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QUARTERLY PROGRESS REPORT NO. 6
ON
DETONATIVE COMBUSTION

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FOREWORD

The work reported herein is a continuation of the work on detonative combustion by the Aircraft Propulsion Laboratory of the University of Michigan. This research is conducted under Army Air Force Contract W33 (038)-12657 (University of Michigan Project M898).

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INTRODUCTION

During the past quarter the photographic study of detonation waves was continued and some limits of detonation obtained. In connection with the former, spark schlieren photographs of hydrogen-oxygen and propane-oxygen detonations were taken. Usually the reaction was shock-induced, although spark-initiated detonations were also photographed. Other schlieren photographs obtained were of a wave passing over a model, a bullet passing through a bubble of combustible mixture, and a bullet passing through a spray of water droplets.

In addition, the large shock tube (2-1/4 by 3-1/4 inches) was activated and used for photographing hydrogen-oxygen detonations.

The investigation of detonation limits was conducted with the 1/2-inch diameter tube and utilized shock ignition. The velocity was measured in each case as a means of determining whether detonation actually occurred.

The apparent cyclical behavior of the two hydrogen-oxygen photographs discussed in the last progress report is analyzed in the light of the phenomenon of spinning detonation.

SPARK SCHLIEREN PHOTOGRAPHS

The photographic investigation of detonation waves was continued and a number of such pictures are included as a part of this report. In each case, a vertical knife edge on the upstream side was used. All mixture ratios are on a volume basis. Unless otherwise noted, the detonations were shock initiated in the 3/8 by 1/2-inch shock tube; the cross dimension in the pictures corresponds to 1/2 inch.

Figure 1 is such a photograph of a 24% hydrogen-oxygen detonation passing over a block of balsa wood. At this point the shock and combustion pattern is not too different from that in a straight tube. The lines in the left portion of the picture are in the glass.

Figures 2 and 3 are of the same mixture passing over a block of lucite. It was hoped that a transmitted shock might be induced and detected in the lucite itself. However, the only patterns seen are presumably those in the gas between the lucite and the side windows of the tube. The planar attenuation of the combustion zone in Fig. 3 is unusual and could conceivably be attributed to a reflected shock from the lucite. The vertical line to the right in this picture is a wire stretched across the outside of the test section and is used solely for an absolute reference point.

Figure 4 is also a photograph of a 24% mixture; it represents a wave moving into a discontinuous decrease in cross-sectional area. More pictures of this type will be taken in the next quarter, using the large shock tube and rich mixtures. The rich mixtures should serve to yield more information on the reflected shock pattern.

Figures 5 and 6 are also of a 24% mixture but the reactions are spark-ignited. In this case the spark plug was approximately 4 feet from the test section. Seemingly, the pattern is quite different from those of the shock-initiated detonations; further, the time delary settings for these pictures indicate a substantially higher velocity. Considering both discrepancies, there is a possibility that detonation was initiated rather late and that the Chapman-Jouguet type of detonation had not been established as yet. The work of Moradian and Gordon[1] indicates that at the onset of detonation there is commonly a surge to excess Chapman-Jouguet velocity with a gradual diminution to the more stable state, probably as a result of frictional effects.

Figures 7 and 8 are of a 15% propane-oxygen detonation, where it was found necessary to use a hydrogen driver in the reservoir to establish the detonation. Figure 8 differs from Figure 7 only in that it is taken further behind the wave. The "secondary" reaction is highly interesting but difficult to explain. Two possible explanations are offered: first, that the hydrogen piston is reacting, and second, that the initial combustion product formed reacts again. The former seems unlikely in that the piston should not be this close to the front itself. Also, propane-oxygen mixtures are known to be "stage" reactors.

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[1] A. J. Moradian and W. E. Gordon, J. Chem. Phys. 19, 1166 (1951).

It is interesting to note the inclined shocks generated by this "secondary" reaction and also the cyclic behavior. If this combustion zone is considered to be a wedge, the shock angle indicates a Mach number of approximately 3.5. At this rate it would soon overtake the front.

During the past quarter the large shock tube, 2-1/4 by 3-1/4-inches was put in operation. Detonation in this tube is effected by a turbojet spark plug. A schematic drawing of this tube is shown in Fig. 9 with the critical dimensions. As indicated, the visible portion of the test section is 3 1/4 by 8 inches although the smaller schlieren mirror restricts the field to 3 1/4 by 5 1/4 inches.

Figure 10 represents a lean (24%) hydrogen-oxygen detonation in this tube taken well behind the initial wave. It can be seen that the reaction was still confined to the center portion of the tube. It is believed that this effect accounted for the ionization probe not tripping the spark gap at the appropriate time, so that all photographs of this mixture were "late", that is, well behind the initial shock front. For this reason, richer mixtures were utilized and the above difficulty overcome. All the photographs with the larger tube are actual-size. The light rectangular pattern on a few of these pictures is due to a light leakage which has since been eliminated.

Figures 11 and 12 are also of a 24% mixture. In the latter there has obviously been a reaction and the only explanation for the shock front seems to be that it has been reflected from the closed end of the tube.

Figures 13 and 14 are of a 60% hydrogen-oxygen detonation and, except for the shock patterns, are similar to the rich mixtures in the small tube. It is interesting to note that the shock to the left in Fig. 14 is inclined at 45°. Elsewhere in this report, where spinning detonation is discussed, it appears that quite commonly the tangential velocity of the so-called spin is just equal to the Chapman-Jouguet velocity. For this case the helix angle would be 45°. It is not intimated that the phenomenon in Fig. 14 is spinning, but the correspondence between the two cases mentioned may be more than coincidence and worthy of consideration.

BULLET EXPERIMENTS

During the last period the schlieren system of the shock tube was used with an Army Winchester rifle in connection with other work.*

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*Appreciation is extended to Henry H. Hicks and Albert W. Stohrer for their participation in this phase of the work.

After completion of this work, the setup was used to detonate combustible mixtures with bullets. Very little modification of the equipment was required. The shock tube was removed and the rifle rigidly mounted at one end of the stand. The time delay was changed to operate on a break circuit, made by the bullet intercepting a webbing of fine wire strung across its path. This webbing was approximately 1 foot from the center of the schlieren system, and adjustment of the time delay made it possible to photograph the bullet at different positions.

For the detonation experiment 40 to 50% acytelene-oxygen mixtures were used, as they had proved easiest to detonate in the shock tube experiments. Soap bubbles provided a simple means of isolating the mixture and providing the necessary transparency. Using soap solutions, bubbles of 4 to 5 inches in diameter were obtained regularly. Standard 150-grain 30-caliber shells having a muzzle velocity of approximately 2900 feet per second were used. The bullets were filed flat on the end in order to obtain more normal shocks.

Included in this report are a series of photographs of these studies. Figure 15 shows the bullet inside the bubble. The change in the shock angle across the boundary of the bubble due to the difference in density between the two media can be seen. In Fig. 16 the bullet is just leaving the bubble. Note the darkening at the left, suspected to be caused by a reflected shock from the boundary. Figures 17 and 18 show the bubble when the bullet is approximately 3 and 5 inches, respectively, out of the picture. The small shock patterns are believed to be caused by powder particles or small metallic pieces from the bullet. In Figs. 19 and 20 the bubbles were observed to have detonated, Fig. 19 showing the bullet barely out of the picture. The dark zone and the small patches at the left may be early stages of combustion. Figure 20 shows the combustion after the detonation. It was found that the 30-caliber bullets gave only marginal results as to initiating detonation and the experiments were discontinued.

Several other pictures were taken and are included as a matter of interest to show the effect of shock waves on water droplets. In Fig. 21, a water droplet is suspended from a needle. The reflected wave can be seen clearly. In Fig. 22 a stream of water droplets was sprayed through the path of the bullet, which is passing over an irregular surface. From these pictures and others that were made, the shock waves apparently had little effect on the droplets. However, as in the case of the bubble, an appreciable time lag might be necessary for any change to be realized.

INVESTIGATION OF LIMITS OF DETONATION

The limits of detonation of various gaseous combustible mixtures were investigated by means of the shock tube experiment. The tube is made of 1/2-inch extra-strong steel pipe and has an internal diameter of 0.546 inch. The setup of the equipment was very similar to that described in a previous report on this subject by R. B. Morrison[2]. In a similar way, the detonation velocities were measured by an electronic time-interval measuring device also described in the above-mentioned report. The ionization probes located in the test section of the shock tube were always kept a distance of 2 feet apart.

With each gaseous mixture the detonation velocities of various mixture ratios were obtained, and graphs of the results were drawn as shown in Figs. 23 through 26. The rich detonation limit of a gaseous mixture was determined by the last mixture ratio at which a detonation velocity could be obtained. Similarly, the last mixture ratio on the lean side which yielded a detonation velocity was regarded as the lean detonation limit of that particular mixture.

Several runs were made with each mixture ratio. The detonation velocities were found to be fairly constant at any mixture ratio of each particular gas. Thus, the reproducibility factor was satisfactory.

Reservoir pressures of about 1350 psig were used in order to obtain a high pressure ratio between reservoir and test section. Near the limits hydrogen gas was used in the reservoir. This gas is a powerful driver due to the fact that the speed of sound in hydrogen is relatively high as compared to the speed of sound in the combustible gaseous mixture in the test section.[3]

The graphs indicate a continuous smooth curve for the lean and rich mixture limits of every gaseous mixture investigated, with the exception of the rich acetelyne-oxygen mixture. In this case, the detonation velocities were scattered as the mixture was gradually increased toward the rich limit. In the neighborhood of a mixture ratio of 85% acetylene there seems to be a tendency for the detonation velocities to increase.

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[2] Morrison, R. B., "A Shock Tube Investigation of Detonative Combustion," Engineering Research Institute, Univ. of Mich., January, 1952.

[3] Morrison, R. B., Loc. cit., p. 49.

A summary of the result of the detonation limit study is given below:

Gaseous Mixture	Lean Limit of Detonation	Rich Limit of Detonation	Reservoir Pressure, psig
H_2-O_2	15% H_2	87% H_2	1350
H_2-Air	20.5% H_2	47% H_2	1350
C_3H_8-O_2	4% C_3H_8	35% C_3H_8	1350
C_2H_2-O_2	4% C_2H_2	86% C_2H_2	1350

SPINNING DETONATION

Two photographs of a 24% hydrogen-oxygen detonation were shown in Progress Report No. 5 which revealed very similar shock patterns but that were apparently 180° out of phase. These two photographs are reproduced here as Figs. 27 and 28. There is a possibility that these could represent two phases of spinning detonation (realizing that the same effect could occur if the diaphragm burst differently in the two cases). Assuming that the two waves are entirely reproducible, it is found that one wave is approximately 0.85 inch ahead of the other. This would indicate a pitch of the spin of 1.7 inches.

Fay, in his paper on spinning detonation[4], treats the phenomenon as arising from the natural vibration of the gas particles behind the detonation wave. Using the theory of sound as an approximation, Fay then develops an equation for the frequency of this spin. For a rectangular tube this reduces to

$$\nu = \frac{a}{2}\left[\frac{n^2}{w^2} + \frac{m^2}{h^2}\right]^{1/2} , \qquad (1)$$

where ν = frequency at the wave front,
a = speed of sound in the burned gases,
w = width of the tube,
h = height of the tube,
n = an integer denoting the number of circumferential crests, and
m = an integer denoting the number of radial modes (points of zero radial velocity).

Equation 1 embodies the assumption that the vibrational motion is entirely transverse (i.e., radial excitation), which seems to be justified on the basis of experimental evidence.

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[4] J. A. Fay, J. Chem. Phys. 20, No. 6, 942-950 (June, 1952).

For the small rectangular shock tube where $w = 3/8$ inch and $h = 1/2$ inch, the above equation may be utilized to calculate the spin frequency by assuming different modes of oscillation (i.e. different values of n and m). For $n = 0$ and $m = 1$ the spin frequency is 34,800 cycles/second. If $n = 1$ and $m = 0$ the frequency becomes 46,400 cycles/second. By use of the relation

$$P = \frac{D}{\nu} \quad , \tag{2}$$

where P = pitch of the spin and
D = detonation velocity,
the pitch may be evaluated for these two cases as 1.86 inches and 1.4 inches respectively. This compares quite favorably with the 1.7 inches observed.

For a circular tube Fay derives an equation for the pitch-diameter ration:

$$P/d \cong \left[\pi \frac{\gamma_o + 1}{\gamma_o k_n}\right] \quad , \tag{3}$$

where d = diameter of tube,
γ_o = specific heat ratio of burned gases, and
k_n = a function which depends on the mode of oscillation.

For $\gamma_o = 1.2$ and $n = 1$ this ratio becomes 3.13, which, as Fay points out, is close to the value of 3 reported by Campbell and Woodhead[5]. It appears, then, that for the primary mode of oscillation the pitch-diameter ratio is approximately π or, more simply, that the pitch equals the perimeter. It is highly interesting to accept this as a generalization and apply it to tubes of arbitrary shape. For this comparison the results of Bone, Fraser, and Wheeler[6], as tabulated in Fay's paper, are presented below; they serve to show the agreement between observed pitch and the perimeter.

The values of n and m obtained by Fay were chosen such that his theory best substantiated the observed pitch. From the comparisons made it can be seen that the agreement is quite good for the primary modes of oscillation. In some cases the agreement is better than the theoretical solution. It is interesting to note that for Chapman-Jouguet detonation, where the pitch and perimeter agree, the tangential component of velocity is precisely the same as the Chapman-Jouguet detonation velocity and thus the helix angle is 45°.

If the above reasoning is applied to the 1/2 by 3/8-inch shock tube, the perimeter is 1.75 inches as compared with the observed pitch of 1.7 inches.

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[5] C. Campbell and D. W. Woodhead, J. Chem. Soc. 129, 3010 (1926); 130, 1572 (1927).

[6] Bone, Fraser, and Wheeler, Phil. Trans. Roy. Soc. (London) A 235, 29 (1936).

TABLE I

Tube Cross Section	Size, Cm	n	m	Measured pitch, cm	Fay's Calculated Value, cm	Perimeter cm
Square	1.2 x 1.2	0	1	4.10	4.33	4.8
Rectangle	0.98x 1.2	0	1	4.20	4.33	4.36
"	1.1 x 2.2	1	0	3.75	3.96	6.6
"	1.35x 2.2	0	1	7.28	7.94	7.1
"	2.4 x 3.0	2	2	3.23	3.37	10.8
Equilateral Triangle	1.7 (side)	1	0	5.08	4.60	5.1
"	2.3 (side)	1	0	6.7 - 8.0	6.21	6.9

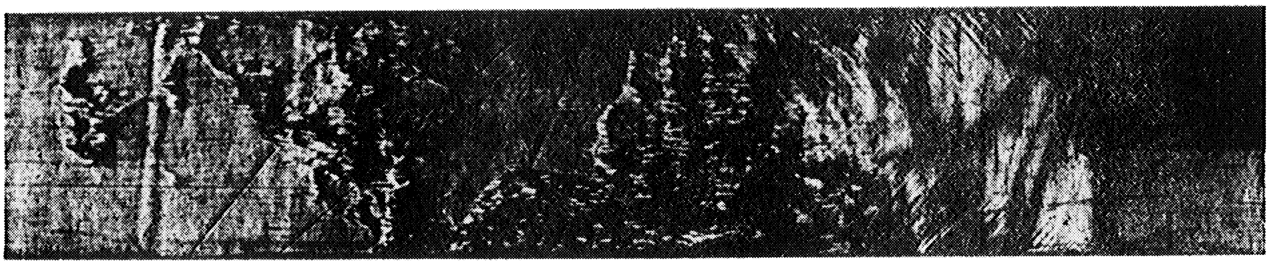


Figure 1

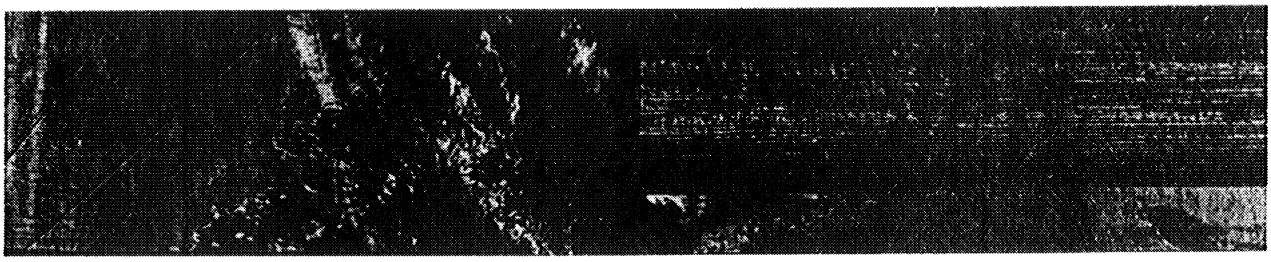


Figure 2

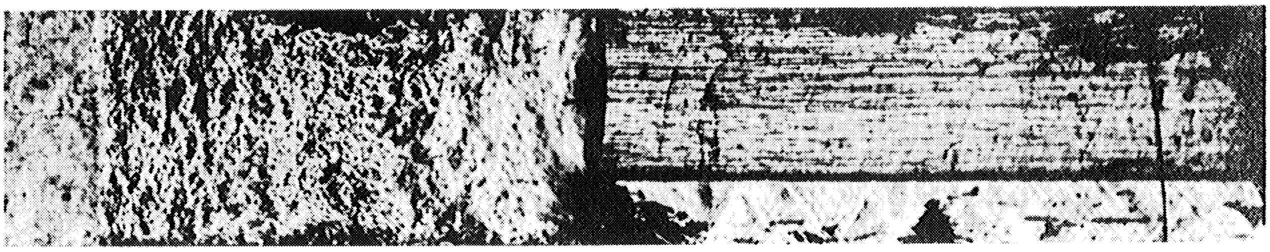


Figure 3

Figure 4

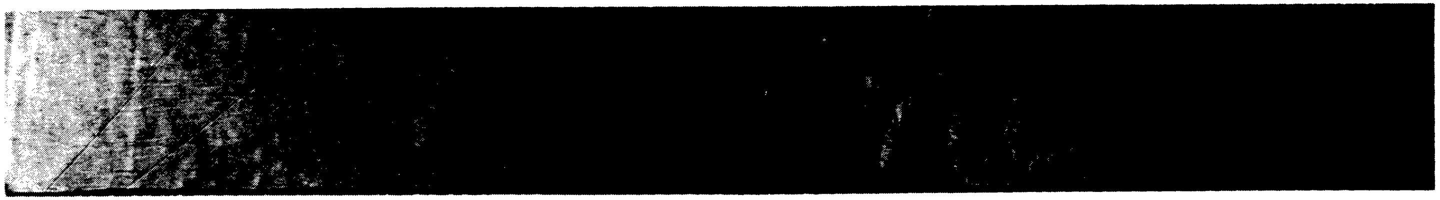


Figure 5

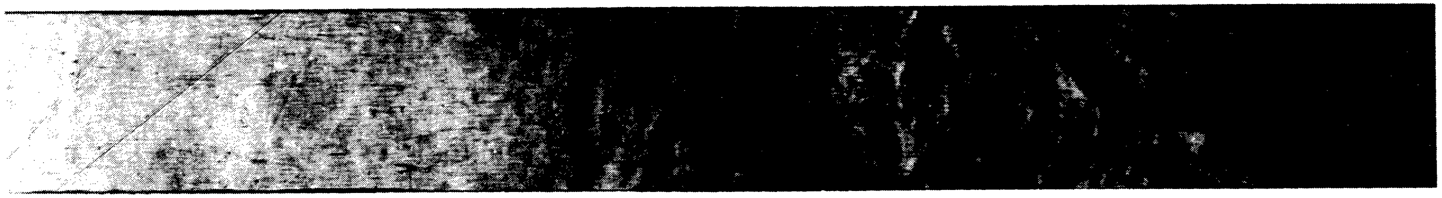


Figure 6

Figure 7

Figure 8

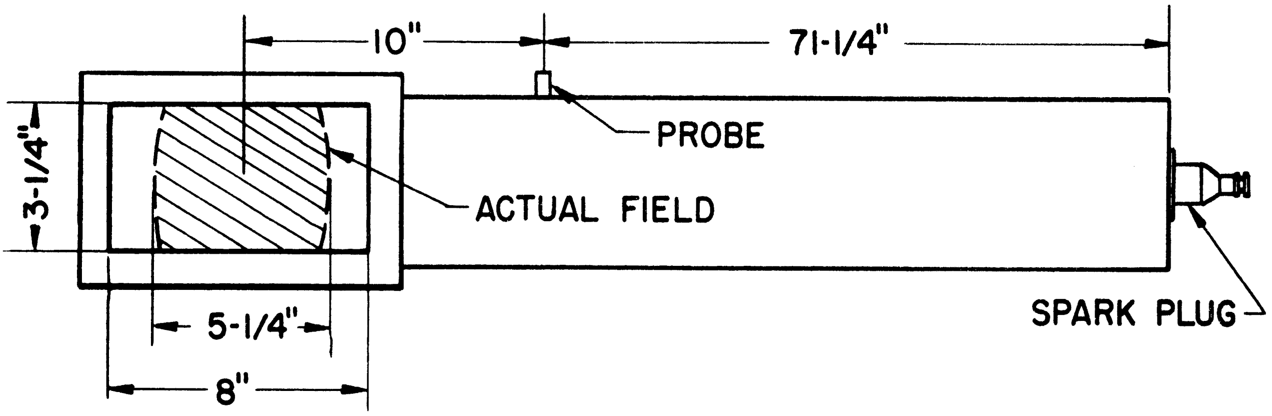


Figure 9
Schematic of Large Tube

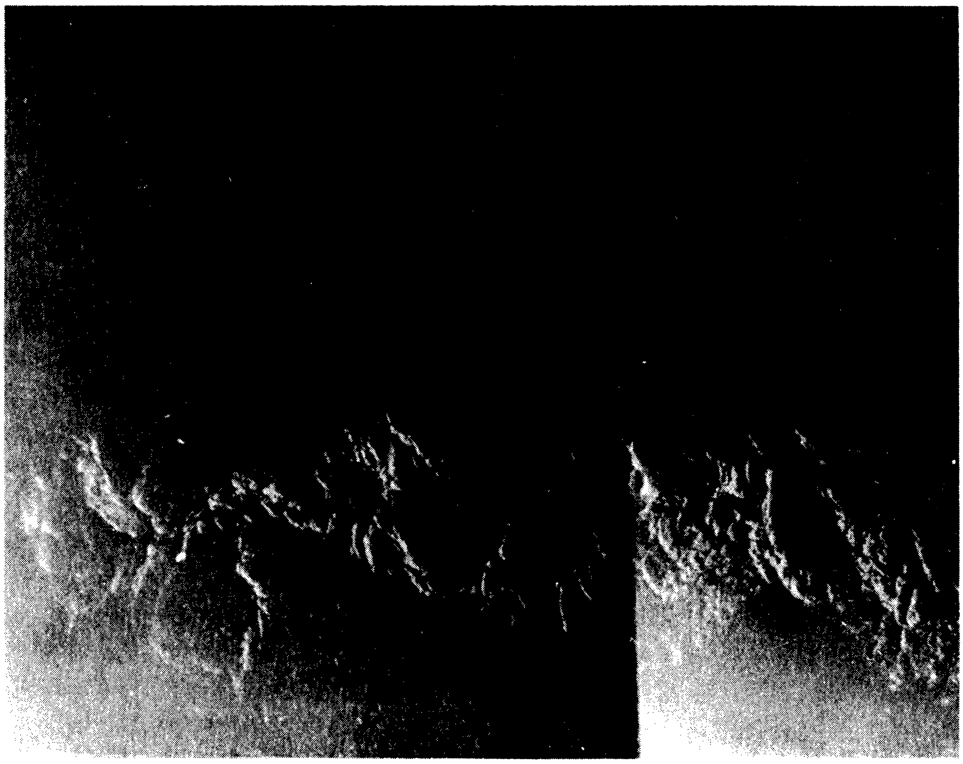


Figure 10

Figure 11

Figure 12

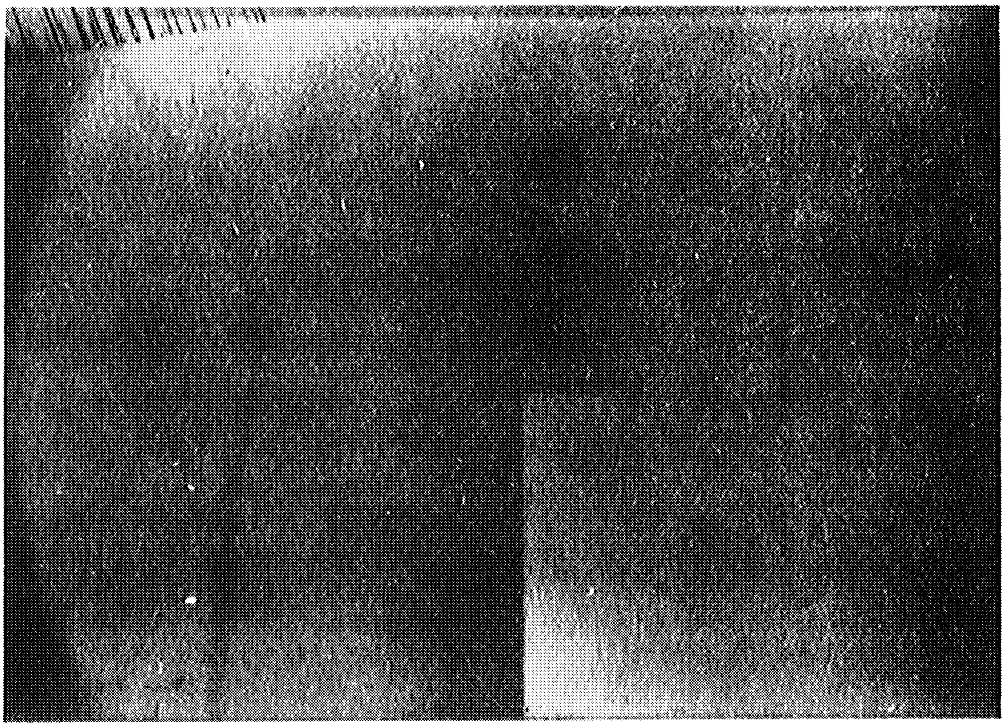


Figure 13

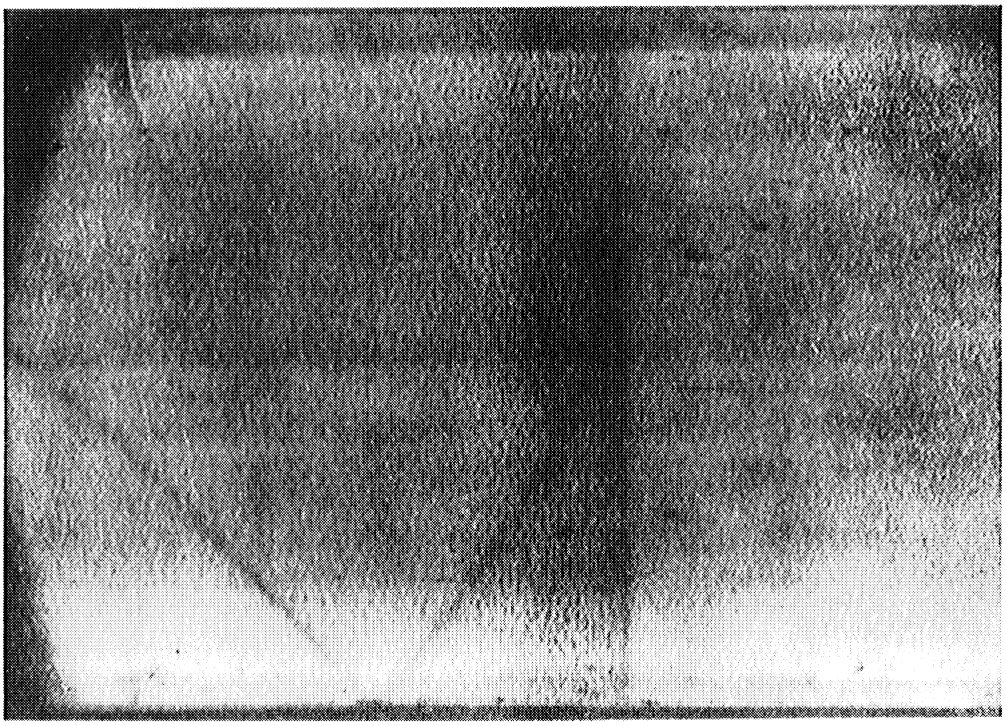


Figure 14

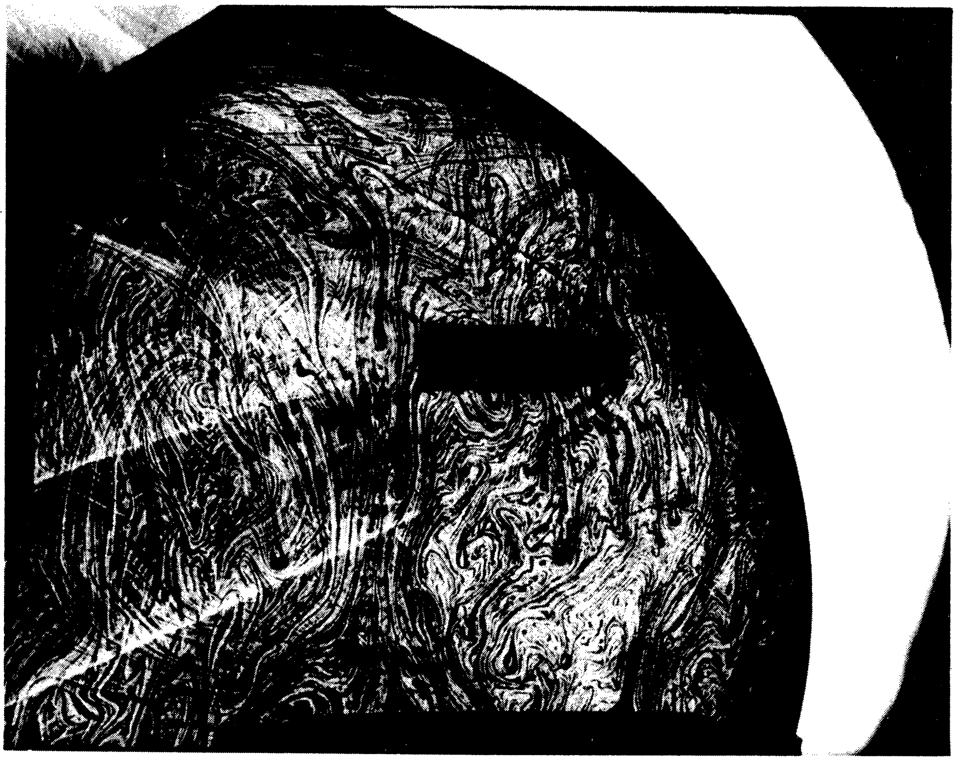


Figure 15

Figure 16

Figure 17

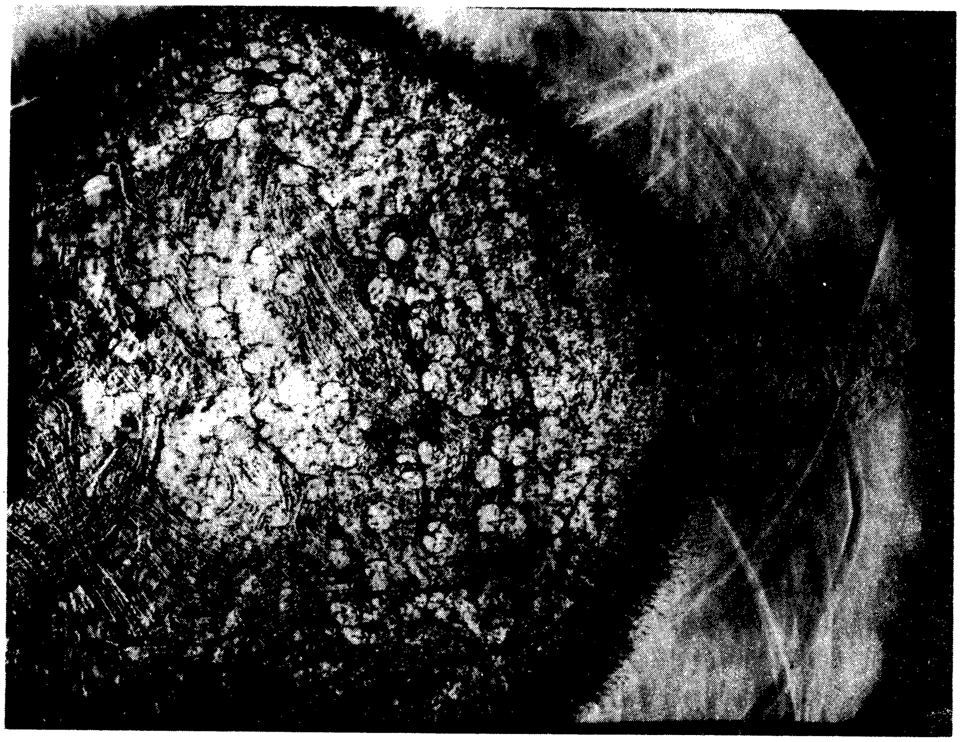


Figure 18

Figure 19

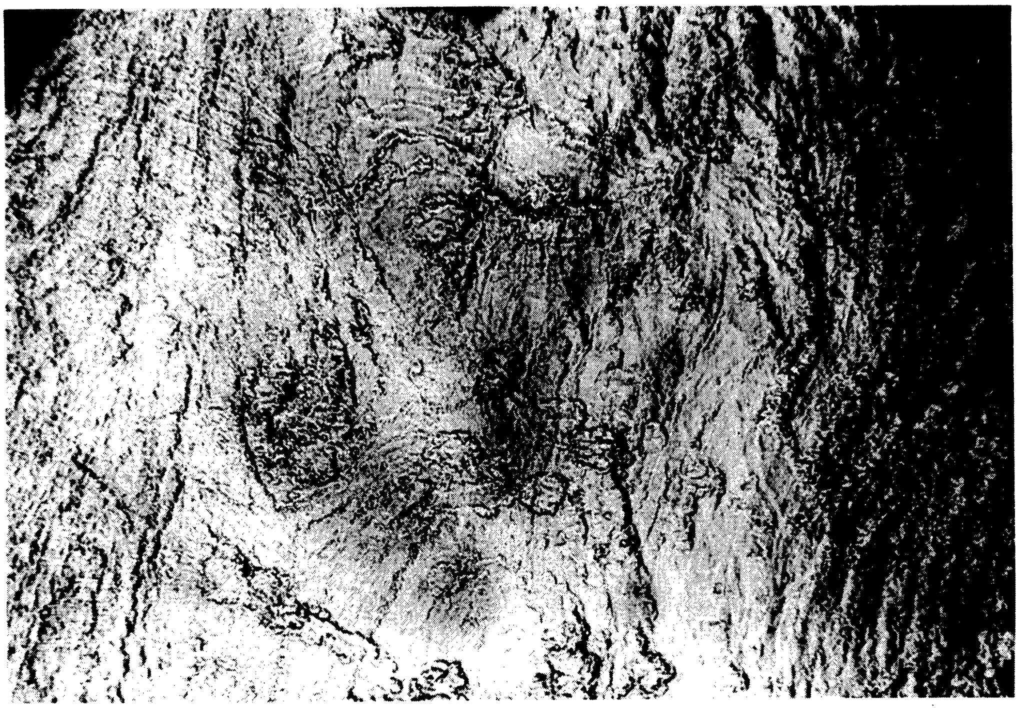


Figure 20

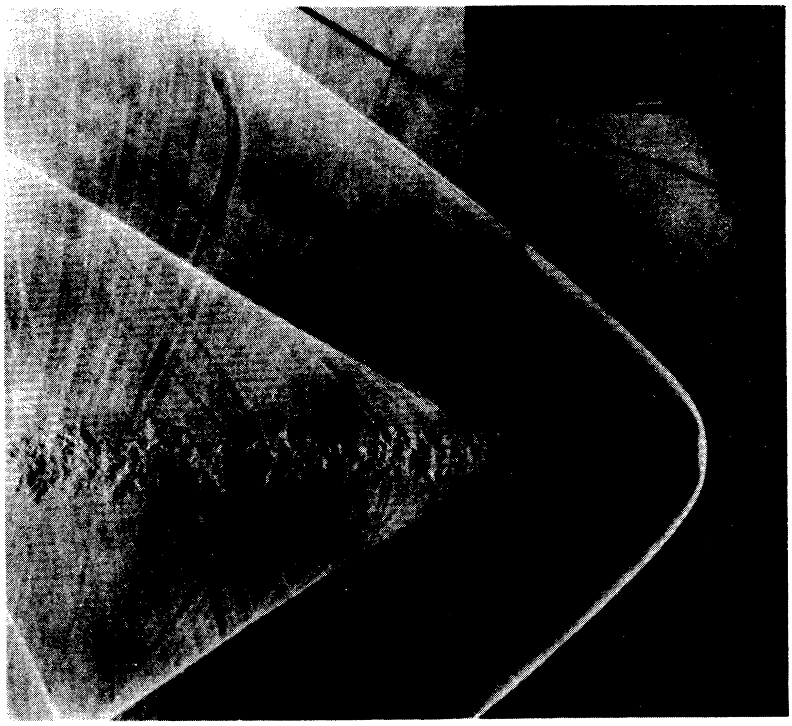


Figure 21

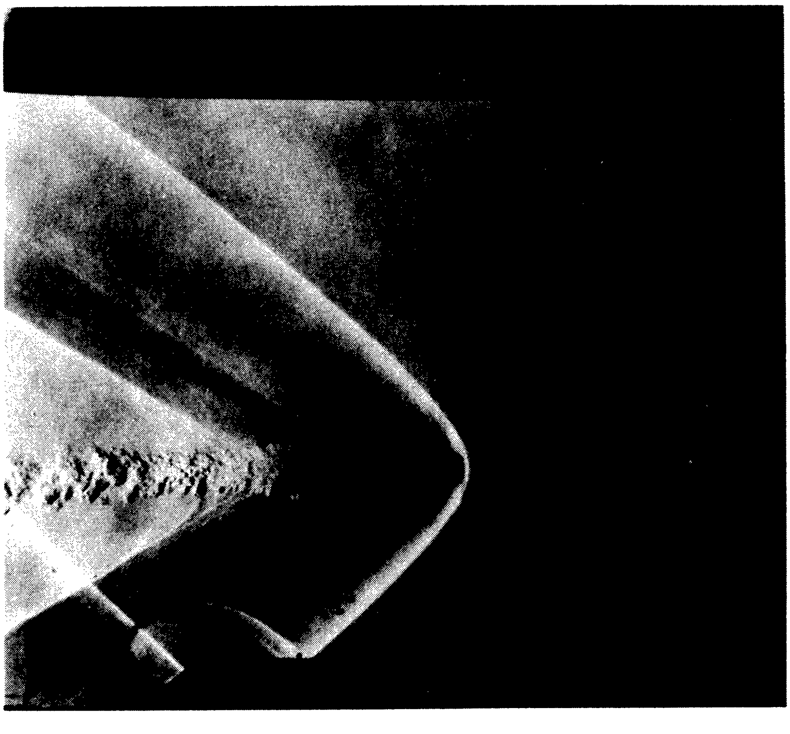
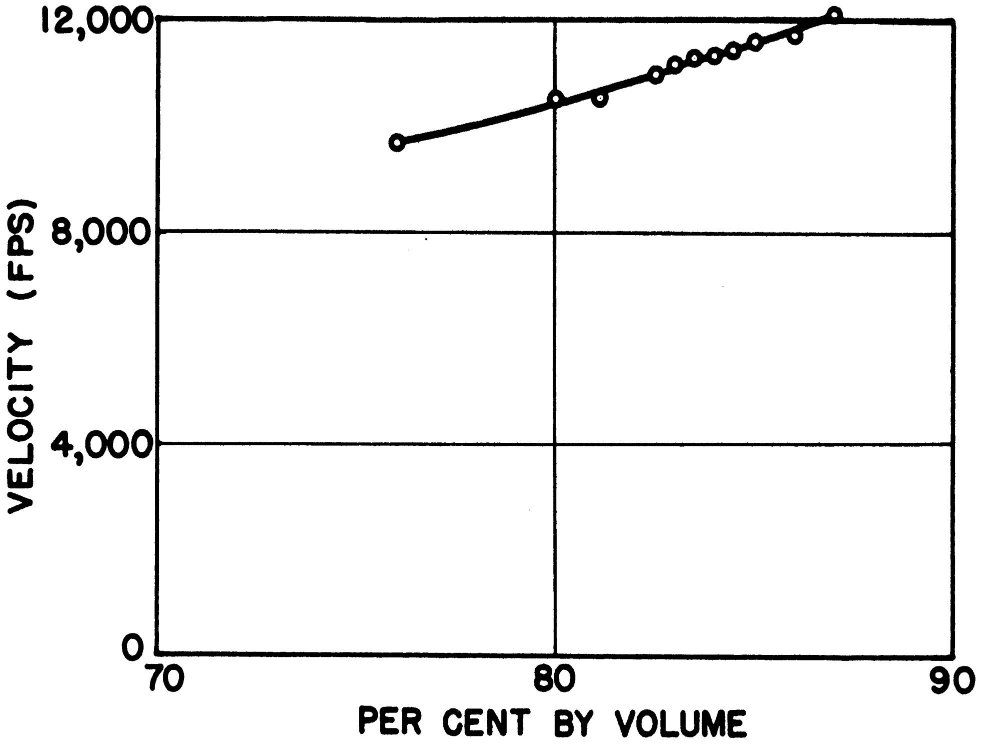


Figure 22



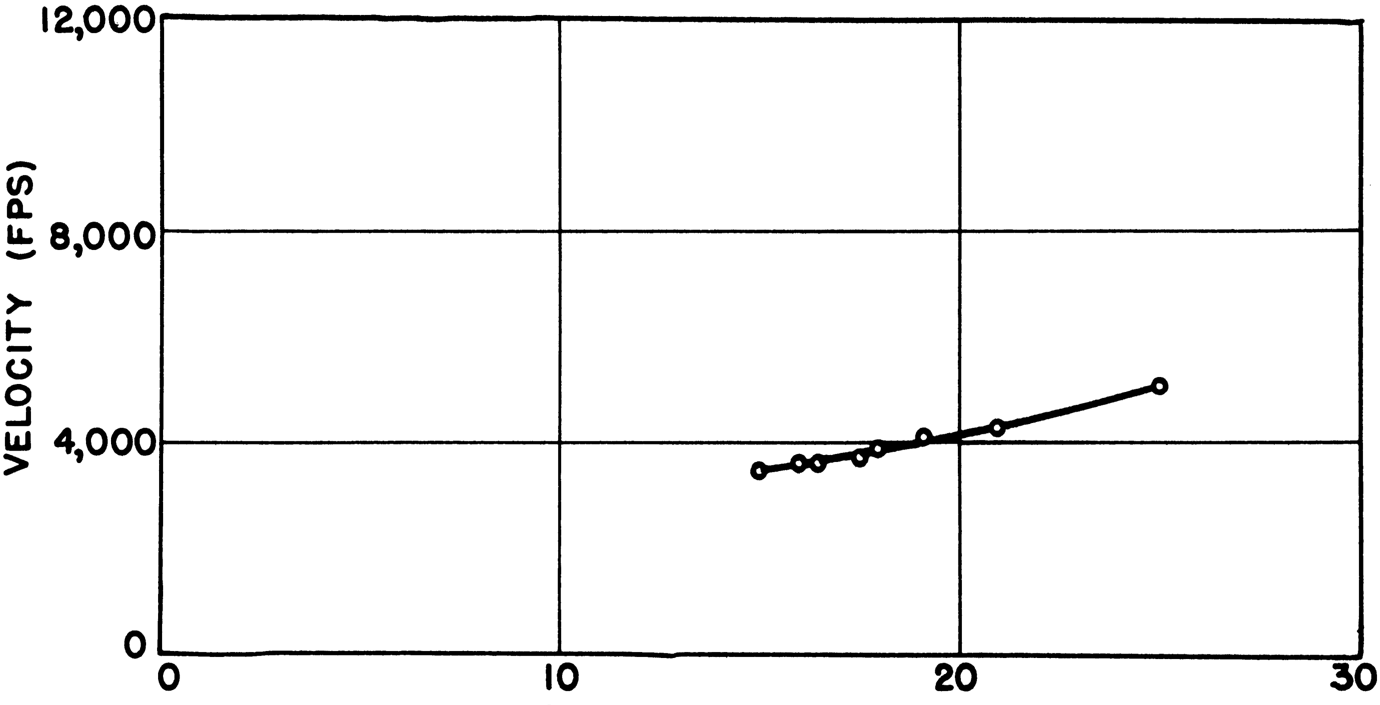


FIG. 23. HYDROGEN-OXYGEN DETONATION LIMITS

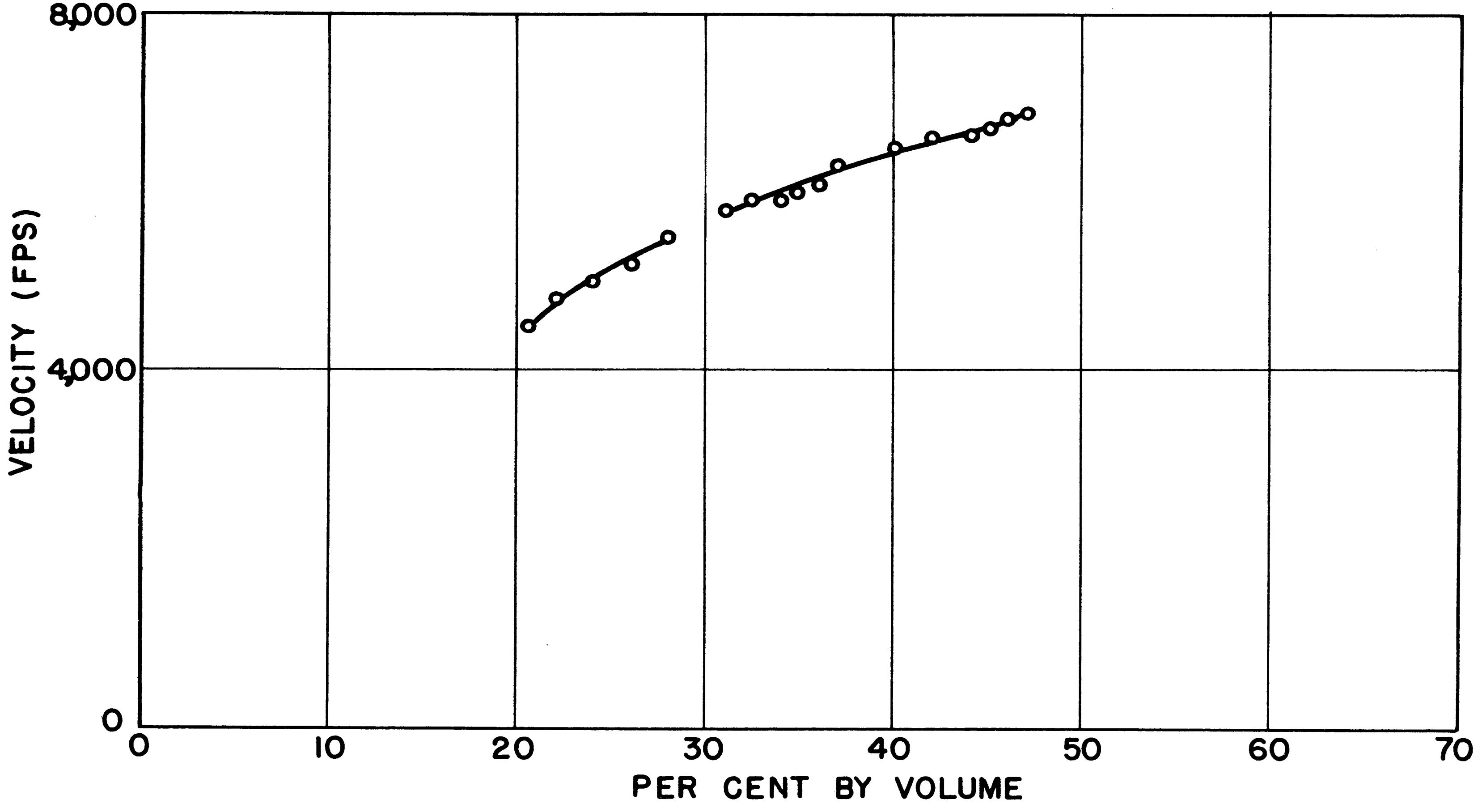


FIG. 24. HYDROGEN — AIR DETONATION LIMITS

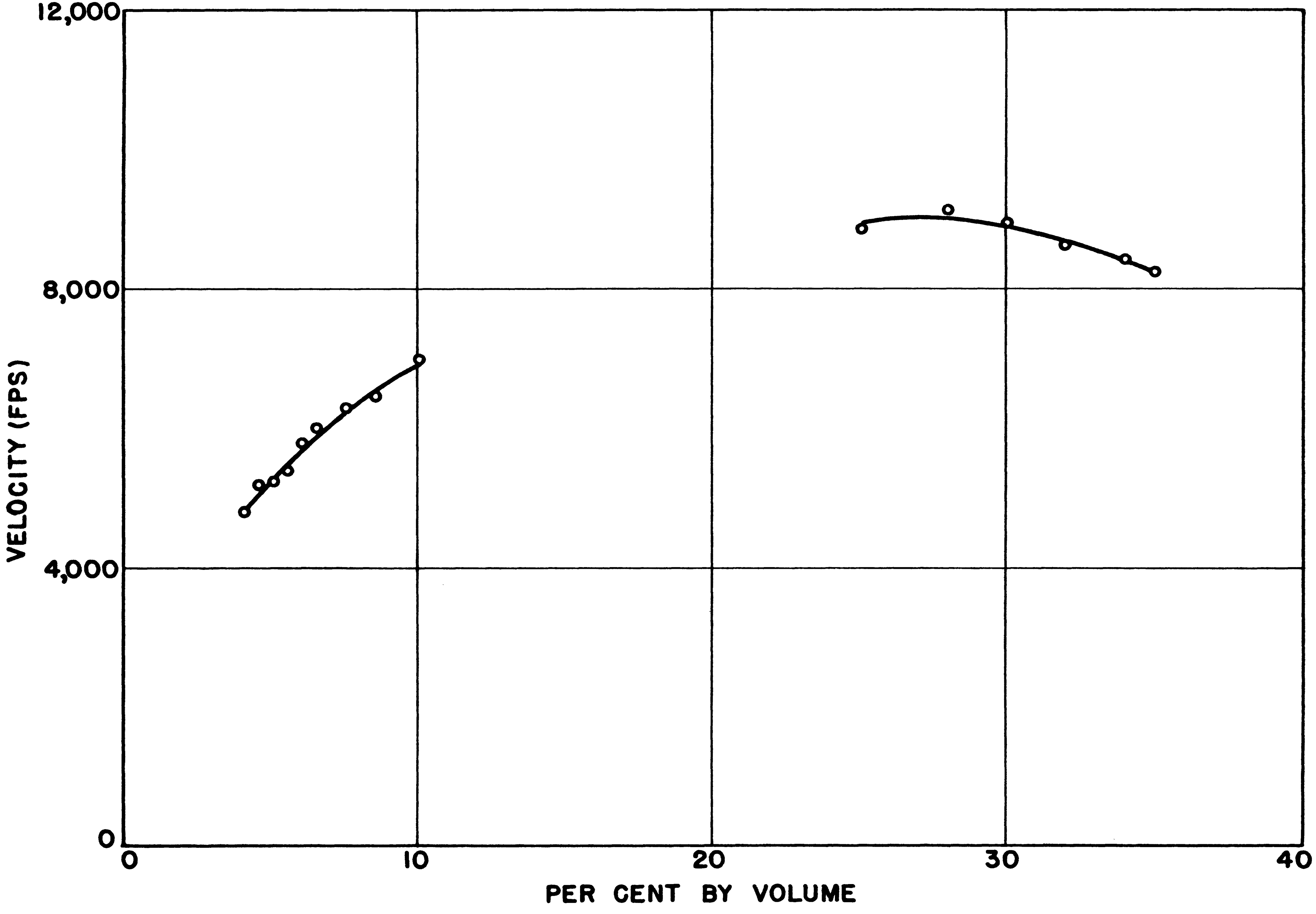


FIG. 25. PROPANE-OXYGEN DETONATION LIMITS

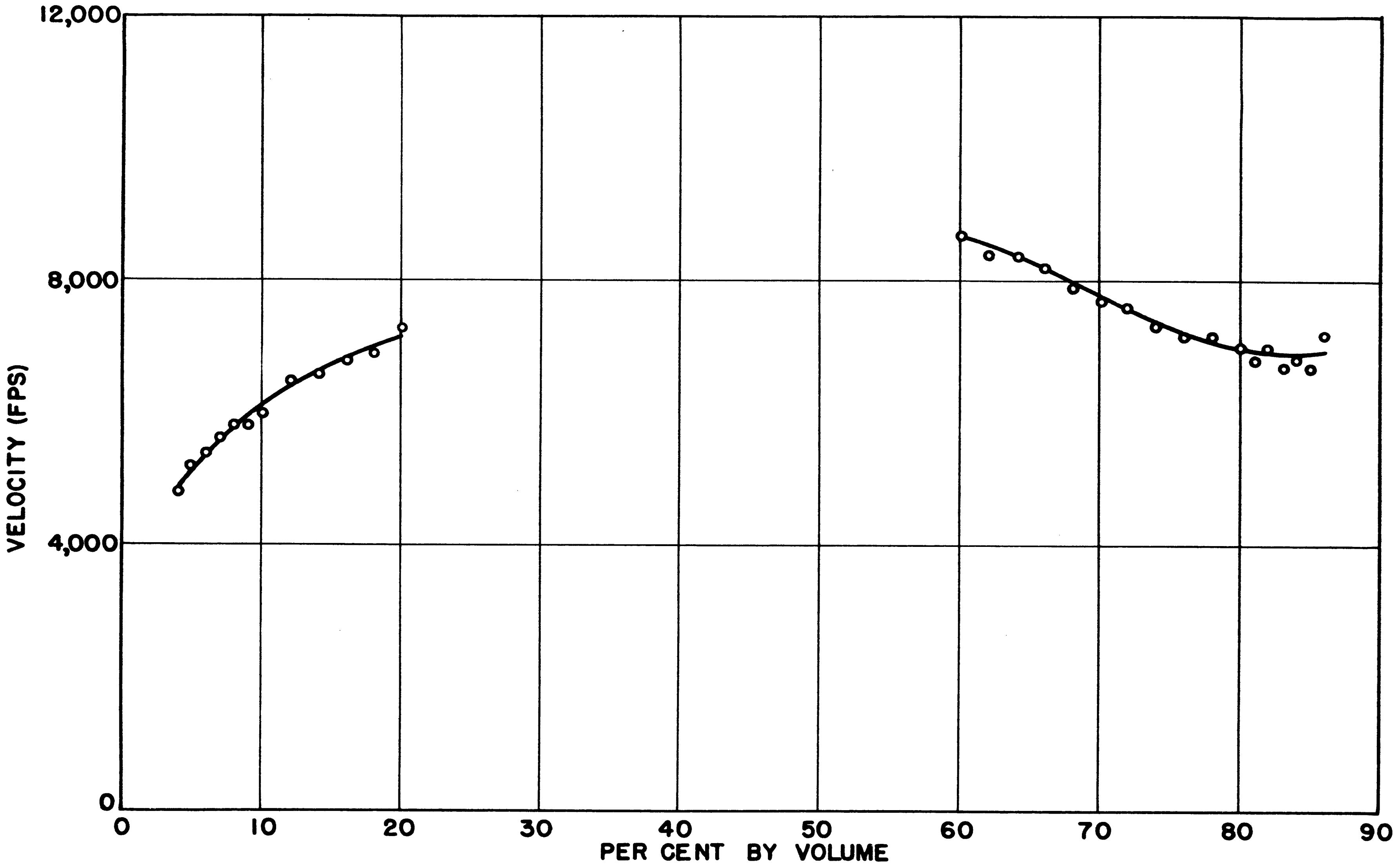


FIG. 26. ACETYLENE-OXYGEN DETONATION LIMITS

Figure 27

Figure 28