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Probability of Spark Ignition in Intrinsically Safe Circuits

By James C. Cawley

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

kΩ	kilohm	μs	microsecond
mA	milliampere	Ω	ohm
μF	microfarad	rpm	revolution per minute
mH	millihenry	s	second
mJ	millijoule	V	volt
μJ	microjoule	V dc	volt, direct current
ms	millisecond	W	watt

PROBABILITY OF SPARK IGNITION IN INTRINSICALLY SAFE CIRCUITS

By James C. Cawley[1]

ABSTRACT

This report presents results of recent Bureau of Mines research to establish the probability of spark ignition as a function of current (or voltage, for capacitor circuits) for resistive, inductive, and capacitive circuits in 8.3% methane-air atmospheres. The data presented quantify the explosion hazard created when low-power electronic devices catastrophically fail in an explosive mine atmosphere. Previous literature dealt with levels of probability between 10^{-3} and 10^{-4}. This report extends the probability data to levels as low as 10^{-7}. This study has verified that when the probability of ignition, p_I, is plotted on a log-log coordinate system versus the current (or voltage), a continuous, straight-line relationship is formed. An interesting result that can be statistically hypothesized is that at some low level of igniting current the ignition process ceases altogether.

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INTRODUCTION

Safety factors are employed by the engineering profession to ensure that a margin of safety exists between engineering test conditions and the conditions of actual use. The safety factor presently used by the U.S. Mine Safety and Health Administration (MSHA) to assess the intrinsic safety of electronic circuits for use in methane-air atmospheres is a factor of 1.5 on energy at the point of test plus two worst case faults. A precise knowledge of the degree of safety over and above the conditions of actual use obtained by using the 1.5 factor, however, is not easily determined. Many variables play a part in establishing the igniting current in a breakflash machine during an intrinsic-safety test. Atmospheric conditions, such as temperature, pressure, and relative humidity, interact to alter the probability of ignition, p_I. Other factors that influence p_I are electrode materials, gas concentration, and elctrode conditioning (1).[2]

The Bureau of Mines has completed an intrinsic-safety research project that lays the foundation for relating the conditions of test and actual use by estimating p_I versus current (or voltage for capacitor circuits) for circuits in an 8.3% methane-air atmosphere. The purpose of the experimental work was to determine the currents (or voltages) and their corresponding p_I in the region where $10^{-8} < p_I < 10^{-4}$. In order to determine such low values of p_I with an acceptable degree of uncertainty, the experiment was designed such that the probability of observing several ignitions must be reasonably high and the probability of not observing any ignitions must be very small. For each experiment, the expected number of ignitions was about 5. If no ignitions occurred during an experiment, then it could be concluded that a statistically unusual event had occurred, since the probability of not getting an ignition was less than 1%. A statistical explanation of the experimental design is presented in the section "Statistical Design of the Experiment."

A review of the literature shows that the relationship between p_I and current (or voltage) is linear when plotted on log-log coordinates over the range where $10^{-4} < p_I < 10^{-3}$. Previous Bureau research (2) investigated alternative test gases and provided a small data base from which to begin an examination of another method of applying safety factors, the simple ignition probability model. Although the earlier work was optimized to establish the mean value of spark-igniting currents, the data also provided some information about the simple probability of ignition. The total number of ignitions (N_I) divided by the total number of sparks (N_s) gives the simple probability of ignition (p_I):

$$p_I = N_I/N_s. \quad (1)$$

In work published by Matasovic (3), the basis of a method for applying safety factors is a circuit's probability of ignition. Matasovic's work established p_I as a function of current for $10^{-4} < p_I < 10^{-3}$. Based on this easily obtained estimate of p_I, Matasovic extrapolated the curve and estimated the current required to produce a lower level of ignition probability, $p_I = 10^{-8}$. This extrapolation was done using the empirically known slope of the p_I-versus-current characteristic in log-log coordinates. To empirically obtain p_I at 10^{-8} would require months, perhaps years of testing. As shown in figure 1, the p_I-versus-current relationship forms a straight line in log-log coordinates (a fact subsequently verified by Bureau research as valid for $p_I < 10^{-4}$). The equation representing such a relationship is

$$(P_1/P_2) = (I_1/I_2)^m, \quad (2)$$

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[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

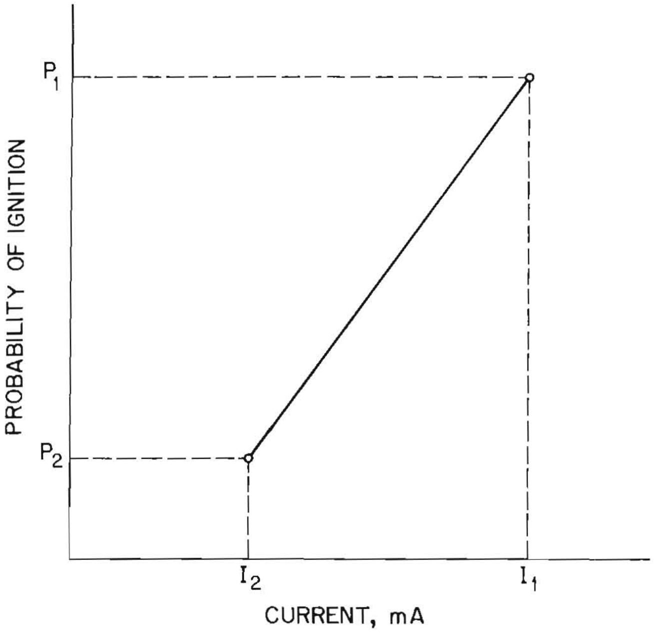

FIGURE 1.—General relationship between probability of ignition and current when plotted on log-log coordinates.

where P_1, P_2 = two levels of simple ignition probability,

I_1, I_2 = currents corresponding to P_1, P_2, respectively,

and m = slope of a straight line in logarithmic coordinates.

Matasovic defines a circuit safety factor, k, as

$$k = I_1/I_2, \tag{3}$$

where I_1 = current at which the simple ignition probability, p_I, is 10^{-3},

and I_2 = current at which the simple ignition probability, p_I, is 10^{-8}.

Methane, propane, ethylene, and hydrogen mixtures in air, listed in order of explosive severity, were tested, and the results are given in table 1 (3). Not surprisingly, the safety factors obtained by this method are not constant nor are they clustered near 1.5. Since Matasovic was dealing with the ratio of two currents and not the ratio of ignition energies as is U.S. practice, one would not expect to arrive at the same 1.5 safety factor. The results obtained in this Bureau research project show that the exponent, m, varies even for the same circuit element in the same gas at different test currents. When using current ratios, then, one would expect differences in safety factor to be a function of current even in the same gas.

TABLE 1. - Safety factor (k) for four gases in three circuit elements

	Inductive	Capacitive	Resistive
Methane...	1.5455	2.7692	2.9481
Propane...	1.3043	2.6667	2.3292
Ethylene..	1.3580	2.4348	2.3133
Hydrogen..	1.6556	2.6517	2.5814

There were two major points to be resolved by this research project. First, to determine safety factors using p_I, it must be assumed that the extrapolation to a lower current is valid for $p_I < 10^{-4}$, when evidence supporting this contention is lacking because of the time needed to produce such data with some degree of statistical confidence. An examination of the data presented (3) reveals that there are no experimental data on current versus simple probability of ignition for $p_I < 4 \times 10^{-5}$ with which to verify the assumption of linearity. Second, the continuity of the ignition process for $10^{-8} < p_I < 10^{-4}$ has not been empirically verified. Since the validity of a safety factor based on the simple probability of ignition model depends heavily on both the above assumptions, a large data base at low levels of probability is needed to confirm them. Based on a limited amount of information for $10^{-4} < p_I < 10^{-3}$, the project described in this report empirically extended the curves of log p_I versus log current down to a level where the probability of ignition is extremely small, i.e., $10^{-7} < p_I < 10^{-5}$.

ACKNOWLEDGMENTS

The author wishes to thank Michael DiMartino, electronics technician, and Robert Kemp, physical science technician, Pittsburgh Research Center, Bureau of Mines, for their tireless efforts in compiling the ignition test data for this report, and Shail Butani, mathematical statistician, Twin Cities Research Center, Bureau of Mines, for her suggestions regarding computation of statistical confidence levels and sample sizes.

STATISTICAL DESIGN OF EXPERIMENT

The purpose of this project was to run a large number of electrical sparks and count the number of ignitions that resulted, thus yielding p_I. The experiment was designed to yield an expected number of ignitions, Θ, of five. Therefore, when the required number of sparks was run, five ignitions should have occurred, subject to normal statistical variations. The experiments were designed to have less than a 1% chance of randomly producing no ignitions. Therefore, when no ignitions occurred during n sparks, it pointed to a statistical anomaly. The following discussion first presents an intuitive approach to determining the random chance of not seeing an ignition in n sparks for a circuit having $p_I = 10^{-6}$, followed by a more formal computation of the sample size required to produce a 98% confidence interval about the p_I statistic.

The process of gathering statistical information on ignitions that have a low probability of occurrence requires a large number of sparks in order to ensure a high degree of statistical confidence. Gas ignitions can be considered binomial events since only two outcomes are possible, i.e., ignition or nonignition. A binomial event can be described by the following equation:

$$P(X) = \binom{n}{X} p_I{}^X q^{n-X}$$

$$= \frac{n!}{X!\,(n-X)!} p_I{}^X q^{n-X}, \qquad (4)$$

where $P(X)$ = probability of observing exactly X ignitions in n sparks,

p_I = probability of observing an ignition during any given spark,

and q = probability of not observing an ignition in any given spark; therefore, $p_I + q = 1$, or $q = 1 - p_I$

As n becomes large and p_I approaches zero, the Poisson approximation to the binomial distribution becomes appropriate. In the case considered here, $p_I < 10^{-3}$ and $n > 5{,}000$ for all cases. The Poisson distribution is given by

$$P(X) = \frac{\Theta^X \times e^{-\Theta}}{X!}, \qquad (5)$$

where $\Theta = n \times p_I$ from the binomial distribution and is the expected number of ignitions in n sparks,

X = the exact number of ignitions,

and $e = 2.718$.

Consider a rare event whose p_I is 10^{-6}; therefore, the probability of <u>not</u> observing an ignition, q, on a given spark is

$$q = 1 - p_I$$

$$= 1 - 10^{-6} = 0.999999. \qquad (6)$$

Using equation 5, the ignition probabilities shown in table 2 can be tabulated for various values of n, p_I, Θ, X, and P(X). As shown in table 2, for $p_I = 10^{-6}$, $n = 10^6$, and $\theta = 1$, there is a 37% probability observing 0 ignitions even though 1 million sparks occur. Figure 2 graphically shows the effect that increasing θ has on the shape of the distribution for values of θ from 1 to 5. Notice that for θ = 1, the most likely number of ignitions to be seen are 0 and 1. As θ increases (accomplished by running more sparks for each test), the likelihood of seeing 0 ignitions decreases and the distribution approaches normality, with θ being the most likely number of ignitions to occur. When n is increased to 5×10^6, θ increases to 5. Under these conditions, the probability of not observing an ignition is 0.0067. Conversely, there is a 0.9933 chance of seeing one or more ignitions. The $n \times p_I = \theta = 5$ condition, therefore, was used in this series of experiments to produce an acceptably small probability of not seeing one or more ignitions, which have a

TABLE 2. - Poisson ignition probabilities

Number of ignitions (X)	Probability of observing exactly X ignitions, P(X)	
	(1)	(2)
0.............	0.3679	0.0067
1.............	.3679	.0337
2.............	.1839	.0842
3.............	.0613	.1404
4.............	.0153	.1755
5.............	.0031	.1755
6.............	.0005	.1462
7.............	.0001	.1044
8.............	(3)	.0653
9.............	(3)	.0363
10............	(3)	.0181
Total......	.9994	.9863

(1) $n = 10^6$, $p_I = 10^{-6}$, $\theta = 1$.

(2) $n = 5 \times 10^{-6}$, $p_I = 10^{-6}$, $\theta = 5$.

(3) 0 to 4 decimal places.

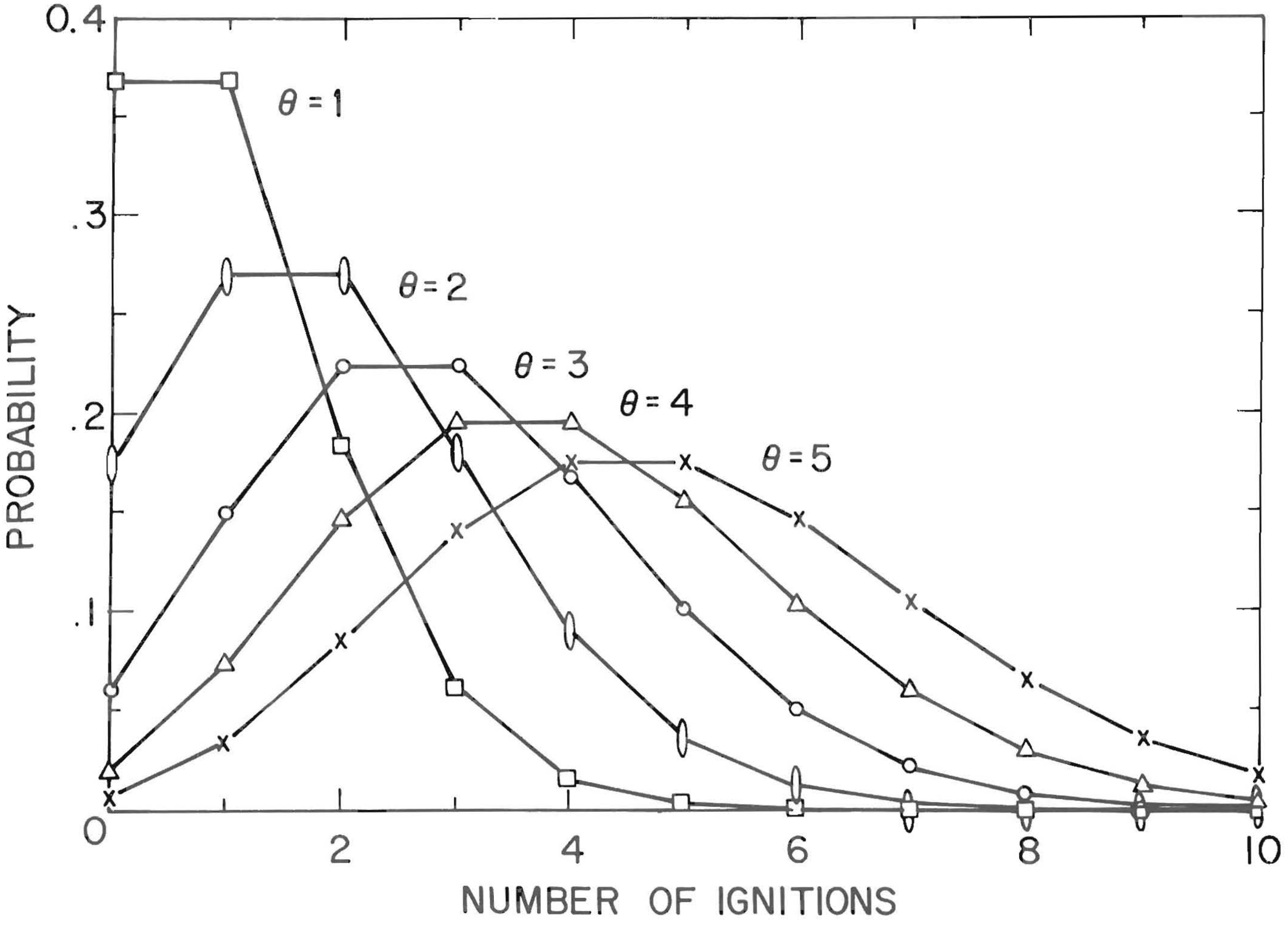

FIGURE 2.–Shape of distribution of spark ignitions as θ increases from 1 to 5.

high probability of occurrence during the experiment. Notice that this condition is dependent only on the number of sparks, n, for a fixed p_I. Any level of ignition probability can be investigated with similar statistical certainty provided that $n \times p_I = \Theta = 5$. For example, to investigate that region where $p_I = 10^{-5}$ requires $n = 1/p_I = 10^5$ sparks to have a 0.0067 chance of seeing 0 ignitions. In summary, if $n = 5 \times (1/p_I)$, then $n \times p_I = \Theta = 5$, and the probability of not observing a highly probable ignition in n sparks (i.e., $P(X = 0)$ when $\Theta = 5$) is 0.0067. A more formal computation of the sample size, n, required to give a 98% confidence level, is given by

$$n = (Z^2 \times p_I \times q)/d^2, \tag{7}$$

where Z = value from a standard Z table corresponding to the desired level of confidence. For a 98% confidence level,

$$Z = 2.326,$$

and d = amount of tolerable error.

An additional restriction on p_I is that $p_I \pm d$ must lie between 0 and 1. For example, if d is selected as 10^{-6} with $p_I = 10^{-6}$, then the true value of p_I lies between 0 and 2×10^{-6}. In this work, in order to attain a 98% confidence that $0 \leqslant p_I \leqslant 2.0 \times 10^{-6}$ when p_I's value was assumed to be 10^{-6}, the required sample size is

$$n = [(2.326)^2 \times (10^{-6}) \times (0.999999)] / (10^{-6})^2 = 5.4 \times 10^6, \tag{8}$$

a number in reasonable agreement with the $\Theta = 5$, or 5 million sparks determined earlier, which was used to establish points where $p_I = 10^{-6}$.

EXPERIMENTAL APPARATUS

All tests were conducted using an 8.3% methane-air mixture. The gas mixing diagram is shown in figure 3. Chemically pure (99%+ purity) methane, oxygen, and nitrogen were separately supplied to the system, and the output gas mixture was accurate to within ±0.3% absolute. Gas mixture accuracy was regularly verified by calibration ignitions per Underwriters Laboratories Standard 913 (UL 913) (4), on-line infrared analysis, and off-line chromatographic analysis.

The resistor circuits tested were simple series circuits. All resistors used for test or for current limiting were low-inductance film type. All inductors used were air cored, and all capacitors were aluminum electrolytics. Figure 4 shows the test setup. Each test was conducted as follows:

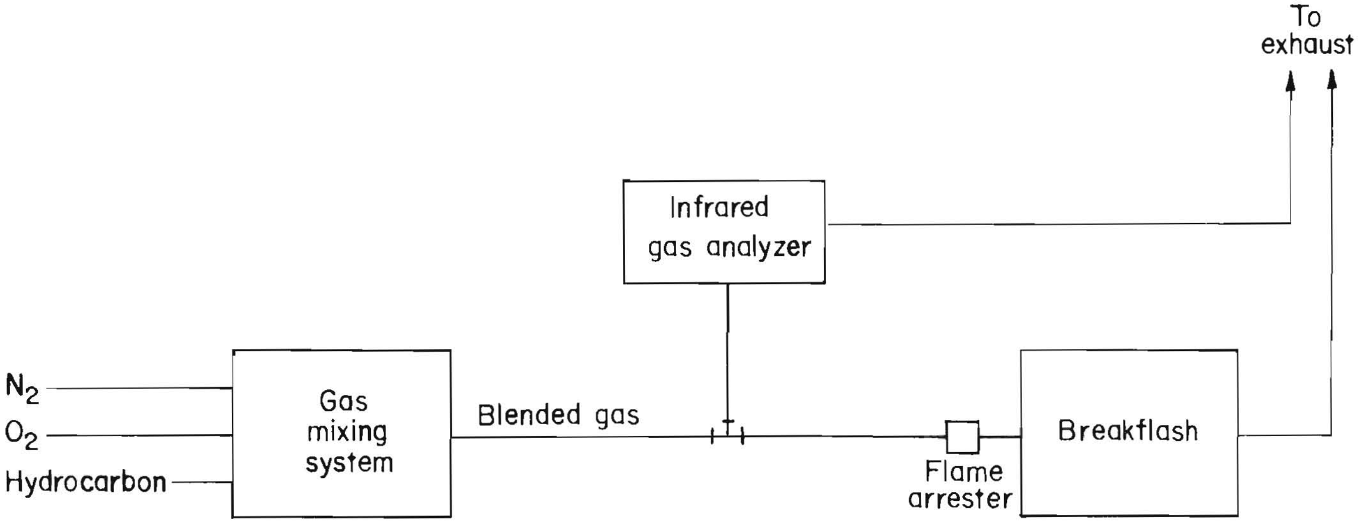

FIGURE 3.–Gas mixing system used in experiment.

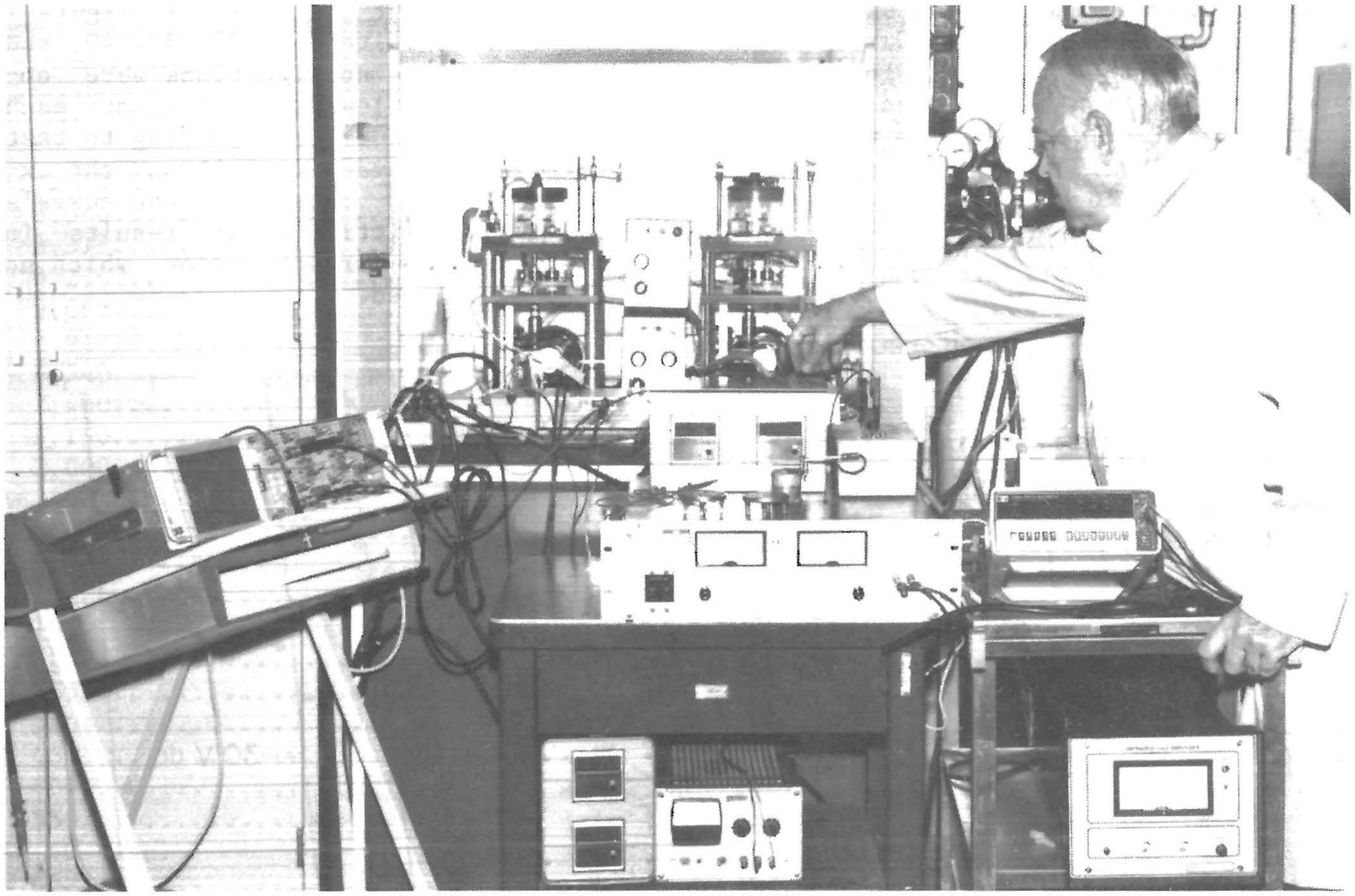

FIGURE 4.–Test setup showing gas mixing system, breakflash machines, and gas analyzer.

1. The initial values of p_I versus current for $10^{-4} < p_I < 10^{-3}$ were drawn from information collected during previous safety factor work by performing a linear regression analysis on the logarithms of the original data. These preliminary curves for resistor circuits are shown in figure 5.

2. The original data can be expressed in the form

$$(P_1/P_2) = (I_1/I_2)^m \qquad (9)$$

as explained previously.

3. Each curve was extrapolated to lower currents using slope m. Appropriate currents on the extrapolated curve were selected as test points to determine if the corresponding expected probability levels could be verified by experiment.

4. If no ignition occurred in $n = 5/p_I$ trials, it was considered a statistically unusual event. The current corresponding to this level of p_I was considered to be the threshold current below which ignition will not occur.

EXPERIMENTAL RESULTS

RESISTOR CIRCUITS

The results obtained for resistors in 8.3% methane-air are shown in table 3. The test circuit is shown in figure 6. The curves shown previously in figure 5 were determined by performing a linear regression on the logarithmically transformed current-versus-probability data, then extrapolating them to the lowest values of p_I shown using the slope determined from the regression. Currents corresponding to the p_I levels indicated by the extrapolation were used as test points in this experiment to empirically verify the level of p_I corresponding to that current. The empirically determined p_I versus current is shown in figure 7 for four test voltages, 20, 30, 40, and 50 V dc. Since no ignitions were obtained for the lowest points on each curve, the p_I value corresponding to that current was assumed to fall on the extrapolated curve. Because of the curve's steep slope, little error results in identifying the current below which no ignitions occurred.

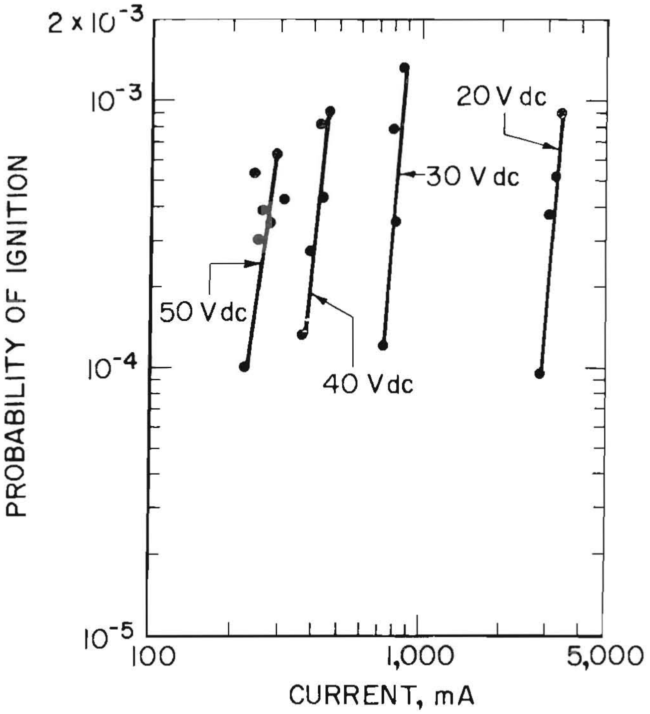

FIGURE 5.–Bureau estimates of spark ignition probability from previous safety experiments.

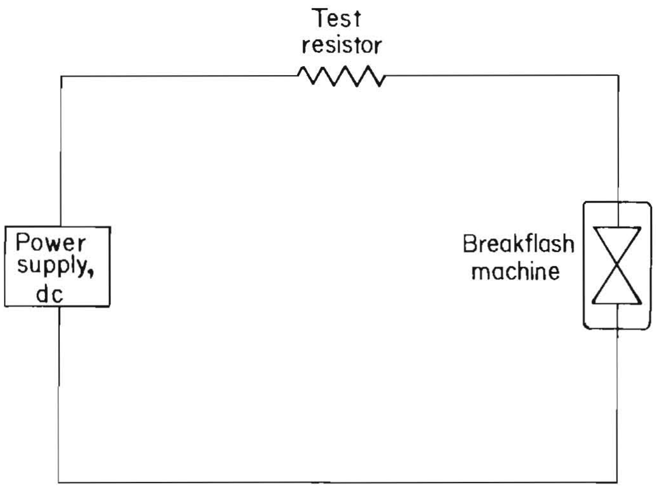

FIGURE 6.–Test circuit used to establish spark ignition probability for resistors.

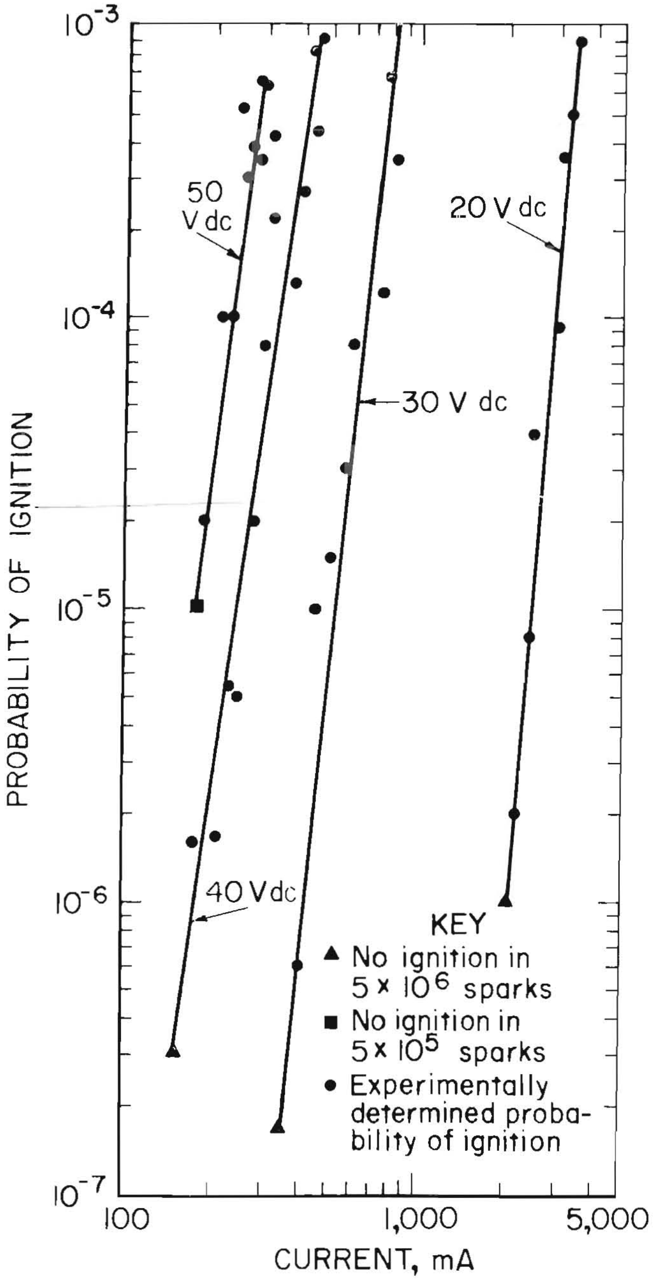

FIGURE 7.–Probability of spark ignition for resistor test circuits versus current in 8.3% methane-air atmospheres.

TABLE 3. - Current (I) versus probability of ignition (p_I) for resistor circuits

Current, mA	Probability of ignition
At 20 V dc:	
3,546	5.4 × 10^{-4}
3,377	8.9 × 10^{-4}
3,216	5.2 × 10^{-4}
3,063	3.7 × 10^{-4}
2,917	9.3 × 10^{-5}
2,540	4.0 × 10^{-5}
2,400	8.0 × 10^{-6}
2,150	2.0 × 10^{-6}
2,000	[1]1.0 × 10^{-6}
At 30 V dc:	
851	1.3 × 10^{-3}
810	3.6 × 10^{-4}
772	6.8 × 10^{-4}
735	1.2 × 10^{-4}
585	8.0 × 10^{-5}
555	3.0 × 10^{-5}
500	1.5 × 10^{-5}
450	1.0 × 10^{-5}
400	6.1 × 10^{-7}
350	[1]1.7 × 10^{-7}
At 40 V dc:	
452	9.0 × 10^{-4}
430	4.1 × 10-4
At 40 V dc--Continued	
410	8.2 × 10^{-4}
390	2.7 × 10^{-4}
371	1.3 × 10^{-4}
305	2.2 × 10^{-4}
290	8.0 × 10^{-5}
270	2.0 × 10^{-5}
240	5.0 × 10^{-6}
225	5.4 × 10^{-6}
205	1.7 × 10^{-6}
175	1.6 × 10^{-6}
150	[1]3.0 × 10^{-7}
At 50 V dc:	
304	4.3 × 10^{-4}
289	6.4 × 10^{-4}
276	3.5 × 10^{-4}
263	3.9 × 10^{-4}
250	3.1 × 10^{-4}
238	5.2 × 10^{-4}
226	1.0 × 10^{-4}
210	1.0 × 10^{-4}
186	2.0 × 10^{-5}
175	[1]1.0 × 10^{-5}

---

[1] Estimated.

At 20 V dc, ignition could not be achieved at a current of 2,000 mA and, thus, p_I is estimated to be 10^{-6}. At 50 V dc, ignition could not be achieved below 175 mA, corresponding to an estimated p_I of 10^{-5}. This result was somewhat surprising but was verified by retesting. At $p_I = 10^{-5}$, the required number of tests is only 500,000 to satisfy the $n = 5/p_I$ condition and produce 98% confidence in the measurement. For the curves representing 40 and 30 V dc, the threshold probabilities of ignition were estimated to be 3.0 × 10^{-7} and 1.7 × 10^{-7}, corresponding to currents of 150 mA and 350 mA, respectively. Unfortunately, because of the low probabilities of these points, their statistical confidence levels are low when $n = 5 \times 10^{6}$. Using the relationship shown in equation 7, the confidence level for the 40-V-dc threshold of ignition is 32%. Similarly, for 30 V dc, the confidence level is 41%. To raise the confidence level of each measurement to 98% would require 162 million and 92 million sparks, respectively, in order to fix each point to within ±1 × 10^{-7}. This level of accuracy demanded time resources beyond those available for the project.

Figure 8 shows data from figure 7 redrawn to present the simple probability of ignition parametrically. Curves such as this are of more practical use to the circuit designer since they are in the same form as the standard curves shown in UL 913 (4).

INDUCTOR CIRCUITS

The inductor test circuit is shown in figure 9. The results obtained for inductors in 8.3% methane-air are shown

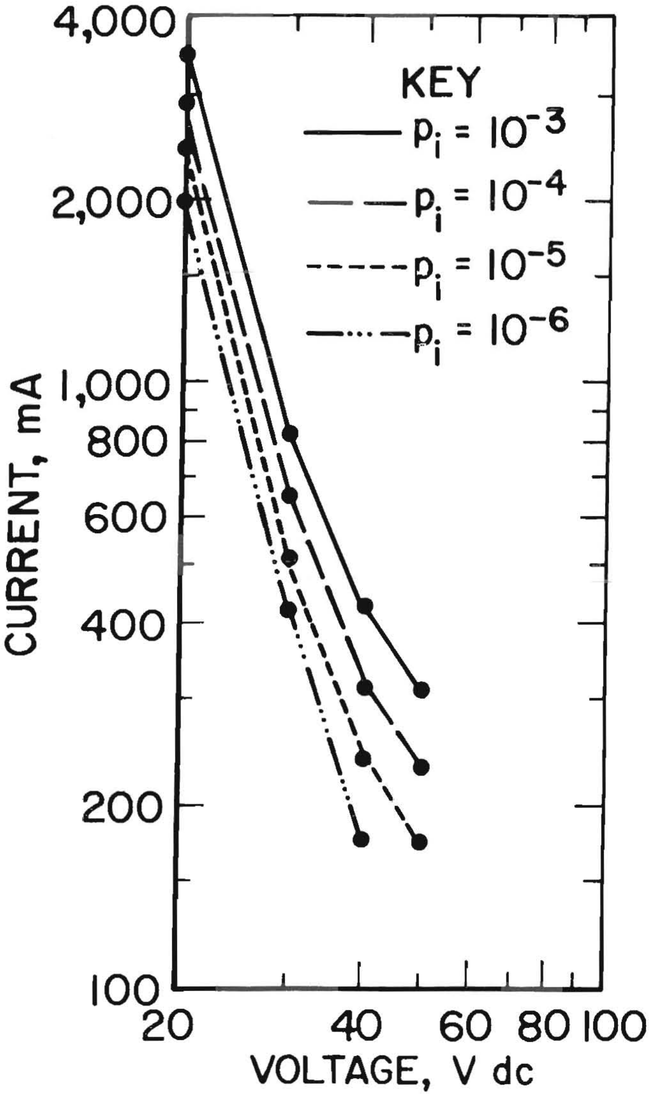

FIGURE 8.–Current versus voltage for resistor test circuits showing probability of ignition (p_i) as a parameter.

in table 4 and graphically in figure 10. For inductor values of 600, 100, and 10 mH, the ignition mechanism ceases for $10^{-6} < p_i < 10^{-5}$. Statistical confidence in these points is better than 98%. For the 1-mH data, the confidence level is approximately 32%, owing to the presence of ignitions at $p_i < 10^{-6}$.

Most intrinsic-safety researchers and test engineers have had, from time to time, great difficulty in obtaining inductive calibration ignitions for cadmium electrodes in methane as described in UL 913 (4). In earlier editions of UL 913, and in UL 1604 (5), there was a

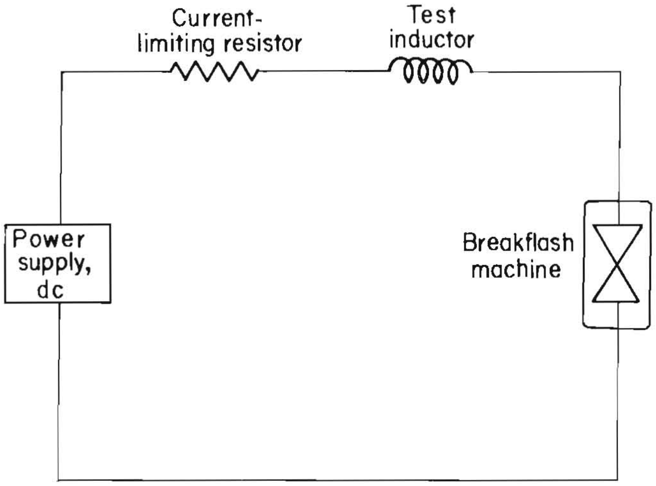

FIGURE 9.–Test circuit used to establish spark ignition probability for inductors.

TABLE 4. - Current (I) versus probability of ignition (p_i) for inductor circuits at 24 V dc

Current, mA	Probability of ignition
600 mH:	
43	2.9×10^{-4}
41	2.3×10^{-4}
37	9.1×10^{-6}
35	[1]1.3×10^{-6}
100 mH:	
122	1.2×10^{-3}
116	7.8×10^{-4}
110	3.1×10^{-4}
105	1.3×10^{-4}
90	[1]4.0×10^{-6}
10 mH:	
325	2.0×10^{-3}
309	3.4×10^{-4}
270	1.5×10^{-4}
260	4.0×10^{-5}
230	[1]2.0×10^{-6}
1 mH:	
1,102	6.4×10^{-4}
1,158	4.0×10^{-4}
1,150	1.1×10^{-4}
920	8.0×10^{-6}
800	4.0×10^{-6}
740	6.7×10^{-7}
700	2.0×10^{-7}
675	[1]1.7×10^{-7}

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[1] Estimated

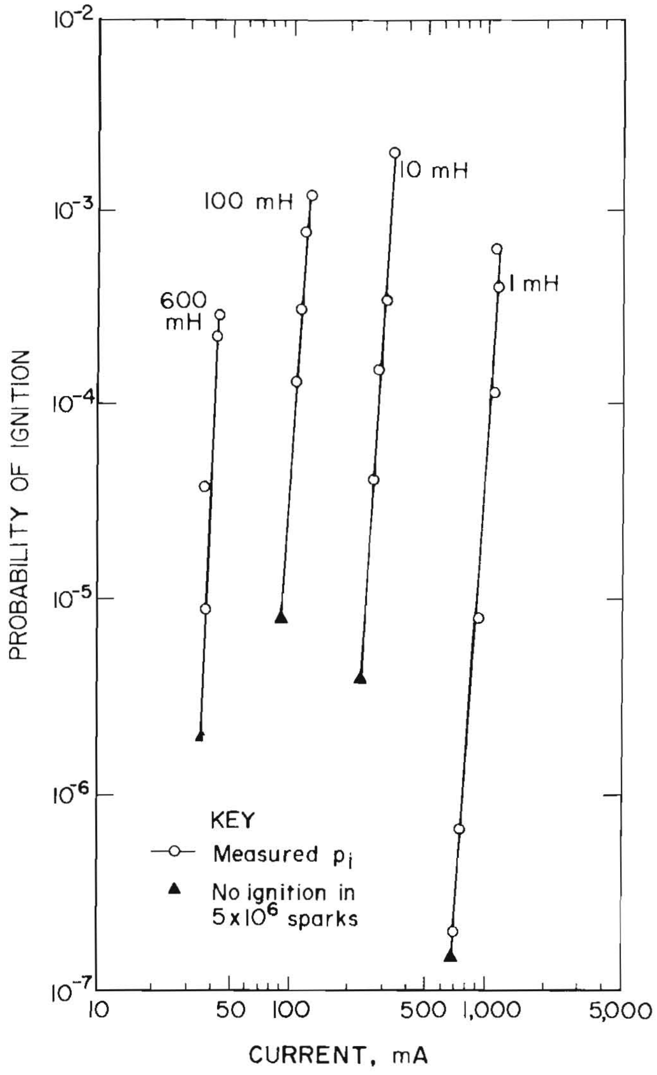

FIGURE 10.–Probability of spark ignition for inductor test circuits versus current in 8.3% methane-air atmospheres.

provision for a methane-only calibration current that was eliminated in UL 913, third edition. This methane-only calibration used an 8.3±0.3% by volume in air test mixture and allowed for a 110-mA test current using a 95-mH air-cored inductor. Since no special provisions are now made for methane-only calibrations, the required calibration current for methane-only approvals in the third edition of UL 913 is 100 mA, the same as for a group D (propane) approval. Although no data were obtained specifically for 95 mH, the 100-mH curve from figure 10 is sufficient to explain why calibration ignitions are difficult to obtain in methane using 100 mA and 95 mH. The p_I corresponding to 100mH at 100 mA is 5×10^{-5}, and the corresponding value for q is 0.99995. If a standard calibration test of 400 revolutions is conducted, with 4 sparks per revolution, 1,600 sparks will result. Therefore,

$$q^{1600} = 0.923, \qquad (10)$$

giving a 0.923 chance of no ignition occurring during a standard calibration test. Fortunately, in practice, more than 1,600 sparks are generated during a test, owing to the grooves in the disk and to random sparking while the two electrodes are in contact, thus lowering the chance of no ignition. When a calibration current of 110 mA is used, the corresponding p_I is 3.1×10^{-4} and the corresponding value of q is 0.99969. During a standard calibration test

$$q^{1600} = 0.609, \qquad (11)$$

which significantly lowers the chance of no calibration ignition. Using the above values for q, 3,466 breakflash revolutions are required to be 50% certain that an inductive calibration ignition will occur when using 100 mA, and 559 revolutions are required when using 110 mA. The author believes that the 110-mA provision for methane-only calibration currents should be restored to UL 913 or its eventual successor document ANSI/UL 4913.

Figure 11 shows data from figure 10 redrawn with p_I as a parameter, to emphasize the probabilistic nature of spark ignition and as an aid for the circuit designer.

CAPACITOR CIRCUITS

When examining capacitor circuits, one must consider the characteristics of the test circuit, shown in figure 12, to be sure that the energy contribution from the power supply during the capacitor discharge time through the breakflash machine does not have a significant effect on the results. The measured characteristics of each test circuit are

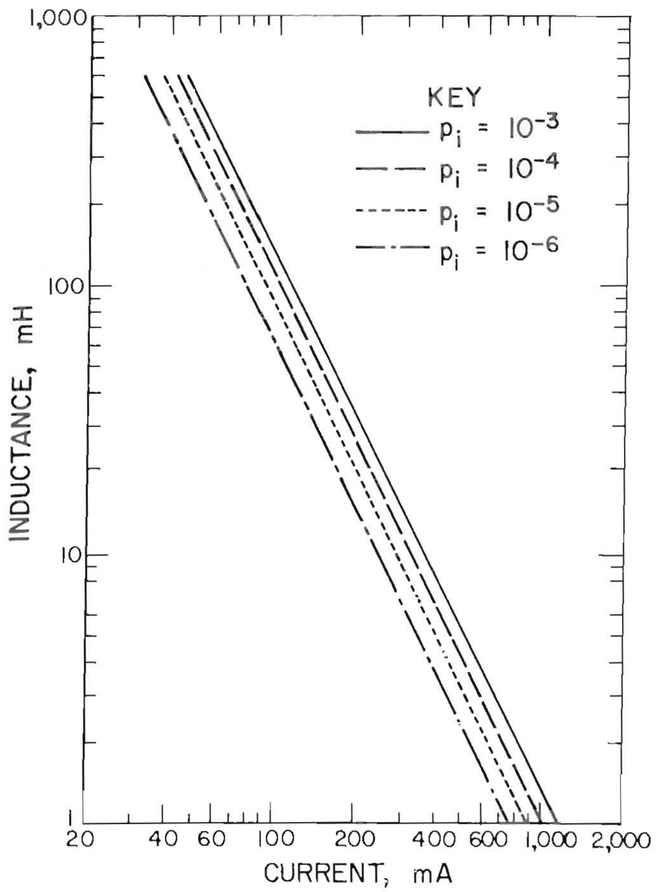

FIGURE 11.–Inductance versus current for inductor test circuits showing probability of ignition (p_i) as a parameter.

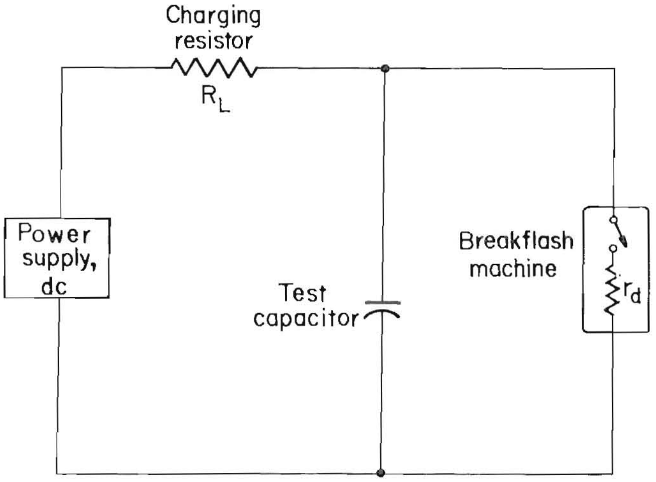

FIGURE 12.–Test circuit used to establish spark ignition probability for capacitors.

shown in table 5. The charging resistor, R_L, was selected in each case to provide a 100-ms charging time constant, but the discharge path was through the breakflash contacts, whose dc resistance was 0.1 Ω. In practice the discharge resistance, r_d, proved to be dependent on breakflash contact resistance and on the level of instantaneous current being discharged. Although the measured discharge times vary somewhat from the time give by

$$t_d = r_d \times C = 0.1 \times C\ \mu F\ (s), \quad (12)$$

where t_d = circuit discharge time through the breakflash contacts, s,

and r_d = nominal breakflash contact resistance, Ω,

the measured and calculated discharge times are in reasonable agreement. The capacitors were charged for approximately five time constants before being discharged through the breakflash contacts. This was accomplished by using only one tungsten electrode instead of the normal four electrodes and running the breakflash machine slower than 80 rpm. Consequently, it took much longer to generate capacitor circuit data than resistor or inductor circuit data.

TABLE 5. - Capacitor test circuit characteristics

	Mallory		Sprague	
	TC56	TC50100	TE1407	TE1211
Capacitance μF..	[1]1.2	[2]1,330	[3]10.3	[4]106
Charging resistor (R_L)....kΩ..	87.0	0.075	10.0	1.0
Charging time constant s..	0.104	0.100	0.103	0.106
Discharge time (t_d)[5] μs..	0.7	500	3.5	200

[1] At 250 V dc.
[2] At 50 V dc.
[3] At 100 V dc.
[4] At 10 V dc.
[5] Measured from test circuits.

The energy contribution from the power supply (E) during the discharge time (t_d) can be estimated by assuming a rectangular discharge pulse at the mean ignition voltage (2) for the duration of the discharge as

$$E = Pt_d = V^2t_d/R_L, \qquad (13)$$

where P = total power contribution from power supply, W,

V = mean ignition voltage, V dc,

and R_L = current-limiting resistance value (from table 5), kΩ.

This relation yields the results shown in table 6. In all cases, the energy contributed to the spark in the breakflash by the power supply, $(V^2t_d)/R_L$, during the capacitor discharge period is less than 1% of the mean stored energy in the capacitor required for ignition (1/2 CV^2). On the basis of the foregoing discussion, the energy contribution from the power supply is neglected in the capacitor data presented in this report.

The experimental results for capacitors, shown in figure 13 and table 7, show increasing variability in the data as capacitor size decreases. This is consistent with the results obtained for both resistors and inductors. The threshold of ignition occurs for $10^{-7} < p_I < 10^{-6}$. For capacitors greater than 100 µF, the voltage values obtained for

TABLE 6. - Ignition energy contribution from power supply (V^2t_d/R) versus 1/2 CV^2 (for methane)

Capacitance..µF..	1.2	10.3	106	1,330
Voltage....V dc..	124	36.8	19.9	12.9
Discharge time (t_d).........µs..	0.7	3.5	200	500
Charging resistor (R_L)....kΩ..	87.0	10	1	0.075
Energy (V^2t_d/R_L).........µJ..	12.4	47	79	1,100
Energy (1/2 CV^2).........mJ..	9.2	7.2	21	111

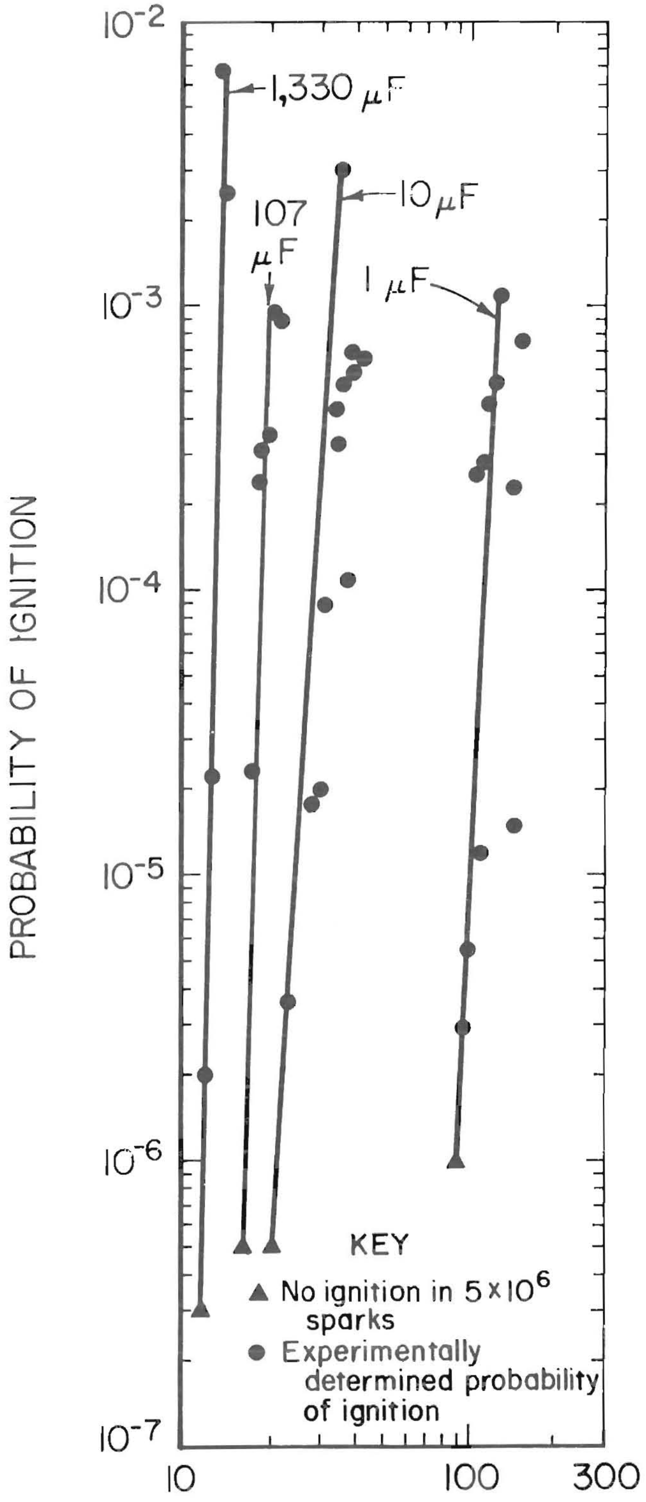

FIGURE 13.–Probability of spark ignition for capacitor test circuits versus voltage in 8.3% methane-air atmospheres.

$p_I \approx 4 \times 10^{-4}$ (approximately the 50th percentile of ignition for a 400-rotation, 80-rpm test per UL 913) agree well with data published in UL 913 (4, "C + 0 Ω (Cd)" curve). For capacitors less than 100 μF, however, the UL 913 values are considerably less than those measured here. For example, for 1 μF, $p_I \approx 4 \times 10^{-4}$ corresponds to 130 V dc, while the value published in UL 913 is approximately 80 V dc. In general, for capacitors greater than 100 μF, the experimental results obtained are more conservative than those in UL 913, while for capacitors less than 100 μF, the UL curves are more conservative. Figure 14 shows the data from figure 13 presented with p_I as a parameter.

TABLE 7. - Voltage (V) versus probability of ignition (p_I) for capacitor circuits

Voltage, V dc	Probability of ignition
1,330 μF:	
13.7	2.5×10^{-3}
13.1	6.7×10^{-3}
12.4	2.2×10^{-5}
12.0	2.0×10^{-6}
11.5	[1]3.0×10^{-7}
107 μF:	
21.4	8.8×10^{-4}
20.4	9.4×10^{-4}
19.5	3.5×10^{-4}
18.5	3.1×10^{-4}
18.0	2.4×10^{-4}
17.0	2.3×10^{-5}
16.0	[1]5.0×10^{-7}
10 μF:	
42	6.5×10^{-4}
39	5.8×10^{-4}
38	6.9×10^{-4}
37	1.1×10^{-4}
36	5.5×10^{-4}
35	2.9×10^{-3}
34	3.3×10^{-4}
33	4.3×10^{-4}
31	8.8×10^{-5}
30	2.0×10^{-5}
28	1.8×10^{-5}
23	3.6×10^{-6}
20[1]	5.0×10^{-7}
1 μF:	
149	7.4×10^{-4}
145	1.5×10^{-5}
142	2.3×10^{-4}
129	1.1×10^{-3}
123	5.4×10^{-4}
117	4.6×10^{-4}
112	2.8×10^{-4}
110	1.2×10^{-4}
106	2.6×10^{-4}
100	5.5×10^{-6}
95	2.9×10^{-6}
[1]90	1.0×10^{-6}

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[1] Estimated

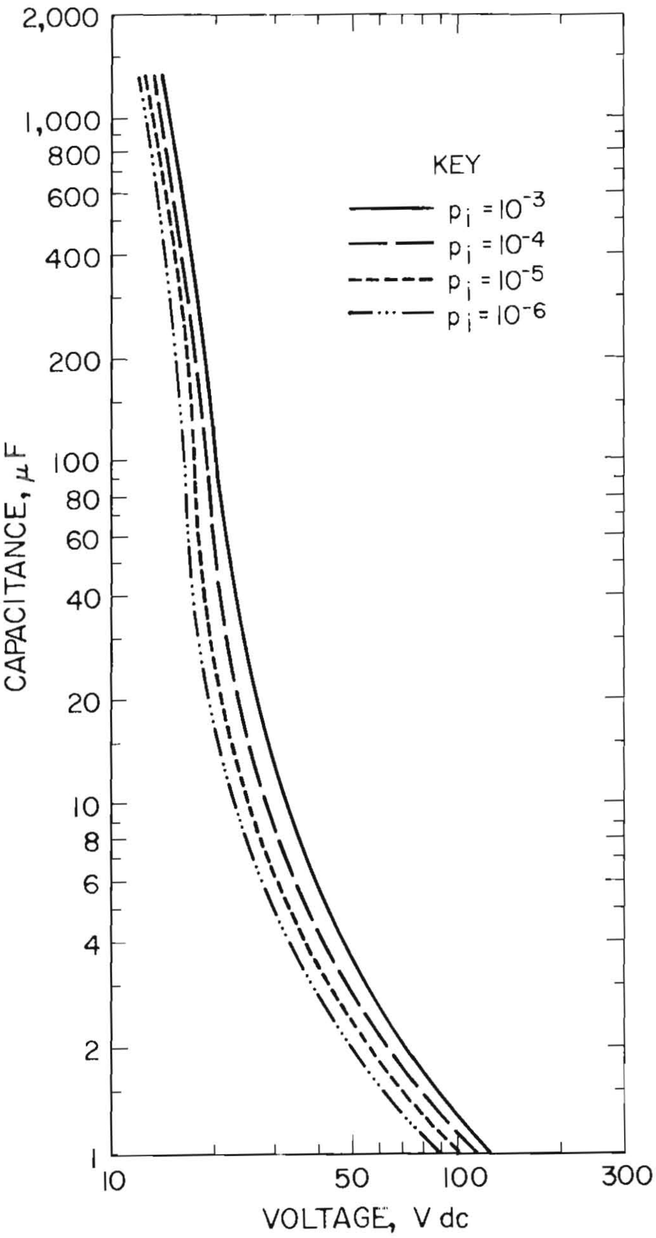

FIGURE 14.–Capacitance versus voltage for capacitor test circuits showing probability of ignition (p_I) as a parameter.

CONCLUSIONS

The probability of ignition and its corresponding currents have been estimated for resistor, inductor, and capacitor circuits in 8.3±0.3% methane-air atmospheres. The circuit values used in this determination represent the range of values most likely to be encountered when designing portable, battery-powered devices and fixed-point monitoring equipment for gassy, underground mines· for resistors, 20 to 50 V dc; for inductors, 1 to 1,000 mH; and for capacitors, 1 to 1,330 μF. The p_I data are valuable for relating the conditions under which equipment is tested to the real-world conditions in which the equipment will operate, i.e., that p_I indicates the true "safety factor."

This project has shown that the spark ignition phenomenon is continuous for $p_I < 10^{-4}$, a fact not previously known for certain. A straight-line relationship exists between p_I and current or voltage validating equation 2 as a predictor of p_I given the current.

For $10^{-7} < p_I < 10^{-5}$, however, a "threshold" has been identified below which spark ignitions do not occur, even though the experimental design limits the probability of ignitions not occurring to less than 1%. For each type of circuit, the spark ignition phenomena stopped below some level of current or voltage. This point was estimated by extrapolating the experimental data. Operation of circuits below this ignition threshold may imply an infinite safety factor.

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