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RESEARCH MEMORANDUM

FREE-JET PERFORMANCE OF 16-INCH RAM-JET ENGINE WITH SEVERAL FUELS

By Fred A. Wilcox

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FREE-JET PERFORMANCE OF 6-INCH RAM-JET ENGINE WITH SEVERAL FUELS

By Fred A. Wilcox

SUMMARY

Several fuels were used in a 16-inch ram-jet engine during a free-jet investigation of ram-jet performance in the NACA Lewis altitude wind tunnel. The fuels used were: gasoline (AN-F-48b), kerosene (AN-F-32), blend (by volume) of 50-percent gasoline and 50-percent propylene oxide, blend (by volume) of 75-percent kerosene and 25-percent propylene oxide, and isopentane.

Data are presented showing ranges of operation, combustion efficiencies, and weight and volume specific fuel consumptions obtained with the various fuels. Maximum ranges of operation were obtained with the blends of propylene oxide. Under the more difficult operating conditions (low inlet temperatures), fuels having the lowest 50-percent boiling points gave the highest combustion efficiencies. Gasoline gave minimum values of weight specific fuel consumption, whereas kerosene gave minimum values of volume specific fuel consumption.

INTRODUCTION

During a free-jet study of the internal performance of a 16-inch ram-jet engine conducted at the NACA Lewis laboratory (reported in reference 1), data were obtained with several fuels. These data, which are reported herein, do not constitute a systematic and comprehensive study of the effect of fuel on ram-jet performance, but are sufficient to give some trends in the effects of specific fuels on engine performance.

The fuels investigated were: clear gasoline (AN-F-48b), kerosene (AN-F-32), blend (by volume) of 50-percent gasoline plus 50-percent propylene oxide, blend (by volume) of 75-percent kerosene plus 25-percent propylene oxide, and isopentane.

The fuels gasoline and kerosene were selected because of their availability and current use in aircraft. The two blends were selected

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on the basis of previous investigations with propylene oxide (references 2 and 3). Isopentane was investigated because of the low 50-percent boiling point, a desirable property for engine operation under severe burner-inlet conditions (references 4 to 7). 1413

In order to provide a basis for comparison, the same burner configuration was used with all fuels. Changes in the combustor design would therefore probably influence the trends reported herein.

Data are presented at Mach numbers of 1.35, 1.50, and 1.73 for altitudes ranging between 35,000 and 44,000 feet. The operable fuel-air-ratio range and the amount of heat contained in the fuel per pound of air are indicated. Inasmuch as the fuel selection will in many cases depend on the engine flight plan, the fuel consumption is reported on both a weight and a volume basis.

APPARATUS AND PROCEDURE

A schematic diagram of the experimental apparatus in the Lewis altitude wind tunnel is shown in figure 1. Free-jet supersonic nozzles were attached to the end of the ram pipe through which air enters the tunnel. The ram-jet engine is shown in figure 2 with the inlet mounted downstream of the supersonic nozzle outlet.

The following 12-inch-outlet-diameter free-jet nozzles were used:

Design Mach number	Distance from nozzle outlet to ram-jet inlet (in.)
1.35	20
1.50	10
1.73	6

Air entering the supersonic nozzle was dried to prevent condensation of moisture and was heated to the stagnation temperature at the simulated flight condition. For each wind-tunnel pressure altitude, the desired pressure ratio across the supersonic nozzle was obtained by throttling the air from initial atmospheric pressure.

A schematic drawing of the 16-inch-diameter engine is shown in figure 3. The over-all engine length was 181 inches, 90 inches of which were combustion chamber and outlet nozzle.

A single oblique-shock inlet designed for external compression was used. The spike (included cone angle, 46°) was remotely adjustable

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so that the shock it generated could be adjusted to intercept the inlet lip at all Mach numbers investigated.

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A vortex pilot burner, built into the downstream end of the diffuser center body, provided a continuous source of ignition. Air entered duct inlets in two of the center-body rear-support struts and was discharged into the pilot-burner chamber. Propylene oxide was introduced through a single commercial spray nozzle and the fuel-air mixture was ignited by a standard turbojet spark plug.

The water-cooled combustion chamber and outlet nozzle were constructed of Inconel. A movable water-cooled outlet-nozzle plug was used with a converging 13.75-inch-diameter outlet nozzle and was set at outlet-area to combustion-chamber-area ratio of 0.74.

The spray-nozzle fuel injector employed is shown in figure 4. Four modified commercial spray nozzles were mounted on each of four segments of this injector. The external contour of the nozzles was machined to reduce the aerodynamic drag; the nozzles were of two capacities, 0.347 and 0.683 gallon per minute at a pressure differential of 100 pounds per square inch. Fuel was sprayed in an upstream direction with the fuel injectors set at a mean fuel radius of 5.22 inches. A corrugated-gutter flame holder (fig. 5) was located 17 inches downstream of the plane of fuel injection.

The fuels used in this investigation have the following properties:

Fuel	Lower heating value (Btu/lb)	Specific gravity	Stoichiometric fuel-air ratio	Initial boiling point (°F)	50-percent boiling point (°F)	Final boiling point (°F)
Gasoline	19,000	0.704	0.067	112	204	309
Kerosene	18,500	.792-.835	.068	318	374	439
Isopentane	19,300	.622	.065	83	----------	83
50-percent gasoline and 50-percent propylene oxide	16,040	.767	.086	91	112	344
75-percent kerosene and 25-percent propylene oxide	17,140	.802-.834	.077	95	366	433
Propylene oxide	13,075	.831	.105	93	----------	93

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Engine air flow was computed from total- and static-pressure surveys at station X (fig. 3). Jet thrust was calculated from pressure surveys at the exhaust-nozzle outlet obtained with a tail rake that had previously been calibrated with the tunnel scales in the connected-pipe phase of this investigation (reference 8). 1413

Values of combustion efficiency are based on the enthalpy rise in the gas flowing through the engine plus the heat lost to the combustion-chamber cooling water divided by the total lower heating value of the main and pilot fuels. The net-thrust coefficient is based on the engine frontal area (area of 16-in.-diam. circle).

RESULTS AND DISCUSSION

Range of Operation

The over-all ranges of fuel-air ratio and equivalence ratio (actual fuel-air ratio divided by stoichiometric fuel-air ratio) at which operation was obtained for the various fuels and engine operating conditions are presented in figure 6. Also presented is the heat input in Btu of available heat per pound of air (lower heating value of fuel multiplied by fuel-air ratio). The narrowest range of operation was obtained with kerosene; burning with both kerosene and isopentane, which also had a narrow range of operation, was rough. Under some conditions, burning could not be obtained with kerosene, whereas operation with the other fuels was possible. Smoothest burning and maximum range were obtained with the blends of propylene oxide with gasoline and kerosene. The range of operation obtained with gasoline was somewhat less than the ranges obtained with the blends.

In the plot of equivalence ratio (fig. 6(b)) gasoline, isopentane, and kerosene have nearly the same heat input at a given equivalence ratio, but the blends of propylene oxide have greater heat inputs because the high stoichiometric fuel-air ratios more than compensate for the low heating values.

Combustion Efficiency

Combustion efficiencies obtained with the 0.683-gallon-per-minute fuel nozzles are shown in figure 7 for an approximate heat input of 800 Btu per pound of air as a function of the 50-percent boiling point of the fuel. The data are for several free-jet Mach numbers and pressure altitudes and for two inlet-air temperatures. Data obtained at an inlet-air temperature of 110° F were for conditions where the inlet-air

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temperature corresponded approximately to the altitude and free-jet Mach number. The data at 180° F were obtained when the air dryer became saturated and the air was heated to 180° to avoid condensation. The effect of the difference in moisture content of the air on combustion efficiency was negligible. Combustion-chamber-inlet static pressures were approximately 1500 to 1700 pounds per square foot, except for the data at a free-jet Mach number of 1.35, where the pressure was 800 to 1060 pounds per square foot. These combustion-chamber-inlet pressures and temperatures represent moderate ram-jet operating conditions. The data obtained at an inlet-air temperature of 110° F, however, represent more difficult conditions of operation than those at 180° F because of the lowered air temperature and also, in the case of the data at a free-jet Mach number of 1.35, the lowered inlet-air pressure.

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Little difference in combustion efficiency was obtained for the various fuels at free-jet Mach numbers of 1.50 and 1.73 with an inlet-air temperature of 180°. Isopentane gave the lowest combustion efficiency, 61.5 percent, and the blend of gasoline and propylene oxide the highest, 70 percent. At an inlet-air temperature of 110° F, however, combustion efficiency decreased as the 50-percent boiling point of the fuel increased. At a free-jet Mach number of 1.35, the combustion efficiency decreased from a value of 68 percent for the blend of gasoline and propylene oxide to 47 percent for gasoline. At a free-jet Mach number of 1.50, the combustion efficiency decreased from 63 percent for isopentane to 49 percent for the blend of kerosene and propylene oxide. No operation could be obtained with kerosene for this condition.

Similar decreases in combustion efficiency with increasing 50-percent boiling point of the fuel are reported in references 2 and 3 with propylene oxide, kerosene, and a blend of 75-percent kerosene and 25-percent propylene oxide. Combustion-efficiency data from these references are presented in the following table:

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Propylene oxide		Kerosene		75-percent kerosene and 25-percent propylene oxide	
Equivalence ratio	Combustion efficiency	Equivalence ratio	Combustion efficiency	Equivalence ratio	Combustion efficiency
0.776	83	0.765	64		
.943	82	.941	62		
.667	85.5	.654	74		
.781	84	.794	62		
.933	83	.932	62		
		1.294	49	1.31	57

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Isopentane gave rather poor performance in spite of the similarity of its 50-percent boiling point to that of propylene oxide, which suggests that other factors such as ignition energy and flame speed are important in the selection of a fuel.

Specific Fuel Consumption

Weight specific fuel consumption in pounds of fuel per hour per pound of net thrust and volume specific fuel comsumption in cubic feet of fuel per hour per pound of net thrust (free-jet Mach number, 1.35) are presented as a function of thrust coefficient in figure 8 for clear gasoline and the blend of 50-percent gasoline and 50-percent propylene oxide. The data are for low values of combustion-chamber inlet pressure.

The maximum thrust coefficient obtained with the blend of gasoline and propylene oxide, 0.55, was considerably better than that for gasoline alone, 0.45. In general, the weight specific fuel consumption was slightly lower for clear gasoline than for the blend. On the other hand, the volume specific fuel consumption was slightly lower for the blend than for gasoline. The two points for the blend at an altitude of 40,000 feet and a thrust coefficient of about 0.48 were obtained at fuel-air ratios greater than those giving peak combustion efficiency; the combustion efficiency decreased so rapidly that the thrust coefficient decreased and the specific fuel consumption increased.

A comparison at a free-jet Mach number of 1.50 of the specific fuel consumption with gasoline, isopentane, and the blend of 75-percent kerosene and 25-percent propylene oxide is given in figure 9.

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No operation could be obtained with kerosene at this condition. The maximum thrust coefficient of 0.55 was obtained with gasoline, as compared with 0.53 for isopentane and 0.44 with the blend of kerosene and propylene oxide. Below a thrust coefficient of 0.50, gasoline and isopentane had approximately the same values of weight specific fuel consumption. The weight specific fuel consumption with the blend of kerosene and propylene oxide was considerably above that for either gasoline or isopentane. When the fuels were compared on a volume basis, however, the blend of kerosene and propylene oxide becomes nearly as high as gasoline because of its greater density, and isopentane becomes less desirable because of its low density. The specific gravity for kerosene was considered as the average of the extreme values given in the physical-properties table in the section "Apparatus and Procedure".

Presented in figure 10 are additional data at a free-jet Mach number of 1.50, but at a higher inlet-air temperature (180° F) than that of figure 9. Increasing the burner-inlet temperature improves combustion and operation was obtained with kerosene. Because of higher combustion efficiencies at the higher inlet-air temperature (fig. 10), the absolute values of specific fuel consumption are lower for the data of figure 10 than for figure 9.

The highest thrust coefficient, 0.555, was obtained with the blend of 75-percent kerosene and 25-percent propylene oxide. Lowest values of weight specific fuel consumption for most values of thrust coefficient were obtained with gasoline, followed in order by isopentane, kerosene, and the blend of kerosene and propylene oxide. Because of the greater density, kerosene gave lowest values of volume specific fuel consumption. Gasoline and the blend of kerosene and propylene oxide had approximately equal values of volume specific consumption and isopentane, the highest.

SUMMARY OF RESULTS

From a free-jet investigation of a 16-inch ram-jet configuration in the Lewis altitude wind tunnel at free-jet Mach numbers from 1.35 to 1.73 and altitudes from 35,000 to 44,000 feet with several fuels, the following results were obtained:

1. With respect to minimum weight specific fuel consumption, gasoline gave the best performance; with respect to maximum thrust

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coefficient at low weight specific fuel consumption, a blend of 50-percent gasoline and 50-percent propylene oxide gave the best performance.

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2. Kerosene gave minimum values of volume specific fuel consumption.

3. Under the more difficult conditions of operation, highest combustion efficiency was obtained with the fuels having low 50-percent boiling points; whereas under moderate conditions of operation, little difference in combustion efficiency was observed for the various fuels.

4. The maximum ranges of operation were obtained with the blends of propylene oxide, whereas the minimum ranges were obtained with kerosene and isopentane.

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

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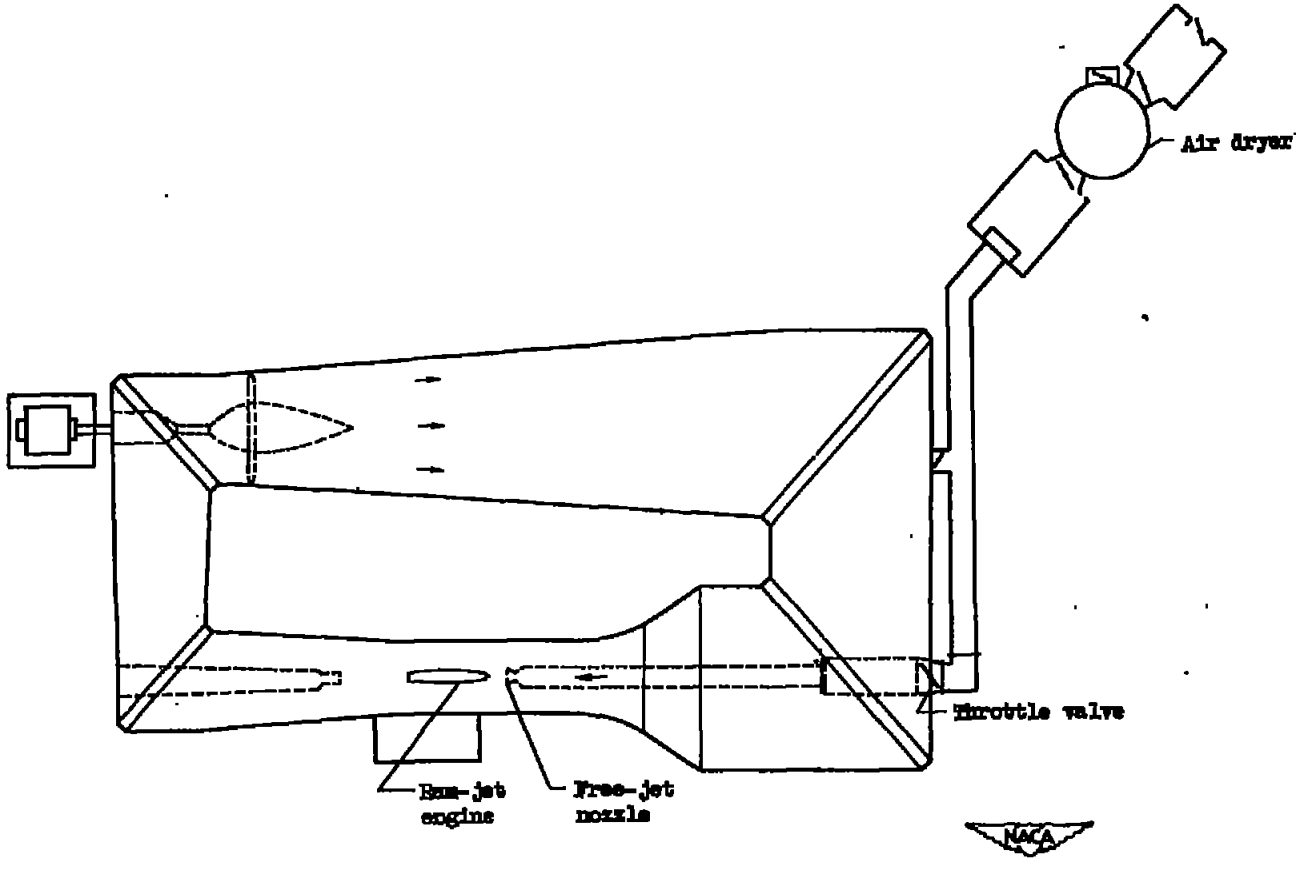

Figure 1. - Schematic diagram of Lewis altitude wind tunnel with free-jet supersonic nozzle installed.

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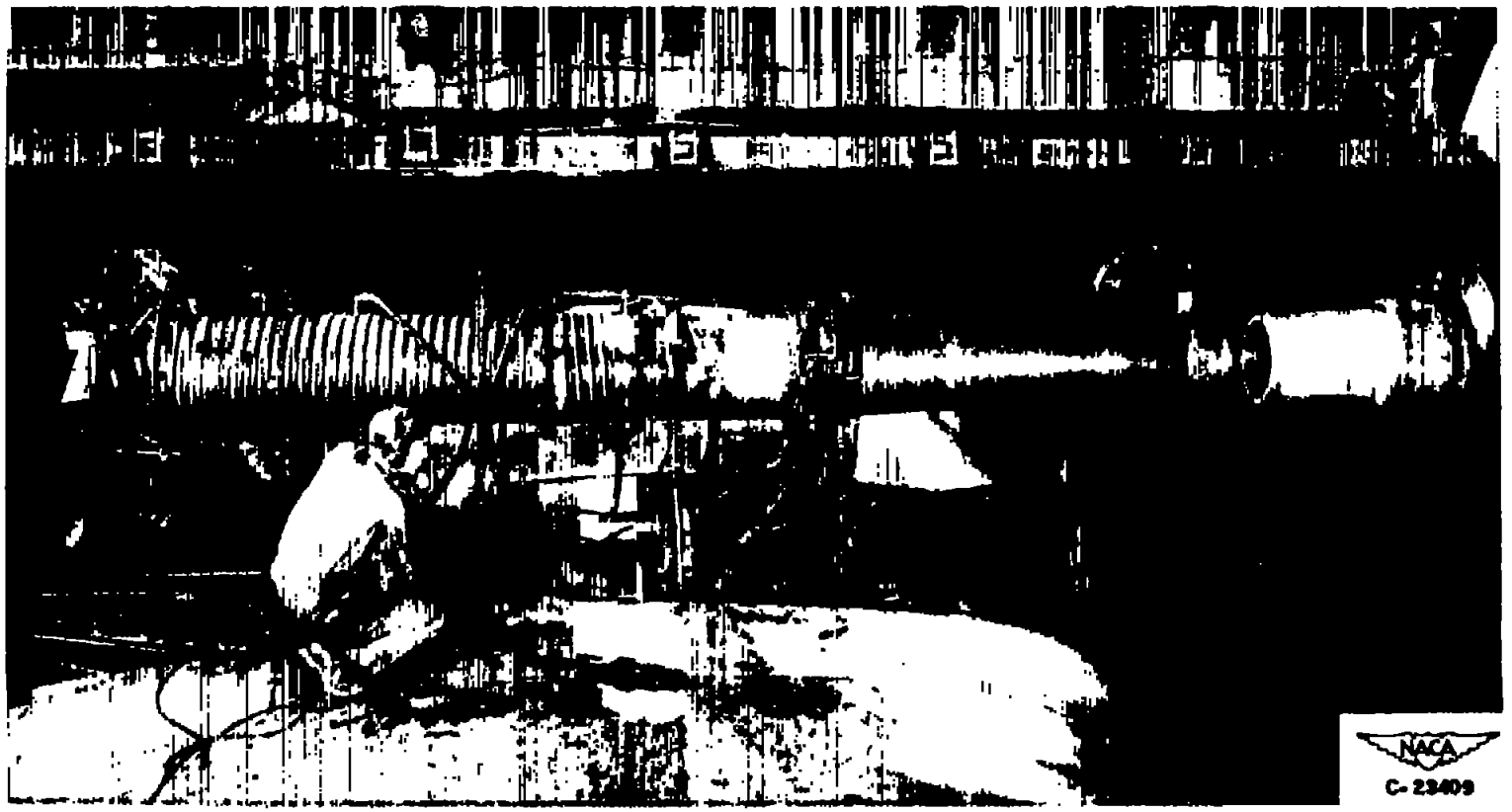

Figure 2. - Installation of 16-inch ram-jet engine in altitude wind tunnel.

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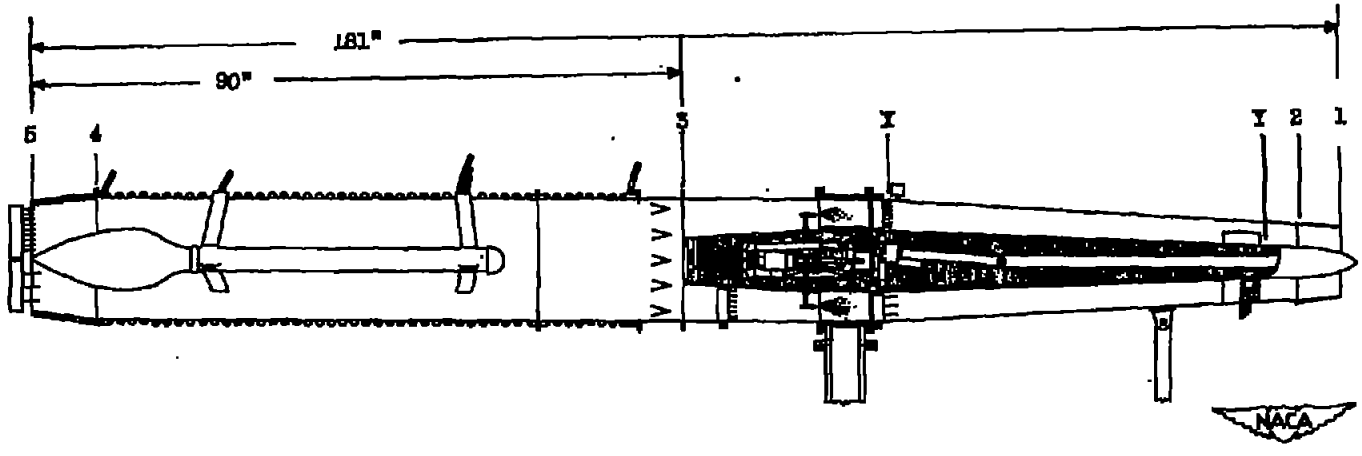

Figure 3. - Schematic diagram of 16-inch ram-jet engine.

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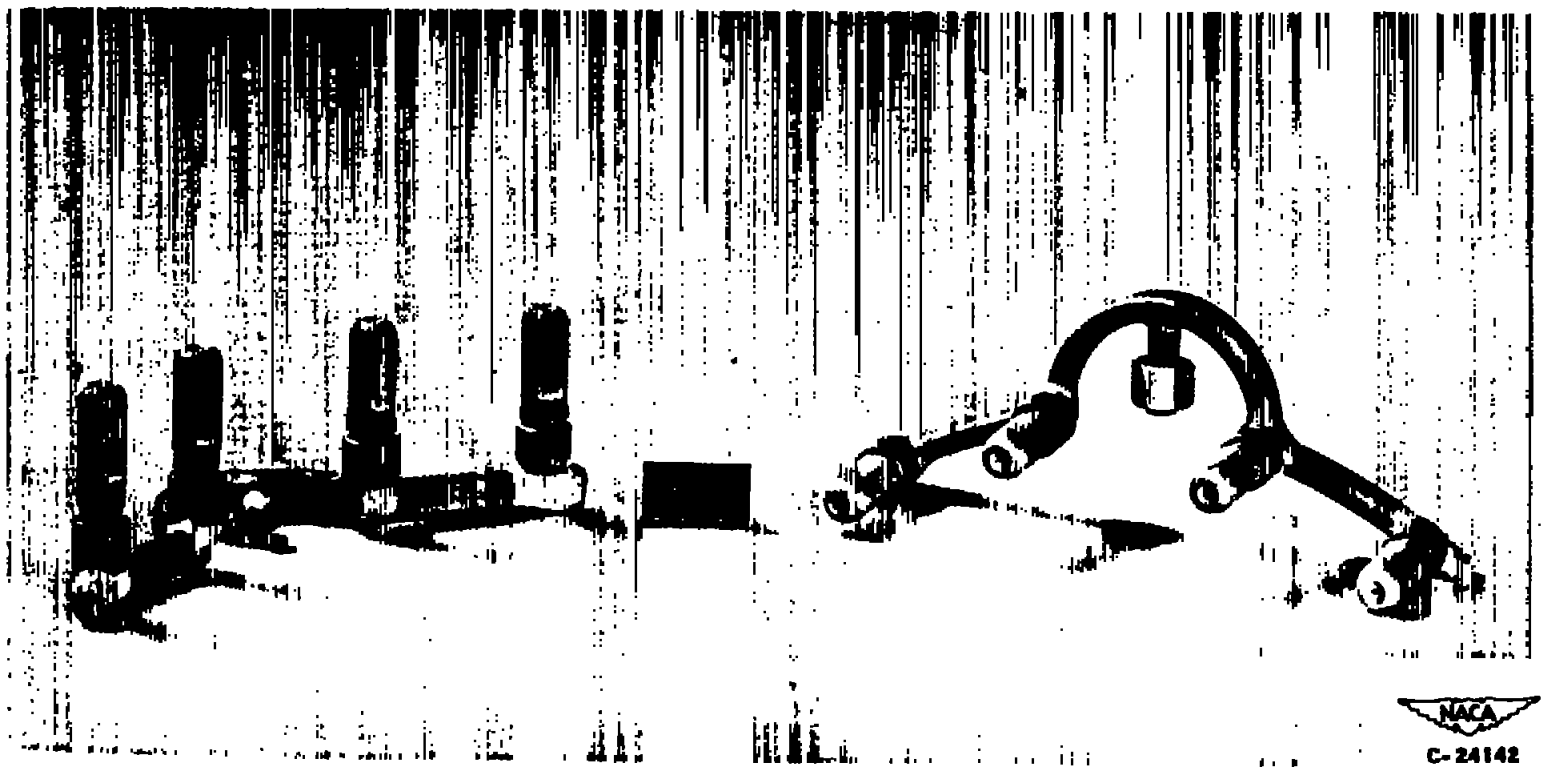

Figure 4. - Spray-nozzle fuel injector used in 16-inch ram-jet engine.

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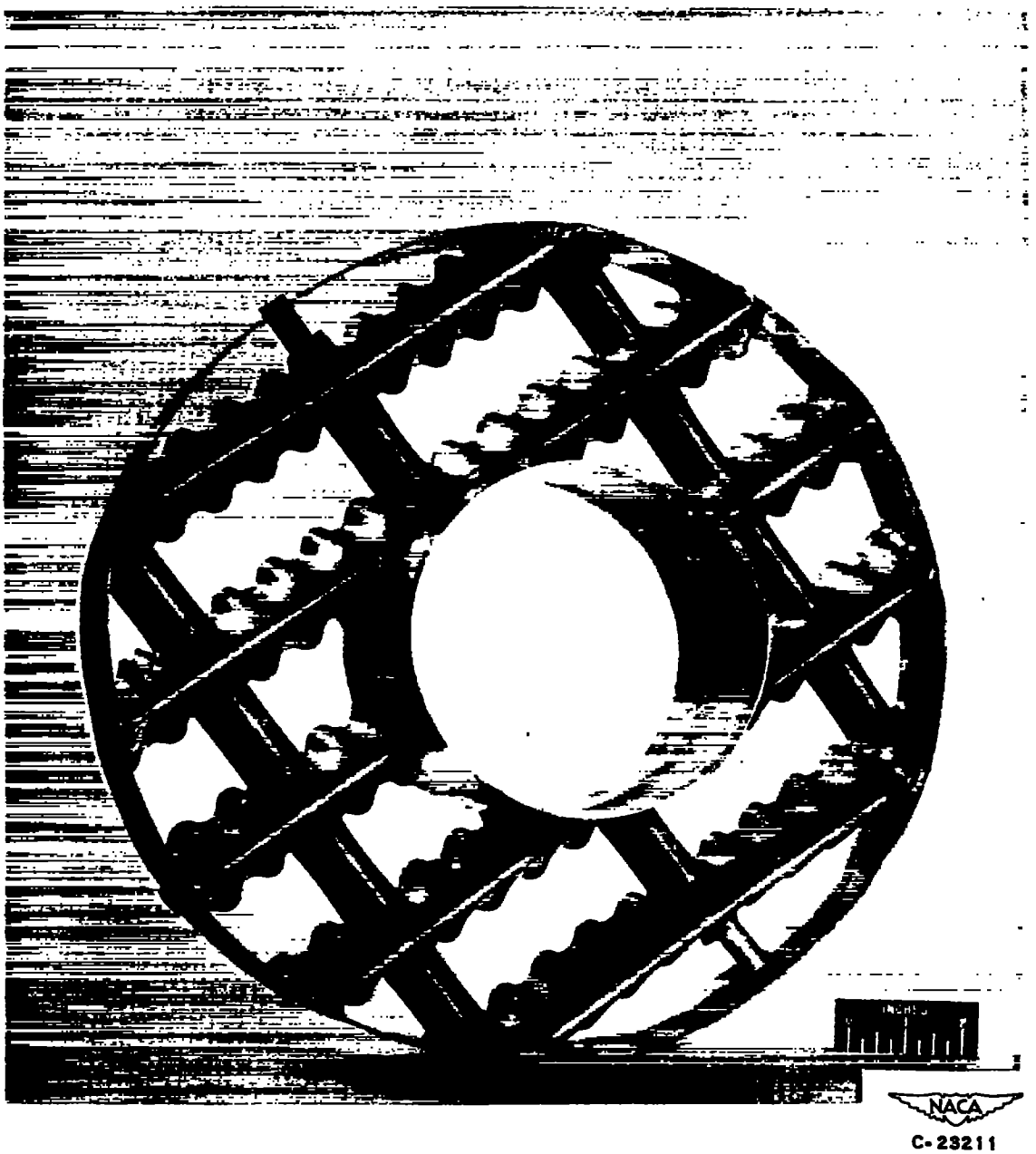

Figure 5. - Corrugated-gutter flame holder used in 16-inch ram-jet engine.

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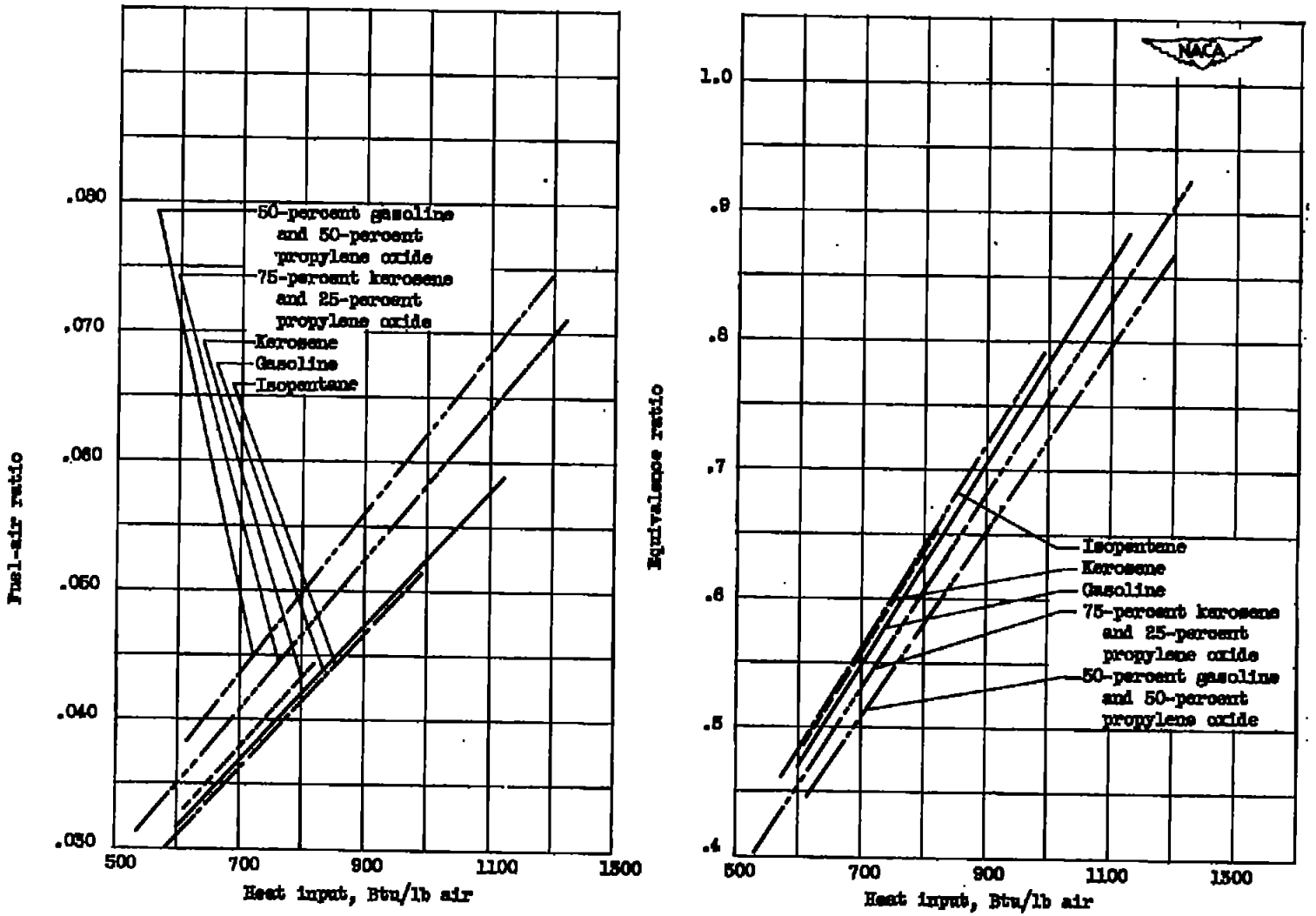

(a) Fuel-air ratio.

(b) Equivalence ratio.

Figure 6. - Operable fuel-air-ratio range and corresponding heat input of 16-inch ram-jet engine with several fuels. Free-jet Mach number, 1.35 to 1.73; altitude, 35,000 to 44,000 feet.

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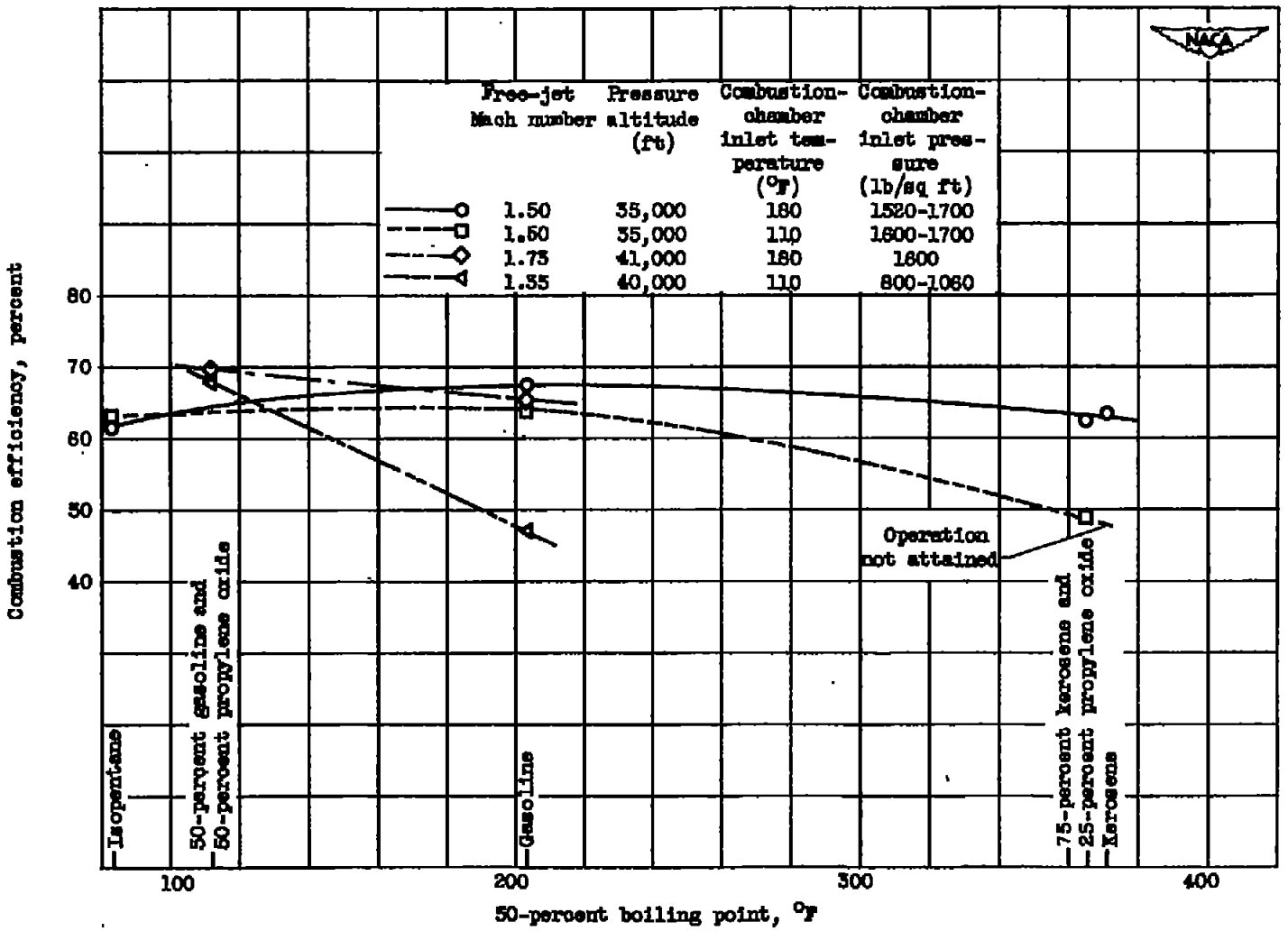

Figure 7. - Effect of 50-percent boiling point on combustion efficiency for constant rate of heat input over range of operating conditions for corrugated-gutter flame holder. Nozzle capacity, 0.683 gallon per minute; approximate heat input, 800 Btu per pound of air.

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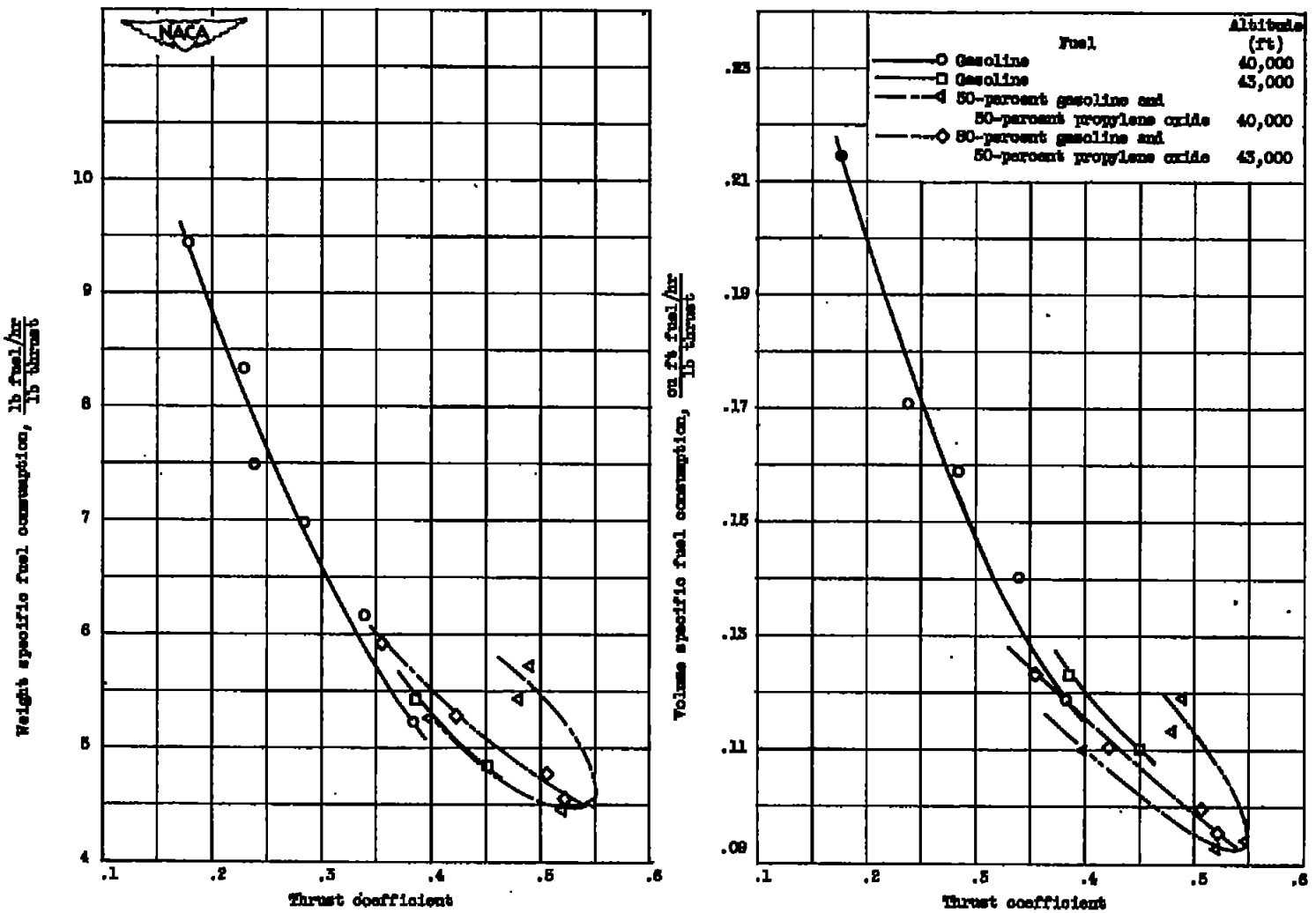

(a) Weight specific fuel consumption.

(b) Volume specific fuel consumption.

Figure 8. - Comparison of specific fuel consumption of 16-inch ram jet engine with gasoline and blend of 50-percent gasoline and 50-percent propylene oxide as fuels with corrugated-gutter flame holder. Mach number, 1.35; nozzle capacity, 0.347 gallon per minute; combustion-chamber inlet pressure, 800 to 1060 pounds per square foot; combustion-chamber inlet temperature, 110° F.

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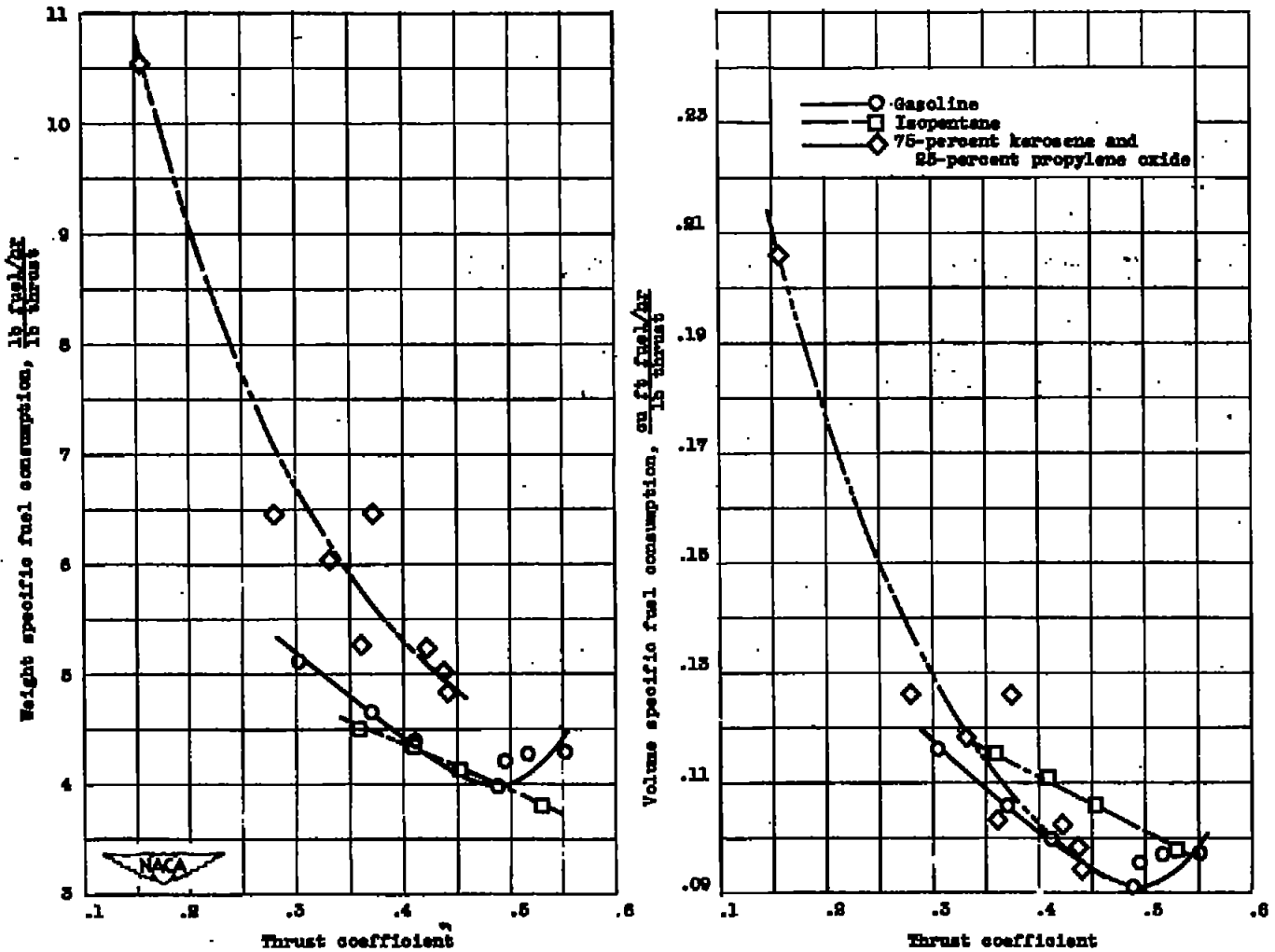

(a) Weight specific fuel consumption.

(b) Volume specific fuel consumption.

Figure 9. - Comparison of specific fuel consumption of 16-inch ram-jet engine with gasoline, isopentane, and blend of 75-percent kerosene and 25-percent propylene oxide as fuel with corrugated-gutter flame holder. Mach number, 1.50; nozzle capacity, 0.683 gallon per minute; combustion-chamber inlet pressure, 1600 to 1700 pounds per square foot; combustion chamber inlet temperature, 110° F.

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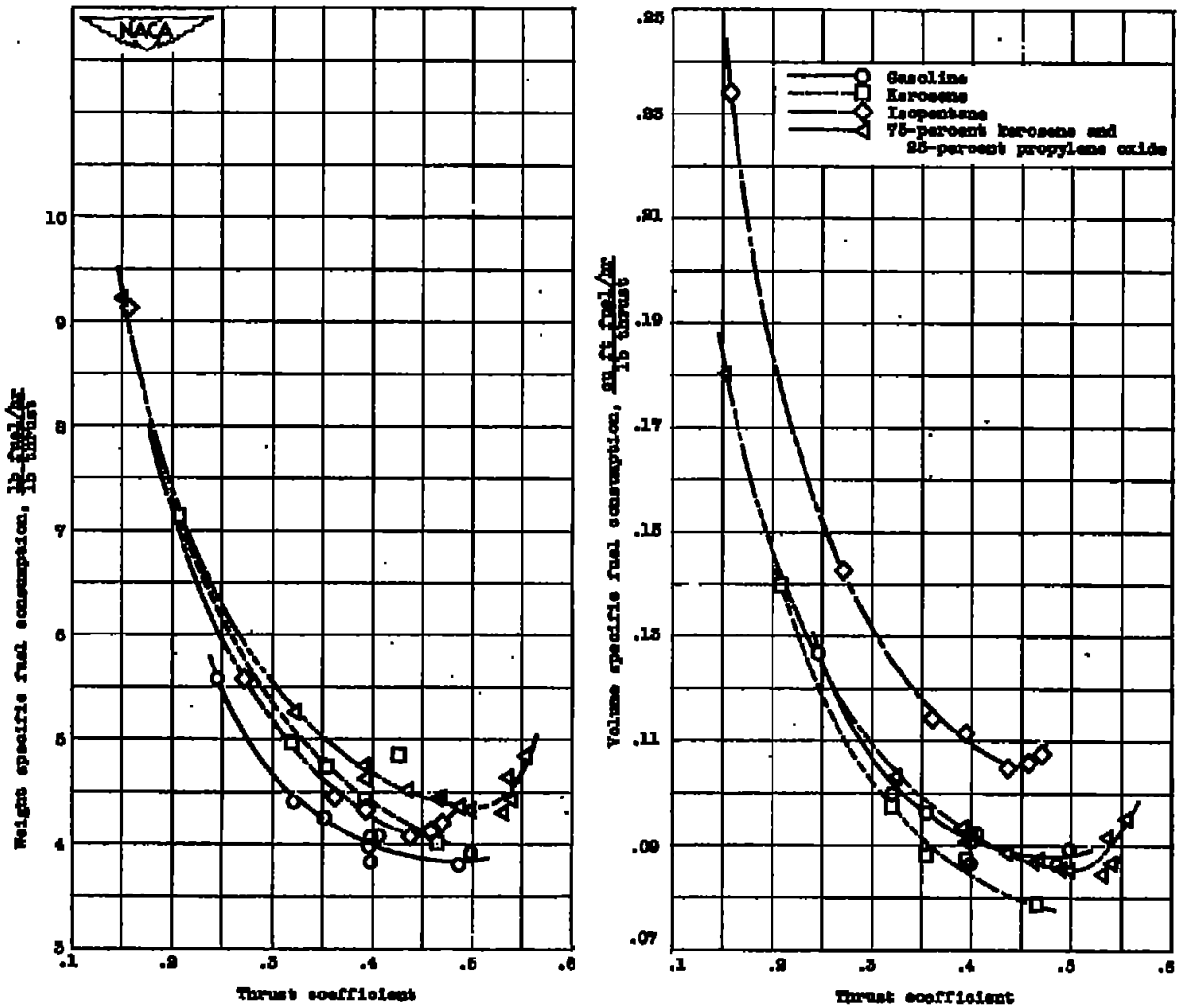

(a) Weight specific fuel consumption.

(b) Volume specific fuel consumption.

Figure 10. - Comparison of specific fuel consumption of 16-inch ram-jet engine with gasoline, kerosene, isopentane, and blend of 75-percent kerosene and 25-percent propylene oxide as fuel with corrugated-gutter flame holder. Mach number, 1.50; nozzle capacity, 0.685 gallon per minute; combustion-chamber inlet pressure, 1690 to 1700 pounds per square foot; combustion-chamber inlet temperature, 180° F.

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