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ABSTRACT

Published information is not available for accurate prediction of the electrical insulating characteristics of helium at high pressures and temperatures. In general, the breakdown voltage increases as the gas pressure is increased and decreases as the gas temperature is increased. The relatively low breakdown voltage of helium accents the importance of additional investigation in this field.

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INTRODUCTION

Electrical insulation characteristics of helium gas are of importance in the design of electrical installations and equipment located within experimental test apparatus and reactors containing helium atmospheres. The purpose of this memorandum is to review published information relative to the design of bare electrical conductors located in commercially pure helium for a pressure range of 1 to 25 atmospheres and a temperature range of 100°F to 1000°F.

No attempt is made to tabulate all available references to related theoretical and experimental information, however, data by some of the investigators will be presented to cover important characteristics of electrical breakdown of gases. Some information for hydrogen will be included, since it is used as a coolant for turbine generators and has desirable coolant characteristics for use in reactors. Air, which is the most commonly used gas insulator, will be discussed in an attempt to extrapolate information for helium.

DISCUSSION

The dielectric strength of a gas is the voltage at which electrical failure or breakdown occurs. It is a property which varies with many factors such as size, shape, spacing, and material of the electrodes used, form of distribution of the field of electric stress in the gas, characteristics of the applied voltage, rate and duration of voltage application, presence of free ions mixed with the gas, temperature, pressure, moisture content, and impurities in the gas.

A gas in the normal state and unexposed to any ionizing agent is a perfect nonconductor at all voltage gradients below its dielectric strength. Various investigators have found that small leakage does occur that is attributed to very feeble ionization of the gas by weak radiations which come partly from the ground and partly from the sky. The current flow reaches a saturation point and does not increase appreciably with the further increase of voltage as shown by ab, Fig. 1.

FIGURE 1.

Gases may be made to have considerable electrical conductivity as a result of agencies present which will produce ionization. Only at low voltages does the gas obey Ohms law, as shown in region oa, Fig. 1. In region bc the electric field in the gas becomes sufficiently intense to cause ionization by itself, and the increase in current is proportionally much greater than the increase in voltage. When the ionizing agent is removed, the conductivity diminishes and finally disappears entirely, indicating that the ions recombine and the gas resumes its normal state.

Electrical breakdown in gases occurs in several different forms, which are usually classified as coronas, glow discharges, sparks, and arcs. It is frequently difficult to differentiate between these forms of discharges because one type may give place to another, depending on the attendant conditions. With electrodes of certain forms, there are certain critical spacings, below which the discharge acts as a spark and above which it starts as corona.

Breakdown voltages may vary considerably, depending on the form of the electrodes and the fields produced.¹ Electrode arrangements which produce uniform fields require higher voltages for breakdown than do electrode arrangements which produce nonuniform fields. The field produced by spherical electrodes, where the spacing is small compared to the sphere diameter, is considered as being uniform. The field produced by a point-to-plane gap is nonuniform and the breakdown voltage becomes comparatively low.

Pollock and Cooper² determined voltages at which corona first appeared and the breakdown voltages for selected gases and gas mixtures. This was done for a 3-mm point-to-plane gap at pressures ranging from 1 to about 30 atmospheres, with both positive and negative point polarity. The gases were of ordinary commercial purity. Figures 2, 3 and 4 present some of the results of the experiments by Pollock and Cooper. At low pressures with the point positive, there is a fairly wide corona region in all gases which readily form negative ions. The principal effect of increasing the spacing would be to shift the curves along the y-axis.

Paschen's law of electrical breakdown in gases states that the sparking potential is a function only of the product of the pressure and the electrode separation. Breakdown voltages³ as determined from the pressure-distance (pd) relationship for sphere gaps are also shown in Figures 2, 3 and 4. Experimental results indicate that as the pressure is increased eventually a point is reached at which the rate of rise in breakdown voltage as a function of pressure decreases and may yield a plateau or even a maximum in the curve. The point is more noticeable as the gap width is increased. Such a point exists near 10 atmospheres in Fig. 4. McConnell⁴ found this point in the pressure range of 8 to 10 atmospheres for uniform fields and at pressures as low as 5 atmospheres for nonuniform fields. An explanation⁵ for this phenomenon has been proposed; however, insufficient experimental data are available to check the agreement for most gases.

Relative dielectric strengths⁶ of air and hydrogen for pressures up to 5 atmospheres are presented in Table I.

TABLE I
Relative Dielectric Strengths For Air and Hydrogen

<u>Pressure</u> <u>(Atmospheres)</u>	<u>Relative Dielectric Strength</u>		<u>Hydrogen</u> <u>Breakdown (volts)</u>
	<u>Air</u>	<u>Hydrogen</u>	
1	1.00	0.87	10,000
2	1.00	0.76	15,000
3	1.00	0.72	20,000
4	1.00	0.69	25,000
5	1.00	0.68	30,000

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Fig. 2. Breakdown Voltages for Helium in a 3-mm Point-to-Plane Gap as a Function of Pressure

Fig. 3. Breakdown Voltages for Hydrogen in a 3-mm Point-to-Plane Gap as a Function of Pressure

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Fig. 4. Breakdown Voltages for Air in a 3-mm Point-to-Plane Gap as a Function of Pressure

With the use of the pd plot for air in Fig. 4 and the relative dielectric strengths given in Table I, breakdown voltages for hydrogen were computed and plotted on Fig. 3. As may be seen, the dielectric strength curve falls slightly higher than the hydrogen pd curve. The relationship applies more favorably to the Pollock and Cooper curves. Loeb and Meek⁷ present calculations of breakdown voltages for air, which very closely follow the pd curve in Fig. 4.

In installations where a gas is used as an insulator, conductors are arranged to provide approximately uniform fields by eliminating sharp corners and irregularities. This procedure will result in breakdown voltages near the values determined by the sphere gap arrangement. Bouwers⁸ presents breakdown voltages for conductor configurations which represent practical applications.

Manufacturers usually design electrical equipment to withstand a standard factory potential test at twice the rated voltage plus 1000 volts applied for a duration of 1 min. The procedures⁹ governing such tests indicate that the breakdown voltage, for a given gap in air, decreases with decreasing pressure and increasing temperature. Figure 5 indicates the breakdown voltage as a function of the gap spacing for 6.25-cm-diameter spheres located in air at 760-mm pressure and a temperature of 25°C. The following correction factor is used to take the relative air density into account:

$$\text{Relative air density correction factor} = \frac{0.392P}{273 t},$$

where P is barometric pressure in mm Hg and t is temperature in degrees centigrade. This relationship indicates that the breakdown voltage for a given gap in air would be twice as large if either the pressure were doubled or the absolute temperature were halved. This correction factor is intended to be used over a relatively small range of conditions since tests are performed at atmospheric conditions where changes are minor. Breakdown voltages obtained from the pressure-distance relationship³ are in agreement with those plotted in Fig. 5 from the AIEE standard. A root-mean-square voltage to peak voltage ratio of 0.707 is applied to convert d-c voltage values to corresponding

Fig. 5. Effect of Gap Spacing of Spherical Electrodes on Breakdown Voltage in Air

a-c values.

Some investigations of breakdown voltages for helium, air, and nitrogen at high temperatures were made at ORNL¹⁰ by Abbatiello and Gnadt. Results are reported which indicate the general magnitude of the reduction in helium breakdown voltage for the conditions of elevated temperature and pressure corresponding to those proposed for a particular experimental apparatus. Within the limits of accuracy and control for which the experiment was designed, the results are generally in agreement with those predicted from Fig. 2 as corrected for temperature and pressure. The breakdown voltage for a 0.063-in. gap at 8 psig was found to be 520-v ac at 80°F and 380-v ac at 1000°F. The results which would be expected for a 0.063-in. gap similar to that of the ORNL arrangement were calculated by applying the pressure-distance relationship and assuming a uniform field, as follows:

$$\text{Gap Spacing: } 0.063 \times 2.54 = 0.16 \text{ cm}$$

$$\text{Pressure: } \frac{(14.7 + 8)}{14.7} \times 760 = 1173 \text{ mm Hg}$$

$$\text{pd: } 1173 \times 0.16 = 188 \text{ mm Hg} \times \text{cm}$$

$$\text{Breakdown voltage at 80°F (from curve}^3\text{): } 1100\text{-v (crest)}$$

$$(60 \text{ cps equivalent}): 1100 \times 0.707 = 778\text{-v ac}$$

$$\text{Temperature: } 80^\circ\text{F} = 27^\circ\text{C}$$

$$1000^\circ\text{F} = 538^\circ\text{C}$$

$$\text{Absolute temperature ratio: } \frac{273 + 27}{273 + 538} = 0.37$$

$$\text{Breakdown voltage at 1000°F: } 778 \times 0.37 = 288\text{-v ac}$$

As shown above, for a 0.063-in. gap in helium at 80°F, the pd relationship indicates a breakdown voltage of 778 v, which is to be compared with the experimental value of 520 v. The calculated breakdown voltage at 1000°F of 288 v is to be compared with the experimental breakdown voltage of 380 v. An important difference in the two cases is in the slopes of the temperature-voltage curves. The experimental data do not show that the breakdown voltage decreases as fast as would be expected. Abbatiello and Gnadt also determined the temperature-voltage curve for a constant current leakage for two parallel wires and found the curve to be very steep. The differences in the slopes of

the breakdown curve and the current curve may be caused partially by the fact that it is very difficult to distinguish between corona and sparkover in many cases.

Based on the information presented in this memorandum, the following are assumptions which might be used in estimating design information:

1. Breakdown voltage will increase with increasing spacing and increasing pressures to 5 to 10 atmospheres, as shown by pd curves.³ Very little increase in breakdown voltage results from higher pressures.
2. Breakdown voltage will vary inversely with the absolute temperature. Experimental verification of this effect is not available.
3. In addition to the allowance for factory test voltages, a factor of safety of 25% should be applied to the voltage.

Table II lists gap spacings that would be required for various gas temperatures using the above assumptions. The results are plotted in Fig. 6. This information is presented for a pressure of one atmosphere. Many systems must be designed to withstand abnormal operation at pressures near atmospheric, although normal operation may be at higher pressures. At pressures below atmospheric the required spacing becomes even larger.

SUMMARY AND CONCLUSIONS

Adequate theoretical information and experimental data are available with regard to the insulating characteristics of specific electrode configurations located in air, hydrogen, and helium at standard atmospheric temperatures and pressures. Only a limited amount of information was found, however, for helium, hydrogen, and air at pressures above atmospheric, and insufficient information is available with respect to the effects of temperature on the breakdown voltages for gases.

A rough evaluation indicates that the breakdown of helium occurs at a voltage approximately 1/10 the breakdown voltage of air and approximately 1/4 the breakdown voltage of hydrogen. Increasing the temperature of helium from 80°F to 1000°F is estimated to reduce the breakdown voltage by at least a factor of 2.7 as a result of the reduced gas density. It appears to be quite likely that the breakdown voltage would be reduced even more because of the behavior of the

TABLE II
Gap Spacing For 480-V A-C System

Temperature		Temperature Ratio ^b	Equivalent Voltage		Helium		Hydrogen		Air	
°F	°K ^a		System ^c	Design ^d	pd ^e (mm Hg x cm)	Gap ^f (cm)	pd ^e (mm Hg x cm)	Gap ^f (cm)	pd ^e (mm Hg x cm)	Gap ^f (cm)
77	298	1.000	480	3464	850	1.12	115	0.15	50	.066
200	366	1.228	589	3850	940	1.23	130	0.17	57	.075
300	422	1.416	680	4171	1040 ^g	1.37	150	0.20	65	.086
400	477	1.600	768	4482	1100 ^g	1.45	165	0.22	72	.095
600	589	1.976	948	5119	1350 ^g	1.78	200	0.26	84	.111
800	700	2.349	1128	5755	1480 ^g	1.95	220	0.29	95	.125
1000	811	2.720	1306	6384	1800 ^g	2.37	260	0.34	115	.151

^aAbsolute temperature $(5/9[F - 32] + 273)$.

^bRatio of higher absolute temperature point to absolute temperature at 77°F.

^cEquivalent system voltage at higher temperature point (voltage at 77°F x ratio of absolute temperature i.e., 480 v applied to a given gap at 1000°F is equivalent to 1306 v applied to the same gap at 77°F.)

^dEquivalent design crest voltage $([System\ voltage \times 2 + 1000] \times 1.414 \times 1.25)$.

^ePressure-distance relationship determined from Linde Rare Gases, p. 13, reference 3.

^fGap spacing (pd/760).

^gEstimated by extending curve.

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Fig. 6. Gap Spacing for 480-v Alternating-Current System as a Function of Temperature

gas molecules and the electrodes at the higher temperatures. The breakdown voltage for an air gap at 80°F would be expected to be approximately 27 times greater than the breakdown voltage for the same gap in helium at 1000°F. The uniformity of the field, which is a function of the configuration of the electrodes, may also affect the gas breakdown voltage by a factor of 2 or 3. An increase in pressure will result in an increase in breakdown voltage, within limits, depending upon the gas and the uniformity of the electric field. Contaminants in a gas have been found to greatly affect the breakdown voltage. A classic example of this is the addition of 1/10 of 1% of argon to neon to obtain breakdown at 1/4 the breakdown voltage of pure neon and at 1/10 the breakdown voltage of pure argon.

As a result of the many variables and the relatively large effect of these variables, it is necessary to obtain specific experimental data when accurate breakdown voltage values are required. The general effects of increased temperature should be verified by experimental data. The combined effects of increased temperature and increased pressure should be investigated. The importance of obtaining additional information for helium is accentuated by its relatively poor insulating characteristic.

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