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HOT GAS IGNITION TEMPERATURES OF HYDROCARBON FUEL VAPOR-AIR MIXTURES

By J. M. Kuchta and R. J. Cato

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
1966

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MARCH 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Stewart L. Udall, Secretary

BUREAU OF MINES
Walter R. Hibbard, Jr., Director

The work upon which this report is based was done by the Bureau of Mines, U.S. Department of the Interior, under U.S. Air Force Aero Propulsion Laboratory Delivery Order 33(657)-63-376, Task 304801.

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HOT GAS IGNITION TEMPERATURES OF HYDROCARBON FUEL VAPOR-AIR MIXTURES

by

J. M. Kuchta[1] and R. J. Cato[2]

ABSTRACT

The Bureau of Mines used laminar hot air jets of 1/8- to 3/4-inch diameter to determine the hot gas ignition temperatures of various combustible vapor-air mixtures. The combustibles were n-hexane, n-octane, n-decane, a hydrocarbon jet fuel (JP-6), and an adipate ester aircraft engine oil (MIL-L-7808). Minimum ignition temperatures occurred at a fuel to air weight ratio of about 0.5 and were not greatly sensitive to variations of fuel concentration. Moderate variations of jet velocity also had little influence on these ignition temperatures. However, these temperatures decreased with increase in heat source dimensions (jet diameter). The hot gas ignition temperatures of the combustibles were not necessarily much greater than corresponding autoignition and wire ignition temperatures when the size of the heat source and the ignition criterion were the same.

INTRODUCTION

Most of the ignition temperature data available for combustible fluids have been obtained using heated vessels, wires, or tubes as the sources of ignition. A jet of heated air or other gas, if sufficiently hot, can also produce ignition when it comes into contact with combustible gases or vapors. Such an ignition source may be a problem during the rupture of an oil seal in a jet engine or during blasting operations in a coal mine where hot gases are released from the explosives employed. The temperatures at which combustible gas mixtures can be ignited by laminar jets of hot air and inert gases have been determined only in recent years by Wolfhard, Vanpee, and Bruszak[3] for

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[1] Research chemist, Explosives Research Center, Bureau of Mines, Pittsburgh, Pa.
[2] Chemist, Explosives Research Center, Bureau of Mines, Pittsburgh, Pa.

[3] Vanpee, M., and A. E. Bruszak. The Ignition of Combustible Mixtures by Laminar Jets of Hot Gases. BuMines Rept. of Inv. 6293, 1963, 84 pp.
Vanpee, M., and H. G. Wolfhard. Comparison Between Hot Gas Ignition and Limit Flame Temperatures. J. Am. Rocket Soc., v. 29, July 1959, p. 517.
Wolfhard, H. G. The Ignition of Combustible Mixtures by Hot Gases. Jet Propulsion, v. 28, December 1958, p. 798.

Work on manuscript completed January 1966.

hydrogen, carbon monoxide, and various low-molecular-weight hydrocarbons. The present Bureau of Mines investigation is a study of the hot gas (air) ignition temperature characteristics of several high-molecular-weight hydrocarbon combustibles mixed with air.

Hot gas ignitions differ from wire ignitions and autoignitions in heated vessels primarily in that surface effects are absent with a hot gas heat source, provided the reaction chamber is relatively large. Generally, hot gas ignition temperatures of hydrocarbon combustible mixtures have been reported to agree with corresponding wire ignition temperatures but to be much higher than the autoignition temperatures (AIT's) of the mixtures.[4] However, according to data recently reported by the Bureau,[5] some of which are included here, the variation between such ignition temperatures can depend greatly on the size of the heat source and on the ignition criterion. The hot gas ignition temperature data of this work were obtained with laminar jets of hot air injected into combustible vapor-air mixtures under near-stagnant flow conditions. Data are included on the effects of combustible concentration, jet diameter, and jet velocity for a given size of reaction chamber. The combustibles included n-hexane, n-octane, n-decane, a hydrocarbon jet fuel (JP-6) and an adipate ester aircraft engine oil (MIL-L-7808).

EXPERIMENTAL APPARATUS AND PROCEDURES

The apparatus used for the hot gas ignition temperature determinations is shown in figure 1 and, except for some minor modifications, was similar to that employed by Wolfhard.[6] Basically, it consisted of a tubular ceramic furnace that was used to heat the air stream, a cylindrical reaction chamber into which was fed the hot air jet and combustible vapor-air mixtures, and feed assemblies that provided the desired mixture at a uniform rate. The tubular furnace was wound externally with platinum-rhodium wire and was enclosed in a cylindrical Nichrome-wound[7] furnace (3-inch ID). The reaction chamber consisted of a 4-inch ID Pyrex pipe (26 inches long) that was also heated to maintain the combustible mixture at a given temperature. Narrow slits on both sides of the enclosed pipe along its longitudinal axis permitted visual observation of flame propagation. The combustible mixture was fed to the reaction chamber through a "mixing ring" (perforated coil of tubing) and a bed of ceramic beads located just below the base of the hot jet; a water jacket between the ring and the ceramic tubular furnace helped maintain the mixture at a uniform initial temperature.

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[4] Third work cited in footnote 3.

[5] Kuchta, J. M., A. Bartkowiak, and M. G. Zabetakis. Hot Surface Ignition Temperatures of Hydrocarbon Fuel Vapor-Air Mixtures. J. Chem. Eng. Data, v. 10, July 1965, p. 282.

Kuchta, J. M., R. J. Cato, and M. G. Zabetakis. Comparison of Hot Surface and Hot Gas Ignition Temperatures. Combustion and Flame, v. 8, December 1964, p. 348.

[6] Third work cited in footnote 3.

[7] Reference to trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

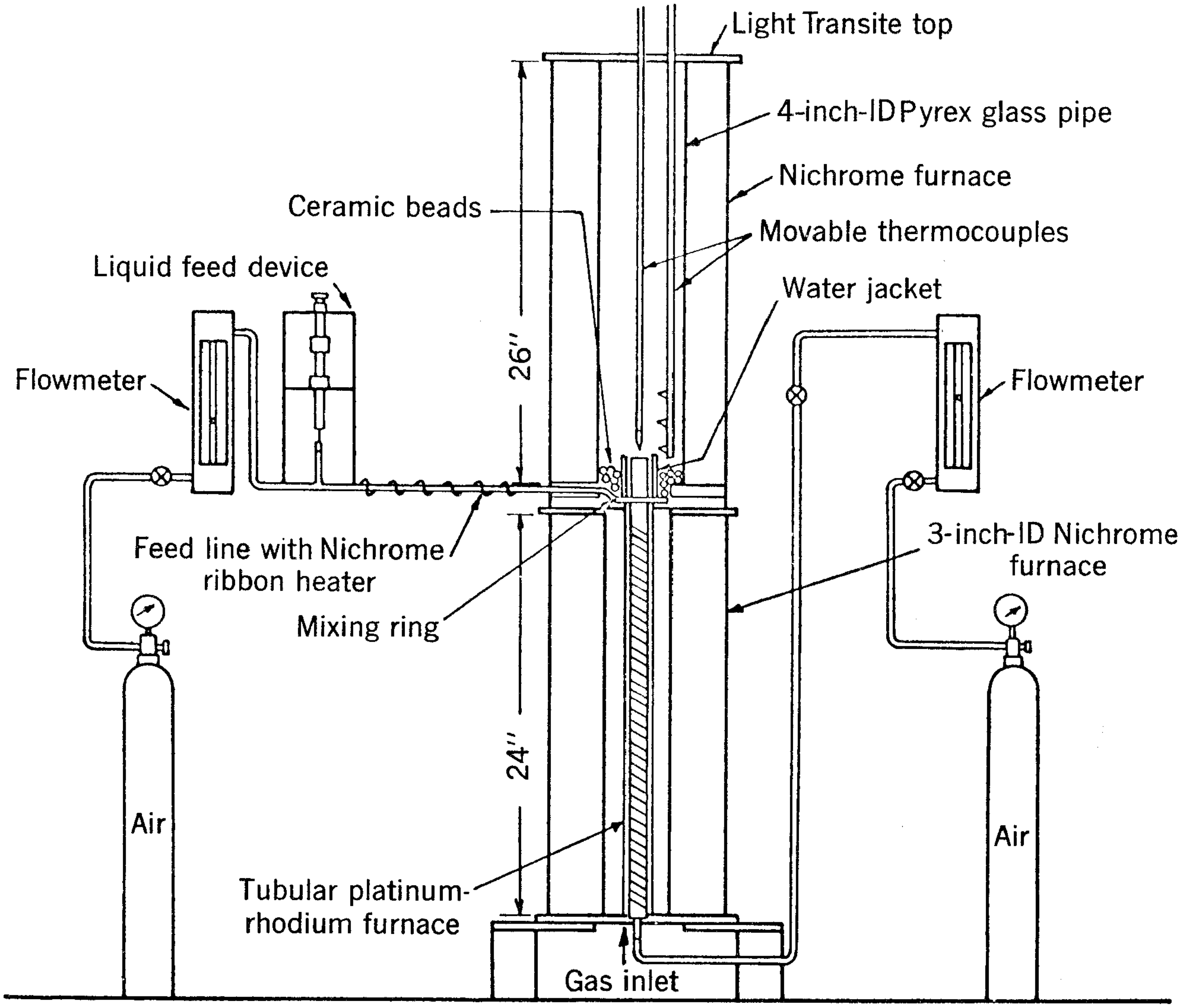

FIGURE 1. - Hot Gas Ignition Temperature Apparatus.

Temperatures of the hot air jets were measured with a 33-gage Brown & Sharpe platinum-platinum-10 percent rhodium thermocouple about one-fourth inch above the jet base; temperature decreased progressively with height above the jet base at a rate that was determined in part by the jet diameter and velocity. The temperatures of the combustible mixtures were measured with three 28-gage Chromel-Alumel thermocouples spaced 3 inches apart; recorded temperature differences were usually not in excess of ±25° F. Initial mixture temperatures were 350° F for the hydrocarbon fuels and 600° F for the engine oil which contained higher-boiling-point constituents than did the fuels. The mixture flow rate was 365 in^3/min (about 1 in/sec)[8] and the jet flow rate was 185 in^3/min ($\geq$ 50 in/sec), both at NTP conditions (60° F, 1 atm), in the

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[8] Values in parentheses are the flow velocities corresponding to the given volume flow rates.

experiments with 1/8-, 1/4-, 3/8-, and 1/2-inch-diameter jets; the jet flow rate was 365 in^3/min (about 50 in/sec) with a 3/4-inch jet. These jet flow rates appeared to be optimum for ignition of the mixtures in the 4-inch-diameter reaction chamber and were therefore used to obtain the minimum ignition temperature values reported here. The use of jets larger than three-fourths of an inch was not investigated because dilution effects could be great for this size of reaction chamber.

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 was introduced, flowing coaxially with the hot jet. If ignition did not occur, the jet temperature was increased in successive increments until ignition was evidenced by the propagation of flame throughout the combustible mixture. Normally, a faintly visible precursor flame or luminous column formed above the base of the jet when the temperature was within 100° to 200° F of that required for ignition (fig. 2); this flame was pale blue and extended to a height of 6 inches or less above the jet base. The height at which ignition occurred decreased with increasing jet temperature. Motion picture records of the ignition of n-octane vapor-air mixtures indicated that ignition occurs about 3 inches above the jet base with a 1/2-inch-diameter jet at 1,400° F (fig. 3) and within 10 to 60 seconds after the combustible mixture is admitted. The minimum temperature values were repeatable to within ±25° F.

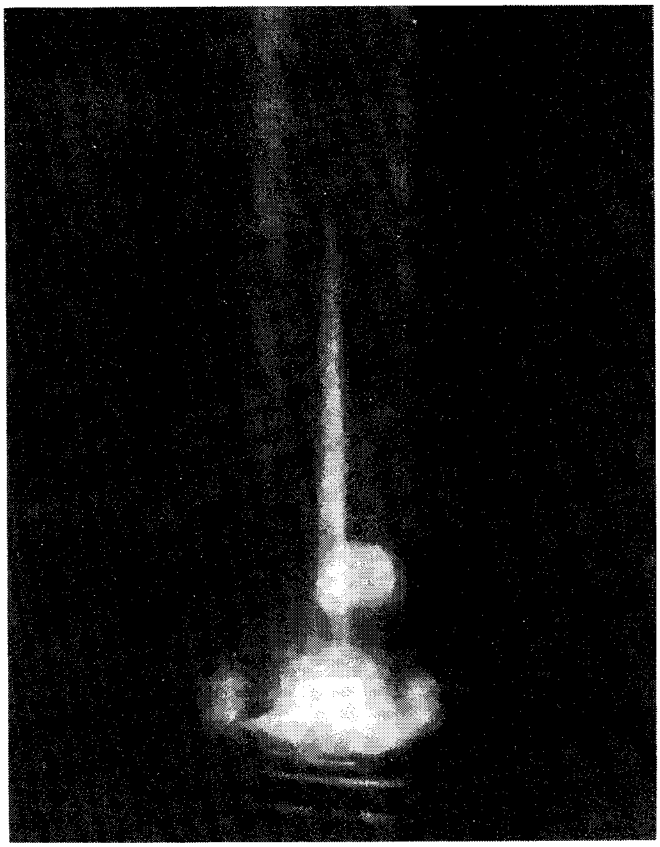

FIGURE 2. - Precursory Flame Formed in Preignition Reaction of ¼-Inch-Diameter Hot Air Jet (1,670° F) With Uniform Octane Vapor-Air Mixture at 350° F. Jet flow rate, 185 in^3/min; fuel-to-air weight ratio, 0.14; mixture flow rate, 365 in^3/min; scale, 1 inch = 0.935 inch.

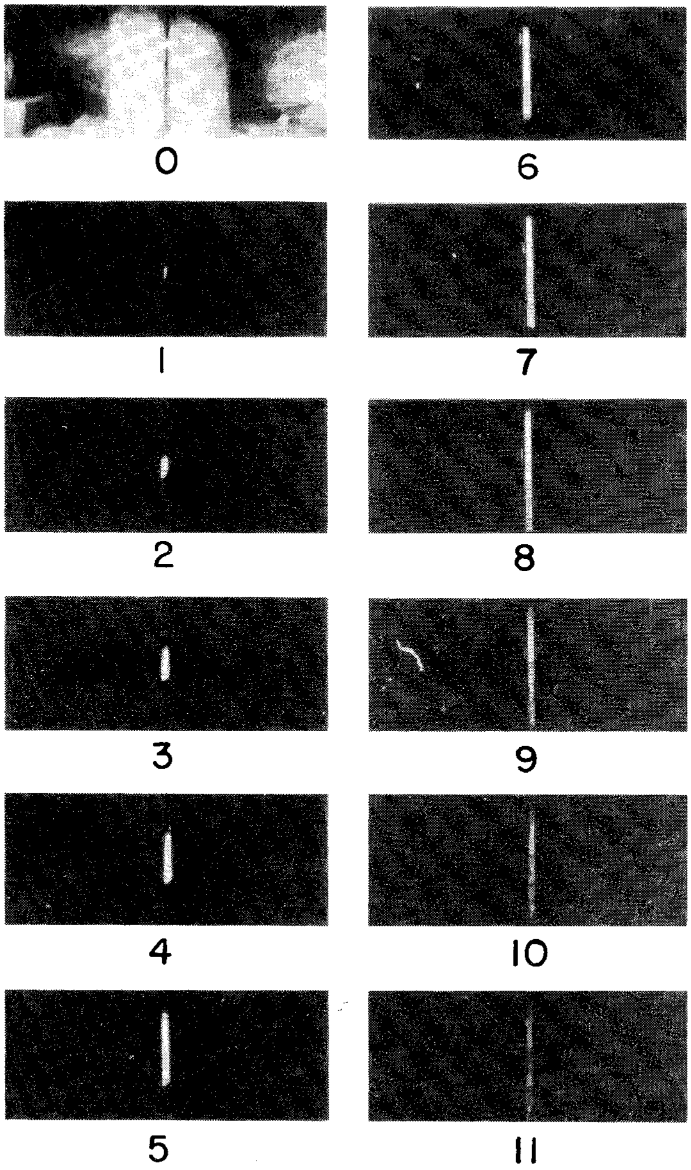

FIGURE 3. - Motion Picture Records Showing Ignition of n-Octane Vapor-Air Mixture With ½-Inch-Diameter Hot Air Jet at 1,400° F. Jet flow rate, 185 in^3/min (NTP); mixture flow rate, 365 in^3/min (NTP); camera speed, 360 frames/sec; scale: ¼ inch = 4.5 inches for frame 0, ¼ inch = 5.4 inches for frames 1-11.

The neat hydrocarbon fuels used in this work were of chemically pure grade, at least 99 percent pure. The MIL-L-7808 engine oil consisted primarily of adipate diesters which vaporized between 480° and 780° F; its flash point was 435° F. The JP-6 jet fuel contained about 85 percent saturated hydrocarbons and 14 percent aromatic hydrocarbons; its flash point was 100° F.

RESULTS AND DISCUSSION

Hot Gas (Air) Ignition Temperatures

The temperature required to ignite a combustible vapor-air mixture with a jet of hot gas depends on the dimensions of the jet as well as on the composition and velocity of the jet and combustible mixture. Since jets of hot air were used in the present work, the combustible vapor-air mixture was diluted by the air jet, particularly along the interface between the two moving fluids. Accordingly, relatively high fuel concentrations and low jet flow rates should be optimum for ignition; low flow rates provide low air dilution rates and long contact times with the combustible which are favorable for ignition. The results presented here for n-hexane, n-octane, n-decane, JP-6 jet fuel, and MIL-L-7808 engine oil vapor-air mixtures were consistent in this connection.

In the minimum ignition determinations with the 1/2-inch-diameter jet, the jet velocity was about 50 in/sec (185 in^3/min) and the mixture velocity 1 in/sec (365 in^3/min). Data obtained under these and other flow conditions are summarized in table 1 from experiments with the 1/2-inch air jet and MIL-L-7808 engine oil vapor-air mixtures. These data show that the influence of jet velocity on minimum ignition temperature was not great for the range of velocities used in these experiments; this behavior is consistent with that reported by other investigators.[9] The ignition temperature increased 60° F at most when the jet velocity was varied from 36.5 to 81.0 in/sec with a constant mixture velocity of 1.0 in/sec. The variation of ignition temperature was also small when the mixture velocity was varied between 0.7 and 1.5 in/sec; here, the jet-to-mixture velocity ratio was maintained at a near-constant value, slightly above 50. Although a jet velocity of approximately 50 in/sec was near optimum for ignition of the mixtures with 1/2- and 3/4-inch jets, higher jet velocities were required with the smaller diameter jets to provide ideal heat inputs for ignition.

TABLE 1. - Effect of jet and mixture velocity on minimum hot gas ignition temperature of MIL-L-7808 engine oil with a 1/2-inch-diameter hot air jet

(Fuel-to-air weight ratio, 0.55)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Jet-to-mixture velocity ratio.......	36.5	52.1	52.5	52.7	54.7	81.0
Mixture velocity.............in/sec	1.0	0.7	1.0	1.3	1.5	1.0
Ignition temperature............° F	1,240	1,255	1,250	1,270	1,315	1,300

Figure 4 shows the variation of hot gas ignition temperature with fuel-to-air weight ratio (F/A) obtained with the 1/2-inch-diameter air jets (185 in^3/min) flowing into the various combustible vapor-air mixtures (365 in^3/min). As in hot surface ignition temperature determinations,[10] the effect of F/A ratio is slight except at low ratio values (≤ 0.3) where the ignition temperatures tend to increase noticeably as the F/A ratio is decreased. Similar behavior was also noted in the ignition temperature determinations made with 1/8-, 1/4-, 3/8-, and 3/4-inch diameter hot air jets; figure 5 shows the data obtained for n-decane with various-sized jets. Generally, a F/A ratio of approximately 0.5 was required to obtain the minimum temperatures for ignition; this ratio corresponds to 11.6 volume-percent fuel for n-octane. Since uniform mixtures of these combustibles in air usually would not be expected to propagate flame at such high F/A ratios, the observed behavior is probably due

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[9] First work cited in footnote 3.

[10] First work cited in footnote 5.

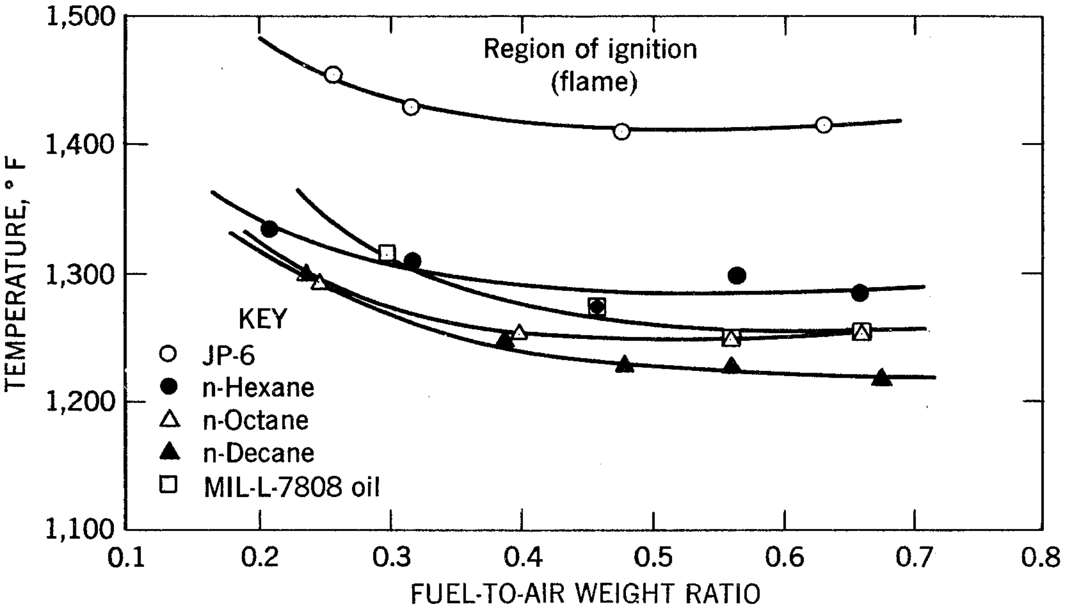

FIGURE 4. - Variation of Hot Gas Ignition Temperature With Fuel-to-Air Weight Ratio for Various Combustible Hydrocarbon Vapor-Air Mixtures With ½-Inch-Diameter Jets of Hot Air.

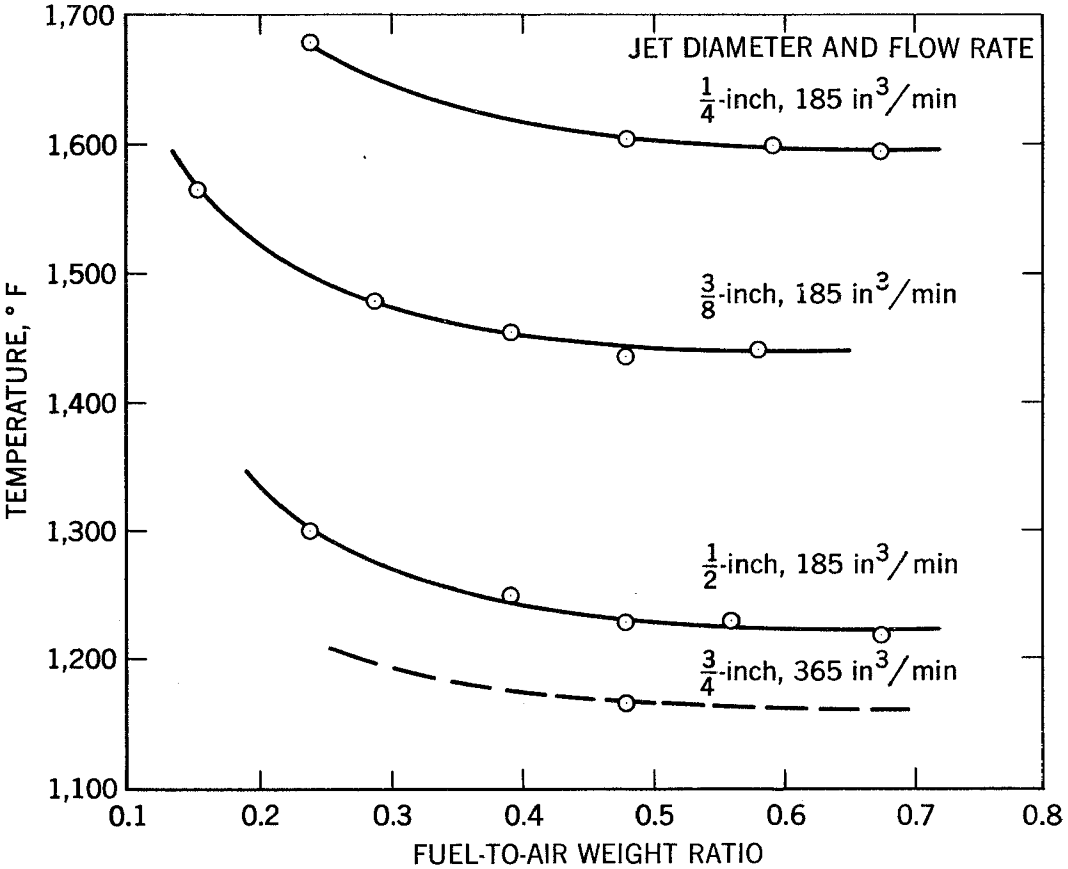

FIGURE 5. - Variation of Hot Gas Ignition Temperature With Fuel-to-Air Weight Ratio and Diameter of Hot Air Jet for n-Decane Vapor-Air Mixtures.

to the dilution of the mixtures and to the elevation of the initial mixture temperatures (≥ 350° F) by the hot air jet.

Table 2 lists the minimum hot gas ignition temperatures found for the hydrocarbon fuel and engine oil vapor-air mixtures with the different-sized jets of hot air. These data are also shown graphically in figure 6, where the minimum ignition temperature values are plotted against the reciprocal of jet diameter (1/d). Consistent with thermal ignition theory, the ignition temperatures of these combustibles decreased as the heat source diameter was increased. For all the fuels, the ignition temperature decreased almost 700° F when the jet diameter was increased from one-eighth to three-fourths of an inch. For the engine oil, the temperature decreased only approximately 400° F. The decrease was least (≤ 70° F) when the jet diameter was varied from one-half to three-fourths of an inch, except for the JP-6 fuel. Although the values for the paraffin hydrocarbons varied little at a given jet diameter, those for n-hexane were usually the highest. Also, the values for the JP-6 fuel were always the highest, whereas those for the MIL-L-7808 engine oil were the lowest for a jet diameter less than one-half inch. These results are unusual since the engine oil is a high-AIT (750° F) combustible, whereas the jet fuel is a low-AIT (450° F) combustible like the previously discussed paraffin hydrocarbons. However, the trend is consistent with that observed for these materials in autoignition and wire ignition temperature determinations with varying heat source diameters.[11] Since the thermal stability of the combustibles at the pertinent temperatures may account for such observations, decomposition studies would be interesting to pursue, particularly with the adipate diesters which largely make up the engine oil. The decomposition species of such oxygenated compounds would be expected to play an important role in the ignition of the combustible. Apparently, as indicated by the present results, the ignition temperatures of such materials should not be extrapolated over a large range of temperature.

TABLE 2. - Minimum hot gas ignition temperatures of hydrocarbon fuels and engine oil (fuel vapor-air mixtures) with various hot air jets
(Mixture flow rate, 365 in^3/min (NTP); fuel-to-air weight ratio, optimum for ignition (about 0.5))

Diameter of jet, inch	Jet flow rate, in^3/min	Ignition temperature, ° F				
		JP-6	n-Hexane	n-Decane	n-Octane	MIL-L-7808 oil
1/8	185	1,985	1,910	1,890	1,875	1,605
1/4	185	1,670	1,630	1,600	1,610	1,530
3/8	185	1,500	1,450	1,440	1,440	1,410
1/2	185	1,410	1,280	1,220	1,250	1,250
3/4	365	1,290	1,210	1,170	1,220	1,210

Comparison of Hot Gas and Hot Surface Ignition Temperatures

A comparison was made of the autoignition, wire ignition, and hot gas ignition temperatures of the hydrocarbon combustibles used in the present work

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[11] First work cited in footnote 5.

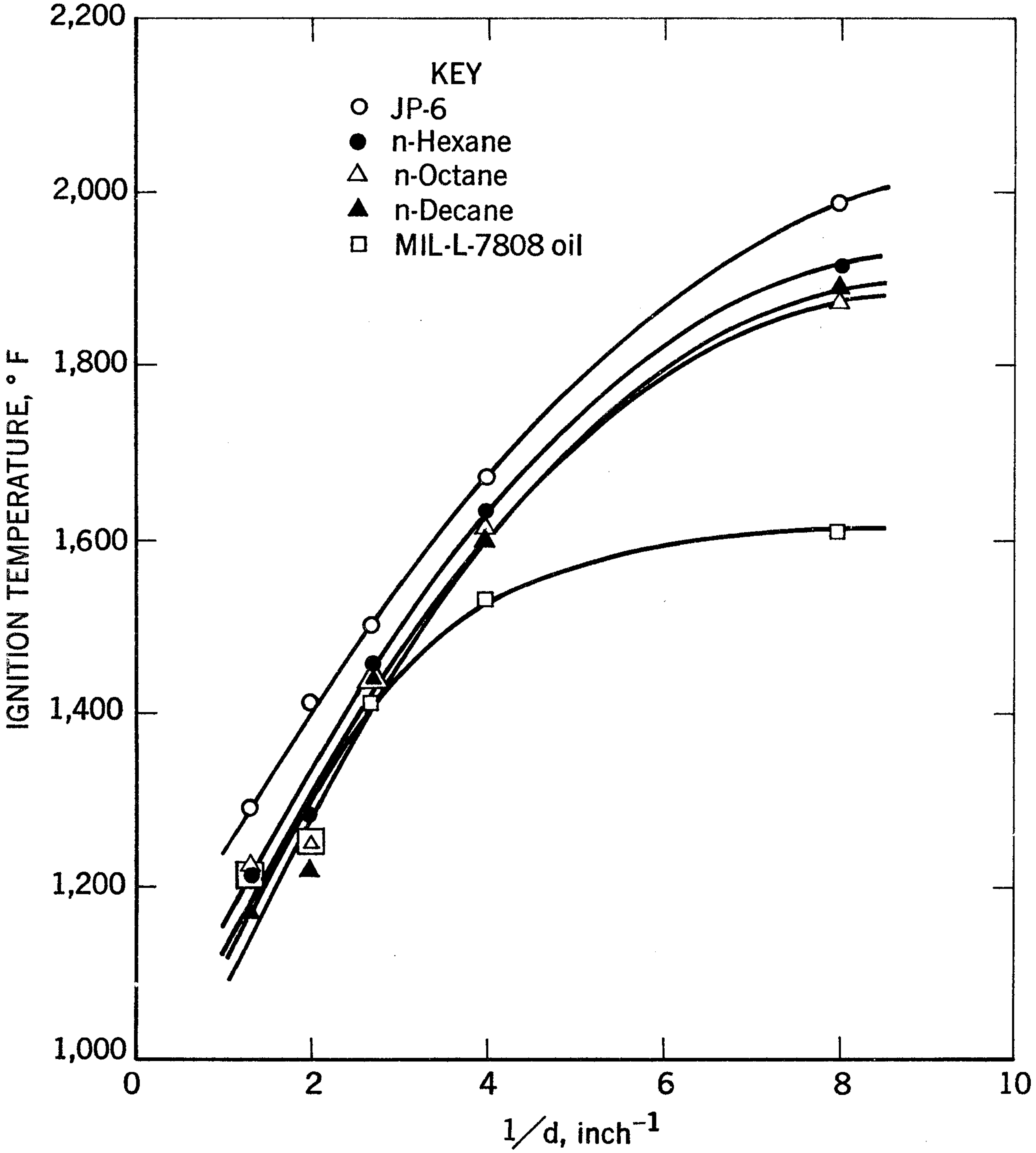

FIGURE 6. - Variation of Hot Gas Ignition Temperature With Reciprocal Diameter of Hot Air Jet for Various Combustible Hydrocarbon Vapor-Air Mixtures. (Flow conditions in figure 5 and table 2.)

and of hydrogen, benzene, and several low-molecular-weight paraffins with air as the oxidant. Table 3 lists the ignition temperature values for these combustibles with cylindrical heat sources of about 0.4-inch diameter. The hot gas ignition data given for hydrogen, benzene, and the low-molecular-weight hydrocarbons are those of Vanpee and Wolfhard.[12] They were obtained by injecting hot air jets at 365 in^3/min, compared with 185 in^3/min for the data included from the present study, into pure fuel under near-stagnant conditions (about 1 in/sec). According to the data in table 1, the difference in jet flow rates should not be serious. The autoignition temperatures[13] were determined in a quiescent air atmosphere by injecting liquid fuel into a heated cylindrical Pyrex vessel which was 6 inches long; also included in the table are minimum AIT values found in a 12.2-in^3 (200-cm^3) Pyrex Erlenmeyer. The wire ignition temperatures[14] were also obtained under near-stagnant conditions (0.15 in/sec) where the combustible vapor-air mixture was passed over a heated Inconel wire (2 inches long) mounted perpendicular to the axis of flow. Fuel-to-air weight ratio and fuel residence time (>1 second) were optimum for these conditions.

TABLE 3. - Comparison of hot surface and hot gas ignition temperatures of hydrocarbon combustibles and hydrogen with air at atmospheric pressure

(Fuel-to-air ratio, optimum for ignition; ignition criterion, appearance of flame)

Combustible	Ignition temperature, ° F			
	Pyrex Erlenmeyer,[1] 1.7-in diam by 5 in long	Cylindrical Pyrex vessel, 0.38-in diam by 6 in long	Inconel wire[2] 0.38-in diam by 2 in long	Air jet 0.38-in diam by >4 in long
MIL-L-7808 oil........	760	1,030	1,110	[3]1,410
JP-6 fuel.............	450	1,040	1,290	[3]1,500
n-Decane..............	[4]405	1,085	1,220	[3]1,440
n-Octane..............	[4]430	1,085	1,240	[3]1,440
n-Hexane..............	[4]455	1,120	1,260	[3]1,450
n-Butane..............	[4]760	1,165	-	[5]1,670
Ethane................	[4]960	1,075	-	[5]1,545
Methane...............	[4]1,000	1,375	-	[5]1,905
Benzene...............	[4]1,045	1,265	-	[5]1,870
Hydrogen..............	1,030	1,175	-	[5]1,185

[1] Minimum AIT values obtained in 12.2-in^3 Erlenmeyer (equivalent cylinder diameter of 1.7 inches).

[2] Interpolated values from figures 8 and 9.

[3] Values obtained with hot air jet injected into fuel vapor-air mixture.

[4] Zabetakis, M. G., A. L. Furno, and G. W. Jones. Minimum Spontaneous Ignition Temperatures of Combustibles in Air. Ind. and Eng. Chem., v. 46, October 1954, p. 2173.

[5] Vanpee, M., and H. G. Wolfhard. Comparison Between Hot Gas Ignition and Limit Flame Temperatures. J. Am. Rocket Soc., v. 29, July 1959, p. 517. Values obtained with hot air jet (0.4-in diam) injected into pure fuel for n-butane, ethane, methane, and hydrogen; value for benzene obtained with N_2 jet.

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[12] Second work cited in footnote 3.

[13] First work cited in footnote 5.

[14] First work cited in footnote 5.

As expected, the minimum AIT values obtained with the Pyrex Erlenmeyer are noticeably lower than the corresponding values found with the heated cylindrical vessel, Inconel wire, and air jet of 0.4-inch diameter; the variation is least (150° F) for hydrogen and greatest (590° to 1,050° F) for low-AIT combustibles such as n-hexane, n-octane, n-decane, and JP-6 fuel. By comparison, the cylindrical vessel and wire ignition temperatures do not vary by more than 155° F for n-hexane, n-octane, and n-decane. However, the hot gas ignition temperatures of all the combustibles except hydrogen are noticeably higher than their corresponding hot surface ignition temperatures found with a 0.4-inch-diameter heat source. Table 3 and figure 7 show that the hot gas ignition temperatures of the paraffin hydrocarbons are about 200° F higher than the cylindrical vessel AIT's. These ignition temperatures also decrease with increasing number of carbon atoms or molecular weight of the combustible, although all of the data are not consistent; figure 7 includes the data for JP-6 which was assumed to have 12 carbon atoms. The anomalous hot gas ignition behavior displayed by the ethane and JP-6 fuels in figure 7 was also observed in the autoignition and wire ignition experiments.

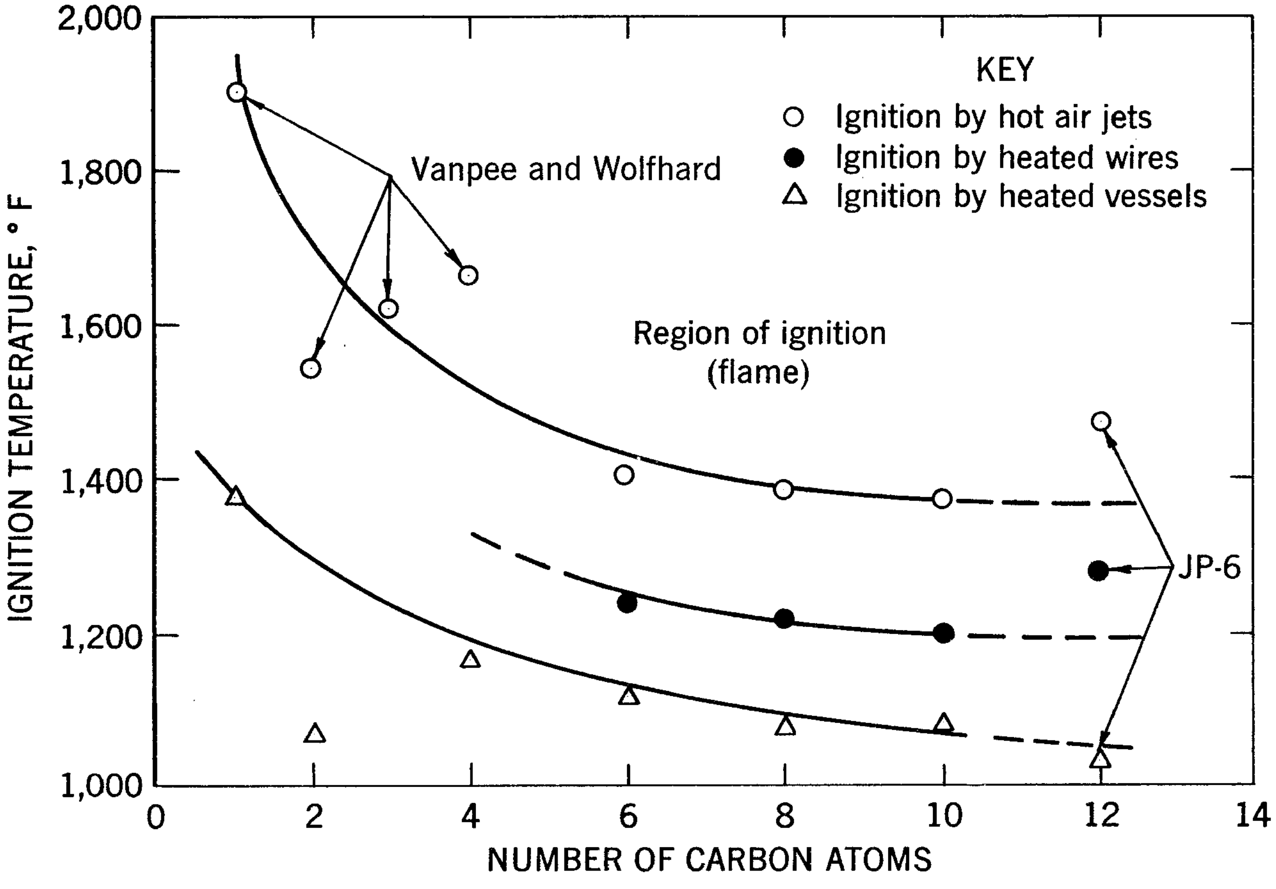

FIGURE 7. - Variation of Minimum Ignition Temperatures With Number of Carbon Atoms for Paraffin Hydrocarbon and JP-6 Vapor-Air Mixtures Ignited With 0.4-Inch-Diameter Cylindrical Heat Sources.

Figures 8 and 9 show comparisons of these ignition temperatures at various heat source diameters for the five combustibles employed in the present investigation. Here, the hot gas ignition temperatures again are the highest, and their variation with the reciprocal of heat source diameter (1/d) resembles most closely that displayed by the autoignition temperatures. The latter behavior is rather surprising since vessel volume and surface effects were negligible in the hot gas ignitions; in comparison, these effects would be expected to be large in the autoignitions, particularly at small heat source diameters, for example, 0.17 inch or 1/d of 6 inch^{-1}. The wire ignition temperatures tend to display the least variation for 1/d values greater than 2 inch^{-1}. However, they do not differ greatly from the hot gas ignition temperatures at 1/d values between 1 and 2 inch^{-1}. Also, the data presented here appear to indicate that the wire and hot gas ignition temperatures may approximate the autoignition, or vessel ignition temperatures when the heat source diameter is greater than 1 inch.

Such correlations may improve if the diameter as well as the length of the heat source is considered. The criterion of ignition is also important. For example, according to our observations, luminous or precursory flame reactions may occur at jet temperatures 100° to 200° F below those required for "hot" flame ignition. In these correlations, the hot surface ignition temperatures referred to any visible flame, whereas the hot gas ignition temperatures referred only to "hot" flame ignitions. Furthermore, the latter temperatures were measured near the jet base and were at least 200° F higher than those at the plane where ignition occurred above the jet base. Thus, although the hot gas ignition temperatures of the given combustibles are generally higher than their hot surface ignition temperatures, the differences are not necessarily great when the ignition criterion and the heat source dimensions are the same. Admittedly, some variation should be expected between these different temperatures, since the chemical kinetics involved in hot gas and hot surface reactions would normally be different.

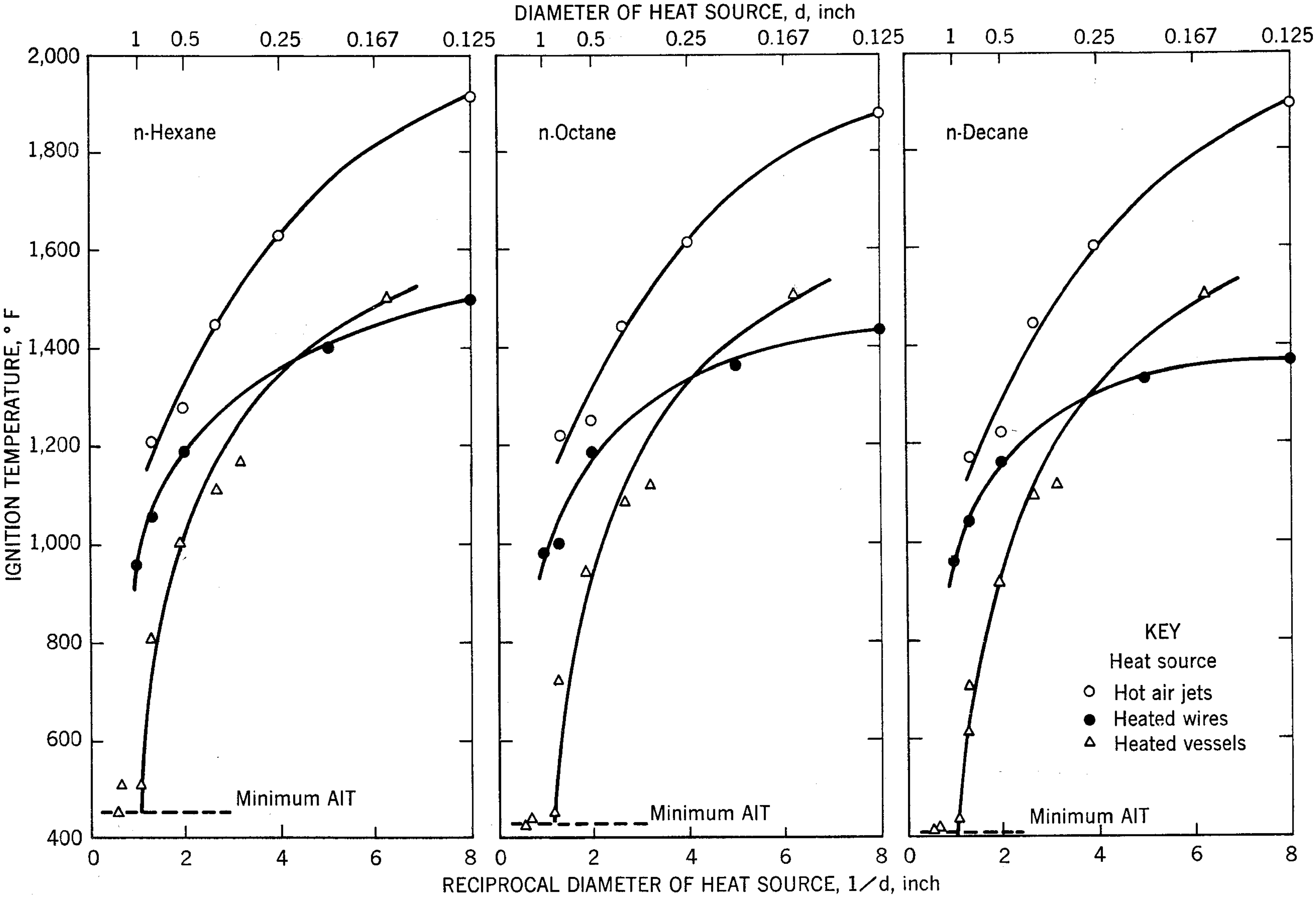

FIGURE 8. - Variation of Hot Gas and Hot Surface Ignition Temperatures With Reciprocal Diameter of Heat Source for n-Hexane, n-Octane, and n-Decane Vapor-Air Mixtures.

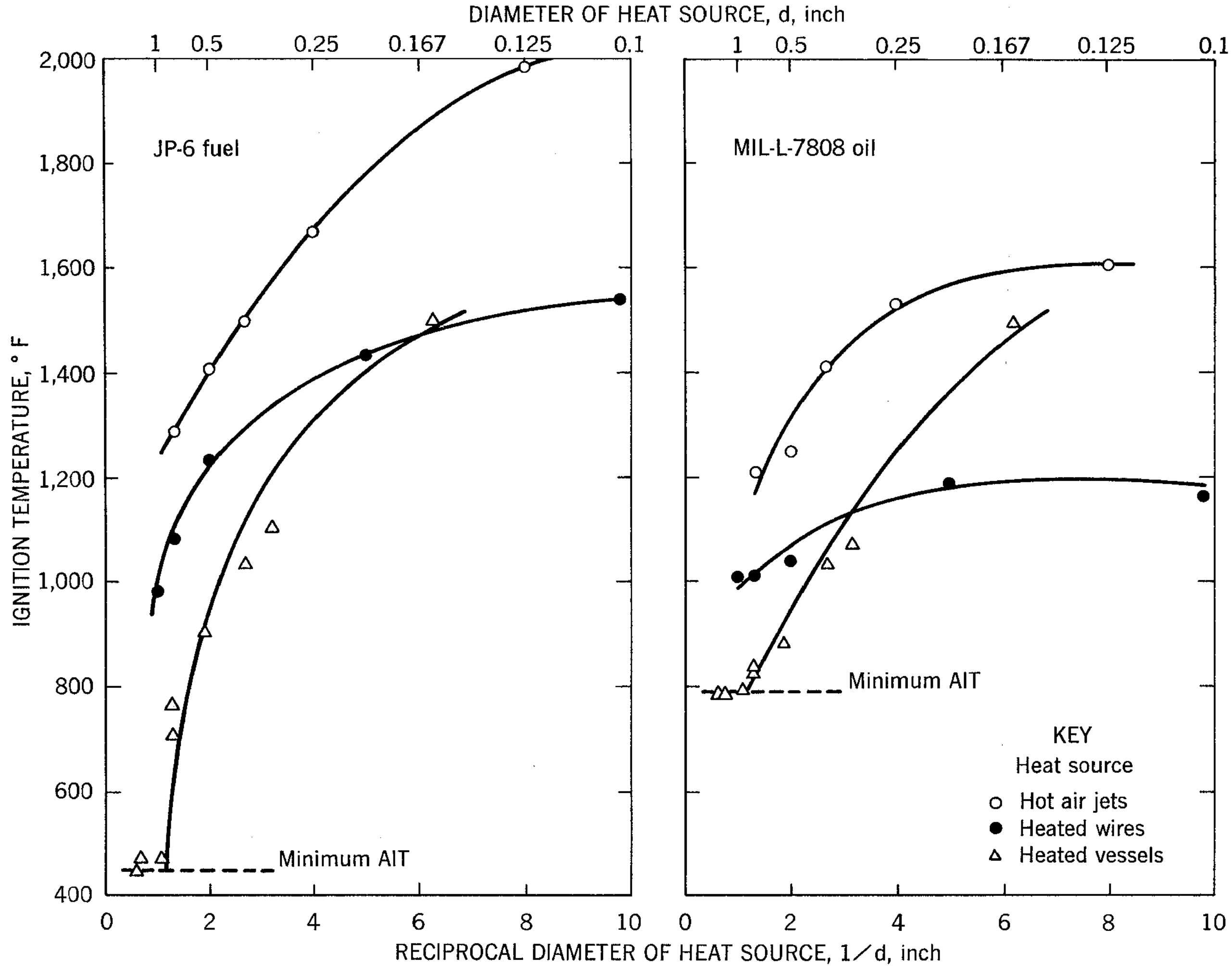

FIGURE 9. - Variation of Hot Gas and Hot Surface Ignition Temperatures With Reciprocal Diameter of Heat Source for JP-6 Fuel and MIL-L-7808 Engine Oil Vapor-Air Mixtures.

CONCLUSIONS

The hot gas ignition temperatures of various hydrocarbon fuel and engine oil vapor-air mixtures decreased with increasing diameter of the hot air jet. Their variation with heat source diameter was similar to that observed in wire ignitions and particularly in autoignitions with the same combustibles. These temperatures are not greatly dependent on fuel-to-air ratio and jet flow rate. Also, they do not necessarily differ greatly from hot surface ignition temperatures when the ignition criterion and the heat source diameter are the same.

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