NACA

RESEARCH MEMORANDUM

EVALUATION OF ALTITUDE-IGNITION CHARACTERISTICS OF THREE FUELS OF DIFFERENT VOLATILITY IN A TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
March 10, 1954

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SUMMARY

An investigation was conducted on a full-scale turbojet engine installed in an NACA Lewis laboratory altitude chamber to obtain the altitude-ignition characteristics of three fuels with different A.S.T.M. distillation curves. Two of the fuels had a Reid vapor pressure of 2.7 pounds per square inch and the third fuel had a Reid vapor pressure of 1.7 pounds per square inch. However, at temperatures above 100° F, the fuel having a Reid vapor pressure of 1.7 had a much lower distillation curve than either of the others. The altitude-ignition and flame-propagation characteristics of the fuels were compared at an altitude of 50,000 feet and a flight Mach number of 0.8. Also, the ignition and propagation limits of one of the fuels were determined over a range of altitudes for the particular engine, ignition system, and combustor-inlet conditions of the investigation.

The relative quantities of fuel evaporated at the combustor-inlet static pressure and temperature, as indicated by the A.S.T.M. distillation curves, were found to give a better indication of the effect of fuel volatility on altitude ignition than did Reid vapor pressure. As noted in several previous investigations, the fuel-air ratio required for ignition and propagation decreased with increasing volatility. The minimum time for both ignition and propagation was obtained with the same fuel-air-ratio setting over the range of altitudes investigated.

INTRODUCTION

The use of turbojet engines on multiengine high-altitude aircraft requires that these engines be capable of starting at altitudes of 50,000 feet. The altitude-ignition limits depend on the energy per spark and the spark repetition rate produced by the ignition system (refs. 1 and 2), the over-all fuel-air ratio of the mixture to be

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ignited, and the volatility of the fuel (refs. 3 and 4). Reid vapor pressure has been used as an indication of fuel volatility, but the fast rate of climb obtained with current airplanes requires that the Reid vapor pressure be limited to a low value to prevent loss of fuel from the airplane fuel tanks during climb (ref. 5). In an effort to improve the altitude-ignition characteristics of fuels with low Reid vapor pressures, new blends of fuel have been developed that have fewer heavy components and, thus, a higher over-all volatility without an appreciable change in Reid vapor pressure. Using these fuels requires a different method of indicating the volatility of a fuel as it affects ignition. The 15-percent point on the A.S.T.M. distillation curve has been used for this purpose (ref. 4).

In the present investigation, the distillation curves obtained at the combustor operating pressure were considered as an indication of the fuel volatility. The investigation was conducted on a full-scale turbojet engine installed in an altitude chamber at the NACA Lewis laboratory to compare the altitude-ignition and flame-propagation characteristics of three fuels having different distillation curves; two of the fuels had the same Reid vapor pressure. This investigation was conducted at a simulated altitude of 50,000 feet and a flight Mach number of 0.8. In addition, ignition and propagation limits, as defined by the fuel-air-ratio ranges in which ignition and propagation could be obtained, were determined for one of the fuels over a range of altitudes at a flight Mach number of 0.8.

APPARATUS

Engine Installation

A J47-GE-27 turbojet engine was installed in a 10-foot altitude test chamber for use in this investigation. This engine has a 12-stage axial-flow compressor, 8 tubular combustors, a single-stage turbine, and a nonafterburning tail pipe. The fuel system was the standard equipment supplied with the engine.

Two commercially available capacitor-discharge ignition systems were used during the investigation. Each system fired two fixed-gap spark plugs, one in each of two tubular combustors 180° apart. Both ignition systems had spark rates of 1 to 4 sparks per second and spark energies which were 20 to 30 percent of the stored energy. The ignition system used for the fuel comparison had a stored energy per spark of 2.7 joules. The system used for determining the altitude-ignition and propagation characteristics had a stored energy per spark of 1.35 joules.

Instrumentation

The data used for the windmilling-performance and air-flow calculations of this investigation were obtained with the instrumentation listed in the following table:

Station	Total-temperature probes	Total-pressure probes	Static-pressure orifices
Engine inlet	12	24	4 stream, 6 wall
Compressor outlet	12	12	2 wall
Combustor	--	--	2 wall
Turbine outlet	12	15	3 wall

Air flow was calculated from total temperature and total and static pressures measured at the engine inlet. Strip recorders were used to record the variation with time of engine speed, fuel flow, fuel-manifold pressure, combustor static pressure, and total temperature of the gas in each combustor.

Fuels

Analyses of the three fuels used in this investigation are presented in table I, and the A.S.T.M. distillation curves are presented in figure 1(a). Distillation curves for the fuels at a pressure equal to the combustor static pressure at an altitude of 50,000 feet were obtained from the A.S.T.M. distillation curves (which are obtained at sea-level pressure) by the method of reference 6 and are presented in figure 1(b). These three fuels are, in general, within the specifications for MIL-F-5624A grade JP-4 fuel.

PROCEDURE

The engine-inlet total pressure and the ambient static pressure were set to correspond with NACA standard conditions, and the inlet total temperature was maintained at -40° F for all flight conditions. After the flight conditions were established, the engine was brought to its free windmilling speed; the resulting combustor-inlet conditions are listed in table II. The fuel flow was then set at a given value and the ignition system was energized. A time limit of 30 seconds was allowed for ignition to occur. Upon successful ignition, as indicated by a temperature rise in one of the combustors, an interval of 30 seconds was allowed for propagation of the flame to the remaining combustors. At each altitude this procedure was repeated over a range of fuel flows from the lean to the rich limit as indicated by nonignition or until the limit of the fuel-meter capacity was reached. After each ignition above 50,000 feet, the altitude was increased in 1000-foot increments until the altitude limit was reached.

RESULTS AND DISCUSSION

Initiation of combustion in a turbojet engine requires a suitable mixture of fuel vapor and air. This mixture is dependent upon the fuel volatility and the over-all fuel-air ratio as discussed in the following sections.

Effect of Fuel Volatility and Fuel-Air Ratio on Altitude-Ignition and Propagation Characteristics

Ignition was obtained at an altitude of 50,000 feet and a flight Mach number of 0.8 in the following fuel-air-ratio ranges (fig. 2): 0.012 to 0.019 for fuel 52-368, 0.018 to 0.027 for fuel 53-39, and 0.025 to 0.038 for fuel 52-288. Fuel 53-39 had the same Reid vapor pressure as fuel 52-288 (2.7 lb/sq in.), but ignition occurred at leaner fuel-air ratios. However, the distillation curves for the fuels at the pressure level of the combustor inlet (fig. 1(b)) indicate that, at a temperature of approximately 200° F, fuel 53-39 would yield more fuel vapor per pound of fuel than would fuel 52-288. (The temperature of 200° F was selected as the approximate temperature the atomized fuel would likely reach for the combustor-inlet air temperature of 250° F obtained in this investigation.) Although fuel 52-368 had a lower Reid vapor pressure (1.7 lb/sq in.) than the other two fuels, it ignited at leaner fuel-air ratios. Figure 1(b) indicates that fuel 53-368 would yield more fuel vapor at a temperature of 200° F than would the other two fuels. It is evident then that the distillation curves of figure 1(b) gave a better qualitative indication of the fuel volatility as it affects ignition than did the Reid vapor pressure.

The tests indicated that the more volatile fuel (52-368) required more time for ignition than the less volatile fuel (52-288). Because of the limited amount of data on the time for ignition and the large scatter, a quantitative measure of the difference in ignition time could not be established.

The fuel-air-ratio range in which flame propagation with each of the three fuels was obtained at an altitude of 50,000 feet is shown in figure 3. The range for each fuel is similar to, but somewhat more limited than the ignition range. The operable range of fuel-air ratios for propagation is shown to be a function of the fuel volatility as indicated by the distillation curves at the combustor-inlet conditions.

The minimum time required for propagation increased with increasing fuel volatility. This can be explained by considering the mechanics of the propagation of the flame to an adjacent combustor. As reported in reference 1, ignition in the first combustor and the accompanying combustion cause a temperature rise which results in a pressure
3157 rise in this combustor. The pressure rise causes a pressure differential between the adjacent combustors and a flow of burning gas through the cross-fire tube. Since the more volatile fuel had the leaner fuel-air ratio at ignition, the temperature and, consequently, the pressure rise due to combustion would be less than for a less volatile fuel. Hence, the rate of flow of the burning gas through the cross-fire tube would be lower and the time required for the propagation of the flame to the second and all other combustors would be greater.

Effect of Altitude Variation on Altitude Ignition and Propagation Characteristics of Fuel 53-39

At a flight Mach number of 0.8, the range of fuel-air ratios in which ignition was obtained decreased with increasing altitude (fig. 4). The altitude limit of ignition with a 1.35-joule-per-spark ignition system at a flight Mach number of 0.8 was approximately 54,000 feet at a fuel-air ratio of 0.025. Ignition was possible over the range of altitudes investigated in as little as 2 seconds.

Propagation of the flame from the first to the last combustor was obtained in approximately the same range of fuel-air ratios as was ignition for altitudes up to 50,000 feet (fig. 5). The minimum time for propagation increased with increasing altitude. This increase in time was from less than 1 second at 45,000 feet to about 5 seconds at 50,000 feet; no propagation occurred at 54,000 feet. At 50,000 feet, the minimum time for propagation occurred at a fuel-air ratio of approximately 0.025. The minimum time for both ignition and propagation occurred at the same fuel-air ratio at the conditions of this investigation.

CONCLUDING REMARKS

At the combustor-inlet conditions of this investigation, the relative quantities of fuel evaporated at the operating pressure and temperature of the combustor, as indicated by the A.S.T.M. curves corrected to the combustor pressure, were found to provide a better indication of the effect of fuel volatility on altitude ignition and propagation than Reid vapor pressure. The fuel-air ratios required for ignition and propagation decreased with increasing fuel volatility; for one fuel, both ignition and propagation were obtained at the same fuel-air ratio. Due to scatter of the data, no reliable trend of time for ignition with fuel volatility was discernible. However, the data did indicate a trend of increasing minimum times for propagation with increasing fuel volatility.

The fuel-air-ratio range over which ignition and propagation were obtained decreased as the altitude increased. The altitude-ignition limit with a 1.35-joule-per-spark ignition system at a flight Mach number of 0.8 was approximately 54,000 feet at a fuel-air ratio of 0.025.

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With the proper selection of fuel and a 2.7-joule-per-spark ignition system, ignition could be established in all combustors of the engine investigated in as little as 2 seconds at an altitude of 50,000 feet and a flight Mach number of 0.8.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 7, 1953

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TABLE I. - FUEL ANALYSES

NACA fuel number	52-288	52-368	53-39
Gravity			
°API	50.8	62.6	54.2
Specific	0.776	0.729	0.762
A.S.T.M. distillation D86-46, °F			
Initial boiling point	139	190	142
Percentage evaporated			
5	224	201	195
10	253	203	218
20	291	208	239
30	311	211	258
40	324	214	269
50	333	217	285
60	347	220	300
70	363	223	319
80	382	229	339
90	413	239	373
95	442	252	415
Final boiling point	486	332	464
Residue, percent	1.2	1.2	1.4
Loss, percent	0.7	0.8	0.6
Viscosity, centistokes			
-40° F	4.27	1.63	2.57
100° F	0.95	0.59	0.82
Aromatics, total percent by volume			
Silica gel	10.1	11.8	9.7
Reid vapor pressure, lb/sq in.	2.7	1.7	2.7
Hydrogen-carbon ratio[a]	0.168	0.172	0.172
Heat of combustion[b], Btu/lb	18,675	18,850	18,700
Aniline point, °F	136.8	138.0	131.7

[a]Determined in combustion furnace.
[b]Determined by aniline-gravity constant.

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TABLE II. - WINDMILLING CONDITIONS

Altitude, ft	Free windmilling engine speed, rpm	Windmilling air flow, lb/sec	Engine-inlet air temperature, °F	Combustor-inlet temperature, °F	Combustor-inlet static pressure, lb/sq ft abs
30,000	2560	13.9	-40	250	865
45,000	2560	7.0	-40	250	420
50,000	2560	5.5	-40	250	325
54,000	2590	4.6	-40	250	270
55,000	2630	4.4	-40	250	260

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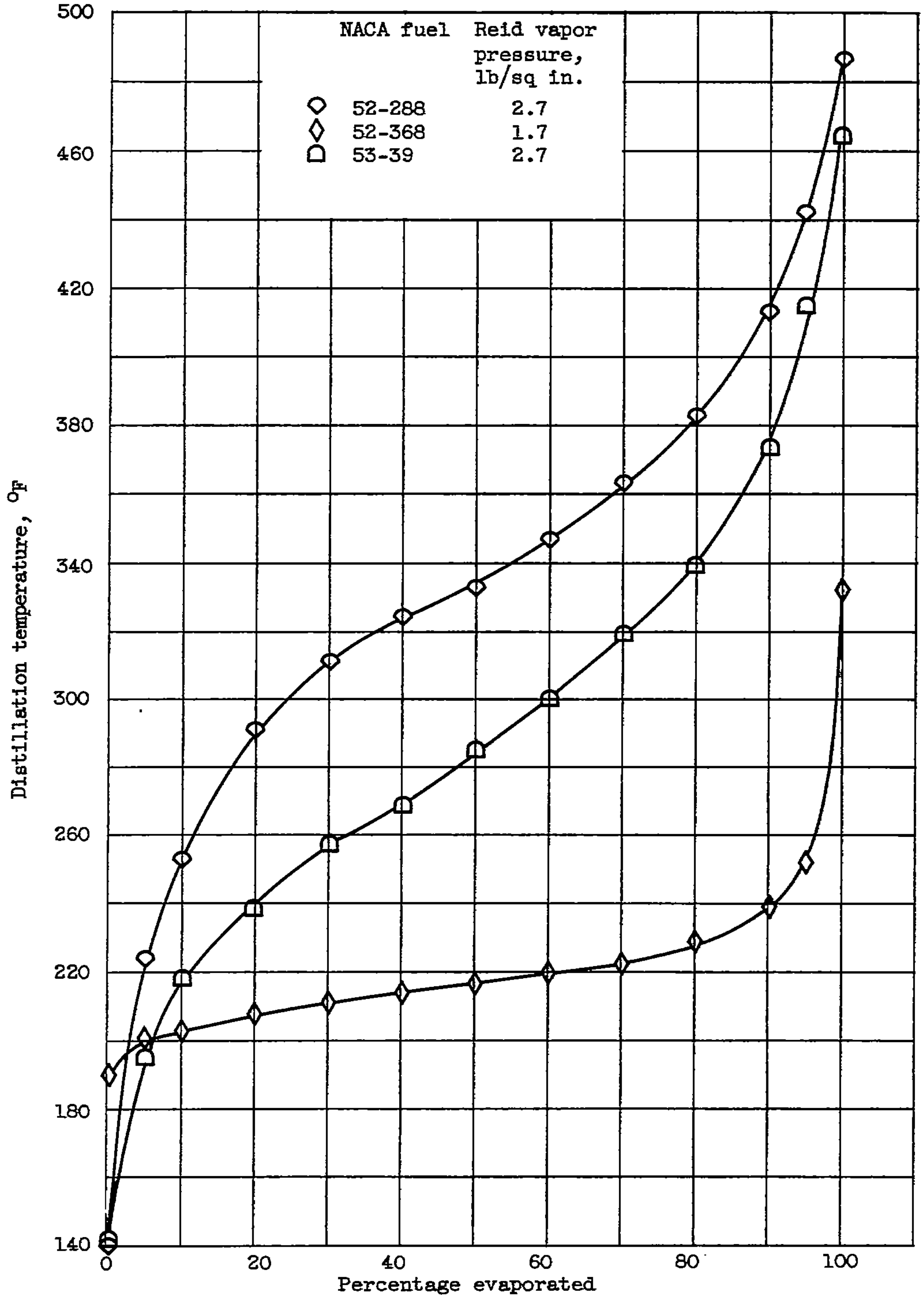
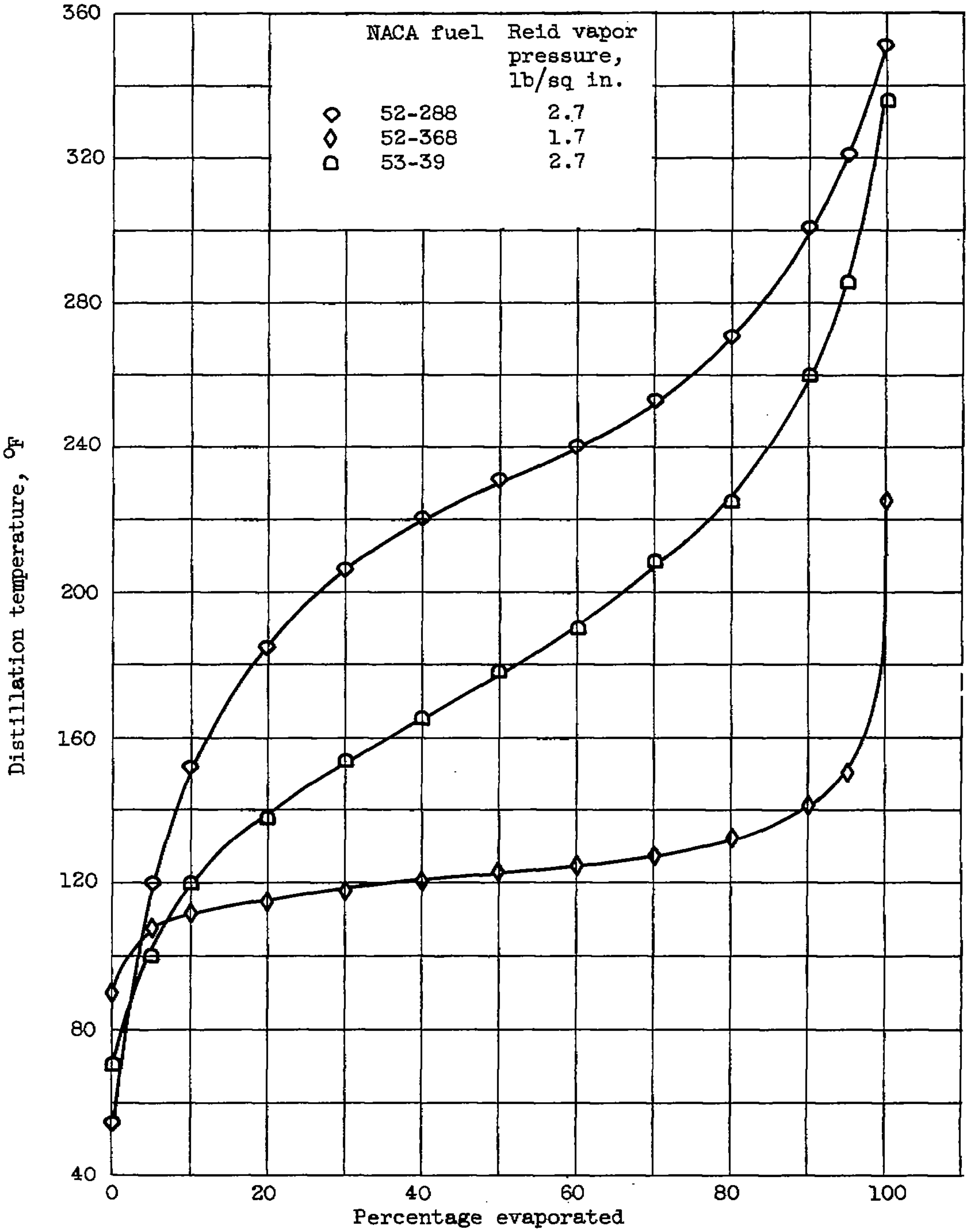


(a) A.S.T.M. distillation curves.

Figure 1. - Distillation curves for three fuel blends.



(b) Distillation curves for pressure of 325 pounds per square foot (combustor-inlet static pressure at 50,000 ft).

Figure 1. - Concluded. Distillation curves for three fuel blends.

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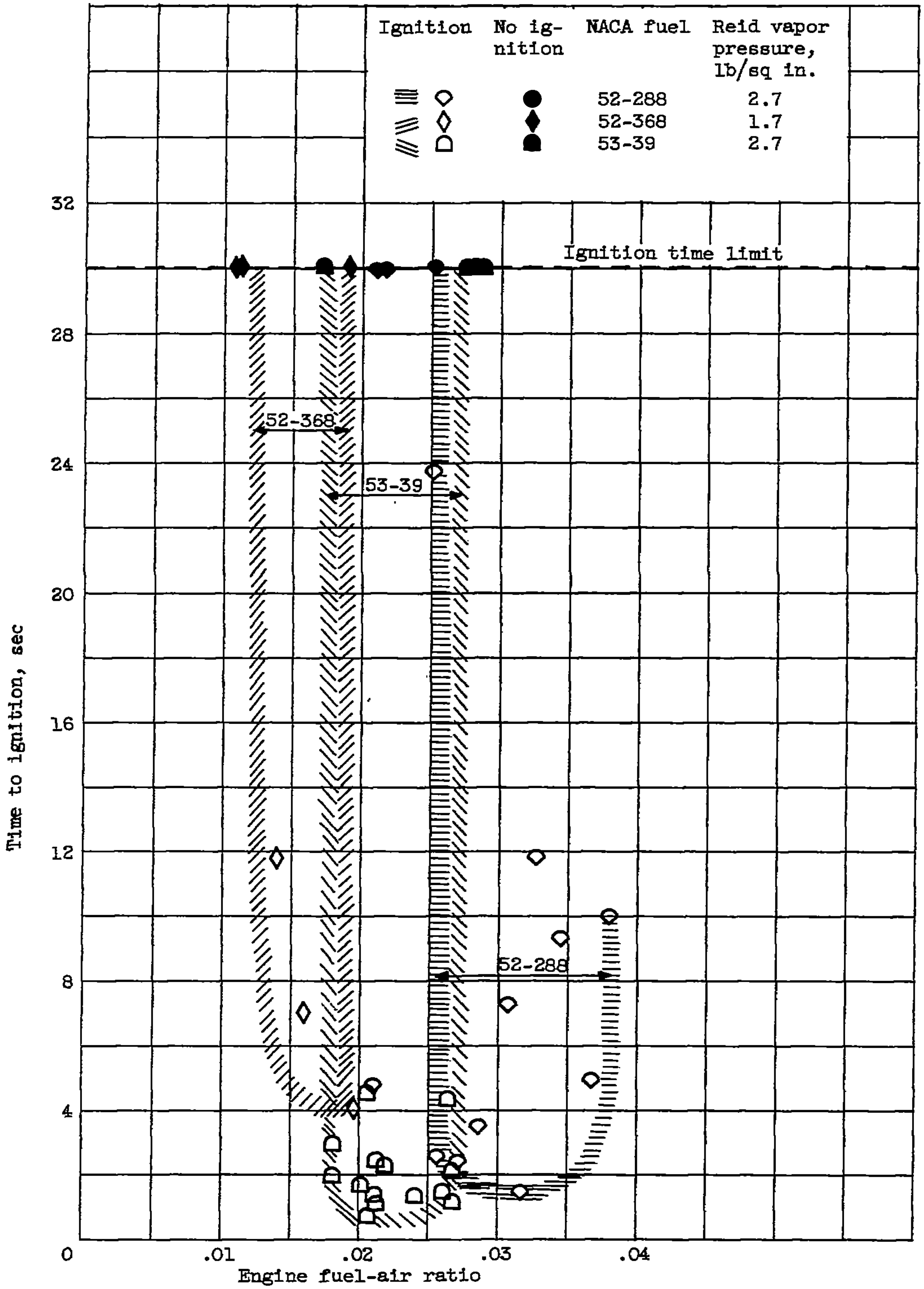

Figure 2. - Effect of fuel-air ratio on ignition of three fuels with 2.7-joule-spark ignition system. Altitude, 50,000 feet; flight Mach number, 0.8.

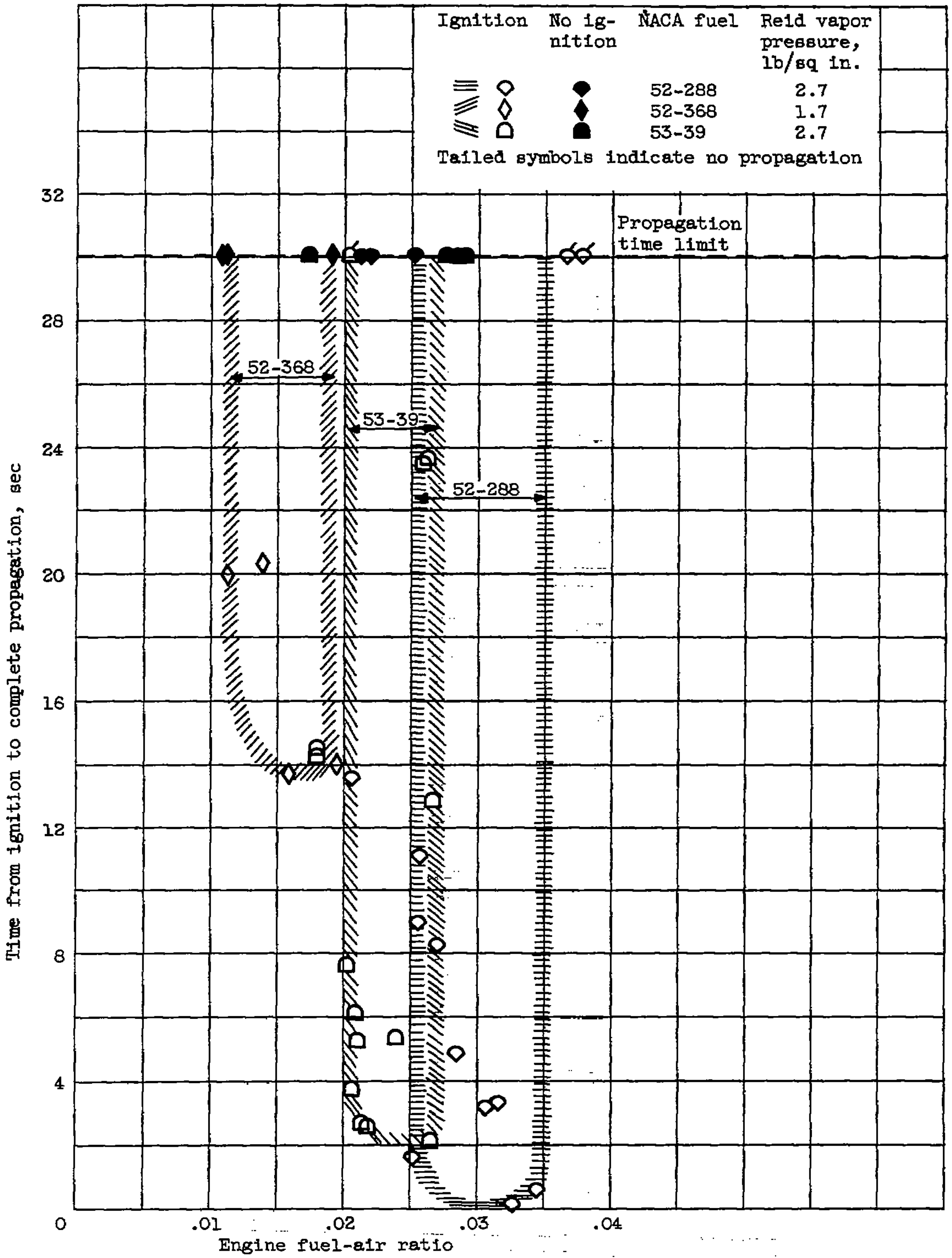

Figure 3. - Effect of fuel-air ratio on propagation with three fuels. Altitude, 50,000 feet; flight Mach number, 0.8.

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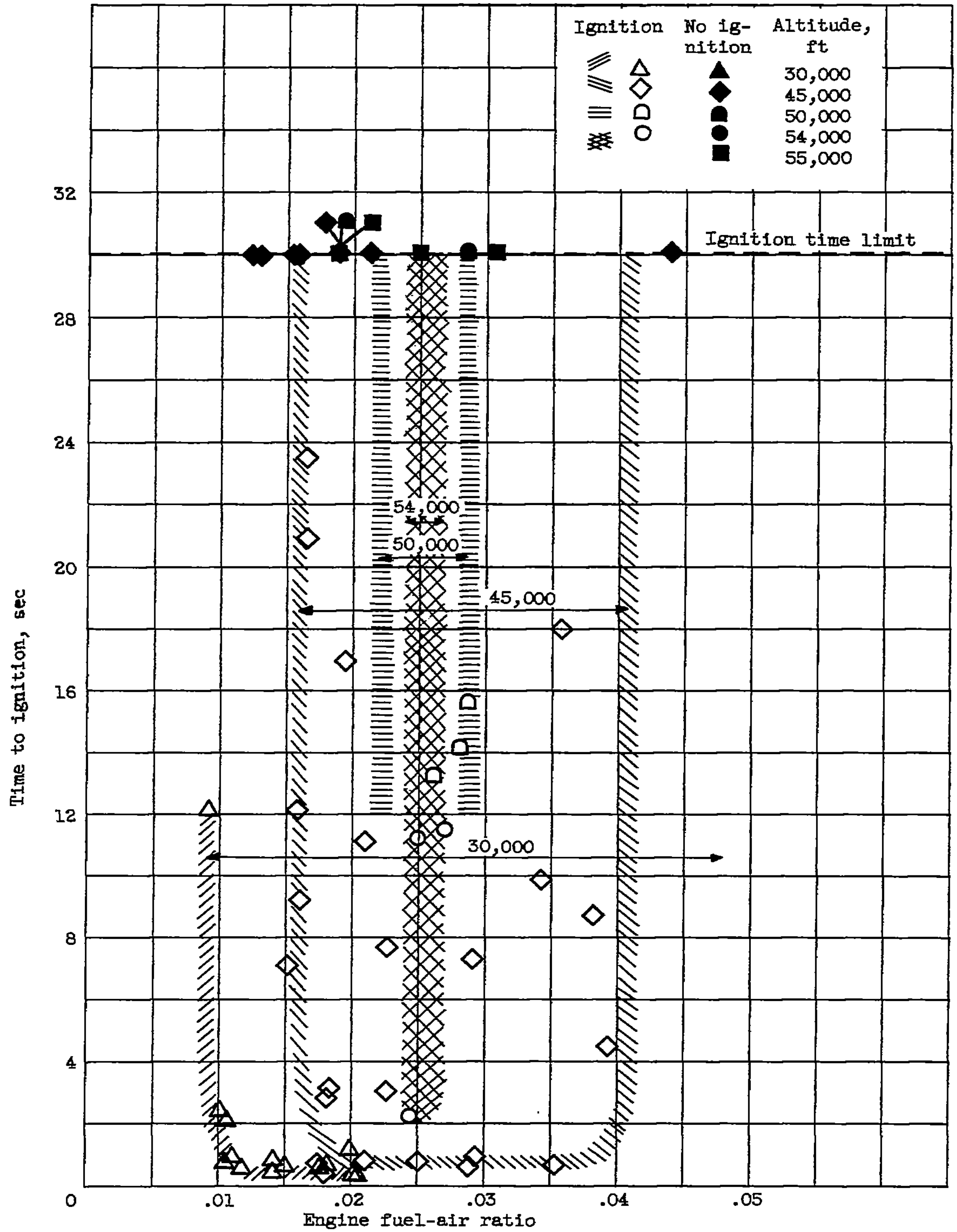

Figure 4. - Effect of altitude on ignition of NACA fuel 53-39 with 1.35-joule spark ignition system. Flight Mach number, 0.8.

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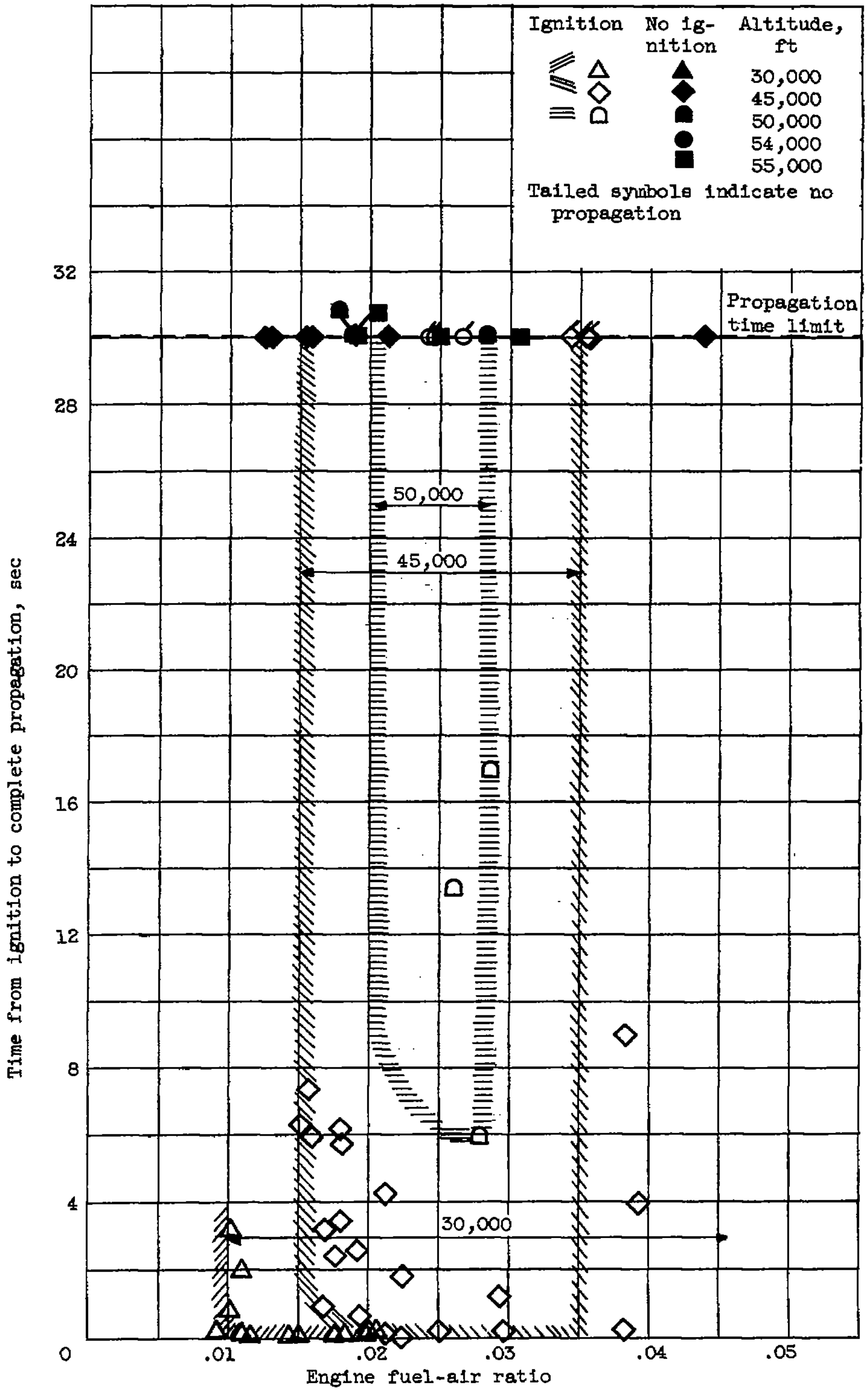

Figure 5. - Effect of altitude on propagation in NACA fuel 53-39. Flight Mach number, 0.8.

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