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RESEARCH MEMORANDUM

FREE-JET TESTS OF A 1.1-INCH-DIAMETER SUPERSONIC RAM-JET ENGINE

By Joseph H. Judd and Otto F. Trout, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
March 5, 1952

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MAR 24 1952

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RESEARCH MEMORANDUM

FREE-JET TESTS OF A 1.1-INCH-DIAMETER SUPERSONIC RAM-JET ENGINE

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SUMMARY

A 1.1-inch-diameter hydrogen-burning ram-jet engine having a design Mach number of 2.13 was tested in a free supersonic jet. Performance characteristics of the engine are presented for a Mach number range of 1.42 to 2.28. A comparison of the performance characteristics of the engine with combustion-chamber lengths of 3.33 and 1.51 engine diameters was made at a Mach number of 2.06.

The maximum thrust coefficient obtained for the ram-jet engine with the 3.33-diameter combustion chamber was 0.905 at a Mach number of 2.06 and a fuel-air ratio of 0.034. The lean burnout of the engine occurred at a fuel-air ratio of 0.008 for all Mach numbers and the rich burnout at 0.082 at a Mach number of 1.42. There was smooth burning over the entire fuel-air-ratio range.

Shortening the combustion-chamber length from 3.33 diameters to 1.51 diameters reduced the thrust coefficient from 0.905 to 0.236 at a fuel-air ratio of 0.034 and a Mach number of 2.06. The smoothness of combustion was unaffected by the change in combustion-chamber length.

INTRODUCTION

The problems of inlet design and engine installation on airplanes are magnified at transonic and supersonic speeds. Furthermore, at high flight speeds the installation and operation of the engine affect the aerodynamic characteristics of the airplane appreciably. To conduct an investigation on the effect of engine installation and operation on the supersonic aerodynamic characteristics of airplane and missile configurations, a small engine that simulates an air-breathing engine, such as a turbojet or ram jet, is needed. Three methods of engine simulation on a small scale are feasible: a ram jet, a compressed-air jet, or a small rocket. From the standpoint of flexibility of operation and

simplicity of installation on a variety of airplane and missile configurations, the supersonic ram jet appeared better than the compressed-air jet or rocket. The primary requirements of the engine were: reliable starting, good control response, and a wide operating range of Mach number and fuel-air ratio.

A 1.1-inch-diameter ram-jet engine was tested in a free jet at the Pilotless Aircraft Research Station, Wallops Island, Va., to determine the practicality of engine operation on a scale suitable for airplane or missile configuration tests in a 27- by 27-inch open jet. In addition, the tests were run to study the operational problems of running a small ram-jet engine at supersonic speeds.

While a wide variety of inlets and exit nozzles may be coupled to a combustion chamber to form a ram-jet engine, the basic configuration selected for testing was similar to the engine of reference 1. A Ferri type inlet with a 40° cone was used as the supersonic inlet. A straight combustion chamber was coupled to a convergent-divergent nozzle. The burner used for these tests was a Pabst burner, modified for hydrogen fuel which gave uniform burning over a wide fuel-air-ratio range. Spark ignition was found to give reliable starting over the Mach number range tested. In addition to tests over the Mach number range on an engine with a 3.33-diameter combustor, a combustion chamber of 1.51 diameters was tested at a Mach number of 2.06 to determine if the engine would operate with a short combustor.

The present paper presents the engine characteristics of a 1.1-inch-diameter ram-jet engine over a Mach number range of 1.42 to 2.28 and a Reynolds number range, based on shell length, of 6.01×10^6 to 15.78×10^6. The Reynolds number range, based on engine diameter, corresponds to an 18-inch ram jet flying at an altitude of 74,000 feet.

SYMBOLS

c	velocity of sound, feet per second
C_D	drag coefficient (D/qS)
C_T	thrust coefficient $\left(\frac{X + D}{qS}\right)$
D	drag, pounds
F/A	fuel-air ratio, weight rate of fuel flow to weight rate of air flow

M	Mach number (V/c)
q	dynamic pressure $\left(\frac{1}{2}\rho V^2\right)$, pounds per square foot
R	Reynolds number (Vm/ν)
S	frontal area of engine, square feet
T	free-stream static temperature, degrees Fahrenheit
V	free-stream velocity, feet per second
X	force measured on thrust stand, pounds
η_c	combustion efficiency (ratio of theoretical F/A to measured F/A for a given impulse)
η_i	air impulse efficiency (ratio of actual to theoretical air impulse for a given F/A)
ρ	free-stream air density, slugs per cubic foot
Φ	equivalence ratio, fuel-air ratio over stoichiometric fuel-air ratio
ν	kinematic coefficient of viscosity
d	outside diameter of engine, feet
l	length of combustion chamber, feet
m	length of ram-jet shell, feet
x	horizontal ordinate, inches
r	radial ordinate, inches

APPARATUS

A sketch of the ram-jet engine is shown in figure 1. The engine is 1.1 inches in diameter and 7.94 and 5.94 inches long with the 3.33-diameter and the 1.51-diameter combustion-chamber lengths. Inner and outer shell ordinates are presented in table I. A single oblique-shock inlet with a 40° cone acted as the supersonic diffuser. The internal shell, acting as a subsonic diffuser, was designed to have an expansion from a minimum area

of 0.191 square inches to the combustion-chamber area of 0.758 square inches over a length of 3.06 inches. The inner body, having ordinates as given in table II, was faired from the 40° cone surface to the burner support. The area ratio of the combined supersonic and subsonic diffuser was 0.41, based on the entrance area and the combustion-chamber area. The inner body was supported by a single hexagonal airfoil with a thickness of 0.25 inch and a chord of 1.37 inches.

The combustion chambers were made of stainless steel with an outside diameter of 1.1 inches and an inside diameter of 1.0 inch. Figures 2(a) and 2(b) show the engine with combustion-chamber lengths of 3.33 diameter and 1.51 diameter, respectively. The stainless-steel exit nozzle had a contraction ratio of 0.839 which choked the inlet over the fuel-air-ratio range tested. This caused lower total-pressure recoveries at the higher test Mach numbers. Nozzle ordinates are tabulated in table III.

Prior to free-jet tests of the ram-jet engine, a series of burners were compared in combustion tests. The modified Pabst burner (shown in figures 1 and 2(c)) was observed to burn over the widest fuel-air-ratio range. This burner acts as a flame holder and fuel injector. The fuel is injected into the combustion chamber through four equally spaced holes normal to the conical after surface of the burner. The ratio of burner to combustion-chamber area was 0.25.

An aluminum rod supported by bakelite struts was inserted through the nozzle to act as an electrode of the ignition system. A 0.062-inch spark gap was held prior to combustion between this electrode and the burner. A potential of 20,000 volts from an induction coil was used for engine ignition. Immediately after ignition the rod and supports were burned and blown from the engine. This type of ignition gave immediate engine starting and was observed to be extremely reliable.

Four bottles of technical-grade hydrogen were connected to a manifold for the fuel supply. A metering flow nozzle was used to measure fuel rate and a hand-operated valve was used to regulate fuel flow to the engine. The fuel was injected into the combustion chamber through the modified Pabst burner which acted as a flame holder and fuel injector.

The drag cup used in determining internal drag is shown installed in the ram jet in figure 2(d). The maximum diameter of the cup was 0.887 inch. The drag cup was designed to choke the exit over the Mach number range tested. A base-pressure orifice was installed in the center of the cup and during drag runs was connected to a pressure pickup through a fuel tube.

The ram-jet engine was supported by a strut with a hexagonal airfoil section having a 0.250-inch thickness and a chord of 4.25 inches.

In order to determine the strut drag, a dummy strut was attached to the engine in the same attitude as the support strut. The model in test position with the drag strut attached is shown in figure 3.

TESTS AND MEASUREMENTS

A high-frequency strain-gage balance was used to measure the net thrust and drag of the engine. Diffuser-exit static pressure was measured in all runs to determine the smoothness of engine burning. The drag-cup base pressure was measured in all drag runs. Measurements of pressure, temperature, and force were recorded simultaneously on a recording oscillograph.

Tests were made to determine the drag and performance of the ram-jet engine at fixed free-jet nozzle Mach numbers of 1.42, 1.75, 2.06, and 2.28. During each run approximately atmospheric pressure was maintained at the free-jet nozzle exit. The average free-stream static temperatures are listed in table IV. Figure 4 presents the variation of Reynold's number, based on shell length, with Mach number for these tests.

Test accuracy.- The magnitude of error in the force-balance measurements was ±1 percent for full-scale deflection. The estimated error of the air-flow and fuel-flow measurements was ±2 percent.

Computations.- Because of the small scale of the engine, the amount and complexity of instrumentation was held to a minimum. The inlet was designed, therefore, to choke over the range of fuel-air ratios and Mach numbers tested so the air mass flow through the engine could be computed by consideration of total-pressure loss (as outlined in reference 1).

The internal, base, and gross external drags were computed by the methods of reference 1. In order to determine external tare drag from the gross tare drag, the strut drag must be determined. This was done by attaching a similar strut to the engine, rotated 180° from the supporting strut, and measuring the total drag of the configuration. The coefficient of tare drag was obtained by taking the difference of the engine drag with and without the drag strut:

$$C_{D_{nacelle}} = 2C_{D_{nacelle + strut}} - C_{D_{nacelle + 2\ struts}}$$

The assumption that the drag of the support strut is equal to that of the drag strut is qualified mainly by the interference of one strut

on the other and the influence of the struts on the boundary layer. The shadowgraphs of figure 5(a) indicate that addition of the drag strut makes the flow downstream of the struts symmetrical. This shows that the drag of the two struts is approximately equal, since an equal and opposite disturbance was introduced into the stream.

The tare drag coefficient of the engine with the 1.51-diameter combustion chamber was computed by subtracting skin-friction values from the external tare drag of the engine with the 3.33-diameter combustion chamber. The value of skin-friction drag was calculated by using values of turbulent skin friction from reference 2:

$$C_{D_{1.51\text{-diameter combustion chamber}}} = C_{D_{3.33\text{-diameter combustion chamber}}} - \Delta C_{D_{\text{friction}}}$$

The gross thrust coefficient was obtained by adding the coefficient of tare drag to the net thrust coefficient. This tare coefficient includes the shell drag and the additive drag; that is, the pressure drag on the streamlines entering the engine. An inspection of the shadowgraphs of the combustion tests as illustrated in figure 5(b), indicated that the additive drag of the engine remained constant for a given Mach number and the fuel-air-ratio range tested.

The heating value of the fuel and thermodynamic properties of the products of combustion used in computing the impulse and combustion efficiencies were determined by the methods of reference 3. The impulse and combustion efficiencies were computed by the methods of reference 1.

RESULTS AND DISCUSSION

The external tare drag coefficients for the 1.1-inch ram-jet engine are shown in figure 6 for both combustion-chamber lengths. The large decrease in tare drag with increasing Mach number is mainly due to the decrease in additive drag as the diameter of the free-stream tube entering the jet approaches the entrance area of the engine.

The thrust coefficients of the engine with the 3.33-diameter combustion chamber are presented in figure 7 as a function of the fuel-air ratio at Mach numbers of 1.42, 1.75, 2.06, and 2.28. At stoichiometric fuel-air ratio and Mach number 2.06, the test thrust coefficient was 0.865. This compares favorably with the 6.5-inch-diameter ethylene-burning ram-jet engine of reference 1, which delivered a thrust coefficient of 0.90 at

Mach number 2.0 and stoichiometric fuel-air ratio. Thus, while the engine size was scaled down, the thrust coefficient was held to the same order of magnitude. The variation of C_T with Mach number for constant equivalence ratio ϕ is shown in figure 8. It can be seen that the peak thrust coefficients occur in the vicinity of the design Mach number of 2.13. The maximum test thrust coefficient was 0.905 at a Mach number of 2.06 and a fuel-air ratio of 0.034.

At all Mach numbers lean burnout occurred at fuel-air ratio near 0.008 for the 3.33-diameter combustion chamber. Rich burnout was obtained only at a Mach number of 1.42 with a fuel-air ratio of 0.082 or an equivalence ratio of 2.98. At higher Mach numbers, the fuel system could not deliver enough fuel to obtain rich burnout. Shadowgraphs of the flow about the engine, observation of the engine during runs, and inspection of diffuser-exit static pressures showed that the combustion was smooth at all Mach numbers and fuel-air ratios tested.

The variation of combustion and impulse efficiencies with fuel-air ratios for the engine with a 3.33-diameter combustion chamber are presented in figures 9 and 10. A maximum combustion efficiency of 0.693 was obtained at a Mach number of 2.06 and a fuel-air ratio of 0.027. The impulse efficiencies obtained during these tests varied from 0.785 to 0.900 over the range of fuel-air ratios and Mach numbers tested.

A 1.51-diameter combustion-chamber length was tested at a Mach number of 2.06 to find the effect on C_T of decreasing combustion-chamber length. The variation of thrust coefficient with fuel-air ratio is presented in figure 11 for both combustion-chamber lengths. Values of impulse and combustion efficiencies obtained with the 3.33-diameter and 1.51-diameter combustion chambers are presented in figures 12 and 13. Greatly reduced values of impulse and combustion efficiencies are noted for the shorter combustion chamber. However, smoothness of combustion was unaffected by shortening the combustion-chamber length.

CONCLUSIONS

A 1.1-inch-diameter supersonic ram-jet engine, burning hydrogen fuel, has been tested through a Mach number range of 1.42 to 2.28 and a Reynolds number range, based on shell length, of 6.01×10^6 to 15.78×10^6 in a free jet at atmospheric pressure. The coefficients of thrust and drag, and impulse and combustion efficiencies were determined through free-jet tests. A comparison was made of the engine performance with ratios of combustion-chamber length to diameter l/d of 3.33 and 1.51 at a Mach number of 2.06. The following effects were noted:

1. Free-jet tests at supersonic speeds show that a 1.1-inch-diameter ram-jet engine operates reliably over a wide range of fuel-air ratios and Mach numbers. Therefore, this engine is suitable for installation on models of airplane and missile configurations that are to be used in supersonic wind-tunnel tests.

2. The combustion in the engine was smooth over a fuel-air-ratio range of 0.008 to 0.082. The spark ignition was demonstrated to be rapid and reliable.

3. A maximum test thrust coefficient of 0.905 was obtained at a fuel-air ratio of 0.034 and a Mach number of 2.06. This is comparable to a maximum thrust coefficient of 0.925 at a Mach number of 2.00 and a fuel-air ratio of 0.070 for an ethylene-burning 6.5-inch-diameter ram-jet engine.

4. Reducing the combustion-chamber length from 3.33 diameters to 1.51 diameters lowered the thrust coefficient from 0.905 to 0.236 at a fuel-air ratio of 0.034 at Mach number 2.06. The smoothness of combustion was not affected by the change in combustion-chamber length.

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1. Faget, Maxime A., Watson, Raymond S., and Bartlett, Walter A., Jr.: Free-Jet Tests of a 6.5-Inch-Diameter Ram-Jet Engine at Mach Numbers of 1.81 and 2.00. NACA RM L50L06, 1951.

2. Van Driest, E. R.: The Turbulent Boundary Layer for Compressible Fluids on a Flat Plate with Heat Transfer. Rep. No. AL-997, North American Aviation, Inc., Jan. 27, 1950.

3. Fricke, Edwin F.: Statistical Thermodynamics Applied to Chemical Kinetics of Combustion. Rep. No. EDR-22-407, Republic Aviation Corp., Oct. 1, 1947.

TABLE I

SHELL ORDINATES FOR TRANSITION POINTS

x (in.)	r (in.)
Outside	
0.424	0.3205
.524	.3405
2.106	.5200
2.581	.5500
7.941	.5500
Inside	
0.424	0.3205
2.681	.4350
3.721	.5000
7.381	.5000

TABLE II

INNER BODY ORDINATES

x (in.)	r (in.)
0	0
.550	.200
.562	.212
.600	.221
.950	.230
1.783	.224
2.283	.217
2.667	.195
3.000	.170
2.500	.120
3.667	.100
3.750	.096

TABLE III

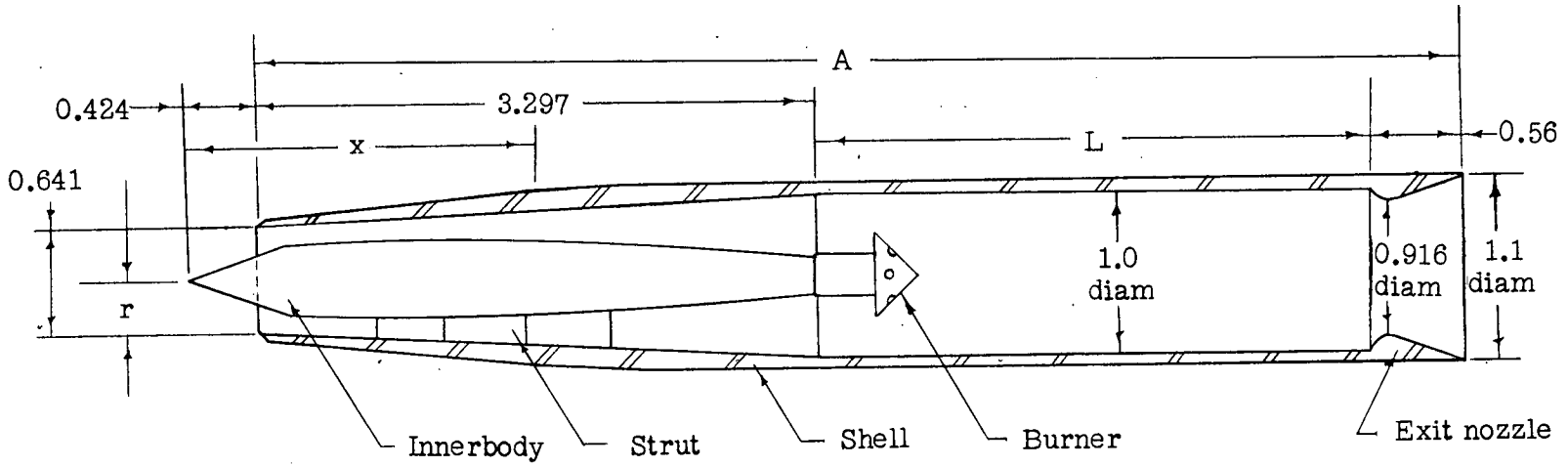
EXIT NOZZLE INSIDE ORDINATES

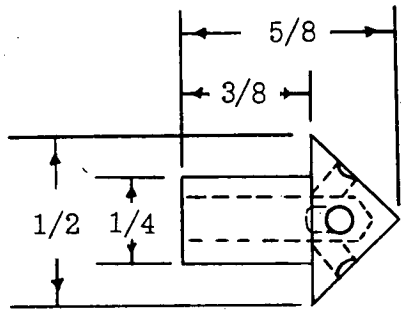
x (in.)	r (in.)
7.381	0.500
7.431	.470
7.566	.458
7.941	.550

TABLE IV

AVERAGE STATIC TEMPERATURES OF TESTS

M_o	T_o (deg)
Combustion chamber $\frac{l}{d} = 3.33$	
1.42	47
1.75	-3
2.06	-55
2.25	-55
Combustion chamber $\frac{l}{d} = 1.51$	
2.06	-50





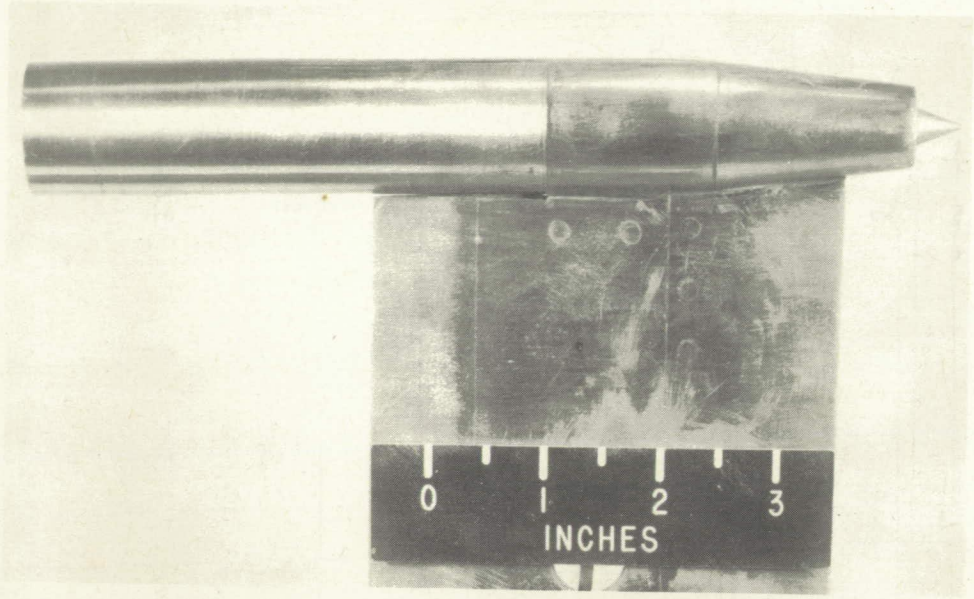
Burner

Tabulated Model Data

Frontal area, based on max. diameter, sq in.	0.950
Inlet area, sq in.	.322
Combustion chamber area, sq in.	.758
Minimum nozzle area, sq in.	.658
Shell length	A
3.33-inch combustion chamber	7.517
1.51-inch combustion chamber	5.517
Combustion-chamber length	L
3.33-inch combustion chamber	3.66
1.51-inch combustion chamber	1.66

NOTE: Ordinates of model with 3.33-inch combustion chamber are tabulated in Tables I, II, and III.

Figure 1.- Arrangement of 1.1-inch-diameter ram-jet model and burner. All dimensions in inches.



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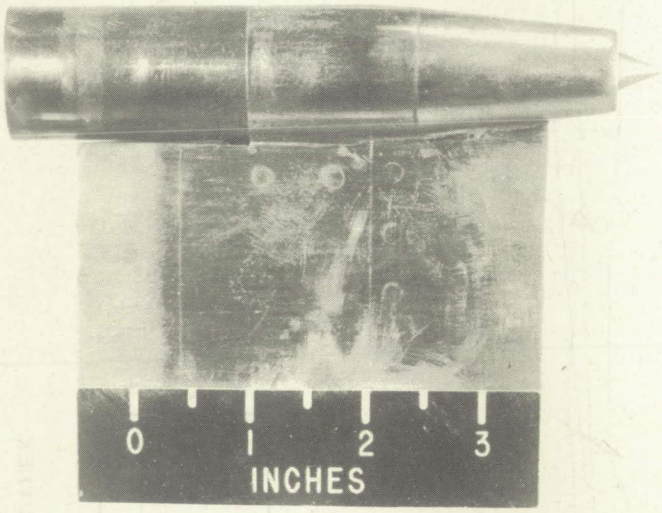
(a) Ram-jet engine with 3.66-inch combustion chamber; $\frac{l}{d} = 3.33$.



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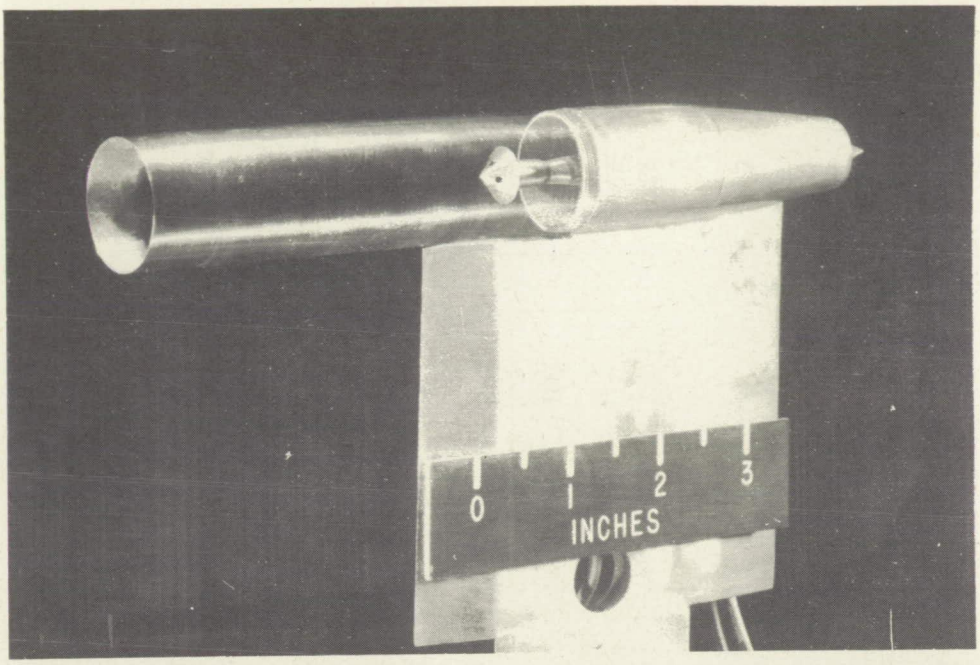
(b) Ram-jet engine with 1.66-inch combustion chamber; $\frac{l}{d} = 1.51$.

Figure 2.- General views of 1.1-inch ram-jet test model.



(c) Ram-jet engine showing modified Pabst burner.

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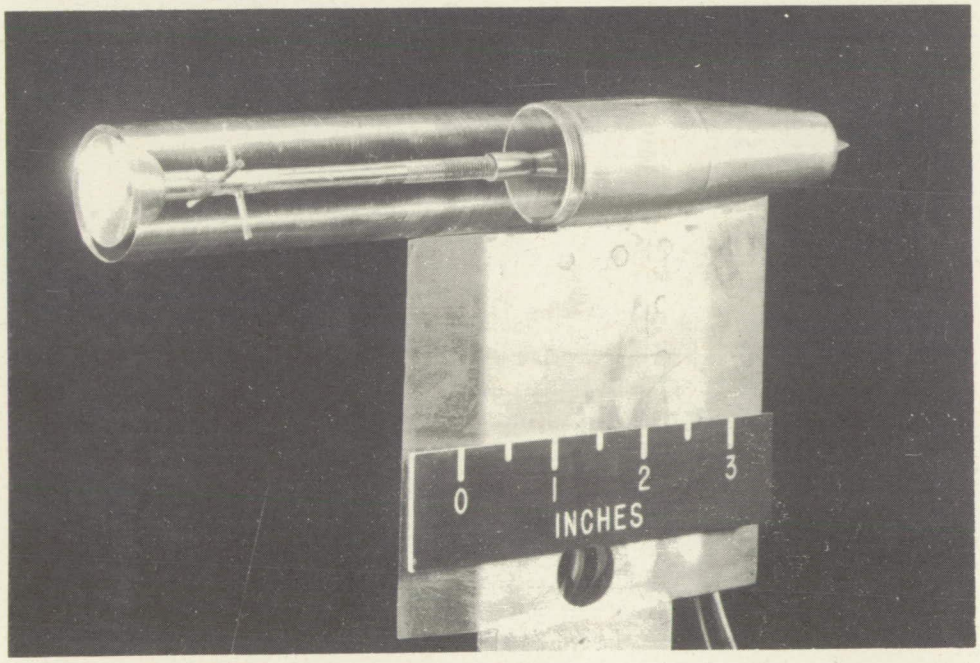

(d) Ram-jet engine showing drag cup.

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Figure 2.- Concluded.

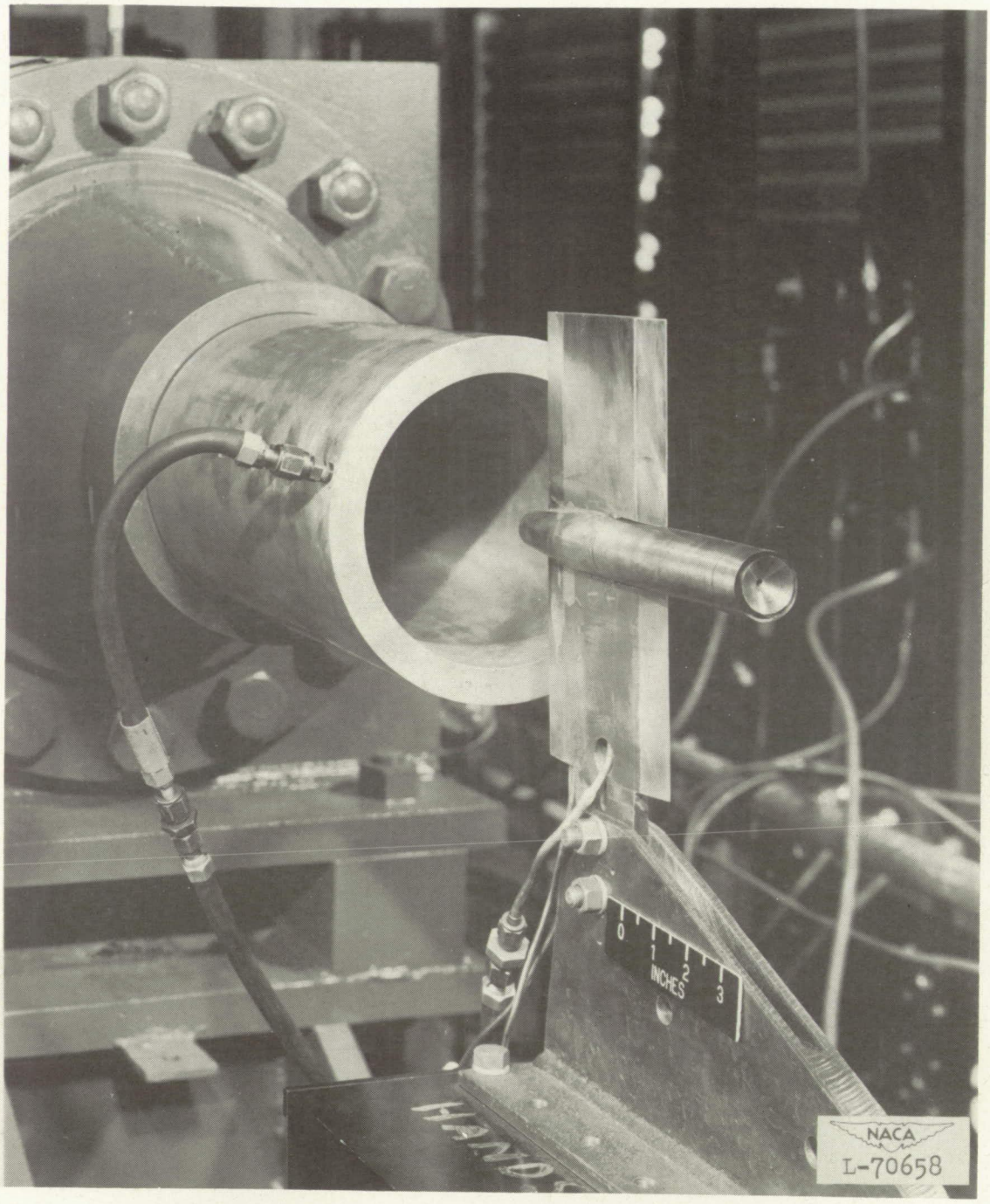


Figure 3.- Ram-jet engine, with 3.33-inch combustion chamber and drag strut, in test position.

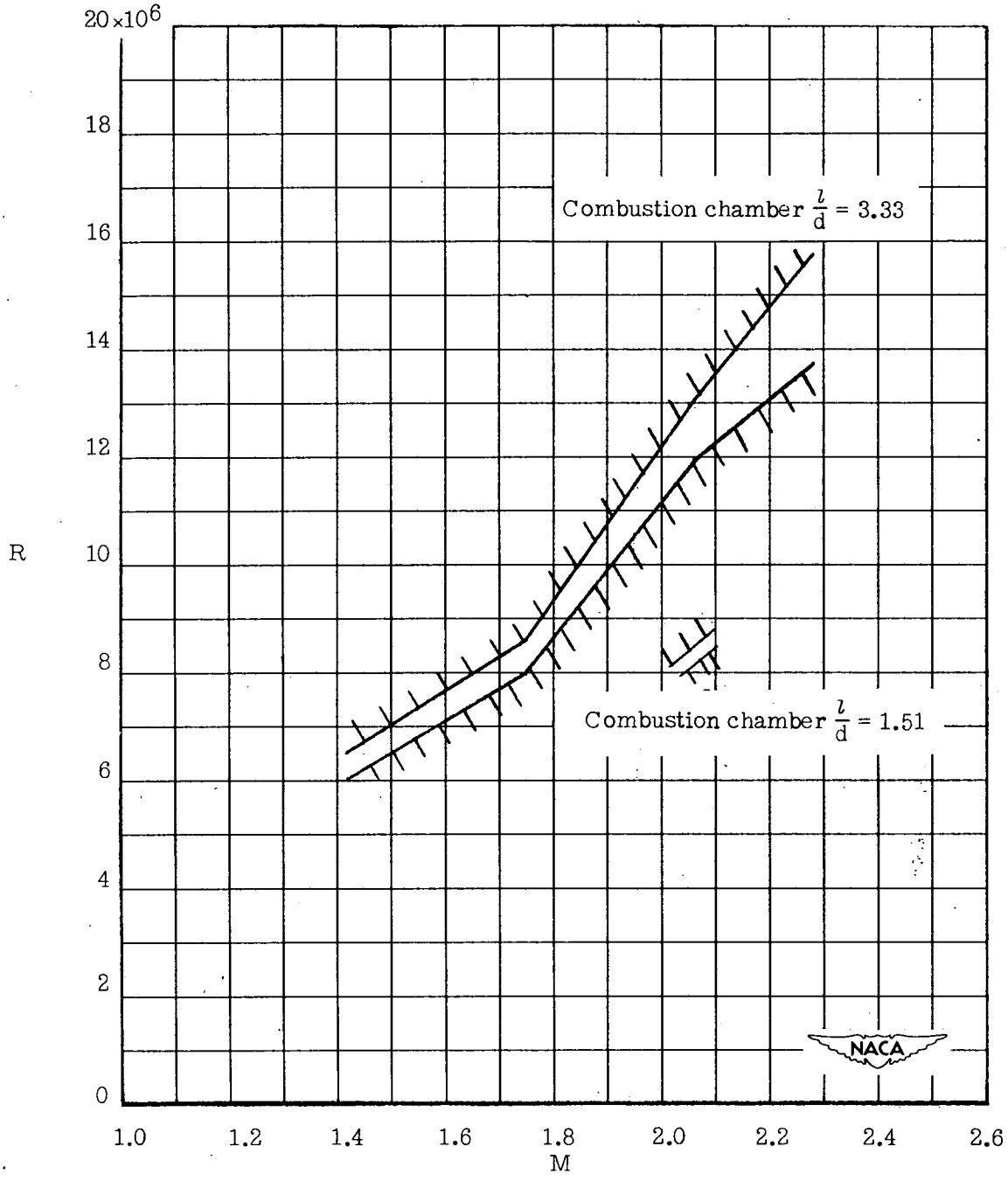
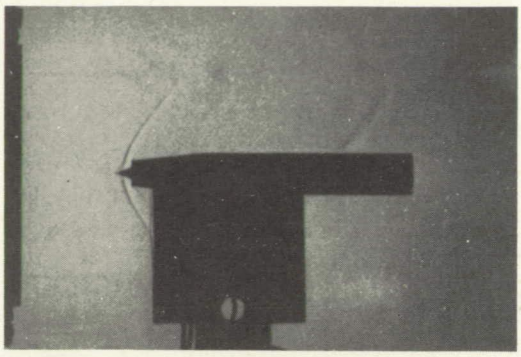
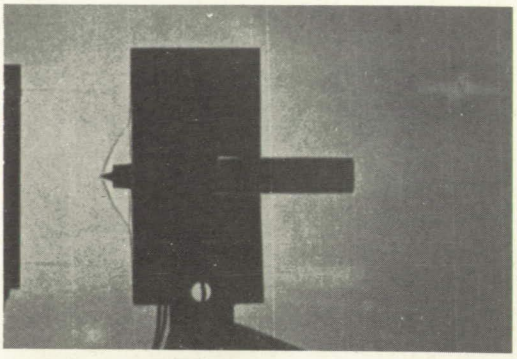


Figure 4.- Variation of Reynolds number with Mach number for the engine.

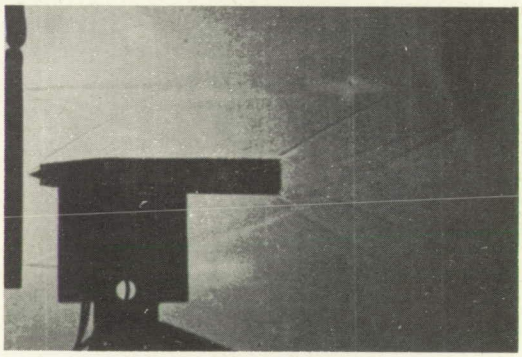


Without drag strut

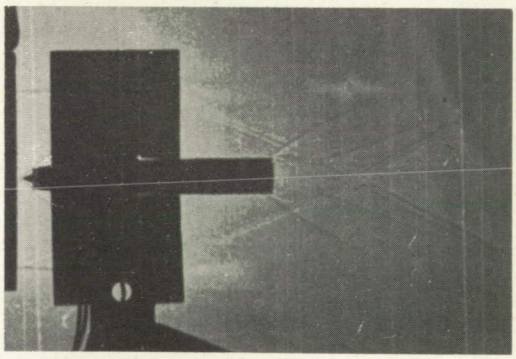


With drag strut

M = 1.42



Without drag strut



With drag strut

M = 2.28

(a) Flow about engine with drag cup installed.

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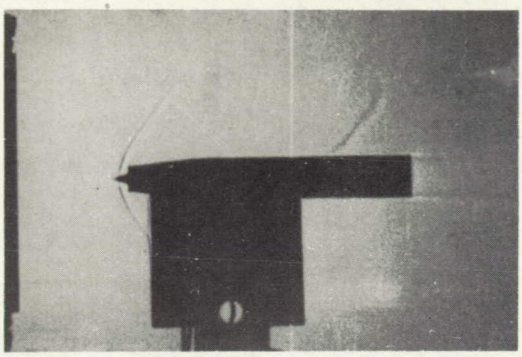
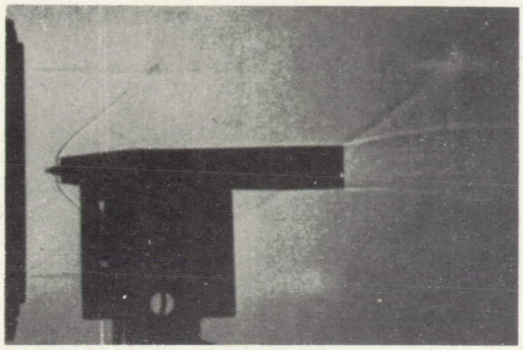
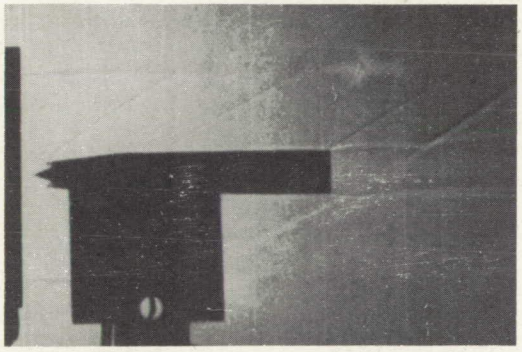
Figure 5.- Shadowgraphs of the flow about the ram-jet engine with the 3.33-inch combustion chamber.



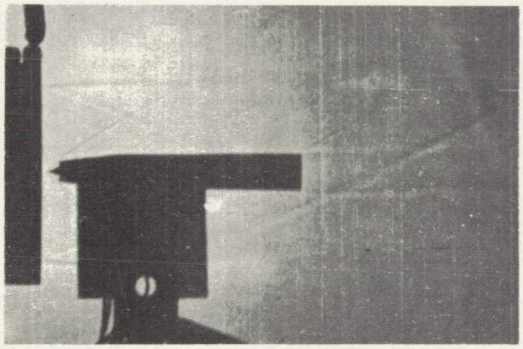
M = 1.42



M = 1.75



M = 2.06



M = 2.28

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(b) Ram-jet engine burning at stoichiometric fuel-air ratio.

Figure 5.- Concluded.

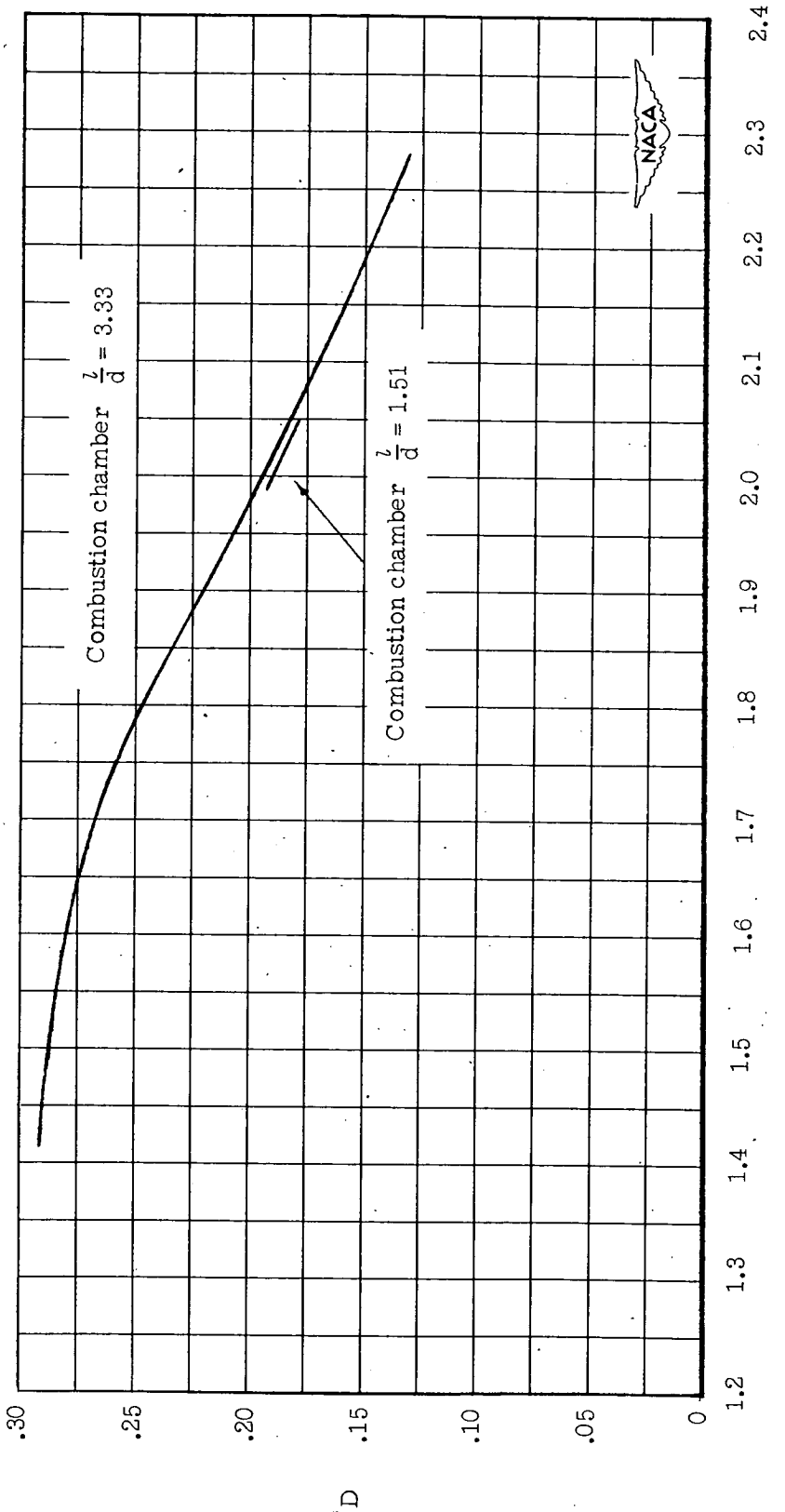

Figure 6.- Variation of tare drag coefficient with Mach number.

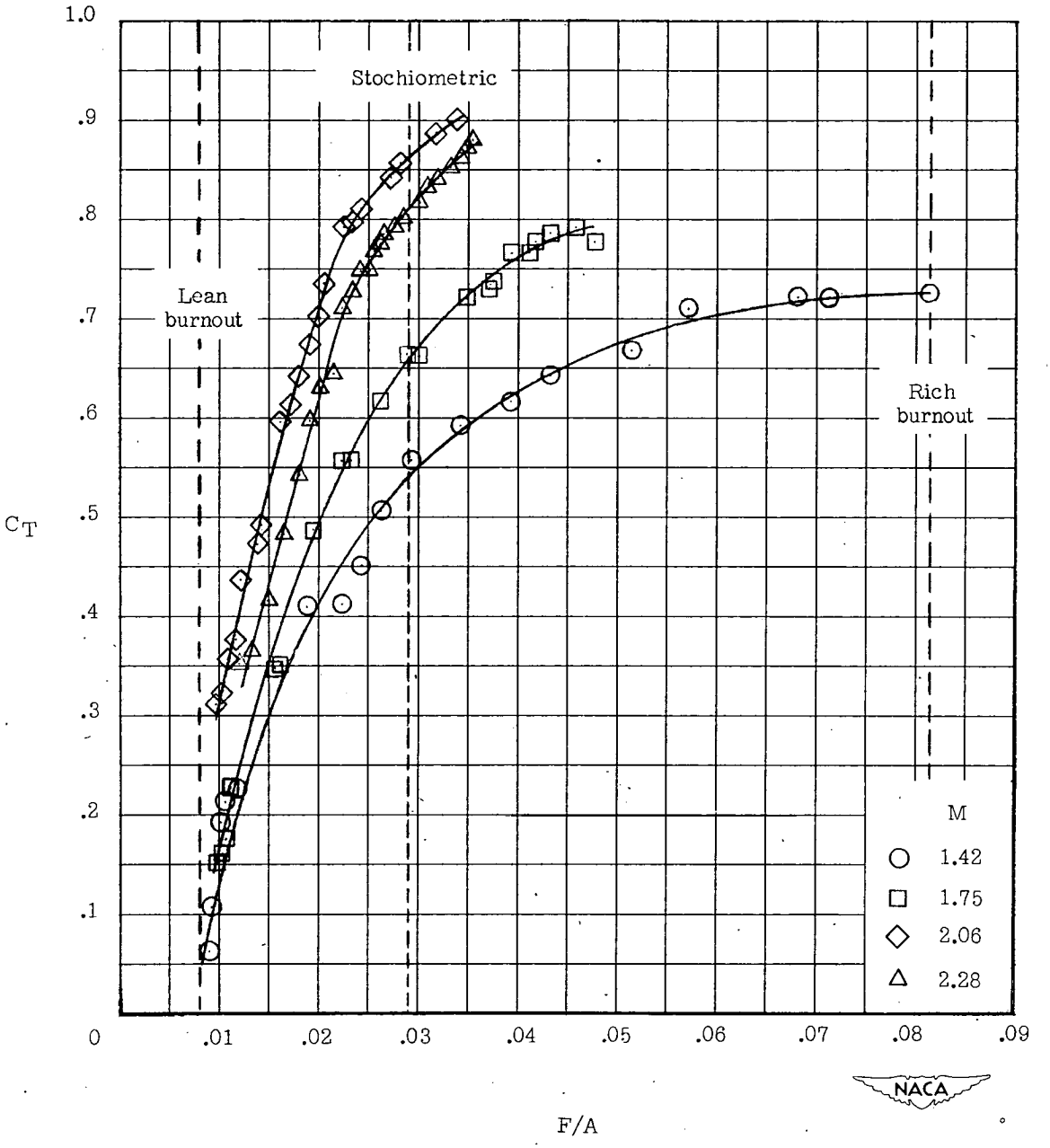

Figure 7.- Variation of coefficient of thrust with fuel-air ratio with combustion chamber $\frac{l}{d} = 3.33$.

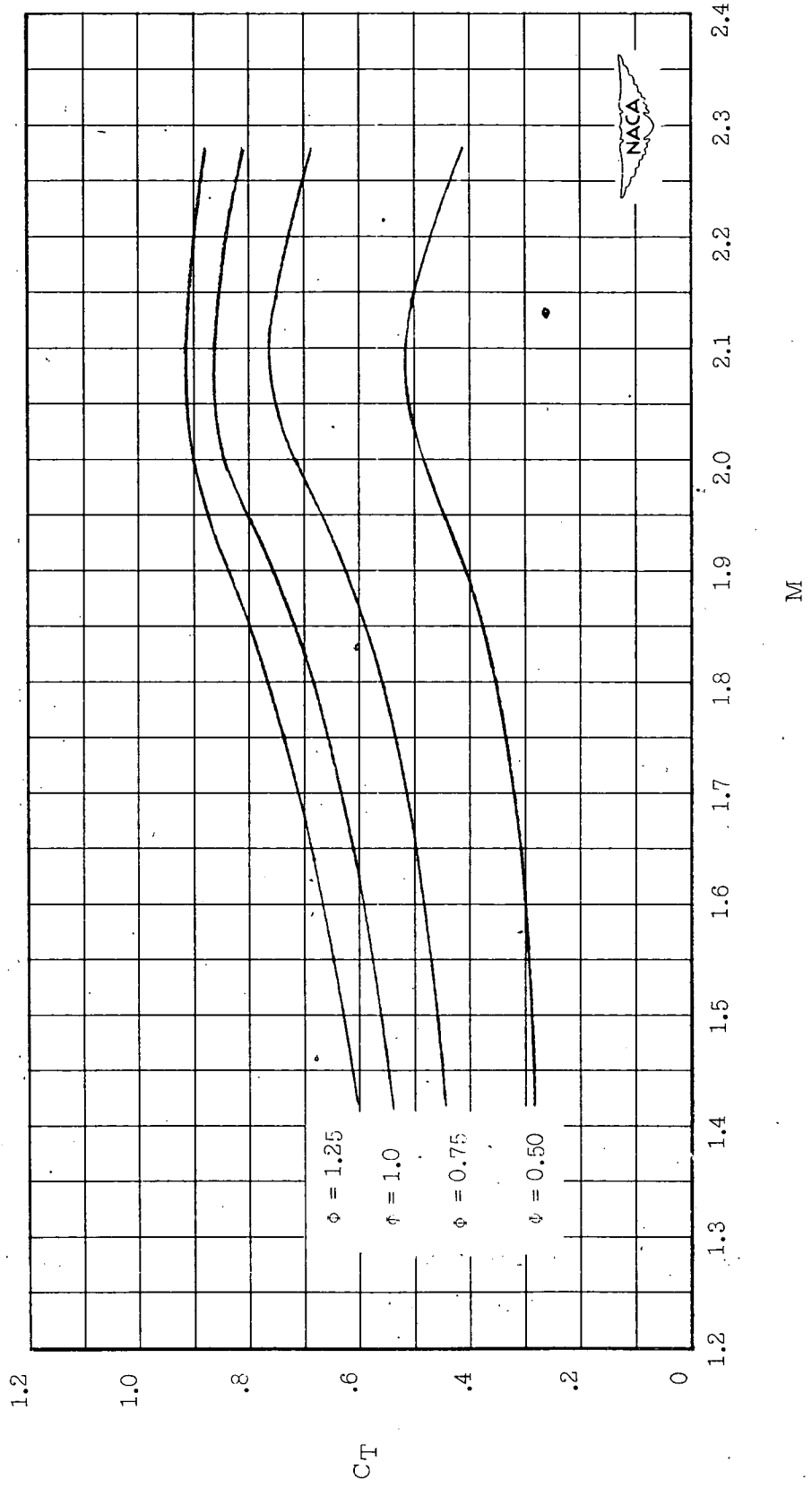

Figure 8.- Variation of thrust coefficient with Mach number for constant equivalence ratios with combustion-chamber length $\frac{l}{d} = 3.33$.

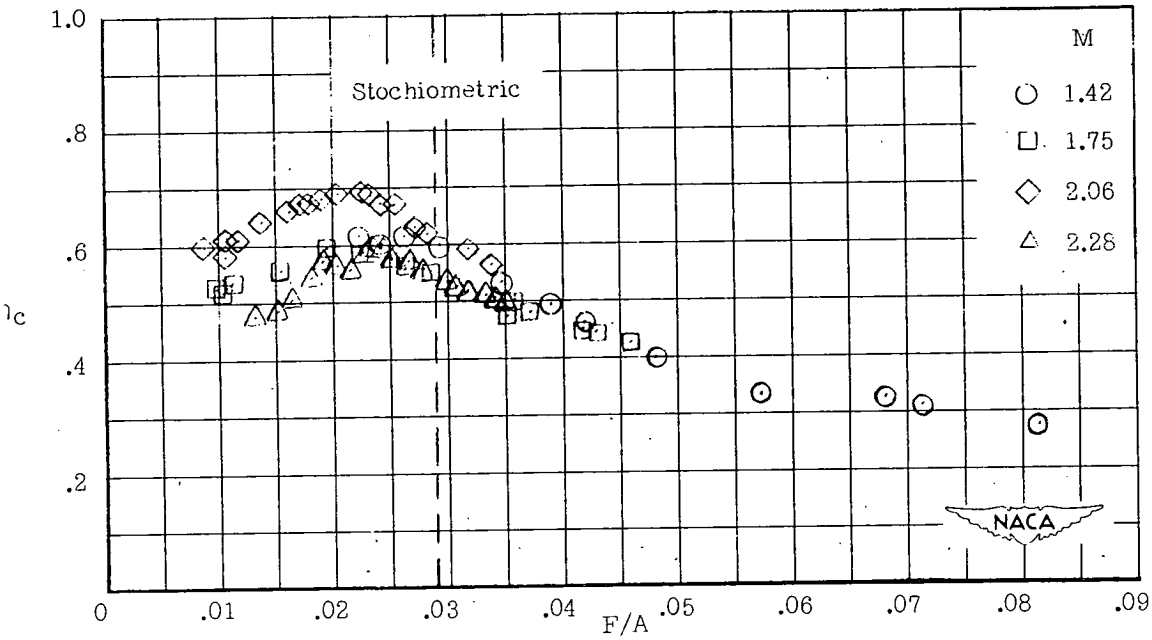

Figure 9.- Variation of combustion efficiency with fuel-air ratio with combustion chamber $\frac{l}{d} = 3.33$.

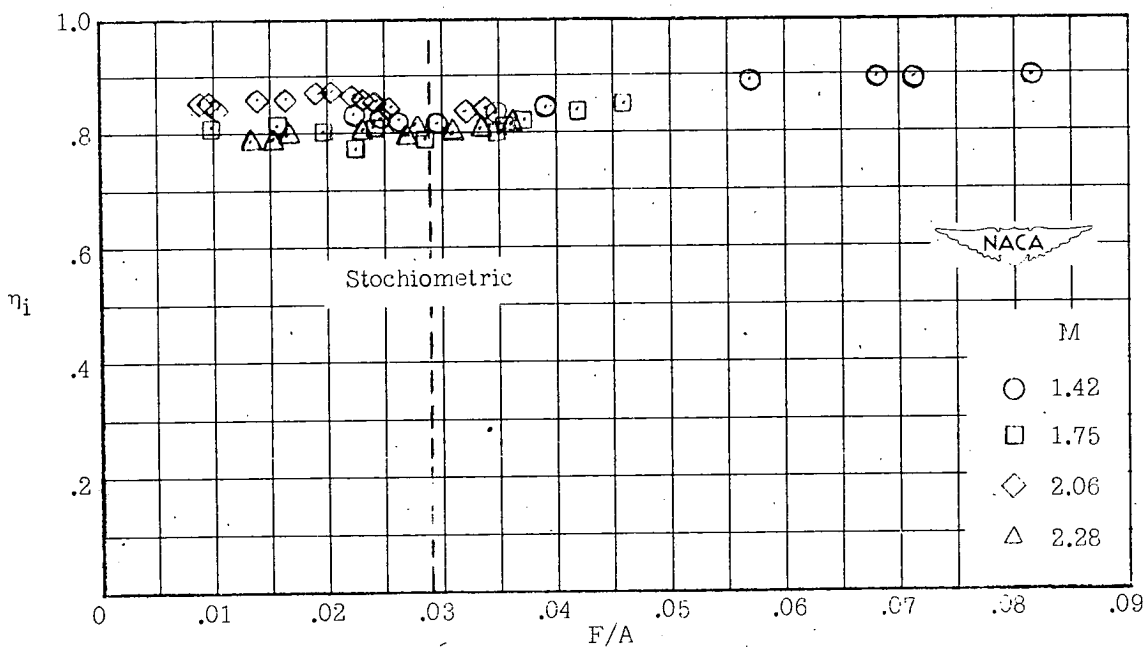

Figure 10.- Variation of impulse efficiency with fuel-air ratio with combustion chamber $\frac{l}{d} = 3.33$.

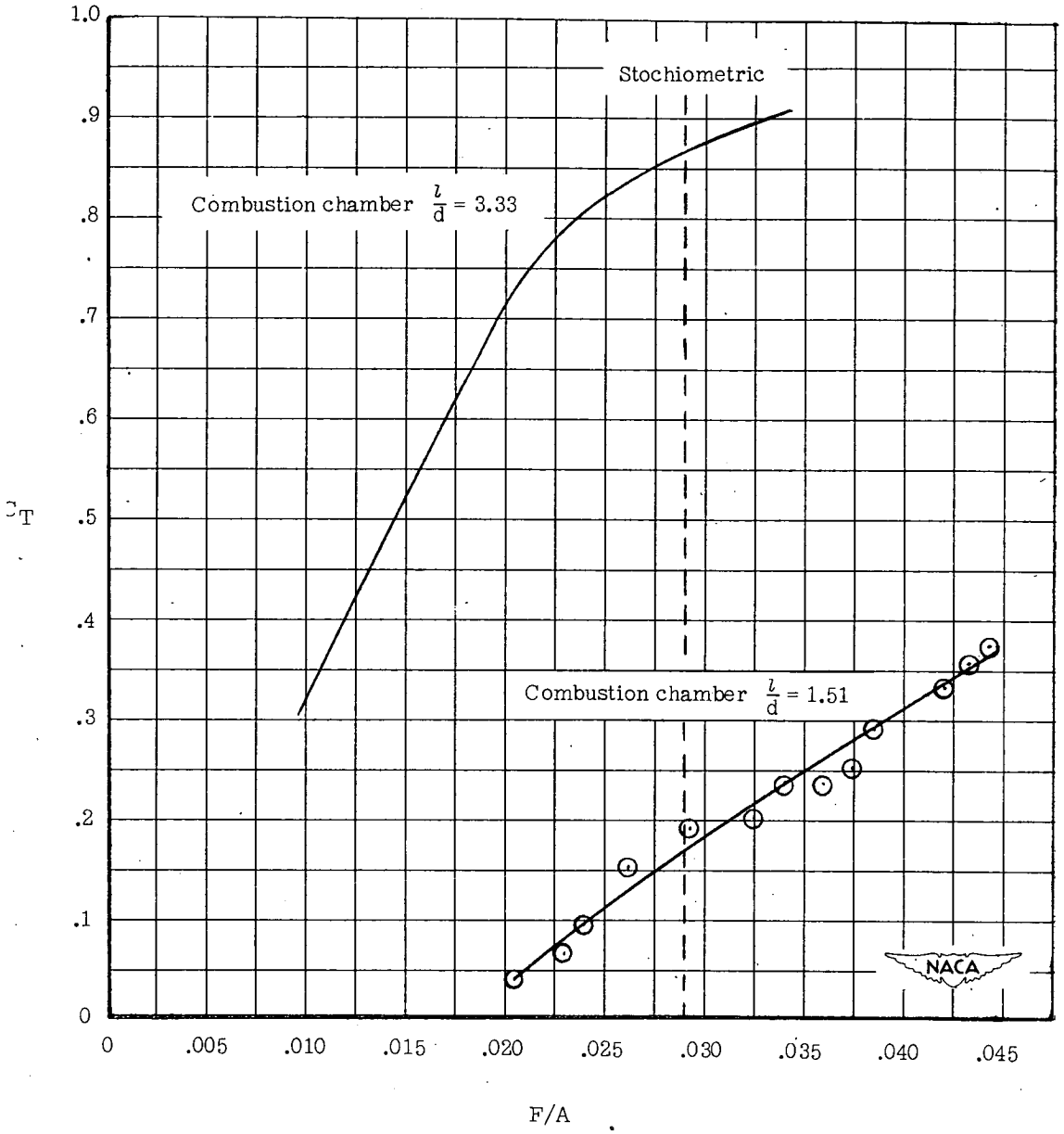

Figure 11.- Effect of decreasing combustion-chamber length on C_T at $M = 2.06$.

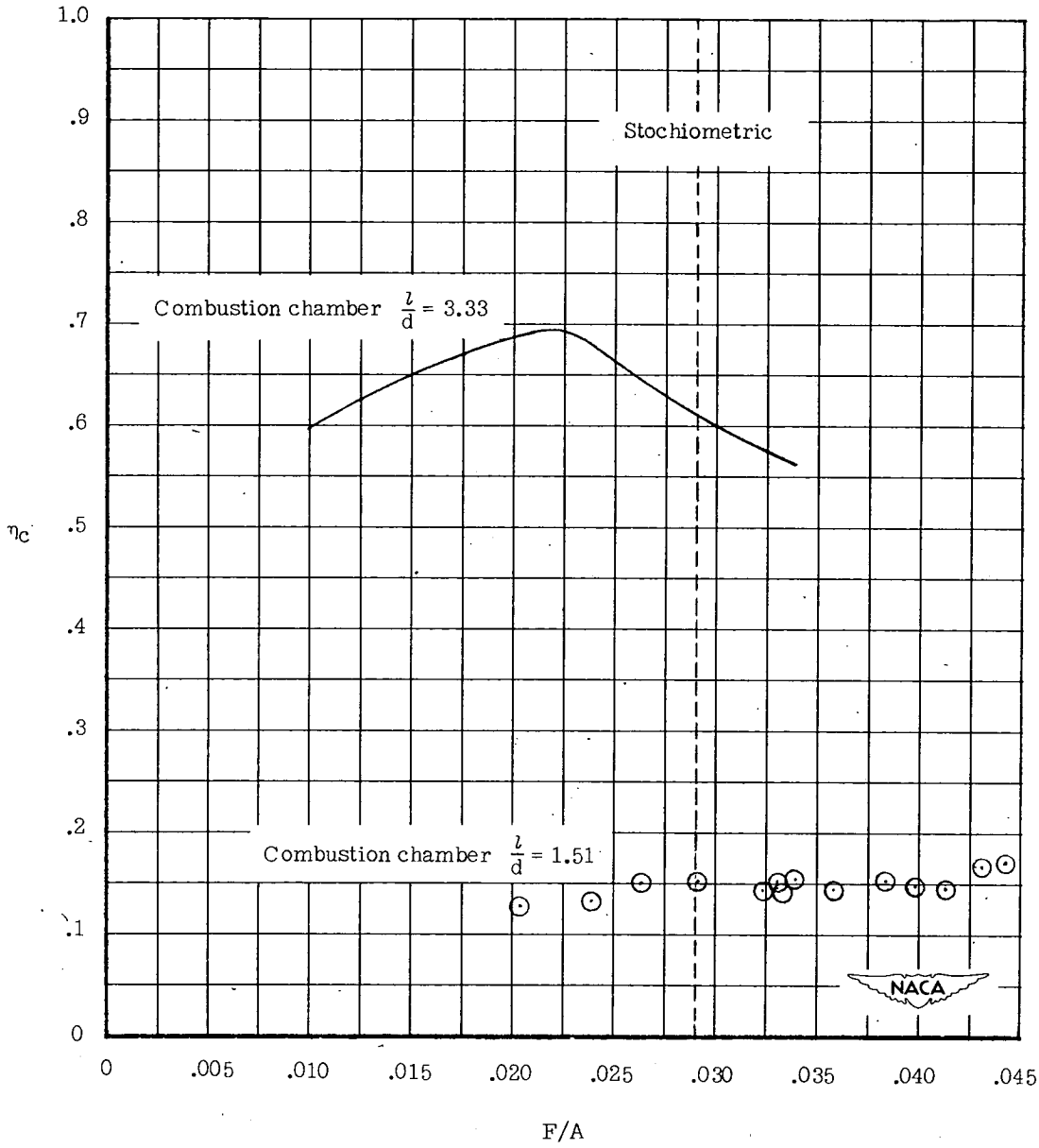

Figure 12.- Effect of reducing combustion-chamber length on combustion efficiency at M = 2.06.

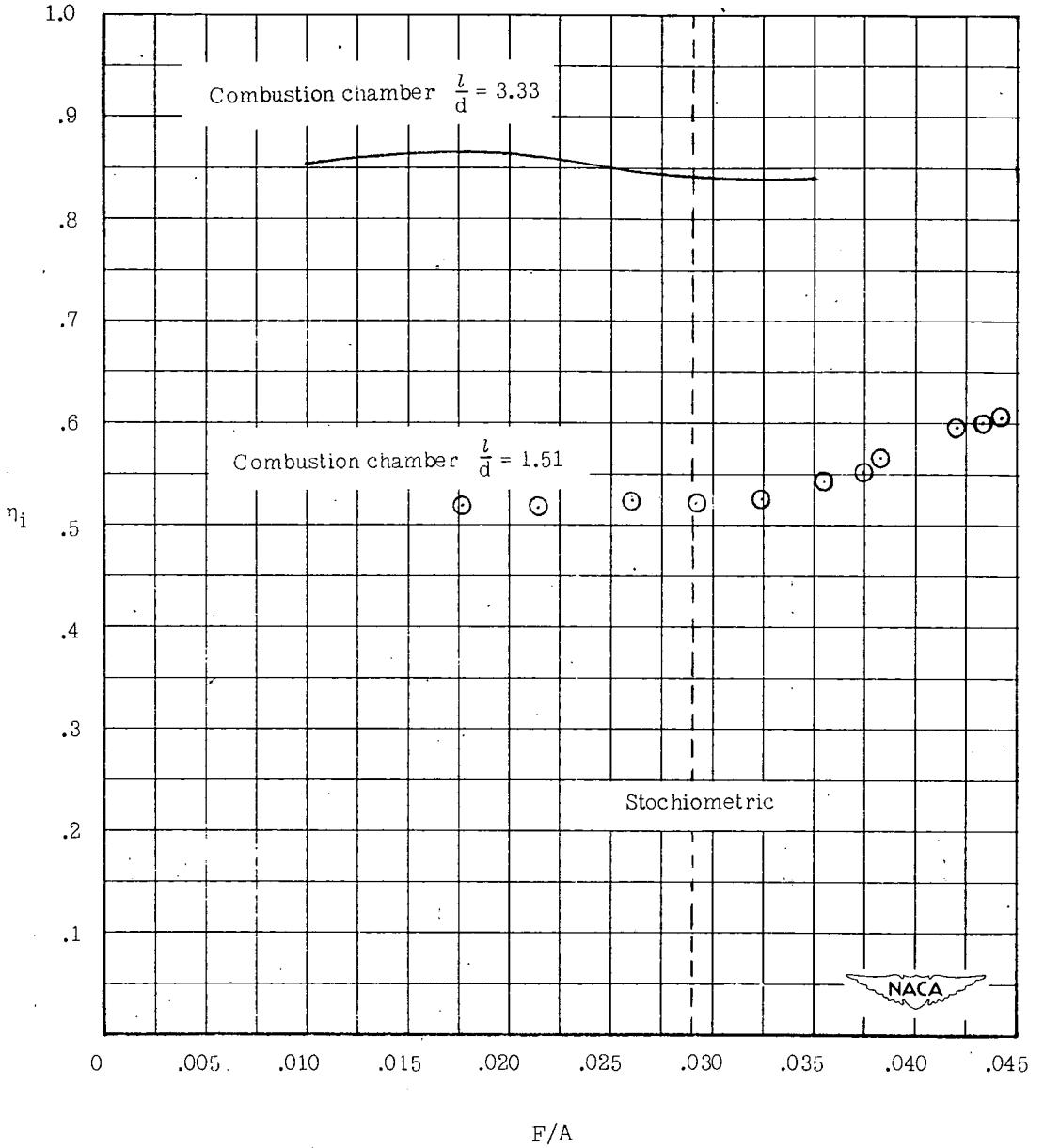

Figure 13.- Effect of reducing combustion-chamber length on impulse efficiency at M = 2.06.

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