# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

## TECHNICAL NOTE

## No. 1609

# EFFECT OF HYDROCARBON TYPE AND CHAIN LENGTH ON UNIFORM FLAME MOVEMENT IN QUIESCENT FUEL-AIR MIXTURES

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## SUMMARY

The results of flame-speed measurements of quiescent fuel-air mixtures in a 2.5-centimeter horizontal glass tube of 16 straight-chain hydrocarbons of the paraffin, olefin, diolefin, and acetylene series and of four cyclic hydrocarbons are presented in graphical form.

The paraffin hydrocarbons all had essentially the same peak flame speed. Increased unsaturation in a molecule of given size resulted in a higher peak flame velocity. This effect was most pronounced in the smaller molecules and dropped off rapidly as the chain length was increased. Peak flame speed decreased as the chain length of the unsaturated compounds was increased.

## INTRODUCTION

As part of an investigation being conducted at the NACA Cleveland laboratory to determine the effect of structure on the flame speed of a fuel, a study of the relation of unsaturation and of chain length to the uniform flame movement in a quiescent fuel-air mixture for 16 straight-chain hydrocarbons up to six carbon atoms in length and for four cyclic hydrocarbons has been made in a horizontal glass tube with an internal diameter of 2.5 centimeters.

Coward and Hartwell (reference 1) have shown that the fundamental flame speed of a fuel, or the burning rate at any point normal to the surface of the flame, is constant over the flame surface and is dependent only upon the fuel-air composition of the mixture at any given temperature and pressure.

Several investigators (references 2 to 5) have shown that in a tube closed at one end and ignited from the open end, the flame travels through the combustible mixture with a uniform velocity over a part of the tube length. The magnitude of this uniform velocity for any fuel at a constant temperature and pressure is dependent upon (1) the fuel-air ratio of the mixture, (2) the diameter of the tube, and (3) the direction of propagation, that is, whether upward, downward, or horizontal.

The uniform flame velocity, that is, the linear rate of flame travel through the tube, is equal to the product of the fundamental flame speed times the area of the flame surface divided by the cross-sectional area of the tube. Thus, by measurements of the uniform flame velocity, the fundamental flame speeds of different combustible mixtures can be relatively compared.

All results reported herein are presented as the variation of the uniform flame velocity with mixture composition and are given in graphical form.

Acknowledgement is made to the American Petroleum Institute Research Project 45 at the Ohio State University Research Foundation for contributing four of the hydrocarbons used in this study.

## APPARATUS AND EXPERIMENTAL PROCEDURE

The flame-speed measuring apparatus consisted of a glass tube, $13\frac{1}{2}$ feet long, with an internal diameter of 2.5 centimeters. The apparatus assembled for the introduction of a fuel-air mixture is shown in figure 1. Two electrodes, which were located in the tube 2 inches from the open end and were connected to the secondary of a 10,000-volt transformer, were used to ignite the mixture.

In order to establish the uniformity of the flame travel and the reproducibility of the results, the speed of the flame was first measured by four ionization gaps, consisting of tungsten wires, located in pairs at 6-inch intervals from the open end of the tube. An electromotive force of 24 volts was impressed across the gaps. The impulse created when a circuit was completed by ionization in the flame front was amplified and photographically recorded along with traces from a timing fork at 1/100-second intervals. The use of four ionization gaps enabled the determination of the speed to be made over three successive parts of the tube and thus to establish the uniformity of the flame travel over that part of the tube. The flame travel was found to be uniform within ±2 percent for a distance of 12 inches starting at the first gap.

The data presented herein were taken using an electronic timing device. This device consisted essentially of two photoelectric cells located at points 6 and 18 inches from the end of the tube, respectively. The impulses caused by the flame front passing the photoelectric cells, after passing through suitable amplifying circuits, were used to start and to stop an electric timer graduated in 1/60-second intervals.

The source and the estimated purity of the fuels used in this investigation are listed in table I.

Gaseous mixtures of each fuel with air were made up in 12-gallon carboys and were allowed to become completely homogeneous by standing several hours before samples were withdrawn. The combustion tube was evacuated to a pressure of a least 1 millimeter of mercury absolute and the sample was introduced and brought up to atmospheric pressure by means of the modified Toepler pump. At least 5 minutes were allowed for the mixture to become quiescent, the stopper was carefully removed, and the mixture was ignited. An average of three such determinations for each fuel-air mixture was taken to obtain the values for flame velocity reported. At the peak flame-speed values, the mean deviation of all the determinations was about ±2 percent.

## DISCUSSION OF RESULTS

The results of the investigation of the straight-chain hydrocarbon fuels are shown in figures 2 to 6. Fuels with the same number of carbon atoms per molecule are shown together on the same figure, so that the effect of increasing unsaturation in a molecule of given size may be noted. Uniform flame velocity is plotted against the function

$$\frac{\text{fuel-air ratio of mixture}}{\text{fuel-air ratio of mixture + stoichiometric fuel-air ratio}}$$

This ratio, denoted R in this report, has values ranging from 0 to 1 for all possible fuel-air ratios and is equal to 0.5 for the stoichiometric mixture.

The peak flame velocity for all fuels occurred on the rich side of the stoichiometric mixture at values of R ranging from 0.52 to 0.56 with the exception of benzene, the peak value of which occurred at approximately 0.61 (fig. 7).

The increase in peak flame velocity of a triple-bond over a double-bond hydrocarbon in a molecule of given size is greater than the increase of a double over a single bond. The effect of one triple bond is greater than that of two conjugated double bonds as is shown by a comparison in the four-carbon and five-carbon series (figs. 4 and 5).

The results for the cyclic hydrocarbons are shown in figure 7. Cyclopropane had the highest flame speed of the compounds tested. Cyclohexene showed an increase in peak flame velocity of about 12 percent over the corresponding saturated ring compound, cyclohexane. The increase in peak flame velocity for benzene over cyclohexene was only about 4 percent. The cycloparaffins, cyclopropane and cyclohexane, had higher peak flame velocities than the corresponding straight-chain paraffins, propane and hexane (figs. 3 and 6, respectively). Similarly, cyclohexene showed a slightly higher flame velocity than 1-hexene.

A plot of the peak uniform flame velocity obtained against the number of carbon atoms per molecule for the straight-chain compounds is shown in figure 8. The paraffin hydrocarbons all had essentially the same peak flame speed. It can be seen from this figure that the effect of increasing unsaturation in a molecule of given size is greatest in the smaller molecules and drops off rapidly as the chain length is increased. Some effect is still apparent, however, in chains of six carbon atoms. With this number of carbon atoms, the peak flame speed of the acetylene hydrocarbon is still about 25 percent greater than the flame speed of the corresponding paraffin hydrocarbon. The point for acetylene on figure 8 was estimated from fundamental flame speed data taken from reference 6.

## SUMMARY OF RESULTS

From an investigation of quiescent fuel-air mixtures in a 2.5-centimeter tube, it was found that for hydrocarbons up to six carbon atoms per molecule:

1. The straight-chain paraffin hydrocarbons had essentially the same peak flame speed.

2. Increasing the unsaturation in a molecule of given size increased the peak flame speed. This effect was most pronounced in the smaller molecules and dropped off rapidly as the chain length was increased.

3. Increasing the length of the carbon chain in an unsaturated straight-chain compound decreased the peak flame speed.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, December 9, 1947.

## REFERENCES

1. Coward, H. F., and Hartwell, F. J.: Studies in the Mechanism of Flame Movement. Part II. The Fundamental Speed of Flame in Mixtures of Methane and Air. Jour. Chem. Soc., pt. II, 1932, pp. 2676-2684.

2. Wheeler, Richard Vernon: The Propagation of Flame in Mixtures of Methane and Air. The "Uniform Movement". Jour. Chem. Soc. Trans., vol. 105, pt. II, 1914, pp. 2606-2613.

3. Mason, Walter, and Wheeler, Richard Vernon: The "Uniform Movement".During the Propagation of Flame. Jour. Chem. Soc. Trans., vol. 111, pt. II, 1917, pp. 1044-1057.

4. Coward, H. F., and Hartwell, F. J.: Studies in the Mechanism of Flame Movement. Part I. The Uniform Movement of Flame in Mixtures of Methane and Air, in Relation to Tube Diameter. Jour. Chem. Soc., pt. II, 1932, pp. 1996-2004.

5. Lewis, Bernard, and von Elbe, Guenther: Physics of Flames and Explosions of Gases. Jour. Appl. Phys., vol. 10, no. 6, June 1939, pp. 344-359.

6. Jost, Wilhelm: Explosion and Combustion Processes in Gases. McGraw-Hill Book Co., Inc., 1946, table 21, p. 122.

## TABLE I - SOURCE AND PURITY OF FUELS USED

| Hydrocarbon | Source | Minimum estimated purity, (mole percent) |
|---|---|---|
| Paraffins | | |
| Ethane | Ohio Chemical & Mfg. Co. | 95 |
| Propane | Ohio Chemical & Mfg. Co. | 99.9 |
| Butane | Ohio Chemical & Mfg. Co. | 99 |
| Pentane | Phillips Petroleum Co. | 99 |
| Hexane | Phillips Petroleum Co. | 95 |
| Olefins | | |
| Ethylene | Ohio Chemical & Mfg. Co. | 99.5 |
| Propylene | Ohio Chemical & Mfg. Co. | 99.5 |
| 1-Butene | The Matheson Company, Inc. | 99 |
| 2-Pentene | Phillips Petroleum Co. | 95 |
| 1-Hexene | OSU Res. Foundation, A.P.I. Res. Project 45 | 99 |
| Diolefins | | |
| 1,3-Butadiene | Ohio Chemical & Mfg. Co. | 98 |
| 1,3-Pentadiene | OSU Res. Foundation, A.P.I. Res. Project 45 | 99 |
| Acetylenes | | |
| Propyne | OSU Res. Foundation, A.P.I. Res. Project 45 | 99 |
| 1-Butyne | OSU Res. Foundation, A.P.I. Res. Project 45 | 99 |
| 1-Pentyne | Farchan Research Laboratories | 95 |
| 1-Hexyne | Farchan Research Laboratories | 95 |
| Cycloparaffins | | |
| Cyclopropane | Ohio Chemical & Mfg. Co. | 99.5 |
| Cyclohexane | Dow Chemical Co. | 98 |
| Cycloolefins | | |
| Cyclohexene | Eastman-Kodak Co. | 95 |
| Aromatics | | |
| Benzene | Barrett Div., The Allied Chemical & Dye Corp. | 98 |

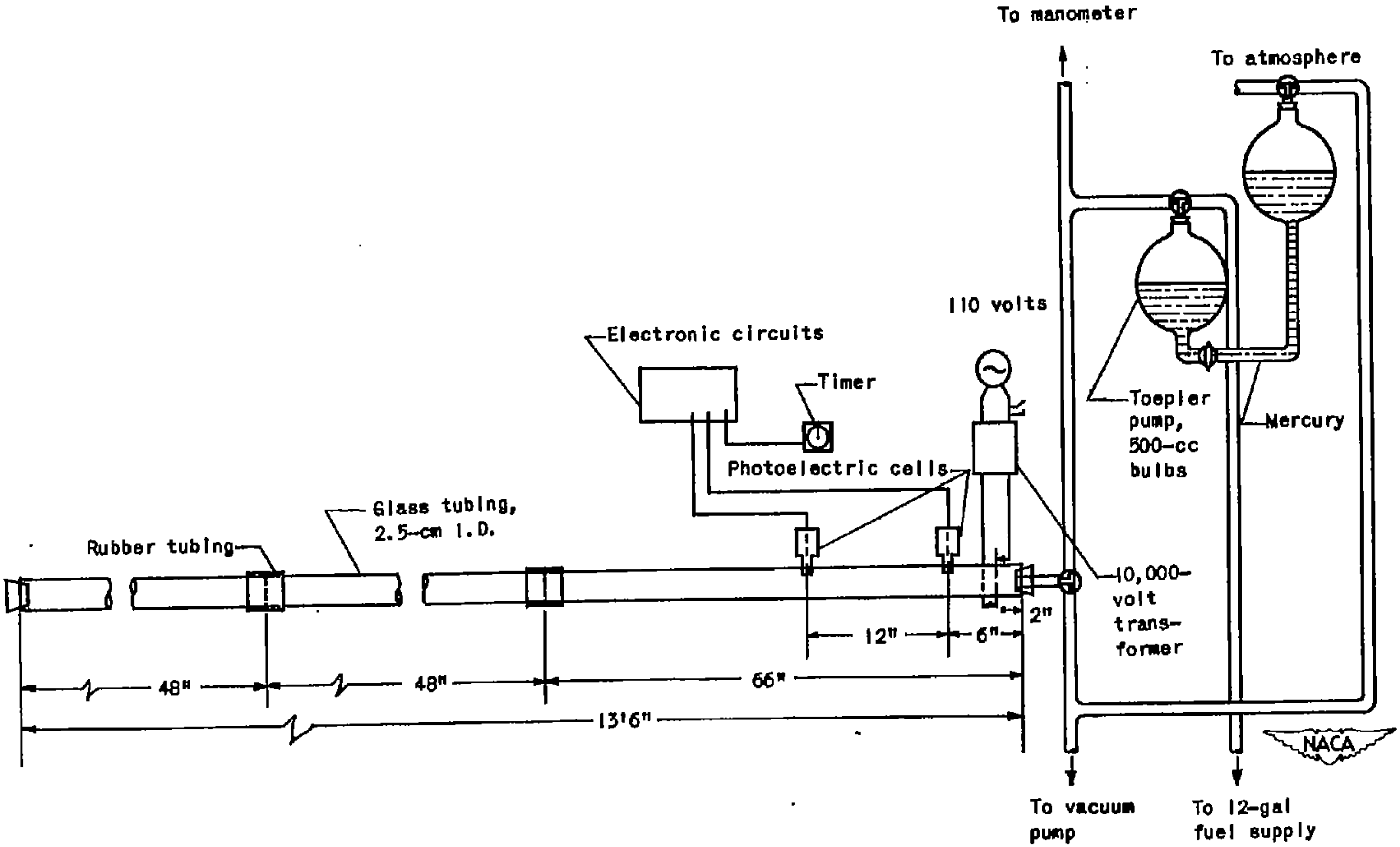


Figure 1. - Flame-speed measuring apparatus.

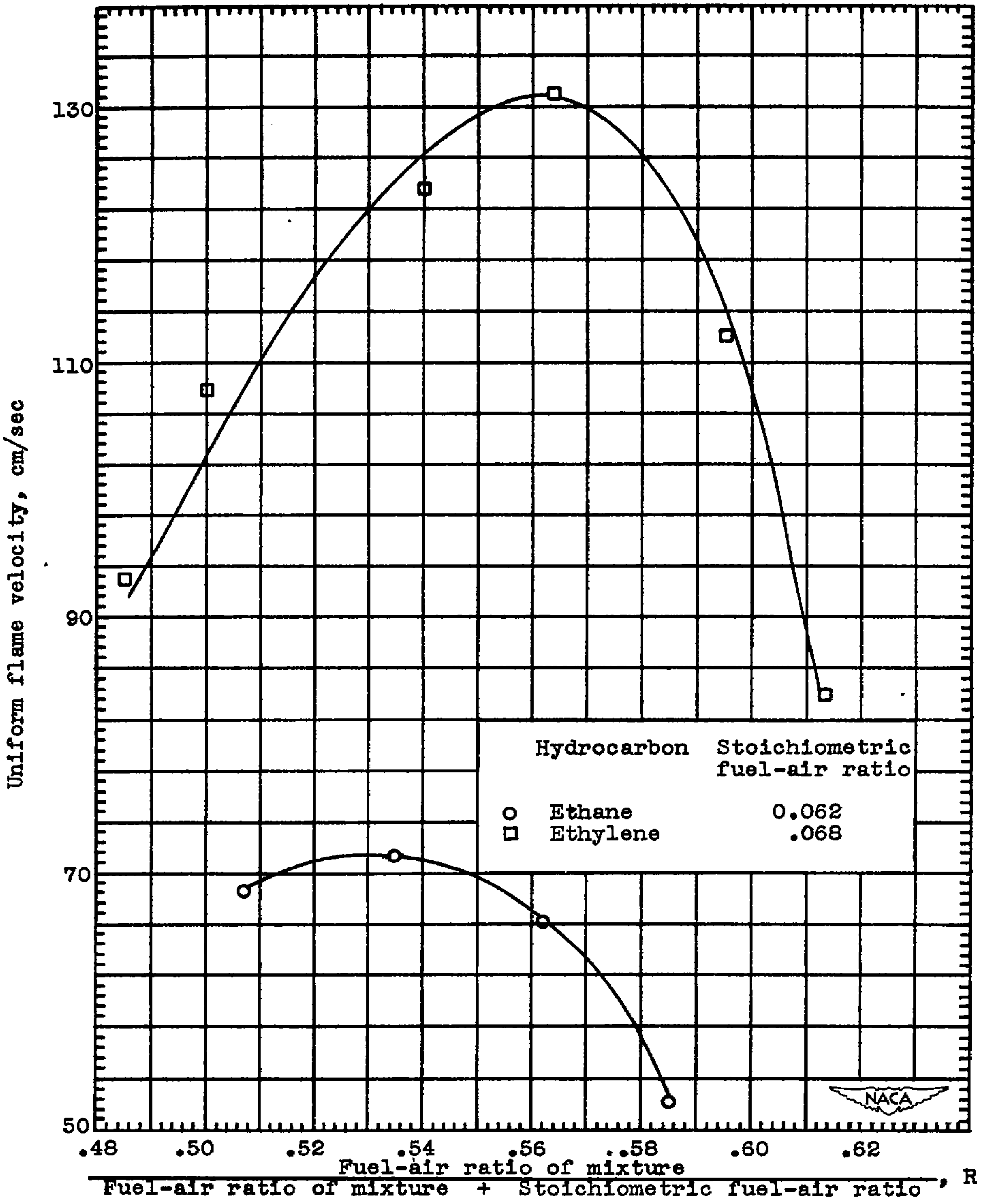
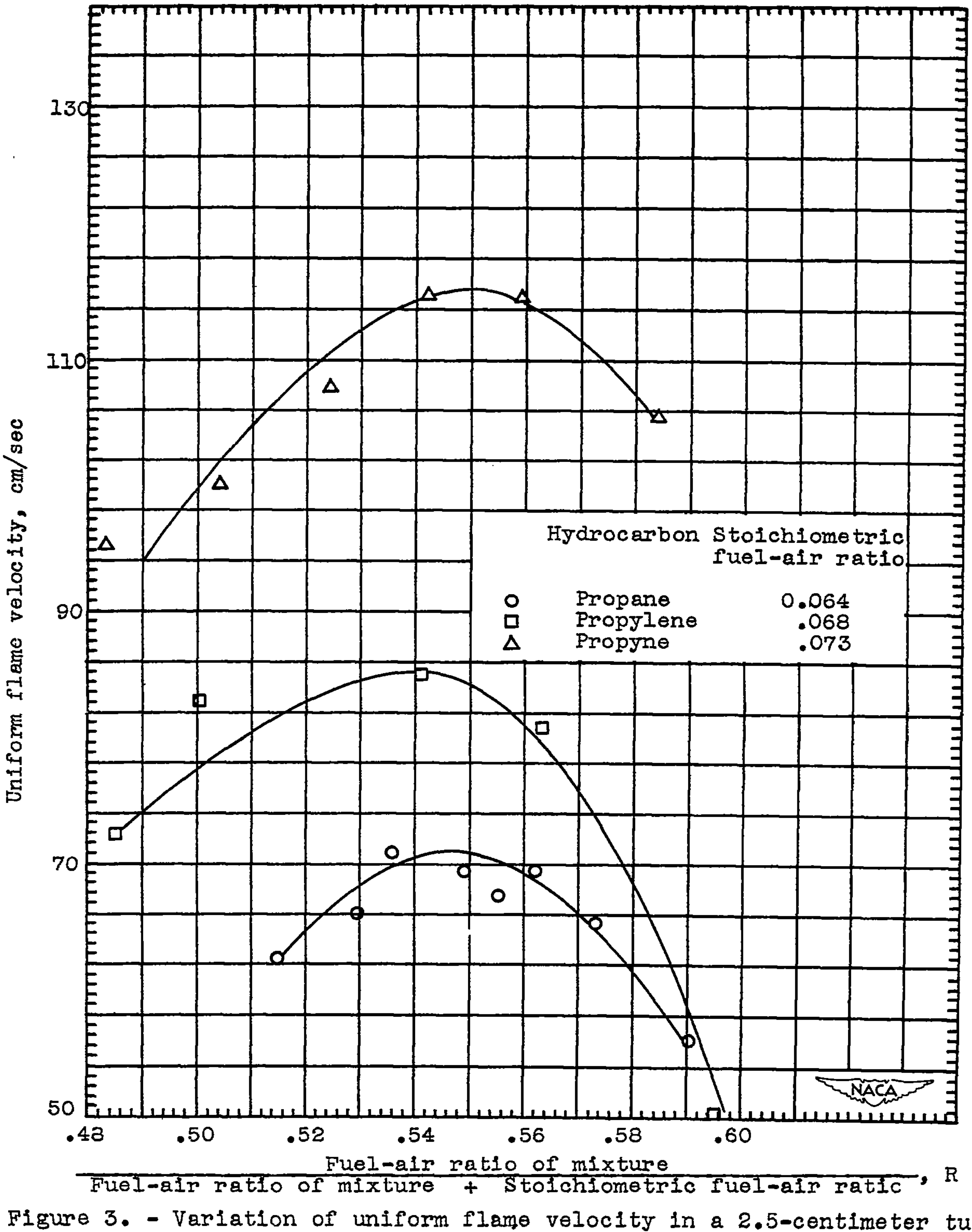


Figure 2. - Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for two-carbon hydrocarbons.



$$\frac{\text{Fuel-air ratio of mixture}}{\text{Fuel-air ratio of mixture} + \text{Stoichiometric fuel-air ratio}}, R$$

Figure 3. - Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for three-carbon hydrocarbons.

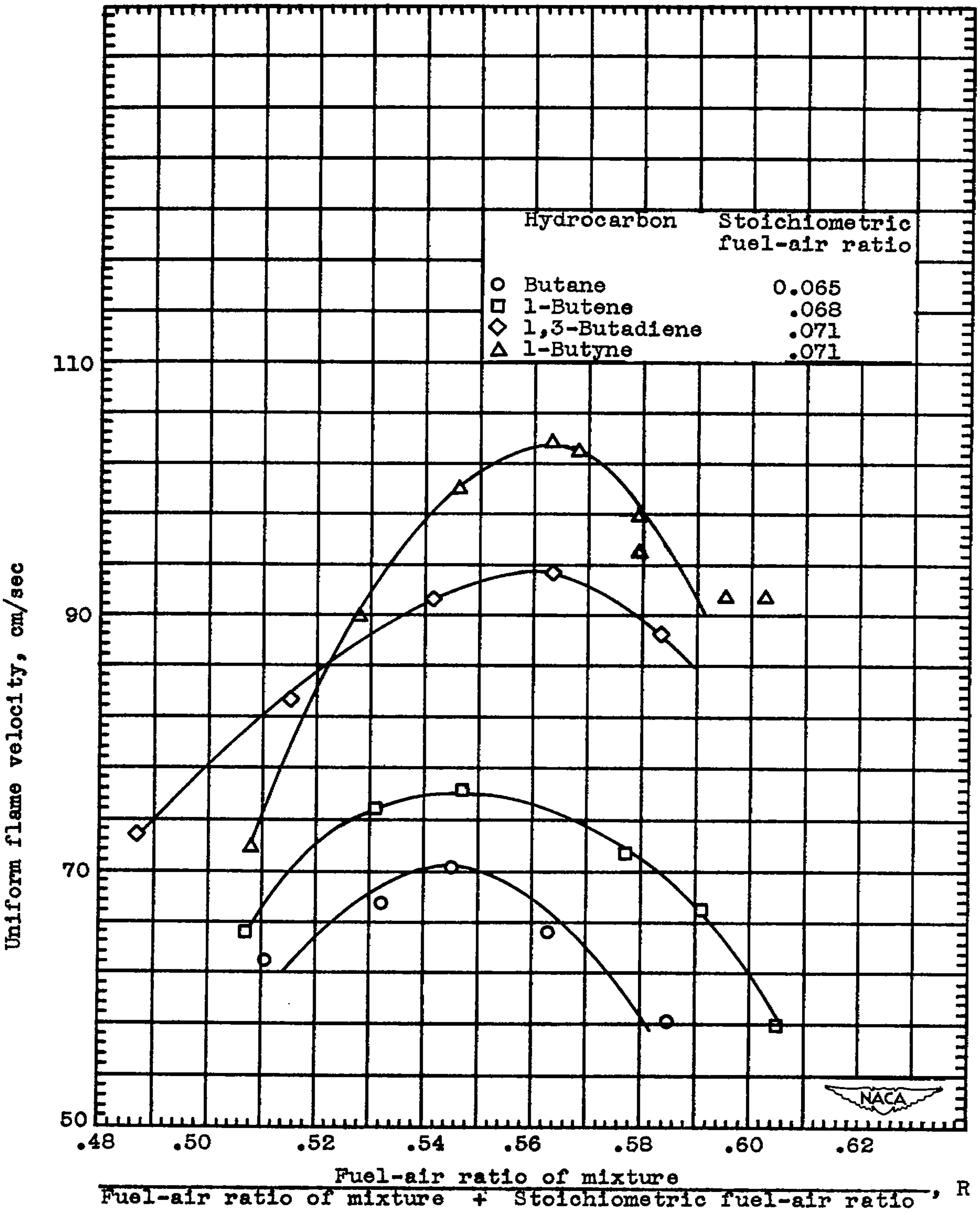


Figure 4. - Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for four-carbon hydrocarbons.

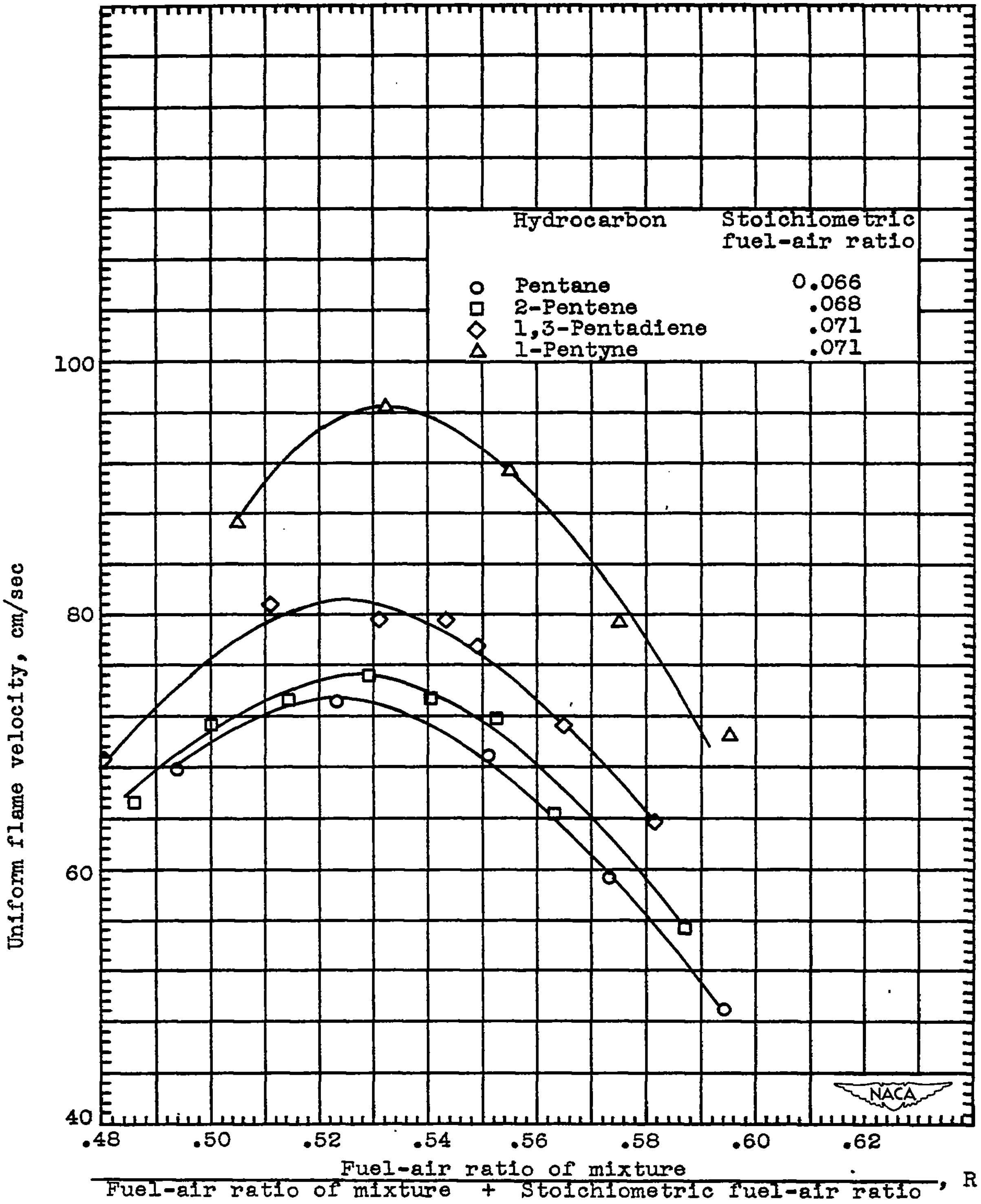


Figure 5.·- Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for five-carbon hydrocarbons.

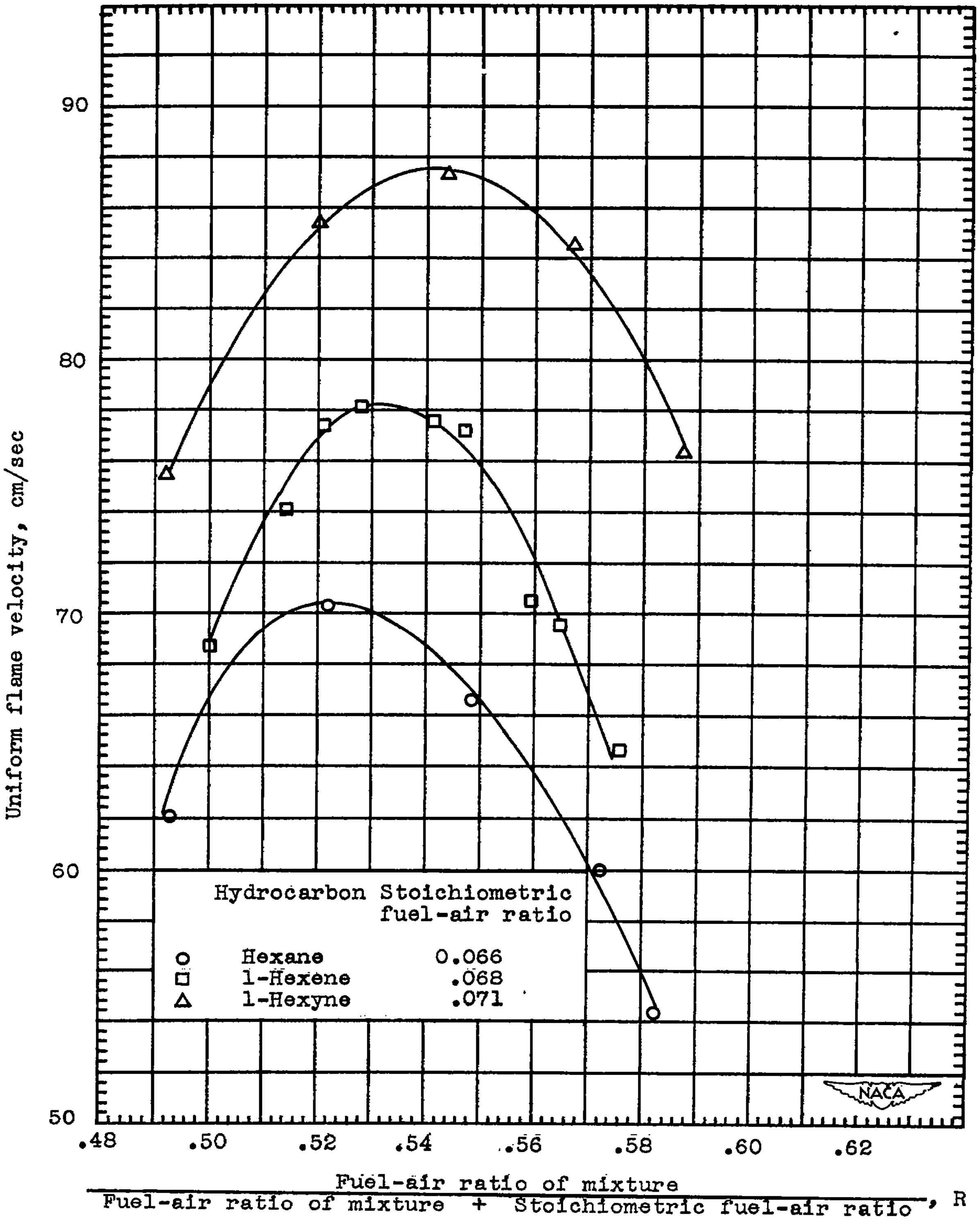


Figure 6. - Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for six-carbon hydrocarbons.

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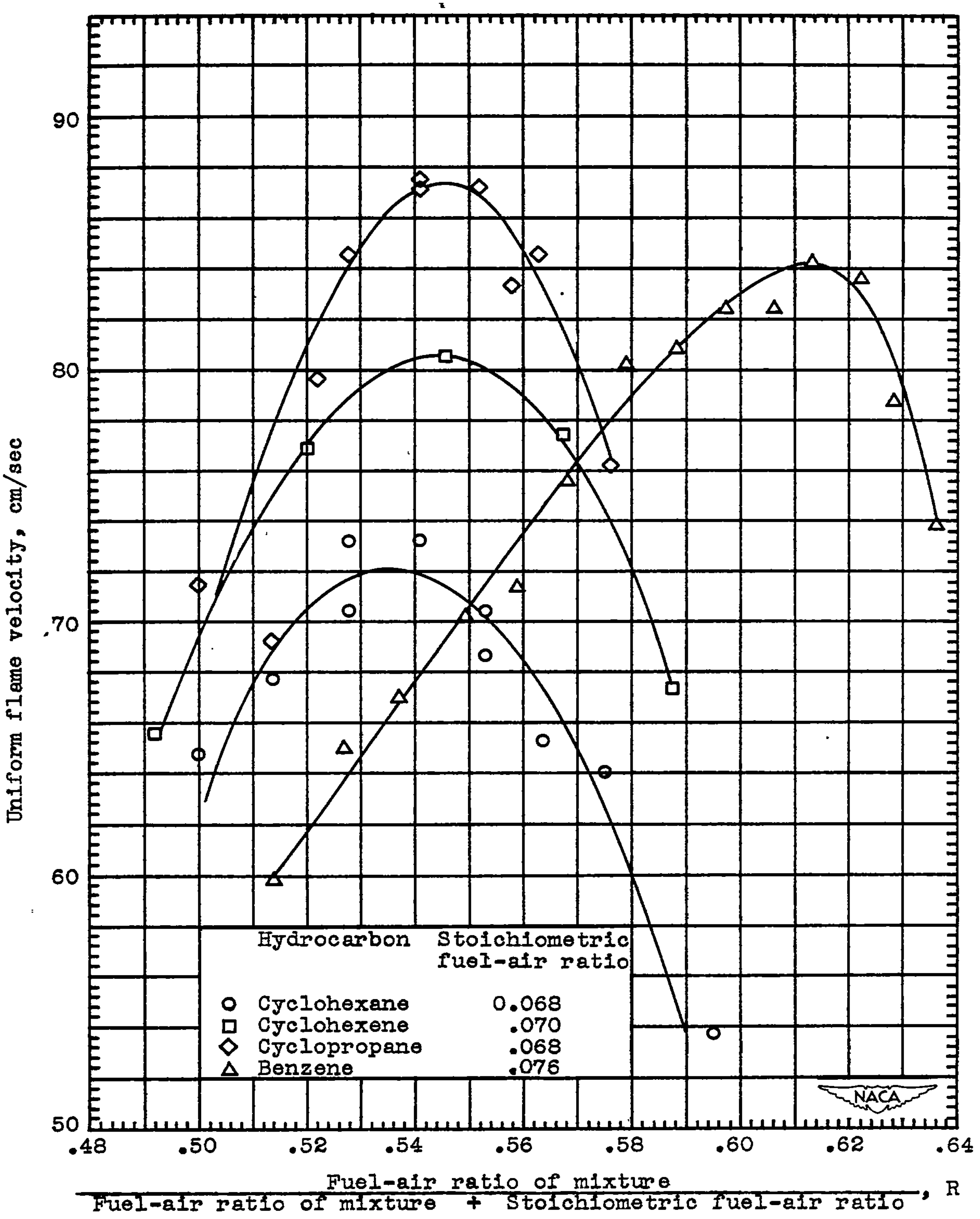

Figure 7. - Variation of uniform flame velocity in a 2.5-centimeter tube with fuel-air composition for four cyclic hydrocarbons.

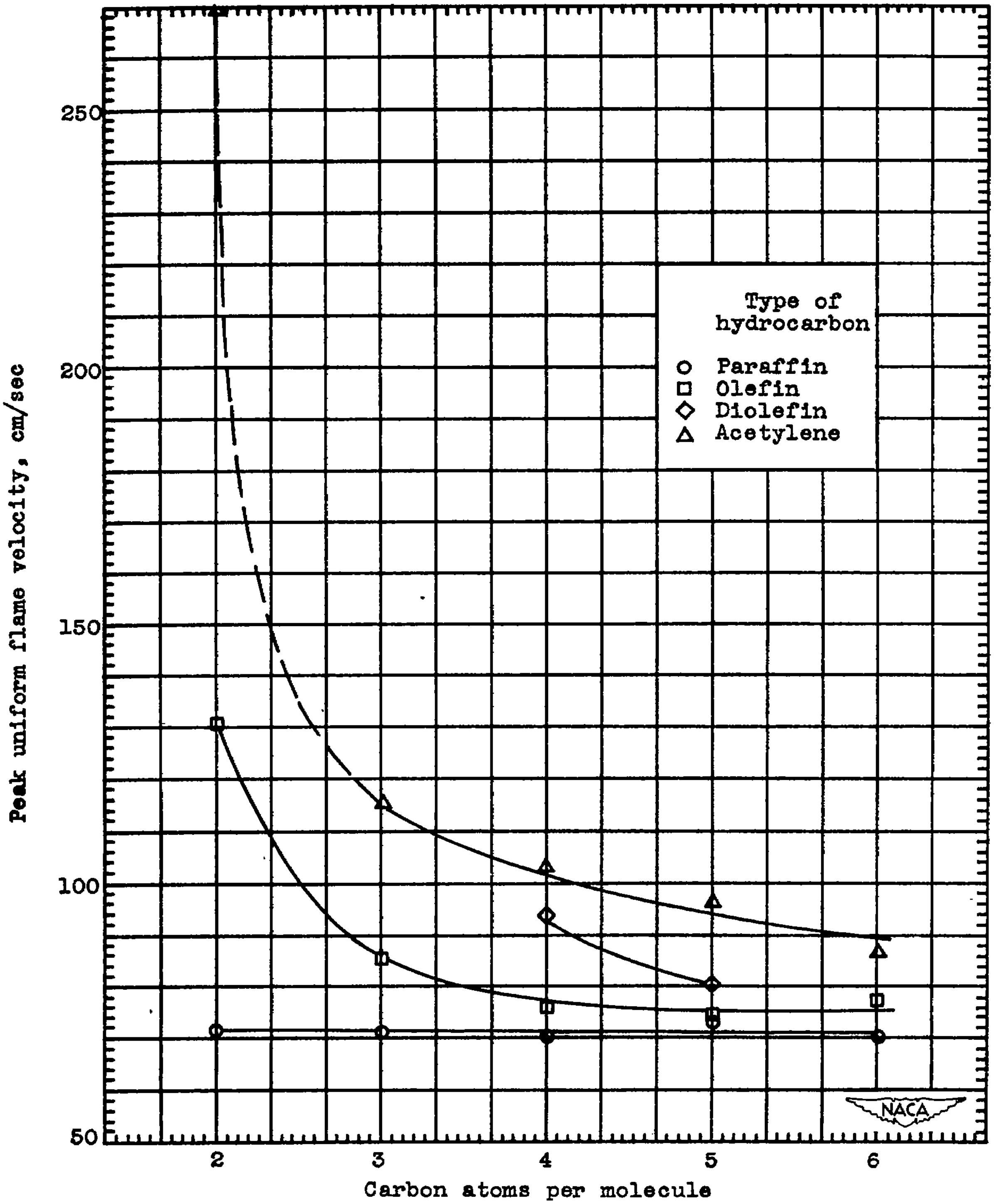

Figure 8. - Effect of molecular weight on peak uniform flame velocity in a 2.5-centimeter tube for straight-chain hydrocarbons. (Point for acetylene calculated from data taken from reference 6.)