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IGNITION CHARACTERISTICS OF FUELS AND LUBRICANTS

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FOREWORD

This report was prepared by the Explosives Research Center of the U. S. Bureau of Mines under USAF Contract No. DO (33-657) 63-376. The contract was initiated under Project No. 3048 "Aviation Fuels", Task No. 304801 "Hydrocarbon Fuels". It was administered under the direction of the AF Aero Propulsion Laboratory, Research and Technology Division, with Mr. H. R. Lander acting as project engineer.

This report is a summary of the work recently completed during the period 1 January 1963 to 31 December 1963.

Dr. Robert W. Van Dolah was the administrator for the U. S. Bureau of Mines and Dr. M. G. Zabetakis, Messrs. J. M. Kuchta, A. Bartkowiak, R. J. Cato, W. H. Gilbert, and R. E. Kennedy actively participated in this work at the U. S. Bureau of Mines Explosives Research Center, Bruceton, Pennsylvania.

ABSTRACT

Ignition temperatures of n-hexane, n-octane, n-decane, JP-6 jet fuel and aircraft engine oil MIL-L-7808 (0-60-18) were determined in air using heated Pyrex cylinders of 0.314-inch to 1.38-inch diameter and Nichrome wires, rods, or tubes of 0.016-inch to 0.75-inch diameter. The ignition temperature varied little with fuel-air ratio but increased as the size of the heat source was decreased. Expressions are given which define the variation of the hot surface ignition temperatures of these combustibles with the radius and the surface area of the heat source. The expressions are applicable to stagnant or low velocity flow conditions (< 0.2 in/sec). In addition, the hot gas ignition temperatures of the combustible vapor-air mixtures were determined with 1/4, 3/8 and 1/2-inch diameter jets of hot air. These ignition temperatures also varied little with fuel-air ratio and increased as the diameter of the heat source was decreased.

This technical documentary report has been reviewed and is approved.

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INTRODUCTION

The autoignition temperature (AIT) characteristics of many aircraft fuels and lubricants have been investigated by the Bureau of Mines as part of a research program for the Air Force on the explosion hazards associated with the use and storage of aircraft combustible fluids. Most of the autoignition data obtained in the earlier studies (Refs. 1 and 2) are primarily applicable to situations in which a flammable atmosphere contacts a relatively large heated surface, such as the walls of a fuel tank. Ignition may also result upon contact of a flammable mixture with a small heat source such as a heated wire or with a jet of hot air or other gases; such jets may be produced by the failure of an oil seal in a jet engine. Accordingly, the present program was initiated to provide experimental data on the ignition behavior of aircraft combustibles by hot surfaces and hot gas jets of various sizes. These will be used to develop semi-empirical relationships that can be used to predict the ignition behavior of representative hydrocarbon fuels under various environmental heating conditions.

Minimum AIT's of combustible mixtures are generally determined under quiescent conditions and in heated vessels sufficiently large to minimize wall quenching. Under such ignition conditions, the fuel residence times or ignition delays are maximum and the rate of heat input is not an important factor. However, these AIT values increase as the size of the vessel and the fuel residence time are decreased. With a sufficiently small heat source, the heat input rate becomes an important factor. This is the case when ignition is effected by an electrical discharge or by a fine heated wire. According to thermal theory (Ref. 3), the temperature at which ignition occurs is proportional to the reciprocal of the logarithm of the diameter of heat source. Thus, the conventional autoignition and the wire ignition experiments are basically similar and should yield results that are in agreement with heat sources of the same size. Surprisingly, little quantitative information is available on the correlation of these ignition temperatures over a wide range of heat source dimensions. Such data were obtained in the present study for several hydrocarbon combustibles whose vapors were ignited in air using various sizes of Pyrex vessels and Nichrome wires, rods and tubes. The combustibles used here included n-hexane, n-octane, n-decane, a JP-6 jet fuel, and an aircraft engine oil MIL-L-7808 (0-60-18).

The temperatures at which combustible mixtures can be ignited by jets of hot air have been determined only recently for several hydrocarbon fuels in oxygen-nitrogen atmospheres (Ref. 4). These ignition temperatures are reported to be much higher than corresponding autoignition temperatures. Since hot gas ignition temperatures also vary with the diameter of the jet and the fuel residence time, again they may not differ greatly from AIT's if these variables are considered. Admittedly, hot gas ignition and hot surface ignition temperatures need not necessarily be the same since the ignition mechanisms may be different with each type of heat source. This appears to be true for the hot gas ignition temperature data which are presented in this report; these were obtained by injecting various hot air jets into vapor-air mixtures of the hydrocarbon fuels and engine oil listed above.

EXPERIMENTAL APPARATUS AND PROCEDURES

1. Hot Surface Ignition Temperature Experiments

In the first phase of the hot surface ignition work, autoignition temperatures (AIT's) of the hydrocarbon fuels and engine oil of interest were determined in quiescent air. These determinations were made in the Bureau of Mines I-8 ignition temperature apparatus (Ref. 1) using cylindrical Pyrex vessels 6 inches long and with volumes between 0.48 and 8.3 cubic inches (0.3 to 1.38-inch diameter); the vessels were covered with a watch glass after addition of the combustible. The vessel temperature, the fuel residence time, and the volume of liquid fuel injected into the vessel were varied to obtain the minimum temperatures for ignition. In all cases, ignition was evidenced by the appearance of flame. The repeatibility of the AIT values was within ±5° at low temperatures ($\sim$ 500° F) and ±20° at high temperatures ($\sim$ 1000° F).

Additional hot surface ignition experiments were conducted under flow conditions with the above fuels and engine oil using electrically heated Nichrome wires of 0.01 to 0.1-inch diameter and rods or tubes of 0.2 to 0.75-inch diameter. These were conducted in the wire ignition temperature apparatus shown in Figure 1. This apparatus was equipped with liquid fuel- and air-feed assemblies capable of providing pre-mixed fuel vapor-air mixtures at a uniform rate to a heated reaction chamber - a Pyrex tube 2 inches ID and 8 inches long (33.2 in^3 volume). Figure 2 is a photograph of the reaction chamber; in use it is normally mounted in a small oven equipped with an observation window. Two side arms at the middle of the tube are fitted with brass adapters for use in mounting the wires (or tubes and rods) normal to the direction of flow. These adapters are spaced 2 inches apart, the length of wire that was heated electrically in each trial. The wire temperature can be varied in large or small increments by use of a toggle switch.

To conduct an experiment, the wire is first heated to a predetermined surface temperature which is measured with a Leeds & Northrup optical pyrometer, calibrated against a General Electric standard lamp. The fuel vapor-air mixture is then passed over the heated wire at a designated flow rate and, depending on whether or not ignition occurs, the wire temperature is decreased or increased in succeeding trials until the lowest temperature at which ignition occurs is found. Minimum wire ignition temperatures were obtained at various fuel-air ratios; these were generally repeatable to within ±20°. In each case, ignition was evidenced by the appearance of flame and by a sudden rise of the gas mixture temperature. These temperatures were measured with two chromel-alumel thermocouples (28-gage) located 1-inch above and below the heated wire. The gas mixture temperatures were recorded continuously on an oscillograph during each run.

In the experiments with Inconel tubes, small cylindrical heaters were inserted into the tubes to heat them to the desired temperature; here, about 1-1/2 inches of the heated section (2 inches) was usually at near uniform temperatures. Each of the tubes was also equipped with a 28-gage chromel-alumel thermocouple to measure surface temperatures (< 1100° F) below the operating range of the optical pyrometer. These thermocouples were spot-welded on the surface and at the mid-point of each tube.

Most of the wire ignition experiments with the fuels were conducted at a mixture temperature of 300° F and a flow rate of 17.8 in^3/min. (N.T.P.). A mixture temperature of 500° F was used with the MIL-L-7808 engine oil which is composed primarily of adipate esters. From the vacuum distillation data obtained with a sample of this oil, it was found that at least 90 percent vaporizes between 734° and 779° F (Table 1). However, the vapor pressure of this oil at 500° F appeared to be adequate to permit the formation of suitable vapor-air mixtures under the flow conditions employed, since no condensation was observed on the vessel walls.

TABLE 1. - Vacuum Distillation Data for Aircraft Engine Oil MIL-L-7808 (0-60-18). Sample distilled at 1.4 mm Hg.

Temperature, °F	480	734	743	745	759	761	770	779	779
Fraction distilled (Vol. %)	1st drop	5	10	20	30	40	50	80	95.2

2. Hot Gas Ignition Temperature Experiments

In this portion of the work, the ignition temperatures of the hydrocarbon fuels and engine oil (vapor-air mixtures) were determined under flow conditions with various size jets of hot air. The apparatus used for these determinations is shown in Figure 3 and except for some minor modifications, is similar to that employed by Wolfhard (Ref. 4). Basically, the apparatus consists of a tubular ceramic furnace that is used to heat the air stream, a cylindrical reaction chamber into which is fed the hot air jet and the combustible mixture, and the feed assemblies that provide the desired combustible vapor-air mixture at a uniform rate. The tubular furnace was wound externally with platinum-rhodium wire and was enclosed in a cylindrical Nichrome-wound furnace (3-inch ID) which serves as a pre-heater. The reaction chamber consists of a 4-inch diameter Pyrex pipe (26 inches long) that is also heated by a Nichrome-wound furnace designed to maintain the combustible mixture at a given temperature. Narrow slits are located on both sides of the enclosed pipe along its longitudinal axis to permit visual observation of the reaction. The combustible vapor-air mixture is fed to the reaction chamber through a "mixing ring" by the fuel- and air-feed assemblies. This ring is located just below the base of the hot jet; a water jacket is positioned between the ring and the ceramic tubular furnace to help maintain the mixture at a uniform initial temperature.

The temperatures of the hot air jets are measured with a 33-gage platinum-90% platinum + 10% rhodium thermocouple at a point of about 1/4-inch above the jet base; the temperature decreases progressively with the height above the jet base at a rate that is determined in part by the jet diameter. With a

1/2-inch diameter jet, the temperature drop is about 160° at a height of 1 inch under the flow conditions employed here; the temperature drop is less with a smaller size jet at the same volume flow rate. The temperatures of the combustible vapor-air mixtures were measured with three Chromel-Alumel thermocouples (28-gage) spaced 3 inches apart as shown in Figure 3. Recorded temperature differences were usually not in excess of ±25°. All of the present experiments were conducted at a mixture temperature of 350° F for the hydrocarbon fuels and 600° F for the engine oil. The mixture flow rate was 365 in^3/min. and the jet flow rate was 185 in^3/min., both at N.T.P. conditions.

To conduct an experiment, the temperatures of the hot air jet and ambient atmosphere in the reaction chamber were measured initially. The thermocouples were then removed and the combustible mixture of interest was introduced, flowing coaxially with the hot jet. If ignition did not occur, the temperature of the hot air jet was increased in successive increments until ignition was evidenced by the propagation of flame throughout the combustible mixture. Normally, a small precursor flame could be seen above the base of the jet prior to ignition; this flame extended to a height of 6 inches or less above the jet base. Fuel residence time and fuel-air ratio were also varied to obtain the minimum ignition temperatures with each size of hot air jet; jets of 1/4, 3/8, and 1/2-inch diameter were employed in this work. Generally, ignitions occurred within about 60 seconds, although a few took place after as much as 180 seconds from the time the combustible mixture was admitted. The minimum ignition temperature values were repeatable to within ±25°.

RESULTS AND DISCUSSION

1. Hot Surface Ignition

Autoignition Temperatures in Quiescent Air

The minimum autoignition temperatures (AIT's) found for n-hexane, n-octane, n-decane, JP-6 jet fuel and MIL-L-7808 engine oil in various cylindrical Pyrex vessels are given in Table 2. These data were obtained with nonuniform mixtures in quiescent air at atmospheric pressure and with the appearance of flame as the ignition criterion. The apparent fuel-air weight ratio required to obtain most of these AIT values was 0.35 ± 0.1. Uniform mixtures of these combustibles in air normally would not be expected to propagate flame at such high fuel-air ratios except as cool flames. The data in Table 2 show that the AIT values for each combustible increased noticeably with decreasing vessel volume between 0.458 cubic inch (7.5 cc) and 3.66 cubic inches (60 cc); they decreased only slightly when the vessel volume was increased from 3.66 to 8.25 cubic inches (135 cc). Also included in Table 2 are the minimum AIT values of these combustibles which were found in a 12.21-cubic inch (200 cc) Pyrex Erlenmeyer. The latter values are still lower than those listed for the 8.25-cubic inch cylindrical vessel, particularly for n-hexane and the engine oil.

To illustrate the effect of vessel dimensions, the ignition temperatures in Table 2 are plotted in Figure 4 versus the surface area to volume ratio (S/V) of the cylindrical vessel employed. Since vessel length (h) was constant (6 inches), this figure essentially shows the effect of vessel radius (r) on the ignition temperatures of each combustible; S/V is 2/r + 2/h for a cylinder with closed ends. It is clearly evident here that the AIT's increased sharply when the S/V ratio was in excess of about 5.0 in^{-1} or when the vessel radius was less than 0.44-inch. Such results are expected since heat losses to the vessel walls and other surface effects should be most critical for ignition in the smallest size vessels. Similar data were not obtained in smaller vessels (< 0.157-inch radius) because of the temperature limitations of the experimental apparatus; the temperatures required to obtain ignitions in the smaller vessels would tend to be prohibitively high since the volume of combustible mixture would take on added importance and the quenching diameters for these combustibles would not be expected to be much less than that of the smallest vessel used here (0.314-inch).

The data obtained with the neat hydrocarbon fuels are consistent in that the ignition temperatures increased with decreasing molecular weight. However, it is of interest to note that the AIT values of the engine oil are comparable or less than those of all the fuels at vessel volumes less than 3.66 in^3 (60 cc), i.e., at temperatures above about 800° F. In contrast, the values for the oil in the larger vessels are less than 800° F and are at least 280° higher than those for the fuels. Apparently, the reaction species effecting the ignition of this oil at temperatures below 800° F are different from those encountered at the more highly elevated temperatures (800-1100° F). It is possible that the adipate esters which largely make up this oil break down to form more thermally unstable species at the higher temperatures required for ignition.

TABLE 2. - Minimum Autoignition Temperatures of the Hydrocarbon Fuels and an Engine Oil in Air at Atmospheric Pressure. Ignition Criterion - Appearance of flame

Vessel Volume in.^{3}	Vessel Volume cc	Vessel Radius in.	S/V[1] in^{-1}	Minimum Autoignition Temperature, °F n-Hexane	n-Octane	n-Decane	JP-6	Engine Oil MIL-L-7808
			Cylindrical Pyrex Vessels - 6-inch length					
0.458	7.5	0.157	13.03	1164	1117	1116	1105	1076
0.610	10	.183	11.44	1117	1081	1089	1036	1035
1.41	23	.276	7.58	1006	941	914	903	883
2.50	41	.375	5.66	808	720	703	766	833
2.75	45	.390	5.46	810	720	612	707	826
3.66	60	.445	4.95	511	450	435	471	795
8.25	135	.590	3.23	509	441	417	468	790
			Pyrex Erlenmeyer - 5-inch length					
12.21	200	(.88)[2]	(2.34)	453	428	406	449	759

[1] Surface area to volume ratio of vessel.

[2] Equivalent radius of a 5-inch cylinder with a 12.21 in.^{3} volume.

Hot Wire Ignition Temperatures

The ignition temperature data obtained with electrically heated Nichrome wires of 0.016 to 0.103-inch diameter are presented in Figures 5-9 for n-hexane, n-octane, n-decane, JP-6 jet fuel, and aircraft engine oil MIL-L-7808, respectively. The curves in each figure show the variation of wire ignition temperature with fuel-air weight ratio (0.05-0.5) and wire diameter for each combustible at the flow condition of 17.8 in^3/min (N.T.P.). Fuel-air ratio is seen to be of little influence here except at low ratio values where the ignition temperatures tend to increase appreciably. Minimum wire temperatures for ignition usually occurred at fuel-air ratios between 0.3 and 0.5. Although ignition temperature was not affected appreciably by the fuel-air ratio, it was found to increase appreciably as the wire diameter was decreased. However, the effect of wire size was not the same for all of the combustibles used here and was least pronounced at large wire diameters.

A composite of the minimum wire ignition temperature data from the above figures is shown in Figure 10; these data are also given in Table 3. As in the autoignition experiments, the ignition temperatures for the neat hydrocarbon fuels increase with decreasing molecular weight. Also, those for the engine oil are lower than those obtained for any of the hydrocarbon fuels, including JP-6; this behavior is consistent with that observed in the AIT determinations conducted with small vessels of 1.41 cubic inches or less capacity (0.276-inch radius). However, it should be noted that the wire ignition temperatures for the JP-6 jet fuel are generally higher than those for n-hexane, whereas the opposite was the case in the autoignition experiments. No explanation for this trend is evident at this time.

TABLE 3. - Minimum Hot Surface Ignition Temperatures of the Hydrocarbon Fuels (300° F) and an Engine Oil (500° F) in Air at a Mixture Flow Rate of 17.8 in.^{3}/min. (N.T.P.).
Ignition Criterion - Appearance of flame
Pyrex Reaction Vessel - 2-inch ID, 8 inches long

Diameter of Heat Source inch	Minimum Ignition Temperature, °F				
	n-Hexane	n-Octane	n-Decane	JP-6	Engine Oil MIL-L-7808
		Nichrome Wires (2-inch length)			
0.016	1830	1820	1775	1880	1550
0.032	1720	1670	1650	1770	1295
0.051	1590	1500	1440	1630	1275
0.081	1570	1430	1400	1530	1160
0.102	1530	1440	1355	1540	1165
		Nichrome Rod (2-inch length)			
0.20	1400	1360	1330	1435	1190
		Inconel Tubes (2-inch length)			
0.50	1190	1185	1160	1235	1040
0.75	1060	1000	1040	1085	1015

By using heated rods or tubes, the wire ignition temperature data were extended to include heat source diameters comparable to those employed in the AIT experiments. Table 3 includes the results obtained for the combustibles of interest with a Nichrome rod of 0.20-inch diameter and Inconel tubes of 0.50 and 0.75-inch diameter. It is seen that the ignition temperatures of the combustibles are noticeably lower with the latter heat sources than with the heated wires; but they are still higher than the corresponding AIT values obtained with Pyrex cylindrical vessels of comparable diameters (Table 2).

Only limited data were obtained on the effect of mixture flow rate or velocity on the wire ignition temperatures, but the data indicated that the velocity effect can be expected to vary with the size of wire used. Figure 11 shows that with relatively large wires (0.081 and 0.102-inch diameter) the minimum wire ignition temperatures are essentially the same at the flow rate of 17.8 in^3/min. (N.T.P.) as under quiescent conditions for n-octane and JP-6 fuel vapor-air mixtures; the given flow rate corresponds to a velocity of about 0.145 in/sec. in the 2-inch diameter reaction vessel. With smaller size wires (0.016 and 0.032-inch diameter), the ignition temperature of JP-6 was at least 100° higher at the above flow. At flow rates greater than 17.8 $in^3/min.$, the ignition temperature apparently increases (Figure 11). It should be mentioned that reliable ignition temperature data were not obtained at very low flow rates (less than 4 $in^3/min.$); the values obtained at very low flow rates were usually at least 100° higher than the minimum values found under quiescent and higher flow conditions. Other investigators have also noted the inconsistency of wire ignition temperatures at very low velocities (Ref. 5). This behavior can probably be attributed to the poor mixing of the reactants and to the accumulation of reaction products around the heated wire prior to ignition.

2. Relationship Between Hot Surface Ignition Temperature and Heat Source Dimensions

Theoretically, the ignition of a combustible vapor-air mixture in contact with a heated surface should occur at a point in the mixture where the temperature is greatest. In AIT experiments, the gaseous mixture and the walls of the heated vessel are generally at a uniform temperature; therefore, ignition should occur where heat reaction losses are minimum, usually in the center of the vessel. However, in ignition temperature experiments with heated wires, the temperature of the wire is ordinarily much greater than that of the confining vessel and the combustible mixture not in contact with the heated surface; in such cases, ignition should take place at or close to the heated surface, as was found in the present work (Figure 12). The motion picture records in Figure 12 show the ignition and subsequent development of flame in two wire ignition experiments with an octane vapor-air mixture at 300° F and at a flow rate of 17.8 $in^3/min.$ (N.T.P.); a Nichrome wire of 0.102-inch diameter was used in each case. These photographs show that the ignitions occurred downstream and essentially at the surface of the heated wire. The initial kernel of flame developed at ignition is somewhat obscured in the pictures because of the light emitted by the wire and that reflected from the vessel walls. In run No. 2, the start of ignition was detected in the second frame of the original film. The development of flame during the early stages was nearly spherical in both runs but proceeded at a higher rate in run No. 2; flame speeds measured about 150 cm/sec. during the early stages (0 to 15 milliseconds) and about 50 cm/sec. subsequently until the flame front became ill-defined. Also of interest in these photographs is the fact that the ignitions in both instances occurred at about the same point along the wire surface. This behavior could be expected if a wire has an irregular or contaminated surface at some point and could explain some of the inconsistencies which were found in the data reported here.

According to thermal theory, the ignition of a combustible mixture by a heated surface is governed by the rate of heat release from chemical reaction and by the rate of heat loss from the system. The size and temperature of the heated surface determine the amount of heat available for initiating the reaction. For thermal ignitions in heated vessels, Frank-Kamenetskii (Ref. 6) has derived an expression which defines the relationship between the ignition temperature (T) and the radius of the vessel (r); he assumed the existence of a stationary temperature distribution and ignition in the center of the vessel. For a cylindrical vessel this expression is:

$$r = \left[\frac{2\lambda}{QE} \quad \frac{RT^2}{Z\ e^{-E/RT}} \right]^{1/2} \tag{1}$$

where Q is the heat of reaction of the combustible mixture with thermal conductivity λ, R is the universal gas constant, E is the activation energy and Z is a rate collision factor. It is applicable primarily to ignitions in small vessels and at low pressures where convective heat transfer may be neglected.

Semenov (Ref. 3) derived a similar expression for the case of thermal ignition by heated wires. He assumed a conductive heat transfer process and ignition in a thin boundary layer near the wire surface. For this case,

$$r \ \ln \frac{r'}{r} = \left[\frac{\lambda E}{2Q} \quad \frac{(T-T_O)^2}{RT^2 Z\ e^{-E/RT}} \right]^{1/2} \tag{2}$$

where r is the radius of the wire, r' is the radius of the vessel and much greater than r, T_O is the temperature of the vessel, and the other symbols have their previous meanings. If convective heat transfer is assumed, r' should be replaced by the radius of the laminar layer of gas within which heat transfer is by conduction.

The above expressions indicate that the ignition temperature, T, should vary inversely with the radius of the heat source, r. Furthermore, as a first approximation, a plot of 1/T vs ln r should be linear over a limited range of temperatures and heat source dimensions. Figure 13 shows such a semi-log plot of the ignition temperature data obtained here for the hydrocarbon fuels and the engine oil with heated vessels, wires, and rods (or tubes). It is evident that the wire and rod ignition temperature data for each combustible tend to display a linear relationship between 1/T and ln r but do not correlate with the AIT data found with heated cylindrical vessels. The slopes of the straight lines drawn to represent the wire and rod ignition data for the hydrocarbon fuels do not vary significantly. Therefore, the following expression may be used to describe the approximate variation of these ignition temperatures (T, °R) with the radius (r) of the heat source between 0.008 and 0.25-inch:

$$\ln r = \frac{21000}{T} - k \tag{3}$$

where k is 13.50 for JP-6 and hexane, 14.30 for octane, and 14.41 for decane.

Similarly, for the MIL-L-7808 engine oil, the following equation is applicable for r values between 0.008 and 0.375-inch:

$$\ln r = \frac{25800}{T} - 18.53 \quad . \tag{4}$$

For larger heat sources than those indicated above, it appears that the ignition temperatures may be expected to decrease sharply, according to the AIT results in Figure 13.

The correlation of the above data was not improved by plotting ignition temperature instead of its reciprocal against the radius of the heat source (ln r); this plot is shown in Figure 14. However, some improvement was obtained by plotting the ignition temperatures (T) against the surface area of the heat source (ln A) as shown in Figure 15. Here, at least the AIT data for the small vessels, those of less than about 0.3-inch radius or 11 in^2 surface area, are more consistent with the wire, rod and tube ignition temperature results than is indicated by the plots in Figures 13 and 14. For the engine oil, the variation of ignition temperature with surface area of the heat source is approximately linear over the entire range of surface areas investigated. The straight (regression) lines drawn to represent the data in this figure were determined by the method of least squares and are given below:

n-Hexane $T = 1415 - 177 \ln A$; $0.1 \leq A \leq 11$; $S_{y/x} = 43$ (5)
n-Octane $T = 1367 - 173 \ln A$; " ; " $= 56$ (6)
n-Decane $T = 1339 - 161 \ln A$; " ; " $= 61$ (7)
JP-6 $T = 1430 - 201 \ln A$; " ; " $= 37$ (8)
Engine Oil $T = 1174 - 115 \ln A$; " ; " $= 65$ (9)

where T is the ignition temperature in °F and A is the surface area of the heat source in square inches; $S_{y/x}$ is the standard error of estimate and is a measure of the scatter in the vertical (y) direction about the regression line. Most of the AIT values fall within $\pm S_{y/x}$.

Although it appears that the hot surface ignition temperatures of the combustible vapor-air mixtures of interest may be approximated as some function of the heat source dimensions, other factors must also be considered. The expressions given above are primarily applicable to cylindrical heat sources and to stagnant or low velocity flow conditions where ignition delay times are relatively long (> 1 second) and unimportant. However, ignition temperatures ordinarily are higher under high velocity conditions where delay times are shorter. They also may vary with the shape, length to diameter ratio, and the construction material of the heat source. The effects of these and other pertinent variables must be known to predict the ignition temperatures of the combustible mixtures under the various heating conditions encountered in practice. In this connection, chemical kinetics data on the pre-ignition reactions can be useful in determining the significance of the ignition temperature data obtained and their consistency with thermal ignition theory.

3. Hot Gas Ignition Temperatures

Luminous columns or precursory flames were observed prior to the ignition of each of the combustibles (fuel vapor-air mixtures) investigated with hot air jets of 1/4, 3/8 and 1/2-inch diameter. These flames were blue in color and became longer and brighter with increasing jet temperature until the temperature conditions were favorable for flame propagation through the test mixture. The latter temperature conditions were used to define the minimum hot gas ignition temperatures presented in this report. Figure 16 shows a photograph of a representative precursory flame obtained in a run at temperatures slightly below those required for ignition; the combustible mixture was n-octane and air at a fuel-air weight ratio of 0.14 and the diameter of the hot air jet was 1/4-inch. In this run, the flame persisted for over 180 seconds without effecting ignition of the combustible mixture. Where ignitions occurred, these appeared to originate near the top of the flame. In some experiments conducted with the neat hydrocarbon fuels, such precursory flames were observed at jet temperatures as much as about 150° below those required for ignition; although the flames were barely visible to the observer, even these may not be tolerated in aircraft systems from the standpoint of safety.

Figure 17 summarizes the hot gas ignition temperature data which were obtained with a 1/4-inch diameter air jet flowing into n-hexane, n-octane, n-decane, JP-6 jet fuel, and the MIL-L-7808 engine oil vapor-air mixtures. Each of the curves shows the variation of the jet ignition temperature with fuel-air weight ratio at a jet flow rate of 185 in^3/min and a mixture flow rate of 365 in^3/min, both measured at the N.T.P. conditions of 60° F and 1 atmosphere. The data are similar in many respects to those reported in the wire ignition experiments. In particular, the effect of fuel-air ratio was not great and minimum hot gas ignition temperatures were found at a fuel-air weight ratio of about 0.5; also, the lowest ignition temperatures were observed with the aircraft engine oil and the highest ones with the JP-6 fuel. Furthermore, there was little variation between the hot gas ignition temperatures of the three neat hydrocarbon fuels.

Similar results were obtained for each of the above combustibles with a 3/8-inch diameter air jet (Figure 18) and for the engine oil with a 1/2-inch diameter jet. However, the ignition temperatures decreased noticeably with an increase in the diameter of the hot gas jet. For example, the minimum hot gas ignition temperatures of all the combustibles were between 110° and 180° lower when the jet diameter was increased from 1/4-inch to 3/8-inch (Table 4). Although the results with the 1/2-inch diameter jet are complete only for the engine oil, it appears that substantially lower ignition temperatures can be expected with air jets greater than 3/8-inch diameter.

TABLE 4. - Minimum Hot Gas Ignition Temperatures of the Hydrocarbon Fuels and Engine Oil (fuel vapor-air mixtures) with Various Jets of Hot Air.

Mixture Flow Rate - 365 in^3/min (N.T.P.)
Jet Flow Rate - 185 in^3/min (N.T.P.)

Diameter of Jet, inch	Ignition Temperature, °F				
	n-Hexane	n-Octane	n-Decane	JP-6	Engine Oil MIL-L-7808
1/4	1630	1610	1595	1665	1525
3/8	1450	1435	1435	1500	1410
1/2	--	--	--	--	1250

The minimum hot gas and hot surface ignition temperatures of the hydrocarbon fuels and engine oil tend to display much the same dependence on heat source diameter, although the former temperatures are observed to be higher. Figure 19 gives the ignition temperature data obtained here with the three hot air jets and with heated wires, rods and tubes $\geq$ 0.1-inch diameter. The comparison of the hot gas and hot surface ignition temperatures may be misleading since the mixture flow rates, the contact areas, and the corresponding contact times with the various heat sources were not the same in each case. Information on the influence of these variables is required before a more realistic comparison of hot gas and hot surface ignition temperatures can be made.

CONCLUSIONS AND RECOMMENDATIONS

The hot surface ignition temperatures of the combustible vapor-air mixtures of interest increased as the size of the heat source was decreased; the combustibles included n-hexane, n-octane, n-decane, JP-6 jet fuel, and the MIL-L-7808 engine oil (0-60-18). Consistent with thermal ignition theory, a logarithmic relationship appears to exist between the radius of the heat source and the ignition temperatures determined with heated wires, rods, and tubes (0.016 to 0.75-inch diameter). In addition, these ignition temperatures tend to correlate with the autoignition temperatures (AIT's) obtained in small cylindrical vessels when compared on the basis of the surface area of the heat source. However, with vessels larger than 0.6-inch diameter, the AIT's of the combustibles, except for the engine oil, decrease sharply and indicate a change in the reaction controlling mechanism(s).

The hot gas ignition temperatures of the above combustibles also increased as the size of the heat source, a hot air jet, was decreased. Although ignition temperatures obtained with 1/4, 3/8 and 1/2-inch diameter jets were higher than corresponding hot surface ignition temperatures, additional data are needed to make a valid comparison.

In accordance with the program proposal on the subject contract (Purchase Request NR 182981RCN, Delivery Order 33(657)-63-376) the following recommendations are made for future work with the hydrocarbon fuels and engine oils.

Hot Surface Ignition Temperatures

1. Determine the effects of shape and nature of the construction material of the heat source.

2. Determine the variation of wire and rod ignition temperatures with initial combustible mixture temperature and pressure in quiescent air or with nearly stagnant combustible vapor-air mixtures.

3. Determine the variation of wire and rod ignition temperatures with flow parallel and perpendicular to the cylindrical heat source.

4. Conduct kinetic studies in confined systems to determine the effects of heat source dimensions on the rates of pressure rise and chemical reaction prior to ignition.

Hot Gas Ignition Temperatures

1. Complete the ignition temperature determinations with the combustible vapor-air mixtures of interest using hot air jets between 1/16 and 1-inch diameter.

2. Determine the effects of jet flow, mixture flow, and mixture temperature using air jets flowing parallel and perpendicular to the combustible mixture.

3. Determine the variation of the hot gas ignition temperatures with oxygen concentration of the combustible mixture.

4. Determine critical jet heat flux required to produce "cool" and "hot" flame propagation through combustible mixtures of interest.

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Figure 16. - Precursory flame formed in pre-ignition reaction of 1/4-inch diameter hot air jet (1670° F) with a uniform octane-vapor-air mixture at 350° F.

Jet flow rate - 185 in^3/min   Fuel-air weight ratio - 0.14

Mixture flow rate - 365 in^3/min   Scale: 1 inch = 0.935 inch

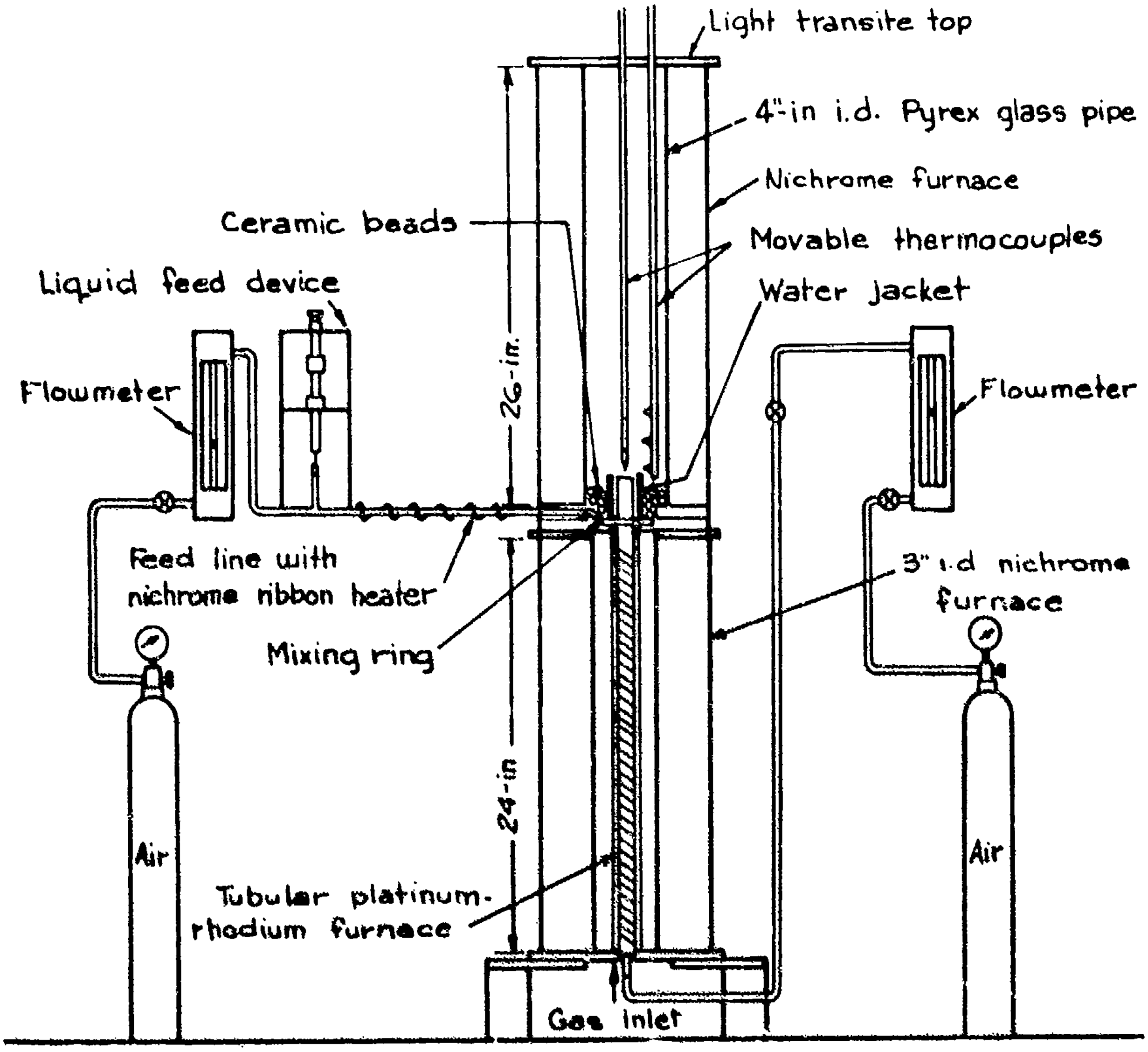


Figure 3.- Hot gas ignition temperature apparatus.

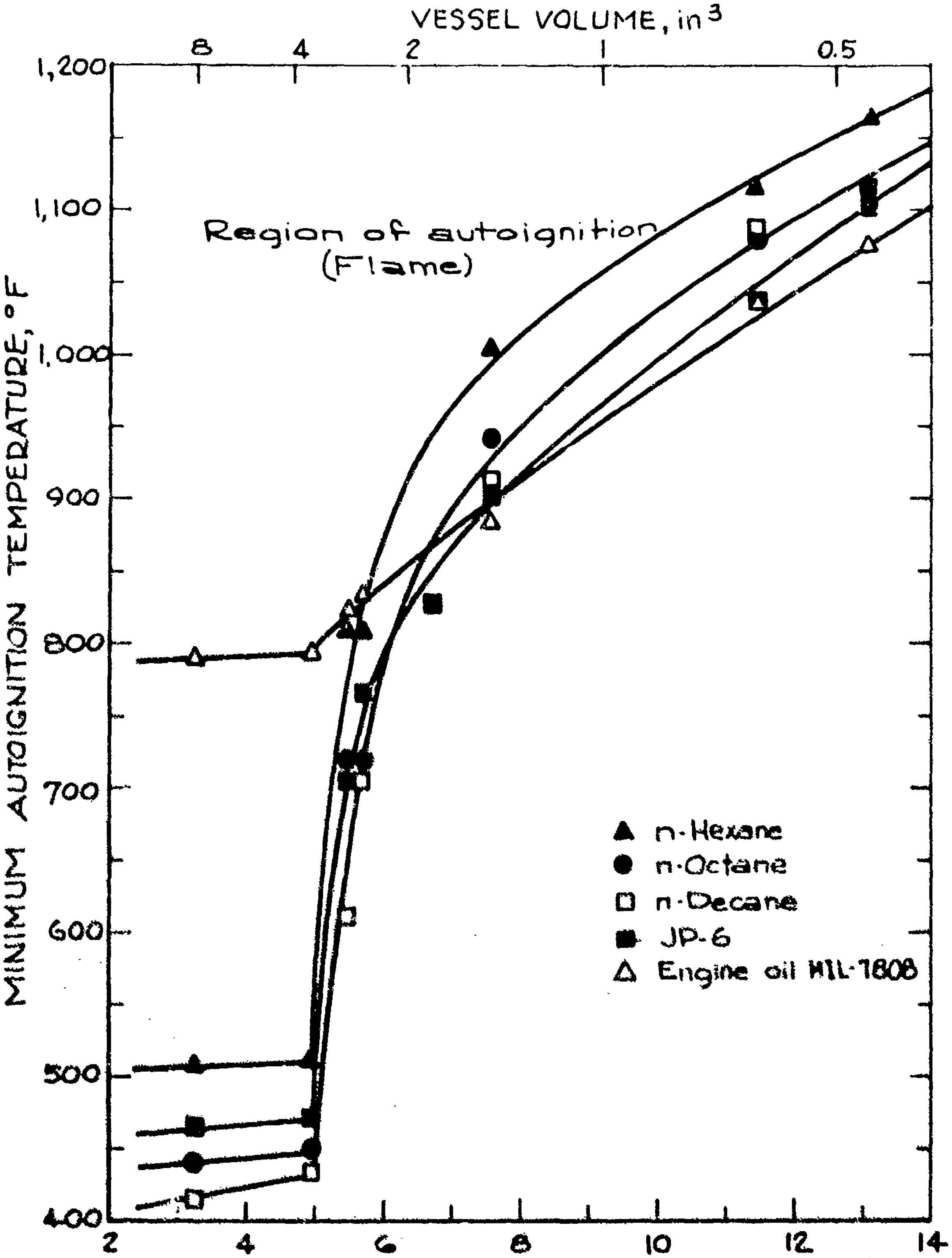


Figure 4.- Effect of vessel surface-volume ratio on minimum autoignition temperatures of various hydrocarbon fuels and an engine oil in quiescent air. (Pyrex cylinders 6-in long)

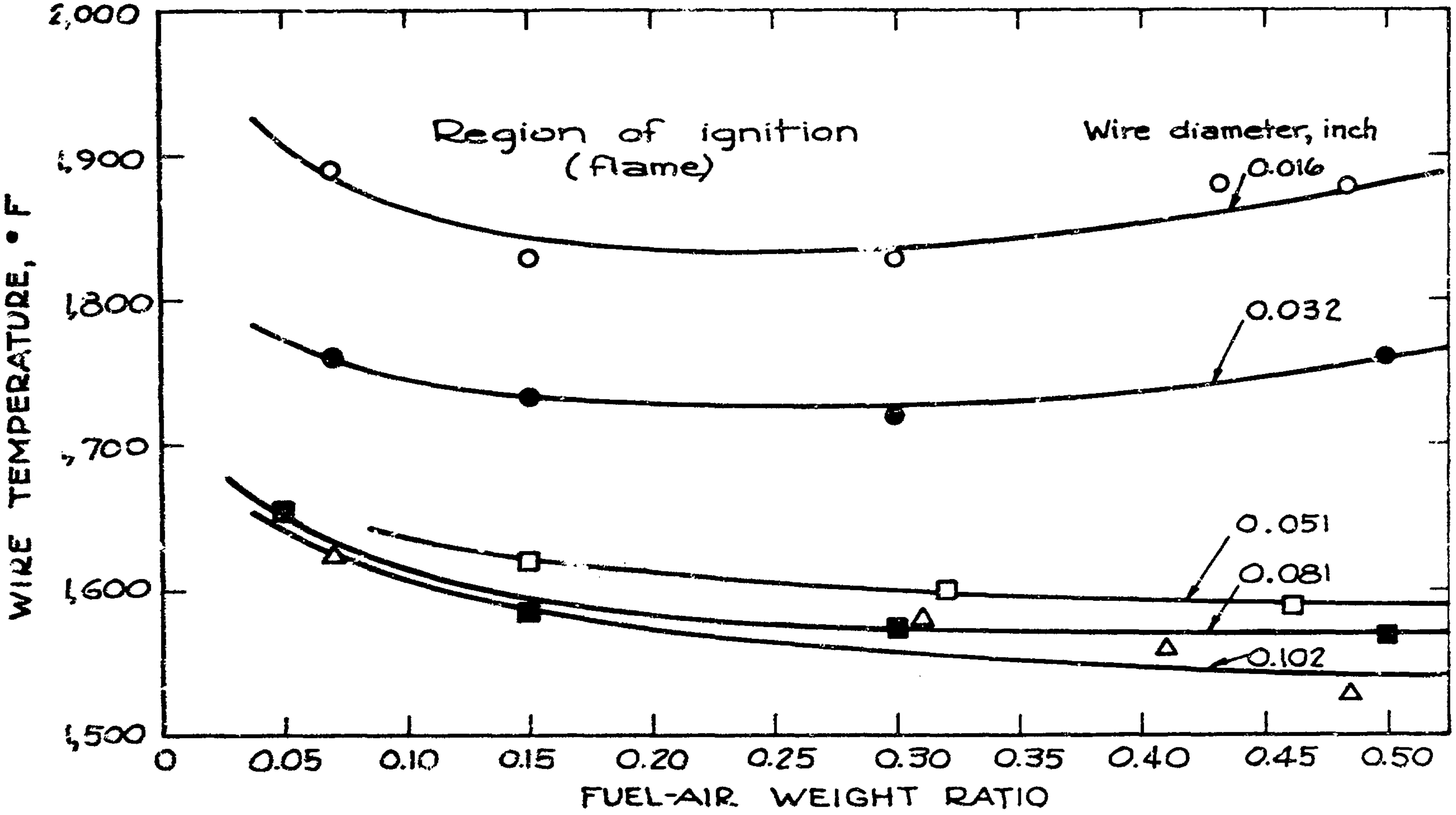


Figure 5.-Variation of wire ignition temperature with fuel-air weight ratio for n-Hexane at 300° F. (Mixture flow rate - 17.8 in³/min, NTP)

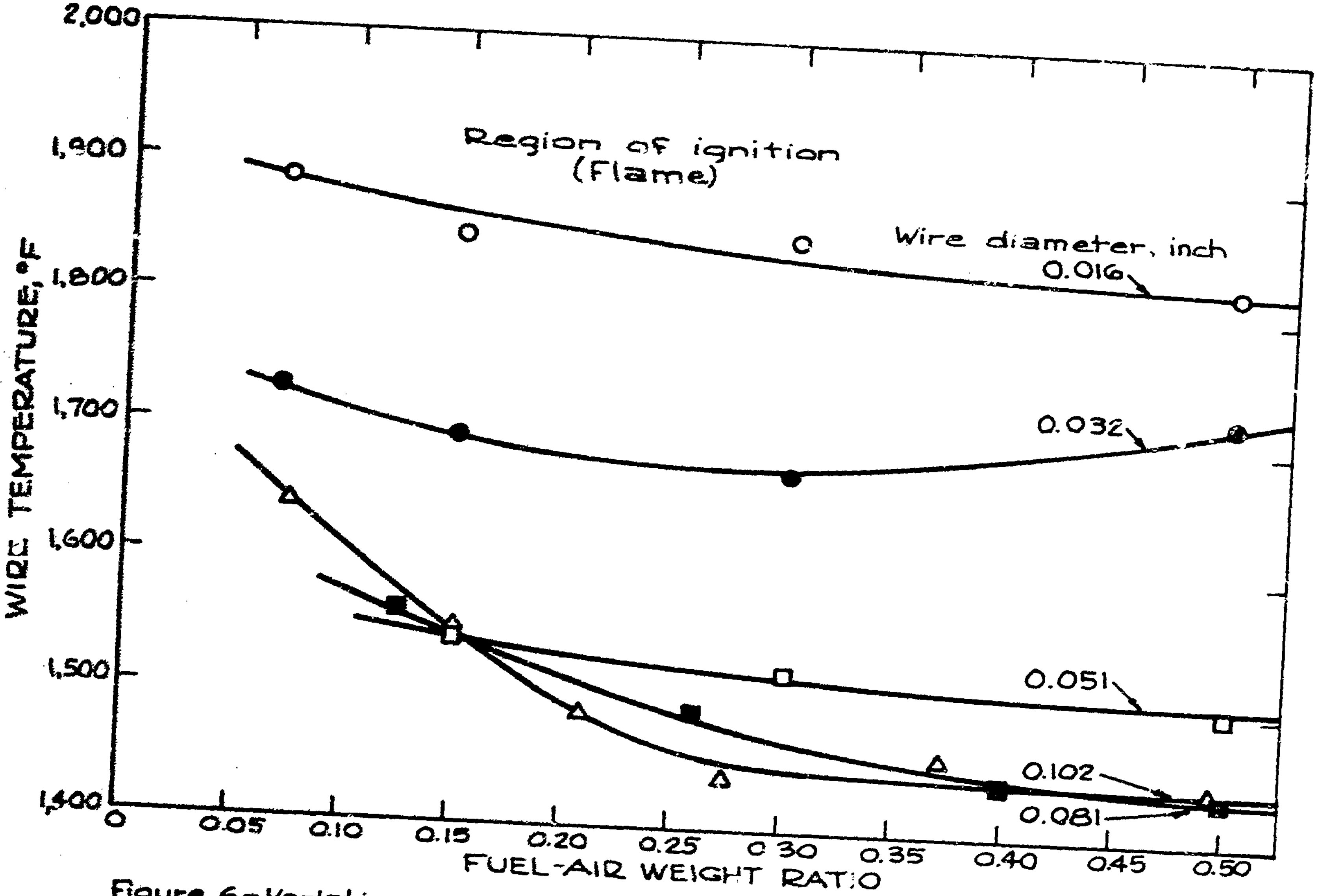


Figure 6.- Variation of wire ignition temperature with fuel-air ratio for n-Octane at 300° F. (Mixture flow rate – 17.8 in³/min, N.T.P.)

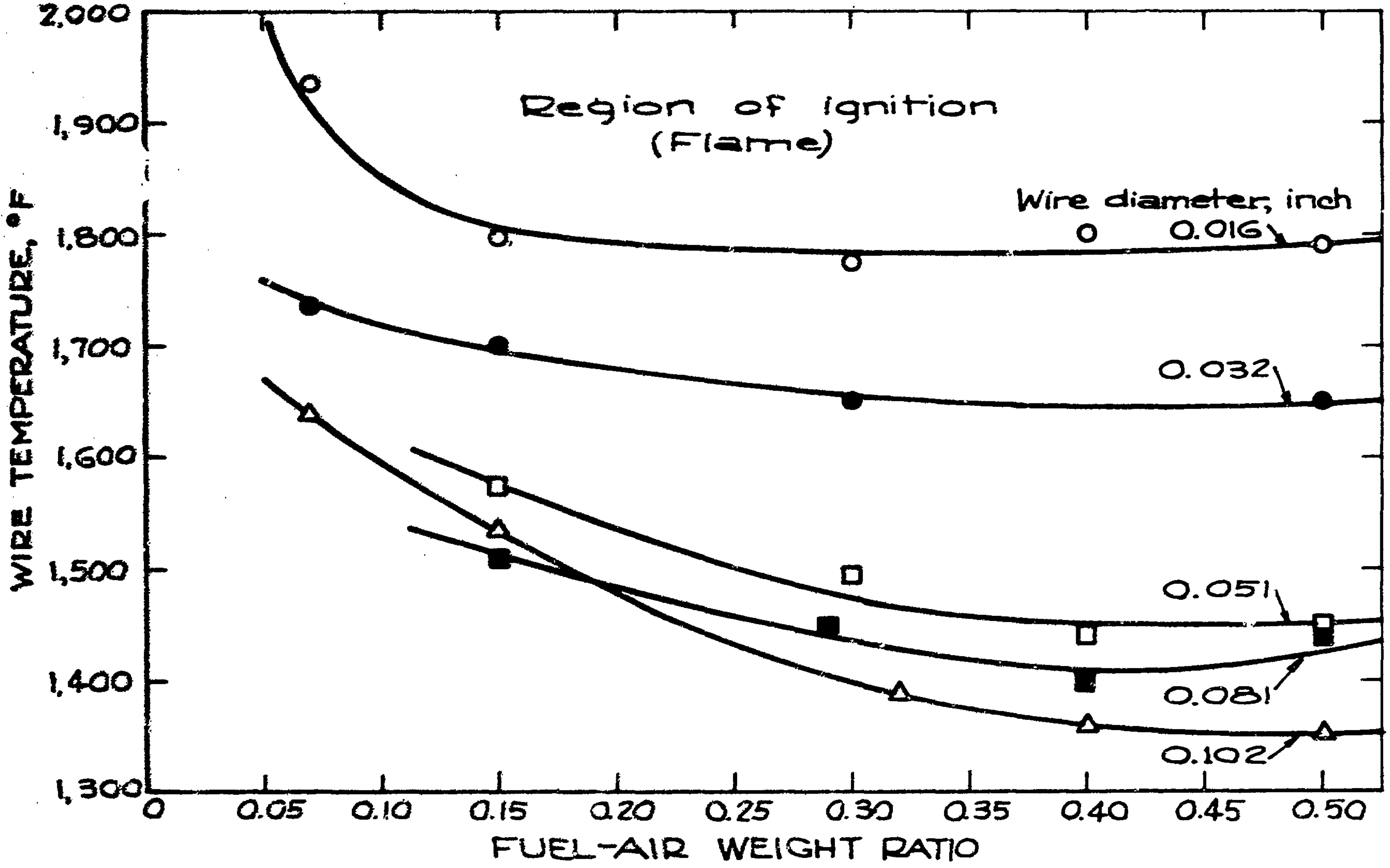


Figure 7.-Variation of wire ignition temperature with fuel-air weight ratio for n-Decane at 300° F. (Mixture flow rate - 17.8 in³/min, N.T.P.)

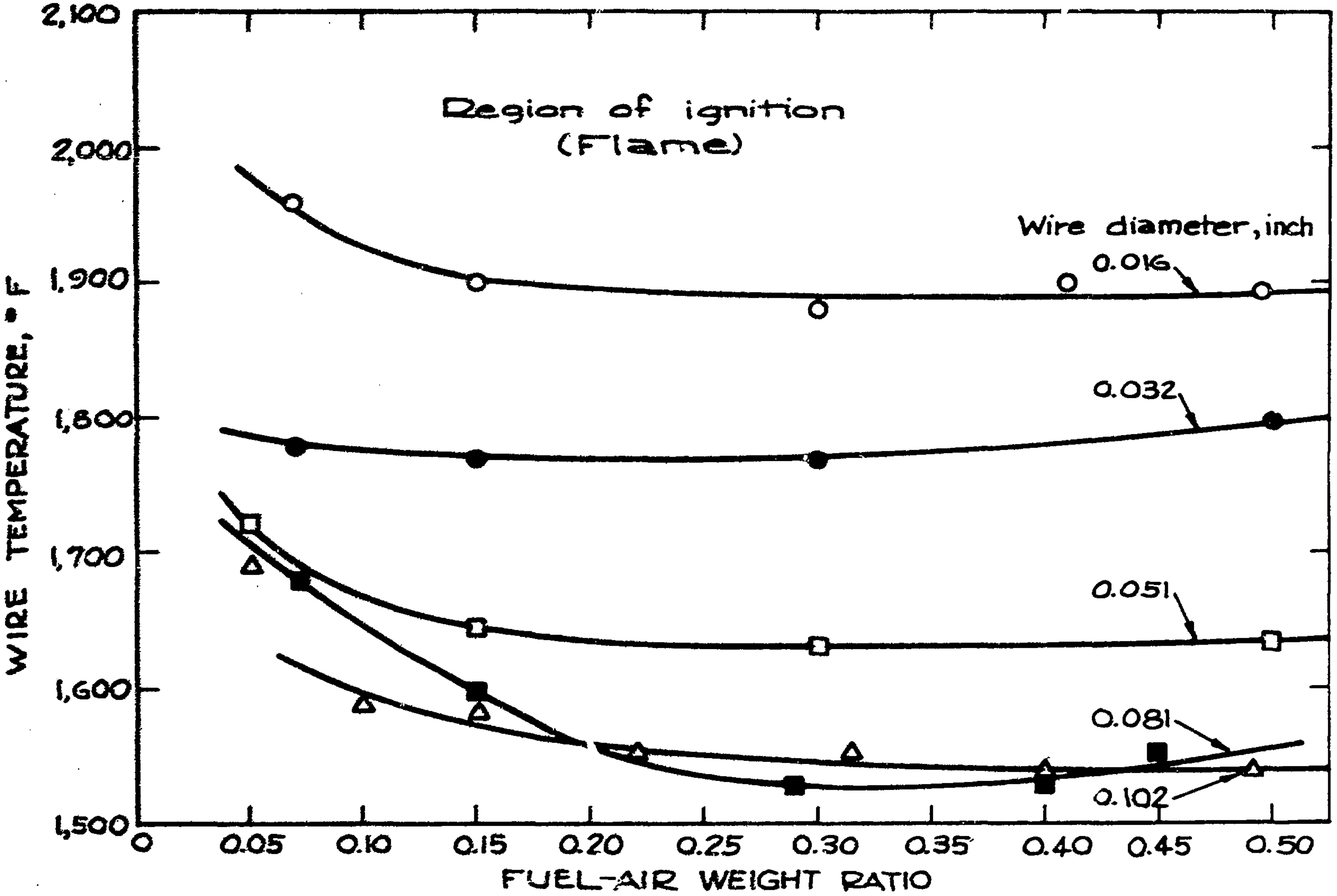


Figure 8.- Variation of wire ignition temperature with fuel-air weight ratio for JP-6 jet fuel at 300 °F. (Mixture flow rate - 17.8 in³/min N.T.P.)

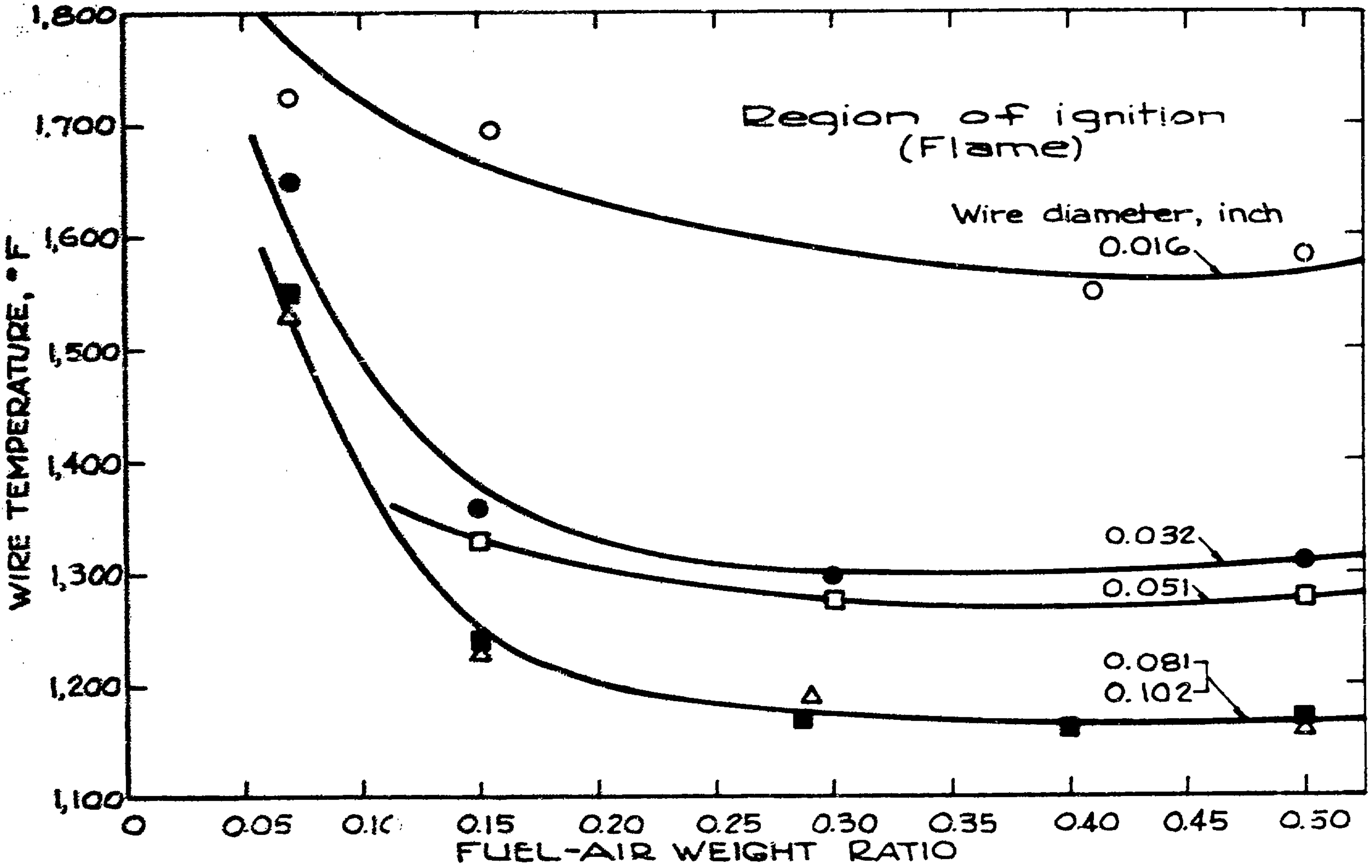


Figure 9 - Variation of wire ignition temperature with fuel-air weight ratio for engine oil MIL-L-7808 at 500° F. (Mixture flow rate- 17.8 in^3/min, N.T. P.)

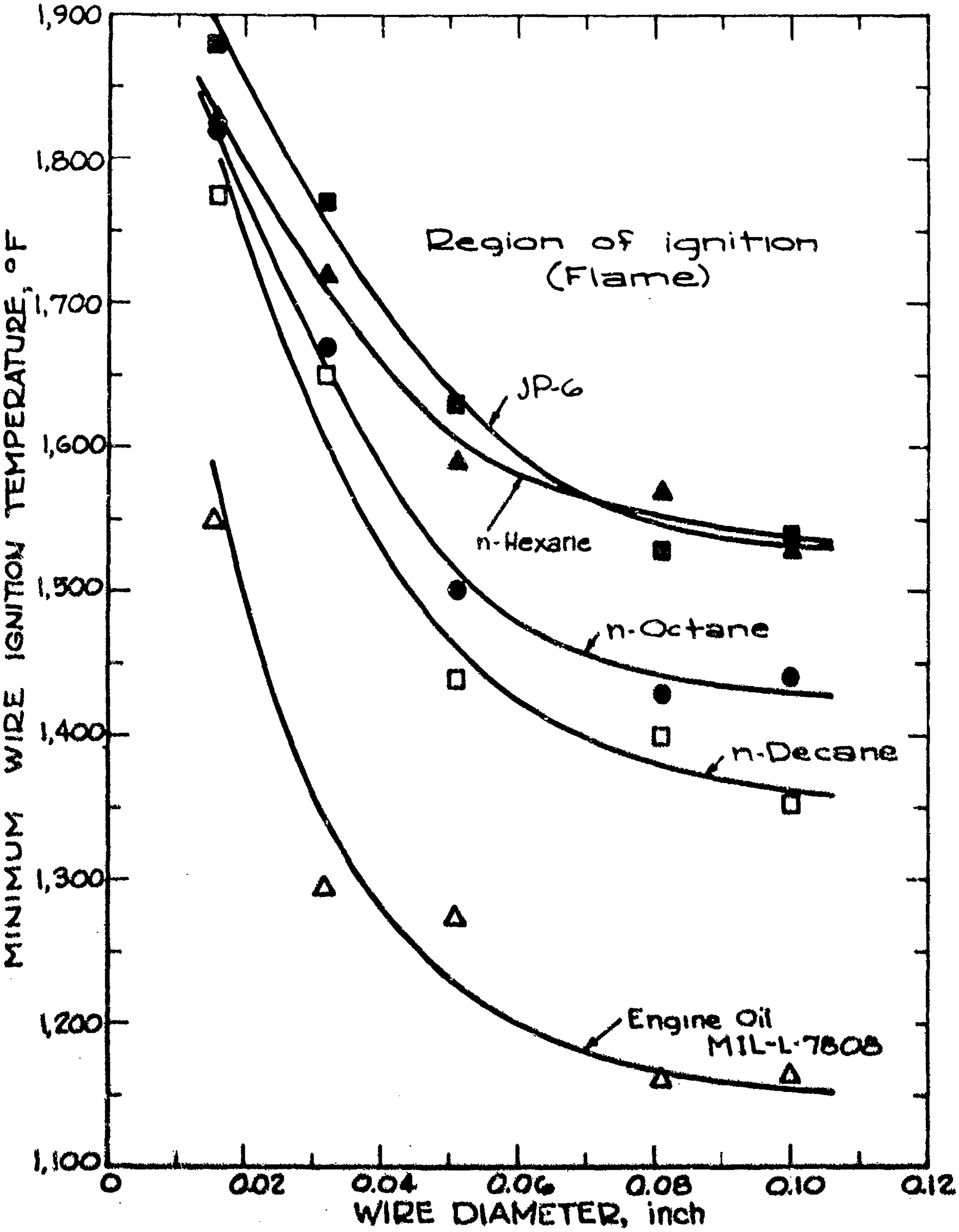


Figure 10.-Minimum wire ignition temperature versus wire diameter for various hydrocarbon fuels (300° F) and an engine oil (500° F) in air at a flow rate of 17.8 in³/min. (N.T.P.)

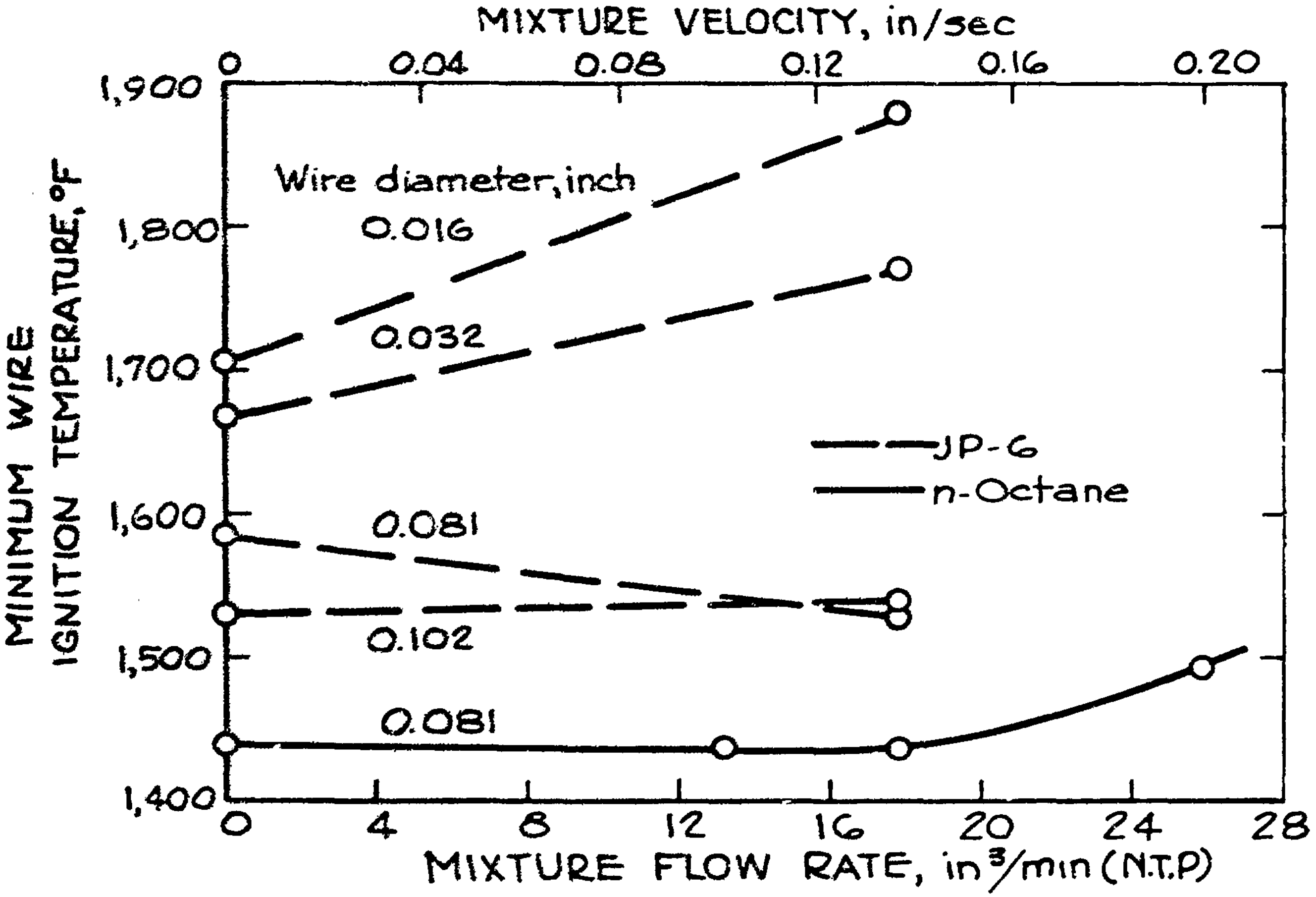
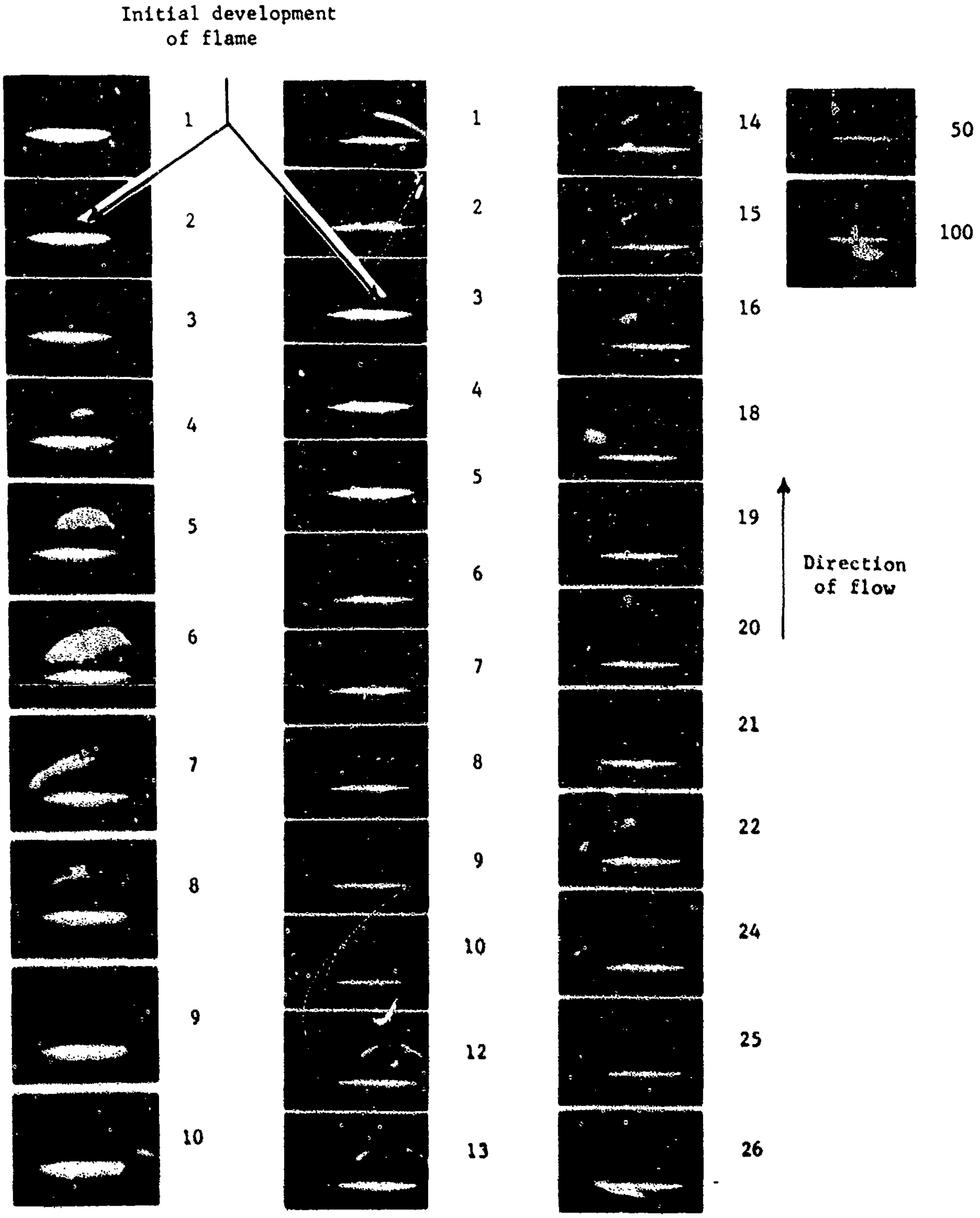


Figure 11- Effect of mixture flow rate on minimum wire ignition temperatures of n-Octane and JP-6 jet fuel in air at 300°F.



Run No. 1
4.58 milliseconds per frame

Run No. 2
1.16 milliseconds per frame

Figure 12. - Motion picture records from 2 experiments showing the ignition of octane vapor-air mixtures with a heated Nichrome wire (2 inches long and 0.102-inch diameter) at 1900° F.
Mixture flow rate - 17.8 in^3/min (N.T.P.)
Fuel air-weight ratio - 0.42 Scale: 1 inch = 3.1 inches

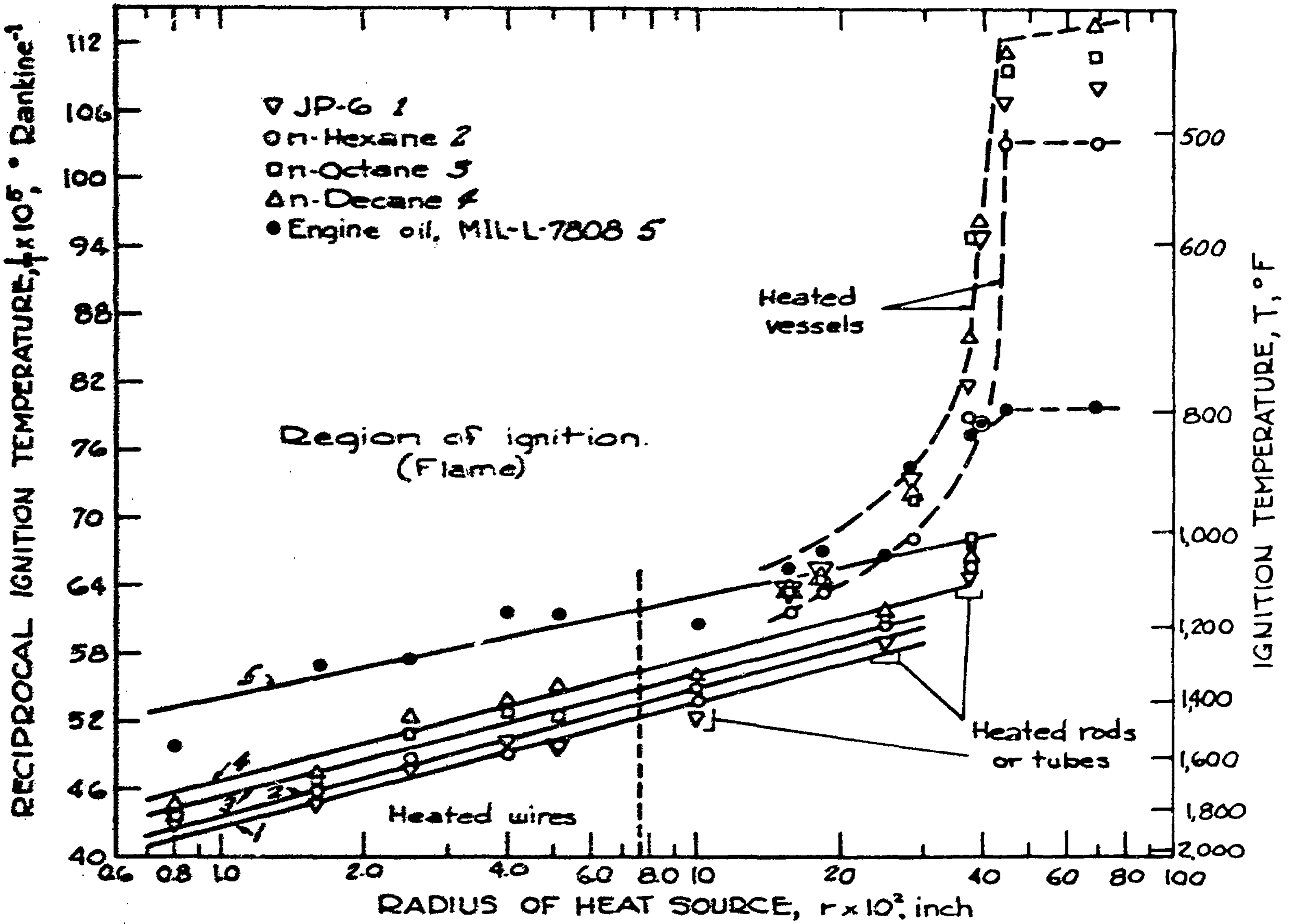


Figure 13.- Reciprocal hot surface ignition temperature as a function of the radius of the heat source for various hydrocarbon fuels and an engine oil in air

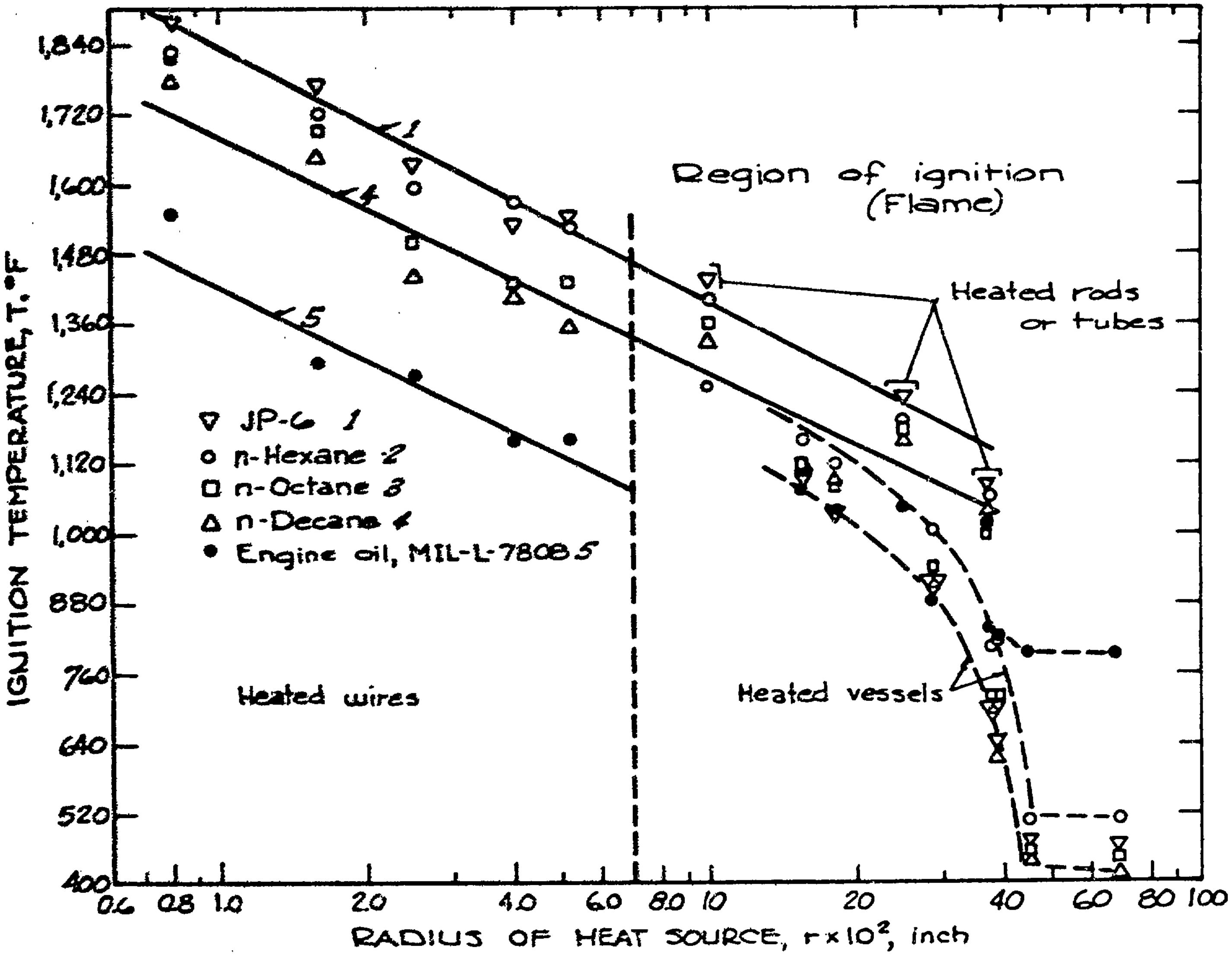


Figure 14.- Hot surface ignition temperature as a function of the radius of the heat source for various hydrocarbon fuels and an engine oil in air.

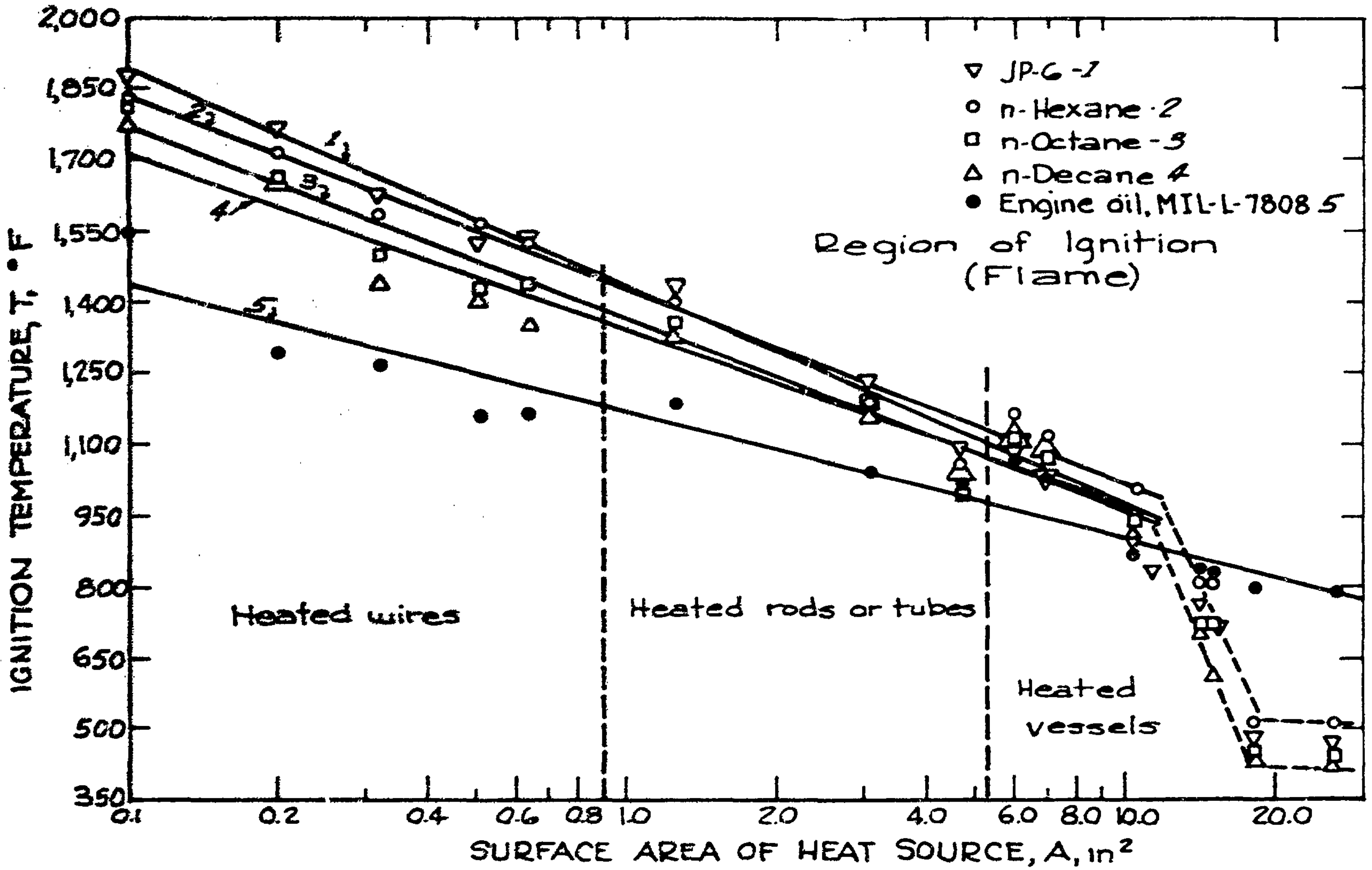


Figure 15.- Hot surface ignition temperature as a function of the surface area of the heat source for various hydrocarbon fuels and an engine oil in air.

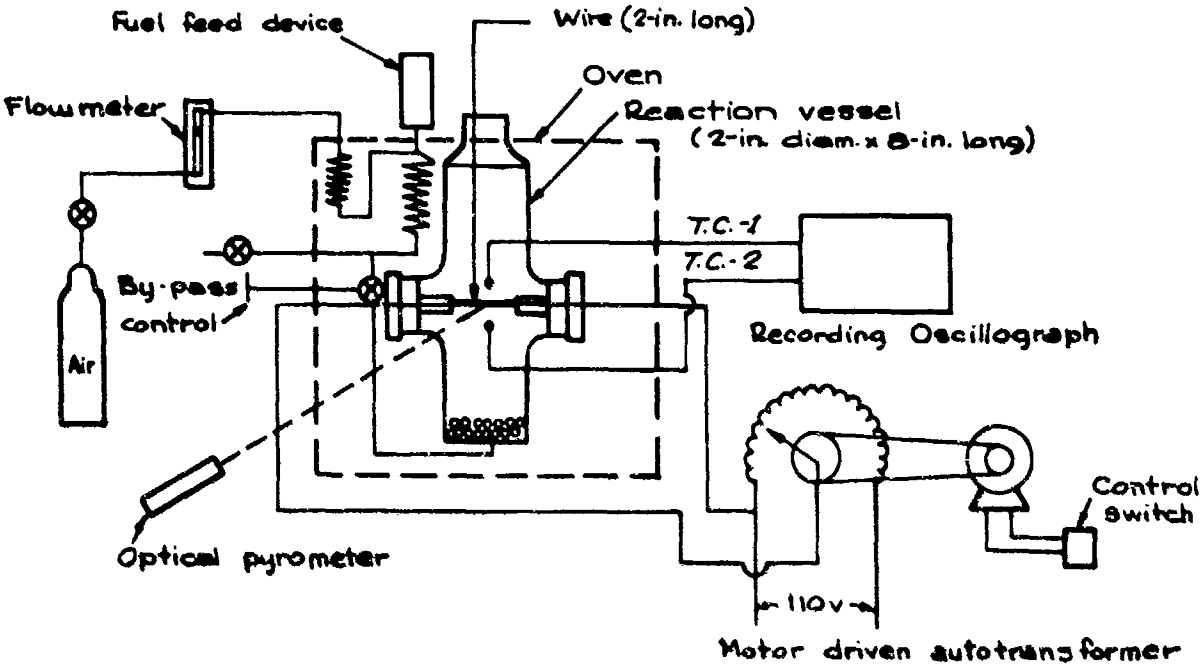


Figure 1. - Wire ignition temperature apparatus.

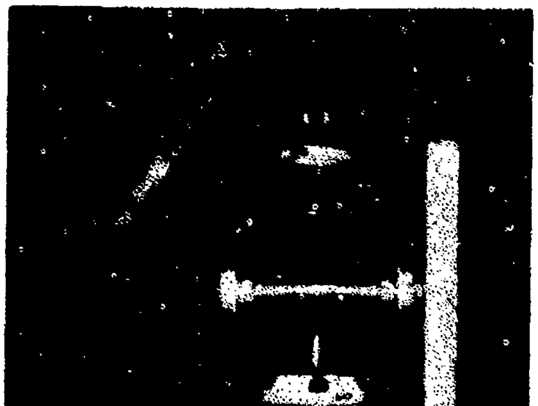


Figure 2. - Reaction vessel of wire ignition temperature apparatus fitted with a Nichrome tube.

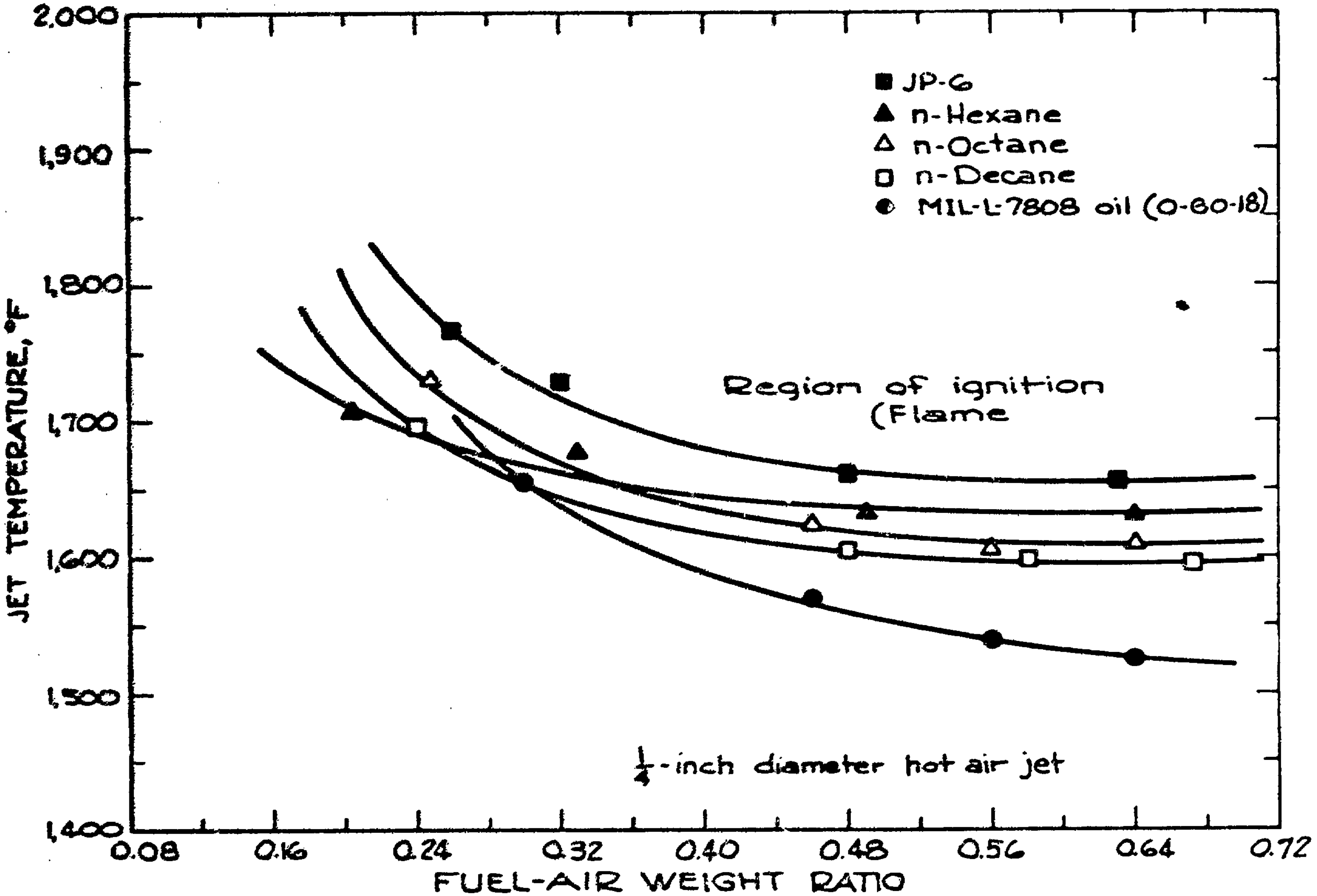


Figure 17.- Variation of hot gas ignition temperature ($\frac{1}{4}$-inch jet) with fuel-air weight ratio for various hydrocarbon fuels at 350°F and an engine oil at 600°F. (Mixture flow rate-365 in^3/min, Jet flow rate-185 in^3/min, N.T.P.)

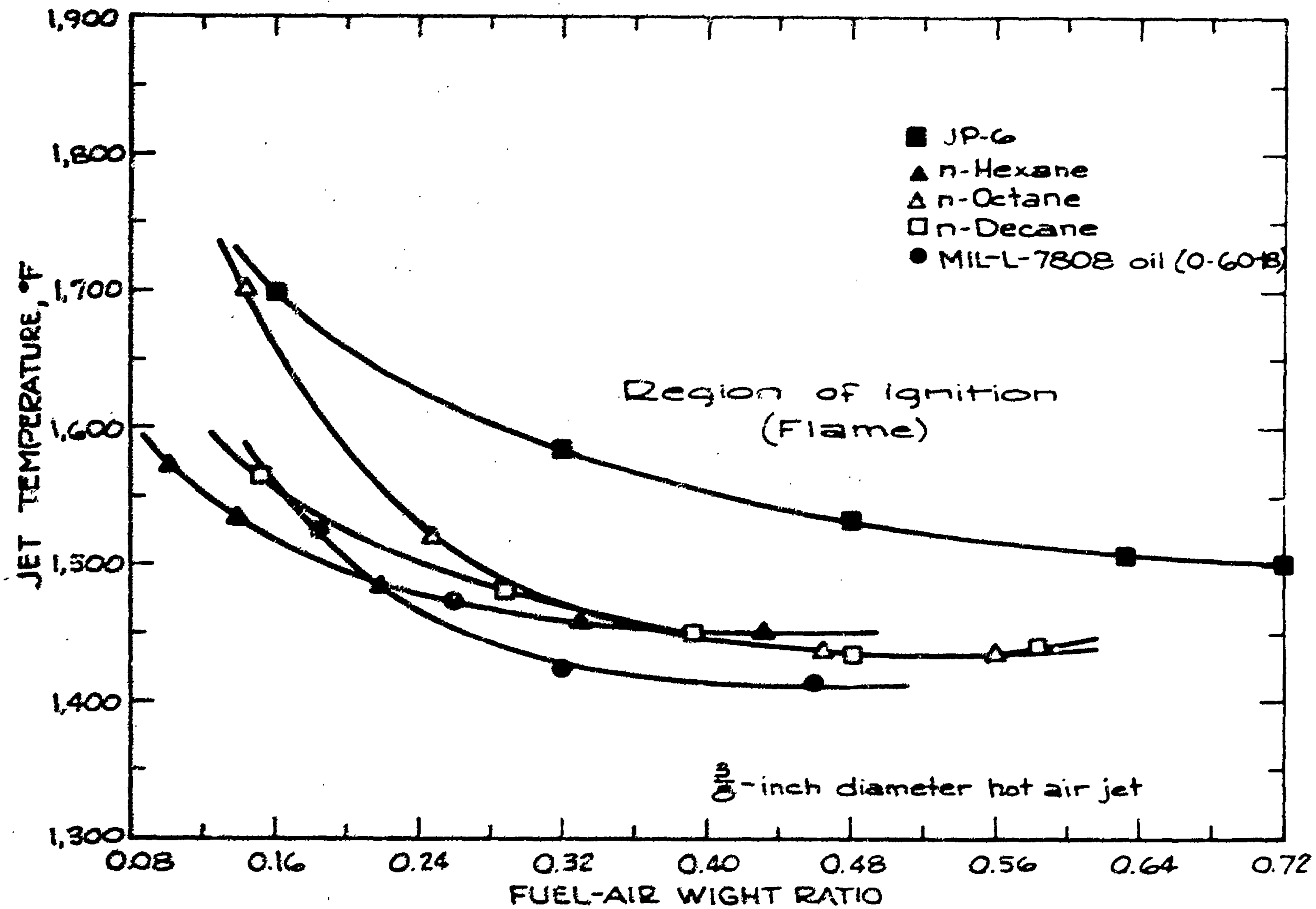


Figure 18 – Variation of hot gas ignition temperature ($\frac{3}{8}$-in jet) with fuel-air weight ratio for various hydrocarbon fuels at 350°F and an engine oil at 600°F. (Mixture flow rate – 365 in^3/min., Jet flow rate – 185 in^3/min. N.T.P.)

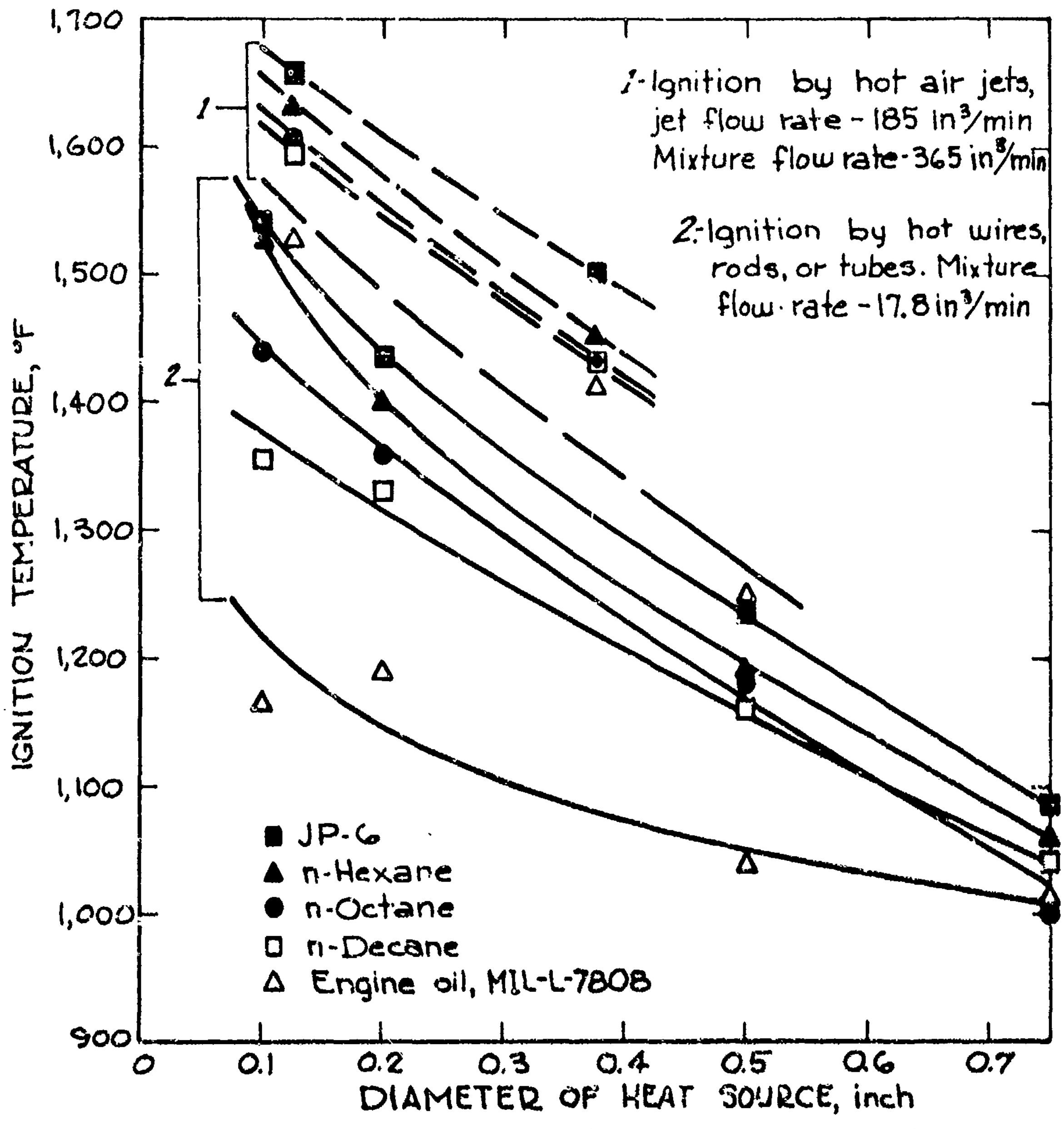


Figure 19.- Comparison of hot gas and hot surface ignition temperatures of various hydrocarbon fuels and an engine oil in air under flow conditions

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