DEPARTMENT OF

MINES AND TECHNICAL SURVEYS

MINES BRANCH

AN INVESTIGATION OF GAS EXPLOSION TRANSMISSION THROUGH SHORT CYLINDRICAL CHANNELS OF VARYING LENGTH AND DIAMETER

E. D. DAINTY & G. K. BROWN

FUELS AND MINING PRACTICE DIVISION

Presented to
Restricted International Conference of Directors of
Safety in Mines Research July 12th to 16th 1965

Reprint Series RS 2

Price 25 cents

Available by mail from the Queen's Printer, Ottawa,
and at the following Canadian Government bookshops:

OTTAWA
Daly Building, Corner Mackenzie and Rideau

TORONTO
Mackenzie Building, 36 Adelaide St. East

MONTREAL
Aeterna-Vie Building, 1182 St. Catherine St. West

or through your bookseller

A deposit copy of this publication is also available
for reference in public libraries across Canada

Price 25 cents Catalogue No.

Price subject to change without notice

ROGER DUHAMEL, F.R.S.C.
Queen's Printer and Controller of Stationery
Ottawa, Canada
1966

14

AN INVESTIGATION OF GAS EXPLOSION TRANSMISSION THROUGH SHORT CYLINDRICAL CHANNELS OF VARYING LENGTH AND DIAMETER

E.D. DAINTY
G.K. BROWN

Restricted International Conference
of Directors of Safety in Mines Research,
Sheffield, England, 1965

Conférence Internationale Restreinte des
Directeurs d'Instituts pour la Sécurité dans les Mines,
Sheffield, Angleterre, 1965

Beschränkte Internationale Konferenz
der Leiter von Grubensicherheits-Instituten,
Sheffield, England, 1965

Международное Собрание Директоров
Научно-Исследовательских Институтов по
Безопасности в Угольной Промышленности,
Шеффильд, Англия, 1965

SUMMARY

The Mines Branch of the Canadian Department of Mines and Technical Surveys recently began a series of studies on gaseous explosion transmission through various types of channels. The results of the initial stage which was concerned with transmission of explosions through cylindrical channels, are presented in this paper.

The experimental results are presented in the form of a diameter versus length characteristic for a 9.5% methane-air mixture. This characteristic is the transition line between a non-ignition transmission region and an ignition transmission region. In addition it is suggested that there is an optimum length at a minimum diameter on this transition characteristic. Consequently, reducing the length below the optimum would require an increase in diameter for ignition transmission to occur.

It is believed that this peculiar reversal is due to an "orifice effect", which differentiates this phenomenon from the behaviour of flat joints. A discussion of this effect suggests that the aerodynamic flow configuration through a round channel is the most important factor determining the location of the optimum length. Also, the discussion suggests an explanation for the reversal effect for cylindrical channels.

AN INVESTIGATION OF GAS EXPLOSION TRANSMISSION THROUGH SHORT CYLINDRICAL CHANNELS OF VARYING LENGTH AND DIAMETER

by

E. D. Dainty[1/] and G. K. Brown[2/]

[1/] Research Scientist, [2/] Head, Electrical Equipment Certification Section, Fuels and Mining Practice Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

Paper presented to

RESTRICTED INTERNATIONAL CONFERENCE
OF DIRECTORS OF SAFETY IN MINES RESEARCH
July 12th to 16th 1965

held at

SAFETY IN MINES RESEARCH ESTABLISHMENT,
MINISTRY OF POWER,
Central Laboratories, Red Hill, off Broad Lane,
Sheffield, 3, Great Britain

CONTENTS

ABSTRACT

Published work on gaseous explosion transmission leads the authors to believe that there is an optimum channel length for explosion transmission through a minimum channel diameter. This paper presents experimental results and discussion confirming the existence of such an optimum length, and the length-diameter ignition transmission characteristic for a 9.5% methane-air mixture.

INTRODUCTION

The Mines Branch of the Canadian Department of Mines and Technical Surveys recently began a series of studies on gaseous explosion transmission through various types of channels. The results of the initial stage, which was concerned with transmission of explosions through cylindrical channels, are presented in this paper.

Experiments of Wolfhard and Bruszak (2) show that a diameter versus length characteristic exists for a given combustible mixture. This characteristic is the transition line between a non-ignition transmission region and an ignition transmission region. In addition it is suggested that there is an optimum length at a minimum diameter on this transition characteristic. Consequently, reducing the length below the optimum would require an increase in diameter for ignition transmission to occur.

It is believed that this peculiar reversal is due to an "orifice effect", which differentiates this phenomenon from the behaviour of flat joints. Experimental results of Riddlestone (3) show that for flat joints, propane-air mixtures require increasing gaps for flange widths increasing from approximately 3 mm.

This paper includes a graphical presentation of an experimental length-diameter characteristic showing the "orifice effect". The subsequent discussion suggests that the aerodynamic flow through the round channel is the most important factor determining the location of the optimum length. Also, the discussion suggests an explanation for the reversal effect for cylindrical channels.

APPARATUS

A scale drawing of the apparatus employed for the experimental work is shown in Figure 1. It consisted of a compartmented cylindrical steel explosion vessel lined with high polish aluminium foil and equipped with viewing windows, circulation fans, igniter, flushing connections, and a partition into which was mounted a brass cylindrical channel. One hundred combinations of channel length and diameter were used, ranging from 1.47 to 50 mm in length and 1.98 to 3.78 mm in diameter.

The viewing windows permitted positive confirmation of ignition in Chambers 1 and 2. The igniter was made so that the position of the spark could be varied and then locked in the desired position by a clamping system. The spark was generated by means of an automobile ignition coil operating in a 10 volt d.c. circuit.

The brass channel blocks were manufactured with flat faces as shown in Figure 1, except for channels of 12 mm or less. The brass blocks for the latter were 15 mm long over-all, but were recessed out to a diameter of 33.3 mm on the downstream face and to a depth that resulted in the desired channel length. To check the effect of this recess on the transmission of ignition, an essentially non-recessed block of short channel length was made.

All of the joints in the vessel, including the partition between Chambers 1 and 2 and the brass channel blocks, were sealed by O-rings or rubber gaskets, so that no pressure relief occurred except through the channel itself.

The 9.5% methane-air mixture was prepared, using 99% pure methane, in a water-sealed gas holder of 70 cubic feet capacity. For analyzing the mixture an infra-red "Liston-Becker Model 15A Plant Stream Analyzer" was used. A wet and dry bulb psychrometer was placed in the flushing line at the outlet from the explosion vessel for relative humidity determination.

Chambers 1 and 2 were fitted with hand operated globe valves to permit individual flushing and to prevent pressure relief during explosions. The flushing system was equipped with a volume counter interlocked with electrically operated valves programmed to close so that the amount flushed through the chamber was duplicated for each test.

PROCEDURE

After the desired channel was mounted and the vessel ends fitted, both chambers were flushed with the prepared methane-air mixture, which was analyzed with the apparatus mentioned above. Providing the analysis was within $\pm$ 0.1% of 9.5%, the mixture was considered satisfactory. After 2 cubic feet of mixture was flushed through both chambers in parallel, the fans vigorously mixed the chamber gases for a period of 30 seconds. Then an additional 2 cubic feet was flushed in an identical manner, including 30 seconds of mixing. The outlet of Chamber 1 was then closed and an additional 2 cubic feet of mixture was flushed in order to provide a positive flow of flesh mixture through the channel itself. The humidity was measured near the end of the last flushing period and all the hand operated globe valves were closed. The mixing fans were turned on for 60 seconds, after which the mixture was permitted to become quiescent during a period of 2 minutes before ignition in Chamber 1 by a single spark located on the channel centre line, one half inch distant from the Chamber 1 channel face. (See Figure 1).

If a non-ignition in Chamber 2 resulted, the hole was drilled out to the next drill size and the process was repeated until an ignition occurred.

Ignition transmission and non-transmission were plotted in Figure 2. The lowest ignition transmissions were joined to produce the characteristic shown.

RESULTS

All the experimental results are shown in Figure 2 and indicate the following:

1. There is an optimum length for minimum diameter for ignition transmission through cylindrical channels.

2. This optimum length occurs in the range of 10 to 20 mm in these experiments at a minimum diameter of 2.26 mm.

3. For shorter channel lengths of 1.47 to 5.76 mm a larger diameter was needed for ignition transmission and its size, 3.46 mm, is close to the laminar flame quenching diameter of 3.2 mm reported by Lewis and von Elbe (4).

4. A gradual increase in diameter, above the minimum diameter at optimum length range, is required for ignition transmission through channel lengths greater than 20 mm.

5. The resulting shape of the length-diameter characteristic is believed to be due principally to "orifice effect" and is referred to at length in the section of this paper entitled "Discussion of the Relationship between Channel Flow and Ignition Transmission".

Consideration of Item 3 of the results is of interest. As the length of the channel decreased toward 6 mm, the channel diameter approached a value of 3.46 mm and this remained constant for the shorter lengths tested. As previously mentioned, this diameter approximates the laminar flame quenching diameter of 3.2 mm. In Figures 11 and 12 of Reference 1, which show photographs of hot jets initiating ignition, a noticeable lateral jet growth indicates that ignition in the external mixture occured only 1 millisecond from the instant of chamber ignition Becaûse the pressure rise in time intervals of the order of 1 millisecond is insignificant and assuming that ignition is near the channel entrance, it is probable that a substantially undisturbed laminar flame would propagate through a hole the approximate size of the laminar flame quenching diameter. On the other hand, hot gas caused ignition through channels of cross-section less than the flame quenching diameter, as is shown for the longer channel lengths of Figure 2.

Points A and B of Figure 2 show the results of varying the location of the recesses relative to the spark in blocks containing channels 12 mm in length, or less. Point A shows the diameter at which an ignition transmission occurred when the block position was the reverse to normal (recessed face upstream of the channel entrance). The same block was then reinstalled in the normal position without changing any dimensions and an ignition transmission resulted. Because this indicated that the recess position may have affected the results, a block of the same channel length and diameter was made having a 3.17 mm step at a radius of 21.4 mm from the channel centreline on both faces. This block was considered to be flat-faced for channel entrance and exit conditions. The result is given by Point B on Figure 2. It appears, therefore, that all the experimental recessed blocks were equivalent to flat faced channel blocks.

DISCUSSION OF THE RELATIONSHIP BETWEEN CHANNEL FLOW AND IGNITION TRANSMISSION

It is well known that, when a flow from a large chamber enters a hole, there is a constriction in the flow downstream of the entrance called the vena contracta. The following is quoted from Fluid Meters, Their Theory and Application (5), "It is definitely known that for any one orifice the distance from the plane of the orifice to the plane where the static pressure is a minimum is nearly or quite independent of the flow. On the other hand, this distance varies considerably with the diameter of the orifice, and the pressure minimum is farther away for small rather than for large orifices". Information from Reference (5) also gives an indication that the vena contracta location (L_V in Figure 3) for the present work would be in excess of 0.7 mm. In addition it states that the axial location of the vena contracta from the inlet is an inverse function of the diameter.

The flow, after constricting to a minimum section at the vena contracta, would then gradually expand to fill the channel thus enclosing a circulating eddy. The length to the reattachment point for this expansion is designated L_R in Figure 3.

Examination of the two-dimensional experimental and theoretical results of Mueller (6) revealed two items of particular interest. The first point is that the reattachment length appears (by extrapolation of the results) to increase a small amount for jet exit Mach numbers from zero to unity. For higher Mach number flows there is an increasing enlargement of the reattachment length. The second point is that the reattachment length varies directly with the jet exit dimension, which is analagous to the diameter of the vena contracta in this study. This vena contracta diameter in turn is directly related to channel diameter. Therefore, reattachment length varies directly with channel diameter. However, a direct computation of the reattachment length is not presented here, because too many assumptions have to be made to adapt the reference data to the physical conditions of the authors' experimental apparatus.

Thus the vena contracta length, L_V, varies inversely with diameter and the reattachment length varies directly with the diameter. The combined effect of these two relationships is to lessen the dependency on diameter of the total length to reattachment (L_V + L_R). In the estimation of the authors, however, the reattachment length, L_R, is the greater of the two lengths, so that the effect of increasing diameter would be to shift the reattachment point downstream.

An increase in the distance of the spark from the channel entrance would require a greater elapsed time for the hot gas to enter the channel. At that time a significant pressure rise may have occurred, causing channel flows approaching Mach 1. Therefore, according to the first point from Mueller (6) it would be expected that the reattachment point would move downstream a small distance. Similarly the reattachment point should move farther downstream for mixtures that generate higher combustion temperatures resulting in increased reaction rates and decreased time to build up pressure in the internal mixture. The authors believe, however, that the shift due to mixture strength would be insignificant when the igniting spark is near the channel entrance.

The above suggests that the present experimental conditions would result in a reattachment length very close to the minimum.

If the channel is longer than the total length to flow reattachment (L_V + L_R), a boundary layer adjacent to the channel wall builds to a thickness that is a function of the length from the reattachment point (Reference 7 for either laminar or turbulent boundary layers). The boundary layer build-up continues until the jet emerges from the channel. The main body of the flow is simultaneously reducing in diameter as the boundary layer grows until the effective jet exit diameter, d_{JET}, is reached. Therefore, the longer the channel length for a given diameter, the more quickly the jet emerges, the more turbulent it is and the larger the channel diameter must be for ignition transmission.

The above flow visualization assumes that the flow through the channel is subsonic for a period longer than it takes transmission to occur. It has been stated previously that there does not appear to be sufficient time for the internal pressure to rise enough to cause a critical pressure ratio across the channel so that the flow should be subsonic. Therefore, the vena contracta and reattachment flow configurations do not act as a supersonic converging-diverging nozzle before transmission of ignition occurs. Thus Mach 1 flow should represent a limit, and expansion in the channel can only result in reduced velocity.

Consider the effect of continually reducing the length of the channel shown in Figure 3, from Station 5 to Station 4, maintaining all other variables constant. Assume that at Station 4 the effective flow diameter is critical and ignition transmission begins to occur. Further reduction in length to Point 3 would result in a continuously increasing probability of ignition due to a continuously decreasing level of exit jet turbulence, which is in turn due to the continuously increasing effective exit diameter. The greatest probability of ignition transmission would occur at Station 3 because of minimum jet exit turbulence.

This suggests that the length from channel entrance to the reattachment point is the optimum length for ignition transmission and is the point (or range) at which the length-diameter characteristic reaches a minimum diameter.

At the optimum length the reattachment takes place at the lip of the exit. Flow disturbances would cause momentary shifts in reattachment. Thus, the eddies under the vena contracta would be occasionally exposed to the exit environment. The eddies would then be able to shed, resulting in flow instability at the optimum length. This instability would be reflected in an increased experimental spread (such as is shown in Figure 3, between the lengths of 12 and 20 mm).

Further reduction in length from Station 3 would result in a reducing effective jet diameter and greater turbulence causing the probability of ignition transmission to reduce until it could not occur without an increase in channel diameter. Also, Wolfhard and Bruszak (2) state that for channels the divergence of the jet increases with decreasing length. It is likely that this effect is due to a lack of channel walls to confine the flow. The dilution of hot gases is accomplished more rapidly so that ignition is inhibited. Therefore, it is necessary to increase the diameter of the channel for lengths shorter than the optimum in order to once again traverse the critical diameter required for ignition transmission. This is necessary until flame transmission can occur at or near the laminar flame quenching diameter (when the ignition spark is near the channel entrance).

The above discussed relationship between channel flow and ignition transmission suggests that the location of the optimum length for ignition transmission in cylindrical channels is determined primarily by the aerodynamic flow configuration.

REFERENCES

1. Wolfhard, H.G., Bruszak, A.E. Communication of Flame Through Cylindrical Channels. Bureau of Mines Report of Investigations 5457, 1959 , pp 16 to 18.

2. Wolfhard, H.G., Bruszak, A.E. Suppression and Transmission Explosions by Cylindrical Channels. Bureau of Mines Report of Investigations 5495, 1959, pp 6, 7 and 18.

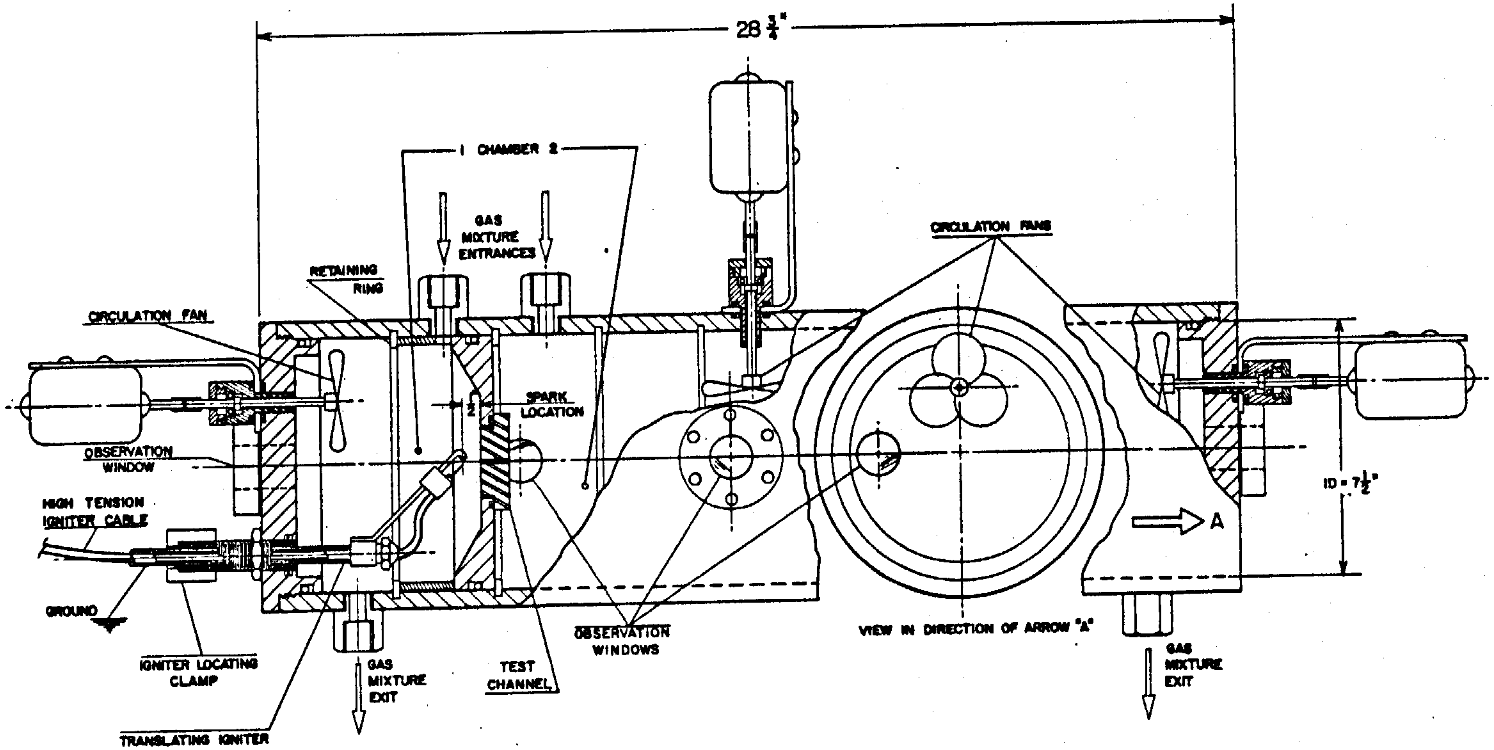
3. Riddlestone, H.G. Explosion-Proof Electrical Equipment for Aircraft. ERA Report D/T 133, 1961, Table 3.

4. Lewis, B., von Elbe, G. Combustion, Flames and Explosion of Gases. Academic Press 1951 p. 303, Figure 132.

5. Fluid Meters - Their Theory and Application, Part I, Second Edition, ASME, 1927. Paragraph 164 and curves of page 37.

6. Mueller, Thomas J. - An Experimental Investigation of the Reattachment of Compressible Two - Dimensional Jets. ASME paper number 64-FE-18, 1964.

7. Kuethe, A.M., Schetzer, J.D. - Foundation of Aerodynamics. John Wiley and Sons, Inc., 1950, pp 228 and 267.



CUTAWAY VIEW OF
COMPARTMENTED
EXPLOSION CHAMBER

FIGURE I

SCALE 1 2 3 4 5 INCHES

VOLUME OF CHAMBER 1 - 0.11 CU FT
2 - 0.53 CU FT

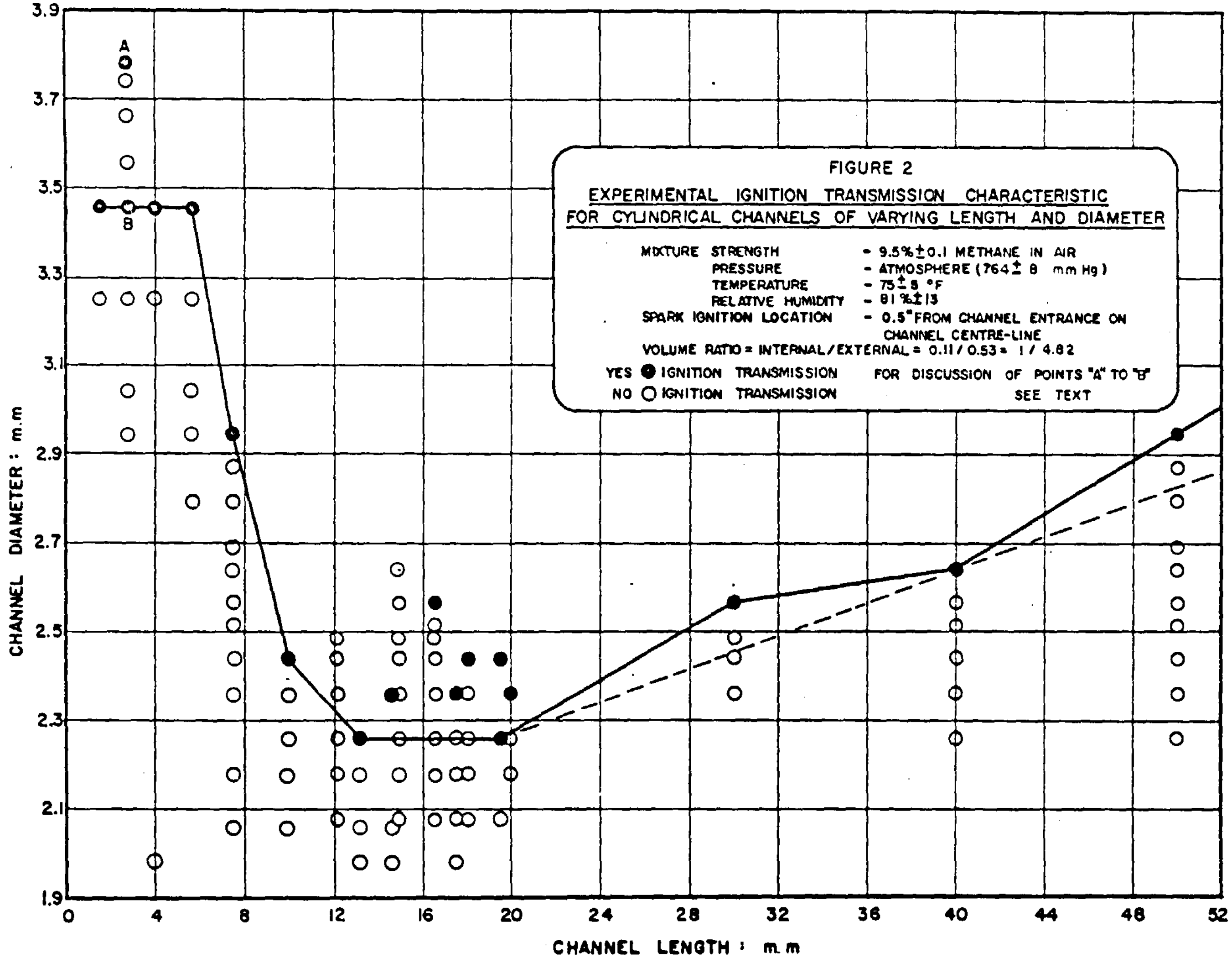


FIGURE 2

EXPERIMENTAL IGNITION TRANSMISSION CHARACTERISTIC FOR CYLINDRICAL CHANNELS OF VARYING LENGTH AND DIAMETER

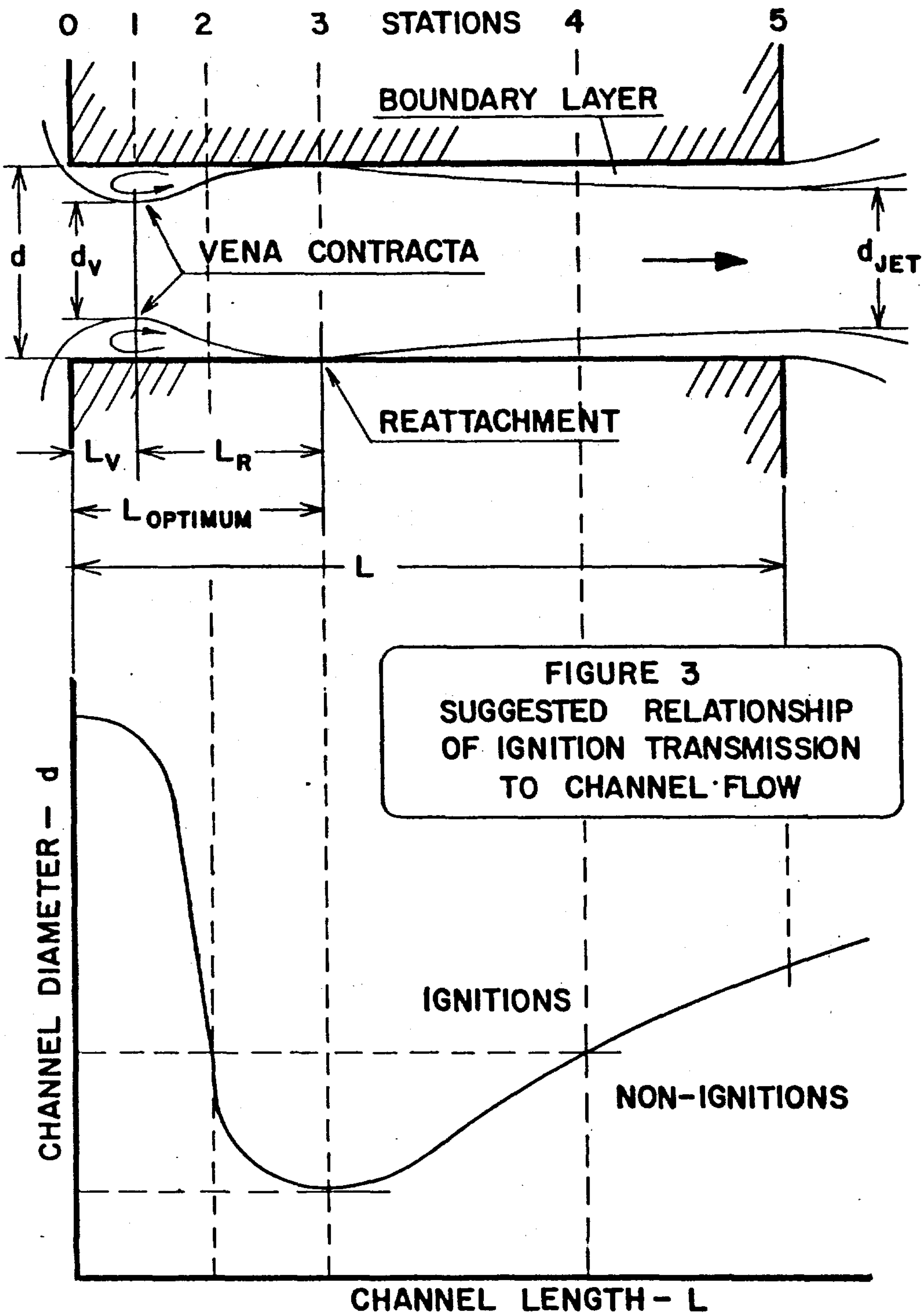


FIGURE 3
SUGGESTED RELATIONSHIP OF IGNITION TRANSMISSION TO CHANNEL FLOW