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RESEARCH REPORT

R 182

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LABORATORY INVESTIGATIONS OF HYDROGEN EXPLOSION PHENOMENA RELATING TO ELECTRICAL APPARATUS

G. K. BROWN, E. D. DAINTY AND
S. SILVER

FUELS AND MINING PRACTICE DIVISION

APRIL 1966

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

Mines Branch Research Report R 182

LABORATORY INVESTIGATIONS OF HYDROGEN EXPLOSION PHENOMENA RELATING TO ELECTRICAL APPARATUS

by

G.K. Brown*, E.D. Dainty** and S. Silver**

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ABSTRACT

The relative ease of ignition of mixtures of hydrogen and air throughout the flammable range by electric spark was found and compared to the ignition of pentane and air mixtures. A determination was made of the relationship of percentage by volume of hydrogen in air to explosion pressure in a small cubical enclosure, one quarter of a cubic foot in volume; and also of the time to reach peak pressure in the same enclosure. A study was made of the transmission of hydrogen explosions through flat joints by means of apparatus which permitted variation of the gap size, the joint width and the free volume. As the apparatus for this study was such that the gap could not expand due to explosion pressure, a further study was made of explosion transmission through the shimmed flat joints of several commercial-type, explosion-proof enclosures and an experimental enclosure, all of which had bolted covers and for which the gap changed due to pressure during an explosion. Experiments were also conducted on diffusion of hydrogen into enclosures and the possibility of transmitting hydrogen explosions through threaded joints. The results of the various studies are presented, discussed, and, in some cases, related to theoretical equations or otherwise interpreted.

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Direction des mines, rapport de recherche R 182

Recherches en laboratoire sur les explosions d'hydrogène causées par des appareils électriques

par

G.K. Brown*, E.D. Dainty** et S. Silver**

Résumé

Les auteurs ont établi la facilité relative avec laquelle des mélanges d'hydrogène et d'air s'enflamment au contact d'une étincelle électrique pour toute l'étendue de la gamme d'inflammation, et l'ont comparée à l'inflammation de mélanges de pentane et d'air. Ils ont déterminé le rapport en pourcentage qui existe entre le volume d'hydrogène dans l'air et la pression de l'explosion produite dans un petit contenant cubique ($\frac{1}{4}$ de pied cube). Ils ont enregistré aussi le temps qu'il faut pour atteindre le maximum de pression dans le contenant. Ils ont ensuite étudié la propagation des explosions d'hydrogène à travers des joints plats grâce à un appareil qui permettait de faire varier la grandeur de l'interstice, la largeur du joint et le volume libre. Vu que la fabrication de l'appareil utilisé pour cette étude ne permettait pas à l'interstice de s'agrandir sous la force de l'explosion, les auteurs ont entrepris une autre étude sur la propagation des explosions à travers les joints plats calés de plusieurs contenants commerciaux à l'épreuve des explosions et d'un contenant expérimental. Ces contenants étaient tous munis d'un couvercle boulonné et les interstices pouvaient s'agrandir sous la pression de l'explosion. Des expériences ont aussi été faites sur la diffusion de l'hydrogène dans les contenants et sur la possibilité que des explosions d'hydrogène se propagent le long de joints filetés. Les auteurs donnent les résultats des différentes études, les analysent et dans certains cas les rattachent à des équations théoriques ou en donnent d'autres interprétations.

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INTRODUCTION

As the use of hydrogen in plant processes increases in Canada so does the need for electrical apparatus which will be safe where hydrogen introduces an explosion hazard. The demand for such apparatus is not confined to Canada and both national and international recommendations for safe construction are currently under consideration. The research work embodied in this report has been carried out in the Fuels and Mining Practice Division of the Mines Branch as a contribution to basic information on hydrogen explosion phenomena, including explosion transmission through joints. Such data are useful in evaluating the hazard involved and the degree of safety afforded by explosion-proof enclosures, particularly those which are constructed with flat joints.

CHAPTER 1

RELATIVE EASE OF IGNITION OF HYDROGEN-AIR MIXTURES BY ELECTRIC SPARKS

Summary

Experiments were conducted to determine the relative ease of ignition of various mixtures of hydrogen with air. The ignition was by electric spark and the results are shown graphically in Figure 3. A similarly obtained curve for pentane is shown in the same figure for comparison purposes.

Experimental Procedure and Apparatus

For the initial series of tests, which were conducted in 1957, mixtures of hydrogen in air were prepared and kept over a solution containing equal proportions of water and glycerine. The volumes of both hydrogen and air were measured using wet test meters and the mixtures were used within a half hour after preparation. Mixtures intended to be 30 per cent and 20 per cent were checked by chemical analysis as 31.8 and 21.3 per cent respectively. The nominal mixture values were therefore adjusted in accordance with the results of chemical analyses.

The instrument used to produce the sparks and to cause the hydrogen ignitions was called a Fast Break-Flash and was constructed by the Department from drawings obtained from the Safety in Mines Research Establishment of Great Britain. The apparatus was designed to close the electrical circuit by means of an elastic wiping contact and to break it by a quick separation of the electrodes in a chosen explosive atmosphere under normal pressure. It consisted mainly of the following parts: a small plastic cylinder to contain the inflammable mixture and to house the electrodes, a pipe connection for the admission and exhausting of the mixture, and a spindle carrying the moving electrode with an external worm gear driving it at the rate of 32 r.p.m. The standard electrodes were made from specially hardened platinum alloy strips 0.25 mm in thickness. The fixed electrode was 5 mm wide and was wedge-shaped to a point at the extremity where the circuit was broken. The moving electrode was 14 mm wide, cut to a length of 20 mm, and bent to a uniform curvature of radius 16 mm. The apparatus is illustrated in Figure 1.

The electric circuit (shown in Figure 2) consisted of a known inductance, non-inductive variable resistors for current regulation, an ammeter, a battery, and the Break-Flash apparatus. The standard air-core inductance had a value of 0.095 henry. The operating voltage was a nominal 24 volts obtained from a series of 16, 1-1/2 volt lead-acid cells. The Break-Flash apparatus was calibrated by measuring the minimum igniting current for a mixture of 3.9% pentane vapour in air. The calibration conditions adopted for tests were as follows: In 100 trials with circuit constants as above, no ignition was obtained when the current interrupted was 0.150 ampere and at least one ignition was obtained when the current was 0.160 ampere. By preliminary trials a current was found at which ignition readily occurred. The value of the current was then progressively decreased, 5 to 10 milliamperes at a time, until a value was reached at which the passage of 100 sparks produced no ignition. The minimum igniting current was taken as the mean between this value and the lowest value at which ignition was obtained.

The Break-Flash apparatus was checked for calibration at the beginning and at the end of a series of tests. If, at the end of a series, the apparatus was found to have departed from the calibration condition, the results were discarded and the apparatus re-calibrated. This was usually done by re-sharpening the strip electrode or replacing the moving electrode, and the tests were then repeated. The results of the initial series of tests are tabulated in Table 1, and shown graphically in Figure 3 along with a curve for pentane-air mixtures obtained from results of earlier departmental investigations of pentane ignition.

A later series of tests was conducted in 1966 to check the ease of ignition of hydrogen-air mixtures in the lower flammable range by electric sparks. For these tests an intrinsic safety testing apparatus constructed by the department from information in the German publication VDE 0170 d/63 was used. In this apparatus, 4 slender tungsten wire electrodes brush across and leave the edge of a rotating cadmium disc.

The hydrogen-air mixtures were prepared in a gas holder and analyzed at the time of the tests with a "thermabridge" (thermal conductivity cell) hydrogen analyzer considered to have an accuracy of ± 0.1% at 6.0% hydrogen concentrations, i.e. 5.9 to 6.1%.

The results for the hydrogen experiments were that 6 per cent hydrogen ignited at 120 ma but not at 110, while 6.5 per cent hydrogen ignited at 95 ma but not at 90.

Discussion of Results

From the results using hydrogen, a comparison was possible with the earlier results for pentane with regard to the ease of igniting of such mixtures by electric sparks and leads to the conclusion that flammable hydrogen mixtures 6% or lower do not ignite as easily as the most incendive pentane-air mixtures. The question arises as to whether or not weaker hydrogen-air mixtures which ignite at the ignition current level of the best pentane-air mixtures would have an equivalent maximum experimental safe gap with regard to explosion transmission through flat joints. Experiments to throw light on this are the subject of Chapter 2.

Conclusions

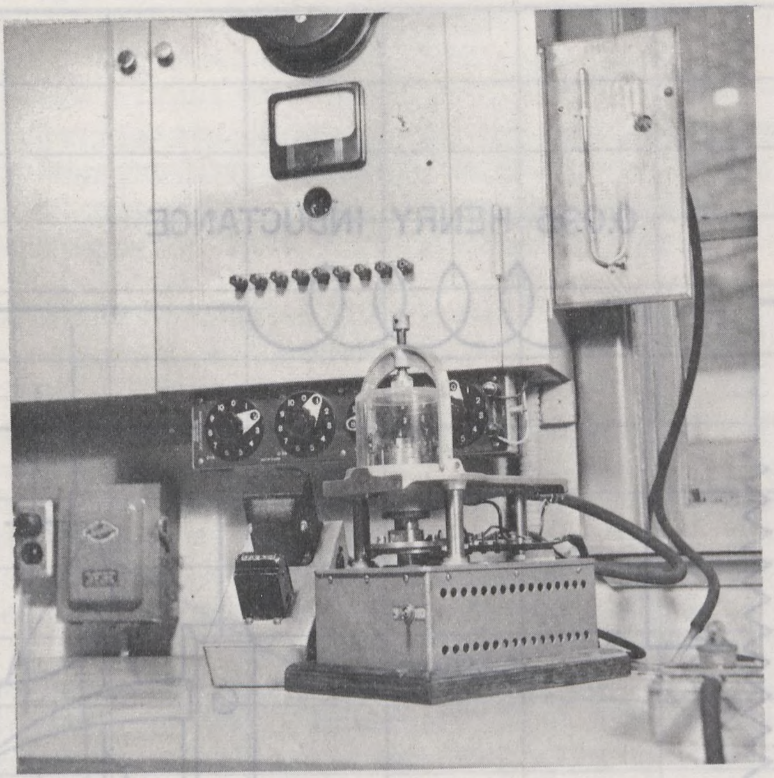
It is concluded that the most easily ignited mixtures of hydrogen-air by electric spark are those between 19 and 23 per cent.

Mixtures of hydrogen-air 6 per cent or weaker are less easily ignited than the most easily ignited pentane-air mixture.

TABLE 1

Experimental Results
(1957 experiments)

Hydrogen Mixture, % By Volume	Ignition Current, Milliamperes	Remarks
5.3	-	No ignition at 250 ma.
7.4	180.0	
10.6	97.5	
16.0	77.5	
21.3	72.5	
26.6	74.0	
31.8	77.5	
40.4	80.0	
53.0	87.5	
63.7	115.0	
74.3	-	No ignition at 250 ma.



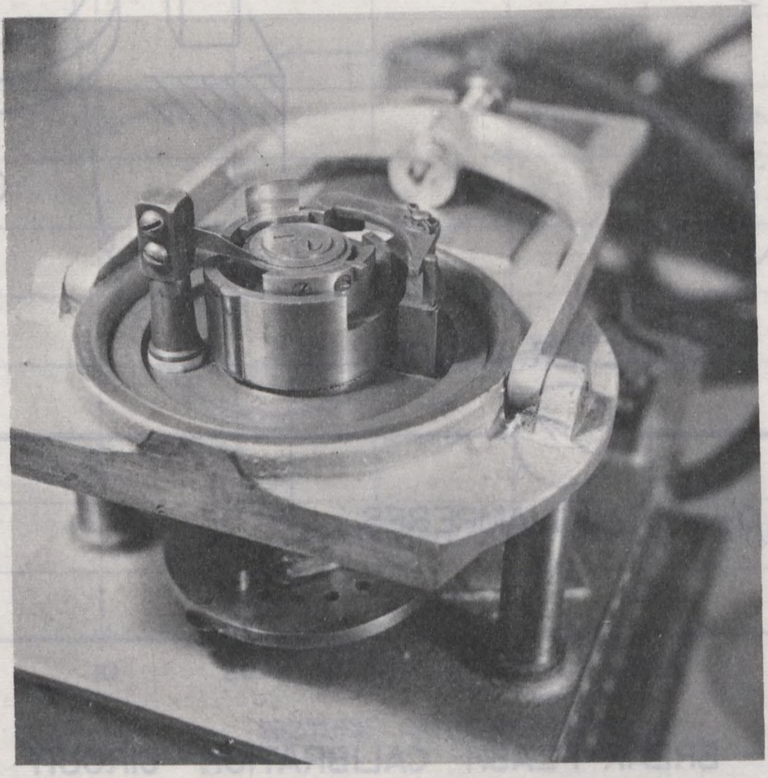


Figure 1. Top - Break-Flash Assembly
Bottom - Close-up of Moving and Stationary Electrodes

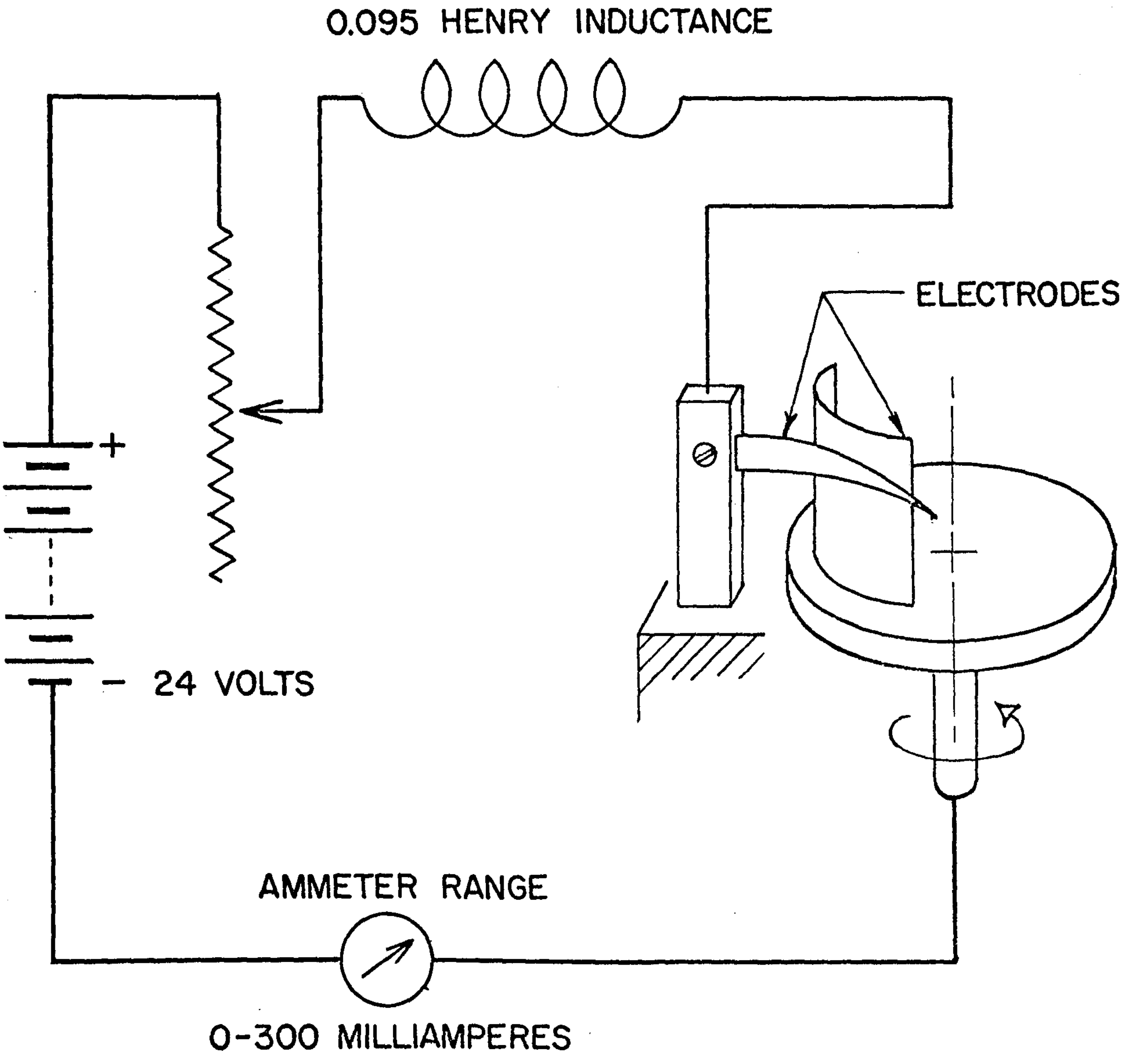


FIGURE 2- BREAK-FLASH CALIBRATION CIRCUIT

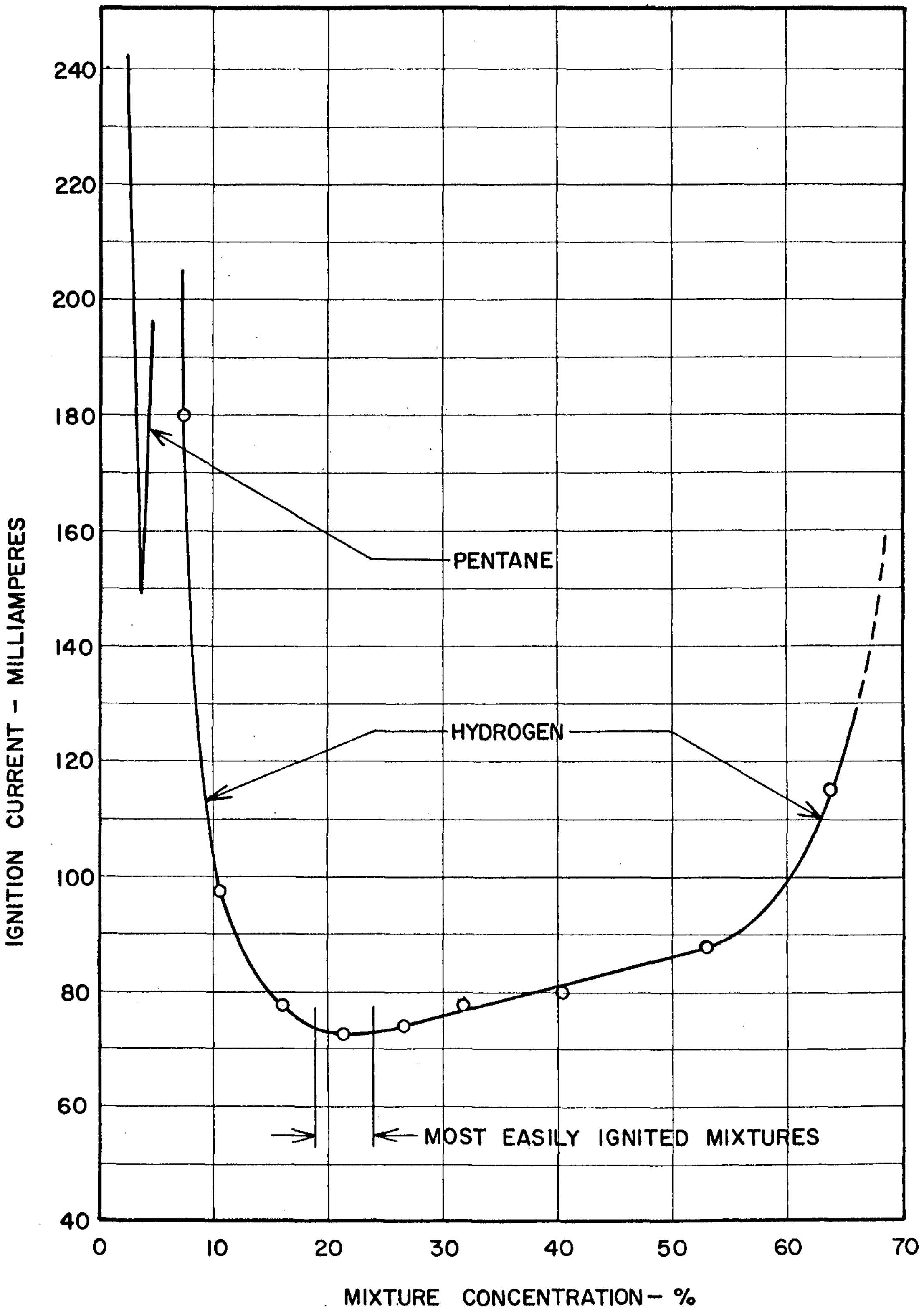


FIGURE 3 - HYDROGEN AND PENTANE IGNITION CURRENT VS CONCENTRATION

CHAPTER 2

DETERMINATION OF THE HYDROGEN-AIR MIXTURE EQUIVALENT TO THE BEST PENTANE-AIR MIXTURES WITH RESPECT TO EXPLOSION TRANSMISSION THROUGH UNEXPANDABLE FLAT JOINTS

Summary

This investigation indicates that the nominal critical hydrogen concentration in air for prevention of explosion transmission through a flat joint of 1-inch width and 0.0395 ± 0.00025 -inch gap size, is 10 per cent hydrogen. Consequently, this hydrogen concentration possesses an approximately equivalent explosion transmission probability when it is compared to the combination of the most incendive mixture of pentane and air inside an electrical enclosure, and the most easily ignited mixture of pentane and air surrounding the enclosure. The maximum experimental safe gap for pentane-air mixtures was previously determined by other investigators to be 0.040 inch.

Experimental Procedure and Apparatus

A scale drawing of the explosion chamber is shown in Figure 1 which also defines the apparatus nomenclature used throughout this report. It consisted of a compartmented cylindrical chrome-plated steel vessel, equipped with viewing windows, circulation fans, translating igniter (inductive electric spark fixed at 0.5 inch from the joint entrance), circulation connections, external volume vent of 1.25-inch diameter, and a partition onto which the flat joint investigated was mounted.

A flat joint of 1-inch width (along the flame path) was used to compare these hydrogen results with those for pentane in Reference 1. The joint length was 3 inches and the gap was measured to be 0.0395 inch ± 0.00025. The joint was arranged as in Figure 1. The internal volume resulting was large enough to eliminate the effect that small volumes have on increasing the gap size necessary for transmission (Chapter 4).

All the joints in the vessel, including the partition between the internal and external chambers and the joint pieces themselves, were sealed with O-rings. Therefore, no explosion pressure relief occurred in the internal chamber except through the flat joint itself.

The hydrogen-air mixtures were prepared by the partial pressure method, using laboratory air and a single dry hydrogen cylinder of 99.5 per cent minimum hydrogen purity for all tests. The mixtures were circulated through the closed system of chambers and flat joint in series by a non-lubricated vane-type rotary pump. The gas mixture circulation nozzles on each chamber were fitted with valves to prevent pressure relief into the circulation system.

The mixture analyses were performed on a "thermabridge" (thermal conductivity cell) hydrogen analyzer having a repeatability of within ± 1% and an accuracy of within ± 2% of full-scale deflection corresponding to 100% hydrogen.

The spark location was 0.5 inch from the inlet to the gap, as shown in Figure 1.

The desired hydrogen-air mixture was prepared, circulated at a rate of 0.5 cfm for a total of 6 minutes, and fanned for 15 seconds of each minute of circulation. After circulation, the mixture was analyzed, the external chamber vent was opened, and ignition was initiated by a single spark in the internal chamber.

Because ignition transmission was difficult to detect (i.e. there was no flame luminosity and a comparatively weak noise resulted compared to the sharp report of richer mixtures), it was necessary to determine whether or not transmission had occurred by an approximate analysis of the resulting mixture in both chambers combined. Less than 1% hydrogen concentration indicated transmission, whereas a substantial hydrogen concentration of 6 to 7.5% indicated that only the mixture in the smaller internal chamber had ignited.

After analysis the circulation lines, pump, joint and chambers were flushed by air from the laboratory supply.

The procedure was repeated 5 times for each of the 3 mixture concentrations investigated. The results are reported in Table 1.

Discussion of Results

The results indicate that the nominal critical hydrogen concentration for prevention of explosion transmission in a flat joint of 1 - inch width and 0.0395 ± 0.00025 inch gap size, is 10% hydrogen in air.

Conclusions

A nominal mixture of 10 per cent hydrogen by volume in air represents an approximately equivalent explosion transmission probability as does the combination of the most incendive and most easily ignited mixtures of pentane in air, when compared on the basis of ignition transmission through a flat joint of 1 - inch width.

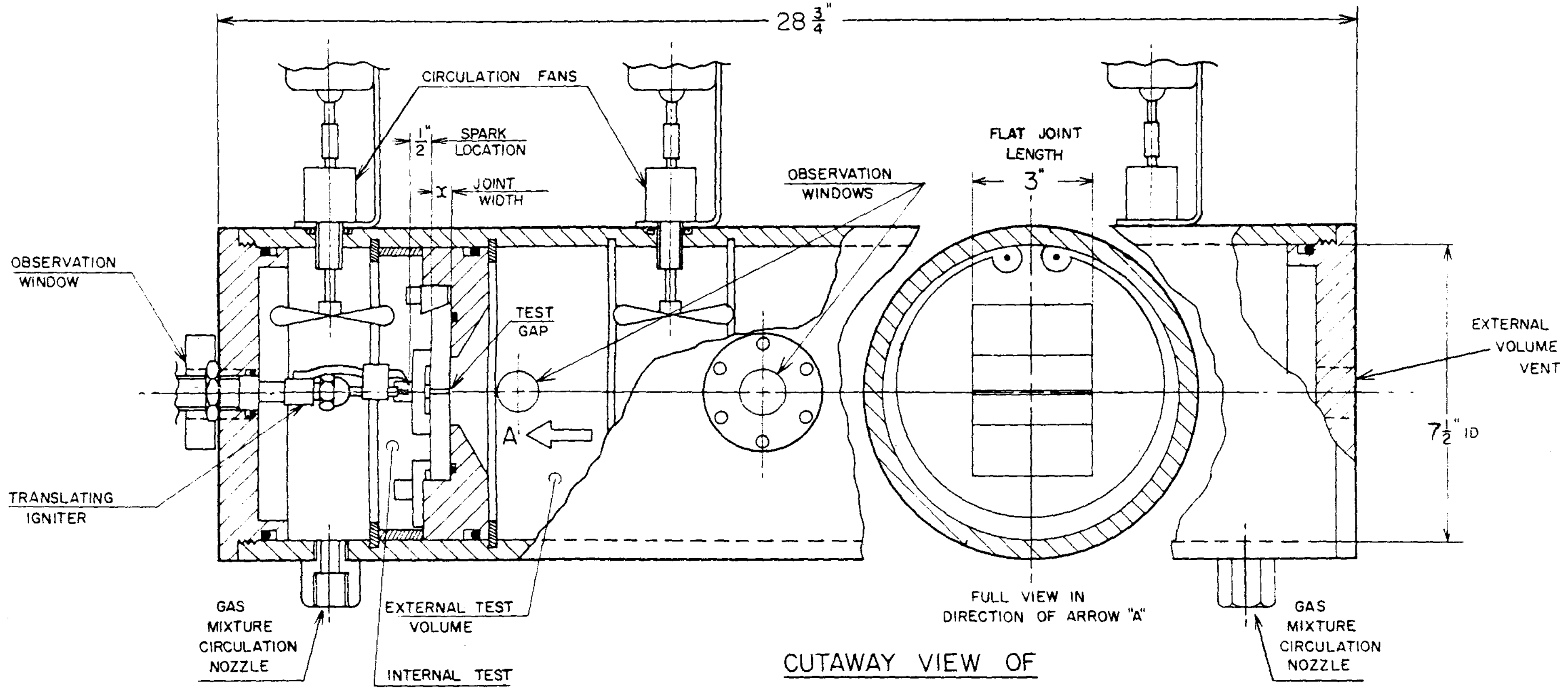
Reference

1. International Electrotechnical Commission, Publication 79-1957, Recommendations for the Construction of Flameproof Enclosures of Electrical Apparatus.

TABLE 1

The Critical Hydrogen Concentration in Air for a Flat Joint of 1 - inch Width and a 0.0395 - inch Gap Size

Test Series	Hydrogen Concentration		Explosion Transmission		Total Trials
	Before Ignition %	After Ignition (Nominal) %	No	Yes	
1	9.95 ± 0.2	7.0	5	0	5
2	10.35 ± 0.2	7.0	4	-	5
		0.7	-	1	
3	11.08 ± 0.2	0.7	0	5	5



CUTAWAY VIEW OF COMPARTMENTED EXPLOSION CHAMBER

FIGURE 1

SCALE 0 1 2 3 4 5 INCHES

CHAPTER 3

RELATIONSHIP OF PERCENTAGE BY VOLUME OF HYDROGEN IN AIR TO EXPLOSION PRESSURE AND TIME TO REACH PEAK PRESSURE IN A CUBICAL ENCLOSURE OF ONE-QUARTER-CUBIC-FOOT VOLUME

Summary

The pressure developed in a quarter-cubic-foot steel enclosure was determined for the range of explosive hydrogen-air mixtures. The time to reach the peak pressure was measured. The effect of central and side ignition was observed and also the effect that hand-operated and electric solenoid valves had on the maximum pressure.

Experimental Procedure and Apparatus

The hydrogen and air were mixed by letting each pass through a separate Fischer and Porter flowrator at a known rate, in cubic feet per minute, and then combining the flows (see Figure 1). The flowrators were rated at 4.6 cfm air and 1.02 cfm air respectively, for 100% readings. As a check on accuracy the flowrators were calibrated by use of a wet-test meter. In addition, spot samples of mixtures were analyzed. It is considered that the percentage figures of hydrogen in air are accurate to 1 per cent.

The mixture of hydrogen and air was flushed through the steel cube (inside volume 1/4 cu ft). The cube was of welded construction and completely sealed except for the threaded holes accommodating fittings for flushing, igniting, and pressure measuring (see Figure 2).

Pressures were measured and recorded, using a Norwood Pressure Monitor Model 5 AC with Transducer, a Dumont Cathode-Ray Oscillograph Type 350, and a Dumont Oscillograph Record Camera.

A Dawe Instruments, Ltd. Wide Range Oscillator was used for timing the oscillograph trace.

Three series of tests were conducted:

1. Solenoid valves were used adjacent to the cube and ignition was by spark plug in a 1/2-in. tee fitting located between one valve and the wall of the test box.

2. Hand-operated valves were used in place of the solenoid valves. Ignition was in the same tee.

3. Hand-operated valves were used but ignition was in the centre of the cube.

The pressures were measured at the centre of one wall for all tests.

Discussion of Results

Results are shown in Table 1 and Figure 3.

The maximum pressure lies between points 30.3 and 33.2 per cent. The fastest time occurs between 30 and 40 per cent. Solenoid valves allowed some pressure release and ignitions occurred in the flushing tube outside the solenoid valve in most tests. No ignitions were transmitted through the hand-operated valves, and pressure points were higher and more consistant when these were used. Central ignition produced maximum pressure and fastest rise time.

Conclusion

In testing explosion-proof enclosures to determine maximum pressure, any mixture from 28 to 35 per cent hydrogen in air should be considered acceptable, as the difference in the resulting explosion pressures would not be significant. The position of the ignition point would not make a great deal of difference with regard to peak pressures in enclosures of the size tested or smaller.

TABLE 1

Experimental Results

Percentage of Hydrogen in Air	Time to Reach Peak Pressure in milliseconds, and Peak Pressures in psi gauge					
	Ignition Point 1* Solenoid Valves		Ignition Point 1* Mechanical Valves		Ignition Point 2** Mechanical Valves	
	ms	psi	ms	psi	ms	psi
15.7	60	63				
18.1	50	70				
19.6	35	79				
23.3	26	81	26	88	17	93
26.4	18	93	15	101	12.5	99
30.3	15	98	13.5	103	10.5	104
33.2	14	93	13	102	9	104
36.6	14	92	12.5	98	9	102
39.8	14	93	12.5	96	9.5	100
42.8	16	92	13	92	11.5	96
46.1	17.5	87	15	90	11	92
49.2	20	89				
57.1	28	73				
64.9	50	61				
68.6	75	51				

*Ignition Point 1 located in 1/2-in. tee 2 1/2 in. from inside wall of enclosure.

**Ignition Point 2 located in centre of enclosure.

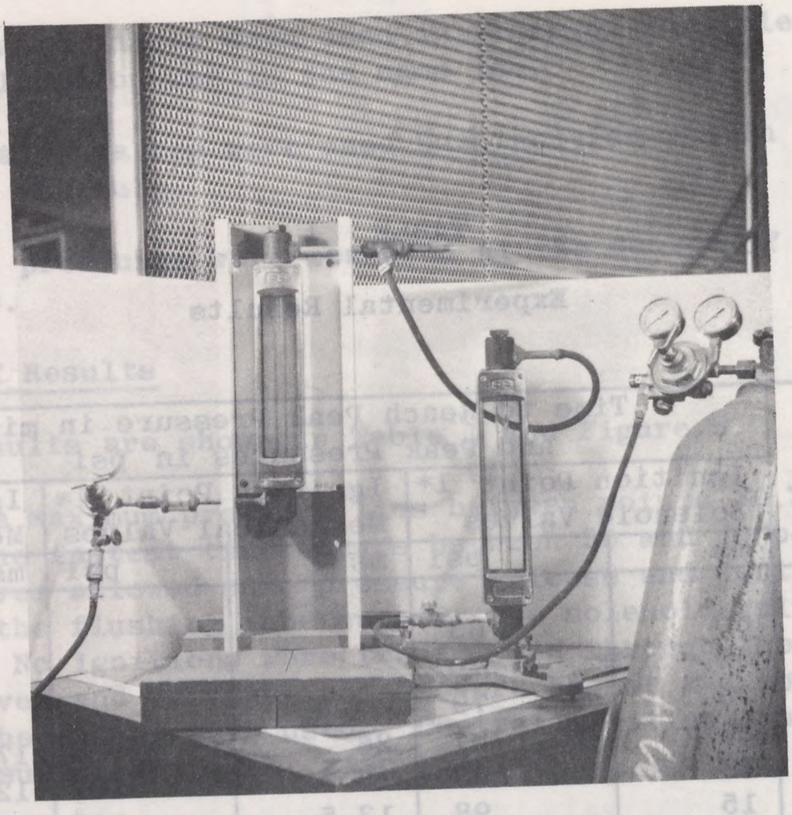


Figure 1 - Apparatus for Mixing Hydrogen with Air

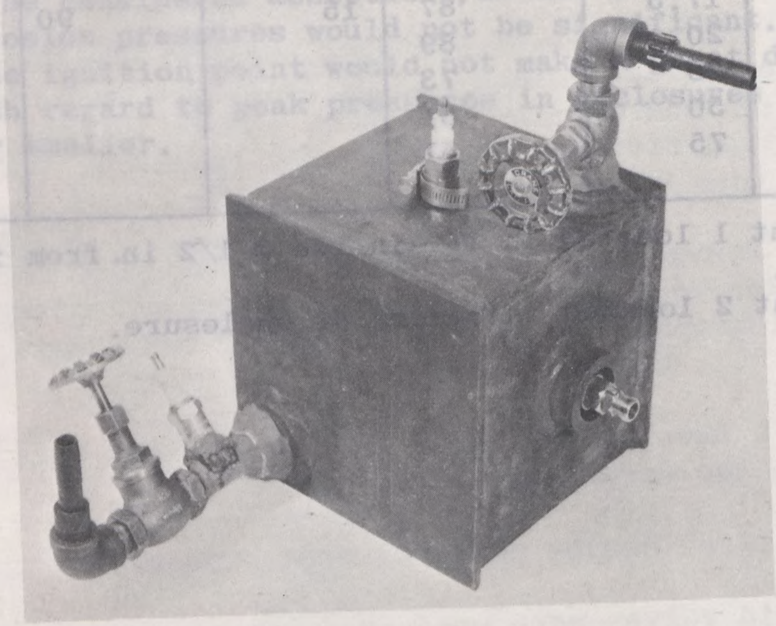


Figure 2 - Steel Enclosure Used for Pressure Tests

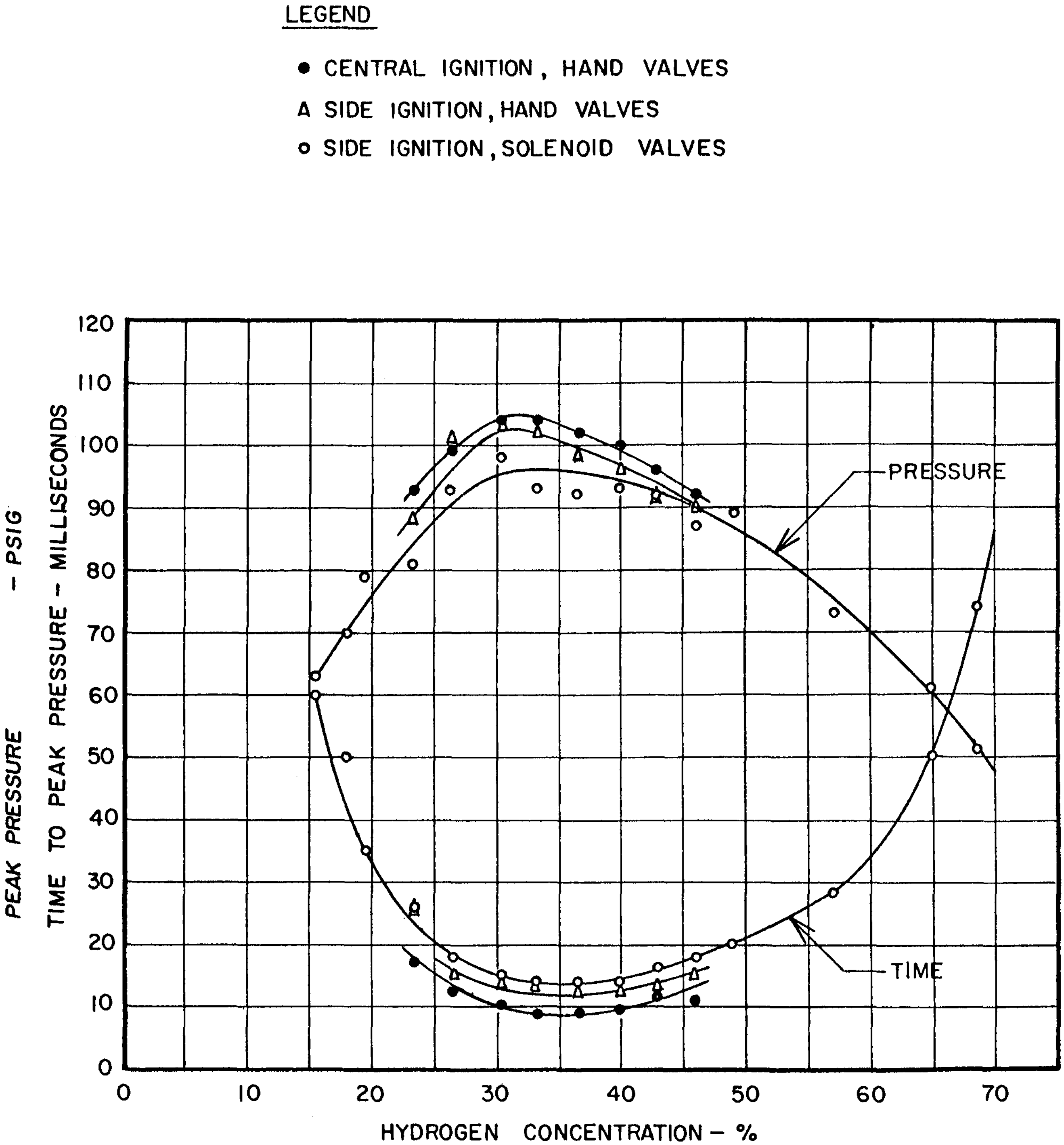


FIGURE 3 - PEAK PRESSURE AND TIME TO PEAK PRESSURE VS HYDROGEN CONCENTRATION

CHAPTER 4

HYDROGEN EXPLOSION TRANSMISSION THROUGH FLAT JOINTS

Summary

Mixtures of 29.6% hydrogen, by volume, in air were prepared in a special vessel divided into two chambers by a partition containing an accurately measured slot (flat joint). The gap size and width of the flat joint and the size of the initial or "internal" volume were varied to determine the effects that these variables produce on the transmission, through flat joints, of explosions initiated by an electric spark in the internal volume.

The results are graphically presented as:

1. Gap Size Variation with Internal Volume.

2. Gap Size Variation with Joint Width.

The first graph indicates that, as the internal volume increases up to approximately 60 cubic inches (983 cm^3), the gap size through which an explosion can be transmitted decreases to a minimum which remains constant for the larger volumes tested.

The second graph shows that, as joint width increases, the size of the gap required for transmission increases at approximately 0.0016 inch (0.0406 mm) per 1/4 inch (6.35 mm) increase in joint width, in the range of joint widths from 1/4 inch (6.35 mm) to 1 inch (25.4 mm).

Experimental Procedure and Apparatus

Because there are several technical terms currently used for each joint configuration dimension, the reader is referred to Figures 1A and 1B for the joint nomenclature used in this Chapter.

A scale drawing of the explosion chamber is shown in Figure 1 A. It consisted of a compartmented cylindrical chrome-plated steel vessel, equipped with viewing windows, circulation fans, translating igniter (inductive electric spark fixed at 0.5 inch - 12.7 mm from the joint entrance), circulation connections, external volume vent of 1.25 inches (31.7 mm) diameter, and a partition onto which the flat joint to be investigated was mounted. The entire assembly could be clamped in the horizontal or vertical position.

Flat joints of a constant 3-inch (76.2 mm) length, and nominal gap size varying from 0.006 to 0.014 inch (0.152 to 0.356 mm) in increments of approximately 0.001 inch (0.0254 mm), were employed. In addition, these flat joints were machined having joint widths of 1/4, 3/8, 1/2 and 1.0 inch (6.35, 9.52, 12.7 and 25.4 mm). The pieces forming the gaps were measured optically and directly by a micrometer. The reported gap sizes in Tables 1, 2 and 3 are those determined from the micrometer measurements. The optical measurements were used to estimate the radius at the edge of the ground gap surfaces, i.e. 0.0003 ± 0.0003 inch (0.0076 ± 0.0076 mm). The maximum machining variation of any particular gap (in an unclamped condition) along the 3-inch (76.2 mm) joint length was ± 0.00025 inch (± 0.00635 mm), whereas the average variation was ± 0.00012 inch (± 0.00305 mm). A wedge was used to clamp the two gap pieces together in a direction normal to their bearing surfaces (see Figure 1 A). In the clamped condition the gap size varied from a maximum at the ends to a minimum at the centre of the gap. The differences between the maximum gaps (as reported in Tables 1 to 3) and the minimum gaps at the centre of the slot were determined for the joint widths and gaps tabulated below:

Joint Width		Maximum Gap		Minimum Gap		Gap Differential	
inch	mm	inch	mm	inch	mm	inch	mm
1/4	6.35	0.0083	0.211	0.0068	0.173	0.0015	0.038
3/8	9.52	0.0092	0.234	0.0082	0.208	0.0010	0.025
1/2	12.7	0.0096	0.244	0.0089	0.226	0.0007	0.018
1	25.4	0.0125	0.317	0.0121	0.307	0.0004	0.010

The above differentials were used to determine the limits of the 50 per cent transmission range as shown on Figure 3 which was established as described in the "Results". The design was such that it was not possible to separate the surfaces of the gap with pressures resulting from the explosion.

Some of the variations in internal volume were achieved by moving the partition location. The location shown in Figure 1 A corresponds to an internal volume of 188 cubic inches (3,081 cm^3), when a 1/2-inch (12.7 mm) joint width was used. In all cases the volume of the circulation piping up to the shut-off valves has been included in the internal volume. Other volumes obtained in this way were 457 and 860 cubic inches (7,490 and 14,095 cm^3). Additional internal volumes, independent of the joint width installed, resulted from the use of a wooden volume reduction block shown in the partial section of Figure 1 B, giving a volume of 11.9 cubic inches (195 cm^3) and an aluminum chamber (see Figure 1 C) with 3 sizes of wooden volume reduction blocks providing internal volumes of 24.0, 29.8, 39.7 and 55.0 cubic inches (393, 488, 651, and 901 cm^3).

All the joints in the vessel, including the partition between the internal and external chambers and the joint pieces themselves, were sealed by O-rings or rubber gaskets. Therefore, no explosion pressure relief occurred except through the flat joint itself.

Variation of hydrogen mixtures from 28 to 35% has little effect on maximum pressure and rate of pressure rise (Chapter 3). Also, there was enough evidence available about most incendive and easily ignited mixtures of hydrogen-air to indicate that the safe gap determination would not be significantly affected by using a single mixture close to the stoichiometric. Therefore, for convenience the stoichiometric concentration of 29.6 per cent hydrogen in air by volume was chosen for both internal and external mixtures. These hydrogen-air mixtures were prepared by the partial pressure method, using laboratory air and a single "dry" hydrogen cylinder of 99.5 per cent minimum hydrogen purity for all tests. The mixtures were circulated through the closed system of chambers and flat joint in series by a non-lubricated vane-type rotary pump. The gas mixture circulation nozzles of each chamber were fitted with valves which prevented pressure relief into the circulation system.

The viewing windows and the explosion noise permitted positive confirmation of ignition in either or both of the internal and external chambers.

The desired volume configuration was selected and the appropriate joint size was fitted to the partition. The 29.6 per cent hydrogen-in-air mixture was prepared, circulated at the rate of 0.5 cfm (14.2 litres per minute) for a total of 6 minutes, and fanned for 15 seconds of each minute of circulation. The chamber was oriented horizontally or vertically as required. After circulation, a one-minute settling period preceded ignition. The external chamber vent was opened and the ignition was initiated by a single spark. After ignition the circulation lines, pump, joint and chambers were flushed with air from the laboratory supply.

The above procedure was repeated 10 times in the case of 10 consecutive ignitions, and 20 times in the case of partial or non-ignitions.

Discussion of Results

There were a total of 390 explosion tests performed to produce Figure 2 which shows the effect of volume change on the critical gap. The results are also tabulated in Table 1. Likewise, a total of 160 explosions were required to produce Figure 3 which illustrates the variation of gap size with changes in joint width. These results are recorded in Table 2.

The shapes of Figures 2 and 3 were determined by plotting the 50 per cent probability lines. The experimental results at a volume of 24.0 cubic inches - 393 cm^3 (see Table 1), and for a joint width of 1 inch - 25.4 mm (see Table 2), indicated that the transition from 0 to 100 per cent transmissions occurred in a gap differential of 0.001 inch (0.0254 mm) or less. Using this variation, the upper boundary line of the 50 per cent transmission probability region of Figure 3 was located relative to the partial transmission gaps recorded in Table 2. Where no partial transmission gaps occurred, the zero transmission points were used to extrapolate to the 50 per cent gap. The lower boundary of the 50 per cent region was determined by deducting the differential due to clamping deformation (see Apparatus), from the upper boundary line for each joint width. The boundary lines for 0 and 100 per cent transmission were then drawn a distance of 0.0005 inch (0.0127 mm) above and below the extremes of the 50 per cent region. The boundaries of Figure 2 were drawn to be consistent with Figure 3 for a 1/2-inch (12.7 mm) joint width, and to represent the trend of the experimental points. The volume characteristic was assumed to reach the flame-quenching gap for zero volume (Reference 1). The volume scale was progressively expanded as volume decreased to show the variation more clearly.

In order to see if gap orientation (jet emitted horizontally, vertically up or down) would significantly affect the results, the tests recorded in Table 3 were done. No significant variation from the curves, as drawn in Figure 2 for the large and small volumes tested, was indicated.

Oscillograph traces were made of the pressure-piling effect of an internal chamber explosion emptying into an external chamber containing air. The pressure-time traces showed that the 1.25-inch (31.75 mm) diameter vent hole did not permit any discernible pressure increase in the external chamber. Therefore, no significant precompression of the mixture in the external chamber occurred due to the influx of the explosion products of the internal explosion.

It was concluded, in Reference 2, that the probability of ignition transmission decreases as the rate of the emergence of the jet from the gap is increased. An increase in joint width (along the gas flow) permits the growth of boundary layers on the joint faces, thus reducing the effective jet exit gap dimension and therefore resulting in an increased jet exit rate. Therefore, as the joint width is increased, the critical gap size should increase. Reference 3 suggests that joint gap and width are directly related by the boundary layer growth. The experimental slope of the gap-versus-width relationship is approximately 0.0016 inch of gap increase per 1/4 inch of joint width increase (0.0406 mm gap per 6.35 mm width).

Conclusions

1. The variation of gap size with internal volume change for a flat joint of half-inch width and 3-inch (76.2 mm) length, has been experimentally determined for mixtures of 29.6 per cent hydrogen in air and for pressure relief through the 3-inch joint length only. The gap size continually decreased as volume increased up to 60 cubic inches (983 cm^3). Further increases in volume above 60 cubic inches did not appreciably affect the critical gap size (see Figure 2 of this report).

2. The change of gap size with joint width change (along the gas flow), for flat joints of 3-inch length (76.2 mm) and for an internal volume of 185 ±8 cubic inches (3,032 ±131 cm^3), has been experimentally determined for mixtures of 29.6 per cent hydrogen in air and for pressure relief through the 3-inch joint length only (see Figure 3 of this report). The experimental slope of the gap versus width relationship is approximately 0.0016 inch (0.0406 mm) of gap increase per 1/4 inch (6.35 mm) of joint width increase.

3. Vertical or horizontal orientation of the axis of the igniting jet does not significantly affect the gap size when all other considerations remain unchanged.

References

1. Lewis, B. and von Elbe, G. - Combustion, Flames and Explosions of Gases. Figure 187, page 414, of 1951 edition.

2. Smith, P.B. - The Role of Flanges in Conferring Protection on Flameproof Electrical Enclosures. Conclusion 1, page 16, of Safety in Mines Research Report No. 77, 1953, and Figure 3, page 14.

3. Dainty, E.D., Brown, G.K. - An Investigation of Gas Explosion Transmission Through Short Cylindrical Channels of Varying Length and Diameter. Figure 3 of Paper 14 of the Restricted International Conference of Directors of Safety in Mines Research, Sheffield, England, 1965.

TABLE 1

Variation of Gap Size with Internal Volume for 1/2-inch (12.7 mm) Joint Width

Internal Volume		Maximum Gap Size		Ignition Transmissions / Total No. of Tests
cu in.	cm^3	inch	mm	
11.9	195	0.0104	0.264	0/10
		0.0120	0.305	0/20
		0.0131	0.333	11/20
		0.0141	0.358	10/10
24.0	393	0.0104	0.264	0/20
		0.0112	0.284	19/20
		0.0120	0.305	10/10
29.8	488	0.0104	0.264	0/20
		0.0112	0.284	13/20
		0.0120	0.305	10/10
39.7	651	0.0091	0.231	0/20
		0.0104	0.264	15/20
		0.0112	0.284	10/10
55.0	901	0.0080	0.203	0/20
		0.0091	0.231	5/20
		0.0104	0.264	10/10
188	3,081	0.0091	0.231	0/20
		0.0104	0.264	10/10
457	7,490	0.0080	0.203	0/20
		0.0091	0.231	6/20
		0.0104	0.264	10/10
860	14,095	0.0091	0.231	0/20
		0.0104	0.264	19/20

TABLE 2

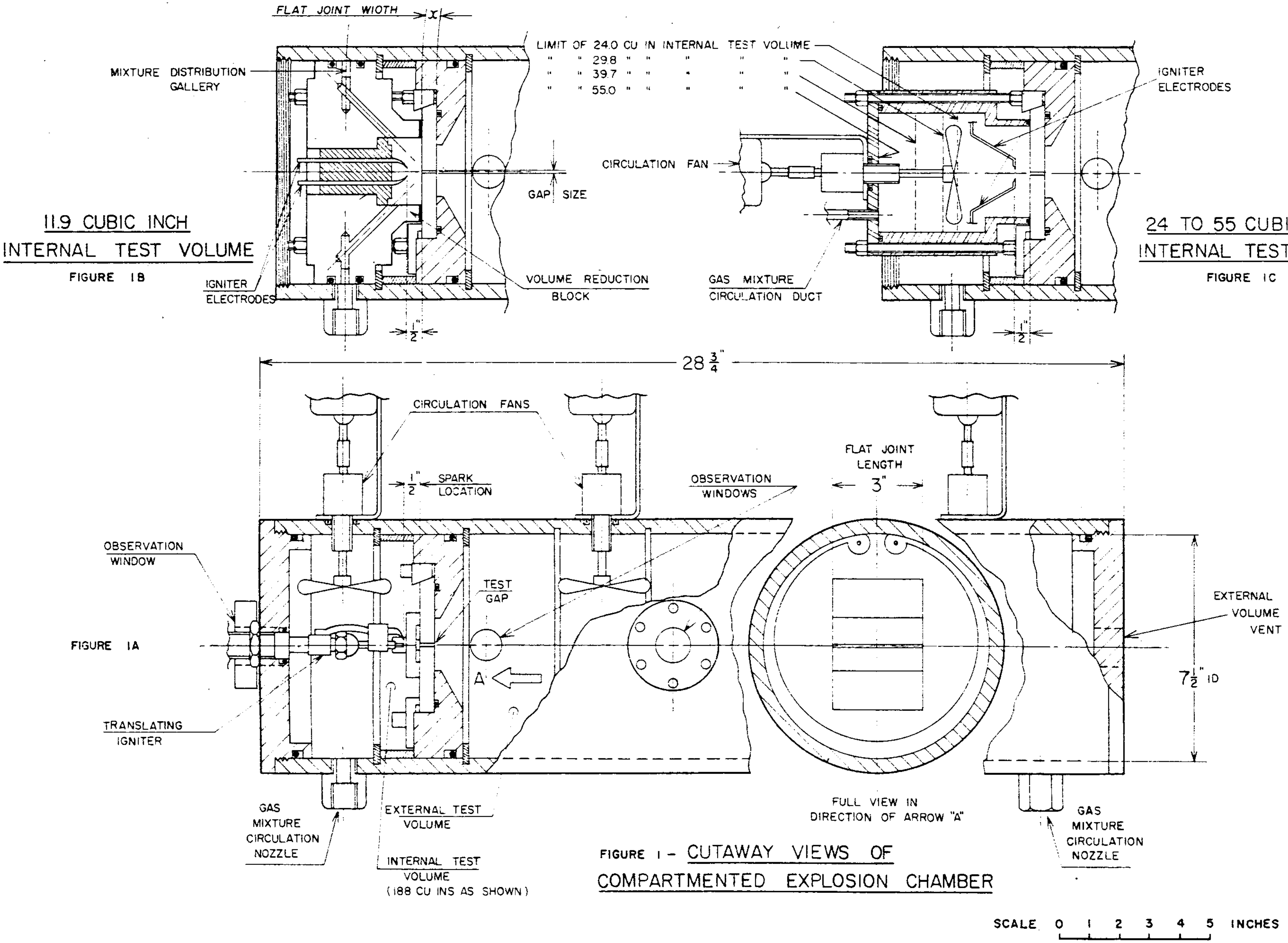
Variation of Gap Size with Joint Width

Joint Width		Internal Volume		Maximum Gap Size		Ignition Transmissions
inch	mm	cu in.	cm^3	inch	mm	Total No. of Tests
1/4	6.35	193	3,163	0.0075 0.0080 0.0090	0.191 0.203 0.229	0/20 4/20 10/10
3/8	9.52	190	3,114	0.0080 0.0088 0.0104	0.203 0.224 0.264	0/20 3/20 10/10
1/2	12.7	188	3,081	0.0091 0.0104	0.231 0.264	0/20 10/10
1	25.4	177	2,901	0.0120 0.0130	0.305 0.330	0/20 10/10

TABLE 3

Gap Orientation Results

Internal Volume		Joint Width		Maximum Gap Size		Gap Orientation	Ignition Transmissions / Total No of Tests
cu in	cm^3	inch	mm	inch	mm		
29.8	488	0.5	12.7	0.0104	0.264	Horizontal	0/20
				0.0104	0.264	Vertically up	0/10
				0.0104	0.264	Vertically down	5/10
				0.0112	0.284	Horizontal	13/20
				0.0120	0.305	Horizontal	10/10
				0.0120	0.305	Vertically up	10/10
				0.0120	0.305	Vertically down	10/10
188	3,081	0.5	12.7	0.0091	0.231	Horizontal	0/20
				0.0091	0.231	Vertically up	0/10
				0.0091	0.231	Vertically down	0/10
				0.0104	0.264	Horizontal	10/10
				0.0104	0.264	Vertically up	9/10



11.9 CUBIC INCH INTERNAL TEST VOLUME

FIGURE 1B

24 TO 55 CUBIC INCH INTERNAL TEST VOLUMES

FIGURE 1C

FIGURE 1A

FIGURE 1 - CUTAWAY VIEWS OF COMPARTMENTED EXPLOSION CHAMBER

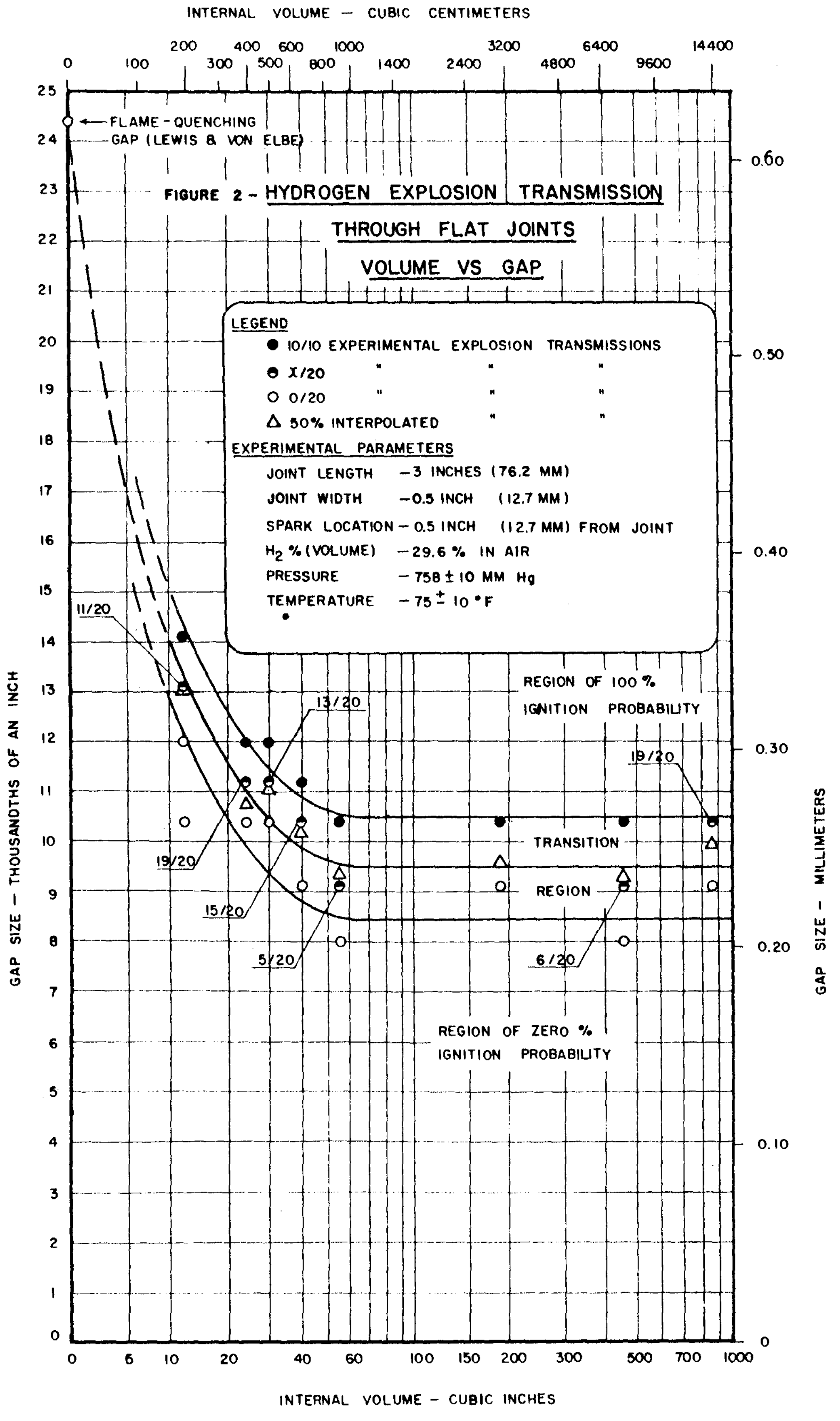


FIGURE 2 - HYDROGEN EXPLOSION TRANSMISSION THROUGH FLAT JOINTS VOLUME VS GAP

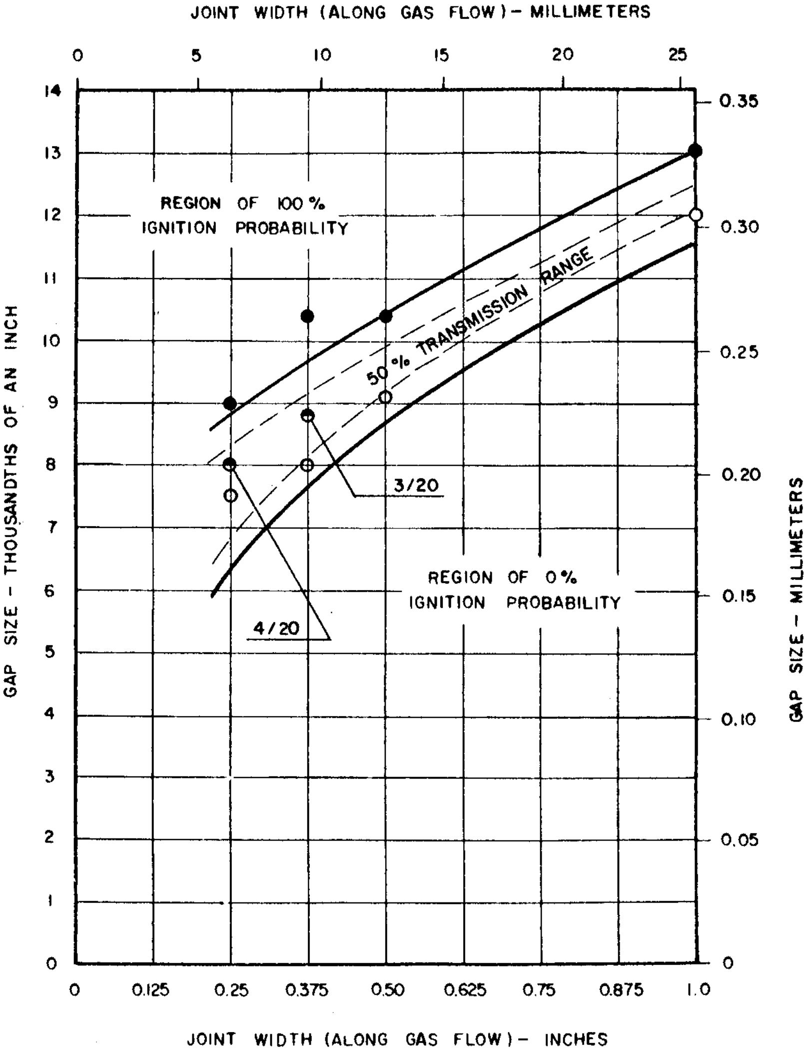
FIGURE 3 - HYDROGEN EXPLOSION TRANSMISSION
THROUGH FLAT JOINTS
JOINT WIDTH VS GAP

LEGEND

● 10/10 EXPERIMENTAL EXPLOSION TRANSMISSIONS
◐ X/20 " " "
○ 0/20 " " "
BOUNDARY LOCATION EXPLANATION IN TEXT

EXPERIMENTAL PARAMETERS

JOINT LENGTH − 3 INCHES (76.2 MM)
INTERNAL VOLUME − 190 ± 9 CUBIC INCHES (3114 ± 148 CM^3)
SPARK LOCATION − 0.5 INCH (12.7 MM) FROM JOINT
H_2 % (VOLUME) − 29.6 % IN AIR
PRESSURE − 758 ± 10 MM Hg
TEMPERATURE − 75 ± 10 °F



CHAPTER 5

TRANSMISSION OF HYDROGEN-AIR EXPLOSIONS THROUGH THE JOINT UNDER THE BOLTED FLAT COVER OF A ONE-CUBIC-FOOT STEEL ENCLOSURE

Summary

Experiments were performed with a one-cubic-foot experimental steel enclosure. In one series of experiments the enclosure free volume was one cubic foot, and in a second series of experiments the enclosure was partly filled leaving a free volume of 360 cubic inches. Explosion transmission occurred through shimmed joints for smaller initial gaps than the safe gaps found in earlier work with unexpandable gaps.

Experimental Procedure and Apparatus

A number of experiments were conducted using a welded steel plate box, Figure 2, having a cubical interior of 1 cubic foot (28.32 litres). The walls of the box were 1/4 inch thick (6.35 mm). The flat flange around the top of the box was 5/8 inch thick (15.9 mm). The width of the flat portion of the flange was 1 5/8 inch (41.3 mm). The top plate was 5/16 inch (7.94 mm) thick and was bolted to the flange by sixteen 1/2-inch (12.7 mm) steel bolts 13 threads per inch (25.4 mm). The top plate covered the box flange and the outer edges of flange and plate coincided, except at 3 positions along one side where the plate had been cut back 5/8 inch (15.9 mm) for a length of 2 7/16 inches (61.9 mm). Therefore, at these 3 positions the flamepath was 1 inch (25.4 mm). See Figure 1.

A spark plug was inserted through the top plate at the position shown on Figure 1, so the spark position would be approximately 3/4 inch (19.1 mm) from the inner edge of flamepath C. A transducer for measuring pressure was also mounted as shown on Figure 1.

A mixture of hydrogen and air was flushed through the cubic-foot steel enclosure and through a surrounding polyethylene envelope. A 31% hydrogen mixture, plus or minus 2% by volume, was prepared using flowmeters. The same percentage mixture was used for the steel box and the outside envelope.

For the first series of tests (Nos. 1 to 6 inclusive), the joint was shimmed open all the way around by placing shims close to the bolts. The width of the shims varied from 1/4 to 1/2 inch (6.35 to 12.7 mm). Feeler gauges of 0.001 inch (.0254 mm) increments were used to check the gap and unless the feeler was a tight fit the gap was assumed to be half way between the feeler which would enter and the one which would not. The torque applied to the bolts was 25 ft lbs (3.46 kg m), except for test 2 for which 35 ft lbs (4.84 kg m) was applied. The additional torque was applied to see if the shims would compress; however, it did not produce a measurable difference in the gap.

For the second series of tests (Nos. 7 to 10 inclusive), the cover was bolted down securely so that essentially no gap existed except at location "C" opposite the spark (see Figure 1). Two shims were used to produce the experimental gap at this 1-inch (25.4 mm) joint width location. One shim was placed beside each of the bolts adjacent to the gap. When the bolts were tightened down the cover plate arched slightly between the bolts over the gap produced by the shims. The larger the shims used the larger the arch was. For 0.0075-inch shims (.19 mm) the gap at the centre measured 0.010 inch (.254 mm); for 0.003-inch (.0762 mm) shims it measured 0.0045 inch (.114 mm). The gap in the centre (not the shim size) is shown in the table as the flat joint gap.

For the third series of tests (Nos. 11 to 16 inclusive), the volume of the steel enclosure was reduced by adding dried sand to a level 2 1/2 inches (6.35 cm) below the cover. The sand was covered with a layer of aluminum foil which was sealed to the inside walls of the enclosure with tape. This left a free volume of 360 cubic inches (5,900 cm^3). The procedure for tests 11 to 16, except for the volume change, was the same as for tests 7 to 10, i.e. there was no gap produced by shims except at position C, Figure 1, adjacent to the spark plug. The largest gap between the shims was taken as the gap size. Results of the tests are tabulated in Table 1. These results have been compared to the earlier work for an unexpandable gap by superimposing information concerning the smallest experimental explosion-transmission-gap and the largest experimental non-explosion-transmission-gap to Figure 3.

Discussion of Results

If the transition region for explosion transmission is considered to be the region between the smallest experimental gap for transmission and the largest experimental gap for non-transmission, then this transition region can be moved into a range of much smaller initial joint gaps for a bolted enclosure compared to a vessel with a fixed unexpandable gap. The shift in the transmission region is considered to be due not only to bolt strain and plate deflection, but also to the rate of pressure rise, which is influenced by the shape of the free volume and the degree of pressure relief. The configuration of the explosion transmission joint (inside and outside) also could affect the gap size required for transmission. In addition, the position of shims also can change the size of the initial gap required for transmission (Chapter 6). If shims are placed on both sides of the bolts, a smaller initial gap can transmit an explosion.

For the experiments conducted, the largest shift occurred for the 360-in.^{3} (5,900 cm^3) free volume and put the transition region between 0.0045 and 0.0055 in. (.114 and .139 mm). These results were for a joint width of 1 inch (25.4 mm). A reduction of joint width would, according to Figure 3 data, lower the transition region still further with respect to gap size.

TABLE 1

Experimental Conditions and Results

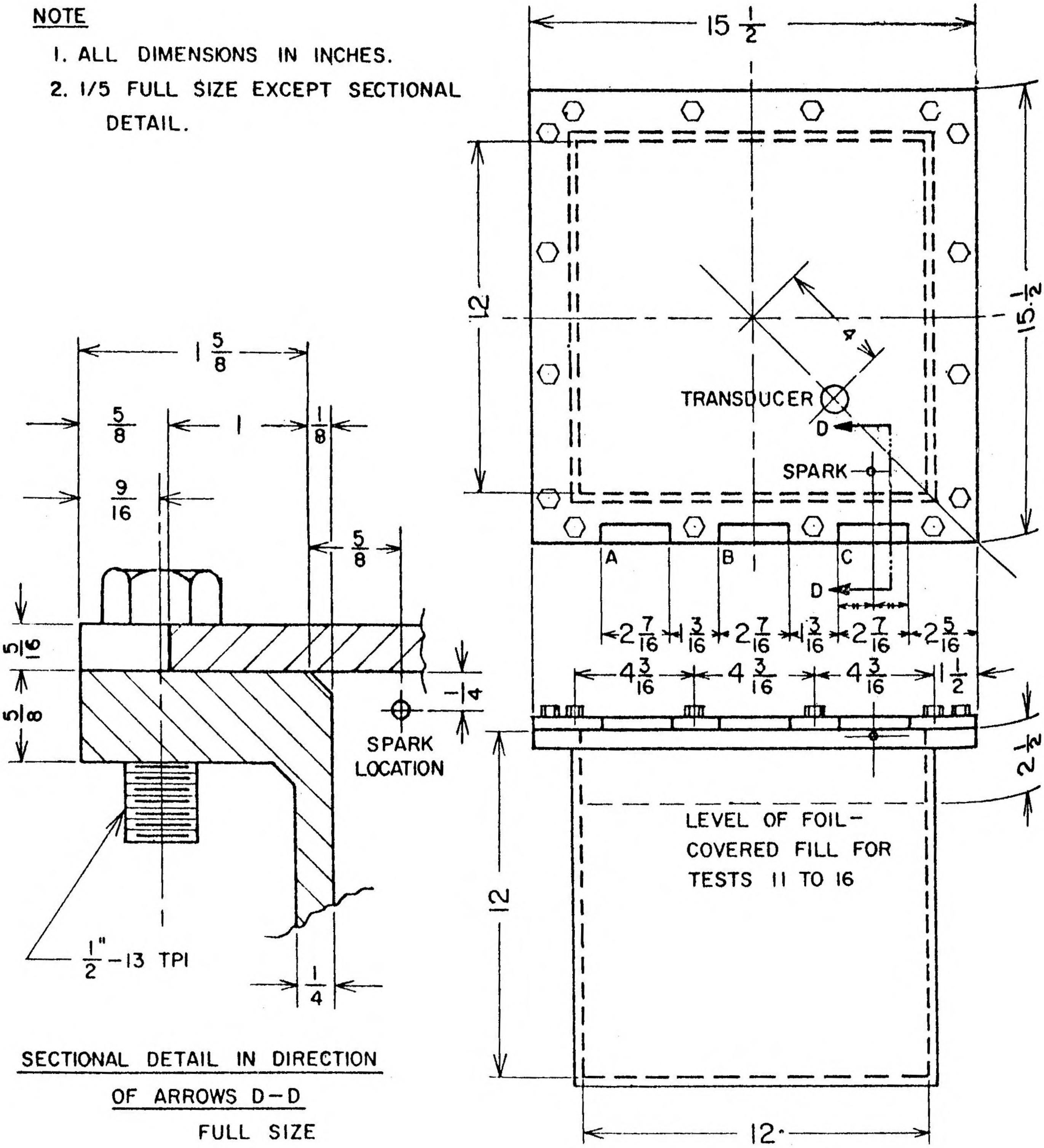
Ignition by Spark Plug 3/4 inch (19.1 mm) from C Joint
Width of Joint at A, B & C, 1 inch (25.4 mm); Joint Width Elsewhere, 1 5/8 inches (41.3 mm)

Test No.	Free Volume	Flat Joint Gap								Explosion Transmission	Pressure		Time to Pressure Peak, milliseconds
		At A*		At B*		At C*		Elsewhere**					
		in.	mm	in.	mm	in.	mm	in.	mm		lbs/in^2	kg/cm^2	
1	1 ft^3	.0115	.292	.0095	.241	.0105	.267	.0115	.292	Yes	100	7.0	24
2	28.32L	.0095	.241	.0085	.216	.0095	.241	.0105	.267	Yes	98	6.9	22
3		.0055	.140	.0045	.114	.0055	.140	.0065	.165	No	105	7.4	22
4		.009	.229	.0085	.216	.009	.229	.009	.229	Yes	98	6.9	22
5		.0075	.190	.0055	.140	.0075	.190	.0075	.190	Yes	100	7.0	22
6		.006	.152	.005	.127	.006	.152	.0055	.140	No	102	7.2	21
7	1 ft^3	***	***	***	***	.0075	.190	***	***	No	106	7.5	21
8	28.32L	***	***	***	***	.011	.279	***	***	Yes	98	6.9	23
9		***	***	***	***	.009	.229	***	***	Yes	108	7.6	21
10		***	***	***	***	.0075	.190	***	***	No	103	7.2	21
11	360in^3	***	***	***	***	.010	.254	***	***	Yes	60	4.2	18
12	5900cm^3	***	***	***	***	.008	.203	***	***	Yes	35	2.5	21
13		***	***	***	***	.0075	.190	***	***	Yes	60	4.2	18
14		***	***	***	***	.0055	.140	***	***	Yes	45	3.2	22
15		***	***	***	***	.0045	.114	***	***	No	47	3.3	22
16		***	***	***	***	.0045	.114	***	***	No	46	3.2	28

*Joint Width, 1 inch (25.4 mm).
** " " , 1 5/8 inch (41.3 mm).
***Joint was closed tightly and checked with a 0.0015-inch (38.1 mm) feeler which would not enter joint.

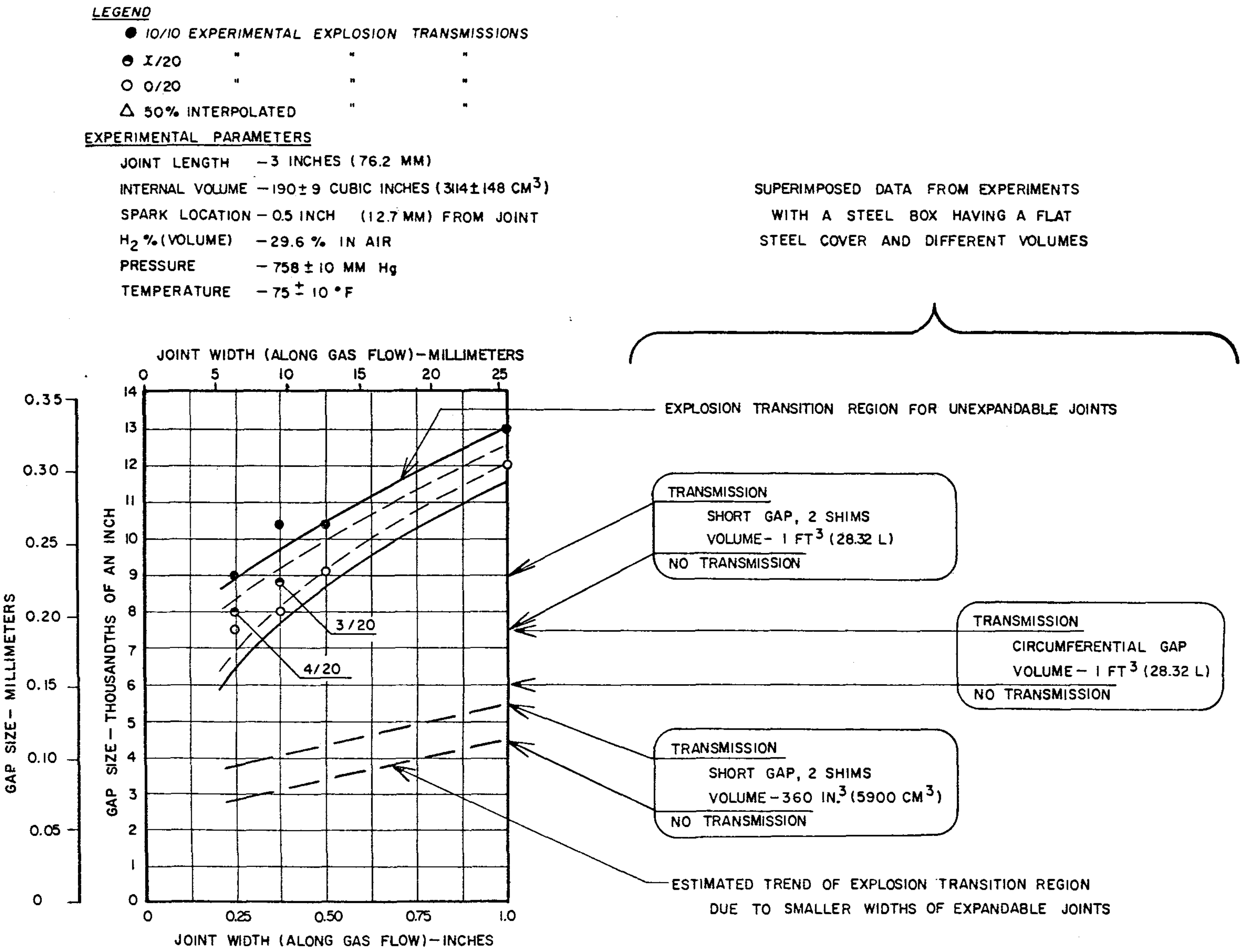
NOTE

1. ALL DIMENSIONS IN INCHES.
2. 1/5 FULL SIZE EXCEPT SECTIONAL DETAIL.



SECTIONAL DETAIL IN DIRECTION OF ARROWS D-D FULL SIZE

FIGURE 1 – DETAILS OF ONE-CUBIC-FOOT FLANGED ENCLOSURE



LEGEND

- ● *10/10 EXPERIMENTAL EXPLOSION TRANSMISSIONS*
- ◐ *X/20 " " "*
- ○ 0/20 " " "
- △ 50% INTERPOLATED " "

EXPERIMENTAL PARAMETERS

JOINT LENGTH — 3 INCHES (76.2 MM)
INTERNAL VOLUME — 190 ± 9 CUBIC INCHES (3114 ± 148 CM^3)
SPARK LOCATION — 0.5 INCH (12.7 MM) FROM JOINT
H_2 % (VOLUME) — 29.6 % IN AIR
PRESSURE — 758 ± 10 MM Hg
TEMPERATURE — 75 ± 10 °F

SUPERIMPOSED DATA FROM EXPERIMENTS WITH A STEEL BOX HAVING A FLAT STEEL COVER AND DIFFERENT VOLUMES

FIGURE 2 — HYDROGEN EXPLOSION TRANSMISSION THROUGH FLAT JOINTS

(FIGURE 3, CHAPTER 4, WITH SUPERIMPOSED DATA)

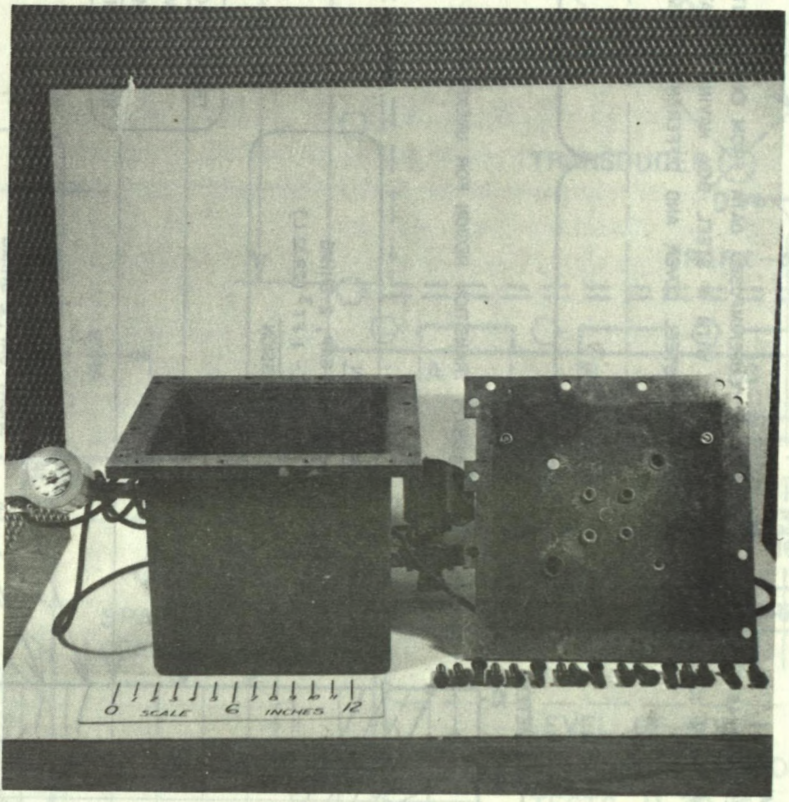


Figure 3 - Photograph of 1-Cubic-Foot Steel Enclosure.

CHAPTER 6

HYDROGEN-AIR EXPLOSION TRANSMISSION THROUGH SHIMMED GAPS IN FLAT JOINTS OF EXPLOSION-PROOF ENCLOSURES

Summary

Following research on hydrogen-air explosion transmission through the unexpandable gaps of flat joints (Chapter 4) and explosion transmission through gaps under the bolted cover of a one-cubic-foot steel box (Chapter 5), additional investigations were made of hydrogen-air explosion transmission through flat joint gaps made by placing shims under the bolted covers of commercial explosion-proof enclosures. The effect of the position of the shims on the minimum initial gap for explosion transmission is shown. Also, the initial minimum transmission gap for these conditions is compared to the minimum unexpandable transmission gap (see Chapter 4).

Experimental Procedure and Apparatus

The enclosures used were identified as A (1), A (2), and B. Figures 1, 2 and 3 show A (1), A (2) and B respectively. They were supplied by a Canadian manufacturer and were of a design found acceptable by Canadian Standards Association for Class 1, Division 1, Groups C and D*. The enclosures were made of cast iron. A (2) was the same enclosure as A (1), except that the flat cover of A (1) was replaced by the domed cover of A (2). Principal dimensions are given in Table 1.

The enclosures were fitted with solenoid valves, a spark plug, and a pressure transducer. A shim was placed next to each bolt in the longest unbolted span of the cover (see Figures 1 to 3). The cover was then tightened down, the torque applied being 5 ft lbs. The gap was measured with feeler gauges and was found to be largest half-way between the bolts. The enclosure was next placed in a test chamber. A 31% ± 1% mixture of hydrogen-air was used for internal and external mixtures. The internal mixture was ignited by a single spark from a spark plug, with the ignition point being approximately 1/2 inch from the flat joint gap. The explosion pressure and time to reach the peak were recorded. The total free volume of the explosion-proof enclosures included free volume to the attached valves. Results are shown in Table 2.

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*Group C (ether), Group D (gasoline).

Because the tightening of the cover bolts produced an initial deflection of the cover, caused by the bolt load producing a moment about the shim which acted as a fulcrum, it was decided to do another set of tests using the same enclosures. For these tests, shims were put on either side of the bolts to prevent initial deflection of the cover. Results are shown in Table 3.

An illustration of a typical pressure curve is shown in Figure 4.

Discussion of Results

Placing shims on one side of the bolts only, produced a gap with a considerable arch. The centre of the gap was almost 0.005 inch larger than the shim, in the case of enclosure A (1) which had a flat cover. The cover of B, being relatively flat, also arched considerably. The cover of A (2) was dome--shaped and arched the least. With the shims on one side of the bolts adjacent to the gap, an explosion would tend to stretch the bolts, remove the lever effect on the shims, and let the arch decrease. Therefore, in the first series of tests not all the explosion effects resulted in gap increase.

When the shims were placed on both sides of the bolts, the gap did not arch. The approximate difference of 0.001 inch between sizes of gap and shim was a permanent set, due either to the explosions of the first series of tests or to initial unevenness of the joint. An explosion in this arrangement of shims would tend to increase the size of the gap by both stretching bolts and bending the cover. As can be seen by comparing the results of Tables 1 and 2, the explosion transmissions through the smallest initial gaps occurred with the shims on both sides of the bolt. This is also in agreement with the results in "Transmission of hydrogen-air explosions through the joint under the bolted flat cover of a one-cubic-foot steel enclosure" (Chapter 5). In the latter work it was shown that shims placed all around the enclosure perimeter resulted in explosion transmission through a smaller initial gap than if shims were placed only on one side of the bolts near the joint gap.

From information in Chapter 4, "The Transmission of explosio in hydrogen-air mixtures through unexpandable flat joints", an estimate could be made of the initial gap which would be required to transmit an explosion if the gap were unexpandable. In the case of the enclosures tested, the comparison of estimated unexpandable gap required and lowest experimental initial gap for explosion transmission was as follows:

A (1)	(Flat Cover, 3/8 inch thick at joint) (Joint width, 5/8 inch)	Estimated	0.0115
		Experimental	0.009
		Difference	0.0025
A (2)	(Domed Cover, 3/8 inch thick at joint) (Joint width, 5/8 inch)	Estimated	0.011
		Experimental	0.01025
		Difference	0.00075
B	(Relatively Flat Cover, 1/2 inch thick at joint) (Joint width, 1/2 inch)	Estimated	0.0095
		Experimental	0.00875
		Difference	0.00075

Different enclosure designs naturally make differences in the amount of joint expansion during an explosion. For example, enclosures of a different material but otherwise of the same design would produce different results. Aluminum would deflect more than cast iron because of its lower modulus of elasticity, and it is estimated that the difference between unexpandable and experimental gaps would be about 1.7 times those found in the experimental work of this report with cast iron enclosures.

Conclusions

1. The thickness of shims required to produce a gap large enough to transmit an explosion depends on the position of the shims. When the shims are placed on both sides of the bolts adjacent to the gap, there is no arching of the cover due to tightening the bolts such as occurs when the shims are placed on the gap side of the bolts only. Without the arching effect, thicker shims are required but the initial gap is smaller at the joint position across which the explosion is transmitted.

2. The enclosures tested, which were of small volume and of a design acceptable for Canadian Electrical Code Class 1 Division 1 Groups C and D, did not permit excessive joint gap expansion. However, because the joint gap expansion is a result of explosion pressure acting on the area of the cover, enclosure cover and fastening design becomes more critical as the cover area is increased, particularly for Group B (hydrogen) enclosures.

TABLE 1

Principal Dimensions of Enclosures A (1), A (2) and B

(Dimensions are in inches)

Enclosure	A (1)	A (2)	B
Height	2 1/2	3 1/4	5
Length	5	5	7 1/4
Width	3 1/2	3 1/2	5
Joint width	5/8	5/8	1/2
Thickness of cover at joint	3/8	3/8	1/2
Number of steel bolts 1/4 inch by 1 inch long 20 threads/inch			4
Number of steel studs 1/4 inch, 20 threads/inch			2
Number of steel nuts			2
Number of steel screws 1/4 inch by 3/4 inch long 20 threads/inch	4	4	

TABLE 2

Results of Explosion Tests with Shims on One Side of the Bolts Adjacent to the Gap

Tolerance of Gap* by Spark ± .00025 inch (.0063 mm)

Test No.	Enclosure	Free Volume		Joint Width		Shim Size		Gap by Spark		Explosion Transmission	Pressure		Milliseconds To Peak
		$in.^3$	cm^3	Inch	mm	Inch	mm	Inch	mm		$lbs/in.^2$	kg/cm^2	
1	A (1)	28 1/2	467	5/8	15.9	.006	.152	.01075	.273	No	55	3.9	4
2						.006	.152	.01075	.273	Yes	60	4.2	4
3						.005	.127	.00975	.248	No	65	4.6	4
4						.005	.127	.00975	.247	No	65	4.6	4
1	A (2)	34	557	5/8	15.9	.0085	.216	.01025	.260	No	55	3.9	6
2						.0085	.216	.01025	.260	No	70	4.9	5
3						.0095	.241	.01125	.286	Yes	75	5.3	5
1	B	109	1790	1/2	12.7	.005	.127	.00675	.171	No	95	6.7	9
2						.0075	.190	.00925	.235	Yes	90	6.3	9
3						.005	.127	.00675	.171	No	80	5.6	11
4						.006	.152	.00775	.197	No	80	5.6	10
5						.006	.152	.00775	.197	No	80	5.6	9
6						.005	.127	.00875	.222	No	80	5.6	9
7						.005	.127	.00875	.222	Yes	80	5.6	9

*Gap by spark refers to the position opposite the spark plug where the largest joint gap was measured.

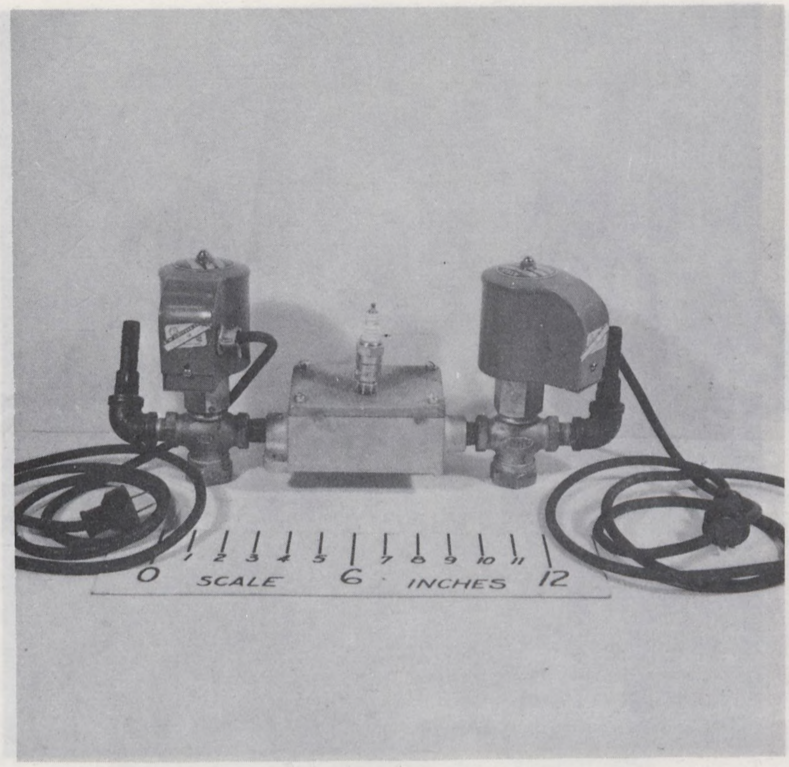
TABLE 3

Results of Explosion Tests with Shims on Both Sides of the Bolts Adjacent to the Gap

Tolerance of Gap* by Spark ± .00025 inch (.0063 mm)

Test No.	Enclosure	Free volume		Joint Width		Shim Size		Gap by Spark		Explosion Transmission	Pressure		Milliseconds To Peak
		in.³	cm³	Inch	mm	Inch	mm	Inch	mm		lbs/in.²	kg/cm²	
1	A (1)	28 1/2	467	5/8	15.9	.008	.203	.009	.229	Yes	70	4.9	4
2						.007	.178	.008	.203	No	72	5.1	4
3						.007	.178	.008	.203	No	72	5.1	4
1	A (2)	34	557	5/8	15.9	.0085	.216	.00925	.235	No	70	4.9	5
2						.0085	.216	.00925	.235	No	70	4.9	5
3						.0095	.241	.01025	.260	Yes	75	5.3	5
1	B	109	1790	1/2	12.7	.006	.152	.007	.178	No	85	6.0	9
2						.006	.152	.007	.178	No	87	6.1	9
3						.007	.178	.00775	.197	No	87	6.1	9
4						.007	.178	.00775	.197	No	87	6.1	9
5						.0075	.190	.00825	.210	No	87	6.1	9
6						.0075	.190	.00825	.210	No	80	5.6	11
7						.008	.203	.00875	.222	Yes	90	6.3	10

*Gap by spark refers to the position opposite the spark plug where the largest joint gap was measured.



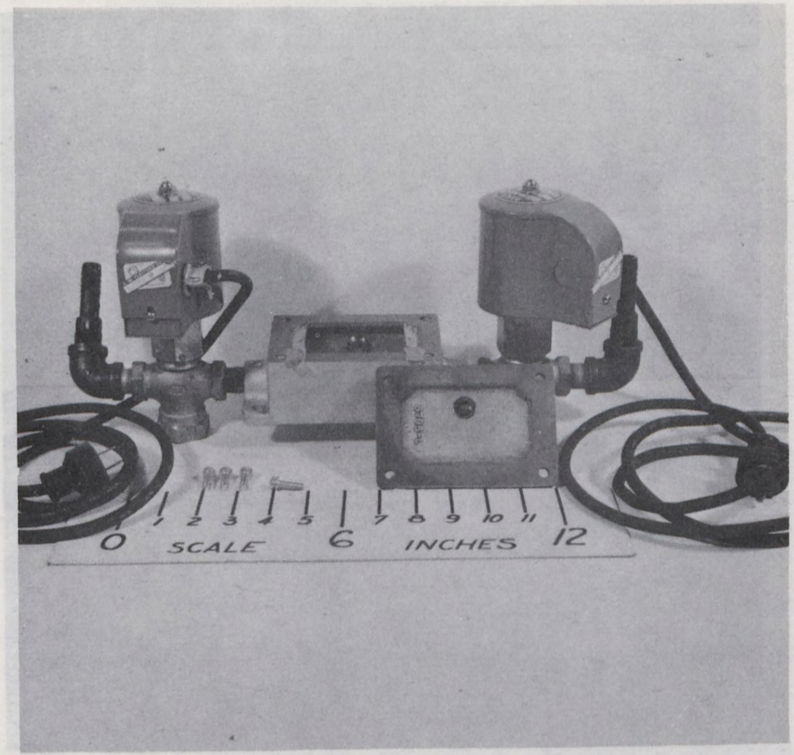


FIGURE 1 - Enclosure A (1)

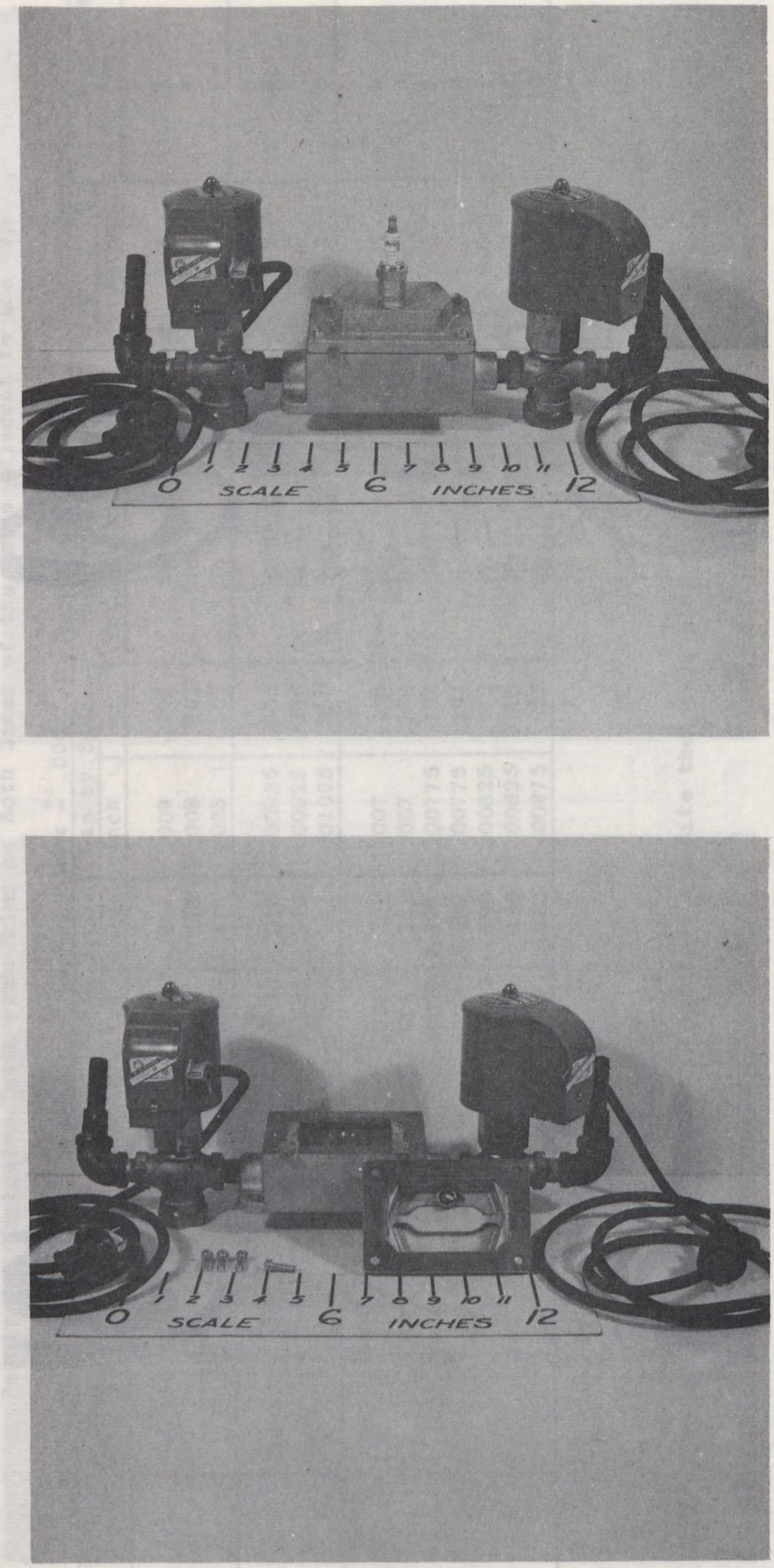


FIGURE 2 - Enclosure A (2)

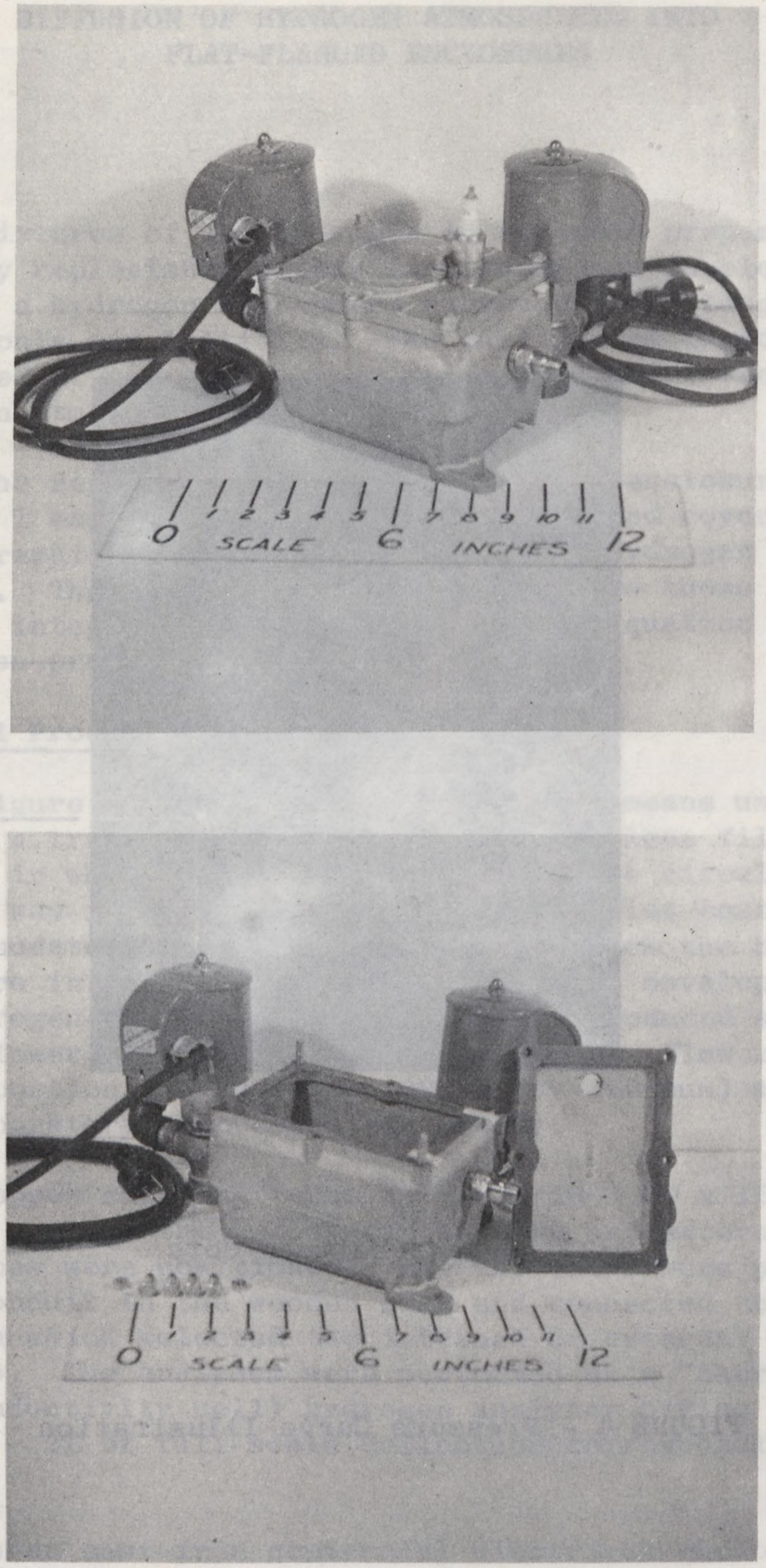


FIGURE 3 - Enclosure B

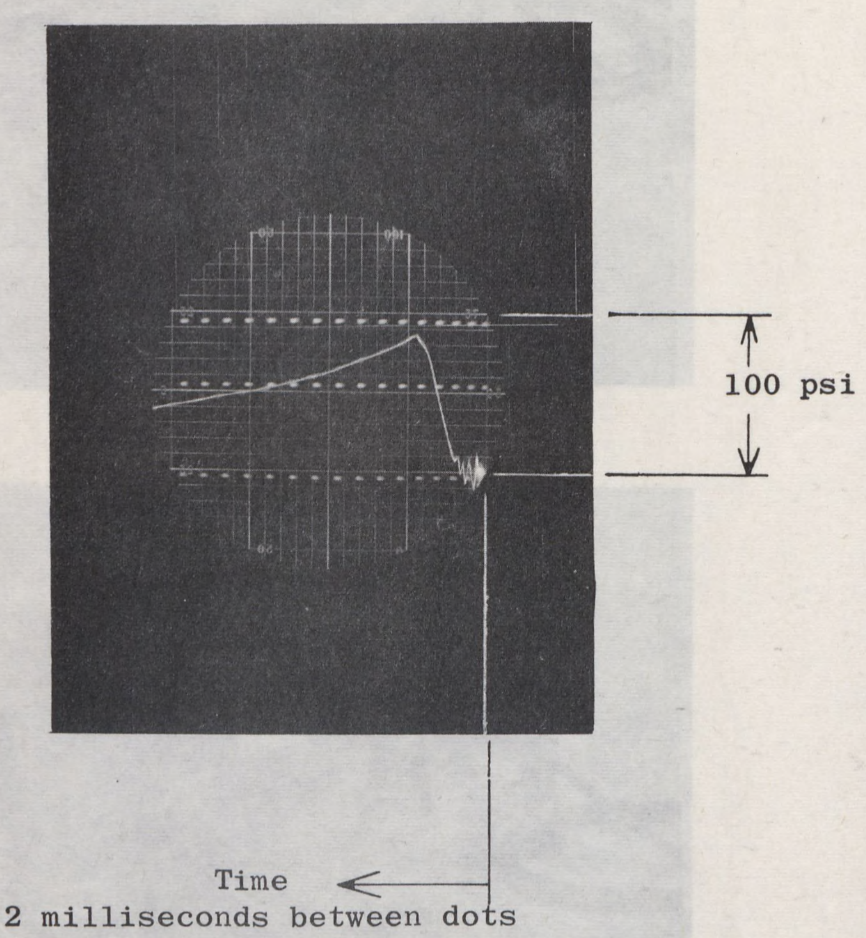


FIGURE 4 - Pressure Curve Illustration

CHAPTER 7

DIFFUSION OF HYDROGEN ATMOSPHERES INTO FLAT-FLANGED ENCLOSURES

Summary

Mixtures of 44% hydrogen in air were prepared and periodically replenished within a polyethylene envelope, thus maintaining a hydrogen atmosphere surrounding a flanged enclosure containing only air initially. The outside and inside mixtures were analyzed at various elapsed times from the introduction of the hydrogen atmosphere into the envelope.

The results of diffusion into four enclosures (3 commercial and 1 experimental) with tightly bolted covers, are presented graphically as characteristics of hydrogen concentration versus time. The curve trends conform well to those predicted by a simple integral form of a differential equation describing the diffusion process.

Experimental Procedure and Apparatus

Figure 1 shows a photograph of the means used to mount and support a transparent 0.002-inch polyethylene film to form an envelope in which hydrogen atmospheres were circulated. The wooden base was fitted with gas inlet and outlet connections which accommodated plastic tubing through which the hydrogen-air mixtures were introduced into and through the envelope. The 44 ± 6% hydrogen-in-air atmospheres were introduced and replenished before the lower tolerance limit was reached. Flow meters were used to proportion the hydrogen (99.5% dry minimum) and the air from the laboratory compressed air supply.

Copper sampling tubes (1/8 x 1/16 - OD x ID) were attached to each of the enclosures in turn, and external mixture sampling tubes were positioned. All the leads were passed through a conduit in the wooden base and connected to a manual valve system which selected the internal or external atmosphere for analysis. The analyses were performed on a "thermabridge" (thermal conductivity cell) hydrogen analyzer having an accuracy of ± 2% of full-scale deflection corresponding to 100% hydrogen.

Three cast-iron commercial electrical enclosures, of a design acceptable for Canadian Electrical Code Class 1, Division 1, Groups C and D*, were studied. Figure 2 illustrates these

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*Group C (ether), Group D (gasoline).

enclosures and Table 1 gives their important characteristics. Torque as in Table 1 was applied to the bolts. The resulting gaps in the middle of each span between bolts were measured, using 0.0005-inch shims. The results are tabulated in Table 2. The joint numbers refer to the joints between each pair of bolts, measured in a clockwise sequence, when seen in the plan views of Figure 2. The larger gaps above may have been produced by an explosion investigation carried out prior to these diffusion tests and reported in Chapter 6. In that investigation, shims were used at joint number 1 only for some of the tests.

The experimental enclosure is shown in the drawing of Figure 3. It was previously used in explosion experiments reported in Chapter 5 . The volume was reduced to 360 cubic inches by sand filling and the fill was covered with cardboard and carefully sealed with a layer of aluminum foil on top of and around the edges of the cardboard.

All the threaded joints in all four enclosures were closed with threaded plugs. The threads were sealed with pressure-sensitive teflon tape to minimize the diffusion through all joints other than the flat joints for which it was desired to determine the diffusion rates.

The volume of each of the internal and external analyzing circuits, including the copper leads and the gas train in the analyzer, was 3 cubic inches. Therefore, the inside hydrogen concentrations of Figure 4 pertain to a total system volume comprising enclosure volume plus the gas train volume. The total system volume is given in Table 1.

Initial 50% hydrogen mixtures were introduced into the polyethylene envelope by flushing. The inside and outside mixtures were analyzed and the elapsed time from the start of the initial flushing period was noted for each analysis.

When the external hydrogen concentration decreased to the minimum, it was replenished and reanalyzed.

Examination of the Diffusion Equation

The differential equation which expresses unidirectional molecular diffusion is Fick's Law which parallels the Fourier equation of steady-state heat conduction. The equation is:

$$\frac{dQ}{dt} = -D\ A\ \frac{dc}{dl} = Vi\ \frac{dci}{dt}, \ldots\ldots\ldots\ldots (\text{Eq } 1)$$

where Q = moles of diffusing gas - moles
D = diffusion coefficient - in.^{2}/sec
A = cross-sectional area of diffusion path - in.^{2}
c = gas concentration in diffusion path - moles/in.^{3}
ci = internal concentration (uniform throughout Vi) - moles/in.^{3}
co = concentration in the outside atmosphere - moles/in.^{3}
l = length of diffusion path (flange width) - in.
Vi = volume into which hydrogen is absorbed - in.^{3}
t = time - sec

When l approaches zero, then $\frac{dc}{dl}$ approaches - (co - ci)/l.

Substituting this expression in equation 1 and cross-multiplying gives

$$\frac{dci}{co-ci} = \frac{DA}{lVi}\ dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\text{Eq } 2)$$

Integration between the limits ci = 0 at time t = 0, and ci = ci at time t = t, and assuming D is independent of c, gives

$$\frac{DAt}{lVi} = \ln \frac{co - cio}{co - ci}$$

or

$$t = \frac{lVi}{DA} \ln \frac{co - cio}{co - ci}$$

or

$$t = \frac{lVi}{DLg} \ln \frac{co - cio}{co - ci} \ldots\ldots\ldots\ldots (\text{Eq } 3)$$

where L is the periphery of the joint - in.
g is the gap size - in.
Cio is the concentration at zero time - moles/in.^{3}

Equation 3 may be rearranged to express ci as a function of time when (DLg/lVi) = x, as follows:

$$ci = \frac{co\ (e^{xt} - 1) + cio}{e^{xt}} \quad \text{and when cio} = 0$$

at time t = 0, then

$$ci = \frac{co\ (e^{xt} - 1)}{e^{xt}} \ldots\ldots\ldots\ldots\ldots\ldots (\text{Eq } 4)$$

Using Equation 3, the apparent gap was calculated by substitution of the appropriate physical constants of Table 1, the concentrations of Figure 4, a coefficient for the diffusion of hydrogen into air of 0.0949 in.^{2}/sec (see Reference 1), and a time of two hours (7200 seconds). The calculated apparent gaps are recorded in Table 4 and may be compared to the approximate measurements recorded in Table 3.

Equation 4 was used to calculate the variation of internal concentration - ci, with time for each of the above enclosures when the initial internal concentration was assumed to be zero and the average external concentration was 44% hydrogen in air. The results of these calculations are summarized in Table 4 and are shown on the experimental characteristics of Figure 4 as black points to permit easy comparison of the theoretical and experimental curve trends.

Discussion of Results

The proximity of the calculated concentrations (based on the calculated apparent gap) to the experimental concentrations for the same elapsed time as shown on Figure 4, shows that the diffusion law as expressed in Equation 4 closely parallels the experimental facts, in spite of the simplifying assumptions which were made in its derivation.

Exact measurements of the actual gap are not easily made and have not been attempted here. However, comparison of the rough measurements recorded in Table 2, with the calculated apparent gaps of Table 4, shows that the gap sizes of enclosures A1, B and A2 bear the same qualitative relationship to one another for both the calculated and measured results. The magnitudes are not easily compared, however. The large apparent gap for the 360 cubic-inch-volume - enclosure C, may have been due in part to small amounts of diffusion through the extra threaded joints which were present in the cover and used for other experimental purposes, and to the lack of a perfect seal in the aluminum foil covering the fill.

Preliminary unrecorded diffusion experiments with two layers of black plastic sticky tape (0.007 inch thick by 0.75 inch wide) placed around the external periphery of enclosure C showed a reduction of only 0.5% hydrogen after 2 hours, compared to Figure 4. Such tape is therefore not effective in reducing diffusion of hydrogen when used this way. However, when in addition a single layer of tape was placed in the joint, gasket fashion, the combined result was to reduce the concentration 2.0% after 2 hours, compared to Figure 4.

Figure 4 shows that lower limit explosive mixtures (4% hydrogen in air) existed inside enclosures A1, A2, B and C after elapsed times of 20, 33, 81, and 171 minutes respectively. Therefore, smaller enclosures permit the buildup of dangerous mixtures more rapidly than larger ones.

Conclusions

1. The diffusion process through joints, as affected by the enclosure design variables of flange width, internal volume, joint periphery and gap size, appears to be adequately defined by a simple diffusion equation. Exact corroboration of experiment and theory is hampered by lack of a suitable method of measuring actual gap size.

2. Lower limit mixtures (4% hydrogen in air) were found to exist inside enclosure volumes of (28.5 in.^{3}), (34.0 in.^{3}), (109 in.^{3}) and (360 in.^{3}), after elapsed times of 30, 33, 81 and 171 minutes respectively. From these results, and inspection of the equation referred to above, it is evident that smaller enclosures permit the buildup of explosive mixtures more rapidly than larger ones.

3. Hydrogen diffuses relatively quickly into air, whereas heavier gases require longer periods to diffuse to the same concentration.

Acknowledgements

Grateful acknowledgement is extended to Mr. N.A. Toews, of the Physics Section of the Fuels and Mining Practice Division of the Department of Mines and Technical Surveys, for advice regarding the derivation of the diffusion equation.

References

1. International Critical Tables, Volume 5, First Edition, page 62.

TABLE 1

Physical Characteristics of the Enclosures Investigated

Enclosure Designation	Type	Enclosure Volume (in.^{3})	System Volume Vi (in.^{3})	Outside Flange Periphery L (in.)	Flange Width 1 (in.)	Bolt Torque (ft lb)	Bolt Size (in.)	Flange Surface Roughness (μ in.)		Enclosure Material
								Body	Lid	
A1	Commercial	28.5	31.5	17.0	5/8	5	1/4 - 20	42	32	Cast Iron
A2	Commercial	34.0	37.0	17.0	5/8	5	1/4 - 20	42	42	Cast Iron
B	Commercial	109	112	22.6	1/2	5	1/2 - 20	50	35	Cast Iron
C	Experimental	360	363	54.5	1 5/8	25	1/2 - 13	70	20	Steel Plate

TABLE 2

Approximate Gap Measurements (inches)

Joint Number	Enclosure Designation			
	A1	A2	B	C
1 *	less than 0.0020 greater than 0.0015	less than 0.0005	less than 0.0010 greater than 0.0005	All joints less than 0.0005 in.
2	less than 0.0005	less than 0.0005	less than 0.0005	
3	equal to 0.0005	less than 0.0010 greater than 0.0005	less than 0.0005	
4	less than 0.0005	less than 0. 0.0005	less than 0.0010 greater than 0.0005	
5	-	-	less than 0.0005	
6	-	-	less than 0.0005	
Number of Bolts	4	4	6	16

*Spark plug located opposite this joint during explosion tests reported in Reference 1 (see Figure 2).

TABLE 3

Experimental Results of Diffusion of Hydrogen Atmospheres Into Flat-Flanged Enclosures
- Inside Hydrogen Concentration vs Time -

Enclosure Designation	Analysis Number	0	1	2	3	4	5	6	7	8	9
A1	Time (hrs)	0	0.25	0.92	1.48	2.27	3.58	3.82	4.87	5.60	-
	% H_2	0	3.1	9.8	13.7	18.2	27.0	27.1	29.5	29.9	-
A2	Time (hrs)	0	0.28	0.88	1.47	2.42	3.01	4.20	5.18	5.83	-
	% H_2	0	2.1	6.0	9.6	14.2	16.1	20.2	22.5	24.1	-
B	Time (hrs)	0	0.22	0.70	1.48	2.10	3.42	3.72	4.47	5.43	6.08
	% H_2	0	0.8	2.5	4.9	6.3	9.7	10.3	12.4	14.5	15.3
C	Time (hrs)	0	0.25	0.63	1.10	1.63	2.57	3.87	4.88	6.07	-
	% H_2	0	0.25	0.95	1.65	2.4	3.6	5.4	6.35	7.9	-

TABLE 4

Summary of Apparent Gap and Internal Concentration Calculations

Enclosure		External Concentration co - (%)	Time t - (sec)	Calculated Internal Concentration ci - (%)
Designation	Apparent Gap-g (inch)			
A - 1	0.00084	44	1,800	5.12
		44	7,200	17.2
		44	14,400	27.7
		44	21,600	34.0
A - 2	0.00065	44	1,800	3.42
		44	7,200	12.2
		44	14,400	21.0
		44	21,600	27.3
B	0.00060	44	1,800	1.67
		44	7,200	6.30
		44	14,400	11.7
		44	21,600	16.3
C	0.00098	44	1,800	0.73
		44	7,200	2.84
		44	14,400	5.49
		44	21,600	8.00

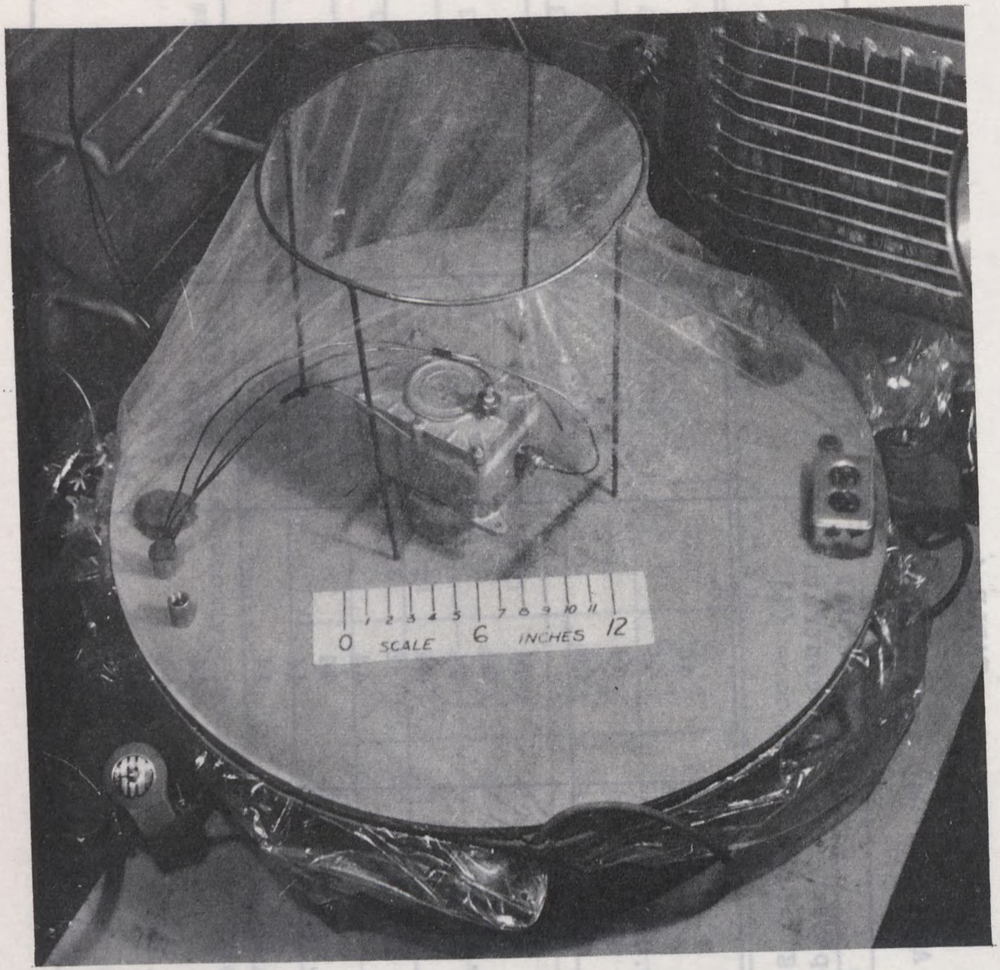


Figure 1 - Photograph of the Apparatus

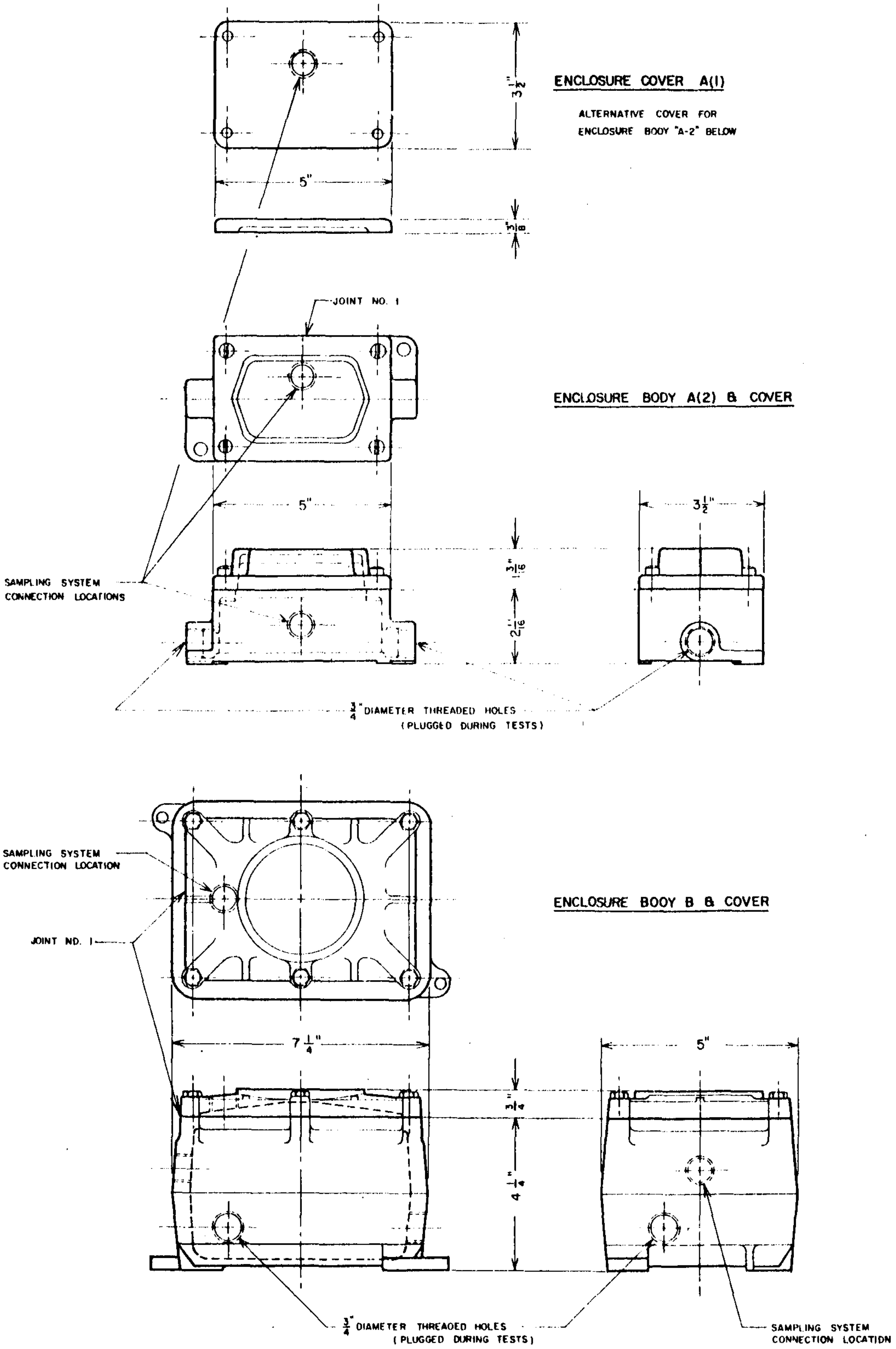
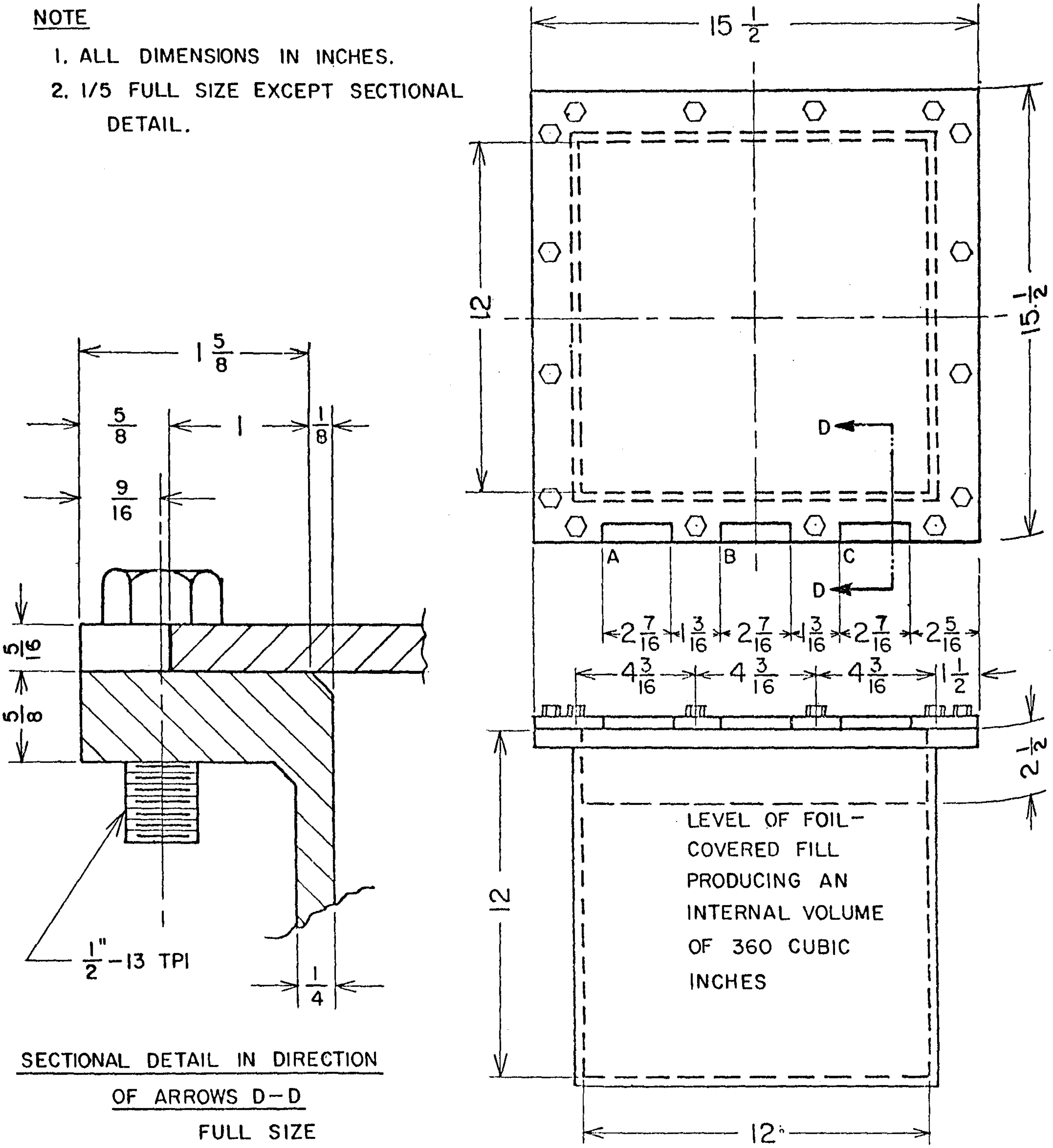


FIGURE 2 - DETAILS OF COMMERCIAL ENCLOSURES A(1), A(2), & B

SEE TABLE I FOR FURTHER PHYSICAL CHARACTERISTICS OF THESE ENCLOSURES

NOTE

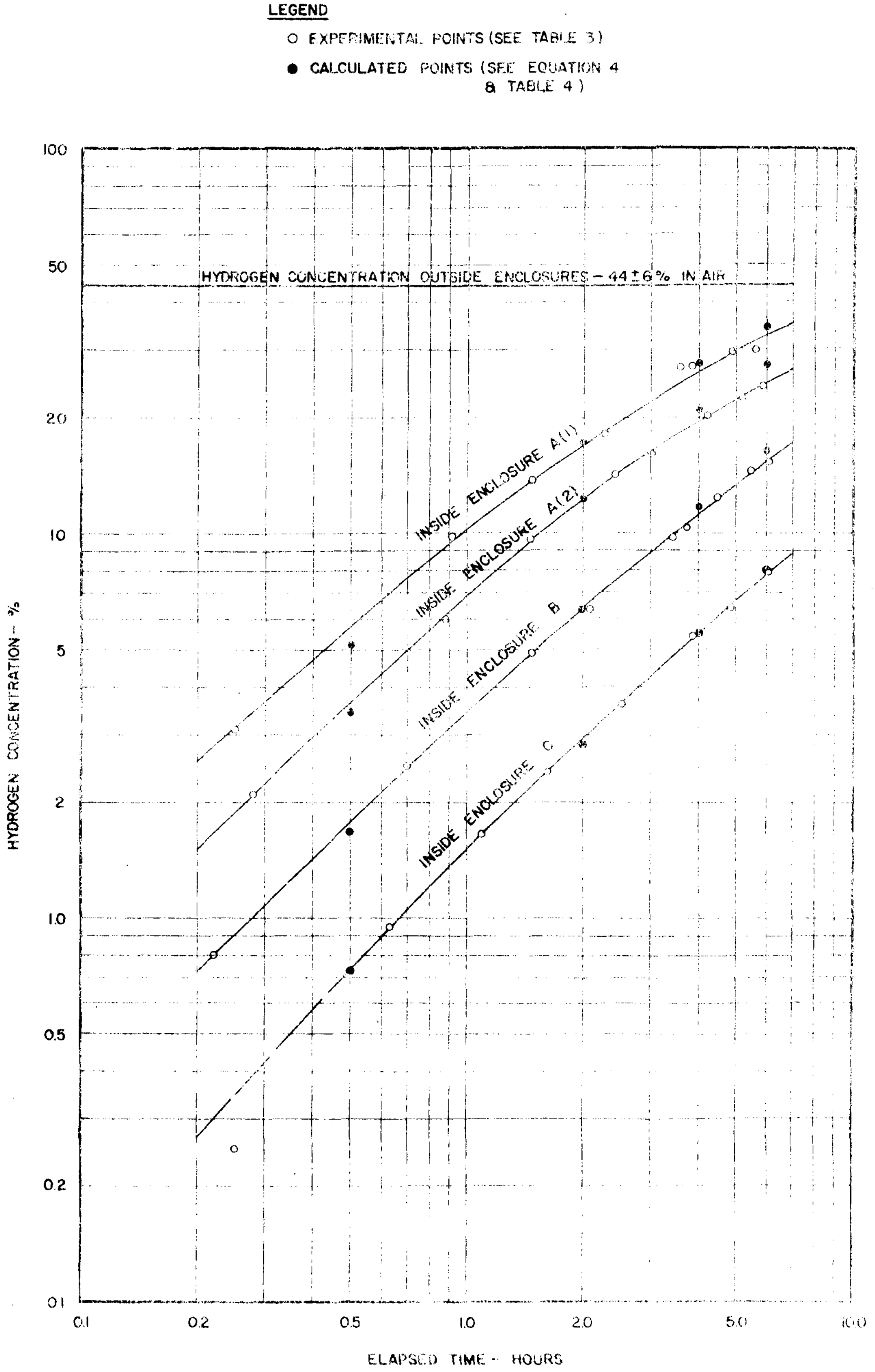
1. ALL DIMENSIONS IN INCHES.
2. 1/5 FULL SIZE EXCEPT SECTIONAL DETAIL.



SECTIONAL DETAIL IN DIRECTION OF ARROWS D-D
FULL SIZE

FIGURE 3– DETAILS OF 360-CUBIC-INCH FLANGED ENCLOSURE-C

FIGURE 4 - DIFFUSION OF HYDROGEN ATMOSPHERES INTO FLAT-FLANGED ENCLOSURES



CHAPTER 8

TRANSMISSION OF HYDROGEN EXPLOSIONS THROUGH THREADED JOINTS

Summary

Two American thread systems, 1/4 - 20 TPI UNC and 2 - 16 TPI UNEF, which had maximum clearances approximating those of the loosest Class I fit, were studied. It was found that no explosion transmissions were permitted when only 1 thread and 3/4 of a thread, of the above two systems respectively, were freely engaged. However, when the 2 - 16 TPI plug was jammed by shims, thus producing a direct saw-tooth gas flow path, 5 consecutive explosion transmissions resulted with 2 full threads engaged and 5 consecutive non-transmissions occurred with 3 full threads engaged.

Experimental Procedure and Apparatus

A scale drawing of the explosion chamber is shown in Figure 1. It consisted of a compartmented cylindrical chrome-plated steel vessel, equipped with viewing windows, circulation fans, translating igniter connections, external volume vent of 1.25 inches diameter, and a partition into which the threaded plug to be investigated was turned to the desired number of threads engaged.

All the joints in the vessel, including the partition between the internal and external chambers, were sealed by O-rings. The gas mixture circulation nozzles and chamber interconnecting line were fitted with shutoff valves. These precautions prevented all pressure relief from the internal chamber, except through the threaded joint itself.

The position of the partition was fixed in the location shown in Figure 1, in order that the internal volume be large enough to permit transmission at the least clearance (see Chapter 4).

Two American thread systems were studied, i.e. 1/4 - 20 TPI UNC and 2 - 16 TPI UNEF. These two threads belong to two series, designated "unified national coarse" and "unified national extra fine" respectively. Figure 2 shows the principal thread characteristics which are defined in Reference 1.

These threads were manufactured to approximate the loosest class of fit, i.e. Class 1, thus providing the most thread clearance and the maximum probability of ignition transmission. It was not considered necessary to exactly duplicate the standard thread diameters of Reference 1, provided that the thread clearances and the thread forms were adequately reproduced. The diametral clearances, C_D, were manufactured within a tolerance of ±10% of the standard.

Hydrogen-air mixtures having a hydrogen concentration of 29.6% by volume were prepared by the partial pressure method, using laboratory air and a single dry hydrogen cylinder of 99.5% minimum hydrogen purity for all tests. The mixtures were circulated through a closed system of the two chambers in series by a non-lubricated, vane-type rotary pump. The gas mixture circulation nozzles and chamber interconnecting line were fitted with valves to prevent pressure relief.

Repeatability of the mixture concentrations was checked on a "thermabridge" (thermal conductivity cell) hydrogen analyzer having a repeatability of ±1% of full-scale deflection corresponding to 100% hydrogen.

The spark location was fixed by clamping the translating igniter at a position near the entrance to the thread channel. This distance was 3/4 inch and 1/2 inch for the 1/4 - 20 TPI and the 2 - 16 TPI test series respectively.

The desired thread configuration was selected and the number of threads engaged was determined by a depth micrometer.

In the case of the unshimmed thread tests, no deliberate restraint of any kind prior to ignition was placed upon the plug, so that only internal pressure closed the direct flow path. For the shimmed thread series of tests, however, the clearance was deliberately maintained by 0.010 - inch shims (note that clearance C_M of Figure 4 for the two-inch plug is 0.0106 inch). The shims were situated at a circumferential separation as given in Table 1. Care was taken in the latter case to ensure that these shims were not diametrically opposed. Therefore, only diametral clearances could result.

The desired hydrogen-air mixture was prepared, circulated at the rate of 0.45 cfm for a total of 6 minutes, and fanned for 15 seconds of each minute of circulation. After circulation the external chamber vent was opened, and ignition was initiated by a single spark in the internal chamber.

After analysis of the products of the explosion, the circulation lines, pump, and chambers were flushed by air from the laboratory supply.

The above procedure was repeated for each of the five tests of each test series. The results are reported in Table 1.

Discussion of Results

Figure 3 shows an assumed orientation of the external plug in the internal thread. This orientation assumes that the force system produced by the explosion pressure is such that the plug is centred in the hole, thus producing a helical gas path through the threads. If the results are interpreted according to this conception, then it was shown that a helical path length of 0.76 inch was too long to permit explosion transmission through a minimum flow path clearance of 0.0063 inch for the 1/4 - 20 TPI of Class I fit. Similarly, a helical path length of 4.51 inches was too long for a clearance of 0.0106 inch for the 2 - 16 TPI. If the explosion pressure does not centre the plug in the threads (a possibility which is discussed further below), the ability of helical gas paths, of the sizes given above, to transmit or to quench explosions has not been determined by these tests. It is improbable, however, that true helical paths of these dimensions would permit explosion transmission. This conclusion results from a comparison of the 1/4 - 20 TPI test results with those of a flat joint of the same gas path length, as in the following table:

Type of Joint	Gas Path Length (in.)	Gap Size (in.)
Flat	0.76	0.0103 (Chapter 4)
Threaded	0.76	0.0063 (C_M herein)

It is seen that the threaded joint clearance (C_M - Figure 3) is considerably less than the safe flat joint gap. The effects of the small cross-sectional dimensions of the helical path and of increased cooling due to the helical movement of gas, would tend to enlarge the above gap size difference, making the threaded joint even safer than the above comparison.

A more probable positioning of the threaded plug than that of the pressure-centred system above is that of an overhanging plug having approximately one thread freely engaged. The plug would rock on its lower thread until the upper thread makes contact with the internal thread, thus effectively closing off the gas flow path altogether. The application of explosion pressure would tend to more effectively seal off the gas flow path. From this point of view the negative results encountered were to be expected.

Whatever positioning system actually occurred during the tests, it is clear that with essentially no loading on the thread no explosion transmission occurred for the 1/4 - 20 TPI and 2 - 16 TPI, when 1.08 and 0.74 threads of a Class I fit were engaged respectively.

When the threads were deliberately jammed by shims they were oriented as in Figure 4. This orientation produced the maximum possible clearance and the minimum length of flow path simultaneously. This set of circumstances, while somewhat artificial, proves to be dangerous when between 2 and 3 threads of a Class 1, 2 - 16 series, are engaged. The tabulation below compares the safe thread direct path dimensions for 3 threads engaged to those of the corresponding flat joint:

Type of Joint	Gas Path Length (in.)	Gap Size (in.)
Flat	0.311	0.0070 (Chapter 4)
Threaded	0.311	0.0106 (C_M herein)

Therefore, the safe threaded joint has a gap C_M approximately 50% larger than the safe flat joint of the same length. This difference in gap size provides an approximate measure of the inhibiting effect which path direction changes have on the transmission of explosions. It is to be noted that the gap C_M is smaller than the diametral clearance C_D (Figure 4).

Conclusions

1. The 2 - inch diameter 16 threads per inch system, when shimmed to produce the maximum available diametral clearance of 0.0212 inch with 3 threads engaged, did not permit explosion transmission in 5 consecutive trials. When 2 threads of the same system were engaged, 5 consecutive ignition transmissions occurred. It is concluded, therefore, that this thread system required a critical joint gap larger than the flat joint gap of the same gas path length, C_M being approximately 50% larger than the experimental safe gap for the same joint flamepath length.
2. The 2 - inch diameter 16 threads per inch system, with no external loads applied to the plug other than its own weight, does not permit explosion transmission when 3/4 of a thread is engaged.

3. Conclusion 2 applies to the 1/4 - 20 TPI system when 1 thread is engaged.

Acknowledgements

Acknowledgement is given to Mr. D.M. Norman, Mechanical Engineer, Technical Services Division of the Mines Branch, for his assistance in the manufacturing of the experimental threads.

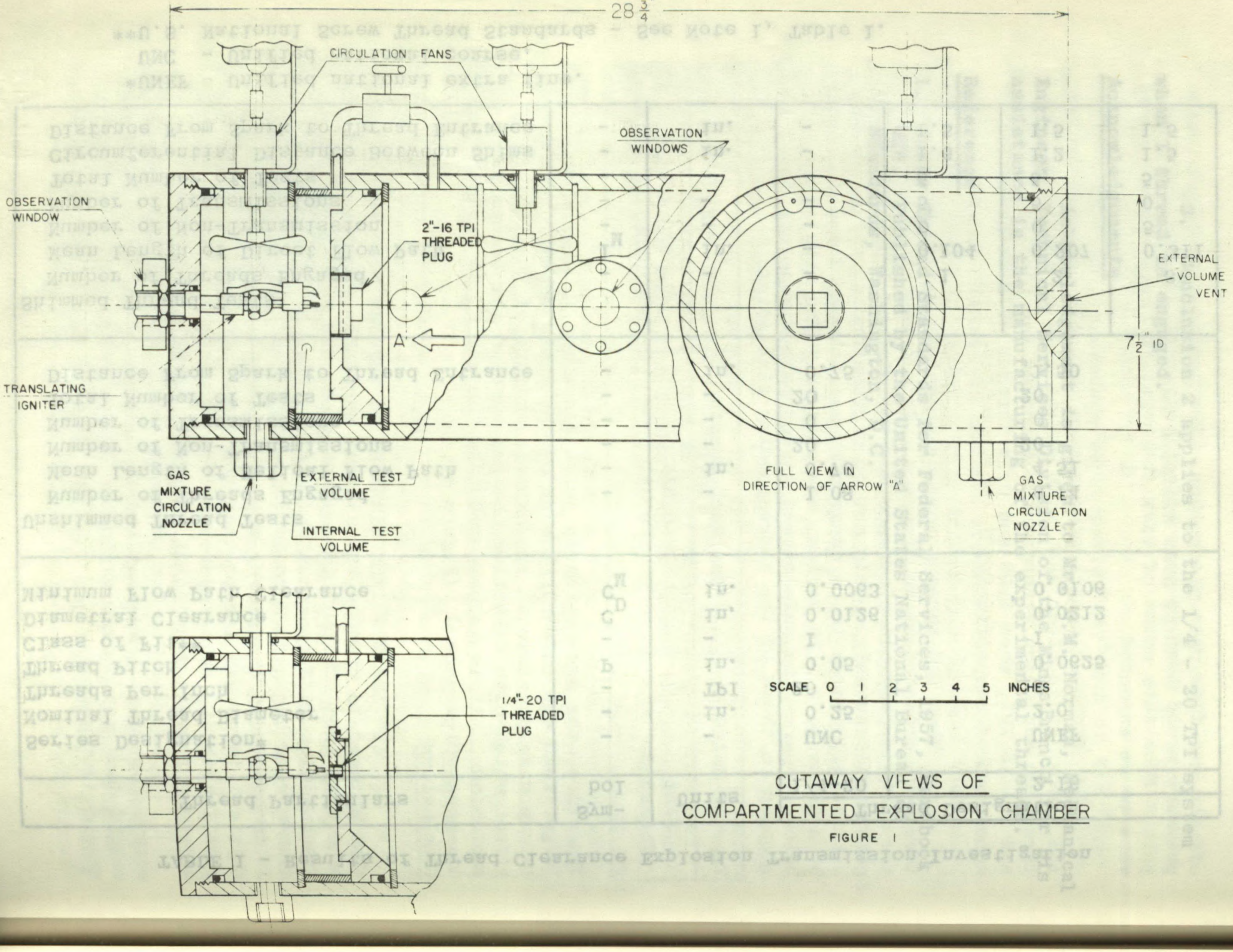
Reference

1. Screw Thread Standards for Federal Services, 1957, Handbook H28. Published by the United States National Bureau of Standards, Washington, D.C.

TABLE 1 - Results of Thread Clearance Explosion Transmission Investigation

Thread Particulars	Sym-bol	Units	Thread Designation			
			1/4-20	2-16		
Series Designation*	-	-	UNC	UNEF		
Nominal Thread Diameter	-	in.	0.25	2.0		
Threads Per Inch	-	TPI	20	16		
Thread Pitch	P	in.	0.05	0.0625		
Class of Fit**	-	-	I	I		
Diametral Clearance	C_D	in.	0.0126	0.0212		
Minimum Flow Path Clearance	C_M	in.	0.0063	0.0106		
Unshimmed Thread Tests						
Number of Threads Engaged	-	-	1.08	0.74		
Mean Length of Helical Flow Path	-	in.	0.76	4.51		
Number of Non-Transmissions	-	-	20	20		
Number of Transmissions	-	-	0	0		
Total Number of Tests	-	-	20	20		
Distance From Spark to Thread Entrance	-	in.	0.75	1.50		
Shimmed Thread Tests						
Number of Threads Engaged	-	-	-	1	2	3
Mean Length of Direct Flow Path	l_M	in.	-	0.104	0.207	0.311
Number of Non-Transmission	-	-	-	0	0	5
Number of Transmissions	-	-	-	5	5	0
Total Number of Tests	-	-	-	5	5	5
Circumferential Distance Between Shims	-	in.	-	1.6	1.2	1.5
Distance From Spark to Thread Entrance	-	in.	-	1.5	1.5	1.5

*UNEF - Unified national extra fine.
UNC - Unified national coarse.
**U.S. National Screw Thread Standards - See Note 1, Table 1.



CUTAWAY VIEWS OF COMPARTMENTED EXPLOSION CHAMBER

FIGURE I

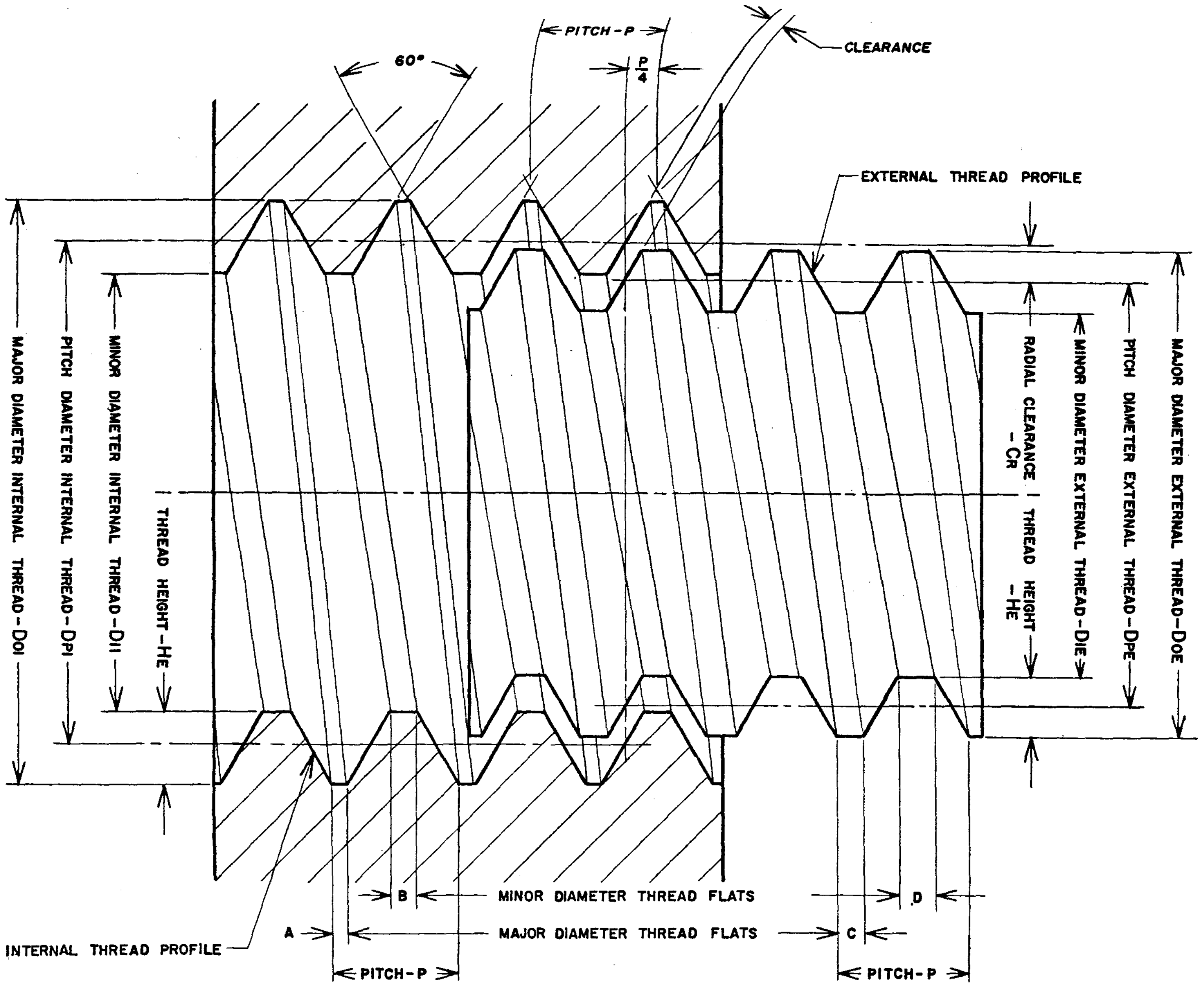


FIGURE 2 - THREAD FORM DEFINITIONS

FOR DATA OF THREADS TESTED SEE TABLE I

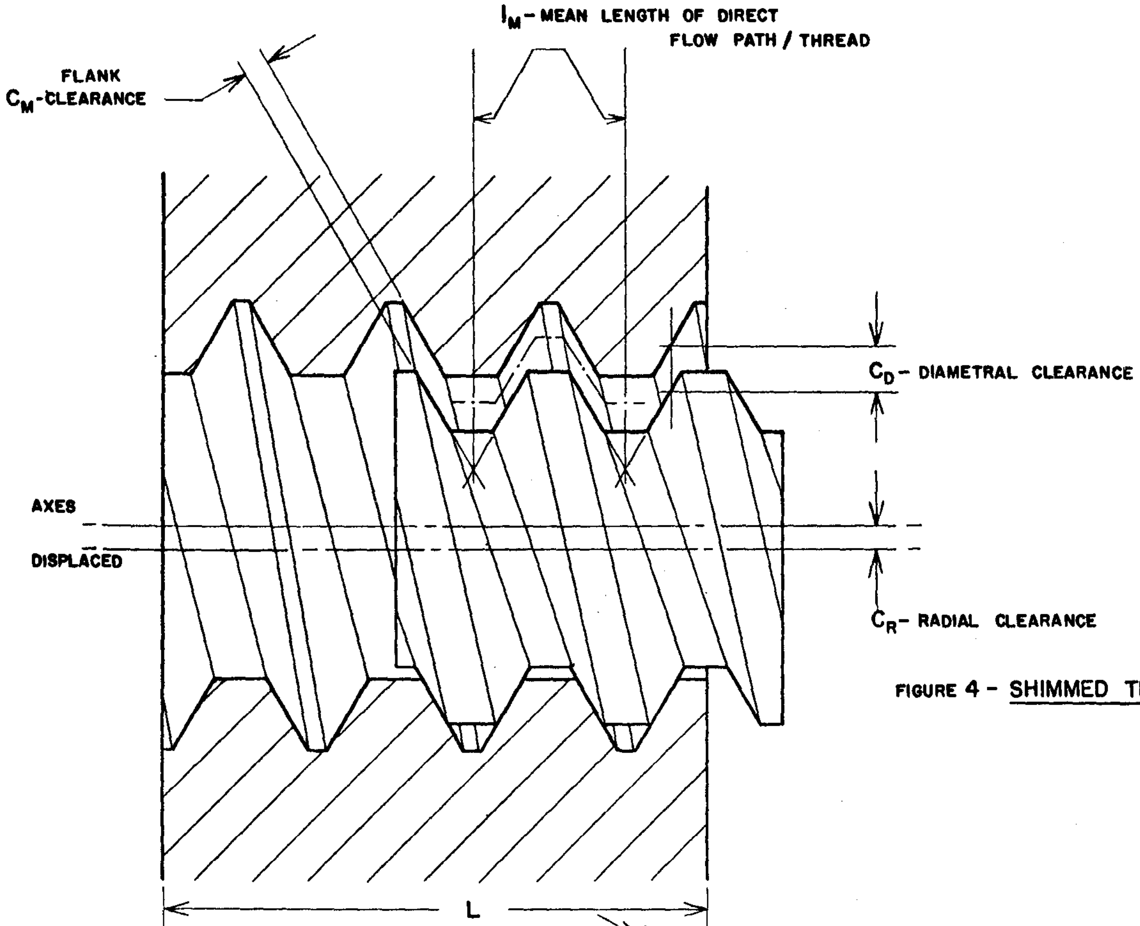


FIGURE 4 - SHIMMED THREAD ORIENTATION

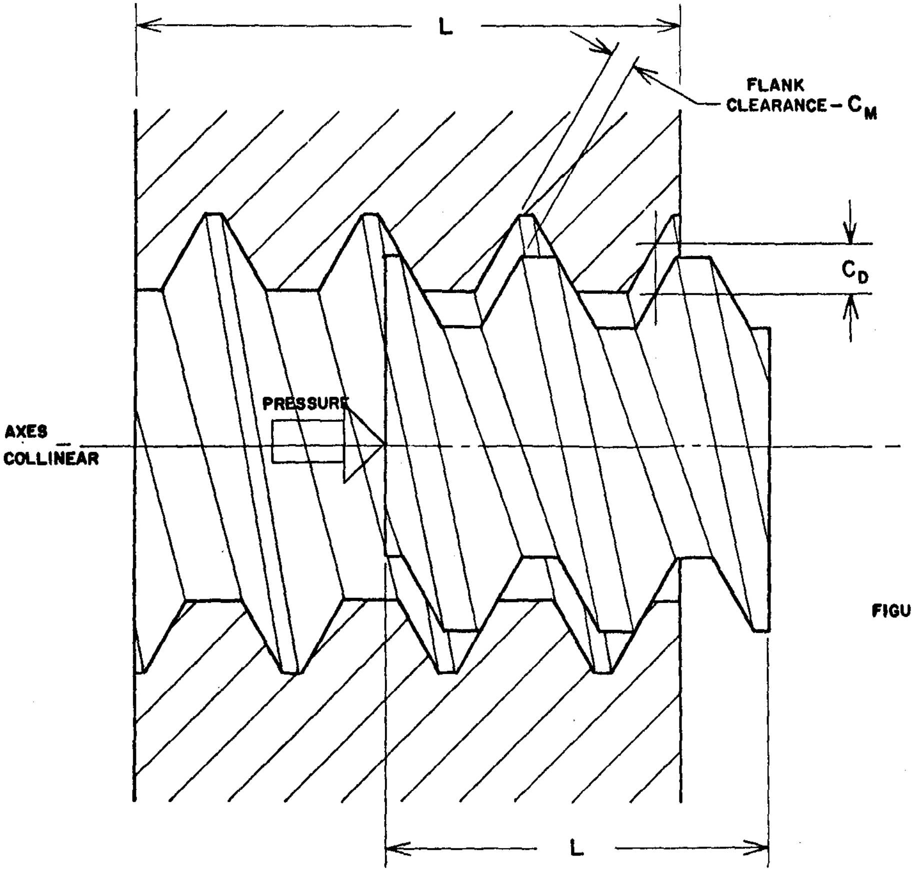


FIGURE 3 - UNSHIMMED THREAD ORIENTATION

CHAPTER 9

DISCUSSION OF THE SIGNIFICANCE OF THE RESULTS

This report has given details of laboratory investigations of hydrogen explosion phenomena the purpose of which was to obtain information useful in understanding explosion transmissions through metal joints of enclosures. Other flammable gases and vapours present a similar problem, but hydrogen is judged to be more hazardous than most. This is principally because of its ease of ignition by electric sparks of low energy, its ability to transmit an explosion through very small openings in joints, its wide range of flammability, and its susceptibility to detonation. When the latter occurs, pressures many times higher than normal for gas-air explosions result.

In considering whether explosion-proof (flameproof) enclosures can be safely used, it is necessary to know what surface temperatures might cause ignition, what pressures the enclosures must withstand, and what types of joints are necessary to prevent explosion transmission from the inside of the enclosure to the surrounding atmosphere. With regard to surface temperature, there was information available (1) which showed this to be above 570°C, and so in this respect hydrogen is far less hazardous than ether and no more hazardous than pentane. There was also considerable information available from other sources on hydrogen explosion pressures. However, with respect to the effect, on explosion transmission through joints in electrical enclosures, of factors such as volume, shape, hydrogen concentration, joint width, joint gap, pressure relief, rate of pressure rise, etc., much information was needed that did not appear to be available. Consequently, the laboratory investigations described in this report were conducted to provide some of the required information.

The results obtained have significance with regard to the practicability of the type of protection known as explosion-proof (flameproof) enclosures, with respect to the hydrogen hazard. For example, the experiments have shown that detonations do not occur in volumes of the shape and size tested for ignition from a single point source. Pressures generated under these circumstances were not excessively high. While explosion transmissions occurred through quite small joint gaps for unexpandable joints, and through even smaller initial gaps for bolted covers that permitted some gap expansion during an explosion, it is still not difficult to machine flat joints which fit closely enough together to prevent explosion transmission. However, before discussing the joint fit, it may be useful to make some observations on the maximum experimental unexpandable gap sizes which would not transmit explosions, obtained from this investigation. The results (see Figures 2 and 3, Chapter 4) are almost the same as those given in a private communication from Great Britain for volumes of 8000 cc and 250 cc. Our results are in good agreement despite differences in the experimental procedures. This may mean that either the differences had insignificant effects on the results or certain effects balanced one another. Among the different experimental conditions of the other tests was the fact that they were carried out with 32 per cent hydrogen inside the enclosure (which would include the joint gap) and 24 per cent surrounding the enclosure, whereas the experiments of this report were conducted with the same mixture, 29.6 per cent, inside and outside. Other differences in the two experimental studies were the shape of the vessels and the ratio of gap relief area to volume. After considering the results, it is the opinion of the authors that a stoichiometric mixture (29.6 per cent) inside and outside appears as effective as any for explosion transmission; that above a certain volume further increases in volume within the range tested do not significantly change the maximum experimental safe gap for enclosures with unexpandable joints; that below a certain volume further decreases in volume will usually result in a larger maximum experimental safe gap. It is thought that the larger experimental safe gaps for small volumes would be obtained unless the enclosure had a large ratio of pressure relief area to volume, which could reduce the rate of emission of the explosion products through the experimental gap and so affect their ignition potentiality. In Document 31 (Germany) 9A of the International Electrotechnical Commission (2), values of experimental safe gaps for joints of 25 mm (approx. 1 inch) width are given which remain at almost a constant level of about 0.31 mm (approx. 0.012 inch) for decreasing volumes of test enclosures down to 15 cm^3 (approx. 0.91 inch^3). It is thought that these results may be due to relatively large gap pressure relief area with respect to the volume. To substantiate this last opinion, it is planned to conduct experiments with several enclosures of constant small volume, 15 in.^{3} (246 cc), but of different shapes (e.g. long and thin, cubical). The enclosures will be fitted with variable pressure relief devices. In addition to showing the effects of pressure relief on the experimental safe gap, these tests should also indicate whether different rates of pressure rise due to shape at this volume level are significant, although this latter is not thought to be likely.

If the above assumptions concerning the relationship of maximum experimental safe gap to the initial pressure relief area of the gap for small volumes should prove correct, then it is favorable to safety for small explosion-proof enclosures in which the initial joint would provide practically no relief area. By the time an explosion in such an enclosure reached sufficient pressure to open the gap, a higher emission rate would result which would not be as effective for external ignition as a lower rate of emission. For ignition to result, it is believed, the gap would need to expand to values as high as or higher than reported in the work of this report.

The experiments of Chapters 5 and 6 with bolted enclosures give some idea of the initial gaps required to obtain explosion transmission for various types of covers and bolting arrangements. It is apparent that in dealing with the hydrogen hazard, a single loose bolt has more significance than it does for gases with experimental safe gaps in the order of 0.030 inch (0.762 mm) or higher.

The experiments of Chapter 7, on the time required for diffusion of hydrogen into enclosures with flat joints, are considered favorable to the use of such enclosures because of the relatively long time required to obtain inside mixtures from highly concentrated surrounding mixtures. Also, it is favorable that the larger enclosures require the longest diffusion time, in order to decrease the possibility of explosive mixtures occurring in them. This tends to offset to some extent the increased hazard of larger enclosures due to greater forces being exerted on larger covers, which in turn makes joint and bolting design more critical.

The experiments of Chapter 2 showed that a 10 per cent hydrogen mixture required a gap (unexpandable) as large as did the best pentane-air mixtures for explosion transmission. The explosions at 10 per cent hydrogen were weak and did not produce the pressure of strong pentane explosions. Therefore the danger of joint expansion is less. This relationship of the weaker hydrogen mixtures to pentane may be of significance in the assessment of hazardous areas, because if it can be determined in advance that the concentration of hydrogen in a given location where the electrical apparatus is to be located could never exceed

10 per cent, then the location would for practical purposes be no worse than locations for less hazardous gases.

In view of the small experimental safe gap, the evidence of varying amounts of gap expansion for bolted covers, information from research centres outside Canada on the effect of obstructions adjacent to or on gaps, and the effect of emission of hot metal vapour or particles from short circuits or arcing, it is evident that, if enclosures with flat joints are used in hydrogen hazardous locations. the joints should fit closely without any gap. Therefore, any maximum gap specified because of machining limitations should be the smallest considered practical. This is believed advisable even for increased width of joints. Such a tight joint would have the desirable effect of increasing the time for diffusion to produce dangerous internal mixtures.

Threaded joints, as shown by Chapter 8, are much better than flat joints for preventing explosion transmission.

In conclusion, it should be pointed out that sources of ignition other than by transmission through the joints of electrical enclosures present a greater degree of hazard with regard to hydrogen compared to many other flammable gases or vapours. It is relatively easy to ignite hydrogen with a static spark. In the laboratory, the stoichiometric mixture issuing from the gas analyzer was, in fact, ignited by a static charge spark from the finger of the analyzer operator. Frictional sparks also are an ignition hazard of consequence.

References

1. National Fire Codes, Vol. 1, Flammable Liquids and Gases - 1959.

2. Document 31 (Germany) 9A, January 1966, of the International Electrotechnical Commission.

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