AN ABSTRACT OF THE THESIS OF

William A. Reinhart for the M.S. in M.E.
(Name) (Degree) (Major)

Date Thesis presented May 9, 1949

Title - A Device for Measuring Inflammability Limits and Rates of Flame Propagation in Fuel Gases.

Abstract Approved [redacted]
(Major Professor)

After extended research in to the methods proposed in the past for measuring the rates of flame propagation and inflammability limits, the author constructed a device similar to the one used by John Corsiglia at the Ame rican Gas Association Laboratory for determining ignition velocity. To this instrument was added apparatus for determining the limits of inflammability.

The device is based on the principal that the rate of flame propagation in a stationary flame, such as that found on a gas burner, is simply the volume rate of flow of the gas being burned divided by the area of surface of reaction in the flame.

The method involved in determining the ignition velocity is to magnify and project onto a glass plate an image of the surface of reaction in the burner flame, and by tracing this image and measuring its dimensions the surface area is calculated. The gas being burned (a mixture of air and fuel gas) is measured to find its volumetric rate of flow. From these two quantities, surface of reaction area and flow rate of combustible, the ignition velocity is calculated.

The method of obtaining the limits of inflammability is to admit a measured amount of fuel gas and a measured amount of air int o a long, vertical glass tube. The mixture is passed through a small gas flame at the upper end of the tube. If the mixture is inflammable, the flame will burn back down into the tube since the mixture velocity is small in comparison with the ignition velocity. The smallest percent of gas, by volume, that will support combus-

tion is recorded as the lower limit of inflammability, while the greatest percent of gas which will support combustion is taken as the upper limit.

Three fuel gases were tested with the apparatus, and the results were compared with the values published by the American Gas Association for similar gases. The three gases tested were Portland Gas & Coke Company oil gas which is supplied as Corvallis city gas, commercial but ane, and commercial propane.

The results of the tests were fairly gratifying. In the case of the oil gas, which has a high ignition velocity, a complete ignition velocity curve was obtained. Also, the limits of inflammability for t his gas appear quite reasonable. The results for propane and butane were not quite so satisfying. The major reason for the difficulty with these two gases was their extremely low ignition velocity. Portions of the ignition velocity curves for these two gases were found to agree reasonably well with curves supplied by the American Gas Association for similar gases. Attempts to obtain the limits of inflammability gave rather inconclusive results, again due to a large extent to the low ignition velocities of the gases.

The results of the tests seem to show that the device is capable of a fair degree of accuracy in obtaining ignition velocity readings, the accuracy increasing as the ignition velocity becomes greater. The accuracy of limits of inflammability obtained with this device are doubtful. If carefully used, however, the device will yield fairly close approximations to the actual limits.

A DEVICE FOR MEASURING INFLAMMABILITY LIMITS AND FLAME PROPAGATION RATES IN FUEL GASES

by

WILLIAM ARTHUR REINHART

A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

JUNE 1949

APPROVED:

[redacted]

Head of Department of Mechanical Engineering

In Chargeof Major

[redacted]

Chairman of School Graduate Committee

[redacted]

Dean of Graduate School

TABLE OF CONTENTS

A DEVICE FOR MEASURING INFLAMMABILITY LIMITS AND FLAME PROPAGATION RATES IN FUEL GASES

CHAPTER I

Introduction

The author became interested in the various methods of obtaining the ignition velocity of gas-air mixtures while studying fuel gases in connection with a course in Gas Technology offered by the Department of Mechanical Engineering at the Oregon State College. The number of different approaches to the problem that have been made in the past, together with the apparent lack of agreement between the results obtained by the various methods, while not unknown in scientific fields of endeavor, were unusual enough to tempt the author to further study.

The suggestion was made by Professor S.H. Graf, Head of the Mechanical Engineering Department, that a possible thesis subject might be the development of an apparatus for the study of flame velocity, which if successful, could be used by students when studying gaseous fuels. Accordingly the project was undertaken, and, since the subject of limits of inflammability is so closely connected with that of ignition velocities, it was decided

that the project also include the development of a device for measuring these limits as well as ignition velocities.

The steps followed in completing this project were the usual ones in such work, namely background research, experimentation, development of an instrument, a testing procedure to determine the degree of success, and an evaluation of the usefulness of the device based on the results of the tests.

Much the same order has been preserved in the arrangement of this paper. The theory is presented in the first chapter following this introduction in order to acquaint the reader with the variable quantities which affect the ignition velocity and inflammability limits. This is followed by a brief chapter presenting the background, or history of the experimental study and methods of procedure which have been proposed to date. The apparatus finally developed by the author is described and discussed in the next chapter with accompanying photographs which, it is hoped, will help the reader follow the word description. A discussion of the test method used in obtaining values for ignition velocity and inflammability limits is the topic of the next chapter. The last two chapters contain a presentation of the results of tests conducted on several gases, followed by an

evaluation of the usefulness of the instrument based on these results. It is hoped that the paper presents to the interested reader the essential facts which may be of use to him, while not overburdening him with too much detailed description and unnecessary explanation.

CHAPTER II

Theory

The terms ignition velocity, burning velocity, flame speed, rate of flame propagation, and reaction velocity will be used synonymously in the discussion to follow to indicate the speed with which the flame front progresses, in a direction perpendicular to its surface, with respect to the unburned combustion mixture. The considerations will be confined to ignition velocities far below the speed of sound, as distinct from ignition velocities with super-sonic values such as would be encountered in an explosion. Such a restriction confines the discussion to flames which are found in industrial applications of gas combustion.

As more and more work is done on the problem of ignition velocity it becomes increasingly apparent that the end result will be exceedingly complicated. The number and complexity of the variables involved are such that any theory must necessarily involve hypothesis and approximations.

It was natural, since the study of chemical kinetics is quite young, that the first attempts at a solution of the problem of burning velocity should have been made from

the standpoint that the rate of conduction of heat from the burnt to the unburnt gas was the primary consideration. In order to illustrate such an assumption, consider the reaction zone of a flame stationary with respect to a coordinate system x-T, as shown in Figure 1. The direction of flow of the unburnt gas is toward the reaction zone as depicted by the arrow. This gas is at a temperature T_u, but as it progresses to the right it is warmed by the heat conducted from the reaction zone until a certain temperature is reached ($T_{i\,g}$) at which ignition takes place. Thereafter the reaction liberates heat to increase the temperature to a maximum at T_b.

Taken as it stands, no serious objections could be raised to this picture even today provided, and herein lurks the difficulty, that proper limitations are placed on the interpretation of the temperature T_{ig}. In 1883 when Mallard and Le Chatelier published their analysis based on the foregoing assumptions, it was widely supposed that this temperature was of the nature of a physical constant for each gas and could be determined by independent experiments. Of course attempts to do this were unsuccessful, and, after a period, the accumulated data made it apparent that, far from being a constant, the ignition temperature was a function of the system as a

whole in which ignition occurs.

Despite the weakness in the original assumption, the expression derived for ignition velocity by Mallard and Le Chatelier is most interesting and extremely helpful in explaining several important ignition velocity characteristics. The fundamental steps in the derivation are as follows (4,pg.347-349):

1. The zero point of the x axis is taken at the point of ignition, or that point at which the temperature of the combustion mixture has risen to T_{ig}. Consider a stream of mixture of unit area cross-section. The unburnt gas at this point is recieving per unit time an amount of thermal energy required for ignition

$$H_{ig}=S_u d_u c_p (T_{ig} - T_u) \qquad (1)$$

where S_u is the burning velocity, d_u the density of the unburned mixture, c_p the average specific heat of the mixture at constant pressure, T_{ig} the ignition temperature, and T_u the temperature of the unburnt mixture.

2. Since the heat is transferred by conduction, it must be equal to

$$H_{ig}=U(dT/dx)_{x=o} \qquad (2)$$

where U is the coefficient of heat conductivity. If it is assumed, as a first

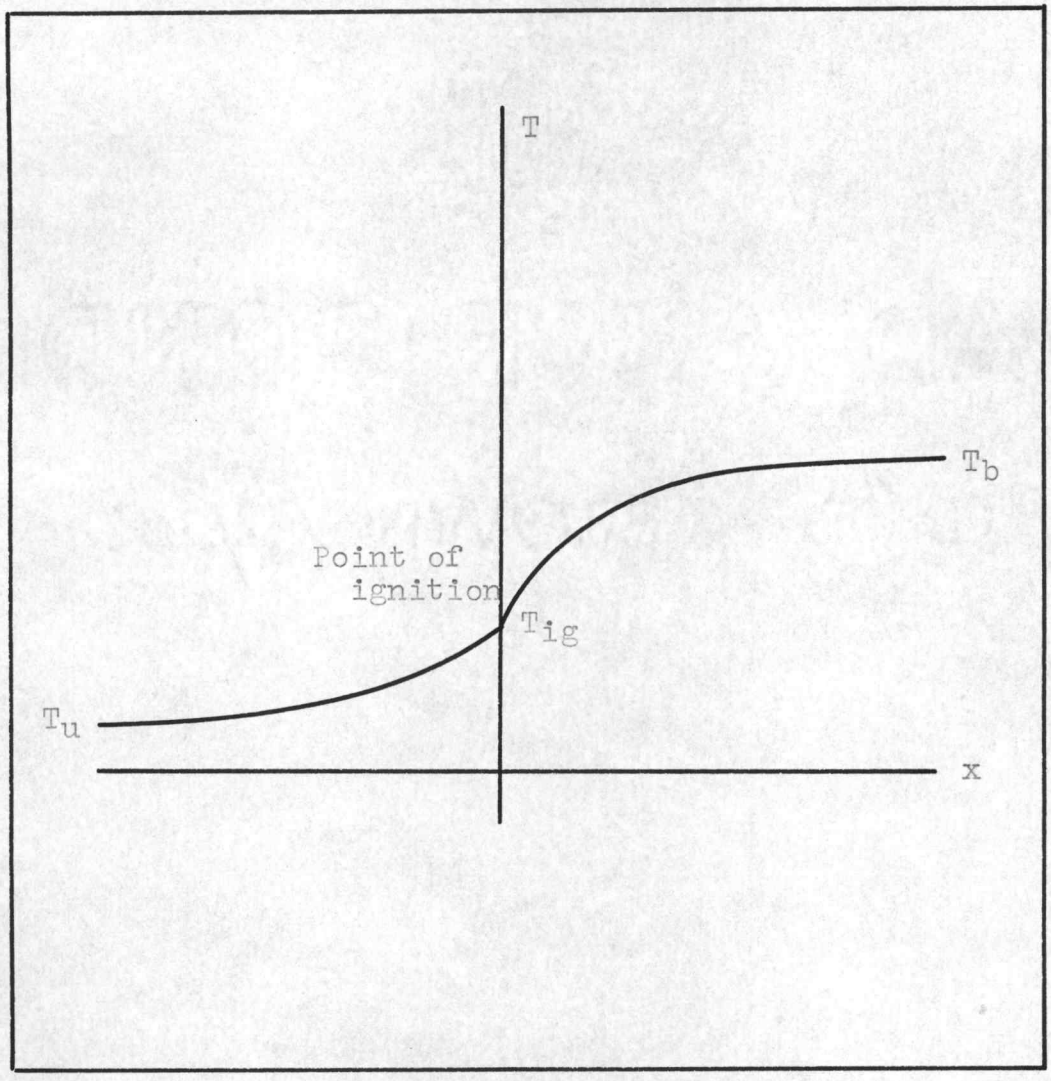

Figure 1 - Flame front stationary with respect to T-x coordinate system.

approximation, the $(dT/dx)_{x\ o}$ is proportional to T_b-T_{ig}, or that the temperature gradient between T_b and T_{ig} is substantially linear, then

$$H_{ig}=U(T_b-T_{ig})/x_b \qquad (3)$$

where x_b represents the thickness of the reaction zone between T_{ig} and T_b, and is a function of the reaction rate. As the reaction rate increases the zone thickness decreases.

3. By combining equations (1) and (3) one obtains the expression

$$S_u = \frac{(U/d_u c_p)(T_b-T_{ig})}{(T_{ig}-T_u)\ x_b} \qquad (4)$$

This is substantially the original equation for ignition velocity proposed by Mallard and Le Chatelier. Others have tried to improve on it by making other assumptions to start with. In each case, however, the prime weakness was overlooked; namely, the indefinite limitations surrounding T_{ig}.

Although it has long since been proven that equation (4) does not yield quantitative results that can be borne out experimentally, it does predict, qualitatively, certain characteristics of flame propagation. For instance equation (4) predicts the existence of limits of inflammability. It is evident that for sufficiently lean or rich mixtures T_b will decrease, and, although T_{ig} is presumably a very complicated function of mixture composition

and other factors, it is evident that $T_{ig}-T_u$ will always remain positive and finite while T_b-T_{ig} will vanish.

It has been shown by test that the lower limit of inflammability is little different in air and in oxygen. This appears to be predicted also by equation (4). The substitution, in a lean mixture, of oxygen for the nitrogen in the air would not change c_p, U, or T_b very much. According to experimental results the diffusion characteristics and reaction velocity will not change very much either, so it is not very unreasonable to assume that the T_{ig} and x_b will also remain substantially unchanged. Thus an application of equation (4) helps to explain the experimental results shown in Table 1.

Table 1 - Lower limits of inflammability of combustibles in air and oxygen under comparable conditions.

Combustible	Lower Limit in Air	Lower Limit in O_2
Hydrogen	9.4	9 - 10
Carbon Monoxide	16.3	16.7
Methane	6.1	6.4
Ethylene	3.13	3.1
Propylene	2.00	2.10

For the same reasons it is understandable that, in sufficiently lean mixtures, the substitution of oxygen for nitrogen has little effect on the ignition velocity.

This is also borne out by experimental data.

The nature of an inert component of the gas mixture will affect principally c_p, U, and T_b. If nitrogen is replaced by argon, whose specific heat is much lower, the ignition velocity should increase. This was confirmed experimentally by Stevens (4,p.344). If nitrogen is replaced by carbon dioxide, whose specific heat is larger and heat conductivity smaller, the burning velocity should decrease. This has also been verified in the laboratory. If the argon in the first case were replaced by helium, which has a still higher heat conductivity than argon, the burning velocity would be increased still further. Again experimental work carried out by Fiock and Roeder (4,p.358) shows this conclusion to be qualitatively true.

Thus it is apparent that, although somewhat crude, the treatment of rates of flame propagation as handled by Mallard and Le Chatelier is, nevertheless, able to explain a number of observation including limits of inflammability, affect of diluent gases on the latter, and affect of diluent gases on the rate of flame propagation.

Certain more recent observations have shown conclusively that diffusion is important in the treatment of burning velocity. Lewis and Von Elbe (4,p.351-356) have attempted a solution, without the use of the indefinite

term ignition temperature, concerning the propagation of ozone-oxygen flames. Using simplifying assumptions concerning the reaction mechanism and the combined affects of heat flow and diffusion, the calculated results show a certain amount of agreement with experimental results. It is interesting to note, in passing, that the calculated width of flame front was in the order of 10^{-3} centimeters.

Though no successful method for calculating flame velocity has yet been discovered, progress has, and is, being made. Coward and Payman (5,p.364-365), in summing up the results of work in the field thus far, have suggested that the outstanding experimental results that must guide future theoretical developements are:

1. The calorific value of the mixture determines mainly the relative speeds of flame in a series of mixtures, in various proportions, of the same constituents.
2. The speeds of flames in various mixtures of equal calorific values may be greatly different.
3. Ignition temperatures corresponding to the very shoet time lags available in the propagation of flames, have not been determined except, perhaps, for mixtures of methane and air. It is, therefore, not yet possible to correlate ignition temperature

with ignition velocity. However, in any case, the ignition temperature is a function of simpler properties, and any connection discovered between ignition temperature and flame speed would be one step toward a final solution to the problem.

4. The propagation of flame is obviously a continuous succession of ignitions of unburnt gas next to the flame front. It might be expected then that the most easily ignited mixtures would be those which would propagate flames the most rapidly. However, this is not so. A further development is necessary in this region to bring light upon the reason behind this seeming anomaly.

5. The relative rates of isothermal reactions of a series of mixtures, at temperatures below those of ignition, are not parallel to the speeds of flames in the same mixtures.

6. There is evidence that, with hydrocarbons, the course of the chemical reactions is the same in flames as at lower temperatures, but rival theories do exist on these oxidations.

7. Of much significance is the smallness of the affect of large differences in thermal conductivity on the speed of flame in different mixtures, other conditions being the same. There must logically be a less

steep temperature gradient in front of the flame in mixtures which have higher thermal conductivity, and it would seem that the preflame reaction should start correspondingly sooner. Nevertheless, since the flame velocity is no greater in such mixtures, it is apparent that the layer of gas just in front of the flame does not ignite any sooner. What is it waiting for? Indications are that the actual bursting into flame is not so much the consequence of the arrival of sufficient heat as the arrival of sufficient concentrations of active particles, which are efficient propagators of flame because of their chemical nature rather than their kinetic energy. More direct evidence of this is to be sought in the future.

The reader, by this time, has surely been convinced that the subject of flame propagation is not easily approached on theoretical grounds. Nevertheless, if an expression for ignition velocity can ever be worked out, so that this flame characteristic may be calculated from the chemical analysis of the gas and the conditions surrounding the combustion, such an expression will be of very great value to industry and science.

CHAPTER III

Background

The first work in connection with ignition velocities in gas combustion was done by Bunsen and published in the year 1866. It was soon discovered that the relationship between the chemical composition of the mixture and the rates of flame propagation is far from simple. So many variables enter into the problem that, to this day, no really satisfactory calculations of this flame characteristic can be made. (See Theory)

When Bunsen first undertook his work he assumed that the downward velocity of the flame just exceeds the upward velocity of the combustible mixture at the moment when the flame flashes back down the burner tube. This could be true only if the velocity of the mixture were uniform across the tube cross-section. Since this was proven not to be the case, some other method of evaluating the burning velocity was sought.

The methods, proposed to date, fall into three classifications according to the type of apparatus used. The first of these is the method classification, in which the flame front is stable with respect to the

observer. The second is the tube method in which the combustible in a long tube is ignited at one end and the flame travel timed to find the rate. The third classification consists of the bubble methods in which the combustible mixture is confined in a soap bubble and ignited at the exact center by means of a spark gap. Photographic analysis of the resulting inflammation yields the rate of flame propagation. The latter method is discussed in an article for Chemical Reviews by Fiock and Marvin (3,p.368-375). In most cases the agreement between results obtained by the three types of test is not at all good. A notable exception will be pointed out later in this section. The author will confine his discussion to tests which fall into the first classification because the apparatus used by him is of this type. Besides, the first type of test approximates very closely the actual burner conditions encountered in industry.

A study of a stable gas flame reveals a bluish inner cone. The surface of this cone is termed the flame front because it consists of a surface of primary chemical reaction. Within this cone there is only unburned combustible mixture. Figure 2 describes the relation between the inner cone and the burner port. Actually the flame cone does not touch the burner port at the inner diameter as shown in this figure. In most cases the diameter of

the base of the inner cone is slightly larger than the port diameter.

Early experimenters, seeking to determine the ignition velocity, with respect to the unburned mixture, assumed that the inner cone was a perfect cone whose diameter was the port diameter. This was first done by Gouy in 1879. He considered the flame velocity to be the product of the velocity of the mixture being burned and the sine of the angle which the side of the flame cone made with the axis. After a time Gouy became aware that the inner cone did not approximate sufficiently a perfect cone, and that the angle depended upon where on the cone he chose to measure it. Throwing out his angle idea, Gouy proceeded upon the assumption that the flame speed is equal to the volumetric flow of the combustible mixture divided by the surface area of the cone. This assumption involves only the concept of flame as the rate of transformation of the mixture, eliminating the necessity for considering the velocity of the gas mixture or its direction of flow.

Gouy determined the area of the cone from measurments taken from an image projected on a screen. Considering the figure as a surface of revolution he obtained the surface area by integration.

Michelson, in 1889, published a report in which he

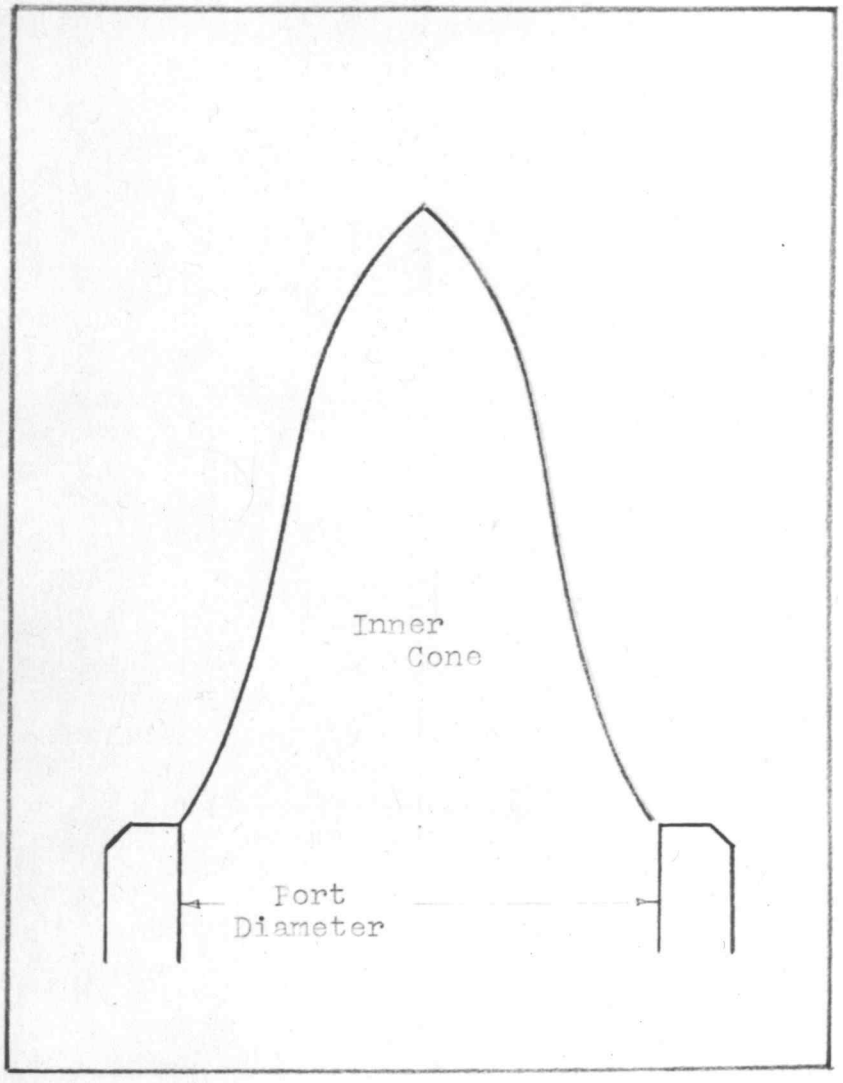

Figure 2 - Relationship between the inner cone and the burner port.

used the same assumption as Gouy proposed. However, he obtained his cone dimensions from enlarged photographs of the inner cone.

A number of years followed in which no new methods were proposed. However, in 1929, Stevens (6,p.390-391) reported on a method which he devised that yielded results in close agreement with results obtained by his bubble method. He assumed that if the flow in the burner was laminar, the rate of flow in a layer at a distance from the axis equal to 0.707 times the radius should be equal to the average rate of the mixture in the tube. This follows from the fact that the velocities vary accross the tube, in laminar flow, in a parabolic fashion. Making use of only the portion of the flame front which resulted from the layer of mixture noted above, Stevens constructed a triagle with the port diameter as a base and the sides parallel to line tangent to the flame surface at this particular portion of the surface (0.707r). From the base and altitude of this triangle he easily calculated the cone surface and computed the flame velocity. Such fine correlation was found, using carbon monoxide and oxygen as the combustible mixture, between results from this method and the bubble method that in many cases the two were interchangeable.

Smith and Pickering (6,p.394-401) chose to measure

directly the angle between the tangent at 0.7 times the radius and the axis of the cone in order to obtain the flame speed. This angle, multiplied by the average mixture velocity, gave the flame speed directly. This method embraces the same general assumptions as the Stevens method as to the relative gas velocities leaving the tube. The relationship between the average mixture velocity and the flame speed is easily shown in a diagram such as Figure 3. The average mixture velocity was found by dividing the volumetric flow of the mixture by the port area.

At least in part, the accuracy of this method depends upon the assumption that the parabolic distribution of gas velocities extends above the burner port for a sufficient distance to embrace the inner cone.

It is still not clear which method of determining flame speed is the most useful. For the purposes of the gas industry, the method, based on Gouy's final premise, that the flame speed is equal to the surface area of the inner cone divided into the volumetric flow of the mixture being burned, is used. This method was outlined by John Corsiglia in 1931 (2). It was used in connection with tests being conducted by the American Gas Association Laboratory on the interchangeability of various fuel gases. Since this time it has been used consistently

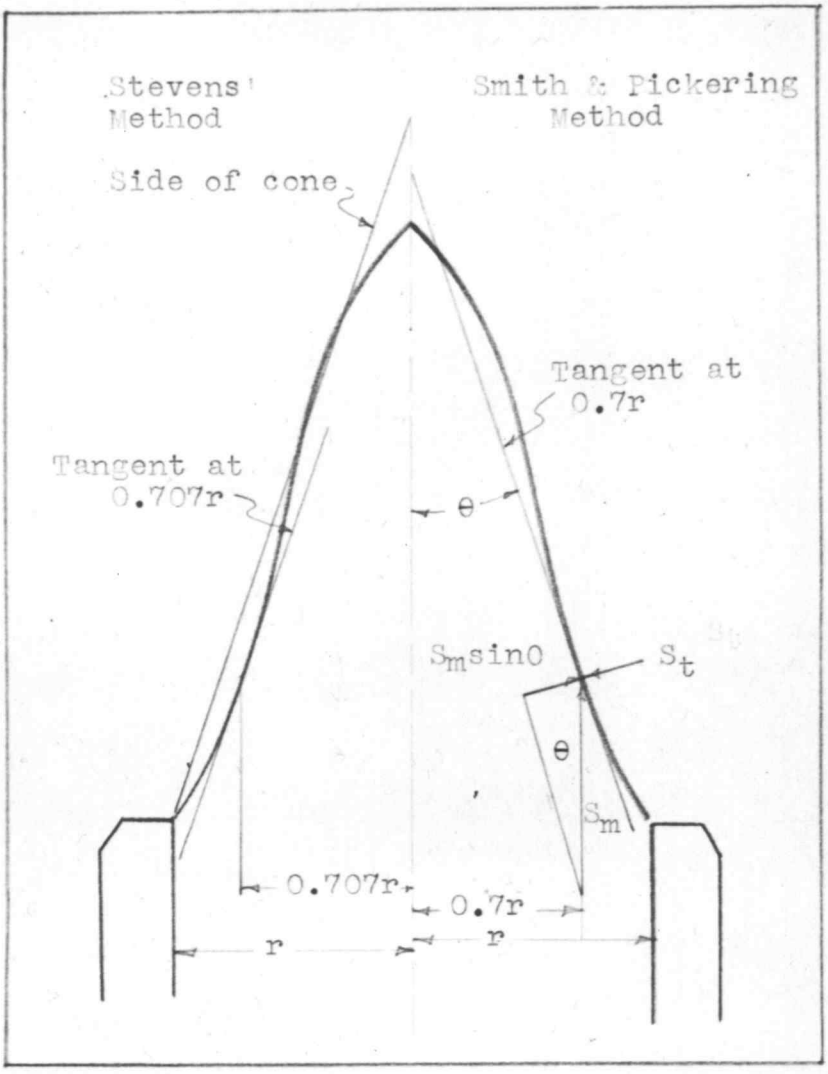

Figure 3 - Relationship between the Stevens and the Smith and Pickering methods of determining flame velocity. S_t is flame speed, S_m is average mixture velocity. $S_t = S_m \sin \theta$

by the American Gas Association, with slight modifications, to determine all ignition velocity curves.

In Corsiglia's method the inner cone is photographed and, after the film has been developed, an enlarged image of the flame is projected onto a transparent screen. The outline of the image is copied and the dimensions (magnified a known amount) are taken from this copy. A modification of this procedure, used in recent tests by the A.G.A. is to eliminate the necessity for photographing the inner cone by projecting the image, by a lens and mirror arrangement, onto a horizontal ground glass plate. From here it is copied as before onto tracing paper.

In his report Corsiglia stated that the results obtained were independent of the port size. In support of this conclusion he cited tests, upon three burners of different port diameters, in which he found the ignition velocity of the same mixture, under the same conditions, to be the same within limits of experimental error.

Smith and Pickering were in doubt as to the validity of this conclusion. They proceded to run a series of tests, using Corsiglia's and their own methods simultaneously, on four burners with widely divergent port diameters. In the final comparison, published in the

Chemical Reviews (6,p.411), ignition velocity curves, determined with each burner by both methods, showed conclusively that both nethods were affected by the port diameter. The curves further proved that the Smith and Pickering method was affected very little in the region of maximum flame speed, while the Corsiglia method was most seriously affected in this region. No comparison as to the relative accuracy of the two methods can be made as yet, but a careful study of them both seems to indicate that the Smith and Pickering method rests upon the poorer assumption, primarily because it has recently been shown that the parabolic distribution of velocity within the burner tube is not likely to apply once the mixture leaves the port, even for a very short distance. The outer layers, that were near the tube wall tend to accelerate while the mixture nearer the center tends to decelerate.

Whatever the case may be, it has been shown clearly that the numerical values for flame speeds, obtained with burners, are affected by the various ways in which the measurments of the flames are made, by the experimental conditions, and by the different ways in which the results are computed, plotted, and interpreted.

The instrument constructed by the author embodies the principles of the Corsiglia method. This method was

decided upon for the reason already pointed out that it most nearly approximates the conditions actually encountered in gas burners.

The property of inflammability limits in gases in important primarily with respect to hazards involving possible explosive mixtures. For this reason these limits are often referred to as the explosive limits. The desired result, in testing for the limits of inflammability, is to determine the smallest and largest percents, by volume, of gas in mixture with air which will continuously support combustion (1,p. 233).

Of the two limits the more important is the first, since, if the amount of gas can be kept below this limit, any additional air which might find its way into the mixture would only make the mixture less apt to explode. For this reason it is always the aim in industry to keep the atmospheres well below the lower limit of inflammability.

Any mixture of gas in air which falls between the inflammable limits will support combustion and the velocity of the flame front will vary depending upon the conditions under which combustion takes place.

In the apparatus developed by the author, the

inflammable limits are determined simply by mixing a known volume of gas with a known volume of air in a long glass tube and attempting to ignite this mixture. The limit is easily recognized by a slow movement of flame through the transparent tube.

CHAPTER IV

Description of Apparatus

The description to follow will be most easily understood by the reader if he will refer frequently to the accompanying photographs. Beneath each photograph appears a complete description of the apparatus pictured in the hope that this will eliminate the necessity for a detailed and involved description in the text.

A discussion of the apparatus may easily be divided into three parts; 1.) the test burner cabinet pictured in Figures 4 and 5, 2.) the glass tube and pilot burner which are attached to the cabinet when testing a gas for its inflammability limits, and 3.) the apparatus with which the air and gas are supplied and measured. The inflammability limits apparatus is shown in Figure 7, and the measuring devices are pictured in Figure 6.

The test burner cabinet contains, in addition to the test burner, a lens and mirror arrangement which focuses a magnified image of the inner cone of the burner flame on a window on the front of the cabinet. This image is approximately 5.5 times as large as the actual inner cone and is copied onto a sheet of tracing paper in the test

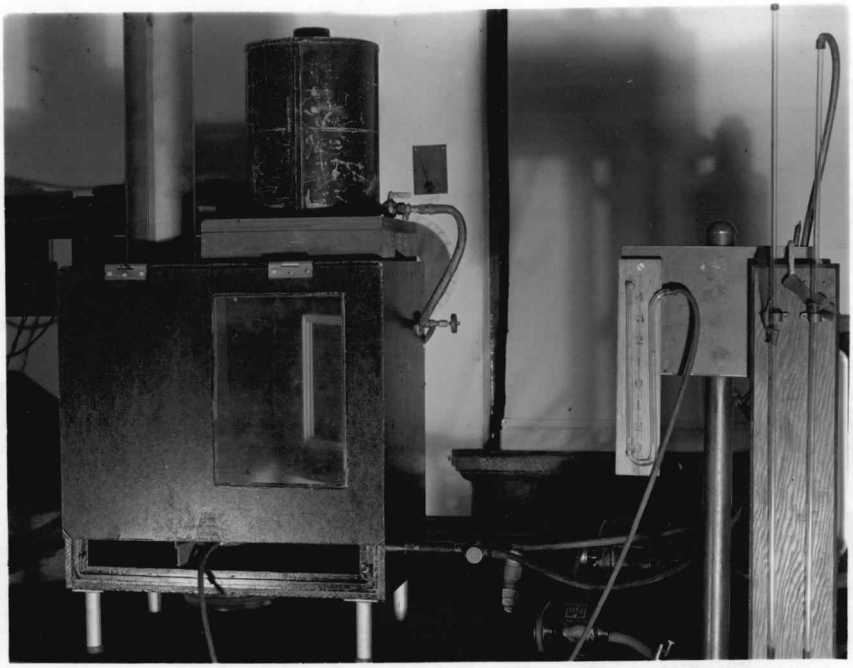

Figure 4 - Exterior view of the test burner cabinet. The exhaust gas stack and cooling water reservoir are on top of the cabinet. The open strip along the lower portion of the front of the cabinet is to admit secondary air to the burner. The image of the inner cone is traced from the window on the front of the cabinet. The reflecting mirror is visible through the window.

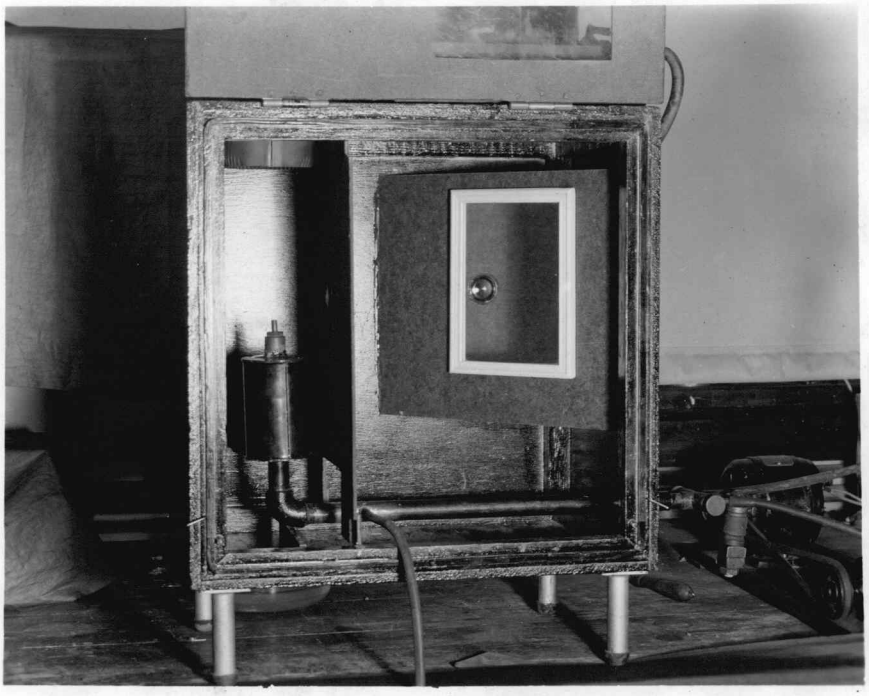

Figure 5 - Interior view of the burner cabinet. On the left is the test burner, surrounded by the cylindrical cooling jacket. The exhaust gas stack can just be seen above the burner. The magnifying lens is barely visible in the partition to the right of the burner, but its reflection is clearly shown in the mirror at the right of the partition. The valves by which the gas and air supply is controlled are visible just outside the cabinet on the lower right hand side.

for ignition velocity. The burner mixing tube extends across the floor of the cabinet from the burner, which is on the left, to the control valves outside the cabinet on the right hand side. A cooling system is provided on the burner to prevent the combustion mixture from being heated appreciably while passing through the burner tube. A 4" stove pipe carries the products of combustion out of the cabinet. The front of the cabinet swings on hinges so that it may be lifted up while adjusting the flame to the desired shape. Upon closing the front of the cabinet the image is automatically brought into focus on the window.

Before testing for the limits of inflammability the exhaust gas stack is removed, and a 1" inner diameter glass tube is fitted over the test burner port in a vertical position so that it extends above the top of the cabinet about a foot. The tube is held in place by a clamp on top of the cabinet as shown in Figure 7. The lower end is made air tight by immersing it in 1/4" of water around the burner port. This is to prevent any gas or air from entering the tube except that which enters through the burner. A pilot burner is strapped to the upper portion of the tube, but is separated from it by a wooden block to prevent the copper burner tube from heating the glass tube. The burner is adjusted so that

its flame will burn about 1/2" above the top of the tube and directly on the tube centerline. The fuel for this burner is gas which passes through a rubber hose directly from an outlet. Its rate is only of relative importance, therefore no metering is necessary.

The air and gas metering devices are shown in Figure 6. Air is supplied by a small rotary compressor of approximately 0.5 cfm capacity which is driven by a 1/30th horsepower electric motor. This arrangement provides sufficient air although some trouble resulted from vibrations set up in the air line by the compressor. The rate of air flow is registered by a rotameter and the air line pressure by a water manometer. The rotameter was accompanied by a calibration curve provided by the manufacturer which converted the arbitrary scale on the meter to standard cfm of air metered at atmospheric pressure (14.7 psi.). This curve was checked against the wet test meter and the two checked very closely. The wet test meter was employed to measure the gas flow, the rate being determined by timing the wet test meter with a Kodak timer.

At first the air and gas rates were controlled at the test burner cabinet by the valves shown in Figure 5. It was soon discovered, however, that a better practice is to control the air rate by a valve, not shown in the

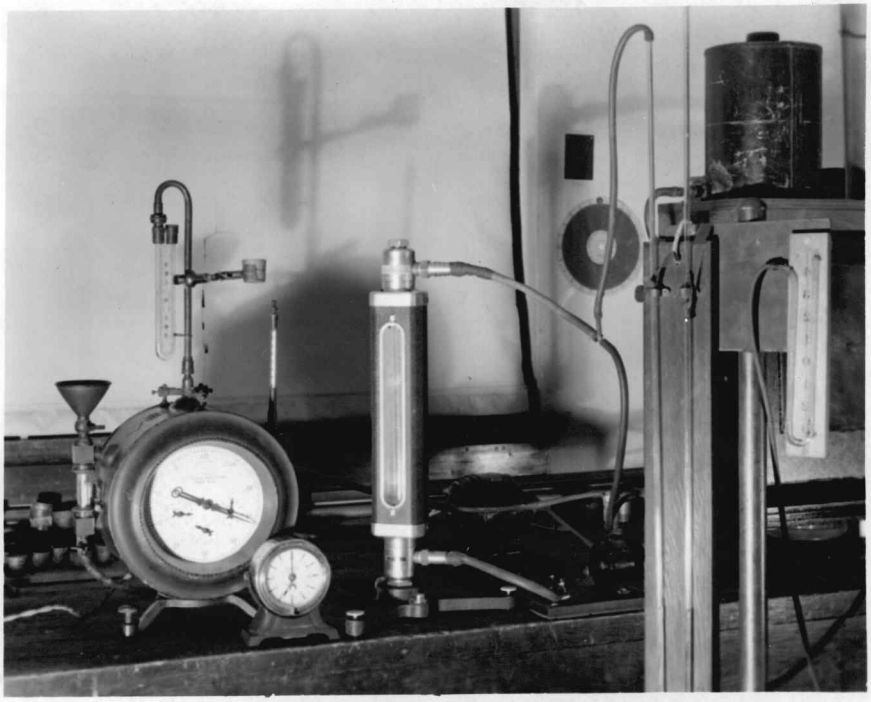

Figure 6 - Instruments used to measure the gas and air rates. The wet test meter is on the left t ogether with the timer with which the gas rate is found. The rotameter for measuring the flow of air is to the right of the wet test meter. The manometer to the right of the rotameter gives a measure of the pressure in the air line. The small manometer is connected to the mixing tube of the test burner.

Figure 7 - View of the burner cabinet with the apparatus used in determining inflammability limits in pla ce. Note the glass tube with the pilot burner over the upper end. The lower end of the tube fits snugly over the test burner port inside the cabinet.

illustrations, between the compressor and the rotameter. This prevented a back pressure on the rotameter, which pressure makes a troublesome conversion of readings necessary. Moreover this valve cuts down considerably on the vibrations from the compressor.

The pressure in the mixing tube is measured by a water manometer, but in all instances this pressure has been found to be entirely negligible.

A rubber bag placed in the air line reduced still more the amount of vibration from the compressor, thus increasing the stability of the inner cone on the test burner.

An explanation of the procedures involved in using the apparatus to obtain the desired combustion characteristics follows in the next chapter.

CHAPTER V

Procedure and Technique

The topic of procedure may readily be divided into two parts, the procedure for obtaining values of the ignition velocity and the procedure for obtaining limits of inflammability.

In testing for ignition velocity the object is to ascertain the speed with which the flame front (inner cone) is progressing in a direction normal to its surface and in relation to the combustible mixture being burned. The principle involved in obtaining values with this instrument is the one first proposed by Gouy, that the ignition velocity is simply the volume of combustible burned per unit of time divided by the area of the flame front (in this case the inner cone). This may be expressed as

$$u = V/S$$

where V is the total volume of mixture admitted to the burner and S is the inner cone surface area.

The volume, V, is obtained by metering the gas and air before they enter the burner. The surface area, S, may be computed from the dimensions of the magnified

image of the inner cone traced from the window on the front of the cabinet. Corsiglia (2) included a complete derivation of the expression used in this computation. The essential steps are as follows:

1. An inner cone of a gas flame is shown in Figure 2. The area of the cone cross-section is that area bounded by the cone outline and in the plane of the paper. Let this area be represented by A. Then A/2 is the area to the left or right of the cone axis. The surface of the inner cone is equivalent to the surface generated by revolving a line of the same length as the side of the cone, L, about, and parallel to, the cone axis, using the average distance of the cone side from the axis, A/2H where H is the height of the cone, as the radius. The surface of the cone is then

$$S = (2\pi A/2H)L = \pi AL/H$$

2. Since the outline of the cone from which these dimensions are taken is a magnified one, it is necessary to insert a de-magnification factor into the above expression in order to get the true cone surface area. If the cone has been magnified M times, then the actual dimensions are

   A/M^2 = actual area of cross section.

   H/M = actual inner cone height.

L/M = actual length of the side of the inner cone.

In order to obtain the actual surface area, then, all that is necessary is to substitute into the derived equation for S the actual dimensions. This substitution yields the expression

$$S = \frac{\pi (L/M)(A/M^2)}{H/M} = \frac{\pi LA}{HM^2}$$

3. In order to be able to solve for the ignition velocity directly, the expression for the surface area is substituted into the original expression for the ignition velocity, u. This gives the final form of the equation

$$u = V/S = VHM^2/\pi LA$$

This the equation used in computing the ignition velocity except for a constant which was inserted to convert the value from the foot-pound-second system of units, in which the measurements were taken, to the gram-centimeter-second system in which most igntion velocity curves are plotted. The actual form used was

$$u = 73.1\ VHM^2/\pi LA$$

where V is cubic feet per minute, H and L are inches, and A is square inches.

The procedure for obtaining values of ignition velocities can be broken down into four steps as follows:

1. Adjustment of the gas and air valves to obtain the desired mixture and the recording of both rates as measured by the meters.
2. Tracing the magnified inner cone from the cabinet window.
3. Measuring the dimensions of the tracing.
4. Calculating the ignition velocity from the data thus obt ained.

Step number one must be carried out with a great deal of care since it is very important to obtain as wide a spread of air/gas ratios as possible. This is necessary to get a complete ignition velocity curve. The best technique was found to be to adjust the mixture for a soft burner flame (a long,faint inner cone), and then decrease the gas rate by steps, taking a complete set of data at each point, until the flame either flashes back or blows off the burner port. Flash back is a result of the ignition velocity's becoming great enough to overcome the speed of the mixture in the burner, the flame front passing down inside the burner with a sharp report. The remedy is to increase both the air and gas rates, thus increasing the mixture velocity. Blow off is the opposite of flash back in that it is the result of the mixture velocity's becoming so great as to blow the flame front off the burner port. Obviously the measure to be taken

in this case is to decrease the velocity of the mixture by decreasing the amounts of air and gas to the burner. In between the flash back and blow off mixture velocities there is a "happy medium" range. It is in this range that the inner cone will continue to grow smaller and shorter with each decrease in gas rate until, quite suddenly, a further decrease in the gas will cause the inner cone to get longer and thinner while the yellow corona which usually surrounds the inner cone will begin to diminish and ultimately disappear. This is the region of maximum ignition velocity. Further decrease in gas slows the ignition velocity down instead of speeding it up, hence the longer inner cone. It is important to obtain a spread of readings through this region if it is at all possible. The adjustments in this region must be extremely fine in order to avoid flash back or blow off.

Step number two, tracing the inner cone, can only be accomplished in near total darkness since the light from the cone is dim to begin with and its magnified projection is still dimmer. In a dark room, after the eyes have become accustomed to the darkness, the image is quite clear and easily copied. A thin sheet of tracing paper is held over the window with left hand or with a strip of masking tape while the outline is traced with the right hand. Of course the greatest care and patience

must be exercised in order to obtain an exact reproduction. Main points to watch in tracing are that the outermost edge of the cone is the line being traced, that the exact base line is caught, and that the exact height is caught. In some cases the cone height may be slightly obscured by vibrations from the air compressor. In such an event it was the practice to mark the average height. If the error is likely to be very large (if the difference between the maximum and minimum heights is over a quarter of an inch) the reading may just as well be thrown out since it will be a mere guess at best. Vibrations are rarely encountered in serious proportions except in the very soft flames.

The measurement of the inner cone tracing dimensions is accomplished with a planimeter, reading in square inches, and a scale graduated in inches, the smallest graduation being 1/50th of an inch.

Step number five involves only substituting known values into the formula for ignition velocity and solving. The volumetric flow rates for the air and gas should be corrected for pressure differences between the meter pressures and the burner tube pressure. These pressures are measured by the water manometers on the air and gas lines and the water manometer on the mixing tube.

The procedure involved in securing inflammability

limits with this device is, in several respects, similar to the procedure just discussed for obtaining ignition velocities. The measurment of the air and gas rates is precisely the same.

The test for the lower limit of inflammability is conducted as follows:

1. Light the pilot burner at the upper end of the glass tube which should be in place as per instructions discussed under apparatus. Adjust this flame to be about 1" in height.
2. Admit air to the tube through the burner and allow the tube to become entirely purged (one minute).
3. Adjust the air rate to give a low velocity of movement to the tube. Common sense must be the guide here since the rate cannot be cut down so far that the reading is innaccurate. The method of obtaining the air rate is slightly more inaccurate than that for the gas, but the gas rate is a great deal less than the air rate. With care the inflammability limit at any air setting can be reproduced to within 1 percent or one unit of gas in one-hundred units of air.
4. Open the gas valve slowly and increase the rate by small increments allowing the mixture to become

stable throughout the system before increasing the rate again. Watch the pilot flame closely for any noticeable change. Particularly watch for a bluish envelope to begin forming along the lower edges. This is usually accompanied by a marked increase in the flame size. When this envelope appears the increments by which the gas rate is increased must be cut down to a bare minimum. Movement of the valve is not a good indication that an increase has been made for such an increase is often too much. A pressure on the valve should be followed by a period of watchful waiting to see if any change will take place in the envelope. A point will come when the envelope will begin to remove itself from the lower portion of the pilot flame. The very slightest increase in gaw rate will cause the envelope, which has now become a separate flame front, to very slowly move down into the mouth of the tube. If it just remains inside the tube and does not wink out, record the air and gas rates.

5. The lower limit of inflammability is the percent gas, by volume, in the mixture, or

$$L_L \ (V_g/V_a \ V_g)100$$

where L_L is the lower limit, V_g is the volume of gas per unit time (cfm), and V_a is the volume of air in cfm. Again both volumes must be corrected to the volumes at the pressure of the glass tube. It has been assumed that the temperature change is negligible until the gas enters the combustion layer. It has also been found that if the gas and air pressures at the meters are under three inches, the correction is entirely negligible. Since the ratio is all that is important this may be extended to mean that if the difference between the pressures of the air and gas is less than three inches, the correction is unnecessary.

The procedure for obtaining the upper limit of inflammability is very similar to that for obtaing the lower limit. It is as below:

1. Same as for lower limit.
2. Open the gas valve, keeping the air valve shut, until a small flame begins to burn on the top of the glass tube. Adjust the gas so that this flame is just large enough to mingle with the pilot flame. Again allow the tube to become well purged before proceeding with the test.
3. Admit air to the tube in the same manner as gas was

admitted in finding the lower limit. In this case, however, the condition to watch out for is the appearance of an inner cone in the flame on top of the tube. Since the mixture in the tube is moving very slowly, this cone may not be noticed with the result that the flame front will flash back down the tube with a resounding fog-horn sound. A second try will usually result in an inner cone if extreme care is taken in admitting the air. If and when the cone does not appear a very slight increase in air will cause the inner cone to move very slowly down inside the tube and progress to the bottom where it will wink out. A new flame will form on top of the tube, an inner cone will slowly form, and again it will move down inside the tube. This cycle will repeat itself over and over. Very very fine adjustments aill cause the cycle to slow up, and it is the object of the test to determine the air and gas rates when the flame just barely moves down the tube.

4. When these rates are obtained they are substituted into the same expression as that for the lower limit

$$L_U \ (V_g/V_a \ V_g)100$$

where L_U is now the upper limit.

It should be added that the upper limit is somewhat

more difficult to obtain , and the assumption cannot be made as to the temperature of the mixture in the tube, as before, because the flame burns directly on top of the tube for a considerable length of time, heating it up,considerably. If however the pressures of the air and gas at the meters is kept within three inches of one another, and assuming that the two gases in the tube are heated the same amount, then the amount of heating will not affect the final calculations as the result is a ratio.

CHAPTER VI

Results of Tests

Three gases were tested with the apparatus to find the degree of success with which it will obtain the flame characteristics desired, namely ignition velocity and inflammable limits. The gases tested were Portland Gas and Coke Co. oil gas supplied as Corvallis city gas, commercial butane, and commercial propane.

The Corvallis city gas yielded the most satisfactory results, it being the fastest burning gas of the three by a great deal. The ignition velocity curve for this gas is shown in Figure 9. Also shown are the curves obtained at the American Gas Association Laboratories, in Cleveland, for comparable gases. The reader will notice that the co-ordinate axes are ignition velocity and primary air - percent of theoretical requirement for complete combustion. This has become the practice since a comparison of ignition velocity curves, with percent air as the abscissa co-ordinate, would offer no basis for comparison. In order to obtain the value of the theoretical air required for complete combustion the chemical analysis of the gas must be known. From this analysis

the amount of oxygen needed, over and above that already in the gas, may be calculated. Knowing the amount of oxygen needed the amount of air necessary to supply this amount of oxygen is calculated knowing that air contains 21% oxygen by volume. In the case of Corvallis city gas the theoretical air required is 4.98 times the amount of gas by volume. The chemical analysis from which this was calculated is:

Constituent	Percent by Volume
CO_2	3.0
N_2	8.0
H_2	46.4
C_2H_6 (Ethane)	.7
C_4H_{10} (Butane)	.2
O_2	.9
CO	8.0
CH_4	27.4
CH_8	.8
C_6H_6	.8
C_2H_2	4.0
	100.2

The theoretical air required for complete combustion of butane and propane was given by the A.G.A. as 30.7 and 23.9 respectively.

The percent of hydrogen in Corvallis city gas is quite high which tends to make it fast burning. On the other hand there is a sizable measure of the slow burning constituent methane also present. Apparently the hydrogen has the greatest effect for the gas has a fairly rapid rate of flame propagation.

The ignition velocity curve for the city gas looks very much as should be expected. Several trials were necessary to pass the region of highest ignition velocity over into the region where the curve drops off with increased air in the mixture. The two other gases shown are compared with the curve because of their high hydrogen contents. The blue water gas has a hydrogen content of 47.5 with almost no methane present, while the coke oven gas has a hydrogen content of 57.4% and a methane content of 23.1%.

The ignition velocity curves for butane and propane were rather disappointing. Only three points were obtained for each. The main difficulty encountered was the tendency of both gases to blow off the burner because of their extremely slow rates of flame propagation. Moreover both gases were very hard to work with because the inner cone formed, when it was possible to obtain one, almost always had a yellow tip on it, making it very difficult to tell where the cone height should be taken. A larger port was tried in order to find a way to secure a more distinct cone, but to no avail. Still another difficulty with these gases was the fact that in order to obtain an inner cone the mixture velocity had to be very small. This necessitated very slow air and gas rates with a decrease in the accuracy with which the instruments

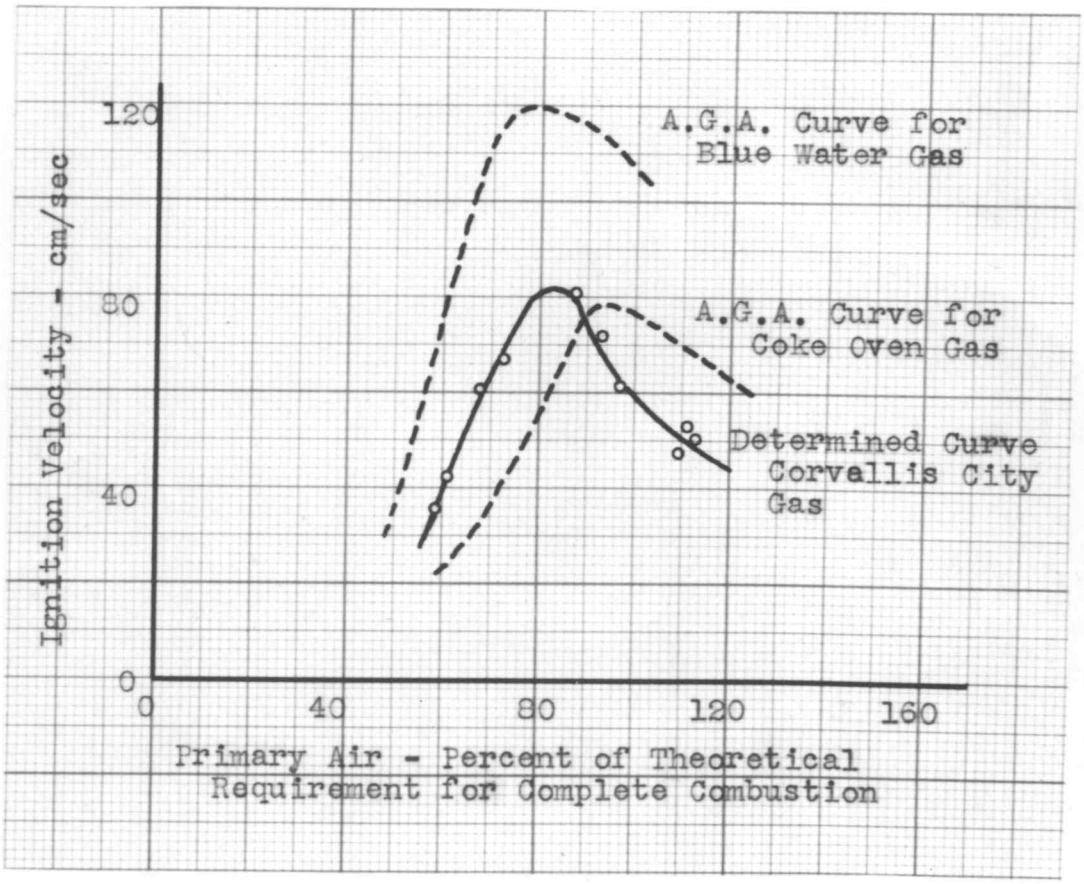

Figure 9 - Comparison between the ignition velocity curve for Corvallis city gas determined by the author and curves determined by the American Gas Association Laboratory for two common gases by the Corsiglia Method.

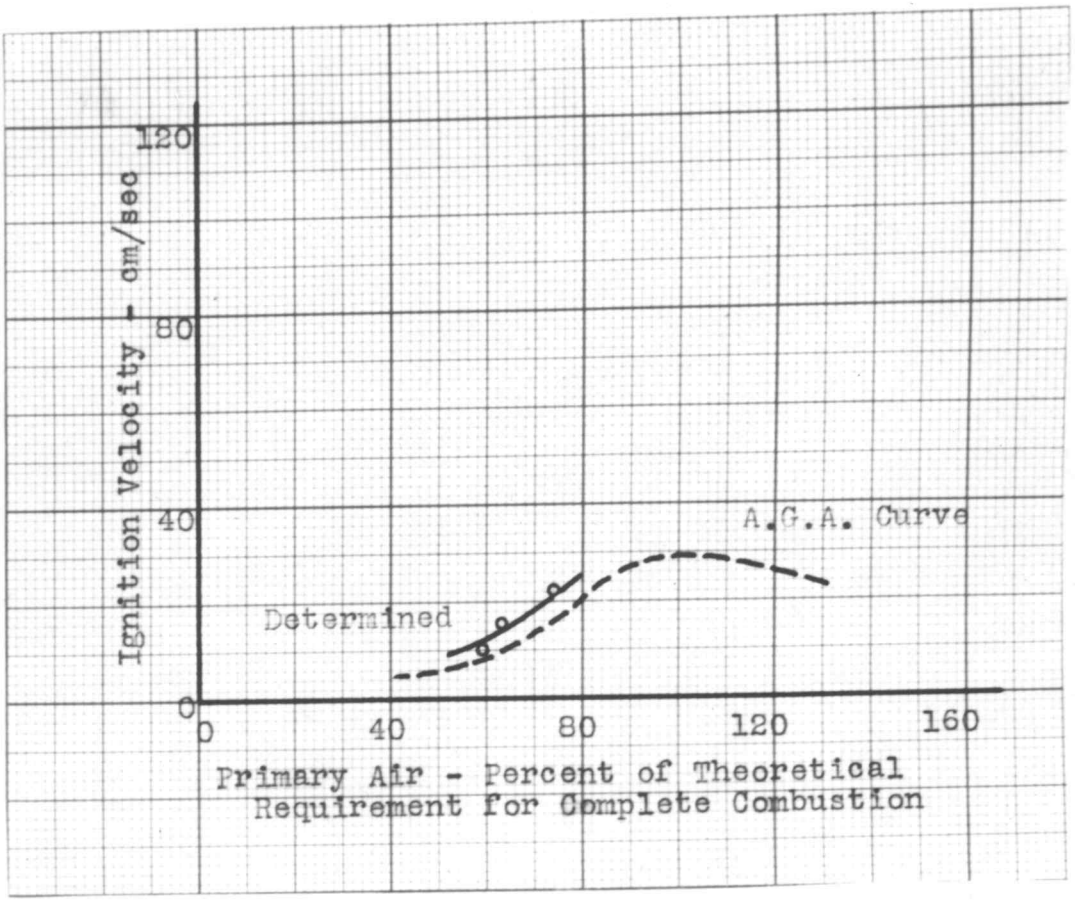

Figure 10 - Comparison between the segment of the ignition velocity curve that the author was able to determine for butane gas and the complete curve obtained by the A.G.A. Laboratory for similar gas.

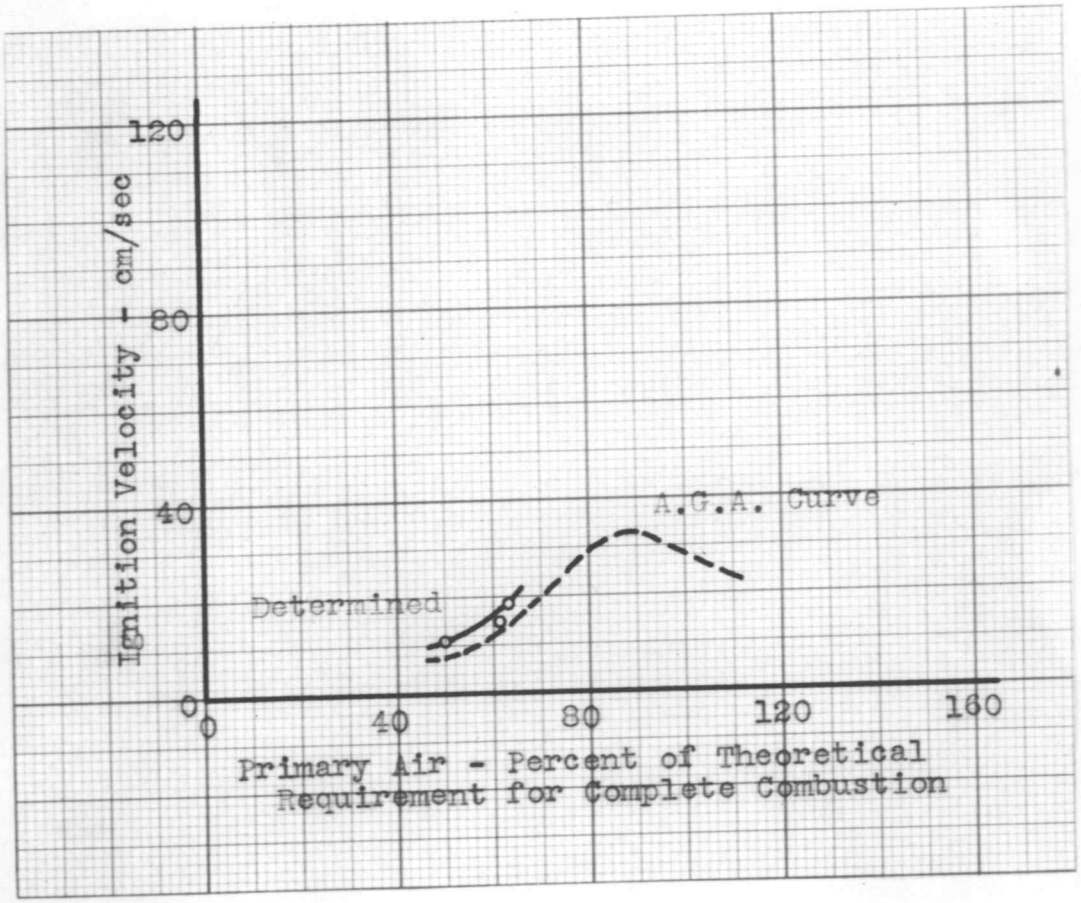

Figure 11 - The segment of the ignition velocity curve obtained for propane compared with a complete curve determined at the A.G.A. Laboratory.

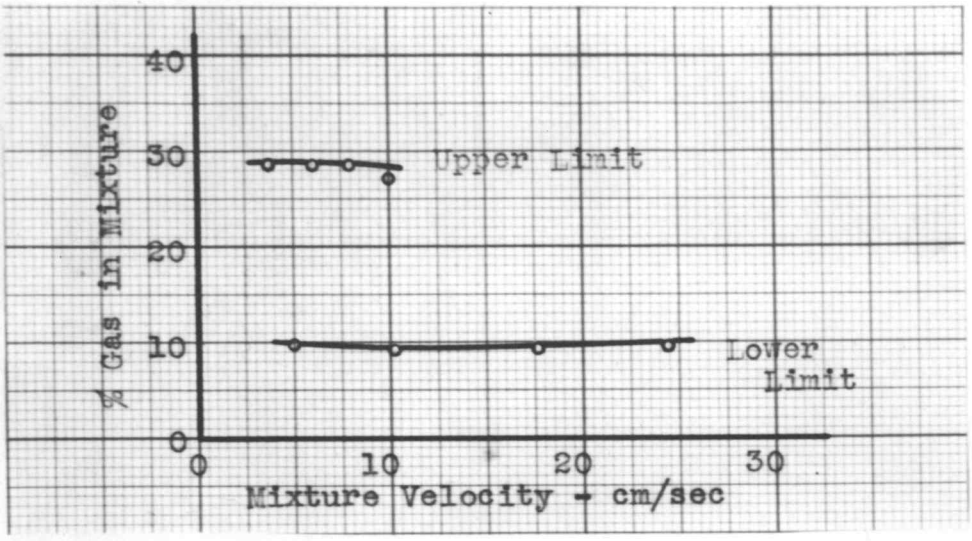

Figure 12 - Variation in limits of inflammability with mixture velocity in Corvallis city gas.

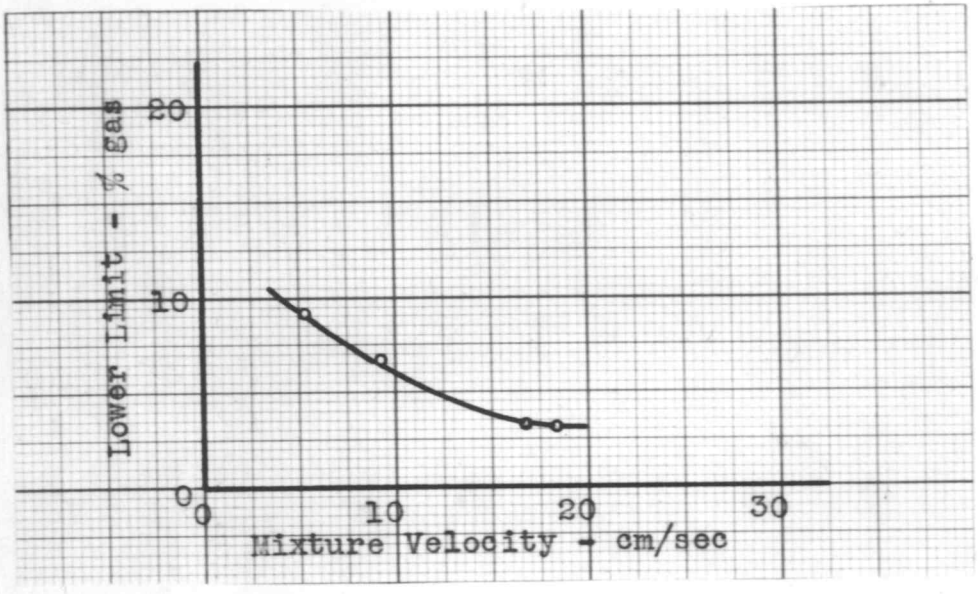

Figure 13 - Variation in the lower limit with mixture velocity in butane.

could be read. In Figures 10 and 11 the segments of the two ignition velocity curves it was possible to obtain are compared to curves for these two gases as determined by the A.G.A. Laboratory. In both cases the curves are not identical by any means, but it is evident that they are somewhere nearly the same. This makes it appear that perhaps the error may be in the readings taken and not in the method used.

The results of the inflammability limits tests on Corvallis city gas are shown in Figure 12. The lower limit is almost constant over the range of mixture velocities tested at about 9.5% gas, by volume, in the mixture. No comparison was possible for this figure, but it does not seem unreasonable. The same may be said of the value obtained for the upper limit (29%). Of three determinations made below a mixture velocity of 10 cm/sec all three yielded the same result exactly - 28.8%.

It must be remembered that as the mixture velocity increases the flame front less readily enters the glass tube, thus the mixture might be inflammable and still not be recognized as such by the observer since the test procedure requires that the flame be in the tube before the limit is considered reached. This is not an unreasonable specification if the mixture velocity is kept quite low.

Attempts to obtain the upper limits of butane and propane were quite inconclusive. The upper limit for butane was found to be about 7% which agrees fairly well with the value given by the A.G.A. which is 8.4%. A possible reason for this discrepancy might be the one mentioned above. The mixture rate was relatively high, since there had to be enough gas passing through the tube to measure on the wet test meter. Therefore the speed might have been high enough to retard the movement of this slow burning mixture down into the tube, thus giving the slightly lower upper limit reading.

The lower limit of butane varied quite considerably as the mixture velocity increased as is shown in Figure 13. The last two determinations were almost the same - 3.1% and 3.4%. This value is not very close to that given by the A.G.A. which is 1.85%. It seems evident from this, and it was apparent during the tests, that the method for obtaining the inflammability limits is likely to be in larger and larger error as the limit becomes less and less. The main cause being the very small amounts of gas and air being metered at such low rates.

CHAPTER VII

Conclusion

The device as developed yields fairly good results for both ignition velocity and limits of inflammability provided that the gas under test is a reasonably fast burning one. The same is not true when testing a slow burning gas such as butane or propane or methane or producer gas.

The main difficulty lies in the methods of controlling and measuring the air and gas. In the case of a slow burning gas the total volume of mixture must be very small in order to achieve any results. When the rates are so slow however, the readings of the metering devices used are not accurate enough. It is the author's opinion that another method of supplying the air would be very helpful along this line. If in this way the vibrations due to the compressor were completely eliminated the ignition velocity values for slow burning gases would be much more accurate.

The method involved in determining ignition velocity is a simple and fairly rapid one. A great deal of care is necessary however, in tracing the inner cone if

consistent results are to be obtainable. The test burner cabinet with the lens and mirror arrangement to enlarge the inner cone has worked very well and with improved methods of supplying the air it should perform even better.

Inflammability limits obtained with this device must be viewed in the proper light. Actually the limits may be found only by mixing air and gas in a tube and attempting to ignite it at one end. In such a case the mixture is absolutely motionless. The method employed in using this device is similar except that the mixture is not motionless at all. A reasonable correlation between results obtained by the two methods may be possible if the mixture velocity is kept low enough. However, the values obtained with this device are not close enough to actual values to be termed the limits of inflammability in the strictest sense. For reasonably close approximations and as a good illustration of the property of inflammability limits in air-gas mixtures the test apparatus is excellent if carefully used.

BIBLIOGRAPHY

1. American gas association. Gaseous fuels New York, The Association, 1948. 367p.

2. Corsiglia, John. New method for determining ignition velocity of air and gas mixtures. American gas association monthly, Oct. 1931.

3. Fiock, Ernest F. and Marvin, Charles F. The measurement of flame speeds. Chemical reviews 21:367-387, Dec. 1937.

4. Lewis, Bernard and Von Elbe, Guenther. Theory of flame propagation. Chemical reviews 21:347-358, Dec. 1937.

5. Payman, W. and Conrad, H.F. Problems of flame propagation. Chemical reviews 21:359-366, Dec. 1937.

6. Smith, Francis A. Problems of stationary flames. Chemical reviews 21:389-412, Dec. 1937.