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RESEARCH MEMORANDUM

EFFECT OF FUEL VOLATILITY CHARACTERISTICS ON IGNITION-ENERGY REQUIREMENTS IN A TURBOJET COMBUSTOR

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2748

SUMMARY

An investigation was conducted to determine the effect of fuel volatility characteristics on the minimum spark energy required to ignite a single tubular turbojet-engine combustor. Data were obtained at simulated static sea-level engine starting conditions for a wide range of combustor-inlet air and fuel temperatures, and also for a range of altitude inlet-air pressures and two air flows. These data and some previous ignition data are presented to indicate the relation between the Reid vapor pressures and the A.S.T.M. distillation temperatures of the fuels and the minimum ignition-energy requirements.

In order to determine the relative ignition characteristics of the fuels at various combustor-inlet pressures and two air flows, a relation between the minimum ignition-energy requirements and an empirical function of combustor-inlet air pressure and velocity $(V/\sqrt{P})$ was developed. The data obtained at both sea-level and altitude conditions showed that the A.S.T.M. 15-percent evaporated temperatures of the fuels were generally indicative of their ignition characteristics; whereas, the Reid vapor pressures of the fuels were not.

For the range of combustor-inlet conditions investigated, spark energies from 0.006 to 4.0 joules were required to ignite the various fuels.

INTRODUCTION

Operating experience has shown that ignition in turbojet-engine combustors is markedly affected by fuel-volatility characteristics. It is necessary, therefore, to specify these characteristics in order to assure satisfactory ignition at all conditions requiring engine starting.

Investigations conducted at the NACA Lewis laboratory have shown that increases in fuel volatility, as represented by decreases in A.S.T.M. evaporation temperatures and increases in Reid vapor pressure, provide improved engine starting at low inlet-air and fuel temperatures and at high altitude operating conditions (references 1 to 8). The data of reference 1 further indicate a direct relation between the A.S.T.M.

10-percent evaporated temperature of the fuel and the minimum fuel flow required for ignition. The results of these investigations do not, however, establish conclusively the fuel property or properties controlling ignition inasmuch as distillation temperature and vapor pressure of the fuels were varied simultaneously. Furthermore, fuel viscosity, which may significantly affect fuel-spray characteristics, varied considerably.

Current jet-engine fuel specifications (MIL-F-5624A, grade JP-4) contain limitations on the maximum 10-percent evaporated temperature and on the range of Reid vapor pressure with a view to assuring satisfactory ignition without too great a compromise in altitude evaporation loss and fuel availability considerations. Inasmuch as it is desirable to minimize the number of specifications of a fuel in order to ease manufacturing and availability problems, further research to determine the specific volatility characteristics that control ignition is warranted. Accordingly, the investigation reported herein was conducted to determine separate effects of A.S.T.M. distillation temperature characteristics and Reid vapor pressure on turbojet-combustor ignition. In order to eliminate viscosity as a factor, four fuels of equivalent viscosities but of different volatility characteristics were chosen. Two additional production-type turbojet engine fuels were included.

2748

The minimum spark energies required for ignition of these fuels in a single turbojet combustor were determined at operating conditions simulating both sea-level and altitude engine starting. Altitude data were obtained at two air flows for a range of combustor-inlet pressures at constant inlet-air and fuel temperature; the sea-level data simulated engine cranking conditions over a range of inlet-air and fuel temperatures. The data are analyzed and compared to indicate the relative importance of A.S.T.M. distillation temperatures and Reid vapor pressure in determining ease of ignition in the combustor. In order to supplement these data, results from an earlier investigation (reference 2) are included.

FUELS

The following six fuels were used in the ignition investigation:

NACA Fuel	Description
51-196	Nominal 7-pound Reid vapor pressure fuel meeting MIL-F-5624A, grade JP-3, volatility specifications
51-194	Nominal 7-pound Reid vapor pressure fuel meeting MIL-F-5624A, grade JP-3, volatility specifications
51-192	Nominal 3-pound Reid vapor pressure fuel meeting MIL-F-5624A, grade JP-4, volatility specifications, except for the 10-percent evaporated temperature requirement

51-190	Nominal 3-pound Reid vapor pressure fuel meeting MIL-F-5624A, grade JP-4, volatility specifications
50-197	Nominal 1-pound Reid vapor pressure fuel (modified JP-3 fuel) obtained by removing volatile components from MIL-F-5624A stock to adjust the Reid vapor pressure to a nominal 1 pound per square inch
52-53	MIL-F-5624A, grade JP-4; "a high quality" JP-4 base

Distillation curves of these six fuels are presented in figure 1; physical properties of the fuels are presented in table I. NACA fuels 51-196 and 51-194 have equivalent Reid vapor pressures but have widely different distillation temperatures; this is also true of NACA fuels 51-192 and 51-190. Physical properties of the three fuels investigated in reference 2 are also included in table I.

APPARATUS

Combustor

A single tubular turbojet-engine combustor (fig. 2) was installed in a direct-connect duct test facility described in detail in references 1 and 9. Instrumentation for indicating combustor-inlet and -outlet air total pressures and temperatures is described in reference 9. Calibrated rotameters indicated the rate of fuel flow required for ignition. A copper fuel-cooling coil (50 ft long and 3/8 in. O.D.) was installed in the inlet-air duct close to the combustor to supply fuel at a temperature near that of the inlet-air temperature (fig. 2).

A small (10.5 gal/hr 80° spray-cone angle) fixed-area fuel nozzle was used in order to maintain fuel atomization as nearly constant as possible. Starting fuel flows were between 25 and 50 pounds per hour for the air flows used; nozzle pressure drops were between 13 and 50 pounds per square inch. At these pressure drops the fuel spray is well developed and is little affected by the air-flow currents in the combustor (reference 10).

Ignition System

The ignition system was of the variable-energy capacitance-discharge type; a simplified circuit diagram is shown in figure 3. In general, the apparatus was similar to that used in reference 2 except that improved means for measuring the condenser voltage was afforded by a calibrated direct-current oscilloscope which showed maximum and minimum voltages during sparking. The voltage and condenser capacitance could be varied through a wide range, allowing a variation in spark energy from several millijoules to over 10 joules. Condenser capacitance was varied (in six steps) from 0.025 to 13 microfarads and the voltage varied from 350 to 1400 volts to obtain the required range of spark energy. The energy was calculated as

$$E = 1/2\ CV^2$$

2748

where

E energy, joules

C capacitance, farads

V voltage, volts

A standard aircraft-type spark plug (electrode gap, 0.060 in.) was used. A spark repetition rate of 8 sparks per second was maintained.

PROCEDURE

The minimum spark energy required to ignite the combustor with each fuel was determined at various combustor operating conditions. Sea-level tests were conducted at conditions simulating a sea-level engine cranking speed of about 9 percent normal rated speed for a range of combustor-inlet air and fuel temperatures from 80° to -40° F. The combustor-inlet air pressures (31.3 to 31.6 in. Hg abs) and flow rates (1.28 to 1.68 lb/(sec)(sq ft) based on a combustor maximum cross-sectional area of 0.267 sq ft) were accordingly adjusted for the simulated conditions. Altitude tests were conducted over a range of combustor-inlet air pressures, two air flows (1.87 and 3.75 lb/(sec)(sq ft)), and a constant inlet-air and fuel temperature of 10° F.

After the combustor-inlet air conditions were established, the ignition system was energized and adjusted to the prescribed spark repetition rate and desired spark energy level. Fuel was admitted to the combustor by opening the throttle slowly until ignition occurred, allowing a maximum time interval of about 30 seconds for ignition. The occurrence of ignition was indicated by a temperature rise in the combustor. The criterion for satisfactory ignition was that the flame fill the combustor and continue burning after the spark was de-energized.

The reported spark-energy requirements were established by first selecting an arbitrary energy value and then successively increasing or decreasing this value to determine a minimum energy that would give repeated satisfactory ignition. One fuel (NACA fuel 50-197) was tested at several conditions between each additional fuel test to establish the degree of reproducibility of the ignition-energy data.

RESULTS AND DISCUSSION

Ignition at Sea-Level Conditions

The data obtained at simulated sea-level conditions indicate the combined effect of variations in combustor-inlet air and fuel temperature on minimum ignition-energy requirements for six fuels (fig. 4). The spark energies required increased about three times for a change in inlet air and fuel temperatures from 80° to -40° F. The total spread among the fuels represents approximately a 2:1 ignition-energy range. It is noted that, although the lowest Reid vapor pressure fuel (fuel 50-197), required higher energies than did most of the other fuels, no consistent relation between Reid vapor pressure and minimum ignition energy was apparent.

Ignition at Altitude Conditions

The minimum ignition-energy requirements of the six fuels at altitude operating conditions are presented in figures 5 and 6. NACA fuel 50-197 was tested at frequent intervals during the investigation; the results (fig. 5) indicate the degree of reproducibility of these data. The data indicate an approximately hundredfold increase in required spark energy with a decrease in combustor-inlet pressure from 1 atmosphere to the limiting value. At constant, low-pressure conditions, similar increases in energy resulted from a twofold increase in air flow. Compared with these effects, the effects of variations in fuel properties on spark-energy requirements (fig. 6) were small. In general, the spark energy required to ignite the various fuels for the range of combustor-inlet conditions investigated varied from 0.006 to about 4.0 joules.

In order to facilitate comparison of the ignition-energy requirements of the fuels, an empirical parameter $V/\sqrt{P}$, where V is the reference velocity (based on inlet-air density and maximum combustor cross-sectional area) and P, the inlet-air total pressure, was developed. The data obtained at the two air flows are thus generalized into a single curve, as shown in figure 7. In general, the degree of correlation was very satisfactory for the range of conditions investigated.

Figure 8 presents a summary of the curves of figure 7 and affords a comparison of the ignition quality of the six fuels investigated. It is noted that, over most of the range of the parameter $V/\sqrt{P}$, nearly straight-line correlations that converge at low values of $V/\sqrt{P}$

were obtained. With respect to effects of fuel properties, it is noted that the two curves representing the fuels with the highest Reid vapor pressures, 6.8 and 6.5, are widely separated; this is also true of the curves representing the fuels with Reid vapor pressures of 3 and 2.9. Also, fuels of approximately 3 and 6 pounds per square inch Reid vapor pressure required very similar ignition energies. Thus, at altitude conditions, as in the case at sea-level conditions, Reid vapor pressure has no apparent relation with fuel ignition characteristics.

Relation Between A.S.T.M. Distillation Data and Minimum Ignition-Energy Requirements

If increased evaporation rate is assumed to facilitate ignition, it is to be expected that decreased evaporation temperatures should reduce ignition-energy requirements. The comparisons shown in figures 4 and 8 indicate that fuels 52-53 and 51-194 were most easily ignited at both the sea-level and altitude conditions investigated. When the A.S.T.M. evaporation temperature data of the fuels (fig. 1) are considered, it is seen that evaporation percentages below approximately 30 percent only would predict the low ignition-energy requirements for fuel 51-194. A relation between ignition energy and the A.S.T.M. 15-percent distillation temperature was found to be most satisfactory. Figure 9, a cross plot of the data of figure 4 shows the relation between the 15-percent evaporated fuel temperature and the minimum ignition energy for the range of combustor-inlet air and fuel temperature at sea-level operating conditions. The increase in ignition energy is about 1.7 times for a change in the 15-percent evaporated fuel temperature from 168° to 344° F. Figure 10 presents a similar cross plot of the results from figure 8 to show minimum ignition-energy requirements as a function of the 15-percent evaporated fuel temperature for the data obtained at altitude conditions. These curves indicate about a 2:1 increase in minimum ignition-energy requirements at the lowest value of the inlet air parameter, and a 10:1 increase at the highest value of the parameter, for an increase in the 15-percent evaporated fuel temperature from 168° to 344° F. A more satisfactory relation between ignition energy and A.S.T.M. 15-percent evaporated temperature was obtained with the altitude data than with the sea-level data. Sea-level data required energy levels near the limits of the ignition system and was subject to greater inaccuracies in energy measurements.

Application of Relation to Data from Previous Investigation

Although the fuels investigated in reference 2 varied considerably in viscosity, and hence may have been tested under varying fuel atomization conditions, it is of interest to compare the results with the results presented herein. Figure 11 shows the relation between the ignition-energy data of reference 2 and the parameter $V/\sqrt{P}$. The air-flow range for these data is much greater (0.37 to 6.40 lb/(sec)(sq ft), seven air flows) and the scatter is considerably greater than was obtained in the present investigation. The increased scatter may be partly attributed to the greater range of air flow; also, the present data were obtained with improved spark-energy measurement instrumentation and with a different fuel nozzle. A summary of the curves of figure 11 is presented in figure 12. The JP-1 fuel curve has been omitted because of the extreme scatter of the data. It is noted that the fuel with the higher Reid vapor pressure required the smaller spark energy for ignition. Figure 13 shows the relation between the sea-level ignition-energy data of reference 2 and the A.S.T.M. 15-percent evaporated fuel temperature. The curves, in general, have steeper slopes and are at somewhat higher spark-energy levels than those obtained in the present investigation. These differences may be attributed to different spark-energy measurement instrumentation, different fuel injection nozzles, or both. For example, the greater combustor-wall wetting (reference 10) obtained with the variable-area fuel nozzle used in reference 2 may decrease the probability of an optimum vaporized fuel-air mixture at the spark electrodes as compared with the small fuel nozzle used in the present investigation. A cross plot of the altitude data of reference 2 (fig. 12) is presented in figure 14 to show minimum ignition energy as a function of the A.S.T.M. 15-percent evaporated fuel temperature. For the two fuels that can be included in this plot, there is about a threefold increase in ignition energy for an increase in the 15-percent evaporated fuel-temperature from 145° to 355° F.

The results obtained from this investigation indicate that the ignition quality of turbojet-engine fuels should be controlled by an A.S.T.M. distillation temperature, probably the 15-percent evaporated temperature. The Reid vapor pressure should not, on the other hand, be considered a significant factor in controlling the ignition-energy requirements of turbojet-engine fuels.

SUMMARY OF RESULTS

From an investigation to determine the effect of fuel volatility characteristics on the minimum ignition-energy requirements of six fuels in a single tubular (turbojet engine) combustor, the following results were obtained:

1. The Reid vapor pressures of the fuels were not indicative of their ignition characteristics at sea-level or altitude inlet conditions; the A.S.T.M. 15-percent evaporated fuel temperature was generally indicative of the ignition characteristics of the fuels at both sea-level and altitude operating conditions.

2. A relation between the minimum ignition-energy requirements and an empirical function of combustor-inlet air pressure and velocity $V/\sqrt{P}$ was used to determine the relative ignition characteristics of the fuels at various combustor-inlet pressures and two air flows.

3. For the range of combustor-inlet conditions investigated, spark energies from 0.006 to 4.0 joules were required to ignite the various fuels.

4. The trends obtained agreed qualitatively with results of a previous ignition investigation with a very limited number of fuels.

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2748

TABLE I - PHYSICAL PROPERTIES OF FUELS USED IN IGNITION INVESTIGATION

NACA fuel number	Fuel	A.S.T.M. distillation temperature, °F													Specific gravity	Reid vapor pressure (lb/sq in.)	Viscosity (centistokes)	
		Initial boiling point	Percentage evaporated											Final boiling point			100° F	-40° F
			5	10	20	30	40	50	60	70	80	90	95					
51-196	7-Pound	109	138	250	343	356	364	372	381	393	412	452	489	530	0.749	6.8	1.305	8.01
51-194	7-Pound	94	122	144	204	325	392	426	454	473	488	517	558	565	0.749	6.5	1.299	8.04
51-192	3-Pound	128	292	337	350	355	360	365	370	377	386	402	419	443	0.754	2.9	1.324	8.58
51-190	3-Pound	129	192	241	329	355	368	375	384	396	417	455	493	523	0.752	2.7	1.293	8.02
50-197	1-Pound	181	242	271	300	319	332	351	365	381	403	441	470	508	0.780	1.0	1.05	----
52-53	MIL-F-5624A grade JP-4	136	183	200	225	244	263	278	301	321	347	400	454	498	0.757	2.9	0.762	----
48-306	MIL-F-5616 grade JP-1[a]	340	350	355	360	364	367	375	380	384	391	402	---	440	0.830	0-0.2	-----	9.2
49-246	1-Pound[a]	210	224	243	276	302	328	355	384	413	441	478	---	560	0.803	1.0	-----	4.28
50-174	MIL-F-5624A grade JP-3[a]	114	128	138	149	160	174	188	204	231	330	439	---	533	0.725	6.5	-----	1.65

[a] Additional data are presented in reference 2.

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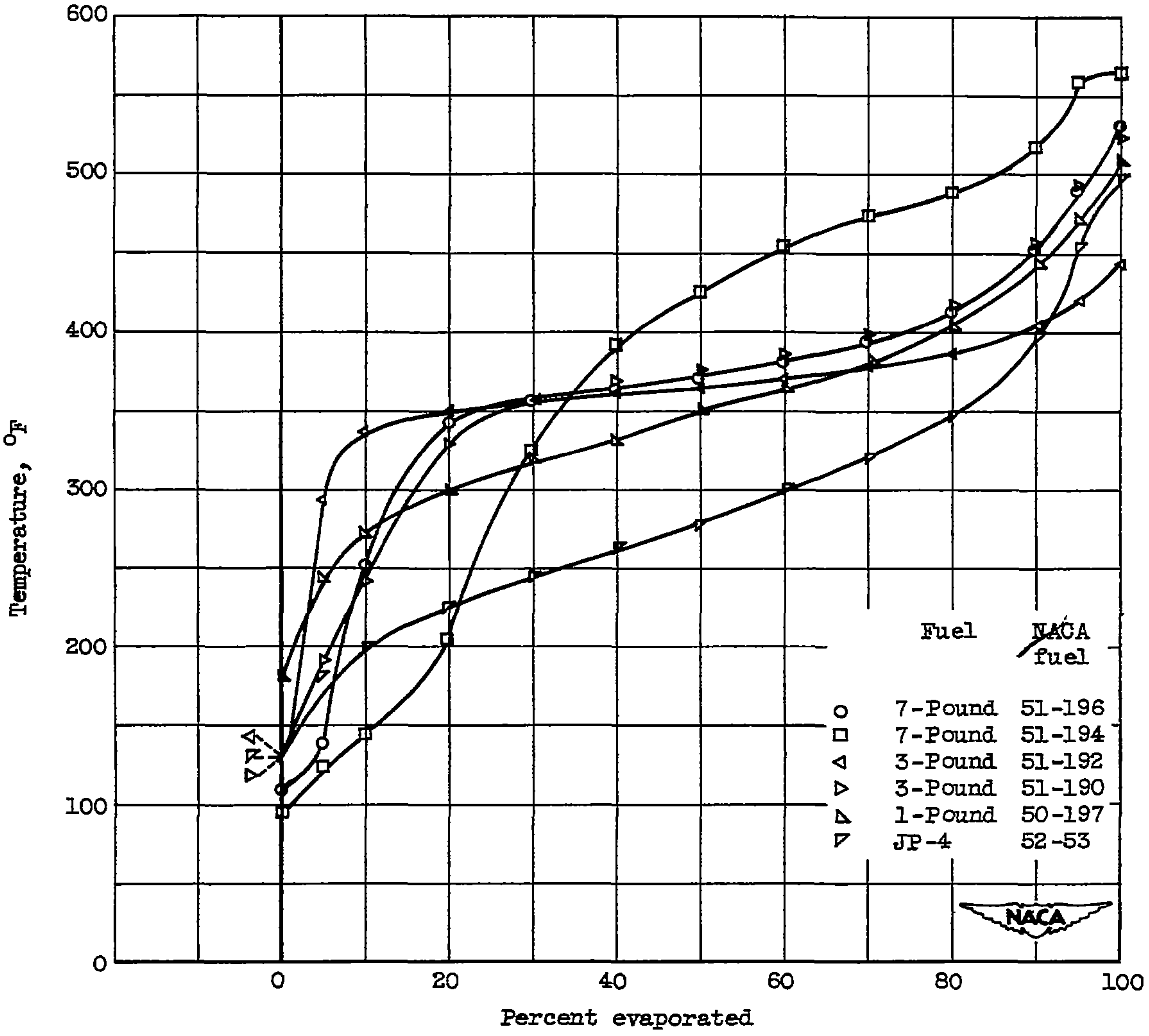

Figure 1. - Variation of A.S.T.M. distillation temperature with percentage evaporated.

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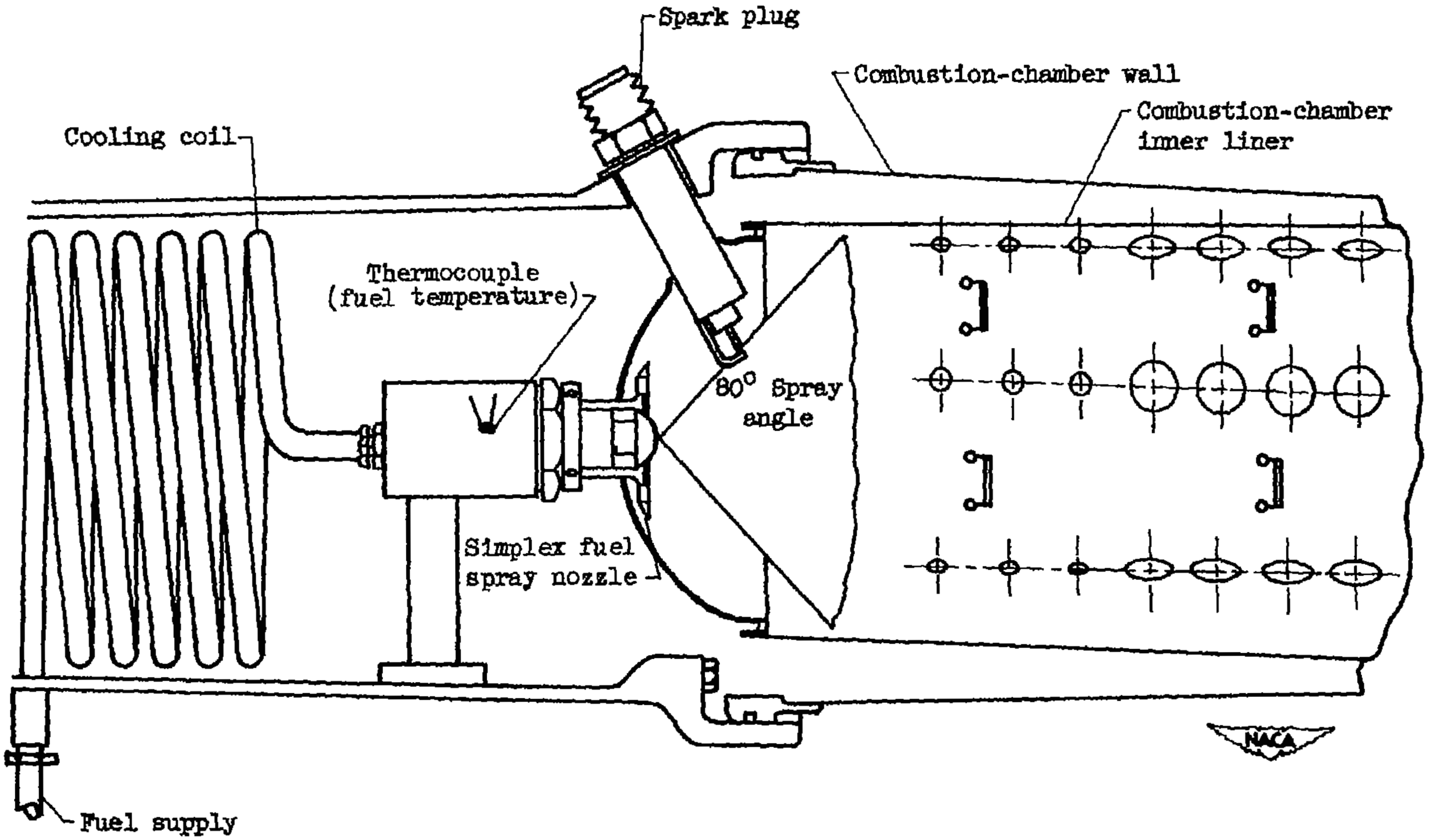

Figure 2. - Diagrammatic cross section of single tubular combustor.

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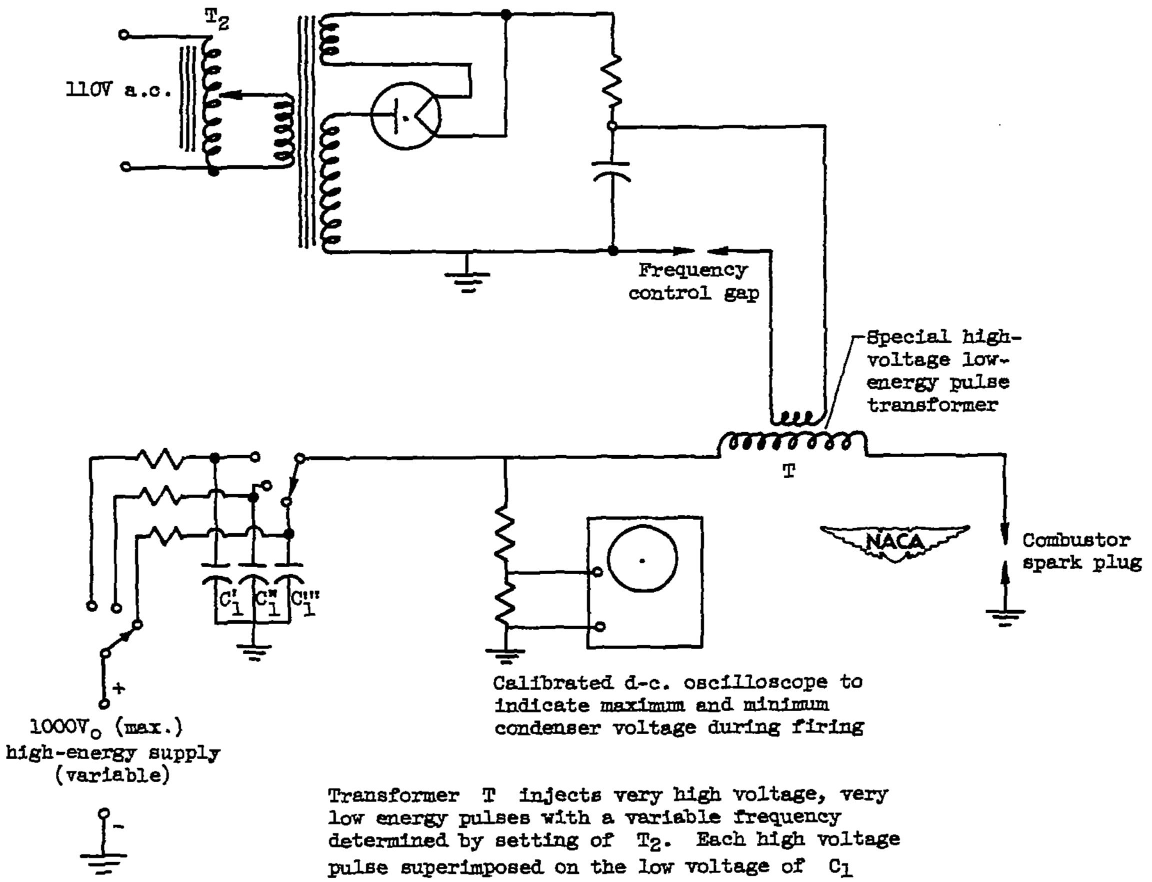

Transformer T injects very high voltage, very low energy pulses with a variable frequency determined by setting of T_2. Each high voltage pulse superimposed on the low voltage of C_1 ionizes the combustor spark plug gap and permits the relatively high energy of C_1 to be discharged through the combustor spark plug. C_1 consists of a bank of condensers any one of which can be selected to provide a specific known energy per spark.

Figure 3. - Simplified circuit diagram of spark ignition system.

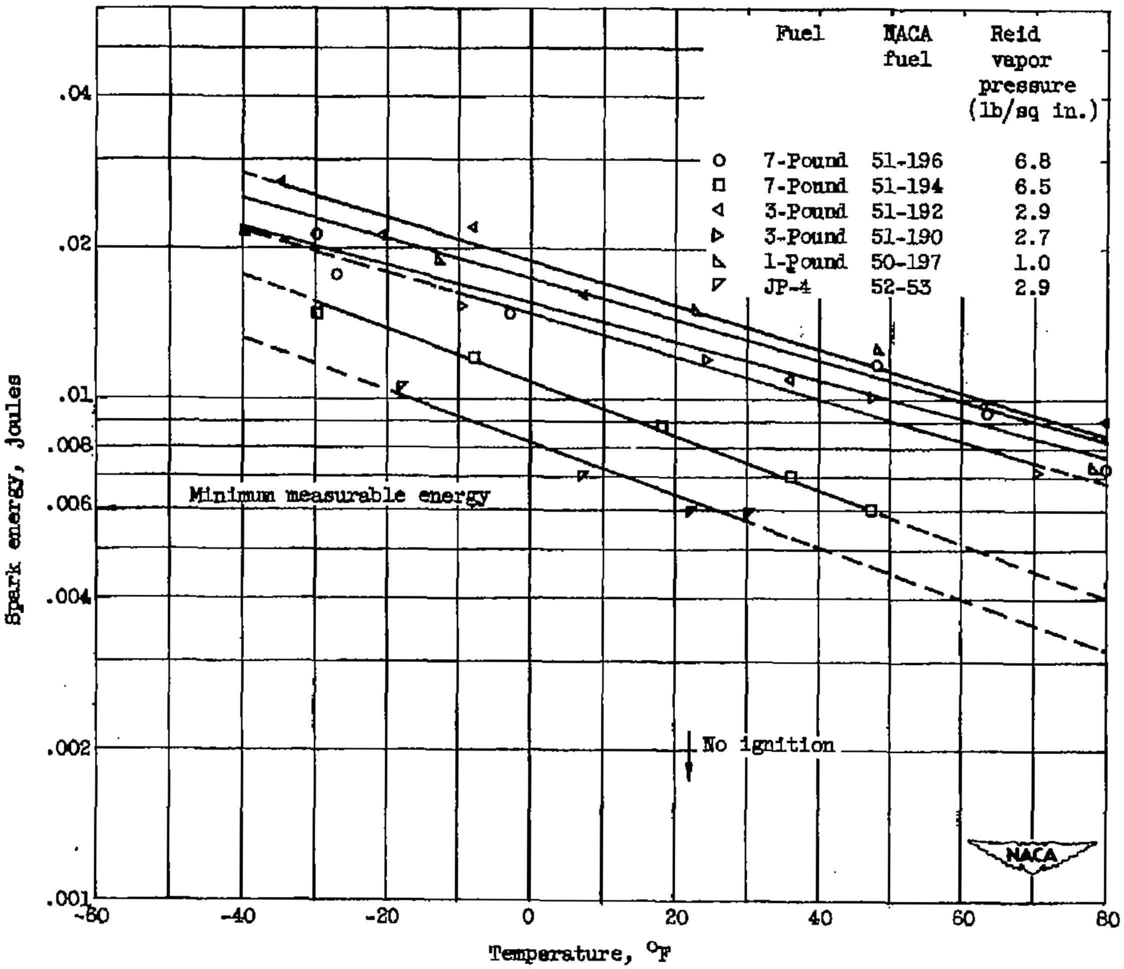

Figure 4. - Effect of combustor-inlet air and fuel temperature on minimum spark energy required for ignition of six fuels of different volatility characteristics. Simulated engine cranking speed of 9-percent normal rated speed; static sea-level conditions; air flow, 1.38 to 1.68 pound per second per square foot; combustor-inlet total pressure, 31.3 to 31.6 inches of mercury absolute.

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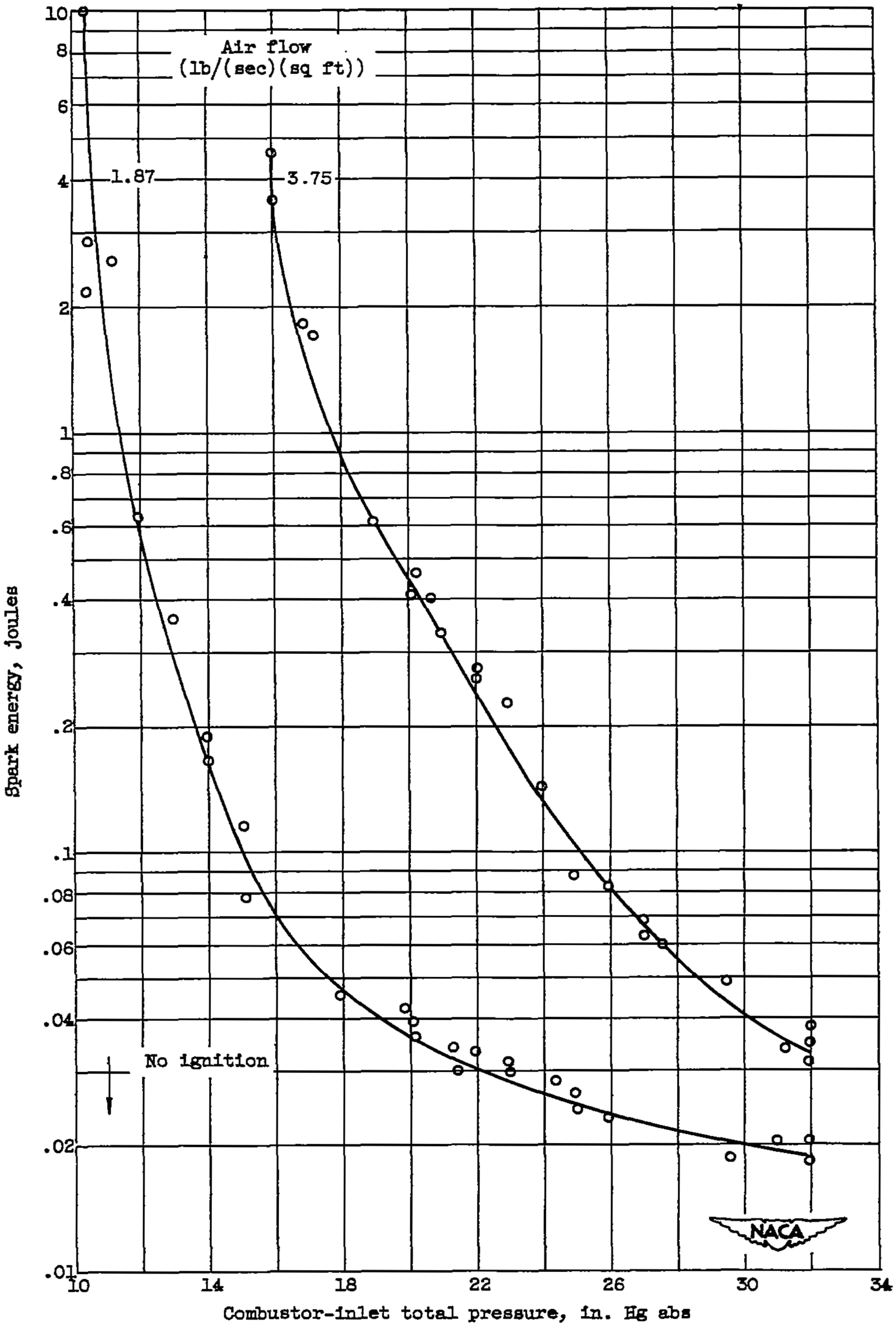

Figure 5. - Effect of combustor-inlet total pressure and air flow on minimum spark energy required for ignition. Data obtained at frequent intervals during investigation. NACA fuel 50-197; inlet-air and fuel temperature, 10° F.

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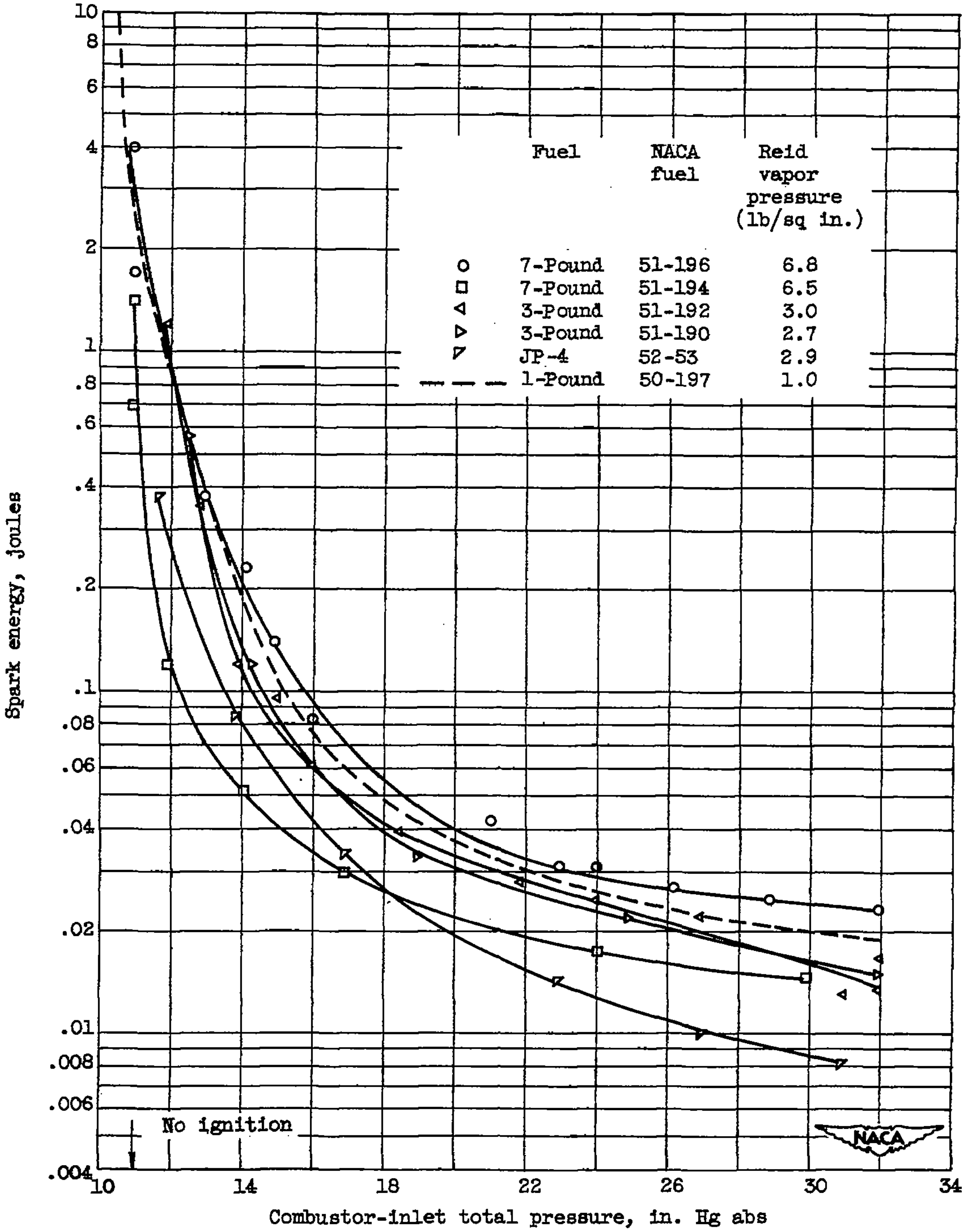

(a) Air flow, 1.87 pounds per second per square foot.

Figure 6. - Effect of combustor-inlet total pressure on minimum spark energy required for ignition of six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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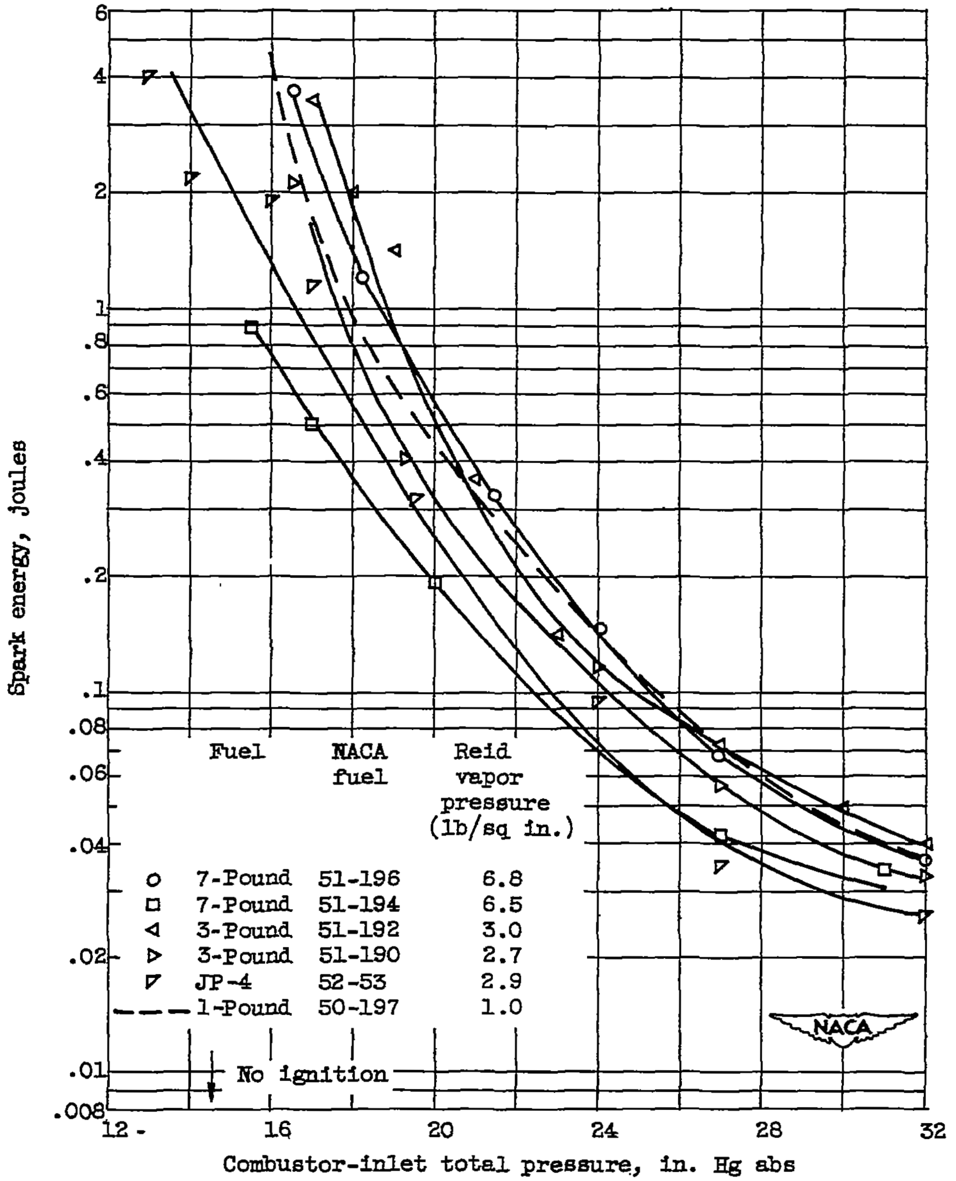

(b) Air flow, 3.75 pounds per second per square foot.

Figure 6. - Concluded. Effect of combustor-inlet total pressure on minimum spark energy required for ignition of six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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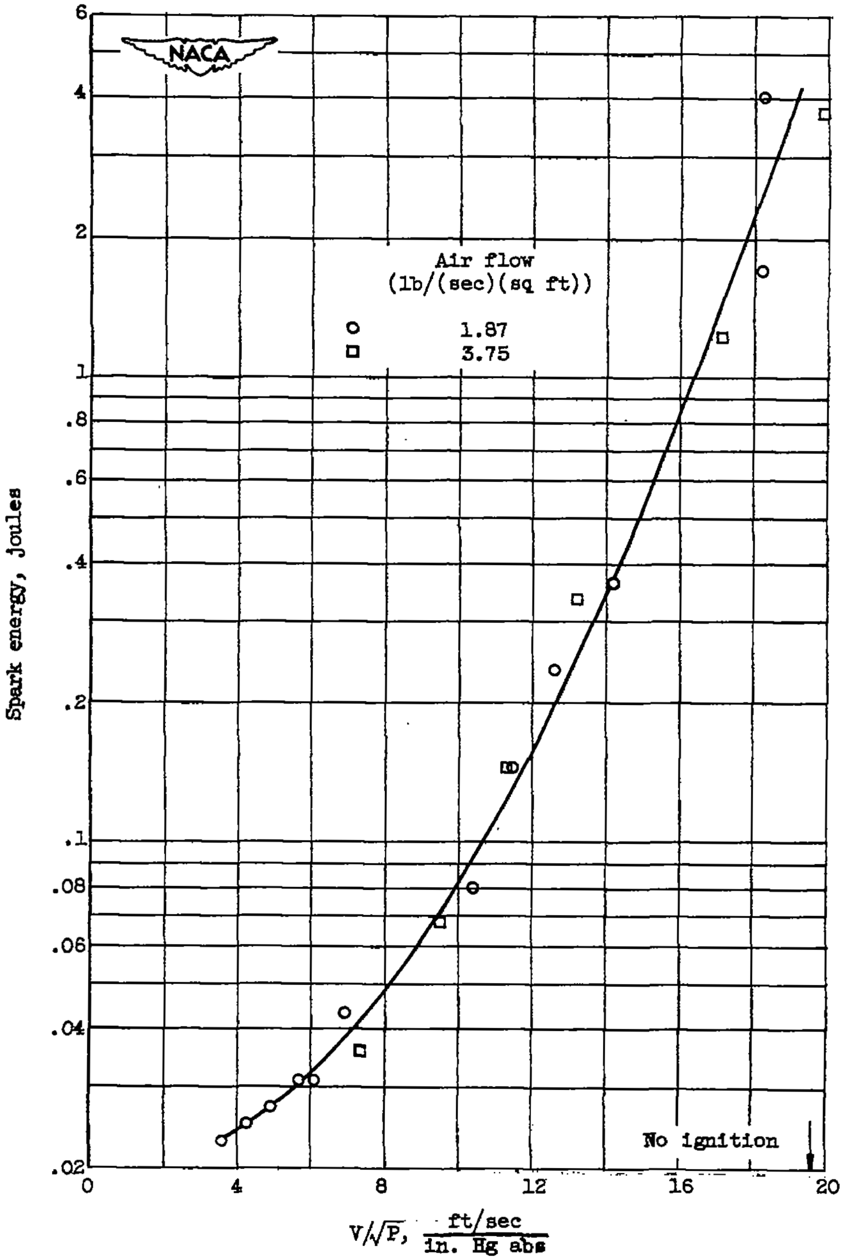

(a) NACA fuel 51-196.

Figure 7. - Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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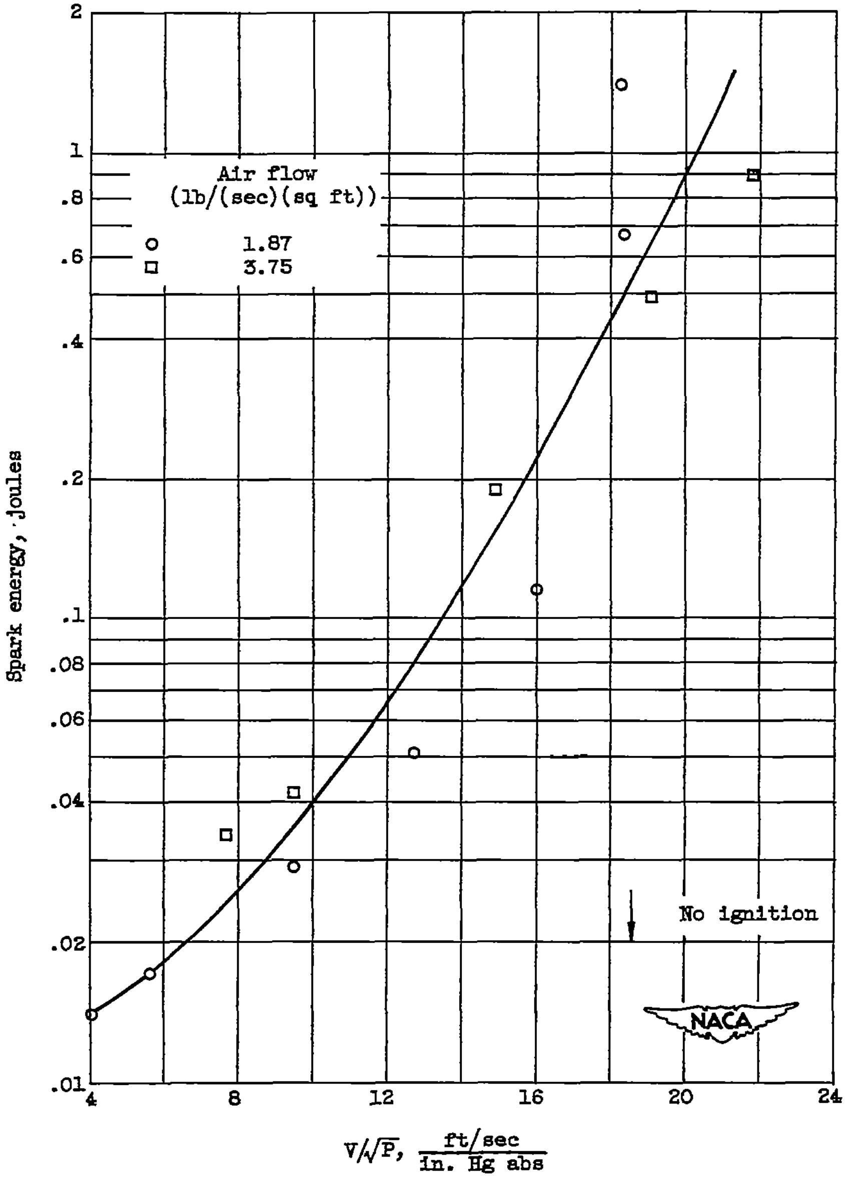

(b) NACA fuel 51-194.

Figure 7. - Continued. Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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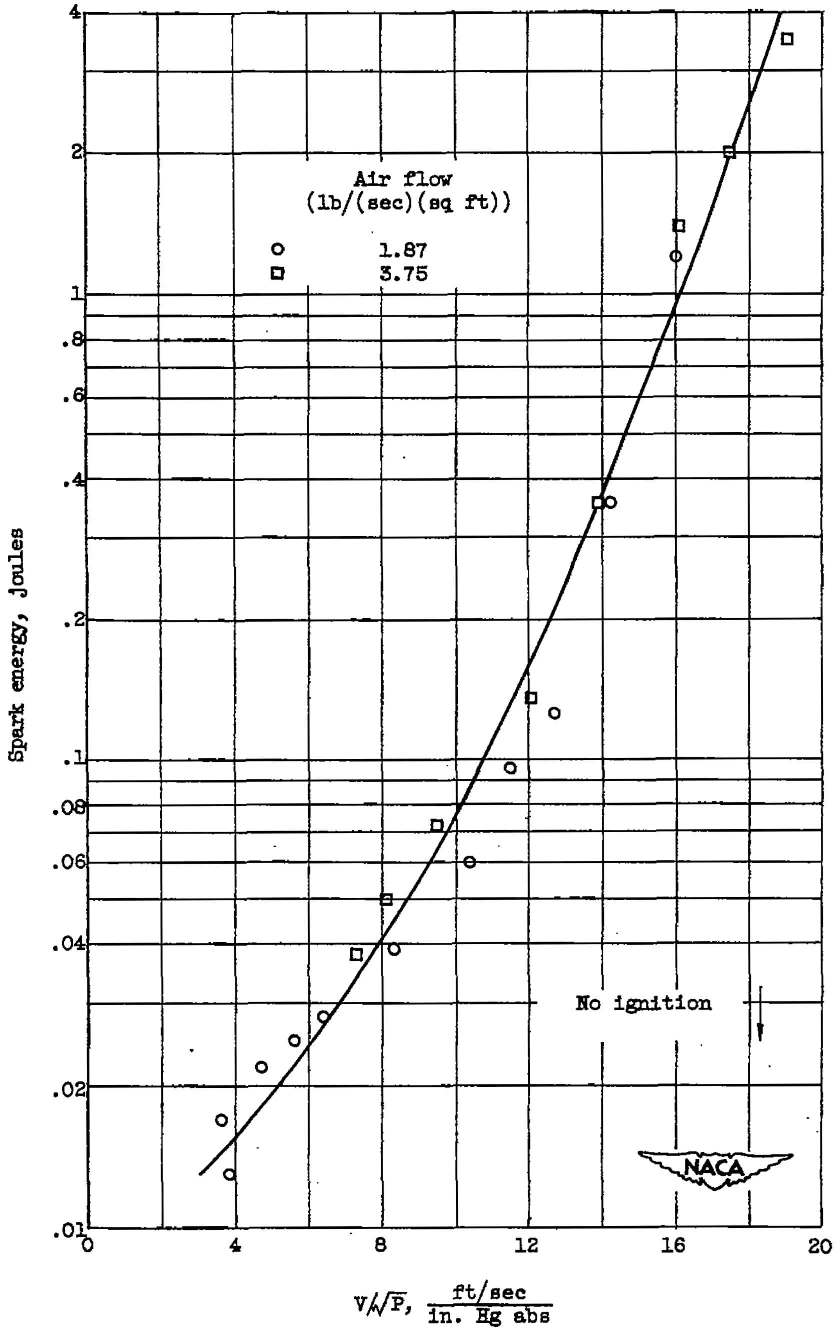

(c) NACA fuel 51-192.

Figure 7. - Continued. Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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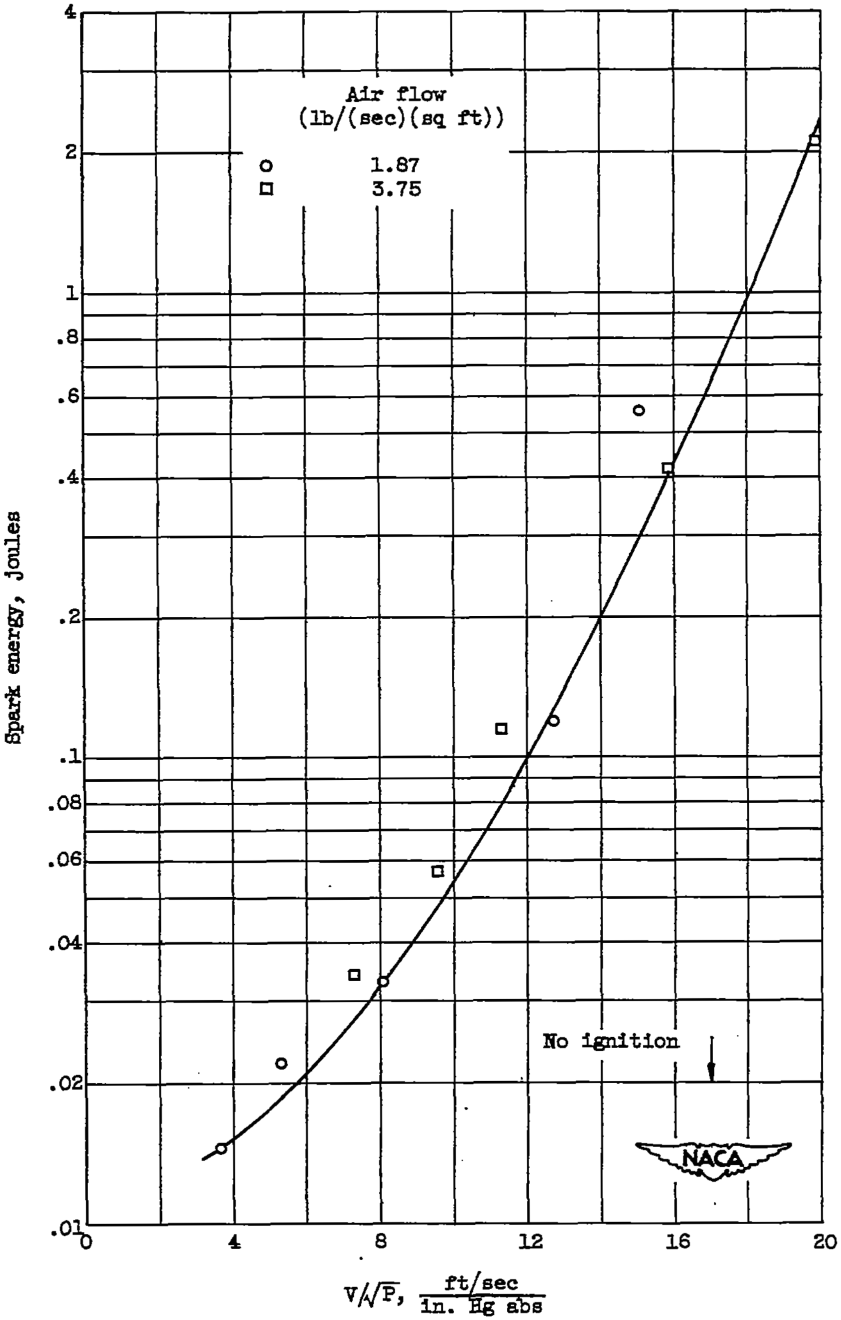

(d) NACA fuel 51-190.

Figure 7. - Continued. Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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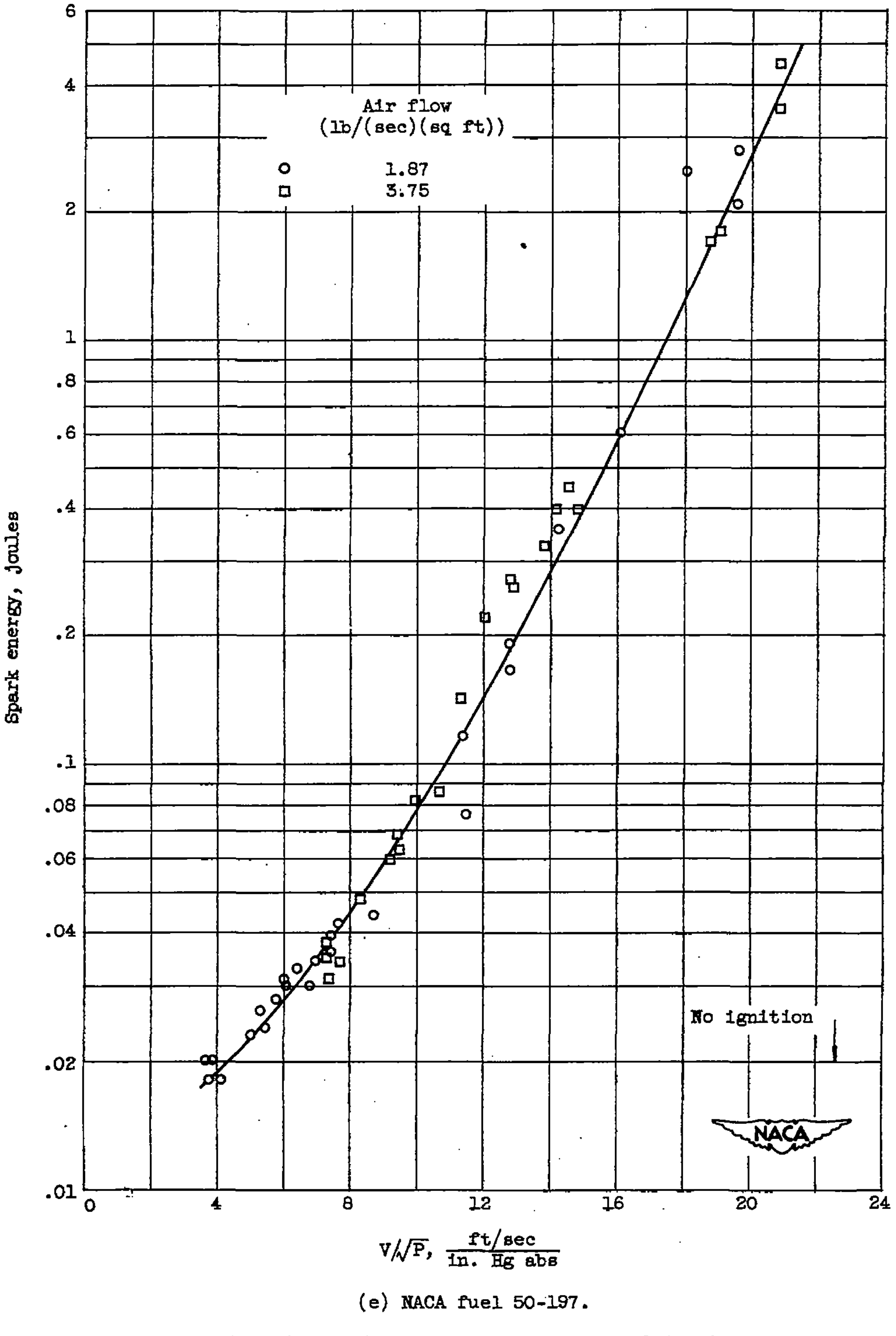

(e) NACA fuel 50-197.

Figure 7. - Continued. Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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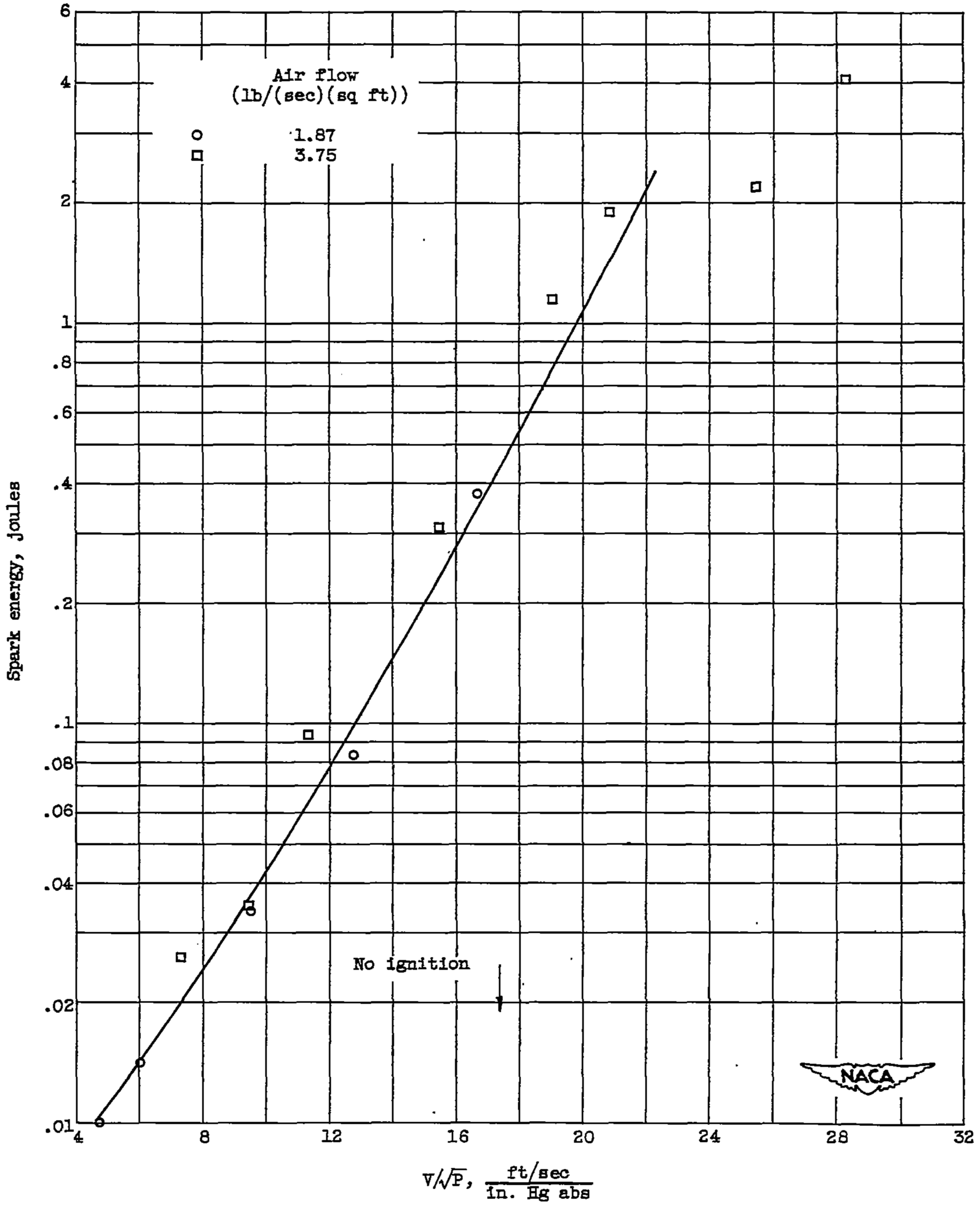

(f) NACA fuel 52-53.

Figure 7. - Concluded. Minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity for six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

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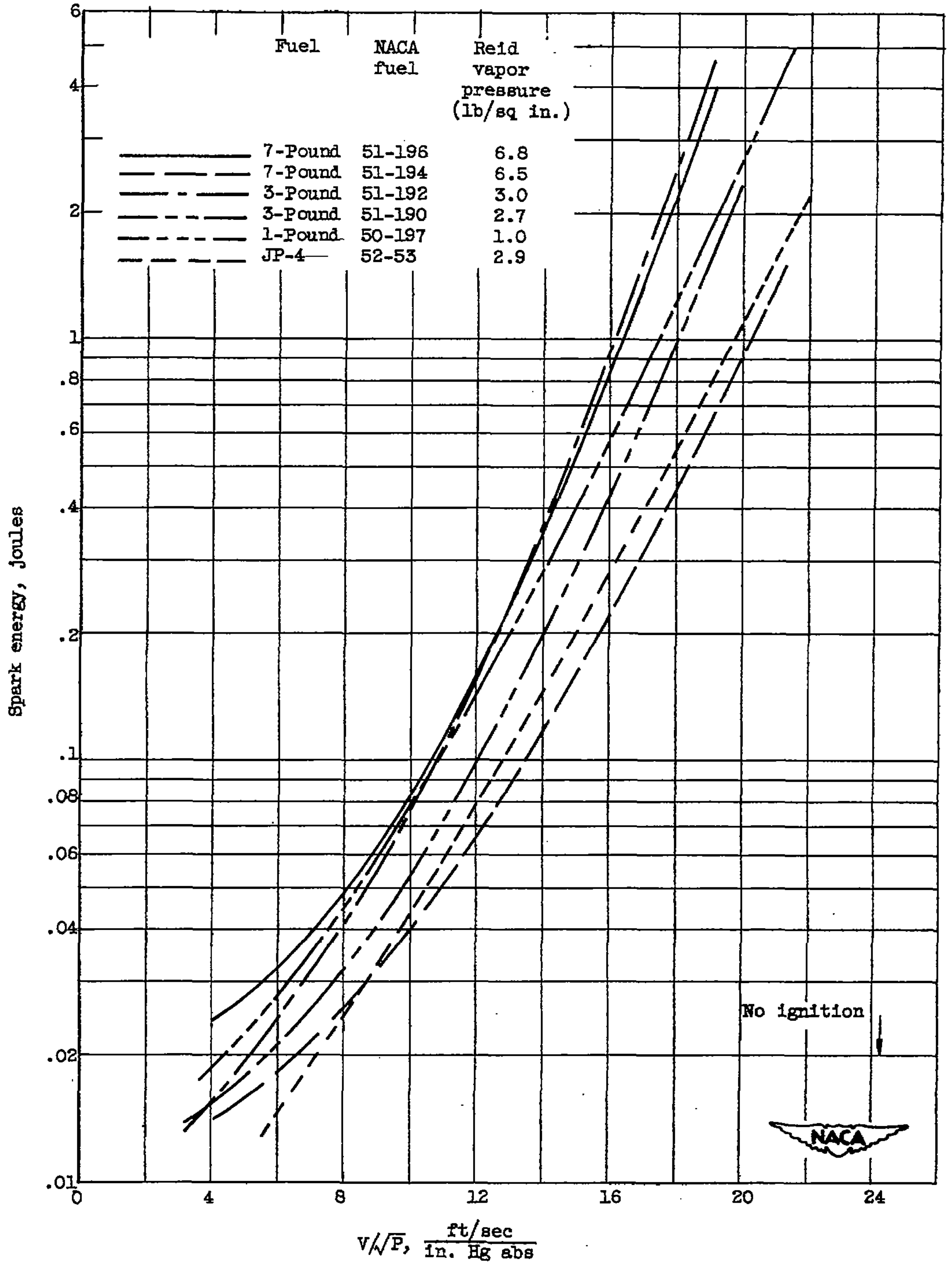

Figure 8. - Comparison of minimum spark energy required for ignition as function of combustor-inlet air pressure and velocity of six fuels of different volatility characteristics. Combustor-inlet air and fuel temperature, 10° F.

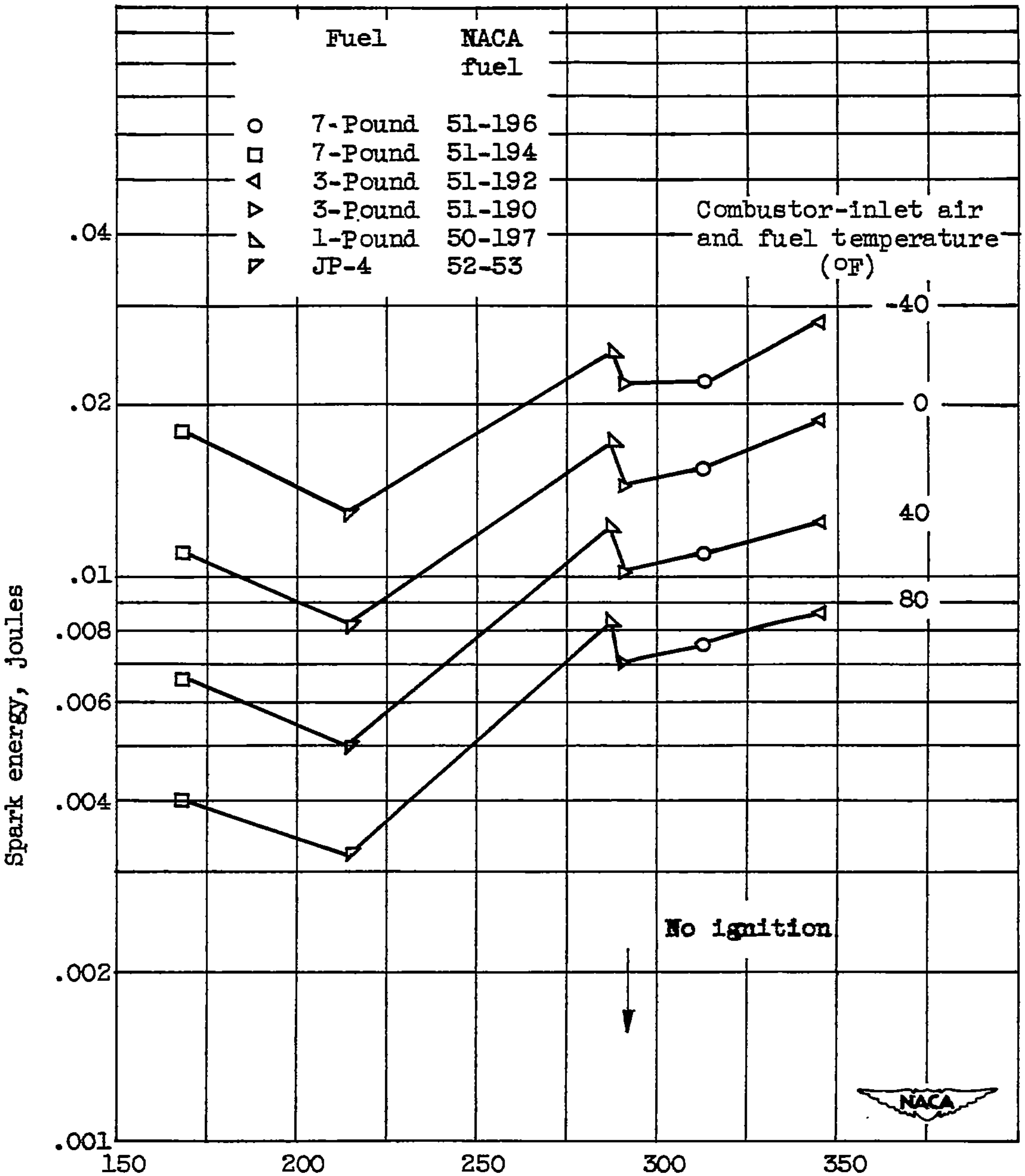

Figure 9. - Minimum spark energy required for ignition for six fuels as function of 15-percent evaporated fuel temperature at several combustor-inlet air and fuel temperatures. Simulated engine cranking speed, 9-percent normal rated speed; static sea-level conditions.

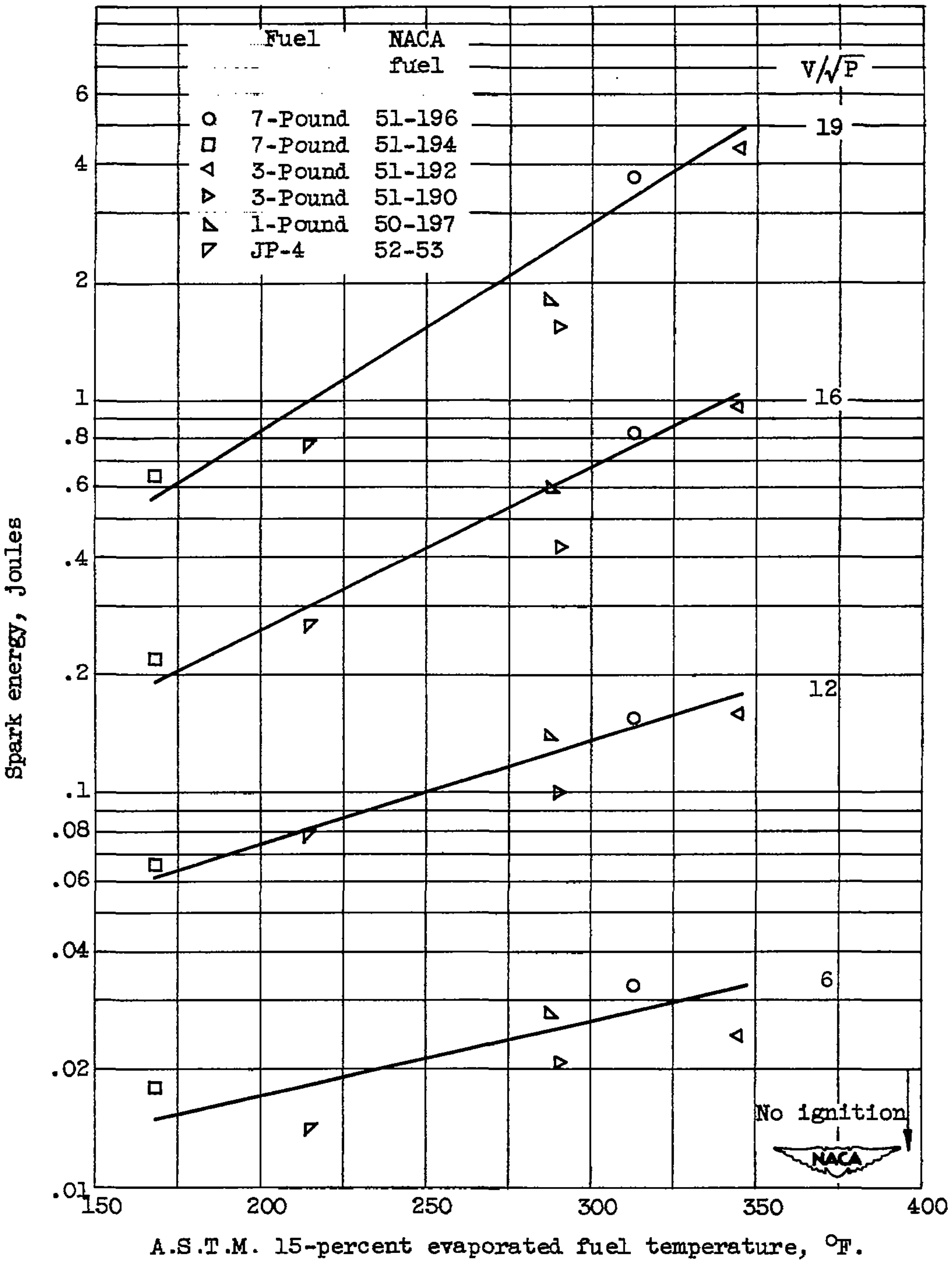

Figure 10. - Minimum spark energy required for ignition of six fuels as function of 15-percent evaporated fuel temperature at several values of $V/\sqrt{P}$. Combustor-inlet air and fuel temperature, 10° F.

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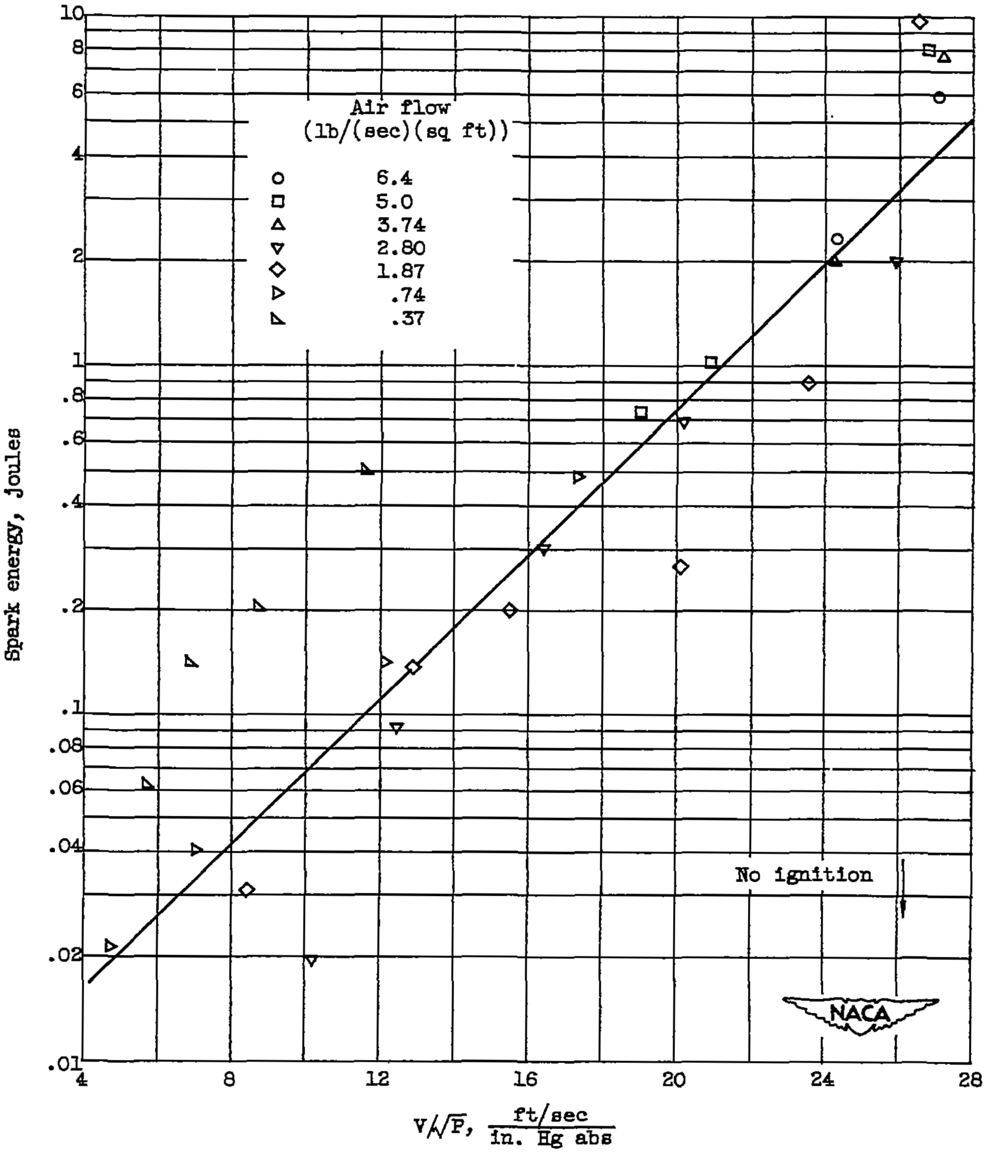

(a) JP-3 fuel (NACA fuel 50-174).

Figure 11. - Minimum spark energy required for ignition as function of combustor-inlet pressure and velocity for data of reference 2. Combustor-inlet air temperature, -10° F; combustor-inlet fuel temperature, -40° F.

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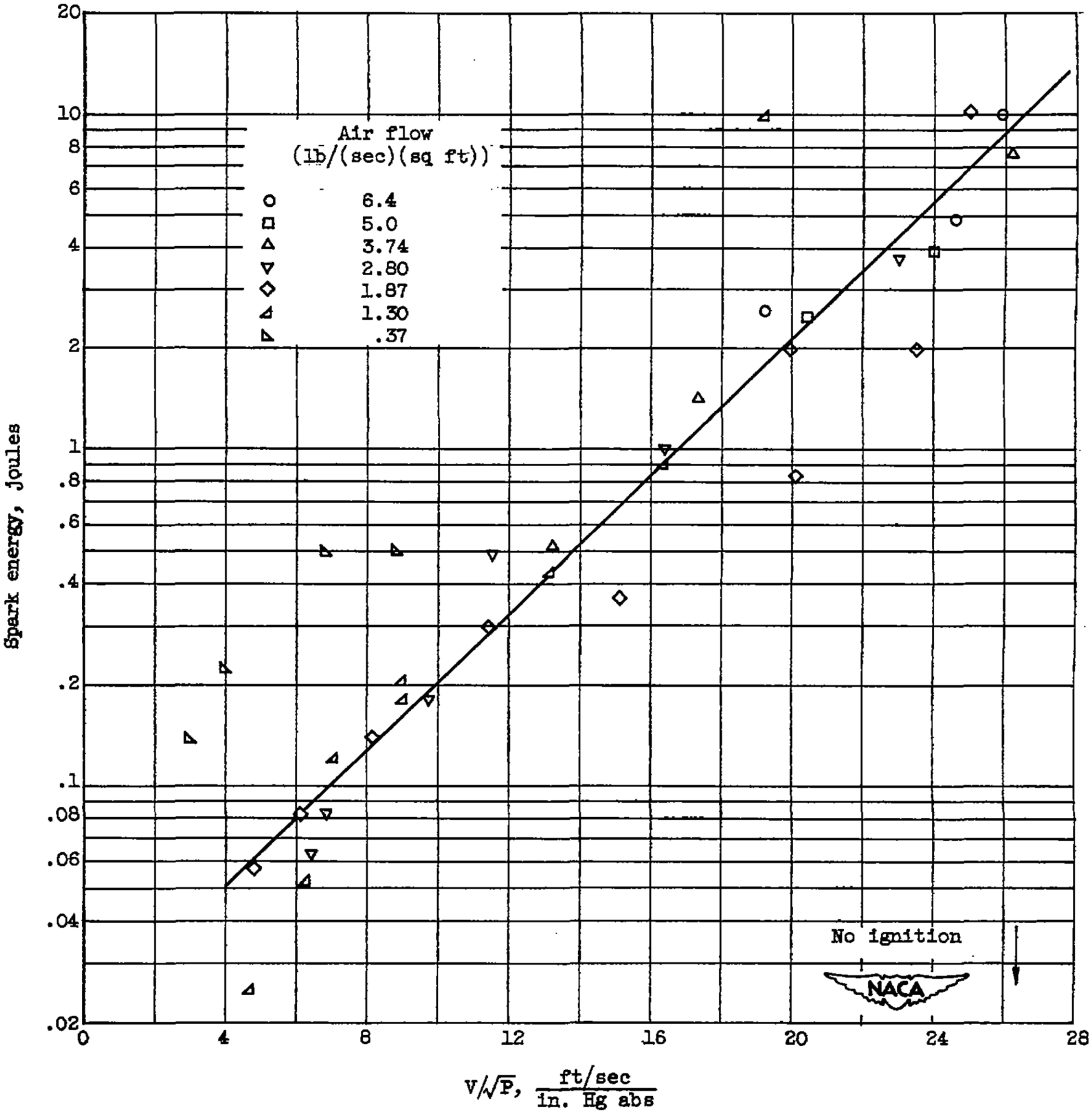

(b) 1-Pound fuel (NACA fuel 49-246).

Figure 11. - Continued. Minimum spark energy required for ignition as function of combustor-inlet pressure and velocity for data of reference 2. Combustor-inlet air temperature, -10° F; combustor-inlet fuel temperature, -40° F.

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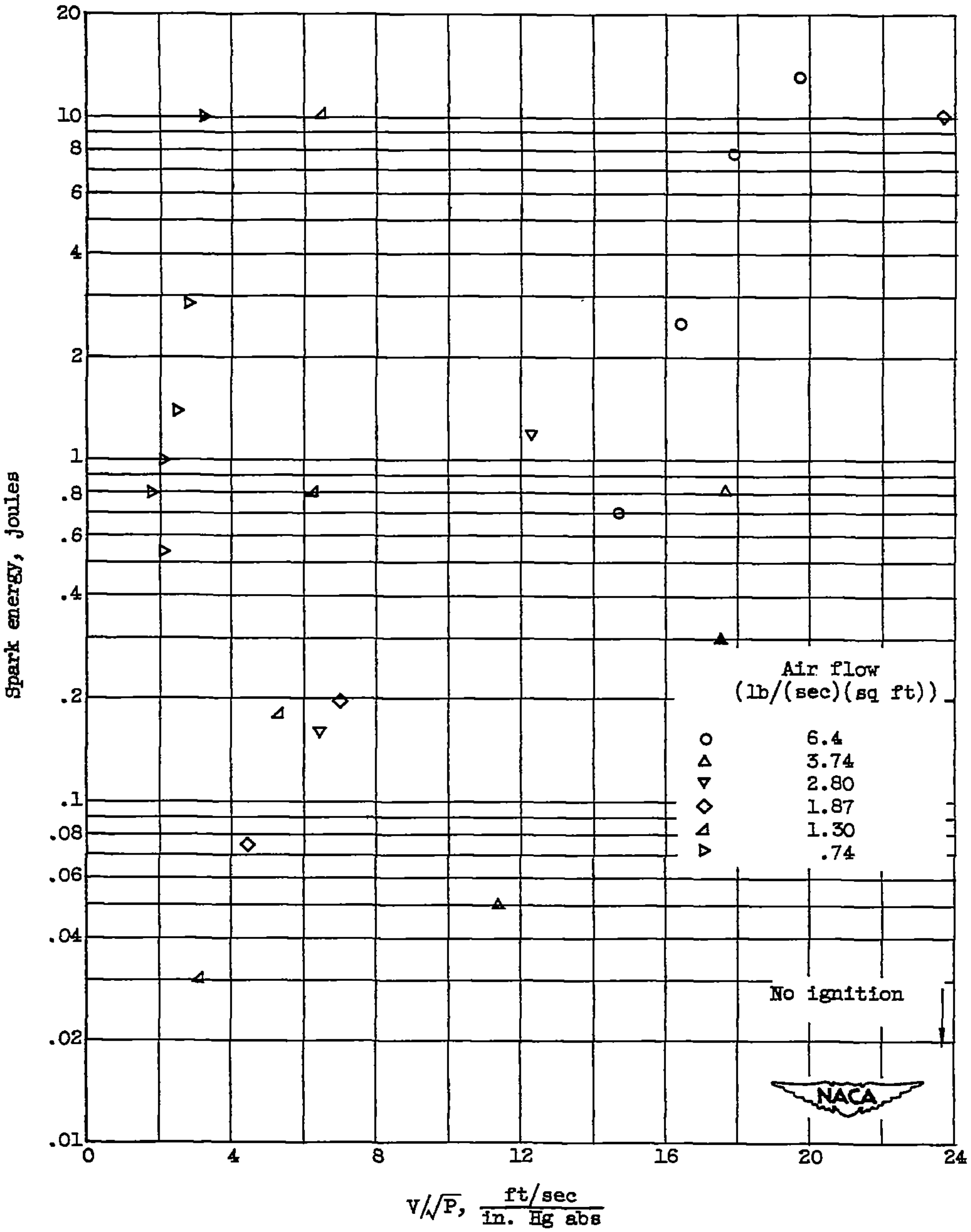

(c) JP-1 fuel (NACA fuel 48-306).

Figure 11. - Concluded. Minimum spark energy required for ignition as function of combustor-inlet pressure and velocity for data of reference 2. Combustor-inlet air temperature, -10° F; combustor-inlet fuel temperature, -40° F.

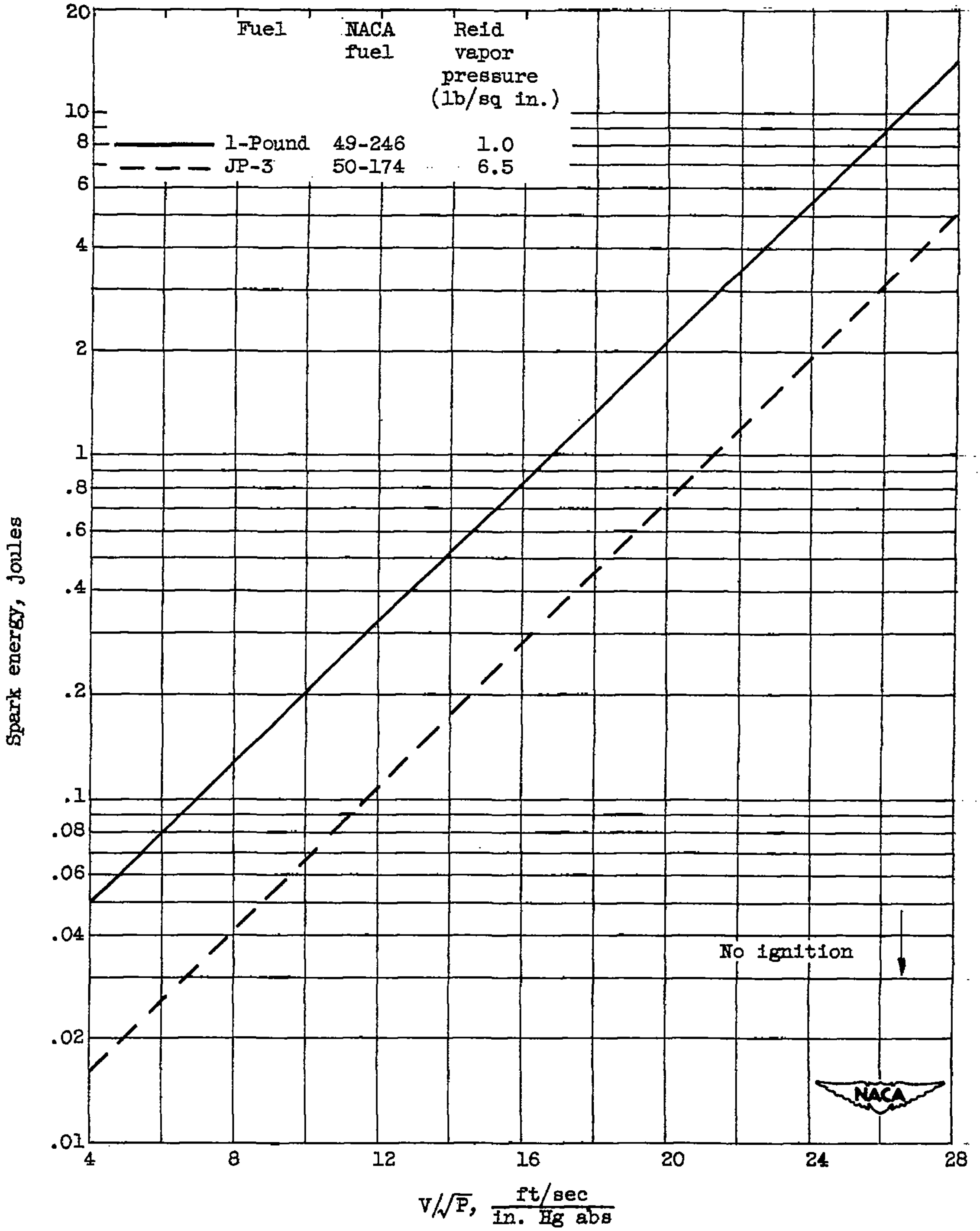

Figure 12. - Comparison of minimum spark energy required for ignition for two fuels of different volatility characteristics (reference 2). Combustor-inlet air temperature, -10° F; combustor-inlet fuel temperature, -40° F.

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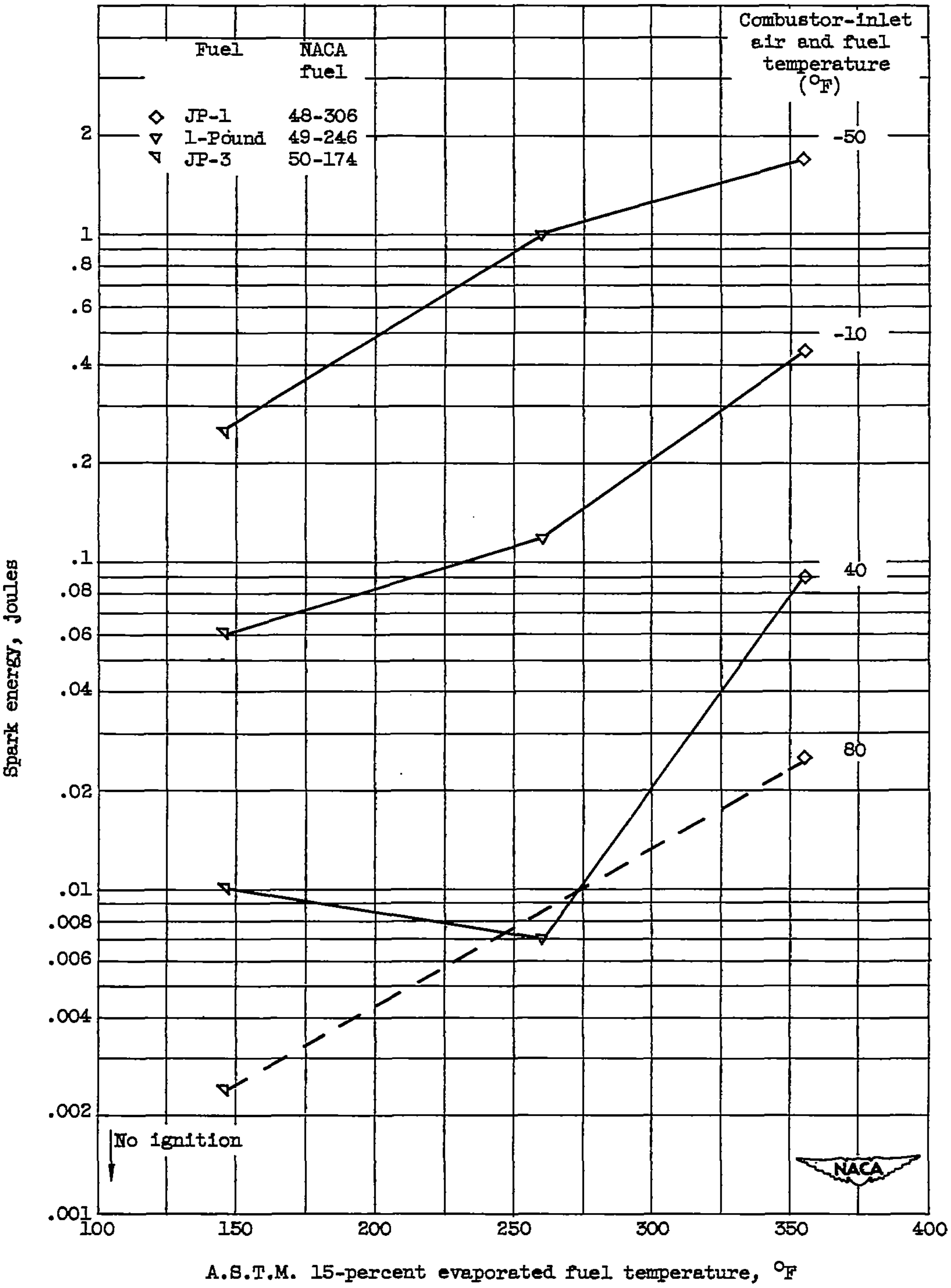

Figure 13. - Minimum spark energy required for ignition for three fuels as function of 15-percent evaporated fuel temperature at several combustor-inlet air and fuel temperatures (reference 2). Simulated engine cranking speed, 9-percent normal rated speed; static sea-level conditions.

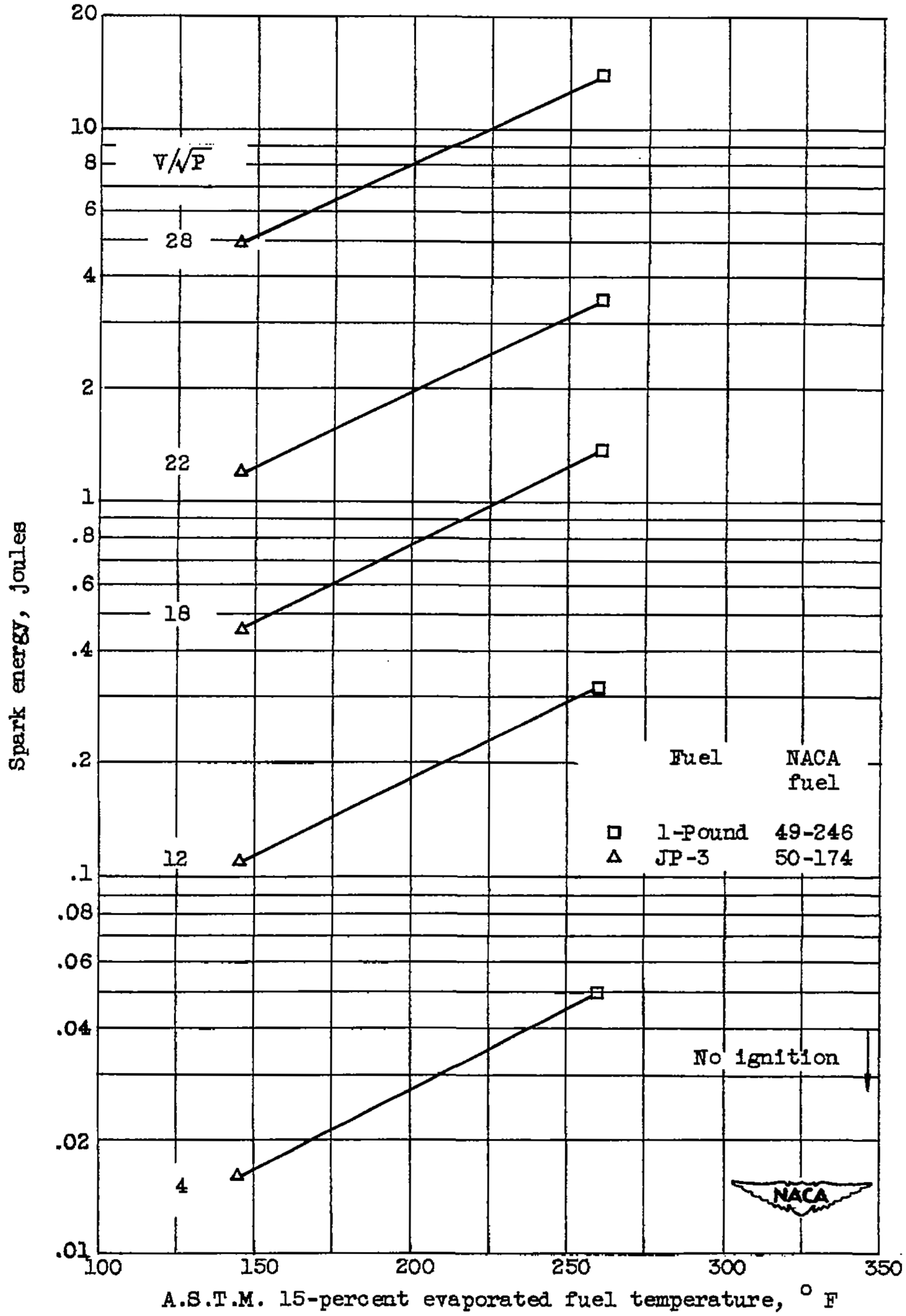

Figure 14. - Minimum spark energy required for ignition for two fuels as function of 15-percent evaporated fuel temperature at several values of $V/\sqrt{P}$ (data of reference 2). Combustor-inlet air temperature, -10° F; combustor-inlet fuel temperature, -40° F.

SECURITY INFORMATION

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