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UNITED STATES NAVY

PROJECT SQUID

TECHNICAL REPORT NO. 7

ATI-33146

A PRELIMINARY STUDY OF FLAMES IN TUBES CONTAINING GRIDS

DECEMBER, 1947

NEW YORK UNIVERSITY

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PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ori - 11 - TASK ORDER II

A PRELIMINARY STUDY OF FLAMES IN TUBES CONTAINING GRIDS

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NEW YORK 53, NEW YORK
DECEMBER 1947

SUMMARY

A preliminary experimental study of the propagation of flames in tubes with grids is reported. The grids are found to produce a flame of high velocity. The influence of grid design, tube length, and mixture composition on the shape of the flame front position--time curve of the high velocity flame is examined. These flames are believed to resemble those in a pulse jet, and it is thought that this information, particularly when used in connection with pressure, temperature, and stream velocity data yet to be obtained, will be useful in understanding the pulse jet.

Acknowledgements: We are indebted to Professor J.K.L. MacDonald for his active interest and participation in this investigation, as well as to other members of the Project Squid group at New York University. Mrs. Emmy Lou Miller interpreted the photographs and constructed the graphs.

INTRODUCTION

Experimental investigations of the combustion processes of premixed gases have indicated that for common fuel-air mixtures, normal combustion velocities generally lie in the range between several decimeters and several meters per second. (1) Normal combustion velocity is usually defined as the velocity of the movement of a flame front into the unburned mixture after all influences of flow have been removed. It is convenient to reserve the term flame velocity for the velocity of the flame front relative to the container. We shall use the terms according to these definitions.

It is generally agreed that the normal combustion velocity is determined by the joint effects of heat conduction and diffusion of active particles from the combustion zone into the fresh gas. The first treatment was given by Mallard and Le Chatelier from considerations of heat conduction alone (2). More recent authors have stressed the importance of diffusion (3,4,5,6). Given sufficient experimental data regarding thermal conductivity and diffusion coefficients, and a knowledge of the reaction kinetics of the system, together with the temperature dependences of the three quantities, it is expected that a complete solution of the problem of normal combustion velocities in static or laminar flow can be obtained.

For a complete picture of combustion processes, however, at least two additional factors must be considered. In the first place flame propagation can scarcely occur without the attendant phenomenon of flow. In some simple cases the normal combustion velocity is easily separable from the hydrodynamic flow of the burning gases, as for example in a bunsen burner flame or in the constant pressure soap bubble bomb (7). Other cases, such as combustion in tubes, are not so simple. The complexity of the problem in these cases suggests that the approach toward an understanding of the phenomena lies in the direction of an aero-thermodynamic analysis, omitting for the time being details of kinetics and substituting general terms such as rate of release of energy and normal combustion velocity.

The second additional factor which must be taken into account is the turbulence of the reacting gases. It was recognized some years ago that turbulence or swirling movements of the gases accelerates combustion (8,9). Flame velocities in Otto-cycle engines, for example, are greater by factors of 10 to 100 than normal combustion velocities (10). As pointed out by Damkohler (11) it has not yet been shown whether these high flame velocities are simulated by flow velocities which are greater than combustion velocities, or whether actually higher combustion velocities are involved, the cause of which is in turbulent diffusion.

For pulse jet engines, high speed movies of moving flames in the jet tube indicate that the flame front moves with an effective flame velocity of 200 or more feet per second relative to the stream, which itself has an average velocity of the order of 200 feet per second. It was suggested by J.K.L. MacDonald (12) that the high flame velocities might be attributable to a multiple jet structure which the sharp-edged intake valves may impose on the pulsing flow in pulse jet motors. In an attempt to simulate in the laboratory the turbulent flow produced by the sharp-edged intake ports in pulse jets, grids were placed in four-inch diameter pyrex tubes four to eight feet long and closed at one end. Attempts were made to pull the grid through the initially quiescent mixture in the flame tube but, because of inertia of the grid, the grid velocity never really approximated the desired 200 feet per second. However, it was observed that stationary grids placed in the path of the flame propagating from the closed end of the tube to the open end produce a sudden and marked acceleration in the motion of the flame relative to the tube.

Inasmuch as it is believed probable that the high flame velocities in the pulse jet and in the flame tube with grid may be due in large part to the same causes, it has been considered important to undertake a fairly comprehensive preliminary study of the behavior of this fast flame under a variety of experimental conditions. It seems unlikely that any large swirling motions of the gas of the type which might be expected in engine cylinders occur here. In that case the high flame velocities cannot be attributed merely to high flow velocities of gas masses, flow velocities greater than combustion velocities. Under conditions of fine grain turbulence in all probability enhanced diffusion of active particles and of heat suffice to explain observed increases in normal combustion velocity. However, for the more violent combustion which appears to take place in the pulse jet and in the tube with grid, it would seem that the increase in velocity is due either to somewhat coarser turbulence in which the velocity is governed by the mixing length $\underline{l}$ and the mean velocity fluctuation $|\bar{u}|$ (11), or to channeling of the burning gas by the grid into jet-like structures which propagate into the unburned gas with a high velocity (12).

The one-dimensionalized aero-thermodynamical theory of flame propagation by MacDonald (13) provides a convenient mathematical framework for experimental data. However, accurate experimental data are limited at present to curves for flame front position versus time, and the formulas presented are general enough to fit almost any such results. When pressure, stream velocity, and temperature data are obtained it should be possible to make a critical comparison of experiment and theory. In the meantime it is helpful to use the mathematical results in qualitative interpretation of experiments.

Experiments reported here may be divided into four groups. We first present data on flame velocities in tubes with and without grid, in order to show the marked effect produced by the grid. Second, it is of interest to know if a change in normal combustion velocity, such as would be produced by varying the percentage composition of the mixture or by substituting one hydrocarbon for another, affects the flame velocity in the tube with grid. Flame velocities have been measured for propane-air and for n-butane-air mixtures, and the percentage compositions have been varied in each case from the minimum to the maximum ignition limits. Third, the effects produced by varying grid design may give some hint as to the validity of the multiple-jet picture of the high flame speed. Several such experiments are described and a number of qualitative conclusions can be reached. Fourth, a series of experiments showing the effect on the fast flame of varying the tube length is reported. It is possible to make a few semi-quantitative comparisons of experiment with theory in this connection.

Other observations such as the duration of burning, the intensity of emitted light, and the effect produced by decreasing the diameter of the tube and by changing the attitude of the tube are briefly mentioned.

APPARATUS AND EXPERIMENTAL PROCEDURE

The flame tube employed in the investigation was a circular pyrex tube four inches in diameter. Tubes four, six, and eight feet in length were used. In general the tubes were mounted vertically, the bottom end being open, the top end closed and holding the igniter. This vertical arrangement was used in order to reduce unsymmetrical convective motions of the gas. Figure 1 is a diagram of the experimental arrangements.

Propane and n-butane were the two combustible gases employed. Both were c.p. grade, the butane being quoted by the manufacturer as 99% pure, the propane as 99.9% pure. In order to control the mixture ratio the inflammable gas was premixed with air in the appropriate ratio, then slowly introduced from the closed end so that air previously in the tube was displaced during the addition. The volume of gas which swept through the tube during each loading was at least three times the volume of the tube. Ambient temperature and pressure applied throughout. The compositions of the premixed gases were accurate to 4% at the lower concentration limit for ignitibility and 2% at the upper. However, since there was a certain amount of diffusion of air up the tube, and dilution of the mixture during loading, these percentages were probably not attained for the mixture in the tube.

Ignition was accomplished by means of a spark, the source of the spark being a high frequency coil. At various times ignition by a heated metal sheet at the top of the tube and also by a hot wire was used, and qualitative observation leads us to believe that little difference in flame behavior will be found for the three methods.

Grids were circular pieces of copper sheet of the same area as the cross-sectional area of the tube. Holes of various size and in various numbers were punched through the metal, and in most cases trailing edges were soldered around the orifices. Grids were mounted by means of holders which fitted the tube snugly and which were held in place magnetically or by means of a wire from the top of the tube.

The first six columns of Table I gave the pertinent characteristics of the grids used. Column two gives the type of trailing edge. The triangular trailing edge and nozzle types are shown in Plate I. The

Grid No.	Type of trailing edge	Length of trailing edges	Number of holes	Area of each hole	Distribution of holes	Overall velocity (a) Experiment performed in	
						July	November
1	none	screen grid wire diameter-0.011" 36 holes /cm^2	36 holes/cm^2	0.0276 cm^2	uniform	170	
2	nozzle	0.7 cm.	20	0.7 cm^2	uniform	520	360
2a	nozzle	0.7 cm.	15	0.7 cm^2	uniform		290
2b	nozzle	0.7 cm.	11	0.7 cm^2	uniform		320
2c	nozzle	0.7 cm.	1	0.7 cm^2	center		170
2d	nozzle	0.7 cm.	1	0.7 cm^2	edge		230
2e	none-tubes	tubes 0.7 cm. long	20	0.7 cm^2	uniform		200 270
3	triangular	0.7 cm.	11	0.5 cm^2	uniform	330	270 330 330 150
4	none-orifices	0	11	0.5 cm^2	uniform	530 620 400	330 150
5	triangular	0.4 cm.	16	0.5 cm^2	uniform		270 210 270

a) Eight-foot tube; 7.04% propane-air; grids five inches from igniter.

Table I - Design of grids, and overall velocities obtained with these grids.

important distinction between nozzle and triangular types is that the latter provides sharp trailing edges but not a true nozzle. Grid 2f is a grid 0.7 centimeters thick which has nozzles but no trailing edges. Grid 1 is a fly-screen grid, and has neither trailing edges nor nozzles. All other columns are self-explanatory with the possible exceptions of column six. This indicates the distribution of the holes over the area of the grid.

A General Radio high speed streak camera, type 651 A-E, with variable speed, was used to record the progress of the flame. The camera was modified so that a continuous strip of film about a foot in length could be used in place of reels. Timing was accomplished by reflecting light from a stroboscopic tachometer on to the film. Eastman Linagraph film was found to be the most acceptable, although it was frequently difficult to obtain images of a slow flame (one which has not passed through a grid) when the film was moving at high speed. Fast flames were readily photographed at high speed except near the minimum and maximum composition limits.

The entire phenomenon in the case of a fast flame occurs in about ten milliseconds. In the interests of convenience a continuous strip of one foot rather than a 25- or 50- foot reel was used for each experiment. In order to prevent overlapping of timing marks it was necessary that the shutter be open only for the time required for the strip to make one revolution. These facts, together with the requirement that the flame front traverse the length of the tube while the shutter is open, made a rather fine degree of synchronization necessary. Proper timing of camera speed, ignition, and shutter-tripping was facilitated by a system of electrical relays which were adjusted by trial and error.

In order to expedite interpretation, the photographs were enlarged and a rectangular coordinate system was superimposed on the print at the same time. Plate II is a streak photograph for a fast flame, that is, a flame which has passed through a grid. The image of the flame emerges from the grid at the lower left-hand corner of the photograph and proceeds to the open end in the upper right-hand corner. The timing marks are spaced at intervals of 0.00417 seconds. Plates III and IV are streak photographs for two typical slow flames. Timing marks for these two experiments are at intervals of 0.0167 seconds. The horizontal bands are produced by the presence of tube supports and are useful for establishing a length scale. The total length of the tube was eight feet in each case.

Measurements of flame front position were made from the enlarged photographs, converted to standard length and time scales, and then transposed to graph paper. Experimental accuracy insofar as measurements of time and length were concerned was estimated at ± 1%.

RESULTS AND DISCUSSION

The Effect Produced by a Grid

A 7.04% propane-air mixture was used for all experiments except for the series in which variation of composition was under investigation.

Figure 2 is a plot of distance of flame front from igniter versus time from first appearance of flame in the tube, for a series of experiments in tubes without grid. Such plots will hereafter be referred to as x-t curves. Two points should be noted in connection with this series. First, the flame velocity was found to be from 40 to 100 feet per second. This value of flame velocity is the same order of magnitude as that reported for flame velocity by Stevens in his soap bubble experiments (7). Our values are somewhat larger, but this is to be expected from the comparative geometries of the experiments. Second, the experiments are not reproducible. Flame oscillations are pronounced, in some cases being so great that the flame appears to reverse its direction.

When a grid is placed in the tube a sudden increase in velocity is observed after the flame passes through the grid. This is illustrated in Figure 3, which is the plot of flame propagation velocity versus time from ignition (v-t curve), for the case of an eight-foot tube with grid 2 placed two feet from the igniter. The flame passed through the grid at t=28 milliseconds. The velocity of the flame before it reaches the grid is seen to be from 20 to 60 feet per second, resembling the velocity of the experiments graphed in Figure 2. As the flame passes through the grid, however, it immediately accelerates to velocities greater by a factor of ten. At the end of the tube the velocity has reached 800 feet per second.

In contrast to observations of the tube without grid, when the grid is placed near the igniter (within five inches), results are quite reproducible under indentical experimental conditions except near the end of the tube, where a certain amount of spreading of experimental points occurs. This spreading may be due to experimental technique in loading, which possibly permits dilution of the mixture near the open end before the gas is fired. The degree of reproducibility of the data may be seen in Figure 4, which is an x-t plot for six experiments made under identical conditions: eight-foot tube, grid 2 placed five inches from the igniter. In this plot and in all other x-t curves for flames in tubes with grid, x=o is the position of the grid, and t=o is that time at which the flame appears below the grid.

While, as is evident from Figure 4, data is repeatable when all experiments are made within several days of each other, it has been found that experiments made at intervals of a month or more do not necessarily give identical results. For example, Figure 5 shows two curves for the eight foot tube with grid 2. One curve, from data taken in July, is the curve of Figure 4. The other is from data taken in November.

Two uncontrolled variables come to mind as possible explanations. The first is the ignition spark, since no great care was taken to maintain constant the energy of the spark or the gap distance. However, spark energy may affect ignition limits, but it would not be likely to affect the flame velocity. The second factor is the humidity of the air. Temperature varied about 14° C. in the laboratory from July to November. Temperature in itself we do not believe would noticeably affect the velocity. However, in July, on the days the experiments were performed the humidity averaged 2.5 mol percent; in November it was 0.24 mol percent.

It has been observed previously that the content of water vapor has a noticeable effect on the normal combustion velocity of $(2CO + O_2)$ mixtures (14), and it is not unlikely that some similar effects exist for hydrocarbon combustion also. It is probable that the increased velocity in the case of CO combustion is due to the formation of H-atoms and OH-radicals (5). While it is to be expected that the effect of water vapor on hydrocarbon combustion will be less pronounced, since H-atoms are already available from the hydrocarbon, this explanation serves at least as a plausible hypothesis. It would, of course, be interesting to check this hypothesis under carefully controlled conditions.

For this reason it is important that any comparisons of velocities should be made between experiments performed at approximately the same period, and all such comparisons made in this paper follow this rule.

It will be noticed in Figure 4 that a curve extends from $x=0.25$ feet at $t=0$ to $x=0$ at $t=2.8$ milliseconds. This is due to the fact that the flame does not become bright enough to produce a photographic image until the flame front has progressed to a distance of the order of 0.25 feet from the grid. The flame then appears to burn in both directions (toward the open end of the tube and also backward to the grid) at almost the same velocities. This characteristic, although not specifically indicated in each curve hereafter, was observed in every case.

If the behavior of the flame below the grid is dependent on the detailed history of the flame and flow above the grid, it might be expected that the x-t curves of flames which have passed through the grid would not be reproducible when it is placed several feet from the igniter. The erratic behavior of slow flames suggests this. This proves to be the case, as may be seen in Figures 6 and 7, which show two x-t curves each for experiments in which the grid was placed two and four feet, respectively, from the igniter. When the grid distance is small there is apparently less time for the flame to develop individual characteristics during passage from igniter to grid, and then the flames are essentially reproducible.

It is pertinent at this point to discuss possible reasons for the erratic behavior of the slow flame. In a gas in violent turbulent motion, in which cross-sectional variations in motion are rapidly averaged, small random increases in flow may be expected statistically to have no perceptible effect on the motion of the flame front. However, in a gas moving with essentially laminar flow, sporadic development of eddies, due perhaps to unsymmetrical ignition, wall effects, or flows developed by the mixture settling out through the end, are not immediately averaged out. They may in fact become major factors in determining the apparent motion of the flame front. For this reason it is not surprising that the highly turbulent flames are reproducible, while the slow flames are not.

A few qualitative statements may be made with regard to visible radiation and duration of burning. For a given mixture roughly the same intensities of visible radiation are observed per unit volume of gas for the slow and fast flames. This estimate was made in the following way. At the high camera speeds used to photograph the fast flames it is difficult to obtain an exposure with the slow flame. However, the speed of rotation of the drum carrying the film can be adjusted so that the same length of film is exposed in each experiment regardless of its duration. When this is done exposures of approximately the same density are obtained.

Judging from the photographs, the duration of burning for any cross-sectional layer of gas is from 8 to 12 milliseconds in the case of the fast flame; for the slow flame the duration of burning is of the same order of magnitude, though somewhat greater, appearing to be about 30 milliseconds. However, the difference in geometrical structure of the two flames makes such comparisons questionable.

A few photographs of the flame with the tube in a horizontal rather than vertical attitude indicated that orientation of the tube has little influence on the shape of the x-t curves for flames in tubes with grids. This suggests that convection currents have little influence on the propagation of the fast flame.

Effect of Varying Mixture Ratio and Hydrocarbon Compound

It is known from the work of Smith (15), that the normal combustion velocity of propane-air mixtures varies with the composition of the gas. This velocity-concentration curve is shown in Figure 8. Concentration is given as percentage of the air theoretically required to burn the propane or butane completely. Similarly, what Bone and Townend (16) call the velocity of the "initial uniform movement" shows a dependence on concentration for both propane-air and butane-air mixtures. While this velocity of initial uniform movement is not the normal combustion velocity, the data, which are quoted from Payman (17) are of value as indications of relative normal combustion velocities. They are therefore plotted in Figure 8 also.

Since normal combustion velocity is a function of mixture composition, it is of interest to know if the velocity of fast flames in tubes with grids can also be correlated with mixture composition (and hence with normal combustion velocities).

A series of experiments were conducted, therefore, in which the mixture ratio was varied from minimum to maximum ignition limits for propane-air and n-butane--air mixtures. In the following discussion and in Table II, concentrations are given in terms of volume per-cent. of hydrocarbon.

A few remarks on ignition limits may be appropriate before the results on velocity are discussed. The characteristics of fast turbulent flames are of course not involved, since ignition takes place in a quiescent mixture. However it is of interest to compare our limits with those obtained by other workers.

For propane mixtures, the lower limit of ignition was found to be at 3.0%. At 8.7% the visible radiation emitted by the flame was relatively faint and it was difficult to obtain a photographic image. Also, for such rich mixtures the burning failed to be reproducible, exhibiting alternately a fast flame accompanied by a loud blast, and a somewhat slower flame with less noise. Ignition was erratic at greater concentrations. It was possible infrequently to obtain ignition in a 10.2% mixture. These values may be compared with those of Jones (18), who gives 2.37% and 9.50% as lower and upper limits, respectively.

Butane exhibited similar characteristics. At 2.4% and below no ignition occurred. At 2.9% ignition took place in the normal manner. Explosions were normal until at 6.4 they seemed, as judged by sound, not to be reproducible. In addition, 6.4% the intensity of emitted radiation was generally low so that photographs could not be obtained above this concentration. Above 7.5% ignition occurred sometimes, but in general only a glow around the spark could be seen. Jones gives as the ignition limits for n-butane--air mixtures 1.86% and 8.41%. Table II compares ignition data of this paper with that of Jones.

	Propane		N-Butane	
	this paper	Jones	this paper	Jones
no ignition at	< 3.0%	---	< 2.4%	---
minimum ignition limit	3.0%	2.37%	2.4%	1.86%
maximum concentration for reproducible ignition (maximum limit for Jones)	8.7%	(9.50%)	7.5%	(8.41%)
highest concentration ignitible	10.2%	---	---	---

Table II - Concentration ignition limits for propane-air and n-butane--air mixtures. Concentrations are expressed in volume per cent.

It will be noticed that the minimum limits for both propane and butane, as given by Jones, are in the direction of lower concentration when compared with this work. This is not true of the maximum limit for butane and is not necessarily true for propane. The upper limits were very uncertain for both compounds. In particular, for propane no repeatable ignition occurred above 8.7%. No effort was made to control the energy of the spark, and it may be that that is the cause of the lack of correlation with Jones' figures. It could conceivably account for the consistent narrowing of the ignition limits.

On the other hand it must be borne in mind that the technique of loading the tube may have diluted the mixtures so that our actual compositions were more dilute than the figures given. Other evidence which may support this idea will be brought forward in a later paragraph. It should be pointed out that for exact data on flame velocities as a function of concentrations a gas-tight flame tube must be used so that the tube can be evacuated and then filled with a gas of precisely known composition. However, the data presented here serve at the least to indicate if fast flame velocities are a function of concentration, and what the form of the dependence is.

Figure 9 shows x-t curves for flames in propane-air mixtures of various compositions, and Figure 10 shows similar curves for butane. In all experiments the eight-foot tube with grid 2 at five inches was used.

Oscillations in the x-t curves make it difficult to assign meaningful numerical values of velocities for purposes of comparison. However, in order to allow some comparison one can consider the average slope over the relatively straight portion of the curve from 1 to 4 feet on the abscissa, or alternatively the average velocity over the entire length of the tube. Either method gives the same general shape of the curve for velocity vs. concentration, the latter method giving somewhat higher higher values. Velocities given here are computed by the first method.

This method gives an average velocity of the flame before any pressure waves reflected from the open end have appreciably affected the x-t curve. In other words it gives a velocity independent of the length of the tube. (See section on the effect of varying tube length.) Furthermore this method avoids errors due to the spreading of the data near the end of the tube.

The data show that there is a correlation between concentration and velocity. Figure 11 is a plot, for propane and butane, of velocity calculated as described above, versus concentration of hydrocarbon, again expressed as percentage of theoretical air. Propane mixtures yield higher velocities except near the stoichiometric composition. However, no significance can be attached to this fact inasmuch as data for butane was obtained several weeks after the propane experiments were carried out, during a period when the humidity was lower. We have just seen that one cannot legitimately compare absolute values for velocity experiments made at different times unless humidity and possibly other factors are controlled. Propane shows a maximum velocity at about 60%, butane at 70%. The curves by Payman (Bone and Townend) for normal combustion in Figure 8, show a maximum for both propane and butane at 81%. Smith's curve for propane shows the maximum at 87%.

It is possible that the shift of the maxima for the fast flames in the direction of greater concentration of hydrocarbon is caused by the dilution during loading, as was suggested above. The shifts in the points of maximum velocity and in the points of minimum concentration of ignition can all be accounted for by assuming approximately the same amount of dilution.

Bearing these possibilities in mind it seems that normal combustion velocity and the fast flame speed exhibit a fairly well marked correlation. In order to check the correlation more carefully, measurements of normal flame speed of butane and propane should be made, and the measurements of fast flame velocity should be made with very carefully controlled concentration.

The question now arises as to why the fast flame velocity should show a correlation with normal combustion velocity. Speculating along the lines of the multiple jet picture, the flame velocity will be the sum of the normal combustion velocity plus the velocity of the small jets. Furthermore, the velocity of the jets themselves may be expected to be a function of the velocity of normal combustion in the volume between igniter and grid. (See also section on effect of grid design.) The form of this function is not too clear at present, but something like a simple proportionality might be expected, in which case there would be close correlation.

Effect of Length of Tube

Streak photographs were made of flames under standard conditions (grid 2 placed at five inches from the igniter, 7.04% propane-air), with various values for the tube length. Figure 12 shows x-t curves for flames in four-, six-, and eight-foot tubes. The eight-foot curve shows a minor hump at 1 to 3 milliseconds and there is a suggestion that the same hump may also be present in the six- and four-foot curves. The four-foot curve shows a possible small inflection at 5 milliseconds. The six-foot curve has an inflection at 5.5 milliseconds and a second at 8 milliseconds. The eight-foot curve has an inflection at 6 milliseconds and a second at 10.5 milliseconds. These inflections are more apparent in the v-t curves shown in Figures 13, 14, and 15. However, since the v-t curves were constructed by differentiating x-t curves, Figures 13, 14, and 15 are not as reliable as Figure 12, and they must be regarded as at best good approximations of the true velocity-time relationships.

The aero-thermodynamic theory referred to in preceding sections (13) provides an analytical solution for equations of conservation of mass, momentum, and energy, subject to initial and boundary conditions appropriate for the gases in the flame tube. A relatively simple form of solution is obtained on the basis of the following assumptions being applicable to the highly turbulent flame propagation: (1) one-dimensionalized equations may be used, (2) open end boundary conditions correspond to the pressure being one atmosphere at a fixed value of the Lagrangian coordinates, (3) the effect of the slow flame between the igniter and the grid in establishing a flow beyond the grid may be represented by a boundary condition specifying the velocity history of that layer of gas which passes through the grid when the fast flame starts to propagate. This boundary condition is to be found by means of a comparison of theoretical and experimental results, (4) the burning of any layer in the fast flame may be represented by a certain combustion function r of $t-t''-(a/f)$, where t is the time since the original ignition, t'' the t interval until the fast flame starts, a the original distance of the layer concerned from a point of reference, and f the intrinsic Lagrangian flame speec (assumed constant) which is a somewhat mathematical quantity related to the effective flame speed relative to the one-dimensionalized stream. The function r is zero before the layer starts to burn, then increases in the same manner for each layer (in a form to be determined by comparisons of theoretical and experimental results). The effective duration of burning t' is taken to be the same for each layer and, after combustion of the layer has been completed, the function r is constant.

On the basis of the above assumptions the expression for the flame velocity in terms of time takes the form of a sum of two types of terms, one type due to the wave pulses generated by the piston-like action of the slow flame between the igniter and the grid, and the other due to the wave pulses generated by the combustion in the fast flames. The original direct pulses contribute to the flow in the direction of the open end, as do their first reflections from the open end. On the other hand their first reflections from the grid (or the closed end) tend to retard the outflow, as do also the pulses that arise at the tail end of the flame band due to cessation of burning.

It is evident that the shapes of the curves for flame front position or velocity versus time will be governed by relative values of the time intervals t'', t', and the time taken for a wave to travel back and forth along the tube. The first terms that arise are due to the direct pulses from the slow and the fast flames. The next terms will come from the slow flame pulses reflected from the open end of the tube provided that $2kL > t''$, where L is the length of the tube and $(1/k)$ is the sound speed corresponding to the initial state of the gas. If, however, $t'' > 2kL$, the effects due to reflection from the grid appear.

Thus the length of the tube can play a part early in the propagation of the fast flames. It appears from the flame pictures that for the lengths of tubes used, t'' is approximately equal to kL, and also that effects which could be due to these early pulses from the slow flame are observable but small. For example, the minor hump at 1 to 3 milliseconds mentioned above may arise in this way. Unfortunately, accurate experimental values for t'' are not yet available.

If these relatively small effects are ignored, the curves should be independent of tube length until reflections of the pulses from the fast flames come back from the open end. Examination of x-t and v-t curves of Figures 12-15 shows that from 0 to 4 milliseconds the curves for the three tubes do resemble each other fairly closely, if small effects are ignored. When the reflections do appear at the flame front, the shape of the curve is dependent on whether the duration of burning t' is greater or less than $(1-kf)2kL/(1+kf)$. If less, then a retardation of the flame occurs first. This may explain the retardation at 5 to 6 milliseconds, particularly marked in the six- and eight-foot curves. Conversely, if $t' > (1-kf)2kL/(1+kf)$ an acceleration will occur before the retardation due to cessation of burning begins. Of course, both effects may occur at approximately the same time, in which case it is difficult to say which would be dominant. Subsequent reflections will also produce further accelerations and decelerations in a complicated sequence.

Effect of Varying Grid Design

Any conclusions as to the effect of grid design on the flame velocity are qualitative and tentative until more information about the flow structure has been obtained. These experiments were performed in order to obtain a general idea of the possible effects, and it is apparent from results that a more detailed study is required for a thorough understanding of the action of the grid.

For this series of experiments, we have chosen to calculate the flame velocity on the basis of the time taken for the flame to traverse the entire length of the tube. It will be remembered that the straightest portion of the curves was used for the velocity calculations for the mixture composition experiments. The over-all velocity is used here because the shapes of the curves to be compared do not resemble each other so closely as do those of Figures 9 and 10. This is illustrated in Figure 16 where x-t curves for selected grids are shown.

Many of the flames were so low in intensity that it was necessary to plot the curves directly from the photographic negatives, and this introduces some inaccuracy. Furthermore, the erratic behavior of the flames near the open end of the tube also undoubtedly causes some error in the values we quote. This spread in data near the end of the tube was mentioned in a discussion above on the reproducibility of data, and was found to be rather small when grid 2 was used. In this series of experiments it proved to be considerably greater. The curves for grids 2e, 4, and 5, in Figure 16 provide examples. As a result, if two values for velocity agree within 15% they must be considered to be essentially equal.

Columns eight and nine in Table I give over-all velocity values for the grids listed in that table. The standard conditions of eight-foot tube, 7.04% propane-air mixture, and five-inch position of the grid were used.

From examination of the data in Table I, the following statements may be made:

1) For the nozzle type of grid at least, the flame speed appears to decrease slightly as the number of nozzles is decreased. Even at the limit of a single nozzle, the resulting flame velocity is four to five times greater than that in tubes without grid.

2) In the case of a single-nozzle grid there appears to be a significant difference in velocity according to the position of the nozzle. A nozzle placed near the wall of the tube produces a faster flame than one placed in the center of the tube.

3) When the thick grid without sharp trailing edges was used, the flame velocity was decreased slightly. The two values quoted in row 2e of Table I represent five experiments, two of which gave 200 feet per second, three of which gave 270. The difference was due to a pronounced slowing down near the open end of the tube in the first case. This will be made clear by reference to Figure 16.

4) A fly-screen grid gives a markedly slower velocity than a multi-nozzle grid, although even in this case the velocity is greater than that in tubes without grid.

5) True, nozzles do not appear to be necessary to obtain high velocity flames. Grid holes with trailing edges of the triangular type, and thin grids with no trailing edges around the hole (orifice grids) give velocities approximating those of the nozzle grids. In particular, also, rows 3 and 4 of Table I show higher velocities for a grid with no trailing edges than for the same grid with triangular trailing edges (but see 6).

6) Grids with nozzles produce flames which show a rather high degree of reproducibility. When grids with short triangular trailing edges (row 5) or thin grids without trailing edges (row 4) are used, the flames are not at all reproducible.

An experiment not directly concerned with grid design, but having a bearing on interpretation, was performed. This experiment involved placing a glass plate along the longitudinal axis of the four-foot flame tube, so that the tube was divided into two equal channels, thereby effectively doubling the ordinary Reynolds number. The plate extended to within two inches of the grid (No.2), so that ignition immediately below the grid could occur in normal fashion. Streak photographs of a propagating flame in this tube showed that the x-t curve corresponded closely with the x-t curve for the four-foot tube shown in Figure 12. It was observed, however, that the flame lost its intensity and could scarcely be photographed during its passage down the last two feet of the tube.

This result allows us to draw one further conclusion:

7) Increasing the Reynolds number which would refer to ordinary turbulence produced by flow through a tube by a factor of approximately two causes no noticeable increase in velocity. Therefore it appears that turbulence of the type considered by Damkohler is at the most of secondary importance as a cause of the fast flame velocity.

No accurate measurements of pressure between the grid and the igniter have yet been made, but a rough estimate indicated a pressure of at least five pounds over atmospheric. This estimate was based on the observed acceleration of a grid which was blown out of a tube during one experiment. The grid had been held in place magnetically and the field was not strong enough to hold the grid. The pressure is, of course, a result of the combustion in the volume between igniter and grid.

Speculating along the lines of the multiple jet hypothesis, it is postulated that the pressure difference on the two sides of the grid causes high velocity jets of burning gas to penetrate into the unburned gas below the grid. These jets can be expected to persist, mainly because of the continuing reaction between the igniter and the grid, and will be slowed only by lateral expansion and mixing with the relatively stagnant gas through which the jets propagate. Aerodynamic effects due to combustion in the jets themselves are not easily determined, and require further theoretical and experimental study.

If there is only a small number of jets, so that a large body of stagnant gas lies between them, the jets will be considerably slowed by mixing with the adjacent slowly moving medium. If, on the other hand, there is a large number of jets, relatively close packed, it is expected that mixing and diffusion effects tending to slow them will be minimized, inasmuch as the proximity of other high velocity jets means that the medium in the layer between one jet and its neighbor will also have a fairly high velocity.

This view is supported by the experimental fact, which we have already noted, that the over-all flame velocity is somewhat decreased as the number of holes is decreased. In particular, if there is only one nozzle a considerably slower flame velocity is observed.

It was further noted above that a single nozzle near the wall of the tube causes a greater velocity than a nozzle in the center. At least two effects must be considered in this connection. In the first place, a small jet near the wall should be slowed to a lesser degree by mixing with the surrounding stagnant medium than a jet in the center, which is completely surrounded by stagnant gas. In the second place, viscosity effects, tending to slow the jet velocity, will be larger near the wall. These two effects act in opposite directions. Judging from the experimental result, the first is dominant, but since relative values of the two effects cannot be estimated confidently it is not worth while to speculate further at this time.

Propagation of the flame should proceed in all directions from the small jets, in a lateral as well as a downward direction. The apparent lateral velocity of the flame will be slower then that in the downward direction since the latter involves major contributions from the jet stream velocity. For this reason the apparent duration of burning at any plane of x might be expected to be greater for a single-nozzle grid than for a multi-nozzle grid. As a consequence the intensity of the emitted radiation would be expected to be less for a single-nozzle grid. This is borne out by the experimental fact that the flames become more and more difficult to photograph as the number of nozzles is decreased.

The thick grid (2e) produces a somewhat slower velocity than grid 2. This lends support to conclusions which might be drawn from steady flow considerations (but which will not necessarily apply in this case). Steady flow reasoning tells us that grid 2 with its sharp-edged nozzles can produce narrower jets, with consequent higher average velocity, than grid 2e with its nozzles with rounded edges.

The fly-screen grid produced a relatively slow flame. This is not surprising for two reasons. First, the ratio of blocking to open area is quite small, so that a high pressure due to combustion cannot be built up in the volume between igniter and grid. As a consequence, no small high velocity jets can be created. Second, the holes in the screen do not have sharp edges and this also precludes the formation of the jets. In fact, the screen probably acts principally as an isotropic turbulence maker. Since the flame velocity is greater than that in a tube without grid, it seems that the kind of turbulence created by the screen does increase the flame velocity to a certain extent. It is possible that the turbulence resembles that produced by Damkohler (11) (but see (7) above).

The last comments to be made are concerned with the nonrepeatable character of the flames produced by thin grids with no trailing edges or with short trailing edges of the triangular type. Such orifices are known to be particularly effective in producing smoke rings which peel off and move away from the orifice at intervals governed by rather poorly understood instabilities. The relative phasing of such peeling off of vortex rings from several orifices would be expected to be subject to chance fluctuations which might also affect the flows in the jets. Such fluctuations might therefore be reflected in the flame speeds measured in separate experiments.

CONCLUSION

A grid structure when placed in the path of a flame propagating down a tube is found to increase the flame velocity by a factor of ten to twenty. The grid design has been varied widely, and the velocity achieved appears to be dependent to a certain extent on the number of holes in the grid and the ratio of open to blocked area. Trailing edges are important in obtaining reproducibility.

The velocity is also dependent to a small extent on mixture composition, which indicates a correlation with normal combustion velocity.

The shape of the curve of position of flame front versus time is a function of the length of the tube after sufficient time has elapsed for pressure waves reflected at the open end of the tube to arrive at the flame front. This may be correlated in a qualitative manner with flame tube equations obtained by MacDonald.

It is felt that turbulence of the Reynolds type has little to do with producing the fast flame. No positive evidence is produced to support the self-propagating multiple jet theory of MacDonald, but no evidence has been obtained which would tend to refute these ideas.

It is desirable to obtain pressure, temperatures, and stream velocity data in order to make a comprehensive check of the aerothermodynamic flame tube theory. A schlieren investigation of flow processes in the tube may provide evidence regarding the method of flame propagation.

It is felt that information of this type will aid considerably in understanding the fundamentals of turbulent flame propagation and pulse jet operation.

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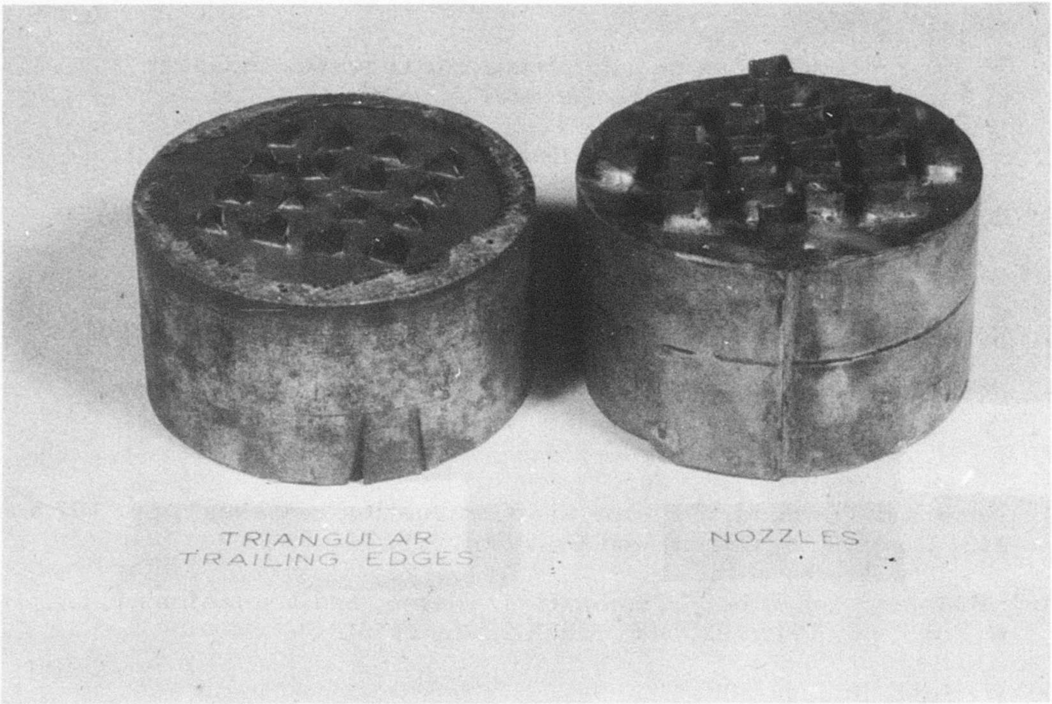


Plate I. Nozzle and triangular trailing edge types of grids.

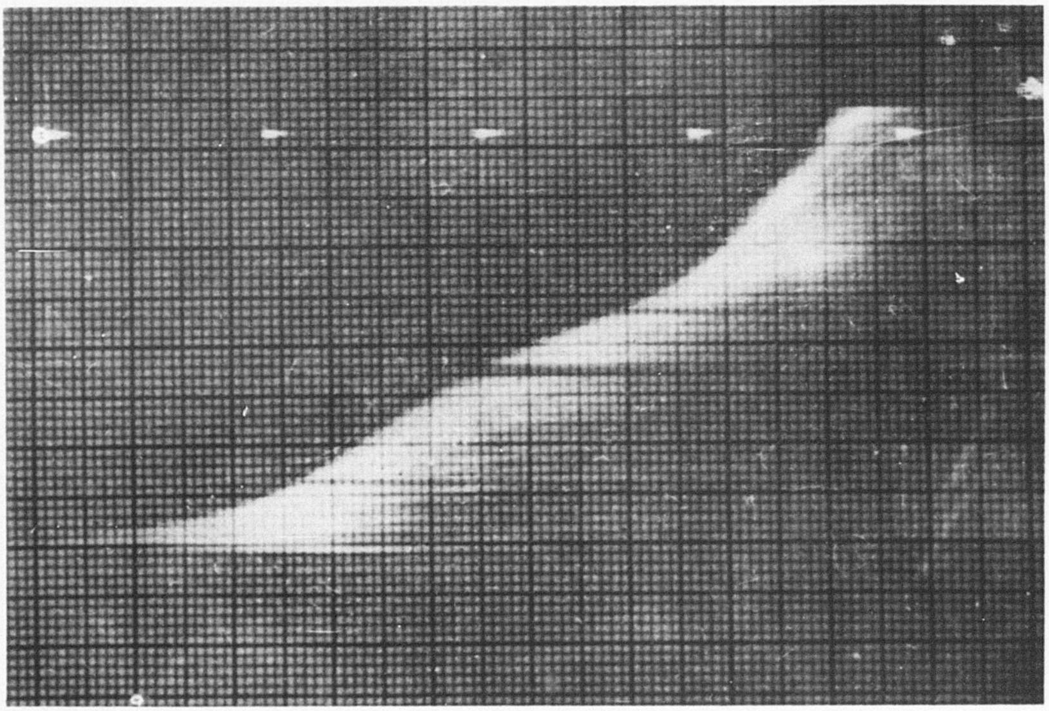
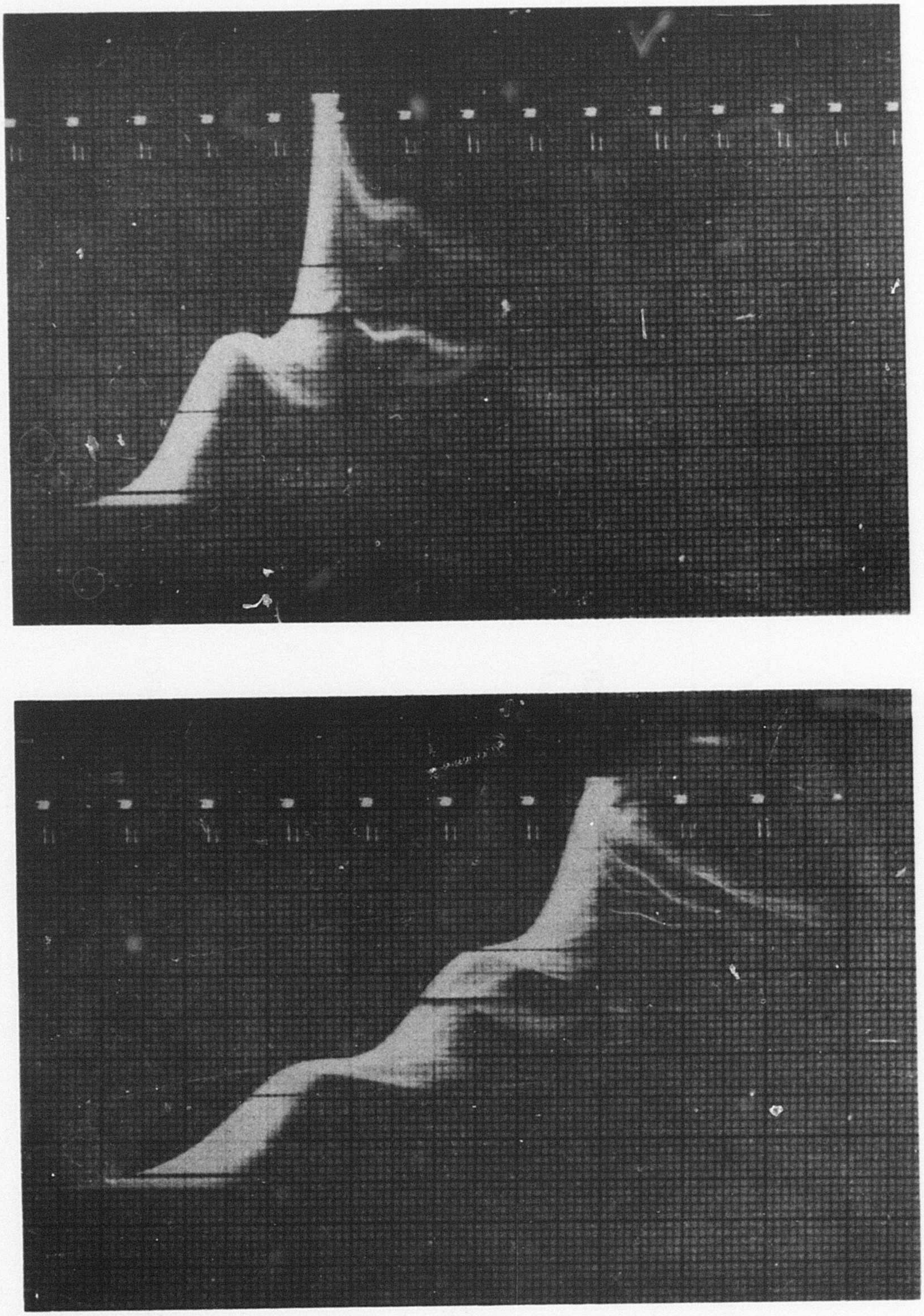


Plate II. Streak photograph of a fast flame.



Plates III and IV. Streak photographs of slow flames.

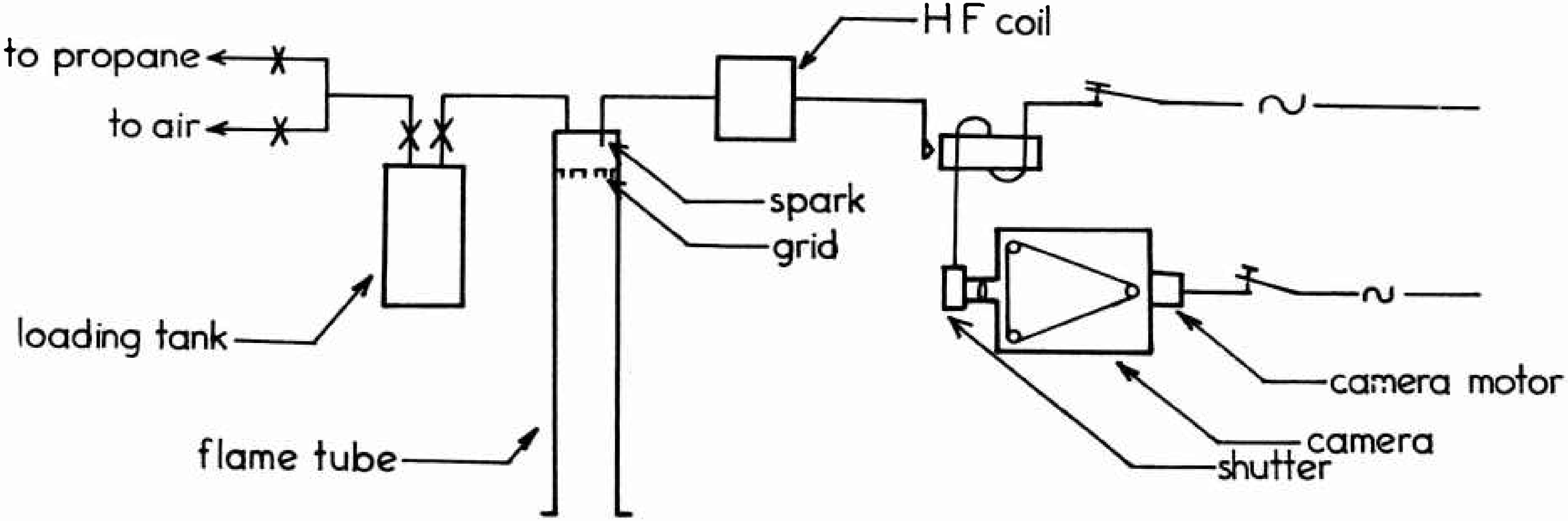


Figure 1. Diagram of experimental arrangement.

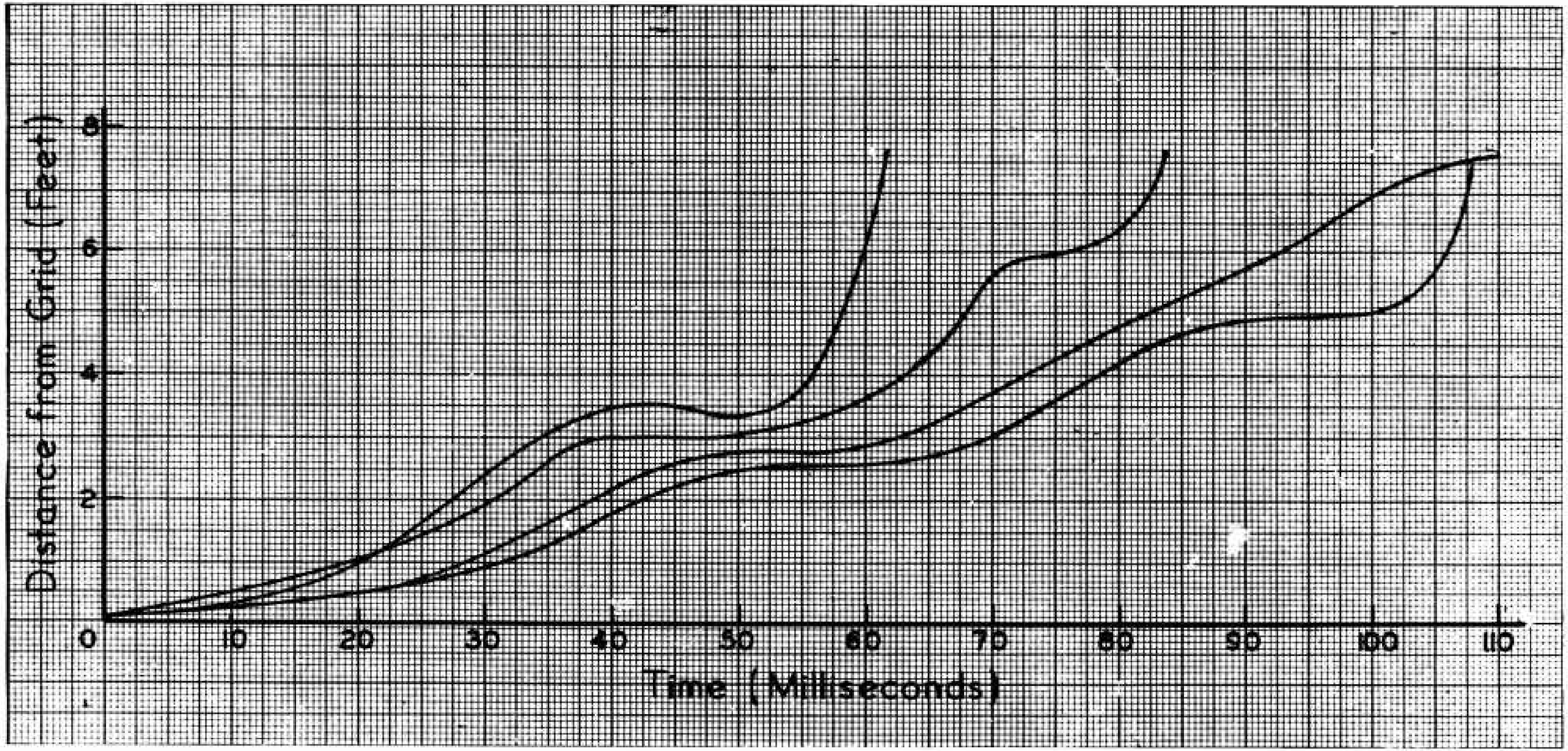


Figure 2. Position of flame front vs. time for slow flames.

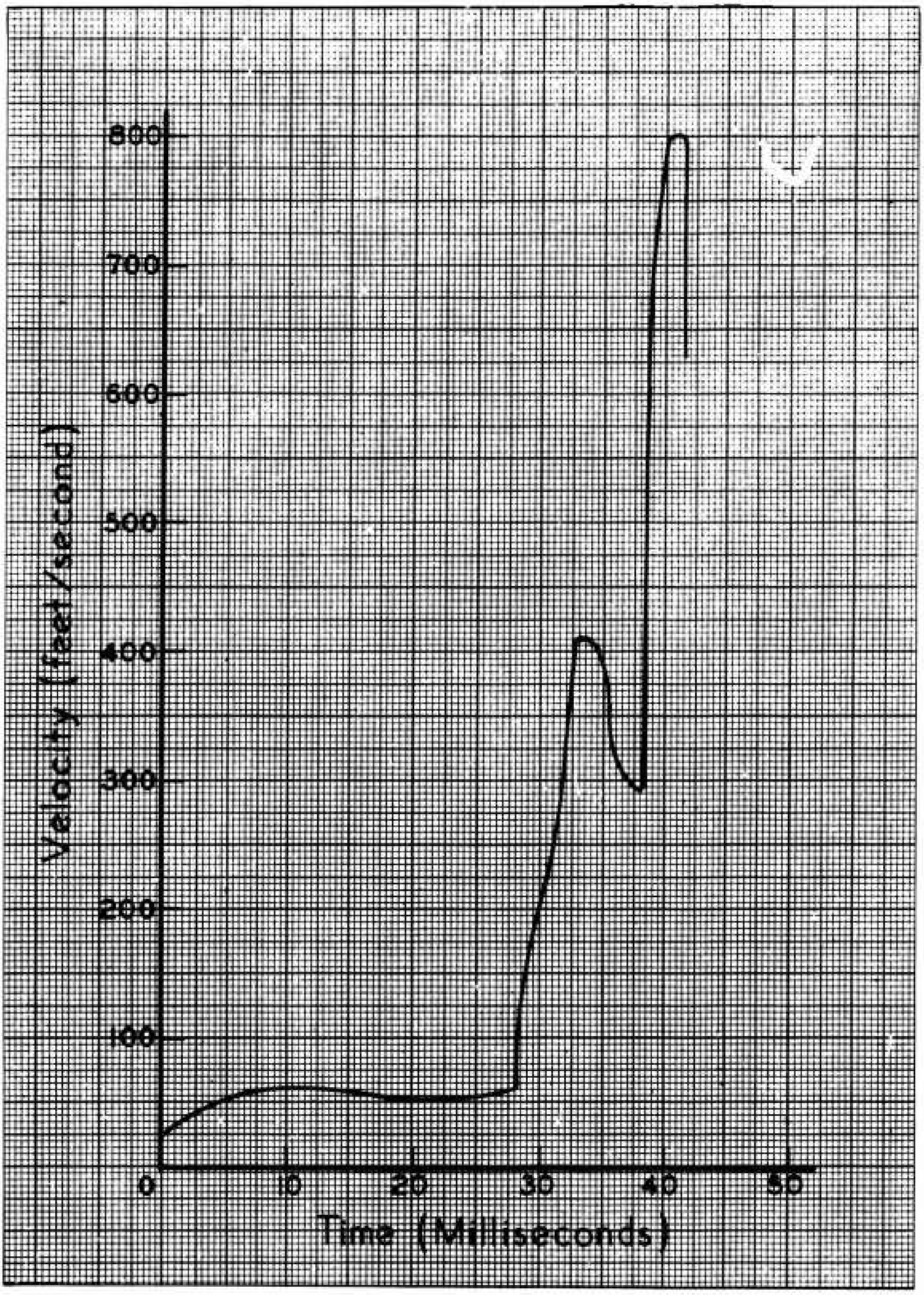


Figure 3. Velocity vs. time for eight-foot tube with the No. 2 grid at two feet. The flame passes through the grid at t=28 milliseconds.

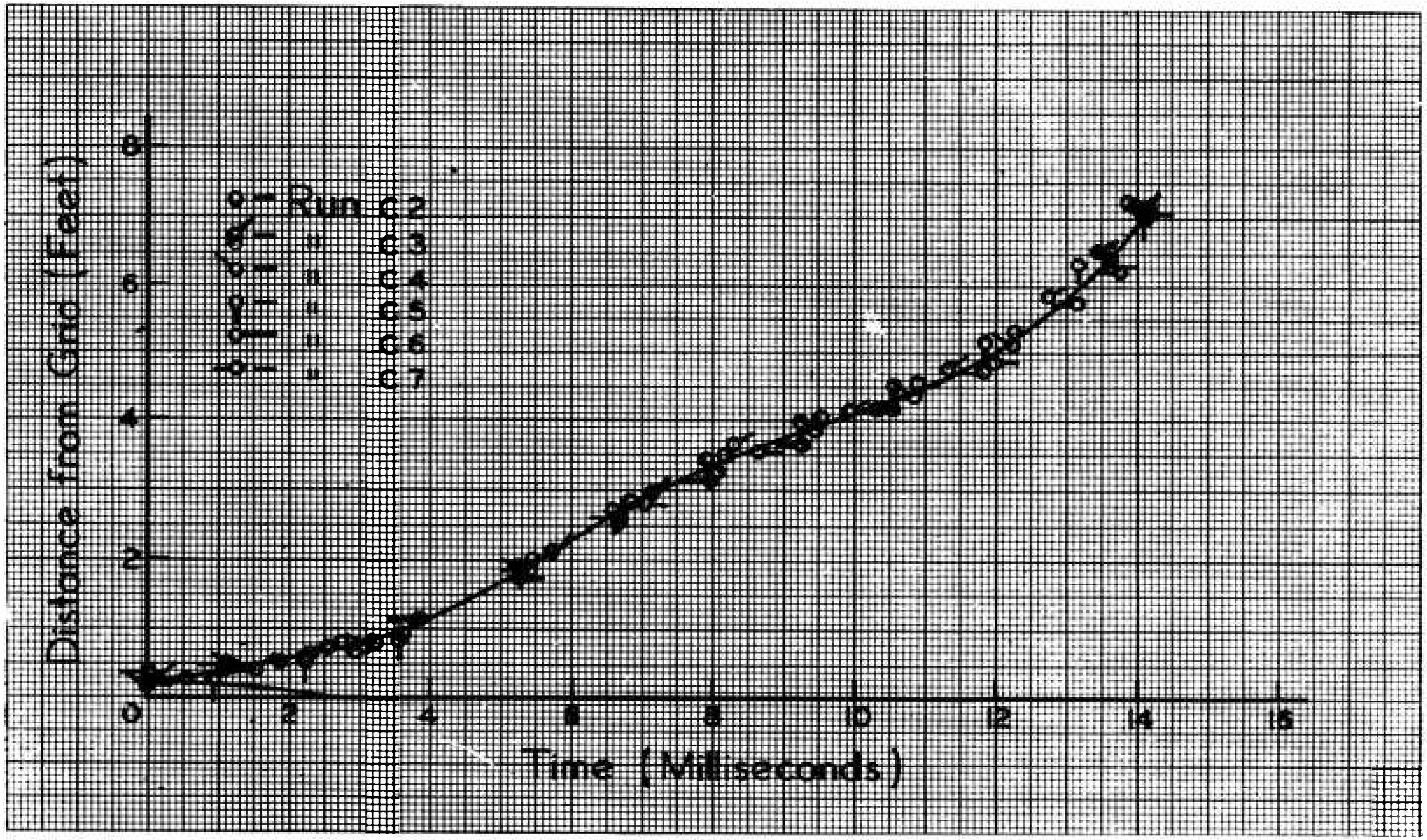


Figure 4. Position vs. time for six experiments with 7.04 x propane, No. 2 grid five inches from igniter, eight-foot tube.

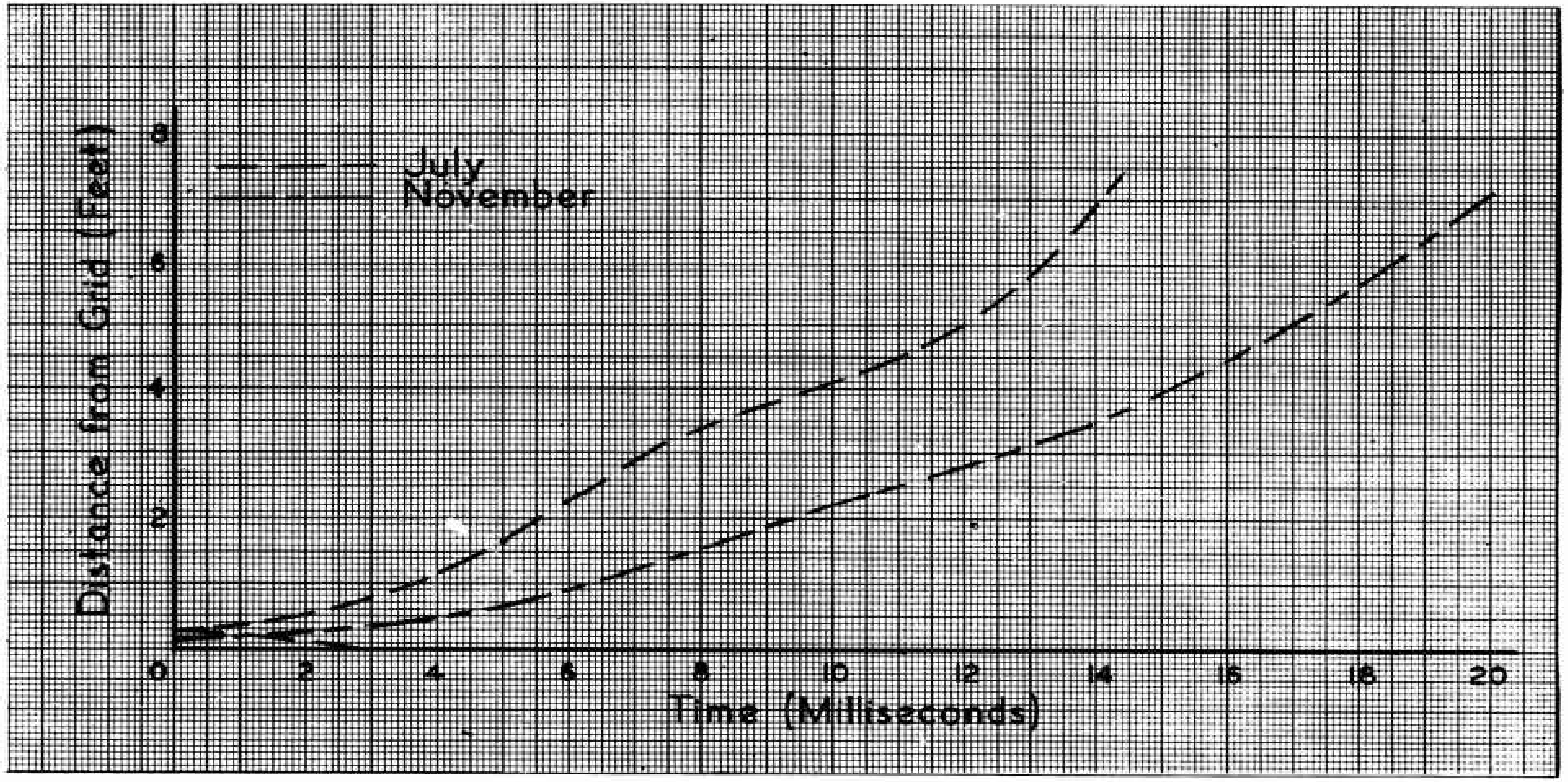


Figure 5. Position vs. time for experiments made in July and November. 7.04 % propane, No. 2 grid five inches from igniter, eight-foot tube.

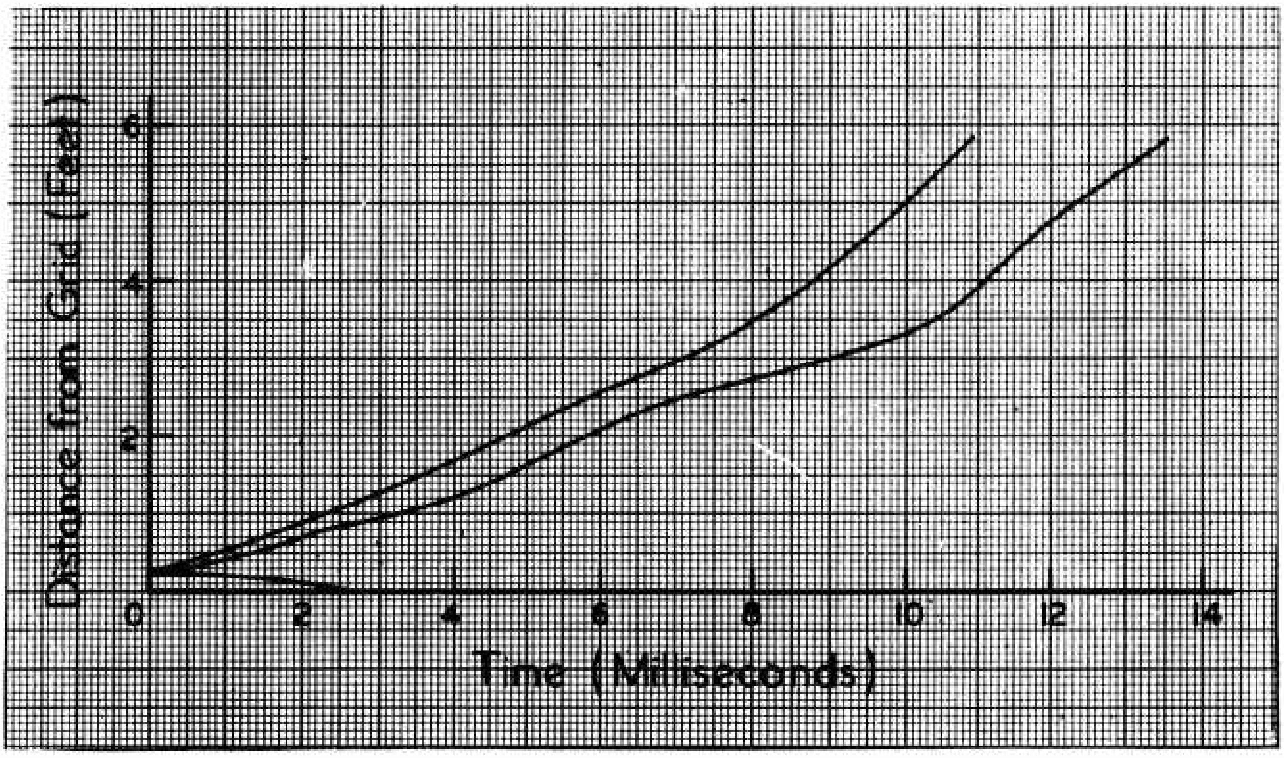


Figure 6. Position vs. time for 7.04 % propane, eight-foot tube, No. 2 grid two feet from igniter.

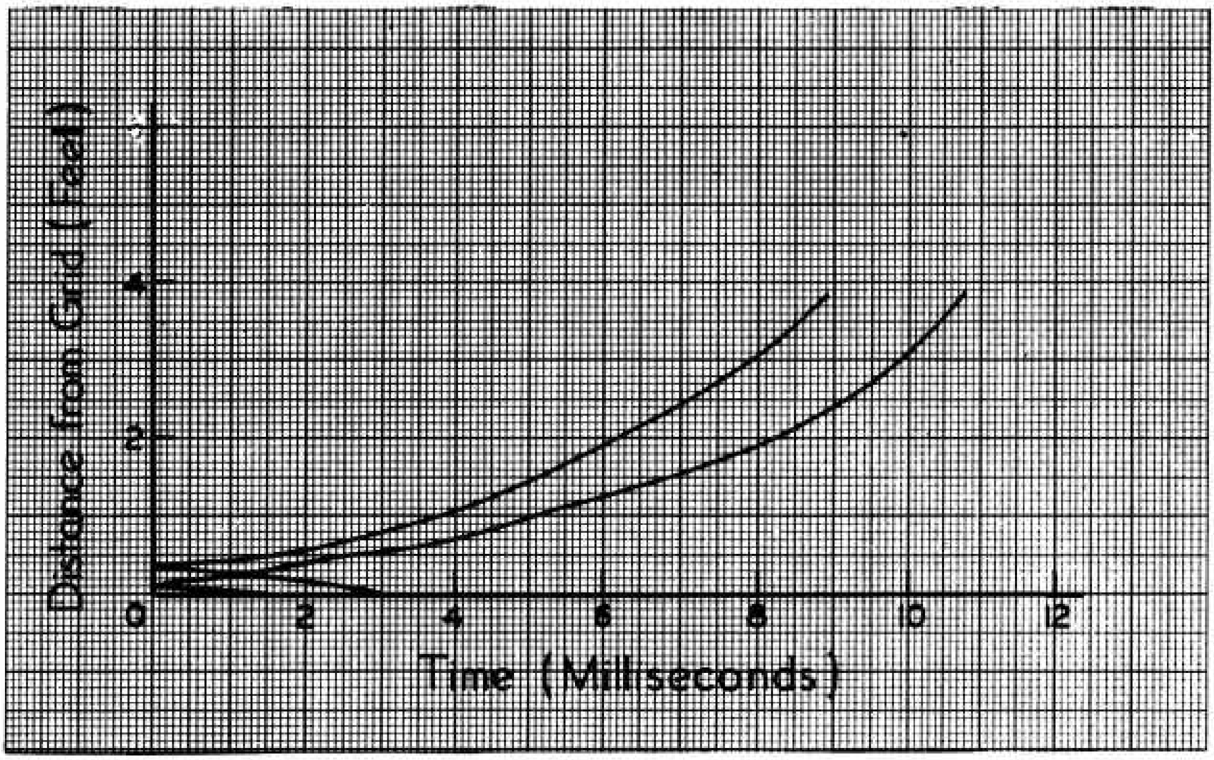


Figure 7. Position vs. time for 7.04 % propane, eight-foot tube, No. 2 grid four feet from igniter.

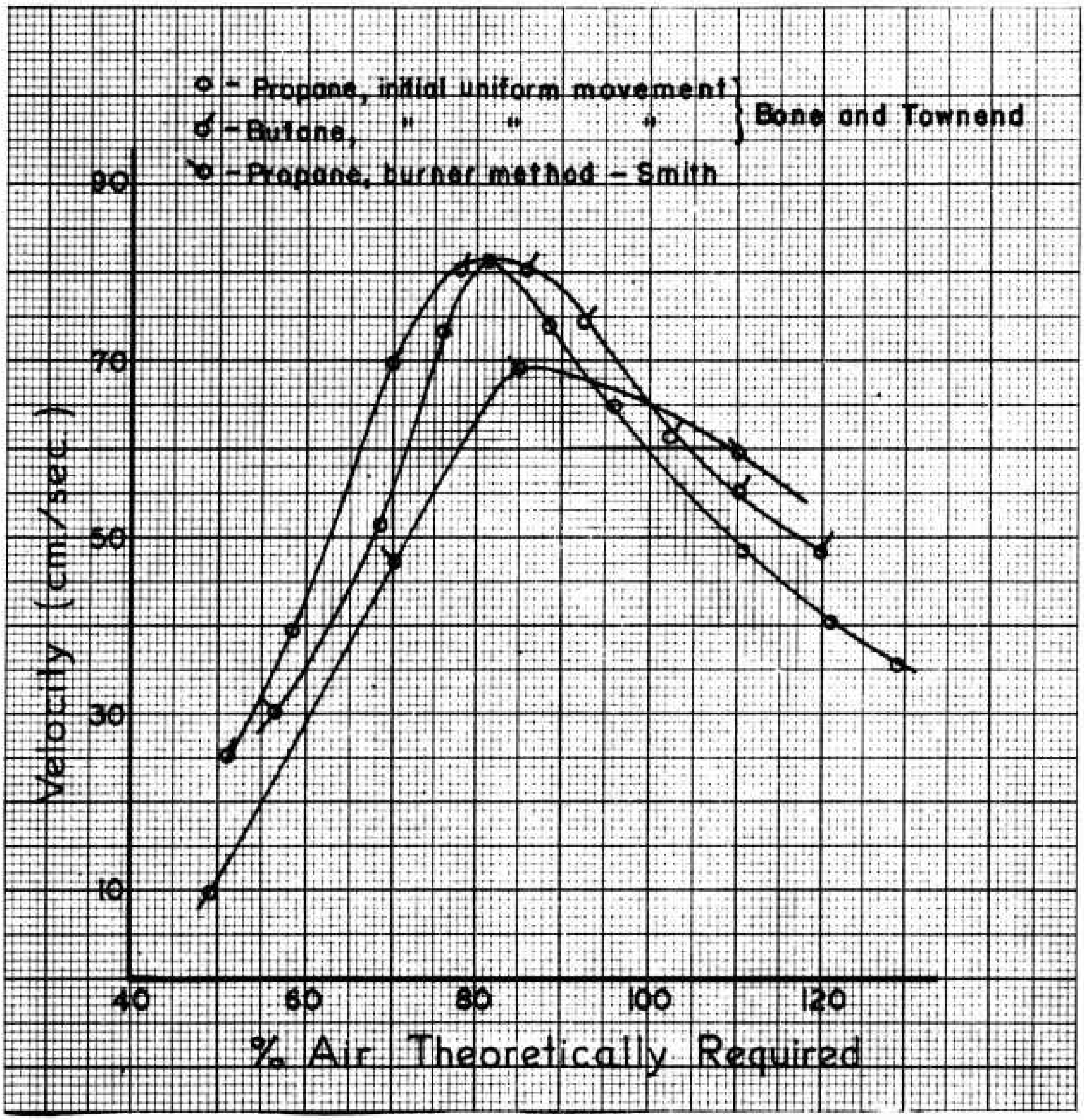


Figure 8. Normal combustion velocity of propane-air mixtures vs. composition of gas (Smith, reference 15; Bone and Townend, reference 16).

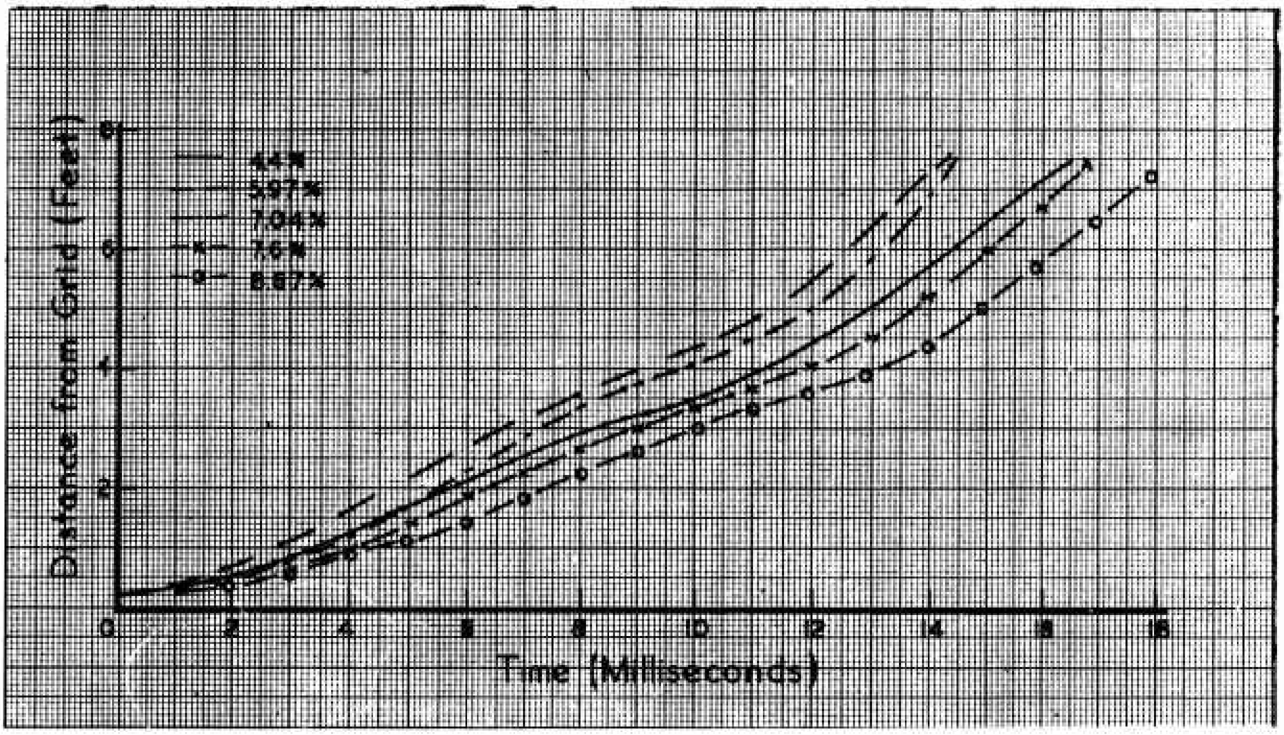


Figure 9. Position vs. time for flames in various propane-air mixtures; eight-foot tube, No. 2 grid five inches from igniter.

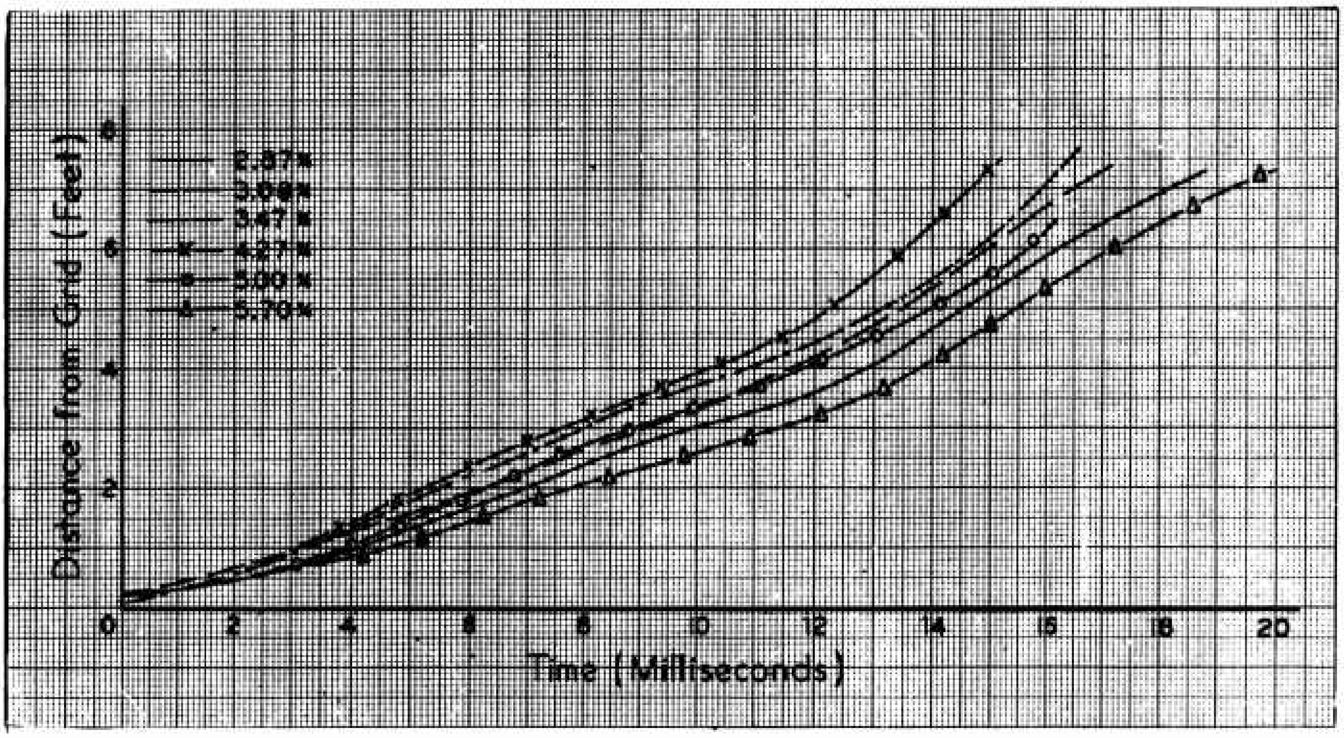


Figure 10. Position vs. time for flames in various butane-air mixtures; eight-foot tube, No. 2 grid five inches from igniter.

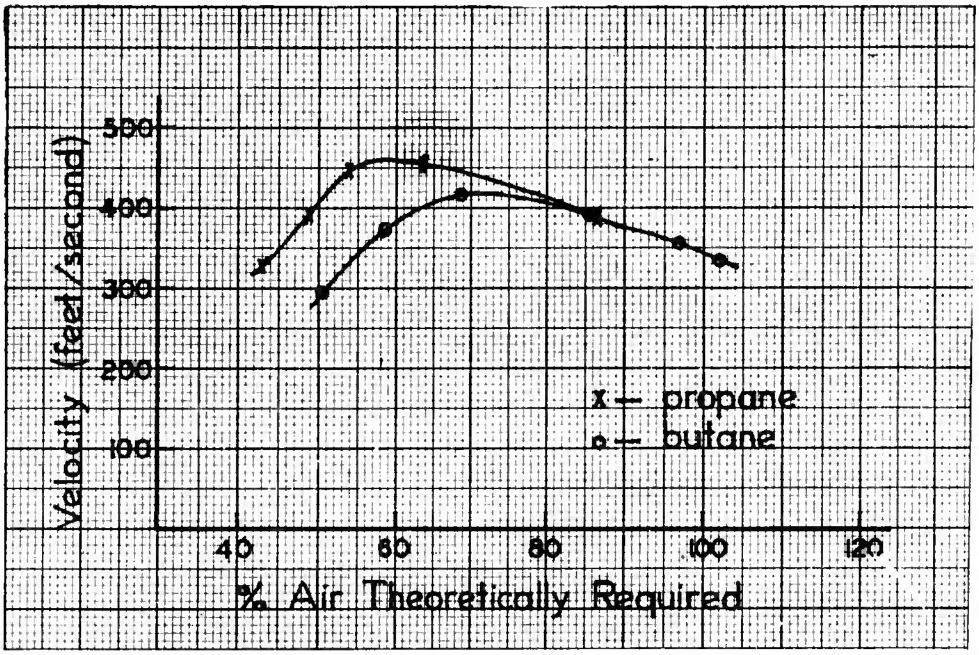


Figure 11. Flame velocity vs. concentration of hydrocarbon for propane-air and butane-air mixtures.

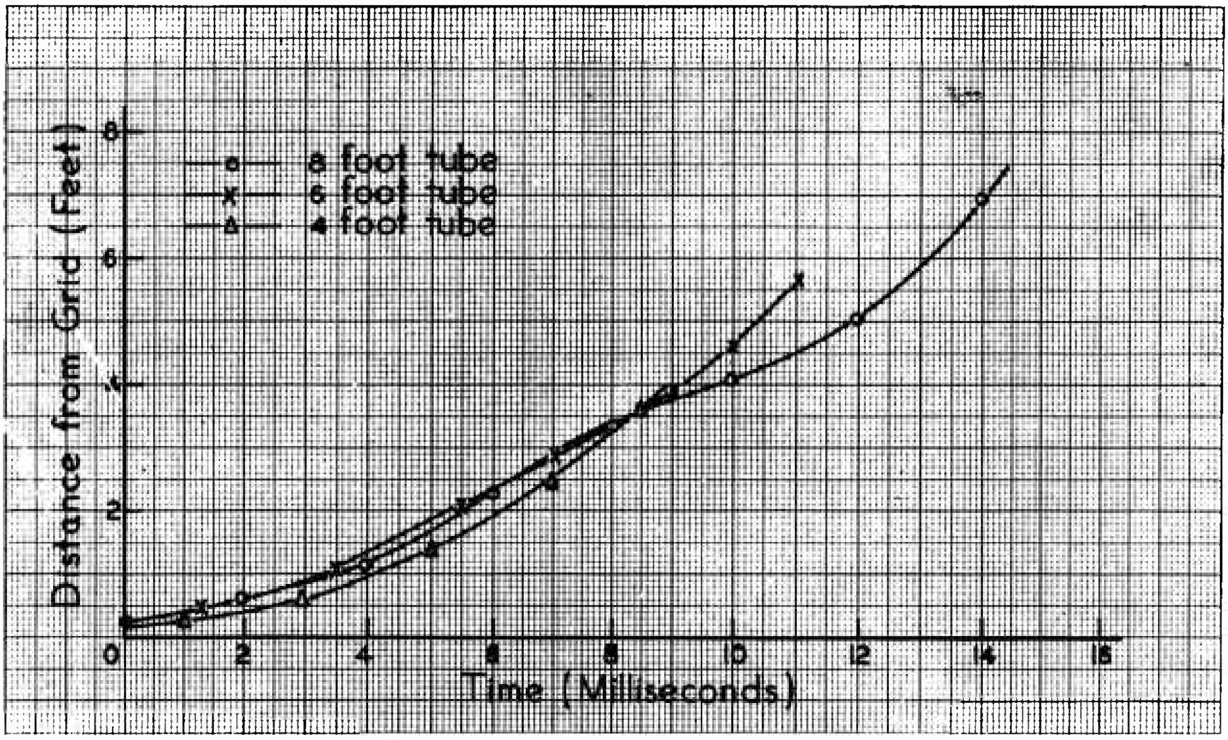


Figure 12. Position vs. time for flames in four-, six-, and eight-foot tubes; 7.04 % propane, No. 2 grid five inches from igniter.

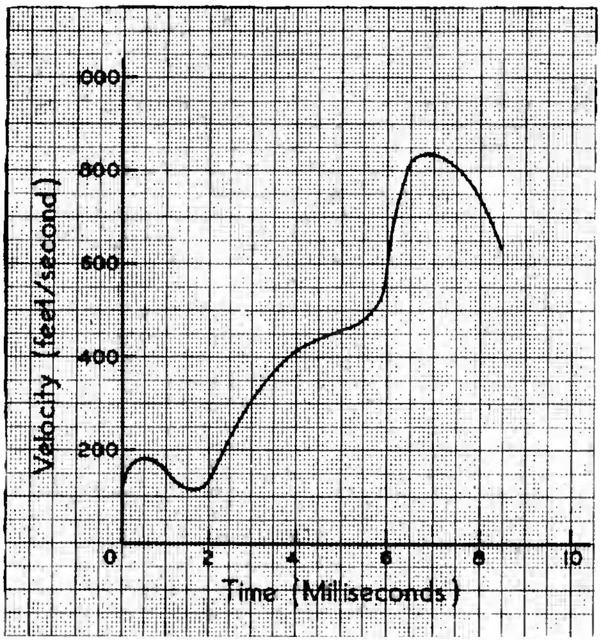


Figure 13. Velocity vs. time for four-foot tube.

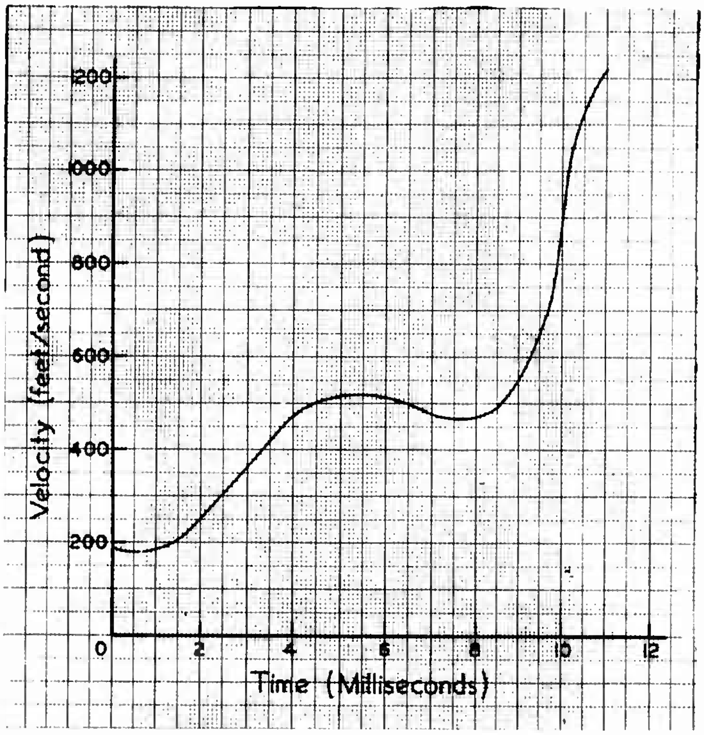


Figure 14. Velocity vs. time for six-foot tube.

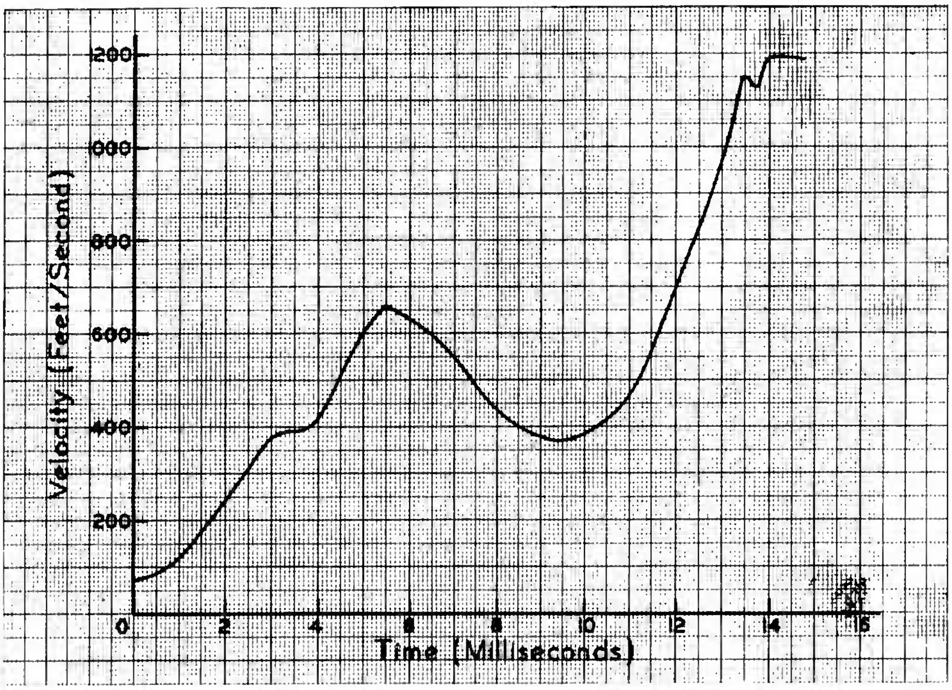


Figure 15. Velocity vs. time for eight-foot tube.

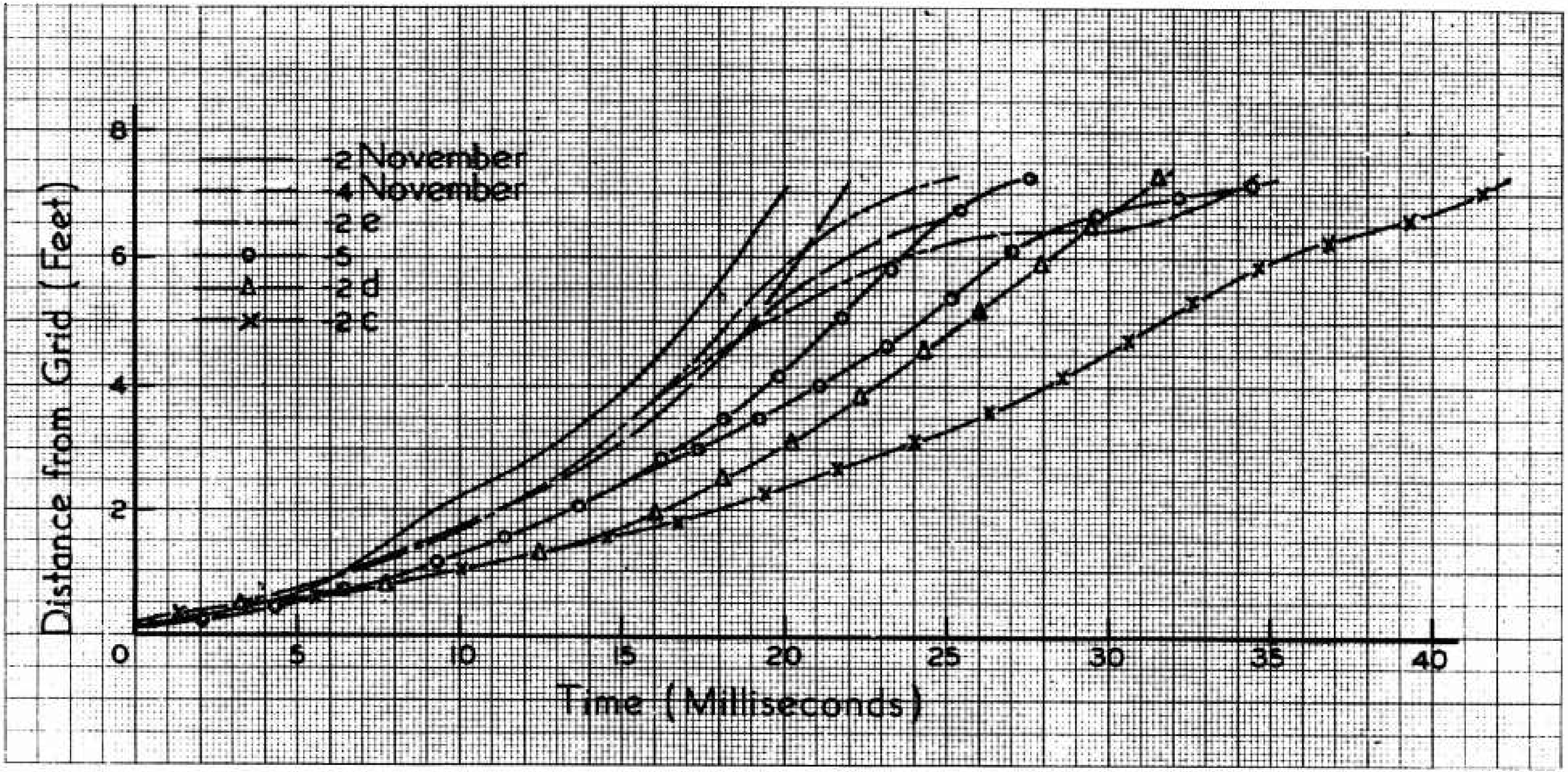


Figure 16. Position vs. time for selected grids; 7.04 % propane, eight-foot tube, grids five inches from igniter.

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TITLE: A Preliminary Study of Flames in Tubes Containing Grids

AUTHOR(S) : Evans, M. W.; Scheer, M. D.; Schoen, Louis J.
ORIG. AGENCY : New York University, New York, N. Y.
PUBLISHED BY : (Same)

P21/5

ATI- 22421
REVIS.ON (None)
ORIG. AGENCY NO. TR-7
PUBLISHING AGENCY NO. (Same)

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Dec' 47	Unclass.	U.S.	English	36	photos, tables, diagr, graphs

ABSTRACT:

Investigations were conducted to determine flame velocity with and without grid, possible change in normal combustion velocity by varying the percentage composition of the mixture, effect on high flame speed by varying grid design and effect on the fast flame by varying the tube length. The grids are found to produce a flame of high velocity. The effect of grid design, tube length, and mixture composition on the shape of the flame front position are shown in time curves. It is thought that this information when used in connection with pressure, temperature, and stream velocity will be useful in understanding pulsejet engines.

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PUBLISHING AGENCY NO. (Same)

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AUTHOR(S): Evans, M. W.; Scheer, M. D.; Schoen, Louis J.
ORIGINATING AGENCY: New York University, New York, N. Y.
PUBLISHED BY: Bureau of Aeronautics, Washington, D. C.

DATE	DOC. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Dec '47	Unclass.	U.S.	Eng.	35	photos, tables, diagr, graphs

ABSTRACT:

A preliminary experimental study is made of the propagation of flames in tubes with grids to improve the understanding of turbulent flame propagation and pulsejet operation. Grids are known to produce a flame of high velocity. The effect of grid design, tube length, and mixture composition on the shape of the flame front position - time curve of the high velocity flame - is examined. It was found in particular that placing a grid structure in the path of a flame propagating down a tube will increase the flame velocity by a factor of ten to twenty. Further, after the grid design was varied widely, the flame velocity appears definitely to be dependent, to a certain extent, on the number of holes in the grid and the ratio of opened to block areas.

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