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RESEARCH MEMORANDUM

DROP BURNING RATES OF HYDROCARBON AND NONHYDROCARBON FUELS

By Arthur L. Smith and Charles C. Graves

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The burning rates of single drops of 15 hydrocarbon and nonhydrocarbon fuels were determined in quiescent air at room temperature and pressure. These drop burning rates were compared with the rates predicted by a theoretical analysis based on the rate of mass transfer from a sphere in an infinite stagnant atmosphere. The experimental results also were compared with the combustion efficiencies of a full-scale, single tubular combustor operating with the same hydrocarbon and nonhydrocarbon fuels, as determined in a previous investigation.

The drop burning rates were proportional to the drop diameter. Drop burning rates of the 15 fuels varied from 0.0086 to 0.0141 centimeter squared per second for methanol and butylsilane, respectively. The experimentally determined drop burning rates were in orderly agreement with those predicted by the theoretical analysis; however, the absolute values differed significantly. The variation in drop burning rates of the fuels considered did not correlate with the changes in combustion efficiency of a turbojet combustor.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to develop design procedures for improving the combustion efficiency of the turbojet combustor at high-altitude operating conditions. Investigations have indicated that the combustion efficiency of turbojet combustors may be controlled or limited by reaction-rate factors. The results of an analysis presented in reference 1 showed that, in one combustor, second-order chemical kinetics controlled the combustion efficiency at very low pressure, and a flame-spreading mechanism controlled efficiency at high pressures. In another study (ref. 2), combustion efficiency was related to the fundamental burning velocity of a number of pure fuels in a full-scale, single turbojet combustor. Studies (refs. 2 and 3) also have shown that combustion efficiency may be influenced by the physical state of the injected fuel. In reference 4, combustion efficiencies of a variety of liquid hydrocarbon and nonhydrocarbon fuels were correlated with a function of the latent heat of vaporization and flame speed.

The studies reported herein were undertaken to provide drop-burning-rate data that could be used to investigate possible correlations with the combustion efficiency data of reference 4. Drop burning rates of some of the fuels investigated in reference 4 previously had been determined in reference 5. However, since a self-consistent set of fuel data was desirable in order to assure uniformity of the results, drop-burning data were obtained in this study for most of the fuels that had been investigated in reference 4.

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Single drops of fuel were suspended from a fine quartz filament in quiescent air. The drop was then ignited and was photographed with a movie camera. A platinum wire having a known diameter was positioned in the plane of the filament and was photographed at the beginning of each series of new runs, in order to convert image distances on the photographs to absolute values of drop diameter.

The data are compared with drop burning data presented in reference 5 and with theoretical drop burning data determined from equations developed in reference 6. In addition, the relative drop burning rates are compared with the relative performance characteristics of the fuels in a turbojet combustor (ref. 4).

FUELS

Physical properties of the fuels tested, including the references from which these properties were obtained, are presented in table I. The fuels selected were as follows:

Hydrocarbons	Oxygenated hydrocarbons	Nonhydrocarbons
Isooctane (2,2,4-Trimethyl pentane)	Methanol	Carbon disulfide
2,2-Dimethyl butane	Propylene oxide	Acrylonitrile
2-Pentene	Diethyl ether	Butylsilane
Isopentane	Acetone	
Benzene		
n-Heptane		
Cyclohexane		
Methyl cyclohexane		

APPARATUS AND PROCEDURE

The apparatus used to determine the burning rate of the fuel drops (fig. 1) was the same as that used in reference 7. Fuel drops

approximately 1800 microns in diameter were suspended from a quartz filament having a bulb diameter of approximately 700 microns. The filament and the ignition source were mounted in a chamber with inside dimensions of 12 by 18 inches. Ignition of the drop was accomplished by pivoting past the drop a small propane flame burning at the end of a hypodermic needle. The burning drops, suspended on the filament, were photographed in silhouette with a 16-millimeter camera driven by a synchronous motor that provided a constant speed of 24 frames per second. A $5\frac{1}{4}$-inch focal length, f/4.5 lens was mounted between the burning drop and the camera,
4446 approximately $6\frac{1}{2}$ inches from the drop. The luminosity of the flame surrounding the drop was obliterated by the strong background illumination provided by a focusing spotlight mounted behind a ground-glass plate.

In recording the sizes of the burning drop, the average of two perpendicular diameters inclined 45° from the vertical and horizontal axes of the drop was taken to compensate for the elliptical deformation of the drop suspended on the quartz filament (fig. 2). This resulting value was taken as the diameter of an equivalent spherical drop. A total of approximately 8900 frames of film was examined, with an average of 55 frames for each individual drop. Every third image was measured. A platinum wire having a diameter of 929 microns was photographed in the filament plane intermittently during each series of runs in order to convert image distances on the film to known distances. In some instances, attempts to suspend the drops resulted in broken filaments; consequently, the installation of new filaments was necessary. The bulb size of each filament was measured; these measured values are shown in table II. In order to determine the consistency of the test results, isooctane was investigated with each filament.

The rate of change of drop diameter with time is expressed in reference 6 by

$$X^2 = X_0^2 - \lambda t$$

where X_0 is the drop diameter at time $t = t_0$, and λ is a constant called the evaporation constant in reference 6 and herein referred to as the drop burning rate.

In figure 3, representative plots of the square of drop diameter against time are presented for four fuel drops burning in quiescent air. The change in drop diameter due to evaporation at low temperature is very small prior to ignition, as indicated by the horizontal portion of the curve in figure 3(a). Following ignition, however, the change in drop diameter increases rapidly, and the data follow the straight-line relation observed in references 5 and 7. The point of intersection between the horizontal and the sloping portion of the curve thus represents the ignition point. The slope of the curve following ignition was considered to be the drop burning rate. The best straight line through all the data was obtained by using the least-mean-square method.

RESULTS AND DISCUSSION

The experimentally determined drop burning rates for each of the 15 fuels investigated are presented in table II. Averaged drop burning rates for each fuel are also shown in the table. Four series of runs were made with isooctane, with an average of approximately nine runs per series. The reproducibility of the test data was determined by these duplicate isooctane tests, which showed an average variation of ± 5 percent. The maximum variation of any individual experimental value from the over-all average drop burning rate value was 9 percent. The data (table II) indicate that the variation of drop burning rate within each series was, in most cases, approximately ± 3 percent. In the case of butylsilane, however, the observed average variation was approximately ± 12 percent; the maximum variation from the average drop burning rate was approximately 21 percent, which is high. During tests with this fuel, a white residue (ref. 4) deposited on the filament during the combustion process. The formation of this residue was erratic and varied with time; consequently, the effective size of the filament varied during a given test. In addition, examination of photographs showed that the drops became distorted with time, which could have affected the burning rate.

In view of the several filament sizes used (indicated in table II) and the variation in the measured drop burning rates of the check fuel (isooctane) during the testing period, normalized drop burning rates based on the isooctane data were calculated. This normalized drop burning rate was obtained by multiplying the average drop burning rate of each test fuel by the ratio of the over-all average drop burning rate of isooctane to the average drop burning rate for isooctane in the same series as the test fuel. The normalized burning rate values are included in table II.

The maximum value of drop burning rate was obtained with butylsilane (0.0141 cm^2/sec). The minimum value of drop burning rate was obtained with methanol (0.0086 cm^2/sec). The variations in average drop burning rate among the fuels tested were relatively small. The difference in burning rate obtained with butylsilane and with methanol was 0.0055 centimeter squared per second, while the maximum difference in drop burning rate for the remaining fuels was only 0.0022 centimeter squared per second.

A relation between vapor heat content at the drop surface and burning rate of fuel drops is presented in reference 5. The assumption was made that, during combustion, a flame front is formed at a distance removed from the drop surface, and the material of the drop is evaporated off and thus feeds the flame front. Consequently, factors contributing to the rate of reduction in size of the drop are the rate of heat transfer to the drop and the enthalpy change required to change the drop to a vapor at its boiling point. In figure 4, normalized drop burning rate is plotted against vapor heat content of the fuels at the normal boiling point; the curve obtained in reference 5 and the data used to establish it are reproduced; and a curve is drawn through the hydrocarbon data obtained in this investigation. The initial reference temperatures for the data of reference 5 and the data of this investigation were 68° and 77° F, respectively. The results presented in figure 4 suggest that there is an orderly relation between the drop burning rate and the vapor heat content for the hydrocarbon fuels. The extreme divergence of the oxygenated compounds indicates that the burning mechanism might have been affected by the presence of the oxygen atom in these fuels.

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A theoretical treatment of the evaporation of small drops of liquid fuels during burning is presented in reference 6. Stagnant films are considered to separate the reaction zone from the drop and the surrounding atmosphere. Equations are developed for heat and mass transport in the appropriate films. The equation for the combustion of a fuel drop, assuming that forced and natural convection are unimportant, is expressed by

$$\lambda = \frac{8k/c_p \ln (1 + B)}{\rho_f} \tag{1}$$

where

λ drop burning rate

k thermal conductivity of gases (assumed value for air)

c_p specific heat at constant pressure of gases (assumed value for air)

ρ_f drop density

and

$$B = \frac{mO_g H/r + c(T_g - T_s)}{Q}$$

where

mO_g oxygen weight concentration in gas stream far removed from the drop surface

H heat of combustion of fuel

r stoichiometric oxygen-to-fuel ratio

c specific heat at constant pressure

T_g temperature in gas stream far removed from surface

T_s drop surface temperature

Q heat reaching fuel surface from gas per pound of fuel vaporized

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The preceding equation was used to estimate drop burning rates for the fuels of this investigation. Since the temperature in the gases surrounding the drop varied between approximately ambient and 4000° R, and since the composition of these gases is complex, thermal conductivity and the specific heat ratio k/c were arbitrarily evaluated for air at two chosen temperatures of 1620° and 700° R. In table III, the calculated burning rates for each of the assumed temperatures are listed for each fuel. Included in the table are the normalized average burning rates for the fuels, determined experimentally in this investigation, and the average burning rates for some of the fuels as reported in reference 5. The calculated burning rates are compared with the experimental values in figure 5. A match line for the data is shown in the figure; in addition, experimental and theoretical drop burning data presented in reference 6 are included in figure 5(a). The calculated data for the hydrocarbon fuels (open symbols, fig. 5) indicated reasonable agreement in trends with the experimental data at both arbitrarily chosen temperatures. Most of the oxygenated and substituted hydrocarbon fuels (solid symbols, fig. 5) deviated considerably from the results obtained with the hydrocarbon fuels. The drop-burning-rate values calculated with the arbitrary choice of the thermal conductivity and the specific heat ratio previously mentioned were not in complete agreement with the experimental drop burning rates obtained in this investigation; however, the absolute values of calculated drop burning rate necessarily are very dependent on the arbitrary choice of a temperature and composition for evaluating the thermal conductivity and the specific heat ratio (eq. (1)).

In reference 4, the performance of a J33 single combustor operating with the same fuels used in this investigation was determined over a range of inlet-air conditions. Combustion efficiencies obtained at one of those test conditions are plotted against measured drop burning rates in figure 6. No apparent relation exists between combustor performance and drop burning rate; similar results occurred for combustor data obtained at other operating conditions. In reference 7, combustion efficiencies predicted by a parameter incorporating drop-burning-rate data likewise were not in agreement with results obtained in a turbojet combustor. Of course, even if a relation between combustor efficiency and drop burning rate did exist at the particular conditions investigated, such a relation would have been very difficult to establish because of the small differences in observed drop burning rate among the fuels. Variations in flame speed among the fuels, however, were considerably larger, and it is noted that combustion efficiency data of reference 7 and of reference 4 were satisfactorily correlated with a flame-speed parameter. Also, it should be noted that conditions prevailing during the combustion process in a turbojet combustor vary considerably from those under which the drop-burning-rate values were determined. For example, the lower pressure and the higher temperature in the combustion test influence the amount of radiant heat transfer to individual particles of the fuel spray, the complex airflow pattern affects the convective heat transfer in the chamber, and the interaction of the various sizes and distribution of drops could influence the burning rate of the individual particles and thus the entire fuel spray. Consequently, additional detailed research on the effects of the aforementioned processes on individual drop burning rates is required before the complex mechanism associated with combustion can be fully analyzed.

SUMMARY OF RESULTS

The results obtained from an investigation of the burning rates of single drops of 15 hydrocarbon and nonhydrocarbon liquid fuels in quiescent air at room temperatures and pressures and from the comparison of these data with turbojet-combustor data of a previous investigation were as follows:

1. Drop burning rates were proportional to drop diameter.

2. The variations in drop burning rates among the fuels predicted by a theoretical analysis incorporating heat- and mass-transfer considerations were in general agreement with the experimental values obtained. However, the absolute values of drop burning rates determined experimentally were not in complete agreement with the theoretical analysis. The highest drop-burning-rate value (0.0141 cm^2/sec) was obtained with butylsilane. The lowest drop burning rate value (0.0086 cm^2/sec) was obtained with methanol.

3. Combustion efficiency data obtained in a tubular combustor were not correlated by drop burning rate.

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National Advisory Committee for Aeronautics
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TABLE I. - PHYSICAL AND FUNDAMENTAL COMBUSTION DATA OF FUELS

Fuel	Normal boiling point, °F	Density at 77° F, lb/cu ft	Heat content 77° F through normal boiling point, Btu/lb	Heat of vaporization at normal boiling point, Btu/lb	Vapor heat content at normal boiling point, Btu/lb	Lower heat of combustion, Btu/lb	Maximum burning velocity, cm/sec
Isooctane (2,2,4-Trimethyl pentane)	[a]210.6	[a]42.9	[a]75	[a]116.7	192	[a]19,065	[b]34.6
Isopentane	[a]82.1	[a]38.37	[a]3	[a]145.7	143	[a]19,303	[b]36.6
2,2-Dimethyl butane	[a]121.5	[a]40.23	[a]25	[a]131.2	157	[a]19,161	[b]35.7
2-Pentene	[a]98.2	[a]40.35	[a]11	[c]155.0	166	[a]19,040	[d]43.9
Methanol	[e]148.1	[f]49.00	[e]25	[e]474.0	499	[g]8,580	[d]51.1
Propylene oxide	[h]95.0	[h]51.36	[i]10	[c]234.0	244	[g]12,994	[j]67.2
Diethyl ether	[e]94.1	[h]44.12	[e]10	[f]151.0	161	[g]14,550	[d]40.1
Carbon disulfide	[f]115.0	[h]78.40	[e]11	[e]148.0	159	[g]5,830	[d]52.5
Acetone	[e]133.0	[e]49.15	[e]37	[k]224.1	261	[g]12,241	[c]42.3
Acrylonitrile	[f]171.0	[f]49.97	[l]84	[l]264.6	[l]349	[l]13,740	[j]47.0
Butylsilane	[m]133.6	[m]42.39*	[i]40	[m]147.1	187	[m]18,366	[j]120.0
Cyclohexane	[a]177.3	[a]48.31	[a]50	[a]153.7	204	[a]18,676	[b]38.7
Methyl cyclohexane	[a]213.7	[a]47.76	[a]67	[a]138.9	206	[a]18,642	[b]37.5
n-Heptane	[a]209.2	[a]42.42	[a]81	[a]136.0	217	[a]19,157	[b]38.6
Benzene	[a]176.2	[a]54.54	[a]45	[a]169.3	214	[a]17,259	[b]40.7

*Density at 68° F.

[a]Ref. 8.

[b]Ref. 9.

[c]Ref. 10.

[d]Data from Appl. Phys. Lab. of the Johns Hopkins Univ., under contract with Bur. Ord., U.S. Navy, corrected by a factor from ref. 9.

[e]Ref. 11.

[f]Ref. 12.

[g]Ref. 13.

[h]Data from Experiment, Inc., Richmond (Va.) under contract to Bur. Aero., U.S. Navy.

[i]Interpolated values from available data.

[j]Calculated data.

[k]Ref. 14.

[l]Data compiled by Monsanto Chemical Co.

[m]Ref. 15.

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TABLE II. - VALUES OF DROP BURNING RATES FOR 15

HYDROCARBON AND NONHYDROCARBON FUELS

Series	Run	Fuel	Burning rate, cm^2/sec	Average burning rate, cm^2/sec	Normalized burning rate, cm^2/sec
Filament 1 (bulb diameter, 552.3 microns)					
A	1	Isooctane	0.009163	0.009571	0.01004
	2		.009636		
	3		.009742		
	4		.009750		
	5		.009668		
	6		.009792		
	7		.009115		
	8		.009702		
B	1	2,2-Dimethyl butane	0.01069	0.01084	0.01137
	2		.01054		
	3		.01058		
	4		.01098		
	5		.01096		
	6		.01117		
	7		.01093		
	8		.01076		
	9		.01095		
	10		.01094		
	11		.01074		
Filament 2 (bulb diameter, 760.1 microns)					
C	1	Isooctane	0.01061	0.01006	0.01004
	2		.01068		
	3		.009813		
	4		.01018		
	5		.009954		
	6		.01023		
	7		.009270		
	8		.009947		
	9		.01022		
	10		.01007		
	11		.009787		
	12		.009969		

TABLE II. - Continued. VALUES OF DROP BURNING RATES FOR 15

HYDROCARBON AND NONHYDROCARBON FUELS

Series	Run	Fuel	Burning rate, cm^2/sec	Average burning rate, cm^2/sec	Normalized burning rate, cm^2/sec
Filament 2 (bulb diameter, 760.1 microns)					
D	1	2-Pentene	0.01195	0.01126	0.01124
	2		.01122		
	3		.01108		
	4		.01118		
	5		.01091		
	6		.01196		
	7		.01104		
	8		.01085		
	9		.01050		
	10		.01090		
	11		.01122		
E	1	Methanol	0.008604	0.00861	0.00859
	2		.008680		
	3		.008667		
	4		.008241		
	5		.008474		
	6		.008753		
	7		.008556		
	8		.008707		
	9		.008641		
	10		.008683		
	11		.008667		
	12		.008548		
F	1	Isopentane	0.01102	0.01123	0.01121
	2		.01193		
	3		.01102		
	4		.01152		
	5		.01092		
	6		.01114		
	7		.01158		

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TABLE II. - Continued. VALUES OF DROP BURNING RATES FOR 15 HYDROCARBON AND NONHYDROCARBON FUELS

Series	Run	Fuel	Burning rate, cm^2/sec	Average burning rate, cm^2/sec	Normalized burning rate, cm^2/sec
Filament 2 (bulb diameter, 760.1 microns)					
G	1	Propylene oxide	0.01095	0.01099	0.01097
	2		.01109		
	3		.01072		
	4		.01126		
	5		.01114		
	6		.01076		
	7		.01098		
H	1	Diethyl ether	0.01054	0.01085	0.01083
	2		.01103		
	3		.01094		
	4		.01077		
	5		.01096		
	6		.01104		
	7		.01089		
	8		.01099		
	9		.01047		
I	1	Acetone	0.01049	0.01057	0.01055
	2		.01098		
	3		.01073		
	4		.01029		
	5		.01046		
	6		.01065		
	7		.01055		
	8		.01044		
	9		.01052		
Filament 3 (bulb diameter, 602.5 microns)					
J	1	Isooctane	0.009936	0.01004	0.01004
	2		.01023		
	3		.01025		
	4		.009840		
	5		.009910		
	6		.01026		
	7		.009931		
	8		.009946		

TABLE II. - Continued. VALUES OF DROP BURNING RATES FOR 15

HYDROCARBON AND NONHYDROCARBON FUELS

Series	Run	Fuel	Burning rate, cm^2/sec	Average burning rate, cm^2/sec	Normalized burning rate, cm^2/sec
Filament 3 (bulb diameter, 602.5 microns)					
K	1	Benzene	0.009300	0.009511	0.009511
	2		.009162		
	3		.009379		
	4		.009460		
	5		.009629		
	6		.009631		
	7		.009847		
	8		.009680		
L	1	_n_-Heptane	.009705	0.009487	0.009487
	2		.009606		
	3		.009465		
	4		.009114		
	5		.009324		
	6		.009522		
	7		.009416		
	8		.009333		
	9		.009608		
	10		.009779		
M	1	Cyclohexane	.009172	0.009112	0.009112
	2		.009361		
	3		.009143		
	4		.009382		
	5		.009376		
	6		.009168		
	7		.008890		
	8		.008962		
	9		.008533		
N	1	Methyl cyclohexane	.009182	0.009101	0.009101
	2		.009340		
	3		.009120		
	4		.009127		
	5		.008734		

TABLE II. - Concluded. VALUES OF DROP BURNING RATES FOR 15

HYDROCARBON AND NONHYDROCARBON FUELS

Series	Run	Fuel	Burning rate, cm^2/sec	Average burning rate, cm^2/sec	Normalized burning rate, cm^2/sec
Filament 4 (bulb diameter, 812.9 microns)					
O	1	Isooctane	0.01018	0.01045	0.01004
	2		.01042		
	3		.01050		
	4		.01064		
	5		.01075		
	6		.01018		
	7		.01051		
	8		.01066		
	9		.01023		
P	1	Carbon disulfide	0.01046	0.009876	0.00948
	2		.009551		
	3		.009845		
	4		.009636		
	5		.009724		
	6		.009405		
	7		.01035		
	8		.009626		
	9		.01041		
	10		.009660		
Q	1	Acrylonitrile	0.01084	0.01061	0.01019
	2		.01041		
	3		.01068		
	4		.01053		
	5		.01102		
	6		.01011		
	7		.01016		
	8		.01067		
	9		.01109		
R	1	Butylsilane	0.01607	0.01465	0.01408
	2		.01510		
	3		.01499		
	4		.01556		
	5		.01365		
	6		.01251		

TABLE III. - COMPARISON OF DROP BURNING DATA

Fuel	Drop burning rate from ref. 6, cm^2/sec	Normalized drop burning rate, cm^2/sec	Theoretical drop burning rate, cm^2/sec (a)	Theoretical drop burning rate, cm^2/sec (b)
Isooctane (2,2,4-Trimethyl pentane)	0.0095	0.01004	0.01400	0.007588
Isopentane		.01121	.01760	.00954
2,2-Dimethyl butane		.01137	.01639	.008778
2-Pentene		.01124	.01612	.00878
Methanol		.00859	.00789	.00434
Propylene oxide		.01097	.01101	.005962
Diethyl ether		.01083	.01498	.008114
Carbon disulfide		.00948	.007813	.004232
Acetone		.01055	.01081	.005855
Acrylonitrile		.01019	.009619	.005213
Butylsilane		.01408	.01354	.007336
Cyclohexane		.00911	.01216	.006589
Methyl cyclohexane		.00910	.01219	.006607
_n_-Heptane	.0097	.00949	.01342	.007275
Benzene	.0097	.00951	.01068	.005790

[a]Using k/c valid for air at 1620° R, and assuming midstream condition.

[b]Using k/c valid for air at 700° R, and assuming near-surface condition.

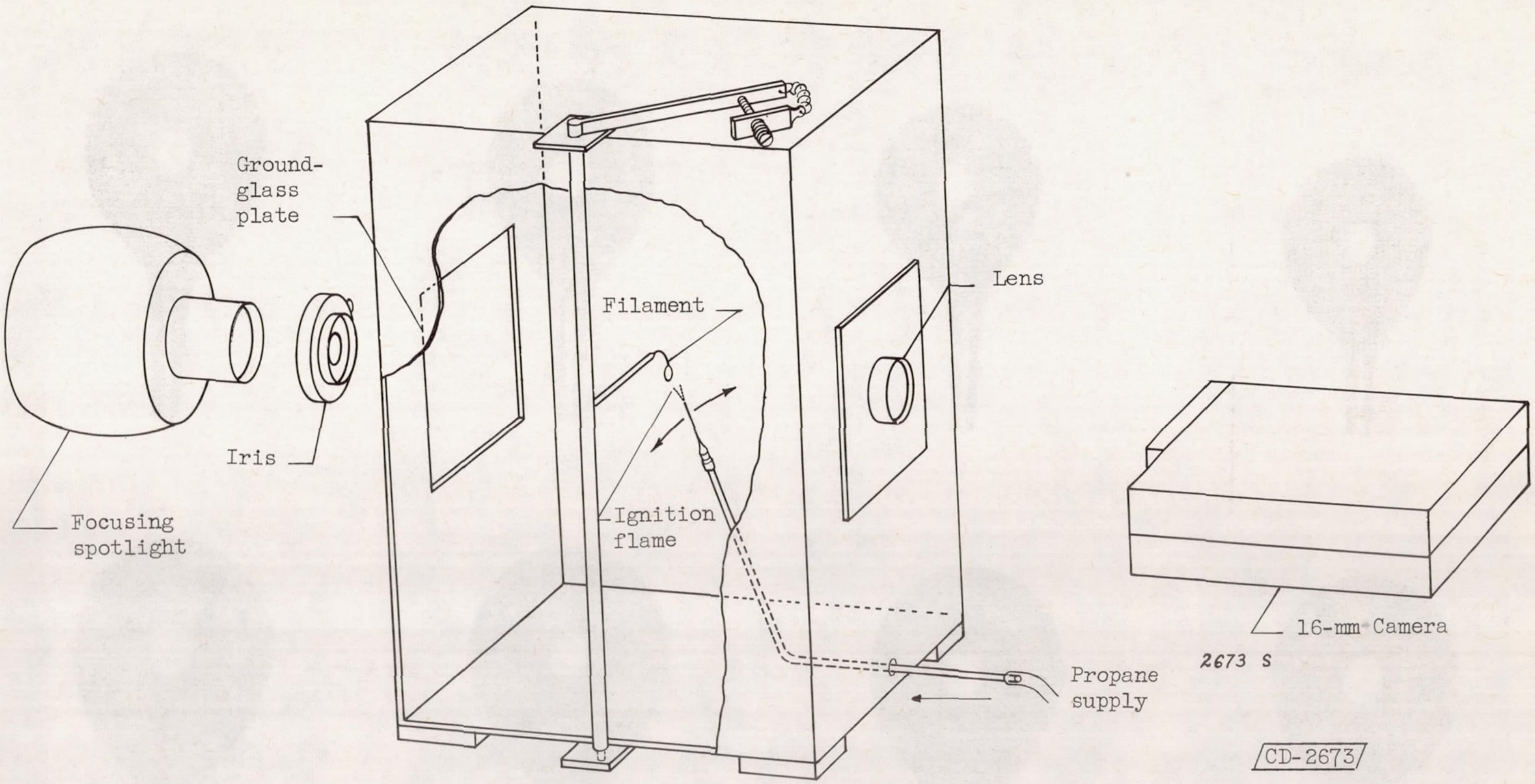

Figure 1. - Drop burning apparatus.

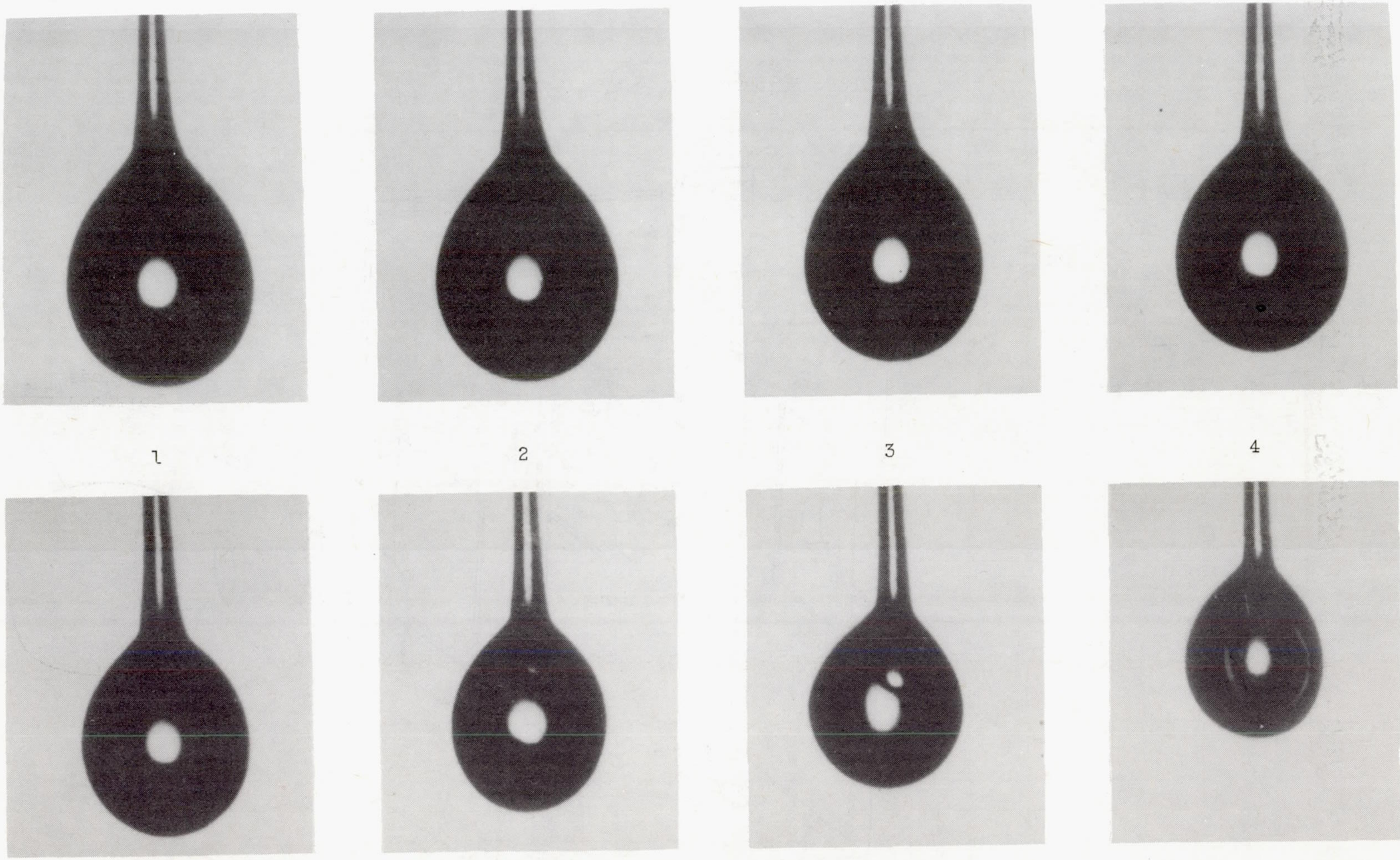

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Figure 2. - Photographs of burning drop taken at intervals of 0.125 second.

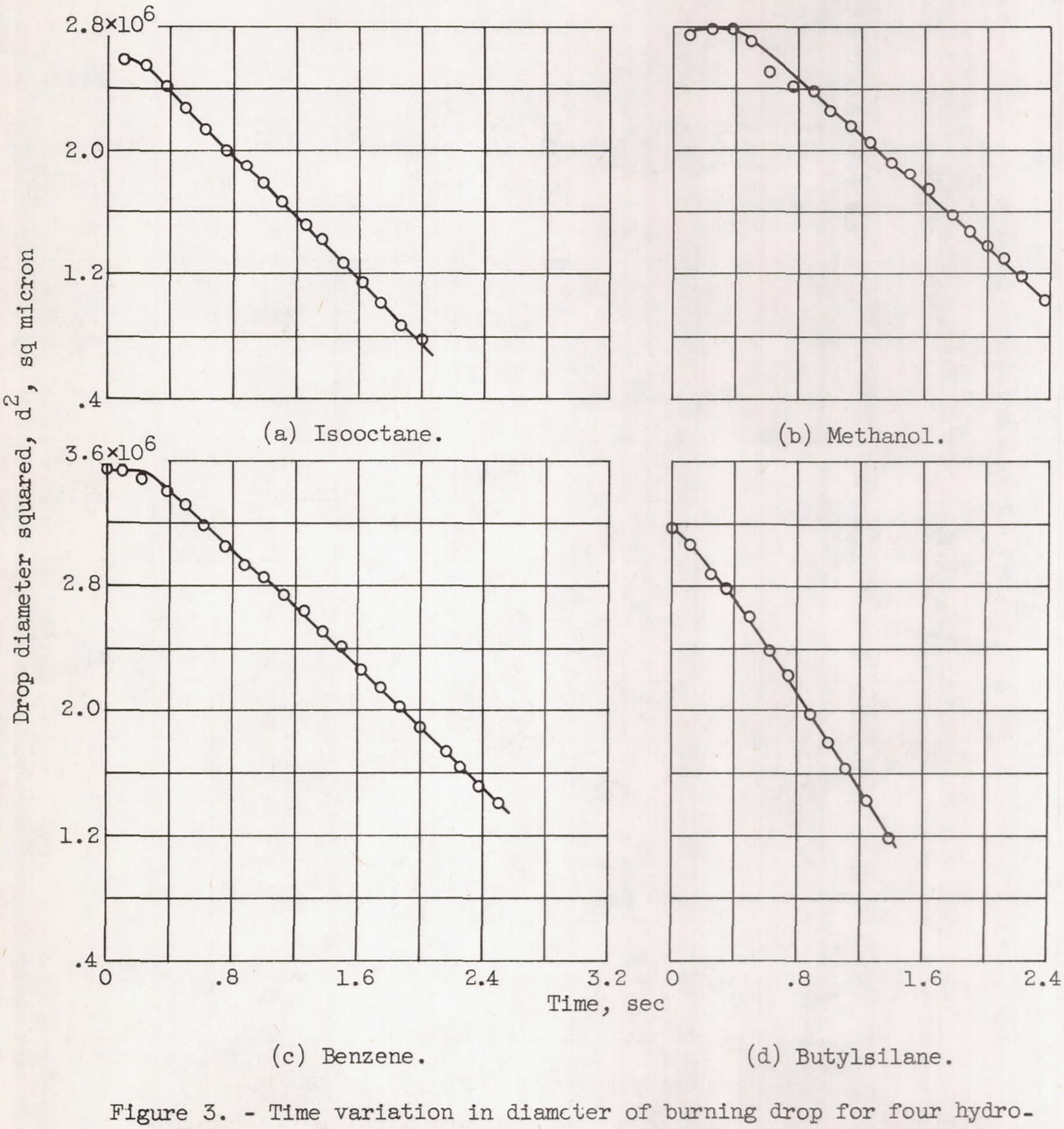


Figure 3. - Time variation in diameter of burning drop for four hydrocarbon and nonhydrocarbon fuels.

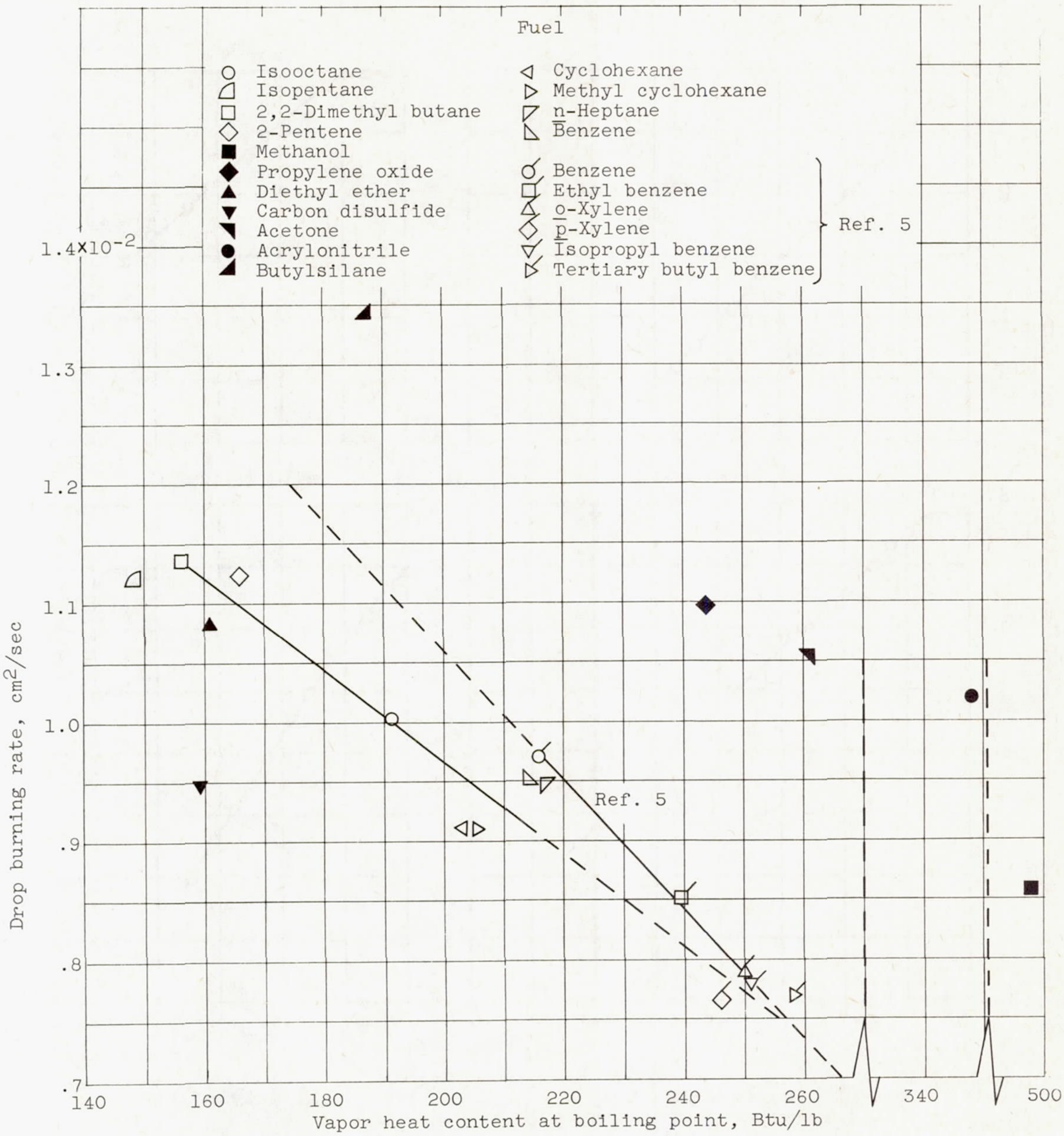
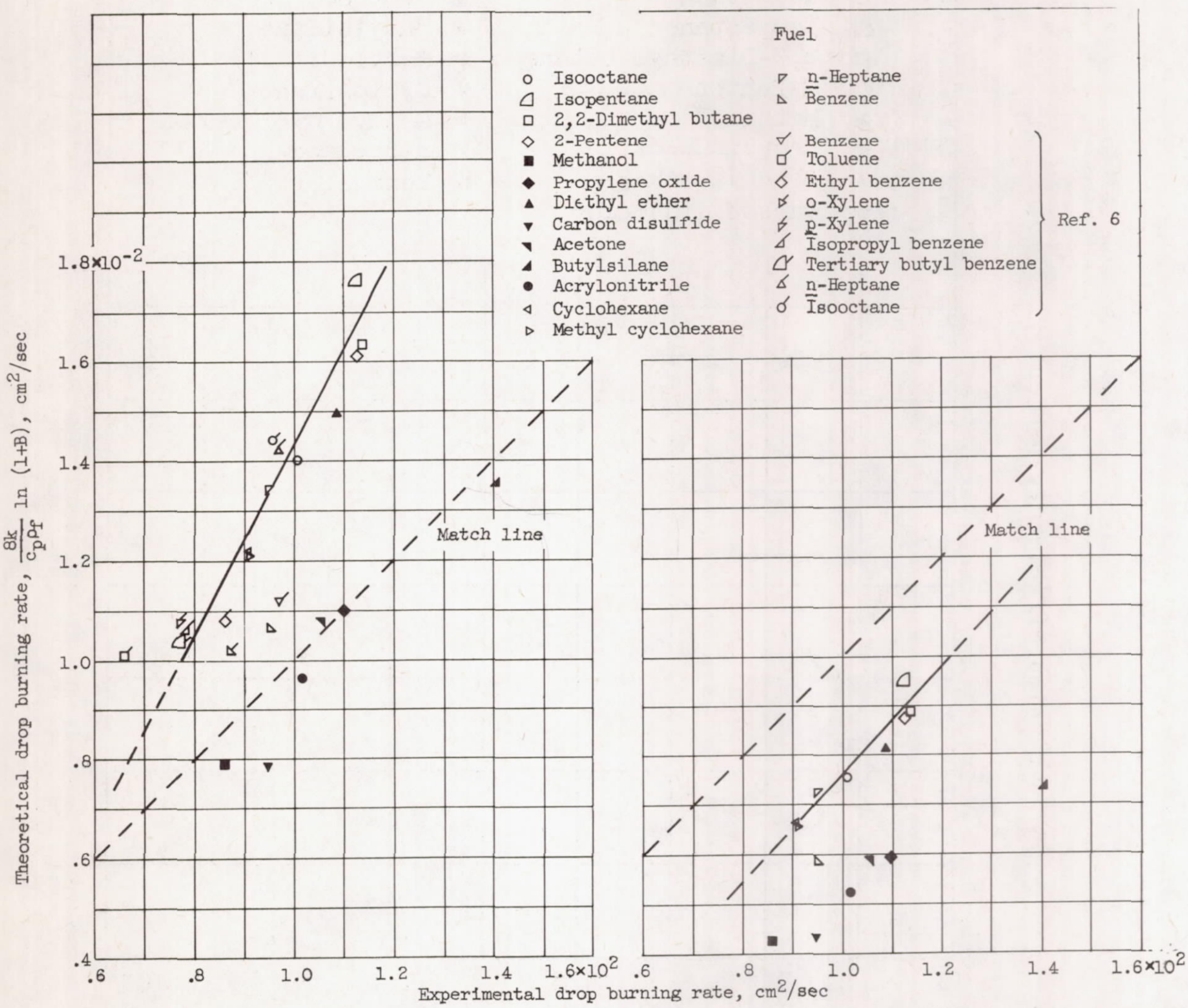


Figure 4. - Comparison of normalized drop burning rate with vapor heat content at normal boiling point of drop.



(a) Thermal conductivity and specific heat ratio valid for air at 1620° R.

(b) Thermal conductivity and specific heat ratio valid for air at 700° R.

Figure 5. - Comparison of experimental drop burning rates with theoretical drop burning rates.

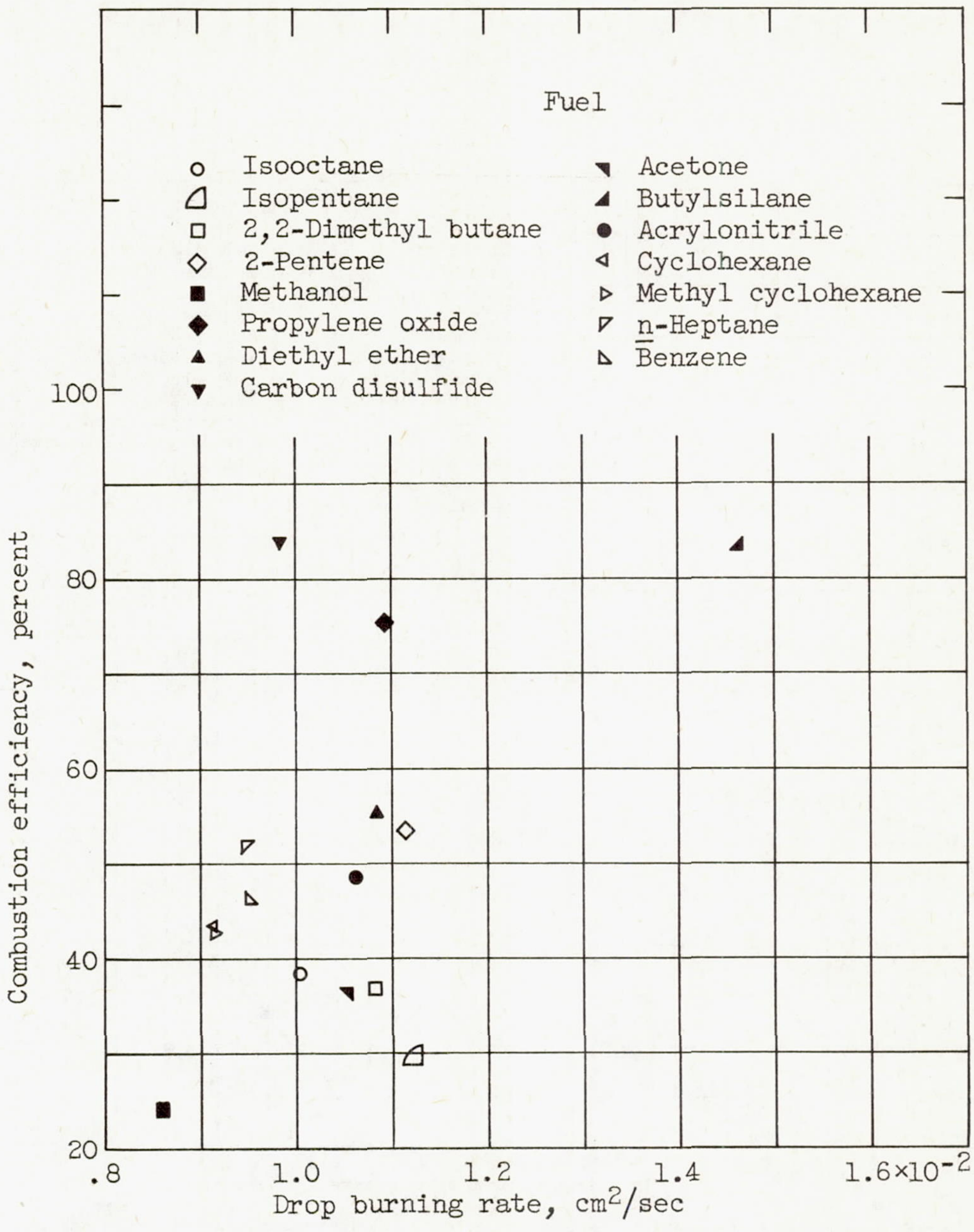


Figure 6. - Variation of combustion efficiency in a turbojet combustor with drop burning rate for 15 hydrocarbon and nonhydrocarbon fuels. Combustor operating conditions (ref. 4): heat input, 250 Btu per pound; inlet air temperature and pressure, 40° F and 14.3 inches mercury absolute, respectively.