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VARIATIONS OF IGNITION SENSITIVITY FOR V.D.E. STANDARD INTRINSIC SAFETY APPARATUS AND OTHER FACTORS AFFECTING ITS CALIBRATION

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ABSTRACT

Operators of the German Standard Intrinsic Safety Test Apparatus (VDE 0170/0171, 1963) in the United States and in the United Kingdom, have expressed concern over the occasional and not so occasional instances when this apparatus has appeared to have gone out of calibration during intrinsic safety testing of some electrical equipment. To gain an understanding of these erratic occurrences the apparatus was subjected to many hours of test runs with explosive hydrogen-air mixtures and the standard 24 volt electrical circuit consisting of a 95 mH inductance coil. The large variations in the ignition sensitivities for this apparatus were noted as the electrodes were progressively worn and eroded due to ordinary usage and explosions. The ignition sensitivity variations were considerably decreased by a slight modification to the wire electrodes. The apparatus was then used to study the effects on the ease of ignitions of hydrogen-air mixtures by such external parameters as: atmospheric pressure, hydrogen-air ratio, water condensate on electrodes, temperature, air humidity, and open-circuit voltage of the standard electrical circuit. This investigation indicated that the observed variations in ignition sensitivity are due to both the external parameter changes (affecting the ease of ignition of mixtures) and changes in the apparatus from usage.

INTRODUCTION

For the past several years, an increasing amount of research work has centered about the V.D.E. Intrinsic Safety Test Apparatus (designed by the Union of German Electrotechnicians) which was adopted as the official international standard by I.E.C. (International Electrotechnical Commission) and proposed as standards (drafts) in Britain, U.S.A., Japan, Canada, and others. The areas of interest have been:

(a) determination of calibration currents for various explosive gas-air mixtures.

(b) preparation of data for curves indicating minimum ignition currents (m.i.c.) vs parameters such as: voltage, inductance, capacitance for the four standard gases (methane, propane, ethylene and hydrogen).

(c) preparation of data for similar curves as (b) for electrode discs machined out from various metals such as steel, brass, etc.

(d) investigations on the repeatability of tests conducted at high currents.

(e) investigations on the repeatability with several different electrode wire configurations (trailing wires, single and double spirals).

(f) determination of the m.i.c. variation with high pressures (2 to 6 atmospheres) and high temperatures (200°C).

The first obvious indication that there were problems concerning the operation of this apparatus, became evident when the various certifying authorities published different values for the "calibration current" (27 to 32mA) for the standard electrical circuit and standard hydrogen-air mixture. Later, Cooper,[1] of the National Coal Board published a paper at an I.E.E. Conference, in which he described his experience (similar to other operators) with this apparatus, as follows:

> "a statistical analysis has shown that over parts of each run the ignition frequency does follow a Poisson distribution with no significant trend but that abrupt changes of the parameters of the distribution occurred twice or three times during each run."

- "detailed examination of the ignition frequency variability has shown that short changes of the sensitivity occur when no observable changes have occurred in the apparatus".
- "high sensitivity is therefore only achieved by making use of a condition of the apparatus which there is very little knowledge and virtually no control".
- "this experience is similar to that found when using the equipment as a routine test apparatus to test for the sensitivity before and after testing circuits for intrinsic safety has often been found very difficult to achieve other than on a hit and miss basis".

At the same conference, Bartels and Howes [2] of the Electrical Research Association, authors of another paper on this subject, indicated that their results, based on the operation of this apparatus, were, to some extent, rather high because "difficulty was experienced in maintaining the test apparatus sensitivity". Such comments were frequently voiced by other operators of this apparatus since that time as well.

Although no one suggested that the cadmium disc apparatus should not be used as the standard because of its application difficulties, the achieving of "calibration conditions" by operators who conduct routine testing on electrical equipment is rather frustrating. The purpose of this investigation is to attempt to answer questions as: 1) why "calibration" is on a hit and miss basis? 2) why a piece of equipment may be tested at a certain current level with this apparatus one day and cause no ignitions but the very next day, ignitions may occur, and 3) what controls are available to the operator to improve reliability of this apparatus?

No suggestion is being made here that this investigation is intended to solve all of the "unknown" quantities of this equipment but only some of the apparent ones that might affect its reliability whether due to changes in its sensitivity or changes in the ease of ignition of the explosive mixture due to some external parameters. Thus, this research project was divided into three main areas of interest:

(A) Effect of electrode deterioration
   - cadmium disc (new, average, and old)
   - tungsten wires (new, spiralled, "L" type, and old)

(B) Effect of modified wire electrodes

- a less sensitive apparatus with increased reliability to remain in the "calibration" condition for an adequate length of time to serve as a tool to further this investigation.

(C) Effect on the ease of ignitions of explosive gas-air mixtures by the following external parameters:

1. atmospheric pressure (850 to 650 mm Hg.)
2. hydrogen-air ratio (19 to 26%)
3. water condensate (light to heavy)
4. temperature (interpreted for 0 to 30°C)
5. humidity (0 to 95% R.H.)
6. open-circuit voltage (6 to 50 volts d.c.)

METHOD

(A) Effect of Deterioration of Electrodes

1. Tests on Electrodes

(a) Cadmium Discs

Four types of cadmium disc surfaces (new, fairly new, average, and old) were tested in combination with either the standard straight wire tungsten electrodes or "L" type of tungsten wire electrodes (with a right angle bend at the tip). The main feature of these latter electrodes, as drawn in the insert, see Figure 3 , is the line to surface contact between the two moving electrodes, i.e. no scraping of the disc surface, or frictional wear of the wire tips. Both tests were conducted with 22% hydrogen-air mixtures, at various ambient temperatures and pressures. The data for the various tests are given in tables 1 and 2, and plotted in Figure 1.

For all tests, the standard series electrical circuit was used consisting of a 95 mH air cored inductor supplied from a 24 volt d.c. lead-acid source through a variable non-inductive resistor for current limitation. The test procedure for the ignition tests involved:

(i) evacuation of the explosion chamber which is then filled with the explosive mixture either at atmospheric pressure or at a controlled pressure. The accuracy of the explosive mixture, prepared in a binary mixer, is about 0.01% (C.E.A.L. Report No. 172)

(ii) the test is started with a circuit current which is high enough to ignite the gas mixture with a reasonable probability. The current is then reduced progressively by approximately 5% (2mA) in successive tests until a "miss" is obtained. The previous ignition current is then recorded as the "lowest ignition current (l.i.c.) value. Depending on the type of test, the test period was varied from 3 to 5 minutes. (250 to 400 revolutions of the tungsten wire holder).

(b) Tungsten Wire Electrodes

The ignition sensitivities of the apparatus were investigated by conducting various tests with the surface of the cadmium disc electrodes held somewhere between "fairly new" and "average" conditions while the following characteristics of the tungsten wire electrodes were varied:

1. fatigue, due to bending at holder clamps
2. length of wire electrodes
3. bending pressure of wire on disc surface
4. wear of wire ends, due to friction and/or burning
5. quantity of cadmium dust particles

1. Wire Fatigue - a series of tests was started after a l.i.c. value of 30 mA was obtained. The test periods were of the 5 minute duration. After a total of 10 minutes of non-ignitions at 25 and 27 mA, the currents were increased from 30 mA in 5% increment steps until ignition of the explosive mixture occurred. The next series of tests was conducted after starting with a l.i.c. value of 30 mA after 40 minutes of testing. The results are recorded in Tables 3 (a) and 3 (b).

2. Variation in Length - this series of tests consisted of finding the l.i.c. values for various tungsten wire electrode lengths. Only one wire electrode was clamped in the holder and its free length was adjusted from a minimum of 10.0 mm to a maximum of 12.5 mm. The l.i.c. values for each length were recorded in Table 4.

3. Variation of Physical Pressures - the physical pressures between tungsten wire electrodes and the disc electrode surface were varied from those pressures applied by straight wires to those lesser pressures applied by wires with single and double 1/8-inch. diameter loops formed near the clamp at the electrode holder. The results of these tests are reported in Table 5.

4. Wear of Wire Ends - the wear or deformation of the contact type of tungsten wire electrodes, with normally fused ends, was examined (see photographs in figure 2) under a microscope (x 66) after undergoing the following test programs:

a) 5,000 revolutions of holder, sparking but with no explosive mixtures

b) after 5 hydrogen-air explosions

c) after 10 hydrogen-air explosions

d) after an unspecified number of explosions

5. Cadmium Dust Particles - these tests compared the ignition sensitivities of the apparatus under the following test conditions:

a) both electrodes (wires and disc) were untampered with between explosions

b) both electrodes were cleaned thoroughly from all cadmium dust particles after each explosion. The l.i.c. results are given in Table 6.

(B) Effect of Different Electrode Combinations

The results of the experiments conducted in Section A of this report indicate some of the physical parameters which may cause this apparatus to go out of calibration from time to time. The aim now is to obtain a combination of disc and wire electrodes for this apparatus that would produce more consistent results over a minimum specified test period.

Of the many different electrode combinations that were tested, only two appeared to be more successful than the others. These electrode combinations are described as:

a) "old" disc plus "L" type wire electrodes

b) "fairly new" disc plus "semi-L" (resembling a hockey stick) wire electrodes.

These ignition sensitivity results (l.i.c. values) and those for the "average" disc plus straight wire electrodes combination are given in Table 7, and are represented graphically in Figure 3. Also, the general shape of the "L" and "semi - L" type wire electrodes are as shown in Figure 3.

(C) Ease of Ignitions by Various External Parameters

(1) Effect of Atmospheric Pressures

(2) Effect of Hydrogen - air Ratios

The V.D.E. apparatus, modified, as described in the previous section, with the "fairly new" disc + "semi-L" type wire electrodes, proved to remain in a "desensitized" calibrated condition for at least one hour long test periods. To ensure that this condition remained constant, the ignition sensitivity tests for variation in atmospheric pressures and hydrogen air ratios were conducted consecutively, i.e. for any one hydrogen-air ratio (18, 20, 22, 24, or 26%) the atmospheric pressures inside the explosion dome were adjusted to various values between 850 and 650 mm Hg. The l.i.c. values are given in Table 8, and are represented graphically in Figure 4.

To obtain a graphical picture of the effect of the sensitivity changes as the hydrogen-air ratio changes for two different but constant atmospheric pressures, two vertical lines are drawn at 730 and 790 mm Hg. in Figure 4, and the l.i.c. values at the intersections with the curves are noted (see Table 9) and plotted against the hydrogen-air ratios as shown in Figure 5.

(3) Effect of Water Condensate

The effects of water condensate on the electrode surface were accidentally noted when, during the "humidity" tests some water collected in the hoses connected to the explosion chamber. Depending upon the amount of water present in the hose, three distinct water condensates formed on the electrode surfaces:

(a) light - formed by a fog in the dome
(b) medium - small tiny droplets on surfaces
(c) heavy - all surfaces wet

For these three test conditions, ignition sensitivity tests were conducted, with the results recorded in Table 10.

(4) Effect of Temperature

A fair estimate only is made here on the effect of small temperature changes on the ease of ignition of hydrogen-air mixtures (due to the lack of a large temperature controlled environment) from experimental data obtained from a paper written by Bartel and Howe [2]. Their ignition values of hydrogen-air mixtures were obtained using the V.D.E. Test Apparatus in a standard electrical circuit consisting of a 1 mH inductance instead of the usual 95 mH. value, at environmental temperatures of 20° and 200°C, see Figure 6.

Assuming their results are fairly accurate, the following additional assumptions were made:

(a) the minimum ignition energies for electrical circuits consisting of a 1 mH or a 95 mH inductance are identical (actual figures are 0.033 compared to 0.035 mJ obtained from SMRE B/213 curves).

(b) the ignition energy efficiency ratios between the apparatus of Bartel and Howe and the desensitized CEAL apparatus is constant at 1.75, based on the ignition energy calculations at 20°C, 1 atmosphere pressure, and hydrogen-air ratios of 22% (280 mA at 1 mH for Bartel and 38 mA at 95 mH for CEAL).
(c) the minimum ignition energy values for different mixture temperatures vary according to Arrhenius Law which states, "the energy of activation is determined by plotting the logarithm of the rate constant E(energy) against the reciprocal of the absolute temperature". This function, when plotted on a semi-log graph paper should be a straight line. Thus, the following steps were taken in this order:

1. the ignition energy values E_1 (for Bartel's apparatus) were calculated for the ignition current values read off the curves shown in Figure 6, for temperatures 20° and 200°C.

2. the ignition energy values E_2 (for CEAL apparatus) were calculated from the E_1 values.

3. the reciprocals of the absolute temperatures (10^3/K) for 20° and 200°C were calculated, and the respective values E_2 were plotted on semi-log graph paper and a straight line drawn between these two points, see Figure 7. Ignition energy values E_2 were then read off this graph for temperatures of 50, 32, 20, 10 and 0°C.

4. the minimum ignition currents I_2 (for C.E.A.L. Apparatus) were calculated for the above E_2 values and a plot of I_2 versus T was drawn as shown in Figure 8. The results of the above calculations are given in Table 11.

(5) <u>Effect of Humidity</u>

The extent to which humidity in the atmosphere affects the "ease of ignition" may depend on (a) the amount of ratio change of hydrogen gas to dry air and/or (b) the degree of interference caused by the presence of another uncombustible gas in the environment. For the former case, the maximum ratio change was calculated (see appendix) for air at 20°C and R.H. value of 100%. For the latter case, explosive hydrogen mixtures were prepared both with dry air and with moist air (about 90% R.H.), and tested with the V.D.E. Test Apparatus. The results are given in Table 12.

(6) <u>Effect of Changes in the Open Circuit Voltage</u>

The open-circuit voltage of the standard electrical circuit was varied from 6 to 50 volts, to determine what effect this would have on the l.i.c. values. The data are given in Table 13, for open-circuit voltage of 6.3, 12.4, 18.4, 24.8, 31.0, and 50 volts.

DISCUSSION OF RESULTS

(A) Effect of Deterioration of Electrodes

(a) Cadmium Disc Electrode (see figure 1) - with the normal electrode combinations (curve a), it was observed that as the cadmium disc surface wears from "new" to an "old" condition, the ignition sensitivity increases (l.i.c. value decreases) fairly rapidly at first, then almost levels off near the "average" and "old" surface conditions. When the straight wire electrodes were changed to the "L" types (curve b) the ignition sensitivity decreased (l.i.c. values increased) almost linearily as the disc surface changed with usage.

(b) Tungsten Wire Electrodes - the physical condition of the wire electrodes (such as fatigue, pressures, condition of tips, and free lengths) and the amount of cadmium dust generated, all contribute one way or another to the degrees of sensitivity attained by the apparatus. As the wire fatigues and/or the pressure between the wire and disc electrodes reduces (length change) the sensitivity of the apparatus is seen to decrease, (Tables 3, 4 and 5). Also, as the wire electrode tip wears or splinters, whether due to friction or burning by successive explosions (see Figure 2) the sensitivity of the apparatus can increase due to either an increase in the production of cadmium dust particles or simply by becoming more efficient at the contact break.

(B) Effect of Different Electrode Combinations

The sensitivity of the V.D.E. Test apparatus (indicated by the l.i.c. values), with the usual combination of cadmium disc plus tungsten wire electrodes, was seen to vary considerably (60 to 30 mA) when tested continuously for 2½ hours, see Figure 3, curve (a). At the end of this test period, the cadmium disc surface appeared several degrees rougher and blacker than at the start, and some of the tungsten wires were either broken off, bent, or shortened with splintered ends. For the next test period, where "L" type wire electrodes replaced the straight wires, the sensitivity of the apparatus varied from 32 to 34 mA (see curve (b)). The wire electrodes showed no tip burning at the end of 1½ hour test period but the cadmium disc surface changed to such a degree that this test could not be repeated. Consequently, the next combination of electrodes was to include a cadmium disc with a "fairly new" surface, (a surface that can be duplicated fairly easily) plus wire electrodes, of the "semi-L" types, which tend to scrape the cadmium surface more so than the "L" types. The sensitivity of the apparatus became somewhat less (38 to 40 mA), see curve (c) but an increase in repeatability of this combination, was obtained, i.e. the degree of sensitivity changes was minimal for hour long test periods when both electrodes were being cleaned of all cadmium dust particles after every explosion.

(C) Ease of Ignitions by Various External Parameters

1. Effect of Atmospheric Pressure Changes

The ignition tests conducted with the desensitized apparatus and 22% hydrogen-air mixtures produced l.i.c. results that increased linearily as the pressure inside the explosion chamber was decreased in 50 mm Hg steps from 850 to 700 mm Hg (see Figure 4). Also when the explosive mixture ratios were changed to 18, 20, 24 and 26% and the pressures inside the chamber were again varied, the l.i.c. results (see Table 8) indicated that the "ease of ignitions" decreased in the same manner for all 5 mixture ratios as the pressure decreased down to 700 mm Hg. At pressures lower than 700 mm Hg, the results appeared erratic.

2. Effect of Hydrogen-air Ratio Changes

The effect of hydrogen-air ratio changes (at constant pressures and temperature) on the "ease of ignitions" is graphically represented by curves (a) and (b) in Figure 5. The data for these curves were obtained from the curves of Figure 4 which clearly showed that the apparatus had remained in its desensitized condition by providing fairly reasonable results for all 5 different hydrogen-air mixtures. The hydrogen-air mixture most easily ignited by this apparatus is 23%.

3. Effect of Water Condensate

The experiments conducted with various amounts of water condensate inside the explosion chamber of the apparatus (see Table 10) clearly indicates that the ignition sensitivity of the apparatus is markedly decreased almost in proportion to the amount of water particles present on the surfaces of the electrodes.

4. Effect of Temperature Changes

The experimental evidence of Bartel and Howe, and the analysis of their results near ambient temperatures, see Figure 8, indicate that as the ambient temperature drops from 100°F to near freezing, the "ease of ignition" decreases logarithmically.

5. Effect of Humidity Changes

The hydrogen to dry air ratio is a function of the humidity in the air i.e. for a constant hydrogen volume added, the ratio is 22.0% for dry air and 22.6% for 100% R.H. air (see appendix). The experimental trials (see Table 12) using hydrogen-air mixtures prepared with dry air and air which was measured to have a 90% R.H. value, indicated no significant difference in the "ease of ignitions" of the mixtures by the apparatus.

6. Effect of Open-circuit Voltage Changes

For open-circuit voltages between 18 and 50 volts for the standard electrical circuit consisting of a 95 mH inductance coil, the effect on the "ease of ignitions" appears unchanged. For open-circuit voltages of 12 volts or less, the l.i.c. values were increased by 25%.

CONCLUSIONS

This report covered the effect of changes in the physical conditions of the two electrodes used in the V.D.E. Test Apparatus together with the effect of other external parameters on the ignition sensitivities (l.i.c. - lowest ignition current) of this apparatus for various hydrogen-air mixtures. The findings can be summarized as follows:

1. Physical Condition of Electrodes

(a) Cadmium Disc

1. the condition of the surface area does not remain unchanged as the test program progresses but varies from smooth and hard when new to rough and soft when old; extreme l.i.c. values: 30 and 60 mA

2. the formation of unpredictable cadmium dust particles on both electrodes; extreme l.i.c. values: 30 and 38 mA

3. at the point of electrical contact break between the disc or wire electrode, the disc edges appear to vary from sharp rise ridges to round sections; l.i.c. value variations: unknown.

(b) Tungsten Wires

1. the free length of these electrodes below the clamping holder does affect the ignition sensitivity. The lengths of each of the four wires do vary considerably after testing due to either or both (a) frictional wear and (b) tip burning after each explosion; extreme l.i.c. values: 30 and 34 mA.

2. the physical condition of the wire at the electrical break-contacts (wire ends) vary from blunt (when new) to chisel point, splintered, or claw like after several test periods and explosions; extreme l.i.c. values: 26 to 52 mA

3. the velocity of the contact break between the wire and disc electrodes (0.7 ft. per sec) is increased by the wire spring action which was found to decrease as wire fatigue sets in: extreme l.i.c. values: 27 to 50 mA

2. Other Contributing Factors (external parameters)

(a) Atmospheric Pressure

For every 20 mm Hg pressure drop, between 850 and 700 mm Hg. the l.i.c. values are required to be increased by 2 mA.

(b) Ambient Temperature

For every 10°C drop in temperature, between 10 and 30°C, the l.i.c. values are required to be increased by 1.5 mA (by interpolation).

(c) Percentage Hydrogen-air Mixtures

For every percentage hydrogen-air less than 23%, (down to 19%) the l.i.c. values are required to be increased by 0.7 mA.

(d) Moisture

Whenever light film of water vapour condenses on the electrodes, the l.i.c. value is required to be increased by about 6 mA.

3. Non-contributing Factors (external parameters)

(a) Humidity (of the air component in explosive mixtures)

No significant changes in the l.i.c. values were noted for air with R.H. of 0 to 95% at 20°C.

(b) Open Circuit Voltage (95 mH inductance in standard electrical circuit)

No change in the l.i.c. values were noted for open circuit voltages from 20 to 50 volts d.c. For open-circuit voltages between 20 and 6 volts, the l.i.c. value is required to be increased by 12 mA.

Under the best electrode conditions, l.i.c. values of 26 mA have been obtained, and under worst conditions, 60 mA. Under ideal environmental conditions (dry, high atmospheric pressures and high ambient temperatures), the l.i.c. values could be reduced by 25%, and under worst condition, be increased by this same amount.

To answer the three questions given in the introduction:
(1) the "hit and miss" difficulties that have been found to occur during calibration of this apparatus are largely due to the wide physical changes that the disc and wire electrodes undergo as the number of conducted tests are varied.

Specific reasons for "hits" can be extended to:

(a) presence of excess cadmium dust particles

(b) increased wire electrode flexibility

(c) sharp cutting and digging points on wire electrode ends

(d) clean, uncontaminated points at the edge of the disc electrode.

Specific reasons for "misses" to occur:

(a) blunted wire electrode tips

(b) blackened and coarse surface and edges of the disc electrode

(c) fatigue of wire electrodes

(d) distorted wire electrodes

(2) the most probable reason why this apparatus may cause ignitions one day and not the next, when the physical conditions of the apparatus appears to be unchanged, might be due to the changes in the external parameters such as those investigated here, i.e. atmospheric pressure, temperature, hydrogen-air ratio, and possible moisture collected on the electrodes.

(3) and finally, the controls that are available to the operator to improve the reliability of this apparatus can be enumerated as follows:

1. only use the cadmium disc electrode in its "average" condition i.e. wear in a new disc before explosion testing, and replace it when any calibration difficulties occur.

2. replace all wire electrodes when the first calibration "miss" occurs.

3. ensure that the explosive gas-air ratio is accurate within ± 1% of a nominal 23% hydrogen - air mixture.

4. check that atmospheric pressure and ambient temperature changes that may occur from day to day are in the direction for improvement of the "ease of ignition" situation.

5. ensure that the apparatus is at the same temperature as the ambient to prevent any possible moisture condensation forming on the electrode surfaces.

RESULTS

TABLE 1 - Cadmium Disc Tests
-(Tungsten Wires, Straight Type)

Condition of Disc Surface	l.i.c. mA	
	Disc # 1	Disc # 2
New	60	52
Fairly New	33	-
Average	-	-
Fairly Old	-	36
Old	32	-

TABLE 2 - Cadmium Disc Tests
- (Tungsten Wires, "L" Type)

Condition of Disc Surface	l.i.c. mA
New	41
Fairly New	46
Average	50
Fairly Old	-
Old	54

TABLE 3(a) - Wire Fatigue Tests of <u>Fresh</u> Wire Electrodes (Tungsten Wires, Straight Types)

Elapsed Time Minutes	Current Tested mA	Mixture Ignition
4.5	30.0	Yes
9.5	25.0	No
14.5	27.5	No
19.5	30.0	No
24.5	35.0	No
29.5	40.0	No
34.5	45.0	No
38.0	50.0	Yes

TABLE 3(b) - Wire Fatigue Tests of <u>Used</u> Wire Electrodes (Tungsten Wires, Straight Types)

Elapsed Time Minutes	Current Tested mA	Mixture Ignition
34.0	40.0	Yes
34.5	37.5	Yes
39.0	30.0	Yes
44.0	27.5	No
49.0	30.0	No
54.0	35.0	No
59.0	45.0	No
60.0	60.0	Yes

TABLE 4 - Variation in Length of Wire Electrodes

Free Length mm.	l.i.c. mA
10.0	45
10.5	42
11.0	40
11.5	35
12.5	32.5

TABLE 5 - Pressure Variations of Wire Electrodes on Disc Electrode

Pressure Variations	Light	Medium	Normal
(Wire Configuration)	(double loop)	(single loop)	(straight)
l.i.c. mA	35	33	30

TABLE 6 - Effect of Cadmium Dust

(a) Electrodes Untouched		(b) Electrodes Cleaned	
Elapsed Time Min.	l.i.c. m.A.	Elapsed Time Min.	l.i.c. m.A.
0.1	34	3.5	34
6.4	33	7.0	36
10.0	33	10.5	36
15.0	30	12.5	36
19.0	30	16.5	36
19.5	32		

TABLE 7 - Effect of Different Electrode Combinations

Elapsed Time Minutes (Approximately)	Electrodes			
	- Disc	"Average"	"Old"	"Fairly New"
	- Wire	Straight	"L"-type	"Semi-L" type
		l.i.c. mA	l.i.c. mA	l.i.c. mA
0			34, 32	40
10			32	
20		60	34	40
30		45	32	
40		45	32	40
50		40	34	38
60		30	34	38
70		50	34	40
80		35	32	
90			32	
100				
110		45		
120		40		
130		40		
140		37		
150		30		
160		30		

TABLE 8 - Effect of Atmospheric Pressure/Hydrogen-air Ratio

% H_2-air	18		20		22		24		26	
	Press. mm Hg.	l.i.c. mA.	Press. mm Hg.	l.i.c. mA.	Press mm Hg.	l.i.c. mA.	Press. mm Hg.	l.i.c. mA.	Press. mm Hg.	l.i.c. mA.
	690	46	700	46	650	45	650	51	650	46
	770	40	764	40	700	44	740	40	764	40
	835	36	768	38	740	40	764	38	766	40
			800	36	752	39	850	34	850	34
			820	34	772	37				
					800	35				
					850	30				

TABLE 9 - Effect of Hydrogen-air Ratios at Constant Atmospheric Pressures

% H_2-air Ratio	l.i.c. (mA)	
	Constant Pressure 730 mm Hg.	Constant Pressure 790 mm Hg.
18	44.0	38.2
20	42.6	37.0
22	41.2	35.5
24	41.2	35.5
26	44.0	38.2

TABLE 10 - Effect of Water Condensate

Water Condensate Description	l.i.c. mA
None (Dry)	36
Light	40
Medium	45
Heavy	52

TABLE 11 - Effect of Temperature (Calculated)

°C Cent.	°K Absolute	$10^3/K$ (1/K)	I_1 mA	E_1 mJ	E_2 $1.75\,E_1$ mJ	$\sqrt{E_2}\,10^{-3}$ mJ	$4.6\sqrt{E_2}\,10^{-3}$ mA
0	273	3.66	-	-	.0780	8.832	40.51
10	283	3.53	-	-	.0730	8.544	39.19
20	293	3.41	280	.0392	.0686	8.286	38.00
32.2	305.2	3.28	-	-	.0640	8.00	36.70
50	323.0	3.10	-	-	.0585	7.65	35.09
200	473.0	2.11	200	.020	.0350	-	-

TABLE 12 - Effect of Humidity

% Rel Humidity	l.i.c. mA	
	Trial # 1	Trial # 2
0	36	35
90	35	34

TABLE 13 - Effect of Open-circuit Voltages

Open-circuit Volts	l.i.c. mA
6.3	50
12.4	52
18.4	40
24.8	39
31.0	38
50.0	38

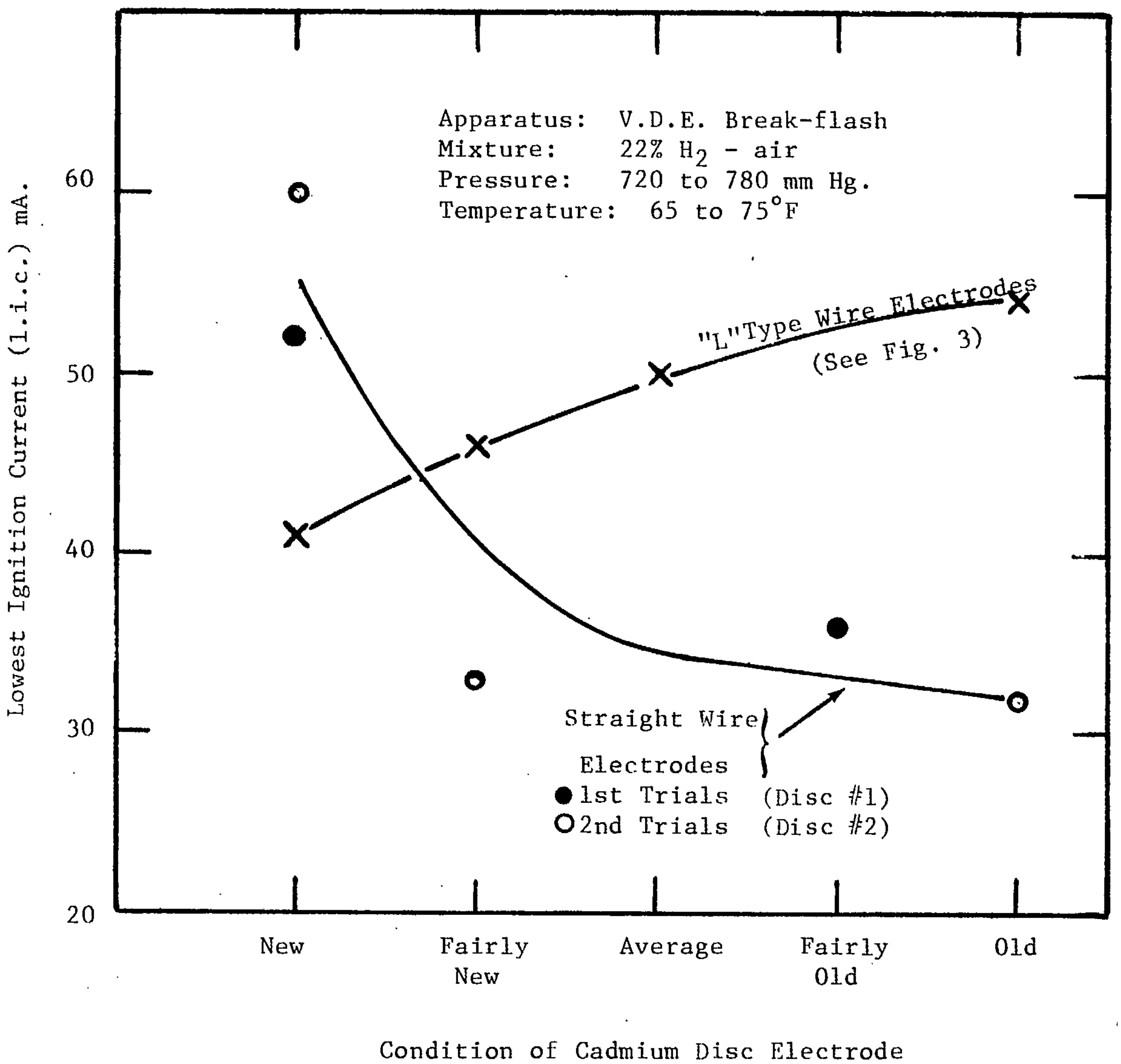
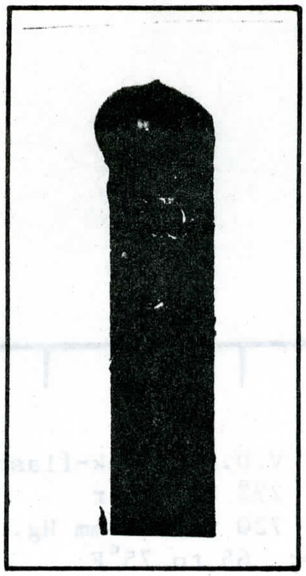
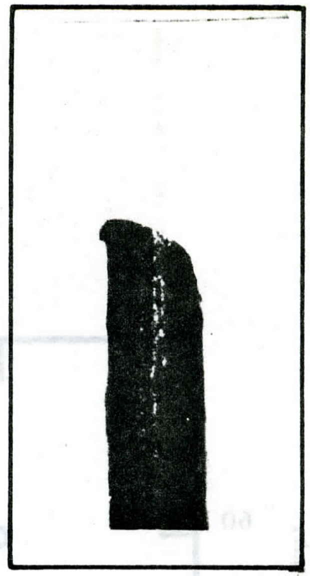


Fig. 1: Effect on the Ignition Sensitives (l.i.c.'s) by Pre-conditioned Cadmium Disc Electrodes

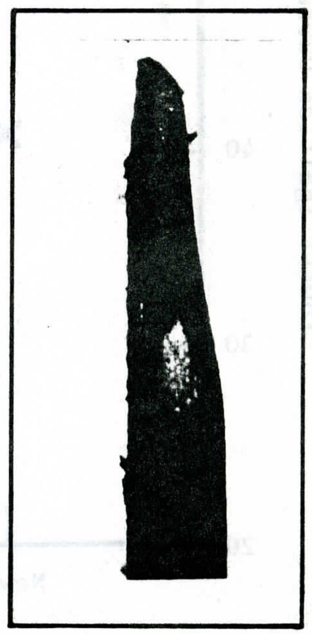


(a) One Hour Wear, Sparking with no Explosive Mixture



(b) Five Explosions

(c) Ten Explosions



(d) Over Twenty Explosions

Fig. 2: Tips of Wire Electrodes After Wear and Explosions

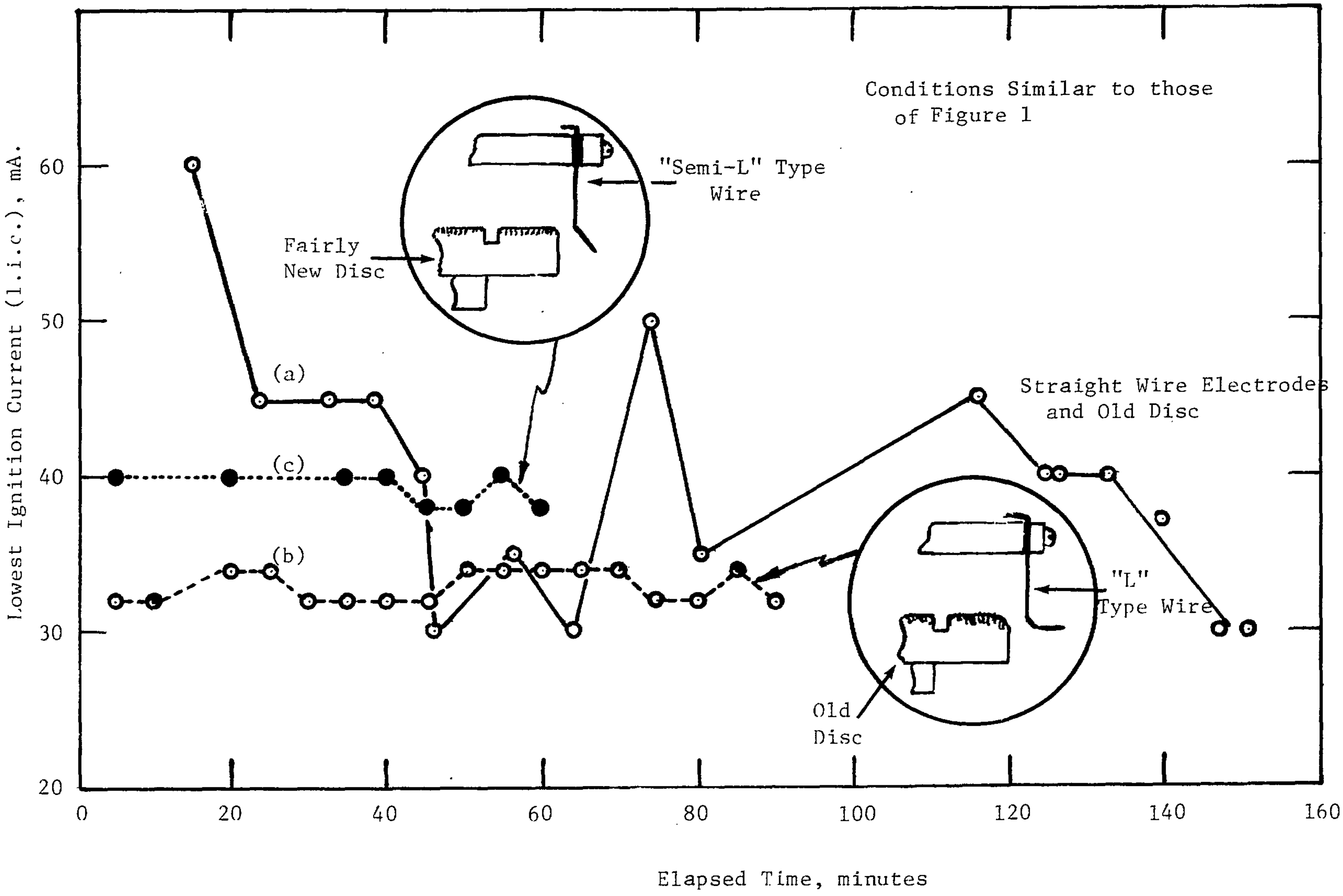


Fig. 3: Comparison of Ignition Sensitivities For Different Wire Electrode Configurations

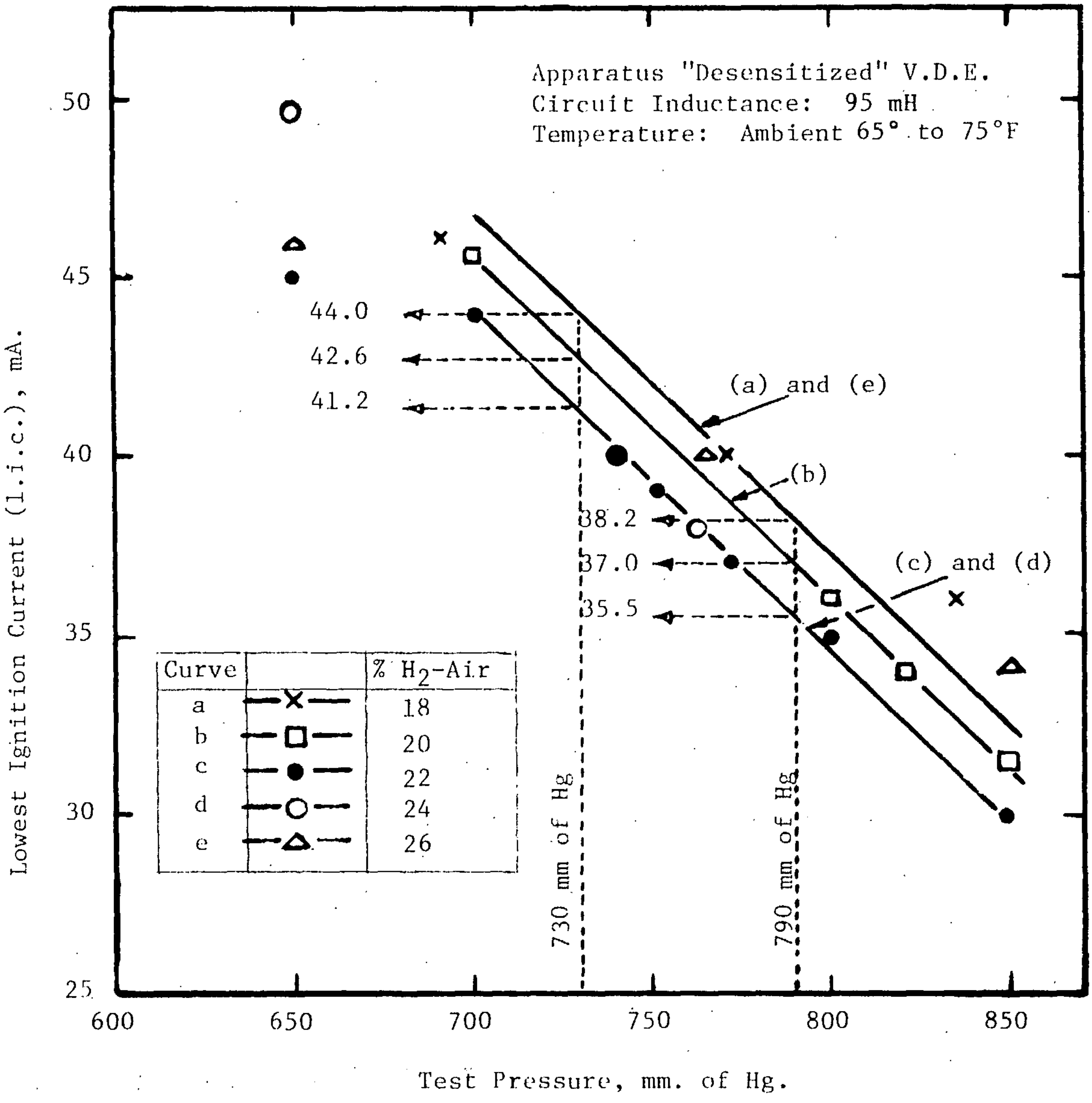


Fig. 4: Effect on Ease of Ignitions (l.i.c.'s) For Explosive Mixtures Under Various Test Pressures

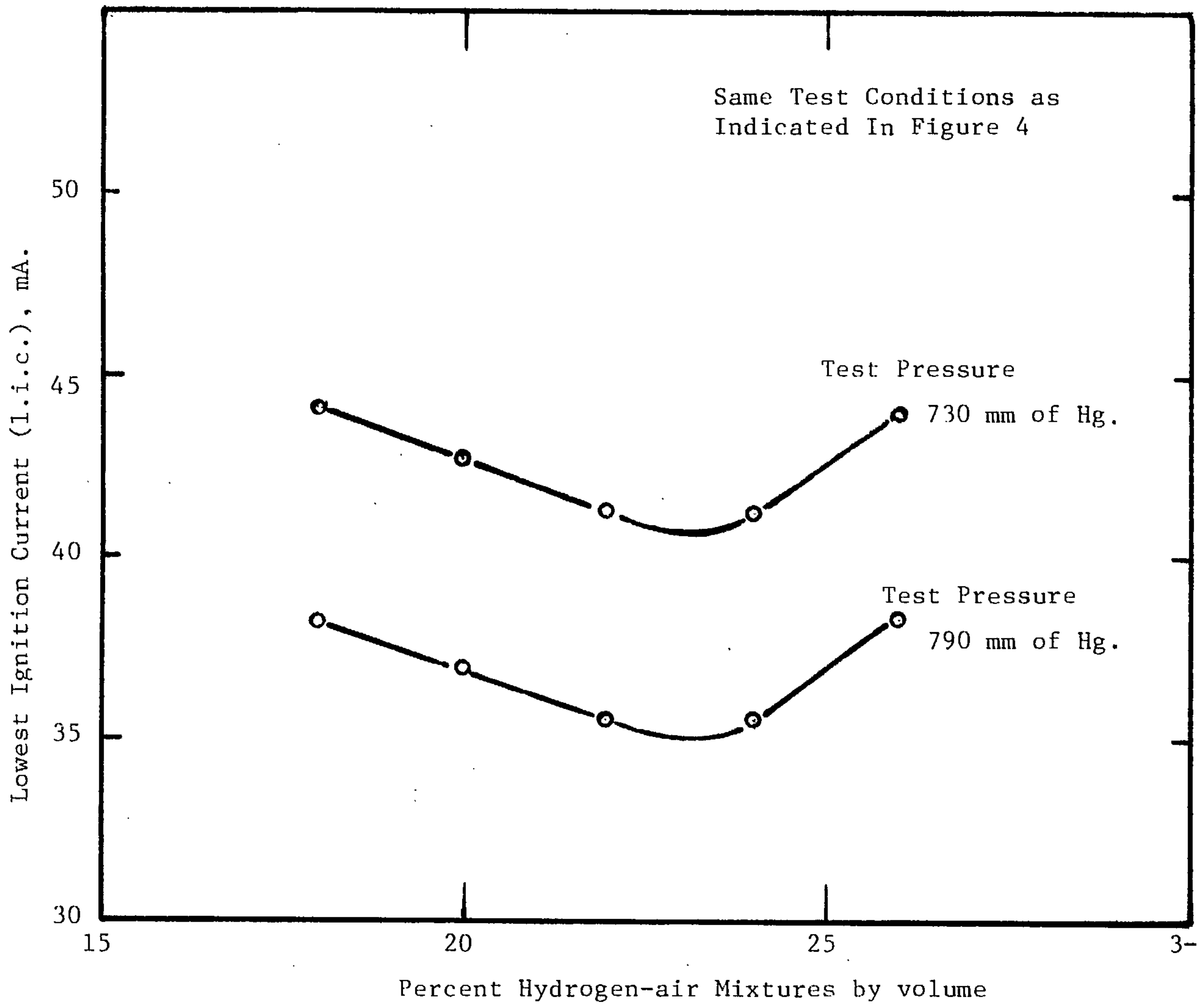


Fig. 5: Effect on Ease of Ignitions For Various Explosive Hydrogen-air Ratios (at Test Pressures of 730 and 790 mm Hg.)

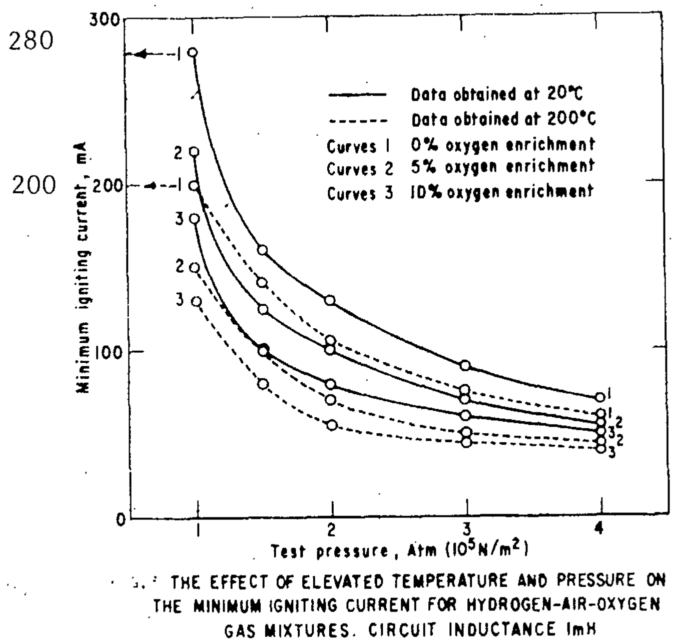


Fig. 6(a) Extraction of M.I.C. Data at 1 atmosphere, temperatures 20° and 200°C from Experimental Curves (see Ref. 2)

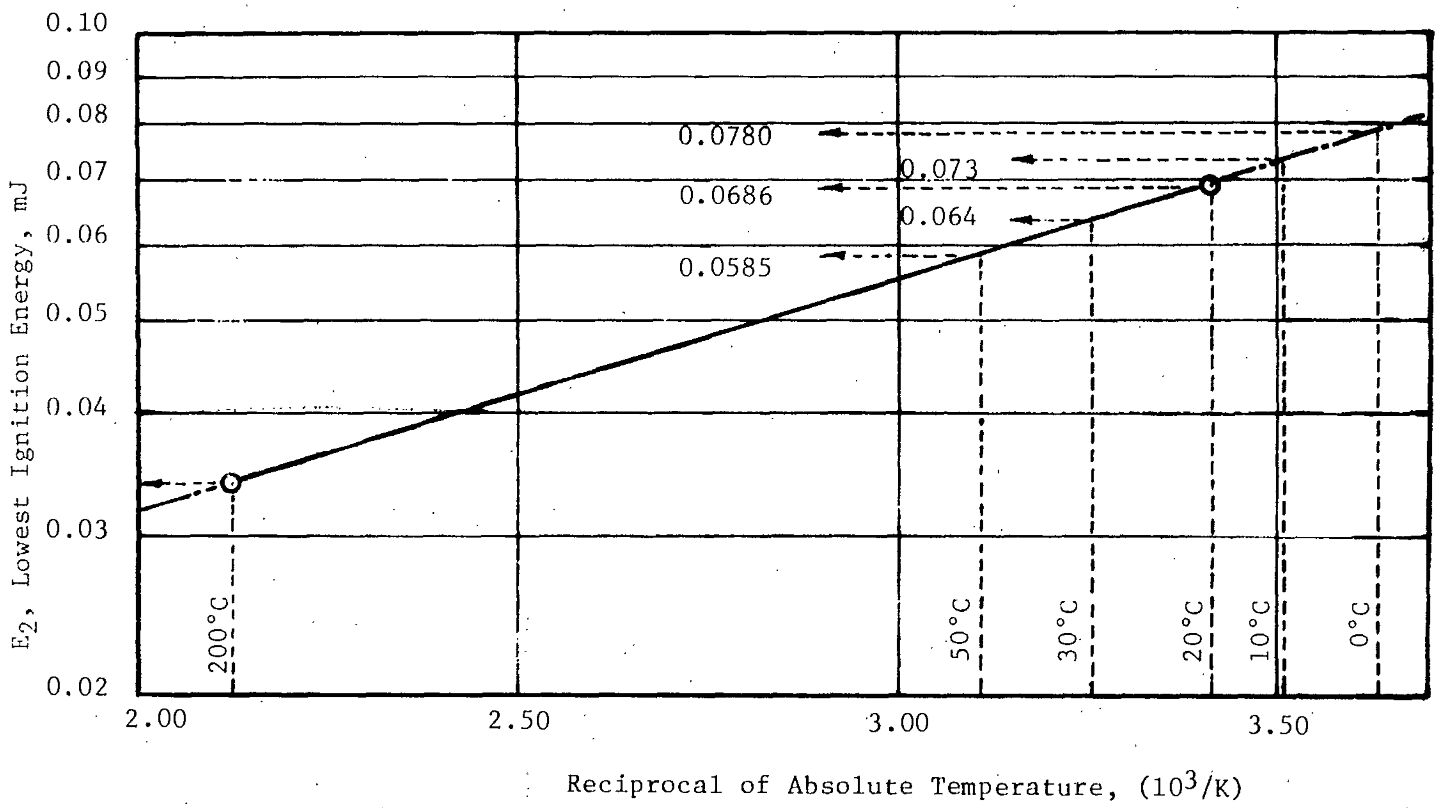


Fig. 6 (b) Arrhenius Plot of Ignition Energy ($\log_{10} E2$), for a "Desensitized" V.D.E. Break-flash, Circuit Inductance, 95 mH, Versus, the Reciprocal of the Absolute Temperature of a 22% H_2 - air Mixture

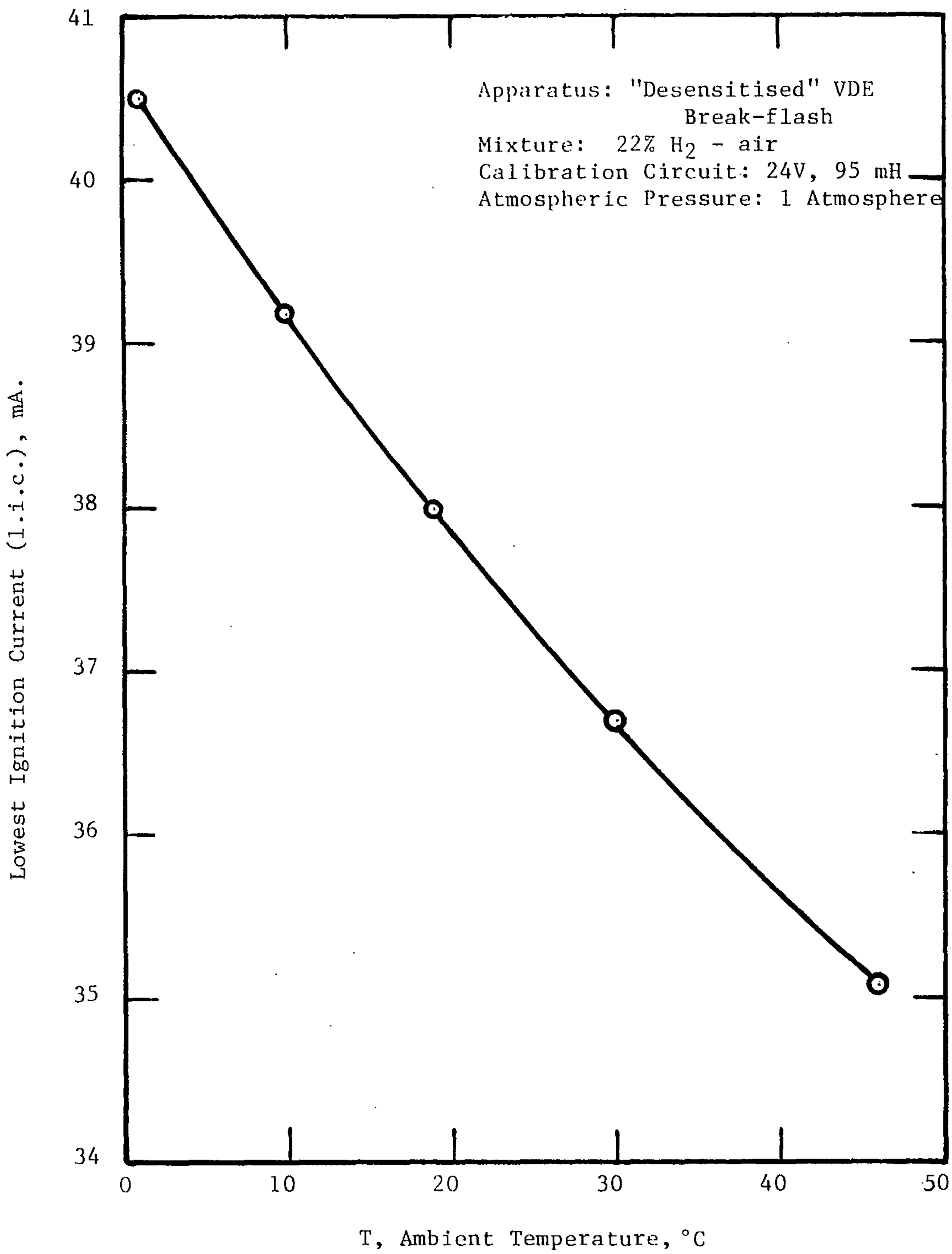


Fig. 6 (c) Effect on Ease of Ignitions For Explosive Hydrogen-air Mixtures at Various Temperatures

ACKNOWLEDGEMENT

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2. Bartels, A.L. and Howes, J.A. - The Variation of Minimum Igniting Currents With Pressure, Temperature and Oxygen Enrichment. Electrical Research Association (U.K.).

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APPENDIX

Change in Hydrogen-Air Ratio for Dry and 100% Humid Conditions

This example illustrates change in hydrogen to dry air ratio when a 22% mixture is prepared with dry air as compared with moist (100% R.H. air) at 10°F.

1. Percent of Moisture by Weight (W_m) for 100 R.H. at 70°F.

From the Relative Humidity Chart, the amount of moisture per pound of dry air at 100% R.H. and 70°F is found to be 0.016 pounds.

$$\therefore W_m\ \% = \frac{0.016}{0.016 + 1.00} \times 100 = 1.575\%$$

2. Volumes (V) for each gas constituent when the total mixture is assumed to weigh 100 grams.

$$V_x = \frac{W_x}{100} \times 100 \text{ grams} \times \frac{1}{\text{M.W. of } x}\left(\frac{\text{moles}}{\text{grams}}\right) \times 22.4 \left(\frac{\text{litres}}{\text{moles}}\right)$$

$$= \left(22.4 \times \frac{W_x}{\text{M.W. of } x}\right) \text{ litres}$$

(a) Water Vapour Volume ($V_{w.v.}$)

$W_{w.v.} = 1.575$

M.W. of w.v. $= 18$

$$\therefore V_{w.v.} = 2.2.4 \times \frac{1.575}{18} = \underline{1.96 \text{ litres}}$$

(b) Air Volume (Va)

$W_a = 100 - 1.575 = 98.425$

M.W. of air $= 29$

$$\therefore V_a = 22.4 \times \frac{98.429}{29} = \underline{76.02 \text{ litres}}$$

(c) Hydrogen Volume (V_h)

$V_a = 1.96,\ V_{wv} = 76.02$

$$\therefore V_h = \frac{22}{100}\left(V_a + V_{w.v.} + V_h\right)$$

$$= \frac{V_a + V_{w.v.}}{1 - 0.22} \times \frac{22}{100} = 77.98 \times \frac{.22}{.78} = \underline{21.98 \text{ litres}}$$

3. Percent by Volume of Hydrogen to Dry Air (H_w) for wet condition

$$\left(\frac{V_h}{V_h + V_a} \times 100\right)\%$$

$$= \frac{21.98}{21.98 + 76.02} \times 100 = \underline{22.6\%}$$

4. Percentage Change for the Dry (H_d) and Wet (H_w) Conditions

$$\%\ \text{change} = \frac{H_w - H_d}{H_d} \times 100$$

$$= \frac{22.6 - 22.0}{22} \times 100 = 2.6\%$$