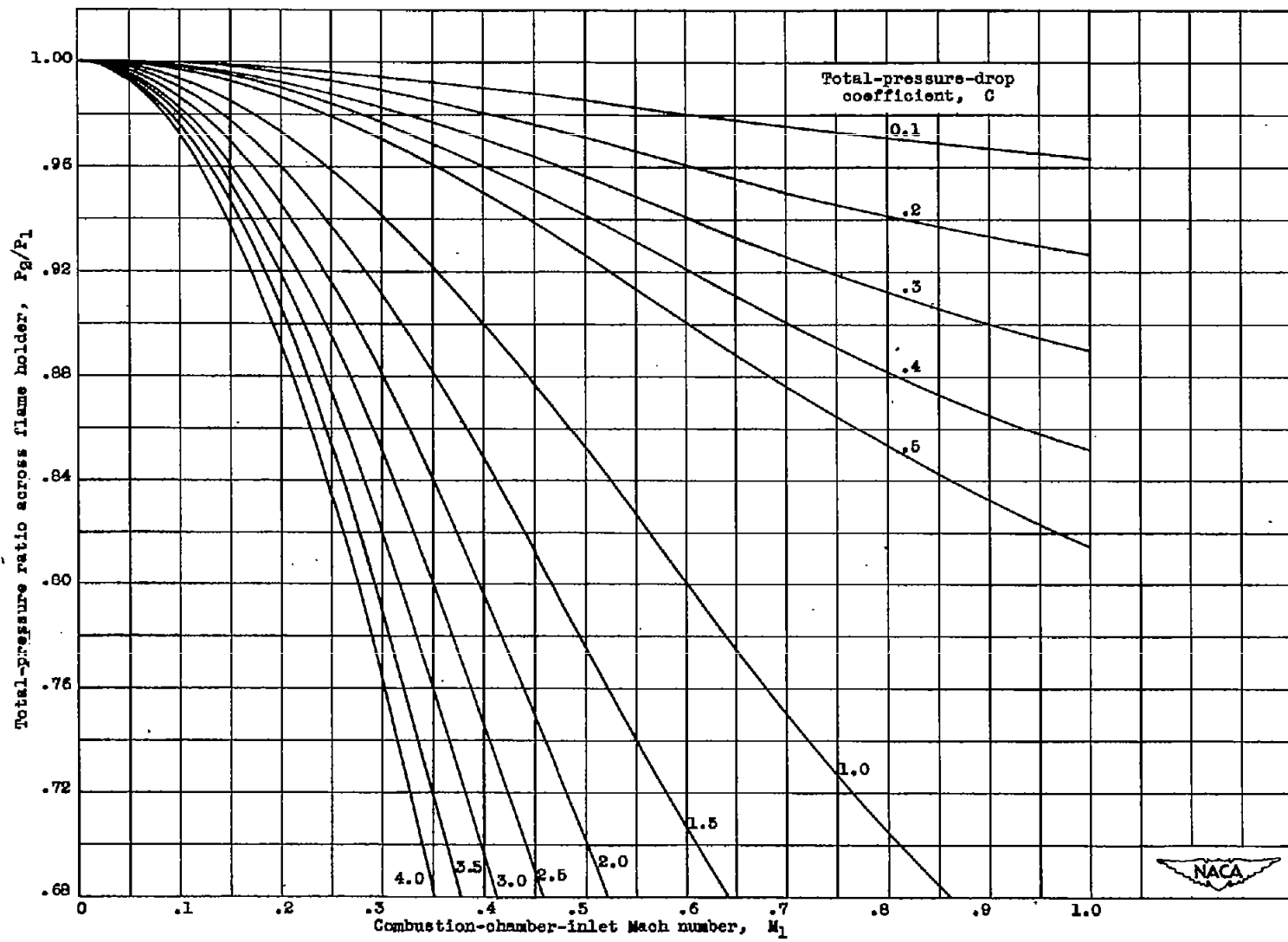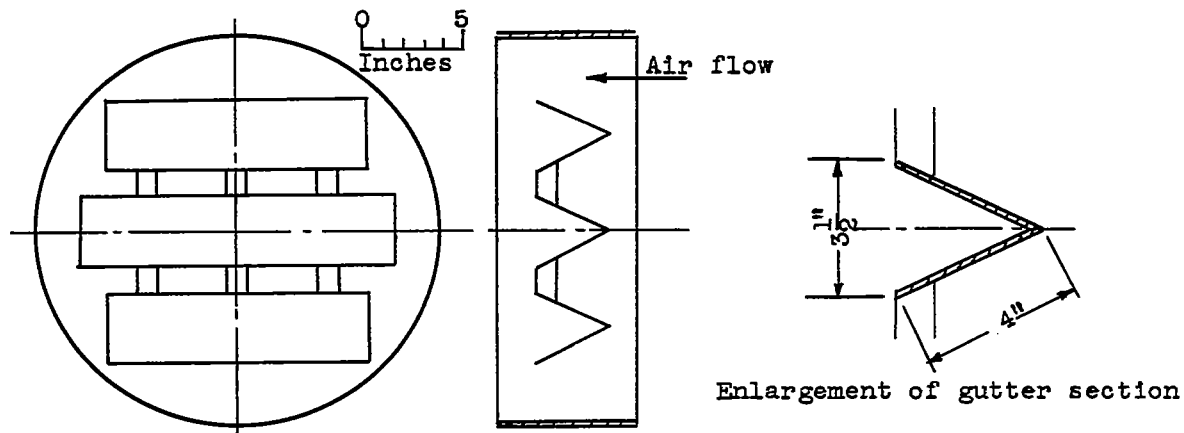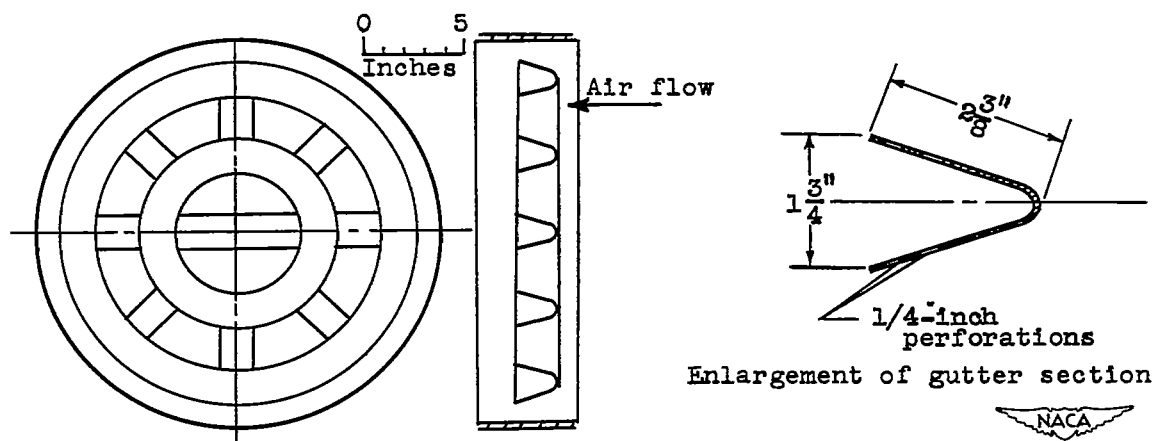
Figure 3. - Variation of total-pressure ratio across flame holder with combustion-chamber-inlet Mach number for various values of total-pressure-drop coefficient. Specific heat ratio, $\gamma = 1.4$.

(a) Three-V-gutter flame holder; $A_f/A_1 = 0.50$.

(b) Perforated annular-V-gutter flame holder; $A_f/A_1 = 0.49$.

Figure 4. - Schematic diagrams of single-plane flame holders.

Enlargement of cone section
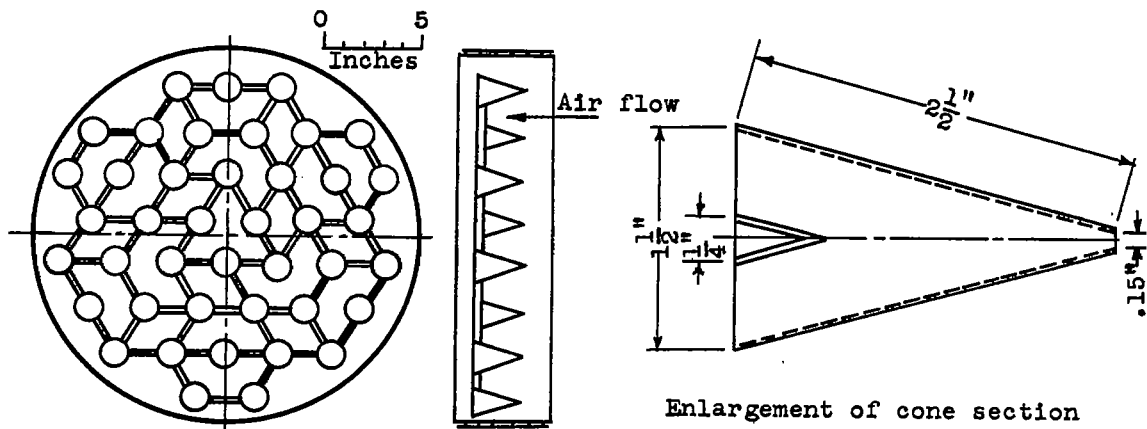
(c) Cone-type flame holder; $A_f/A_1 = 0.70$.

Enlargement of gutter section
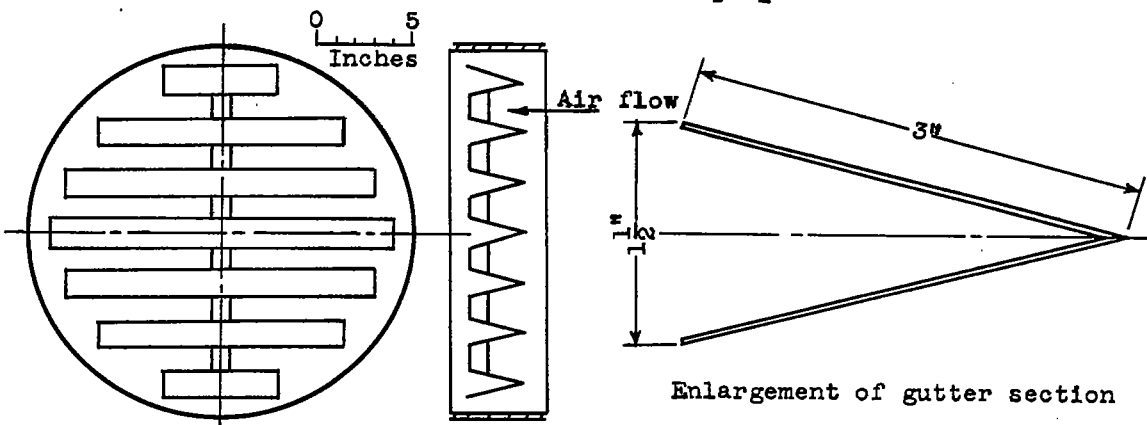
(d) Seven-V-gutter flame holder; $A_f/A_1 = 0.59$.

Enlargement of gutter section
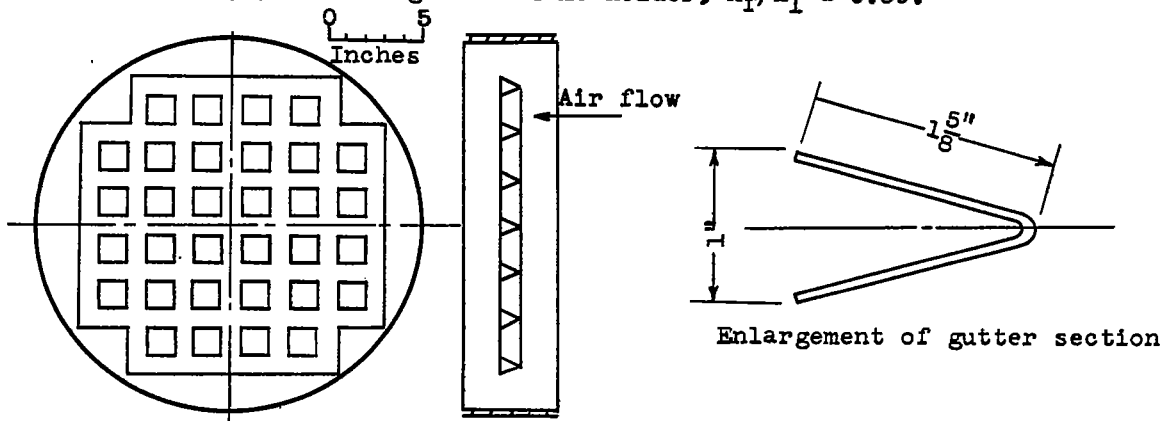
(e) Standard gutter-grid flame holder; $A_f/A_1 = 0.47$.

Figure 4. - Continued. Schematic diagrams of single-plane flame holders.
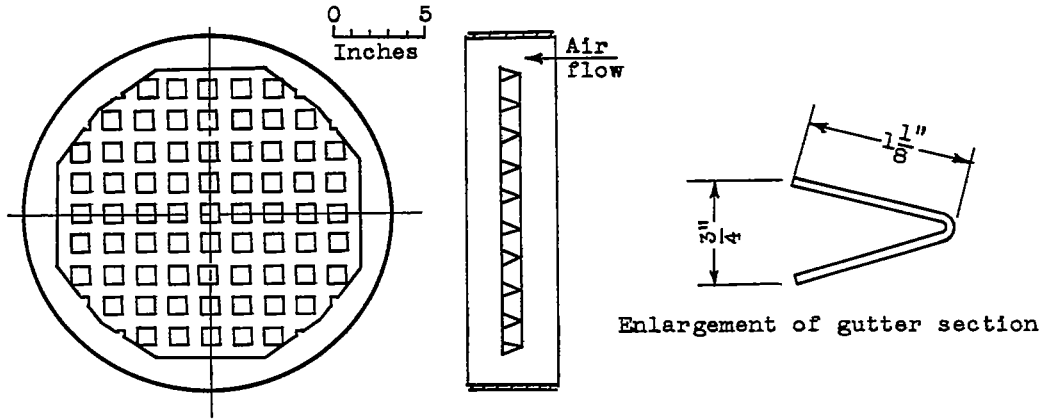
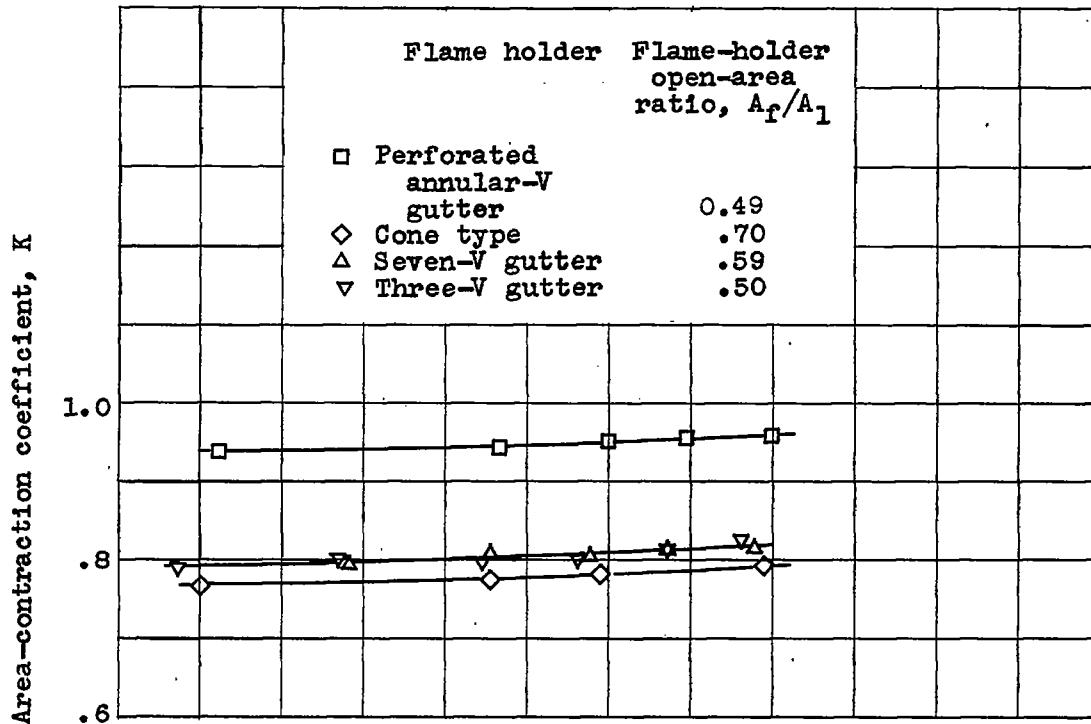(f) Three-quarter-scale gutter-grid flame holder; $A_f/A_1 = 0.46$.
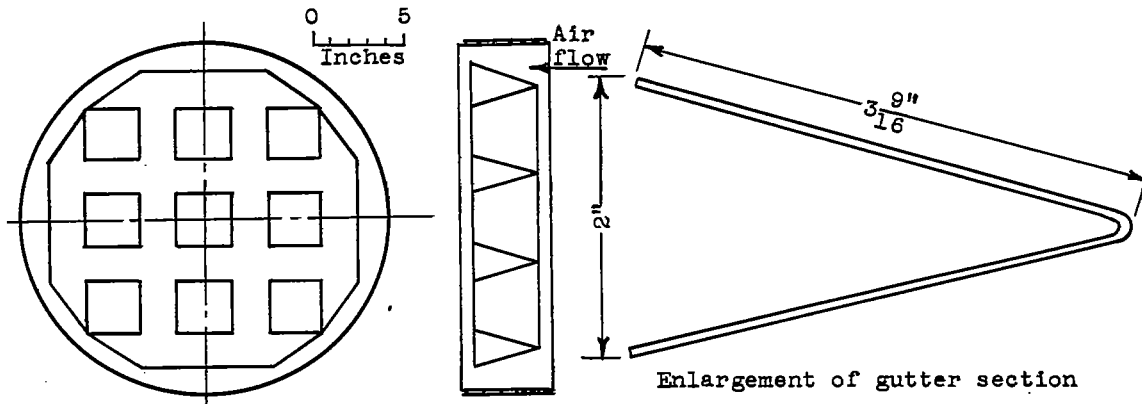
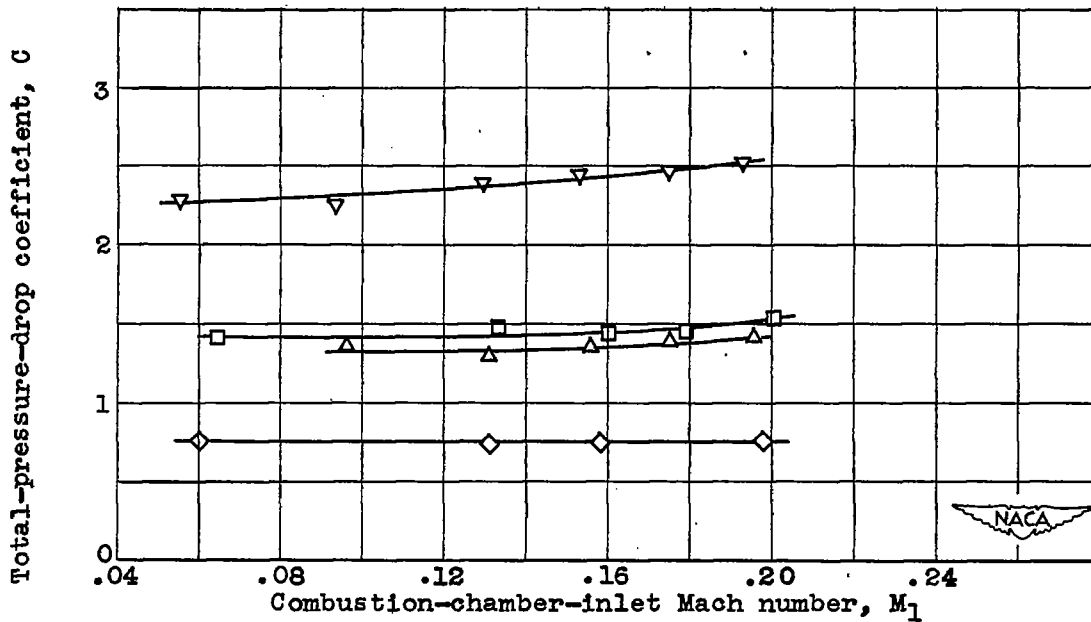(g) Double-scale gutter-grid flame holder; $A_f/A_1 = .0.46$.
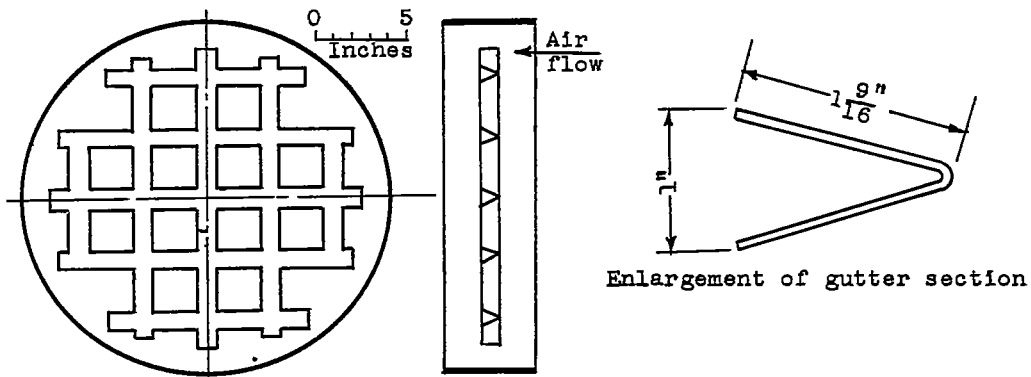
(h) 1.4-spaced gutter-grid flame holder; $A_f/A_1 = 0.62$.

Figure 4. - Concluded. Schematic diagrams of single-plane flame holders.
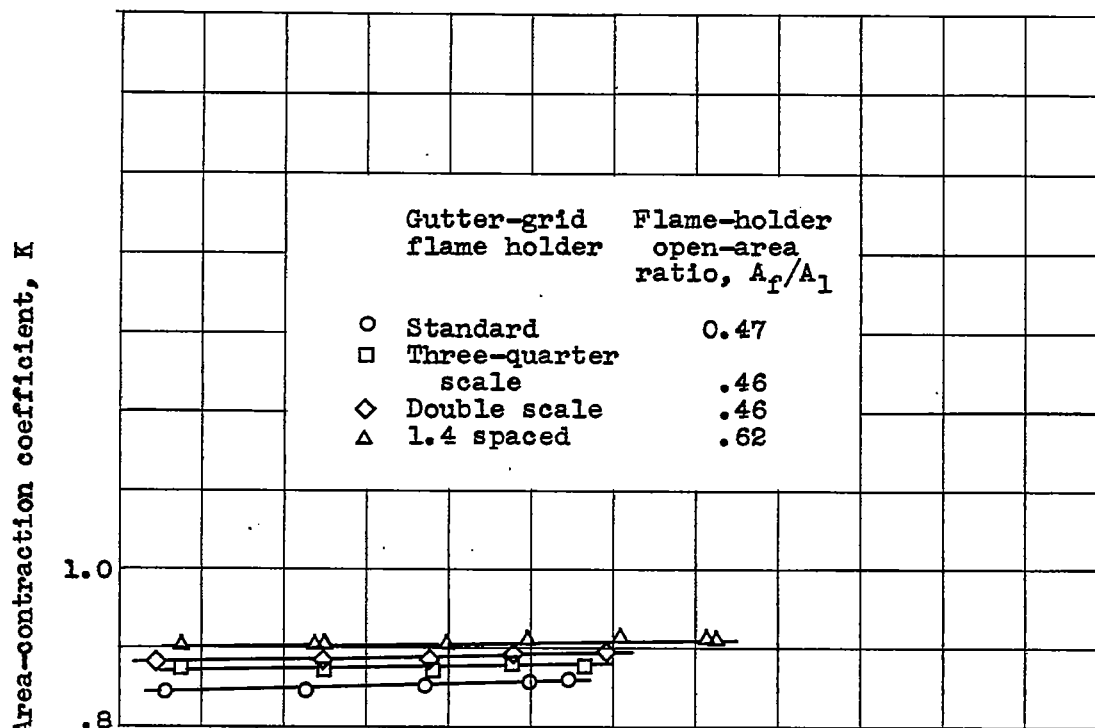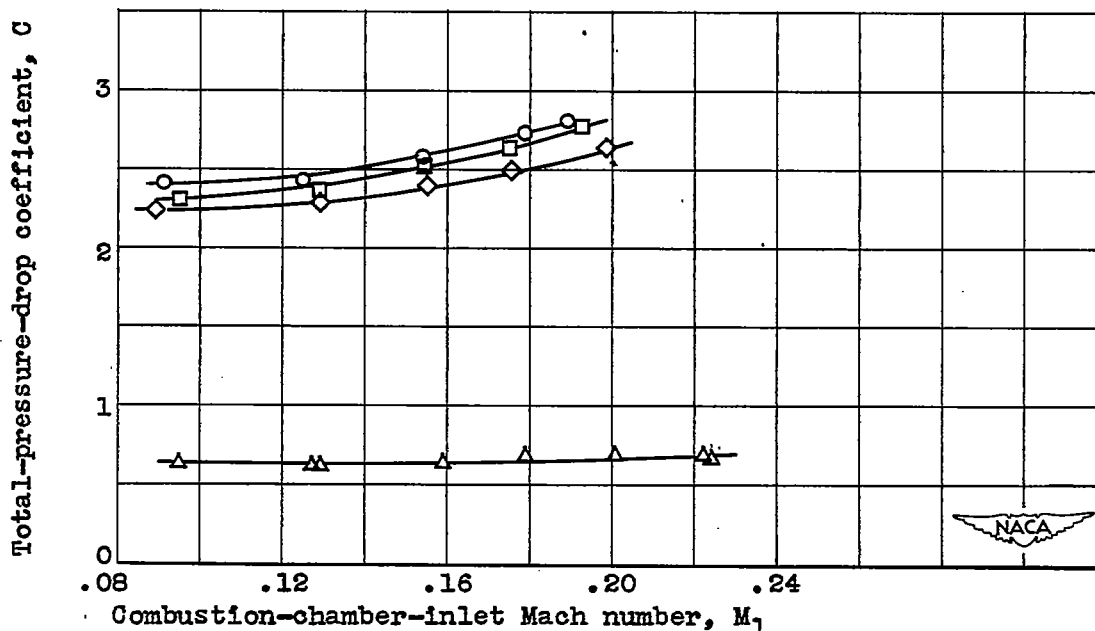
(a) Area-contraction coefficient.

(b) Total-pressure-drop coefficient.

Figure 5. - Variation of flame-holder total-pressure-drop coefficient
and area-contraction coefficient with combustion-chamber-inlet Mach
number for various single-plane flame holders of different designs.
No combustion.

	Gutter-grid flame holder	Flame-holder open-area ratio, A_f/A_1
O	Standard	0.47
□	Three-quarter scale	.46
◇	Double scale	.46
△	1.4 spaced	.62

(a) Area-contraction coefficient.

(b) Total-pressure-drop coefficient.

Figure 6. — Variation of flame-holder total-pressure-drop coefficient and area-contraction coefficient with combustion-chamber-inlet Mach number for single-plane flame holders of same design but different geometric scales. No combustion.
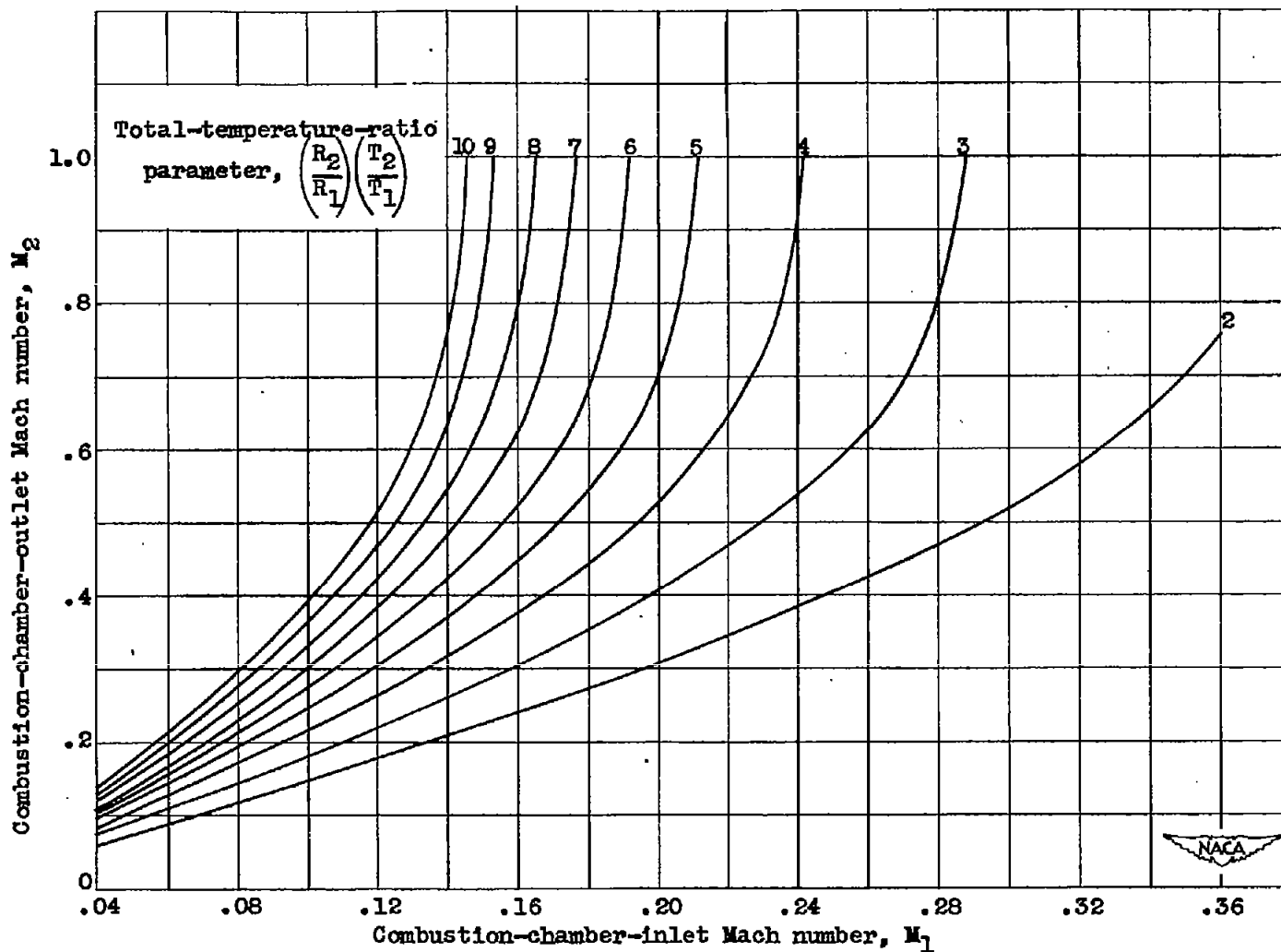
Figure 7. – Variation of combustion-chamber-outlet Mach number with combustion-chamber-inlet Mach number and total-temperature-ratio parameter. Specific heat ratios: $\gamma_1 = 1.4$; $\gamma_2 = 1.3$.
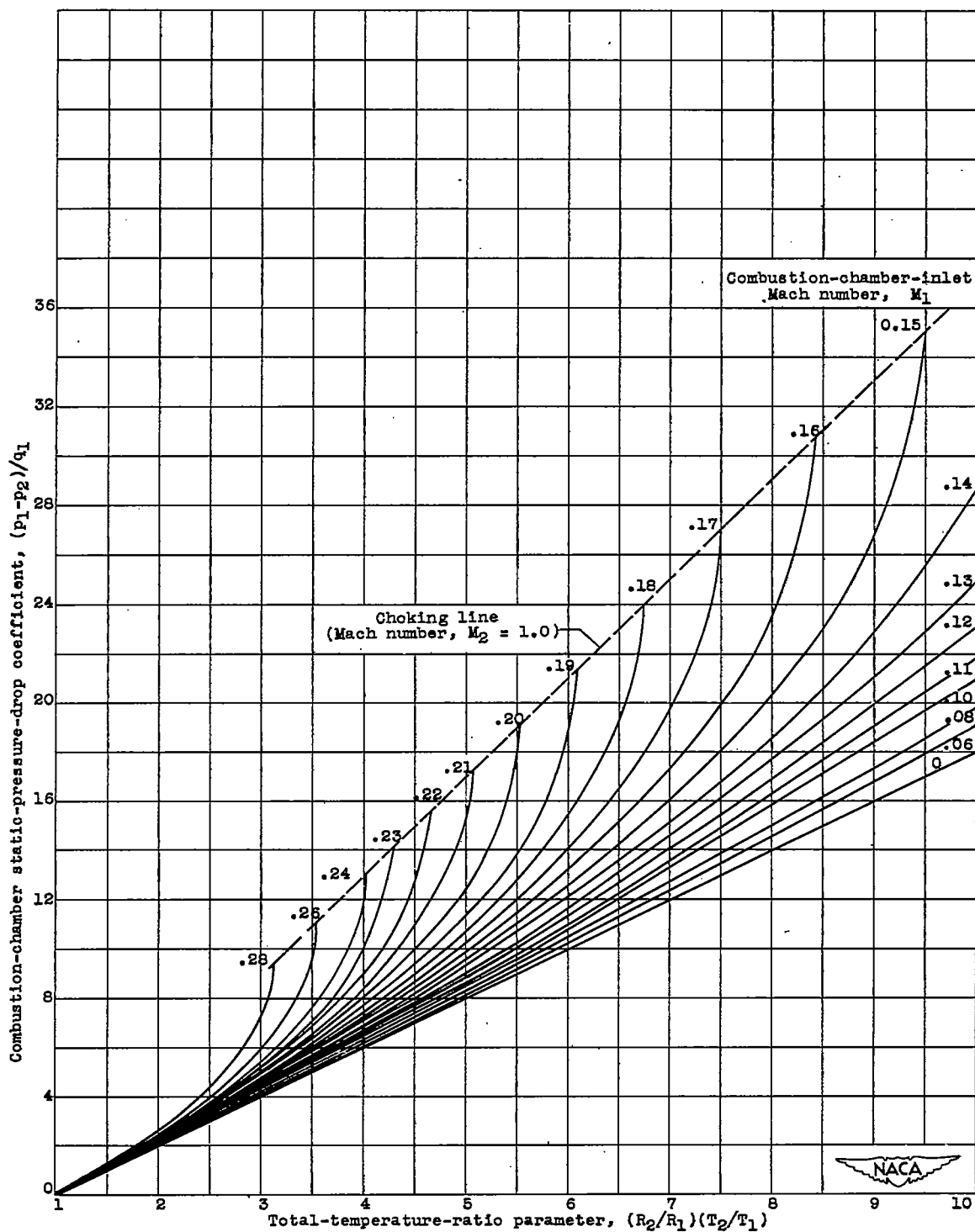
Figure 8. - Theoretical variation of combustion-chamber static-pressure-drop coefficient with total-temperature-ratio parameter for various values of combustion-chamber-inlet Mach number. Specific heat ratios: $\gamma_1 = 1.4$; $\gamma_2 = 1.3$.

(a) Annular-V flame holder; C = 0.6;
   A_f/A_1 = 0.64; combustion-chamber
   length, 5 feet.

(b) Standard gutter-grid flame holder;
   C = 2.5; A_f/A_1 = 0.47; combustion-
   chamber length, 5 feet.

(c) Three-quarter-scale gutter-grid
   flame holder; C = 2.3; A_f/A_1 = 0.46;
   combustion-chamber length, 5 feet.

(d) Annular-V flame holder; C = 1.5;
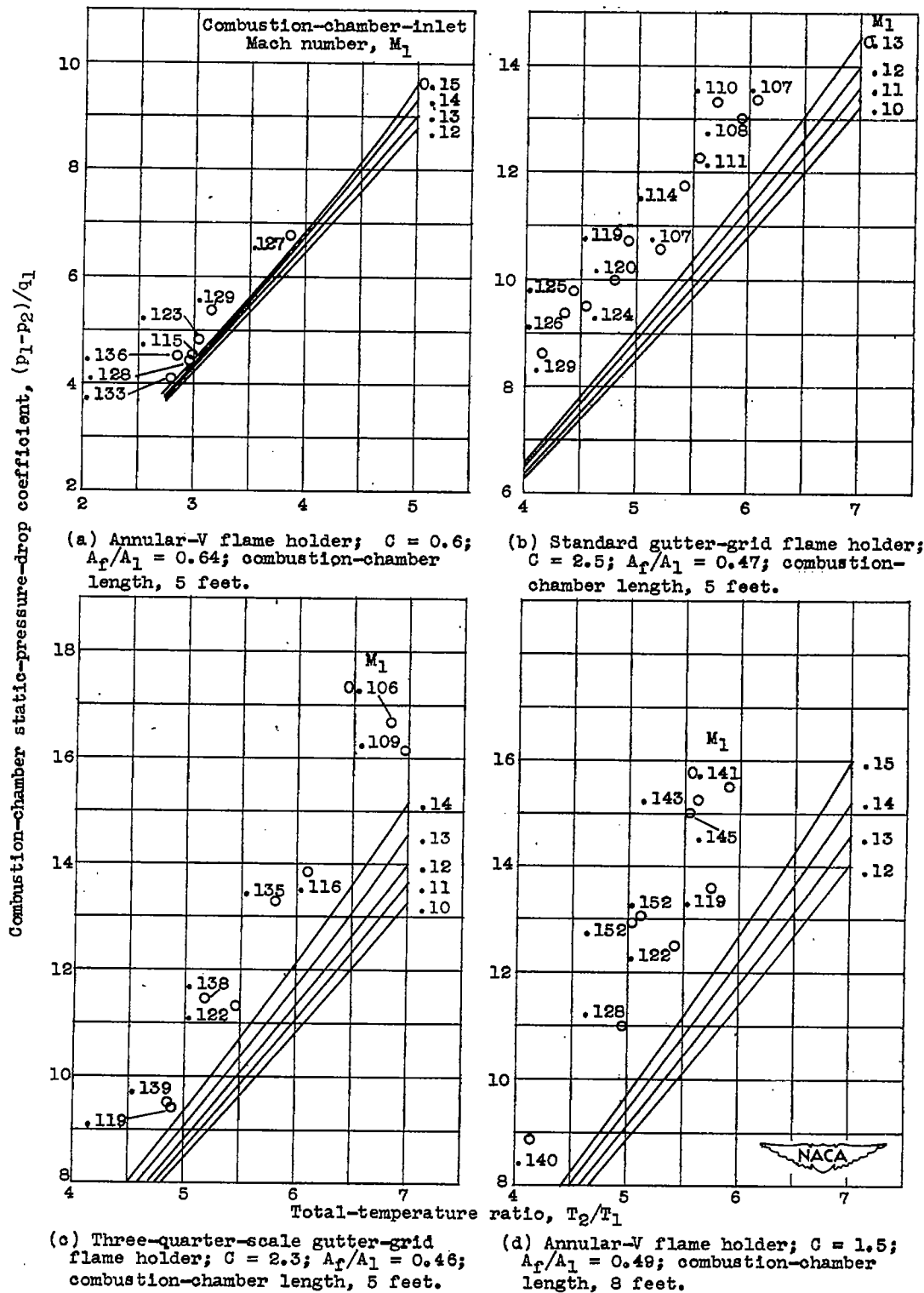 A_f/A_1 = 0.49; combustion-chamber
   length, 8 feet.

Figure 9. — Variation of combustion-chamber static-pressure-drop coefficient with
   total-temperature ratio for various values of combustion-chamber-inlet Mach number.