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Probability of Resistive Spark Ignition Caused by Very Low Currents

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	rpm	revolution per minute
mA	milliampere	V dc	volt, direct current

PROBABILITY OF RESISTIVE SPARK IGNITION CAUSED BY VERY LOW CURRENTS

By James C. Cawley[1]

ABSTRACT

The Bureau of Mines has empirically determined ignition probability versus current for resistive circuits in an 8.3% methane-air atmosphere. Simple ignition probability, defined as the number of ignitions divided by the total number of sparks, was determined, and the corresponding currents were recorded. The experiment was designed to minimize the probability of not observing an ignition that should occur during a series of tests.

For resistive circuits in 8.3% methane-air mixtures, the experimental results indicate that ignition was not achieved below 2,000 mA at 20 V dc, 350 mA at 30 V dc, 150 mA at 40 V dc, and 175 mA at 50 V dc. The simple probability of ignition corresponding to these currents is estimated to be, respectively, 1.0×10^{-6}, 1.7×10^{-7}, 3.0×10^{-7}, and 1.0×10^{-5}. The ignition mechanism seems to break down below this point, implying that a threshold current value exists below which spark ignition does not occur.

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INTRODUCTION

The Bureau of Mines began to investigate the subject of safety factors, as applied to intrinsic safety testing, in 1984. Subsequent research (1)[2] indicated that using test gases that are more easily ignited than methane, such as propane and ethylene, in lieu of applying a 1.5 safety factor on electrical energy at the point of test, is not a satisfactory method by which to achieve a safety factor. In order to estimate the safety factors obtained by using more easily ignited test gases, spark ignition curves were experimentally established that were based on mean igniting currents (or voltages) for resistive, inductive, and capacitive circuits in methane-, propane-, and ethylene-air atmospheres. Each point on the curve was determined on the basis of 100 trials. Each trial was conducted for 400 revolutions at 80 rpm of the International Electrotechnical Commission (IEC) breakflash apparatus (as described in IEC Standard 79-3) (2), or until an ignition occurred. The statistical basis for the curves published in Underwriters' Laboratories (UL) Standard 913 (3) was shown to correspond to, in general, the mean value of the ignition variable.

The safety factor was then defined as the ratio of the mean ignition energy in methane to the mean ignition energy in the substitute test gas. The safety factor provided by testing in a gas more explosive than methane was not constant with voltage or current. For example, the safety factor achieved by testing in propane rather than methane for a resistive circuit increased from 1.19 to 1.51 between 20 V dc and 50 V dc, while the safety factor for methane-ethylene decreased from 2.65 to 1.79 over the same range. The safety factors obtained for inductive and capacitive circuits showed similar trends. Alternate test gases do not provide a safety factor that is constant over a range of current or voltage, even for simple resistor, inductor, or capacitor circuit models. Applying safety factors by substituting a more easily ignited test gas for methane is not a straightforward procedure and is not recommended.

The program that investigated alternative test gases provided a small data base from which to begin an examination of another commonly used method of applying safety factors, the simple ignition probability model. This method is used in the U.S.S.R., Poland, Yugoslavia, and other Eastern European nations. 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):

$$p_I = N_I/N_S. \tag{1}$$

Throughout this report, the term "mean igniting current" (voltage) refers to a current (voltage) that causes spark ignition in half (i.e., 50th percentile) of the 400-revolution, 80-rpm tests as described in UL 913. The term "simple probability of ignition" denotes the probability of spark ignition on any given spark. Therefore, there exists a value of simple ignition probability that corresponds to the mean value of ignition current (voltage) obtained in previous experimental work. The value of p_I that corresponds to the mean value of spark-igniting current obtained when testing resistive circuits in 8.3% methane-air is approximately 4×10^{-4}. Thus, for a standard intrinsic safety test of up to 400 revolutions at 80 rpm, ignition will occur in half of the tests when $p_I = 4 \times 10^{-4}$.

Matasovic (4) showed that log probability of ignition versus log current (or voltage) is a straight line with a constant slope that is independent of the test gas and the value of the circuit parameters. His experiments showed that at $p_I = 10^{-3}$, 20,000 sparks was sufficient for his probability data to

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

their final value. He defines the safety factor, k, as

$$k = I(p_I = 10^{-3})/I(p_I = 10^{-8}) \qquad (2)$$

where

$I(p_I = 10^{-3})$ = current at which the simple ignition probability, p_I, is 10^{-3},

and

$I(p_I = 10^{-8})$ = current at which the simple ignition probability, p_I, is 10^{-8}.

Matasovic shows that k depends solely on whether the circuit element is a resistor, inducter, or capacitor. Tests in methane, propane, ethylene, and hydrogen mixtures in air gave the results shown in table 1.

Interestingly, the safety factors achieved by this method are not constant nor are they clustered around 1.5. For inductive circuits, Matasovic finds safety factors from 1.30 to 1.65 depending on the test gas. Resistive and capacitive safety factors range from 2.31 and 2.43 to 2.95 and 2.77, respectively.

To establish a circuit's safety factor using the simple probability of ignition model, Matasovic tested the circuit at a current (or voltage for capacitor circuits) that provided an ignition probability, p_I, of roughly 1×10^{-3}. This point is relatively easy to establish in a conventional breakflash machine (2) with routine testing. The current at which $p_I = 10^{-8}$ was then extrapolated, using the empirically known slope of the log ignition probability versus log current curve. The ratio of the two currents was then arbitrarily designated as the safety factor for the circuit under test. The safety factors determined by such a method may be considerably different from those arising from the U.S. practice of applying a 1.5 multiplier to energy at the point of test, as can be seen in table 1. Estimation of the simple probability of ignition at a known current allows the entire hazard abatement process to be viewed statistically and allows the assignment of a definite probability of ignition to the current under examination and to the hazardous environment, if other hazards (5) can also be estimated. This allows calculation of the expected number of ignitions in the workplace per unit of time, a desirable quantity for hazard estimation.

TABLE 1. - Safety factor (k) for various gases

Gas	Inductive circuit	Capacitive circuit	Resistive circuit
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

Source: Matasovic, M. Research Into the Probability of Ignition in Intrinsically Safe Circuits. S-Comm. Bull. 6(1977)12, Zagreb, Yugoslavia, 1977, p. 72.

There are, however, two major drawbacks to the present application of the simple ignition probability model. First, the model assumes that the extrapolation to a lower current is valid to $p_I = 10^{-8}$, when evidence supporting this contention is lacking owing to the time needed to produce such data with some degree of statistical confidence. An examination of the data presented (2) reveals that there are no experimental data on current versus simple probability of ignition below about $p_I = 4 \times 10^{-5}$ with which to verify the assumption of linearity. Second, the continuity of the ignition process at low values of ignition probability 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 between $p_I = 10^{-3}$ and $p_I = 10^{-4}$, 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, Pittsburgh Research Center, Bureau of Mines, for his timeless 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.

EXPERIMENTAL PROCEDURE

STATISTICAL DESIGN OF THE EXPERIMENT

The process of gathering statistical information on events that have a low probability of occurrence requires a large number of trials 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:

$$P\,\overset{n}{X} = (X)\, p^{X} q^{n-X}, \tag{3}$$

where $P(X)$ = probability of observing X outcomes in n trials,

p = probability of observing a "successful" outcome in any given trial,

and q = probability of not observing a "successful" outcome in any given trial, $q = 1 - p$.

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

$$P(X) = \frac{\lambda^{x} e^{-\lambda}}{X!}, \tag{4}$$

where $\lambda = n*p$ from the binomial distribution and is the expected number of ignitions in n trials,

X = number of favorable outcomes,

and e = base of the system of natural logarithms.

Consider a rare event whose probability of ignition, p_i, is given by

$$p_i = 10^{-6}. \tag{5}$$

Conversely, the probability of *not* observing an ignition, p_n, on a given trial is

$$p_n = 1 - p_i = 1 - 10^{-6} = 0.999999. \tag{6}$$

Using the Poisson distribution, ignition probabilities can be tabulated for the values of n, p_i, λ, X and P(X) as shown in tables 2 and 3.

TABLE 2. - Poisson ignition probabilities

Favorable outcomes (X)	$n = 10^{-6}$, $p_i = 10^{-6}$, $\lambda = 1$	$n = 5 \times 10^{6}$, $p_i = 10^{-6}$, $\lambda = 5$	Favorable outcomes (X)	$n = 10^{-6}$, $p_i = 10^{-6}$, $\lambda = 1$	$n = 5 \times 10^{6}$, $p_i = 10^{-6}$, $\lambda = 5$
0............	0.3679	0.0067	6............	([1])	0.1462
1............	.3679	.0337	7............	([1])	.1044
2............	.1839	.0842	8............	([1])	.0653
3............	.0613	.1404	9............	([1])	.0363
4............	.0153	.1755	10............	([1])	.0181
5............	.0031	.1755	Total....	.9994	.9863

[1] Approximately zero.

TABLE 3. - Current versus probability of ignition

Current (I), mA	Probability of ignition (p_I)
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	1.0×10^{-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	1.7×10^{-7}
At 40 V dc:	
452	9.0×10^{-4}
430	4.1×10^{-4}
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	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}

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e Estimated.

As shown in table 2, for $\lambda = 1$, there is a 36% probability of *not* observing an ignition even though 1 million spark events occur. When n is increased to 5×10^6, λ increases to 5, as shown in table 3. Under these conditions, the probability of not observing an ignition that has a probability of occurrence of 10^{-6} is 0.0067. The $\lambda = 5$ condition, therefore, was used in this series of experiments to produce an acceptably small probability of not seeing an ignition that should have occurred during the experiment. Notice that this condition is dependent only on λ. Any level of ignition probability can be investigated with similar statistical certainty provided that the product of n and p = 5. In other words, if $n = 5 \times (1/p_I)$, then $n \times p_I = \lambda = 5$, and the probability of *not* observing an ignition in n trials, i.e., $P(X = 0)$ when $\lambda = 5$, is 0.0067. The sample size, S, required to give a 98% confidence level can be computed as follows:

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

where Z = the 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.

If d is selected as 0.001 with $p_I = 0.001$, then the true value of p_I is between 0.000 and 0.002. Also, $p_I + d < 1.000$ and $p_I - d > 0$. In this work, in order to be 98% confident that $0.000000 < p_I < 0.000002$ when its value was assumed to be 0.000001, the required sample size is $S = [(2.326)^2 \times (0.000001) \times (0.999999)]/(0.000001)^2 = 5.4 \times 10^6$, a number in reasonable agreement with the $\lambda = 5$, or 5 million sparks that were run to establish points where $p_I = 10^{-6}$.

EXPERIMENTAL APPARATUS

The experimental procedure used to estimate the statistical properties of the spark ignition curves was in accordance with the procedures in UL Standard 913[3] except that the tests were continuous in duration. All tests were conducted using an 8.3% methane-air mixture as shown in figures 1 and 2. Chemically pure (99%+ purity) methane, oxygen, and nitrogen were separately supplies to the system, and the output gas mixture was controlled to with ±0.3%. Gas mixture accuracy was regularly verified by calibration ignitions according to UL Standard 913,

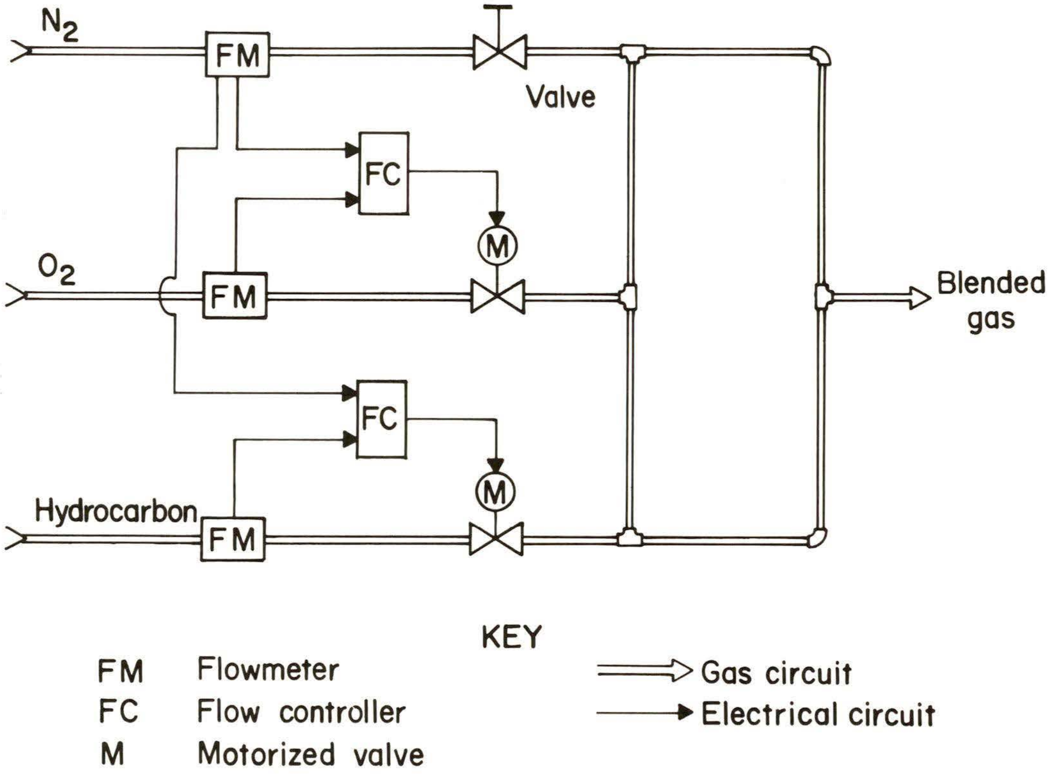

FIGURE 1.—Block diagram of the gas mixing system used.

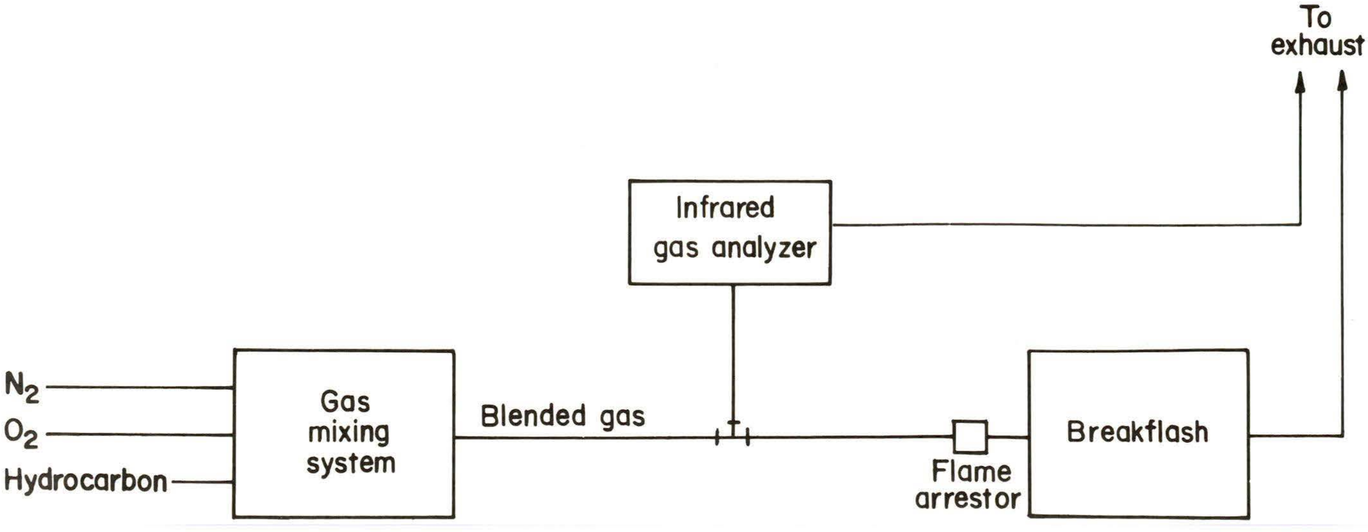

FIGURE 2.—Schematic diagram of the gas circuit.

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[3] Work cited in footnote 4.

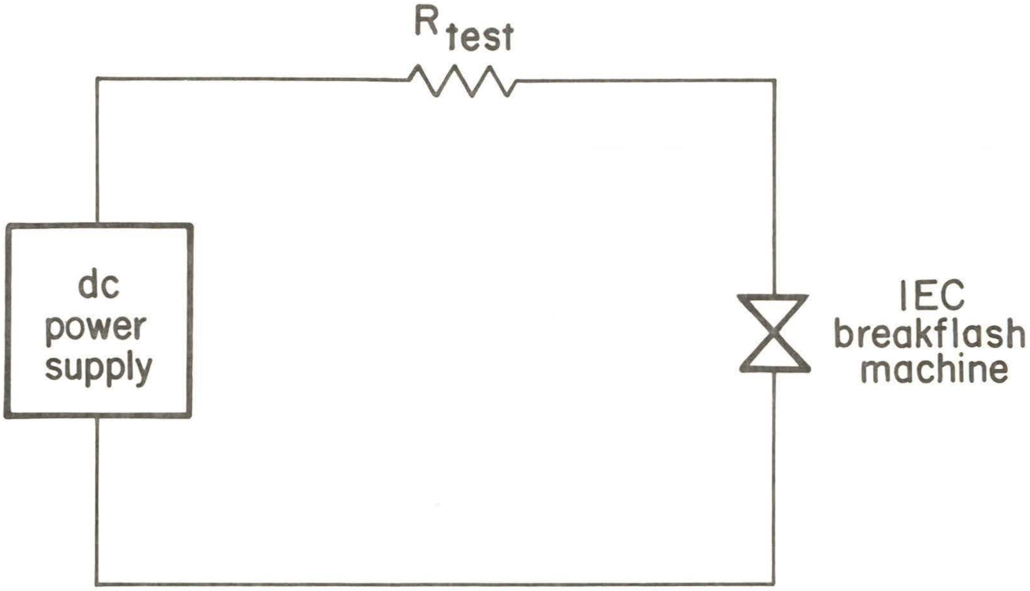

FIGURE 3.—Test circuit schematic diagram.

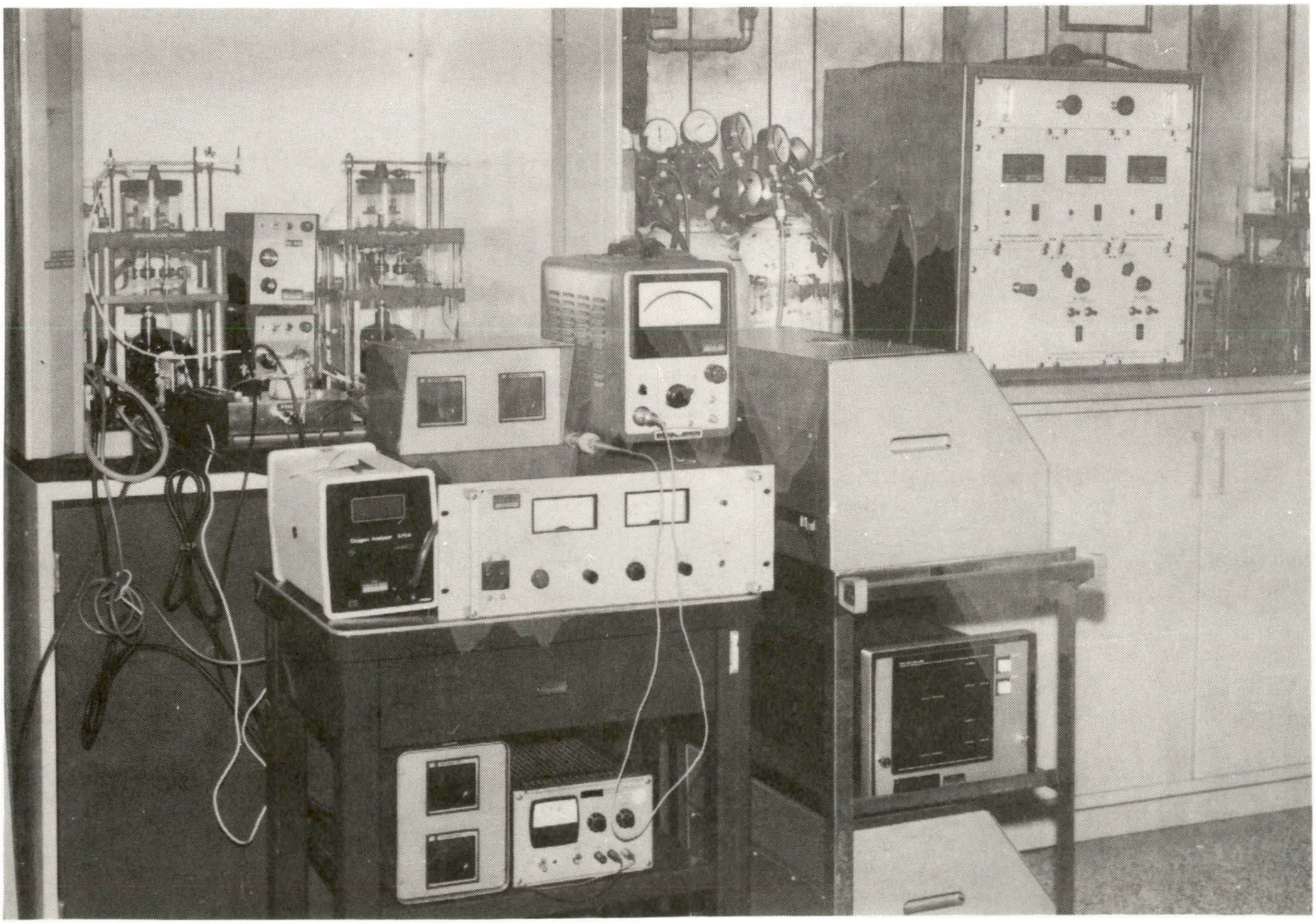

FIGURE 4.—Test apparatus.

on-line infrared analysis, and off-line chromatographic analysis.

The electrical circuit under test consisted of a simple series circuit containing a power supply, a carbon-film (low-inductance) power resistor, an IEC breakflash, and associated test leads. Figure 3 is a circuit schematic, and figure 4 shows the test setup. Each test was conducted as follows:

1. The initial simple ignition probability versus current curves 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 are shown in figure 5.

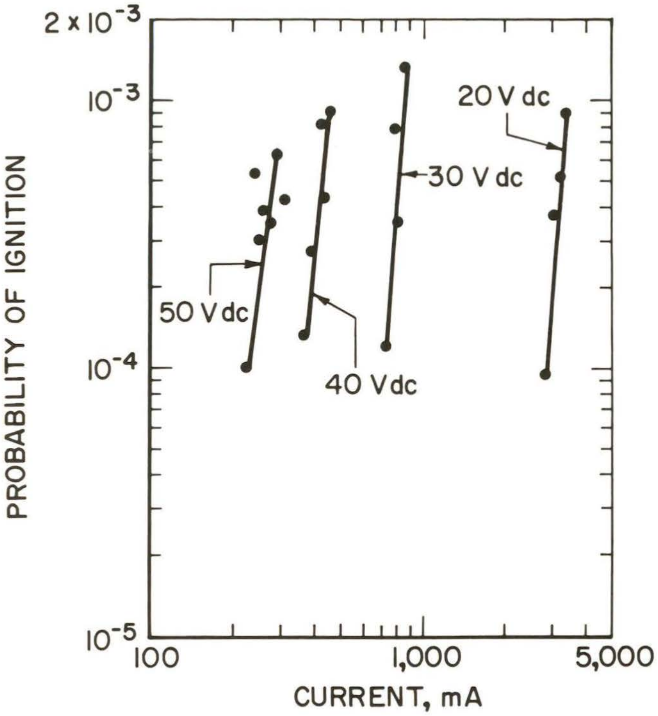

FIGURE 5.—Estimated probability of resistive spark ignition versus current.

2. The original data can be expressed in the form

$$\frac{P_1}{P_2} = \left(\frac{I_1}{I_2}\right)^m \qquad (8)$$

where

P_1, P_2 = two levels of simple ignition probability,

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

and

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

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 their expected probability levels could be verified by experiment.

4. When no ignition occurred in $n = 5/p_I$ trials, it was considered a statistically unusual event. This test current was considered to be the threshold current below which ignition will not occur.

RESULTS

The results obtained from the test program are shown in table 3 and graphically in figure 6. The probability of ignition versus current is shown parametrically for four curves, 20, 30, 40, and 50 V dc. The curves shown in figure 5 were determined by performing a linear regression on the logarithmically transformed current and probability data. The curves were extrapolated using the slope determined from the original regression line. Currents indicated by the extrapolation were used as test points in this experiment. The final curve fit, shown in figure 6, represents the best fit to the experimental data. However, since no ignitions were obtained for the lowest points on each curve, the probability of ignition corresponding to that current was assumed to fall on the extrapolated curve. Owing to the curve's high m value, the error in fixing the current below which ignition was not obtained is rather small.

At 20 V dc, ignition could not be achieved at a current of 2,000 mA; thus, p_I is estimated to be 1.0×10^{-6}. At 50 V dc, ignition could not be achieved below 175 mA, corresponding to an estimated p_I of 1.0×10^{-5}. This result was somewhat surprising but was verified by retesting. At $p_I = 1.0 \times 10^{-5}$, the required number of tests is only 500,000 to satisfy the $\lambda = 5$ condition.

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, owing to 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%, 162 million and 92 million sparks, respectively, would be required at the present levels of probability in order to fix each point to within $\pm 1 \times 10^{-7}$. This level of accuracy demanded time resources beyond those available for the project.

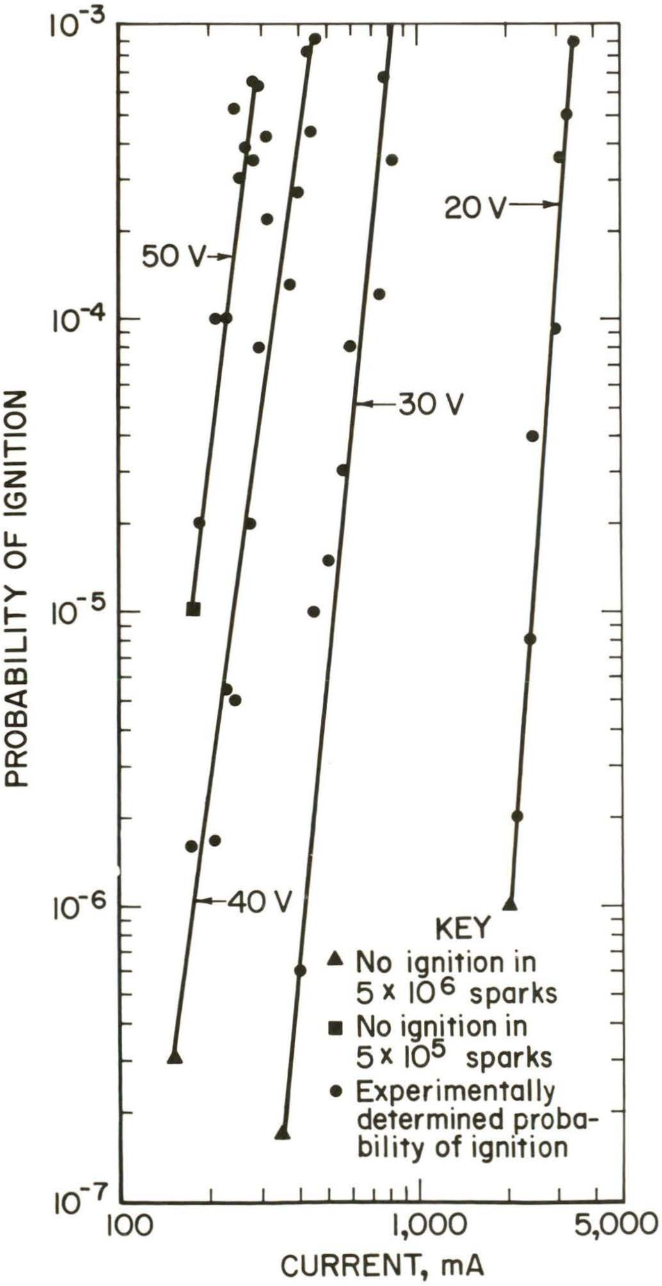

FIGURE 6.—Estimated probability of resistive spark ignition versus empirically determined current.

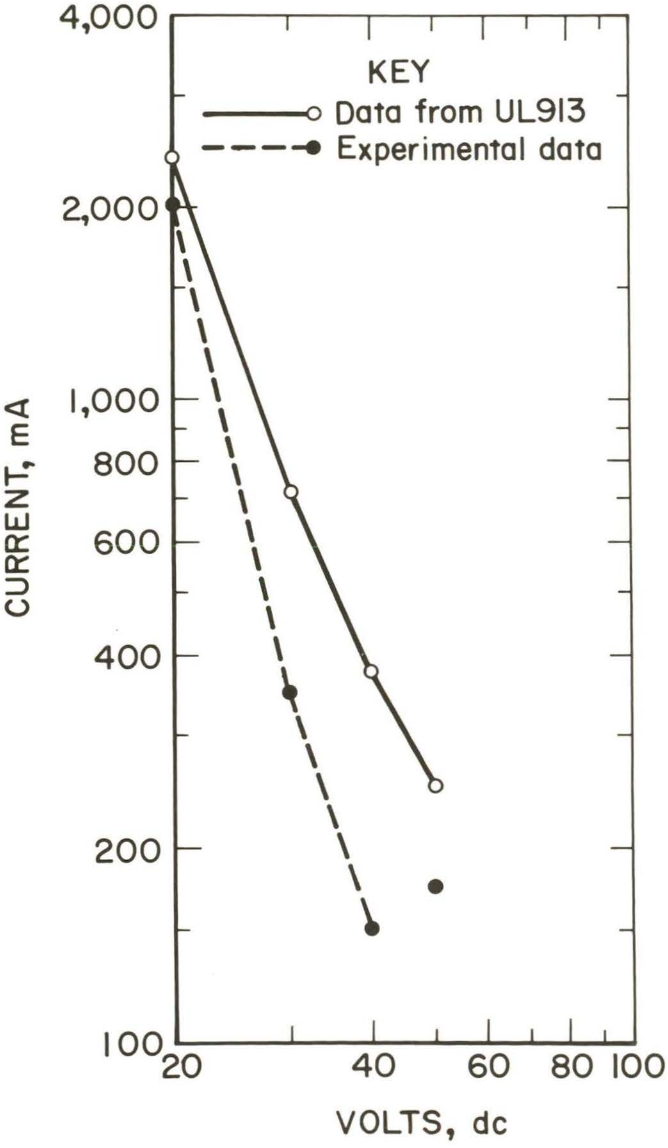

FIGURE 7.—Comparison of UL resistive spark ignition data and estimated ignition threshold currents.

Figure 7 compares the ignition data from UL Standard 913 against the ignition threshold currents obtained in this study. Previous Bureau research (1) showed that the UL Standard 913 resistive spark ignition curves represented approximately mean ignition levels. The threshold of ignition is relatively close to the mean igniting current at 20 V dc, and the difference between mean and threshold of ignition currents increases with increasing voltage to 40 V dc. The 50-V-dc point has not been dismissed as a "wild point" since it was verified through retesting. It does not, however, fit into a smooth curve as do the other points.

Figure 8 shows a family of spark ignition curves with the probability of ignition as a parameter. These curves are derived from the information contained in figure 6. Note the absence of a 50-V-dc point for $p_i = 10^{-6}$ since the lower bound of ignition there was $p_i = 10^{-5}$. Figure 9 depicts how the resistive spark ignition data published in UL Standard 913 may be interpreted on a probability of ignition basis. The UL curve is not the lower bound of ignition but varies between $p_i = 10^{-3}$ and $p_i = 10^{-5}$.

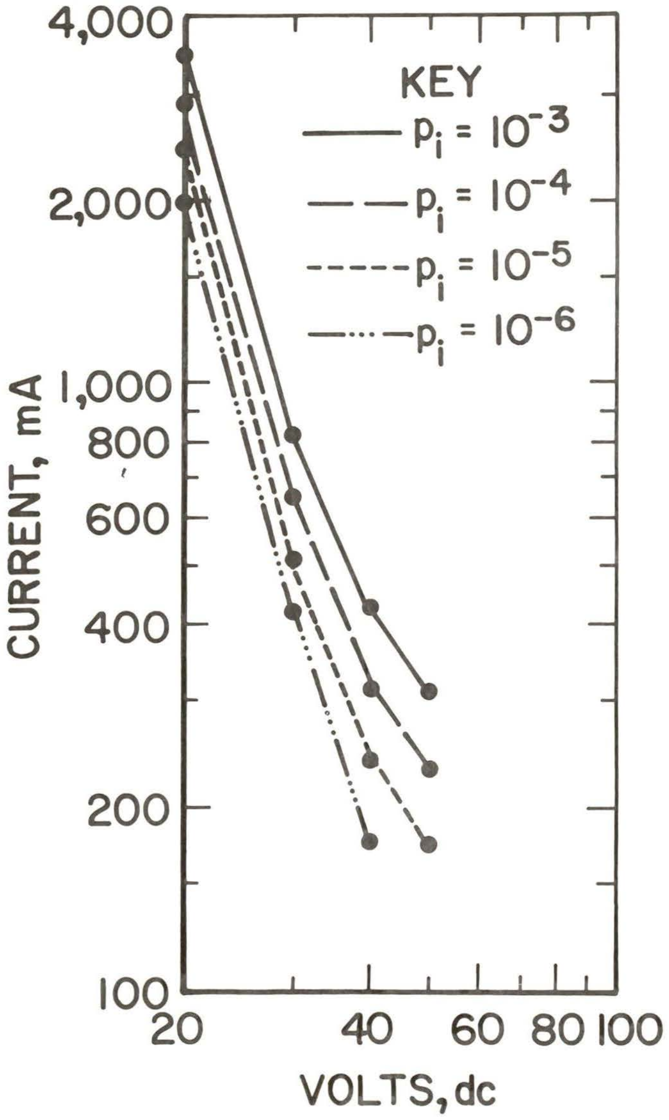

FIGURE 8.—Ignition current versus voltage for various estimated probabilities of ignition.

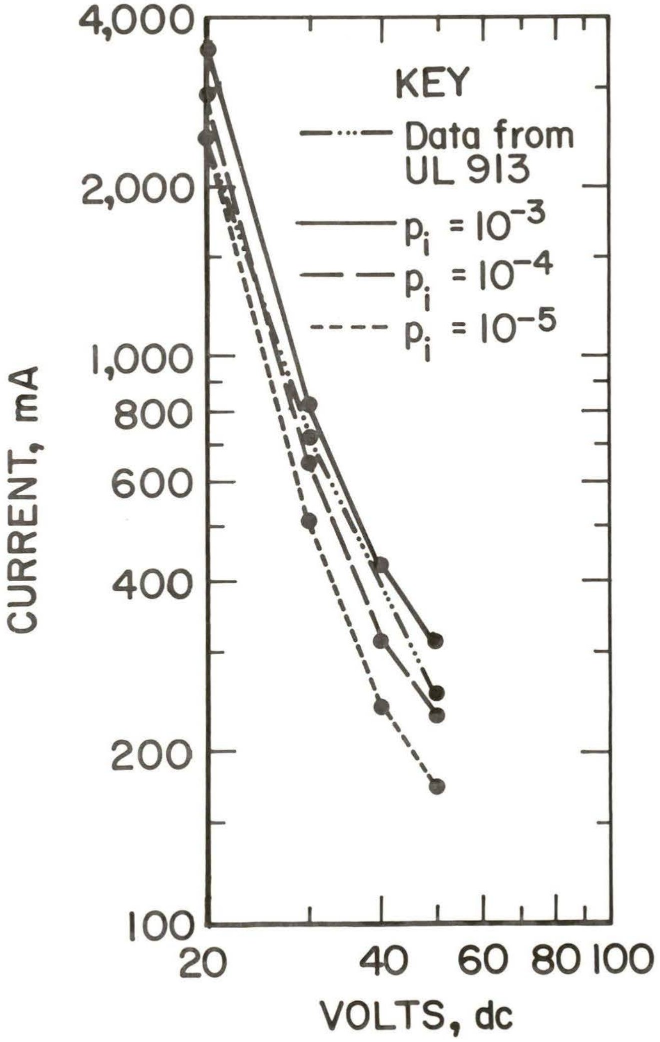

FIGURE 9.—Comparison of the UL resistive spark ignition data versus the estimated probability of ignition.

CONCLUSIONS AND RECOMMENDATIONS

The lower bound of ignition probabilities has been empirically determined for resistive circuits. Ignition probabilities for 20 and 50 V dc, where $n = 5/p_I$, have been estimated with 98% statistical confidence. At 20 V dc, ignition could not be achieved at a current of 2,000 mA, p_I is thus estimated to be 1.0×10^{-6}. At 50 V dc, ignition could not be achieved below 175 mA, corresponding to an estimated p_I of 1.0×10^{-5}. 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. For 40 and 30 V dc, $n < 5/p_I$, and the lower bound of ignition probability has been estimated with 32% and 41% confidence levels, respectively. Time constraints prevented testing to establish 98% statistical confidence since the number of sparks required would have been 162 and 92 million, respectively.

The author recommends that other laboratories should undertake to verify these results on a statistical basis. Further, the results presented here should be extended to inductive and capacitive circuits and to test gases other than methane. The Bureau is currently augmenting the resistive circuit data with inductive circuit data and will include capacitive circuit data in the near future. The subject of safety factors as applied to intrinsically safe apparatus must continue to be thoroughly investigated to ensure a clearer understanding of the subject and to promote regulatory harmony.

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