NASA TECHNICAL MEMORANDUM

NASA TM X-2474

CORONA INCEPTION VOLTAGE IN STATORETTES WITH VARIOUS GAS-SOLID DIELECTRIC SYSTEMS

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1. Report No. NASA TM X-2474	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle CORONA INCEPTION VOLTAGE IN STATORETTES WITH VARIOUS GAS-SOLID DIELECTRIC SYSTEMS		5. Report Date January 1972
		6. Performing Organization Code
7. Author(s) Gary Bollenbacher and Erwin E. Kempke, Jr.		8. Performing Organization Report No. E-6582
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 112-27
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Corona inception voltage was calculated and measured for three statorettes in several gases and gas mixtures at pressures from 50.8 to 1270 torr. In helium the corona inception voltage was lowest, and in air it was highest. In argon and mixtures of helium and xenon the corona inception voltage was between that of air and helium. Correlation between experimental and calculated data was good.

17. Key Words (Suggested by Author(s)) Alternator Helium-xenon Corona discharge Partial discharge Electric insulation	18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price* $3.00

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SUMMARY

Corona inception voltage was calculated and measured for three insulation systems in air, argon, and helium and mixtures of helium and xenon. The pressure was varied from 50.8 to 1270 torr. Helium exhibited the lowest corona inception voltage and air the highest, while in argon and the mixtures of helium and xenon the voltages were intermediate. Lowering the molecular weight of the helium-xenon mixture decreases the corona inception voltage. Good correlation between the experimental and calculated data was obtained.

INTRODUCTION

In the reactor Brayton-cycle space power system (ref. 1) being developed by the NASA, the alternator windings will operate in a helium-xenon gas mixture which may be below atmospheric pressure (ref. 2). In such an environment, corona discharges may occur even at moderate voltage levels. Corona discharges deteriorate the insulation in the vicinity of the discharge site and may jeopardize the 10-year system design life.

Corona discharge (also called partial discharge) as used in this report is the momentary breakdown of only one of several insulators in series (refs. 3 to 10). The remaining insulation continues to function normally and prevents a complete voltage breakdown. Each corona discharge generates electromagnetic noise and dissipates small amounts of energy. Of most concern, however, is the accompanying erosion of insulation adjacent to the discharge site. If this erosion continues for a sufficiently long time, complete insulation failure may result. To achieve long insulation life, it is best to avoid corona discharges entirely.

An experimental program was conducted by using statorettes for which corona inception was determined under conditions likely to be encountered in the alternator stator of the reactor Brayton cycle space power system. Three insulation systems were evaluated in several gases over a pressure range from 50.8 to 1270 torr (2 to 50 in. Hg). Corona inception was also measured for an existing alternator stator (refs. 11 and 12) in air at atmospheric pressure. The results, including a correlation with calculated data, are presented in this report.

CORONA DESCRIPTION

Corona discharges discussed in this report are those which occur in insulation systems consisting of more than one insulator in series. Of particular interest is the case where at least one of the insulators is a gas. The presence of the gas may be intentional or unavoidable, or it may be the result of a manufacturing defect. In any case, if the voltage stress in the gas exceeds its breakdown strength, a momentary gas discharge will occur. If the solid insulator is designed to withstand the entire electrode voltage, only the gas will break down and the solid dielectric will prevent a complete voltage breakdown.

To demonstrate that the gas and not the solid dielectric will break down first, consider figure 1. The figure shows two electrodes separated by a distance $t_0 = t_1 + t_2$. A solid dielectric of thickness t_2 and dielectric constant $\epsilon_2 > 1$ is placed between the
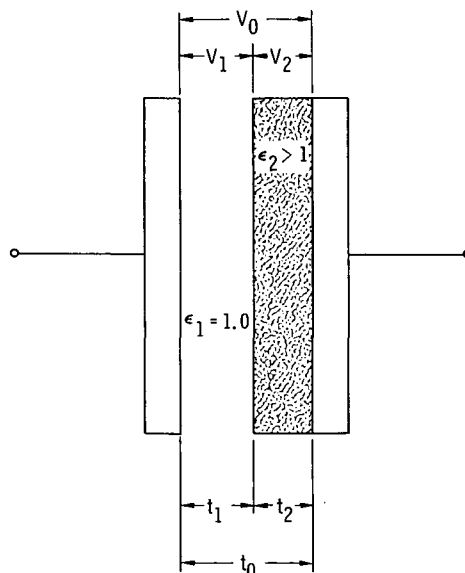

Figure 1. - Electrodes separated by gas-solid dielectric.

electrodes. The remaining space of thickness t_1 is occupied by a gas having a dielectric constant of unity ($\epsilon_1 = 1.0$). If E_1 is the electric field intensity within the gas, V_1 is the voltage across the gas, and E_2 and V_2 are the corresponding quantities for the solid dielectric, then, for a uniform field

$$E_1 = \epsilon_2 E_2$$

$$\frac{V_1}{t_1} = \epsilon_2 \frac{V_2}{t_2} \tag{1}$$

Voltage stress in gas = ϵ_2 (Voltage stress in solid)

While the voltage stress in the gas is several times the stress in the solid, the dielectric strength of a gas is normally less than that of a solid. Thus, it is clear that the gas will usually break down first and leave the solid insulator to support the entire electrode voltage.

The gas breakdown creates ions that move under the influence of the applied field until they impinge on the insulator surface, which prevents further movement. The ions trapped by the insulator form a surface charge which creates an electric field in opposition to the applied field. This reduces the voltage stress across the gas, and the discharge is extinguished. If the applied voltage is constant, a new discharge will occur when the surface charge on the insulator has leaked off. With alternating voltage, additional discharges may occur in the same half cycle if the voltage increases sufficiently to offset the effect of the surface charge. On the next half cycle, with the polarity reversed, the trapped charge aids the applied field to produce breakdown.

During each discharge, energy is dissipated and electromagnetic noise is generated. However, where long insulation life is a major concern, the most serious consequence of corona discharge is the deterioration of the adjacent insulation. If allowed to continue, insulation failure may be the result.

Several mechanisms play a role in the insulation deterioration (refs. 4, 8, and 9). Most important are the localized heating due to the energy dissipated in the discharge and the erosion of the insulation caused by the impacting ions. Which of these or other mechanisms predominates depends on the type of insulation system used.

Alternating voltage produces more insulation damage than direct voltage because it causes more corona discharges in a given time interval. The frequency of the alternating voltage is also important (refs. 8 and 10). Since the number of corona pulses per cycle is nearly constant, the insulation deterioration is approximately proportional to frequency. Because of the number of variables involved, the rate of deterioration is generally unpredictable.

If corona discharges are to be avoided, it is desirable to predict the minimum electrode voltage at which corona is possible. This voltage is variously called the corona inception voltage (CIV), the corona starting voltage, or the corona on-set voltage.

For the configuration shown in figure 1 the electrode voltage V_0 is

$$V_0 = V_1 + V_2 \tag{2}$$

Substituting for V_2 from equation (1) results in

$$V_0 = V_1 + \frac{t_2}{\epsilon_2 t_1} V_1$$

$$= \frac{V_1}{t_1} \left(t_1 + \frac{t_2}{\epsilon_2} \right)$$

$$= \frac{V_1}{t_1} (t_1 + t_{eff}) \tag{3}$$

where $t_{eff} = t_2/\epsilon_2$ is the effective insulation thickness for the purpose of calculating the corona inception voltage.

If the breakdown voltage V_g of the gaseous insulator is substituted for V_1, the resultant value of V_0 will be the corona inception voltage:

$$CIV = \frac{V_g}{t_1} (t_1 + t_{eff}) \tag{4}$$

V_g depends on the type of gas, the gas pressure, and t_1. Values of V_g for a uniform field may be obtained from Paschen curves (refs. 13 and 14). Paschen curves for air, hydrogen, argon, neon, and helium are shown in figure 2.

If more than one solid insulator is in series with the gas, equation (4) is still valid, as shown in reference 6. Only the definition of t_{eff} must be modified to include the effect of additional insulators. Thus, for n solid insulators

$$t_{eff} = \frac{t_2}{\epsilon_2} + \frac{t_3}{\epsilon_3} + \cdots + \frac{t_{n+1}}{\epsilon_{n+1}} \tag{5}$$

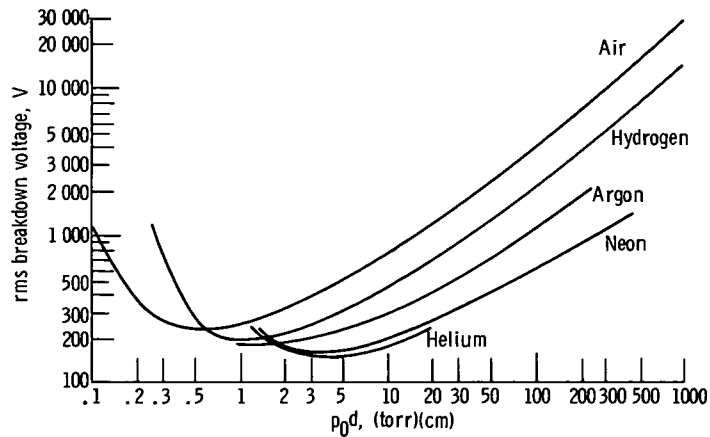The case of more than one gas gap is treated in reference 6.

Figure 2. - Typical Paschen curves for different gases between parallel plate electrodes. Gas pressure in torr corrected to 0° C, p_0; electrode spacing in centimeters, d. (From ref. 11.)

The calculation of the CIV for a statorette and a discussion of assumptions are presented in the section CALCULATION OF CORONA INCEPTION VOLTAGE FOR TEST SPECIMENS.

DESCRIPTION OF TEST SPECIMENS

Three statorettes were prepared to simulate an alternator or motor stator. Each statorette consists of a low-carbon steel block with one slot machined into it. (One statorette had three slots, but only one slot was used.) Conductors and insulators were inserted into the slot to approximate a two-layer form-wound armature winding. The three statorettes can be briefly characterized by describing the insulation as follows:

(1) Statorette 1 - An inorganic (high-temperature) insulation system consisting of alumina (Al_2O_3) slot liners and separators and Anadur insulated nickel magnet wire. (Anadur insulation consists of fiber glass, fusible glass frit, and refractory oxide powders.)

(2) Statorette 2 - A nonimpregnated organic insulation system using polyimide slot liners and polyimide insulated magnet wire.

(3) Statorette 3 - A hybrid insulation system using polyimide and glass-matt slot liners and separators and polyimide insulated copper magnet wire. This specimen was vacuum impregnated by using a solventless silicon impregnant.

Cross-sectional diagrams of the three statorettes are shown in figure 3. Table I lists the pertinent dimensions and parameters. A photograph of specimen 3 is shown in figure 4(a), and figure 4(b) shows a closeup of a cross section of specimen 3 obtained after completion of the tests.

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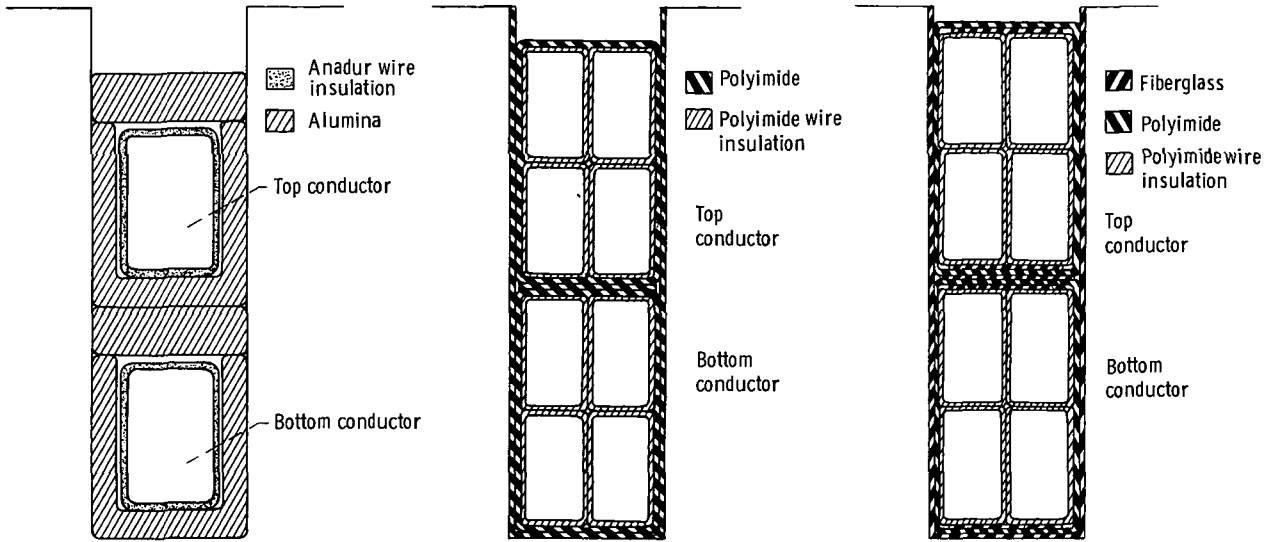
(a) Statorette 1; inorganic insulation, not impregnated; effective insulation thickness, 0.0827 millimeter.

(b) Statorette 2; organic insulation, not impregnated; effective insulation thickness, 0.0724 millimeter.

(c) Statorette 3; hybrid insulation, impregnated with solventless silicone resin; effective insulation thickness, 0.0916 millimeter.

Figure 3. - Cross-sectional diagrams of three statorettes.

TABLE I. - SUMMARY OF PERTINENT PARAMETERS OF THREE STATORETTES

Statorette	Statorette description	Slot size, cm	Insulation system				Effective insulation thickness, $t_{eff} = \dfrac{t_2}{\epsilon_2} + \dfrac{t_3}{\epsilon_3} + \cdots,$ mm
			Component	Material	Thickness, mm	Dielectric constant	
1	Inorganic (high temperature)	0.406 by 1.40	Slot liner U-shaped	Alumina	0.48 to 0.61 (side), 0.736 (bottom)	9.4	$\dfrac{0.48}{9.4} + \dfrac{0.177}{5.6} = 0.0827$
			Separator	Alumina	1.24	9.4	
			Wire insulation	Anadur	.177	5.6	
			Impregnant	None	----------	--------	
2	Organic	0.432 by 1.45	Slot liner	Polyimide	0.076	2.7 to 3.3	$\dfrac{(2)(0.076)}{3} + \dfrac{0.076}{3.5} = 0.0724$
			Separator	Polyimide	.076	2.7 to 3.3	
			Wire insulation	Polyimide	.076	3.5	
			Impregnant	None	----------	--------	
3	Hybrid	0.432 by 1.45	Slot liner	Glass	0.127	6.6	$\dfrac{0.127}{6.6} + \dfrac{0.152}{3.0} + \dfrac{0.076}{3.5} = 0.0916$
			Separator	Glass	.127	6.6	
			Wire insulation	Polyimide	.076	3.5	
			Coil insulation	Polyimide	.152	2.7 to 3.3	
			Impregnant	Solventless silicon	----------	--------	

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(a) As tested.

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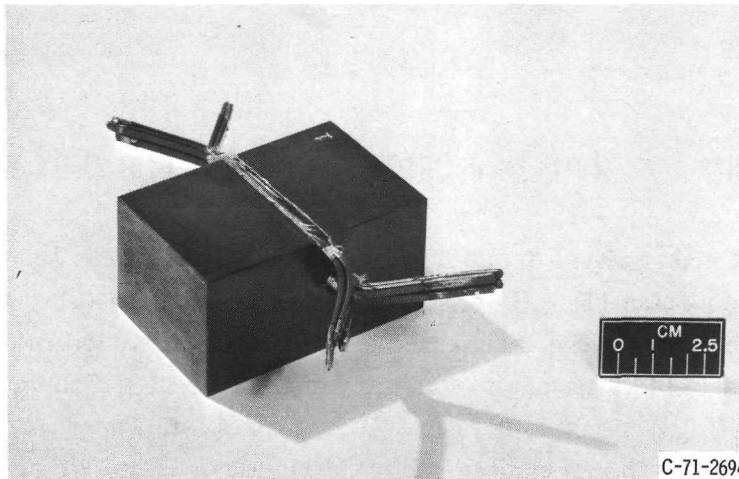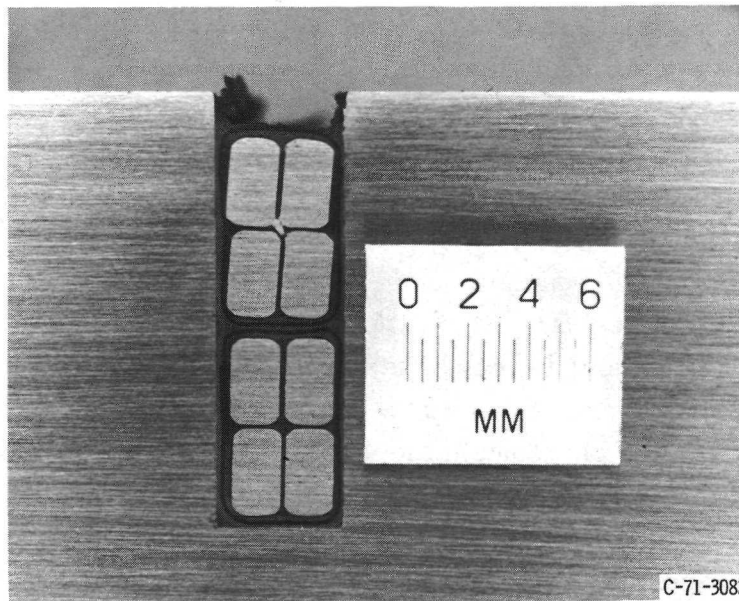
(b) Cross section obtained after completion of test.

Figure 4. – Statorette 3.

In addition to the statorettes, an existing isotope Brayton cycle alternator stator (refs. 11 and 12) was tested. At the time of the test the alternator had been operated for several hundred hours. The minimum insulation thickness between conductor and stator iron consists of a 0.254-millimeter-thick three-ply polyamide/imide slot liner (dielectric constant of 3.15) and a 0.0254-millimeter-thick film of polyimide magnet wire insulation (dielectric constant of 3.5). This results in an effective insulation thickness of

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$$t_{eff} = \frac{0.254}{3.15} + \frac{0.0254}{3.5}$$

$$= 0.088 \text{ mm}$$

CALCULATION OF CORONA INCEPTION VOLTAGE FOR TEST SPECIMENS

The corona inception voltage from line to ground for the three test specimens is calculated by using equation (4) with t_{eff} defined as in equation (5).

For the three statorettes the length of the gas gap t_1, as used in equation (4), is generally not known. The value of t_1 can vary within the slot if the conductor is not perfectly parallel with the sides of the slot. For a complete stator, t_1 will also vary from slot to slot. Where the gaseous void is the result of an imperfect impregnation, t_1 is again unknown. When the CIV is calculated for the statorettes, it is assumed that t_1 takes on all possible values from 0 to some maximum. The CIV is then calculated for all probable values of t_1, and the minimum CIV will be the CIV for the statorette.

To obtain the CIV between the conductor and ground the minimum value of t_{eff} between conductor and ground must be used. For the three statorettes shown in figure 3, the minimum t_{eff} (conductor to ground) is at the sides of the slot. Values for t_{eff} are given in table I.

The following additional assumptions are made:

(1) Although the electric field within a stator slot is not uniform, Paschen curves for a uniform field may be used to obtain the gas breakdown voltage.

(2) Only one gaseous gap of thickness t_1 is in series with the solid dielectric.

(3) The voids within the slot contain the same gas as the gas in which the statorette is immersed.

The CIV for specimen 1 in helium at a pressure of 1270 torr (50 in. Hg) is now calculated. Assume a value of $t_1 = 0.25$ millimeter. Then the product of pressure and t_1 is 31.7 torr-centimeters. The corresponding rms value of V_g from figure 2 is 340 volts. Substituting these values into equation (4) gives

$$\text{CIV} = \frac{V_g}{t_1} (t_1 + t_{eff})$$

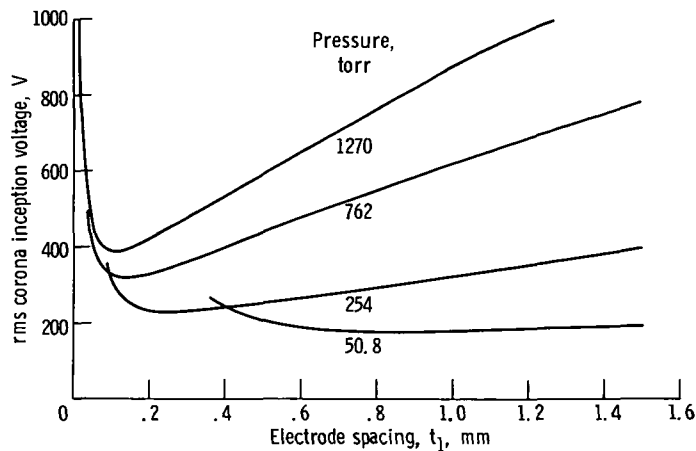$$= \frac{340}{0.25} (0.25 + 0.0827)$$

$$= 448 \text{ V}$$

Figure 5. – Calculated values of corona inception voltage as function of electrode spacing. Statorette 1 in helium; effective insulation thickness, 0.0827 millimeter.

These calculations are repeated for other values of t_1. The results are shown in figure 5 together with the results of similar calculations for pressures of 762, 254, and 50.8 torr.

The minimum voltage of each curve in figure 5 is the actual CIV. These values are plotted against pressure in figure 6(a). The figure also shows similarly obtained curves for air and argon. Figures 6(b) and (c) show the results of calculations for statorette 2 and statorette 3. The effects of the impregnant in statorette 3 were ignored in the calculations.

The calculation of the CIV for the alternator stator was carried out exactly as described in this section but only for air at atmospheric pressure. Again neglecting the effect of impregnation and using the value of t_{eff} = 0.088 millimeter give an rms value of CIV = 1370 volts.

The calculations clearly predict that the CIV can be raised by increasing t_{eff}. This can be accomplished by increasing the insulation thickness or by using insulating materials with lower dielectric constants. However, a large increase in t_{eff} is required to substantially improve the CIV. For example, comparison of figures 6(b) and (c) shows that, although t_{eff} was increased 26 percent, the CIV for air at atmospheric pressure increased only 15 percent. The increase for argon and helium at a pressure of 1270 torr was only 11 and 9.4 percent, respectively.
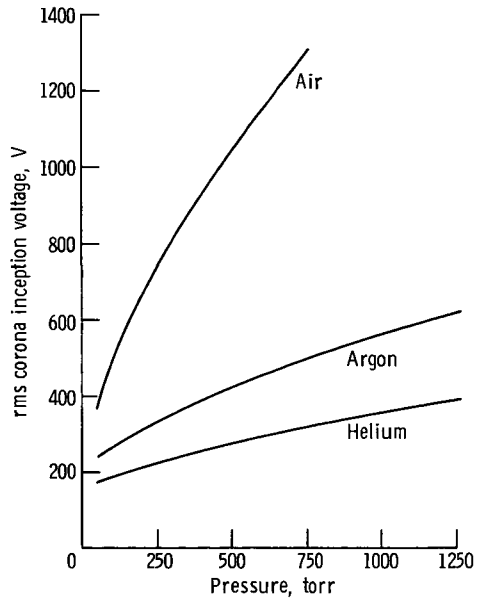
(a) Statorette 1; effective insulation thickness, 0.0827 millimeter.
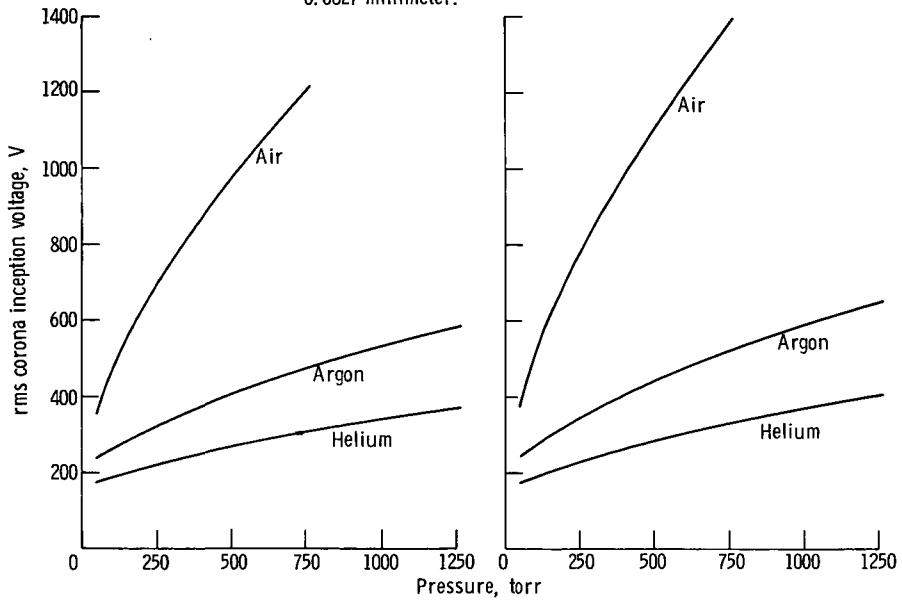
(b) Statorette 2; effective insulation thickness, 0.0724 millimeter.

(c) Statorette 3; effective insulation thickness, 0.0916 millimeter.

Figure 6. - Calculated values of corona inception voltage for three statorettes in air, argon, and helium.

APPARATUS AND PROCEDURE

The corona inception voltage of the three statorettes was measured in several gases over a pressure range from 50.8 to 1270 torr (2 to 50 in. Hg). This includes pressures likely to be encountered in the reactor Brayton cycle alternator cavity. The test gases selected were air, argon, and helium and mixtures of helium (He) and xenon (Xe) having molecular weights of 84, 40, and 20. These gases were chosen for the following reasons:

(1) An He-Xe mixture is the reactor-Brayton-cycle power system working fluid. However, Paschen curves for He-Xe mixtures are not available to permit calculations.

(2) Air and argon are used for ground testing.

(3) Helium was included, along with air and argon, to permit comparison with calculated data.

To measure the CIV, a statorette was placed in a vacuum tank which was modified to permit pressurizing to 1270 torr. The top and bottom conductors are brought out through two high-voltage feed throughs, and the steel block is grounded to the vacuum tank (fig. 7). The tank is closed, evacuated, and then filled with the desired test gas to a pressure of 1270 torr. After the tests at that pressure are completed, the tank is pumped down in steps to pressures of 1016, 762, 508, 254, and 50.8 torr. The same set of corona measurements is made at each pressure setting.

A mixture of He-Xe with a molecular weight of 84 was available for use in the corona tests. Mixtures of He-Xe of lower molecular weight were obtained as follows.
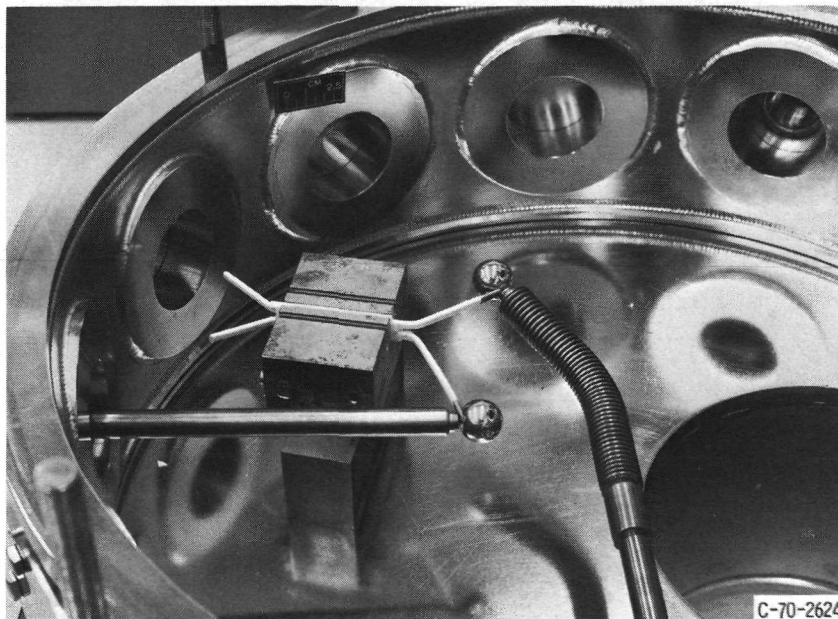

Figure 7. - Statorette 1 installed in vacuum tank. Inorganic insulation.

The tank was evacuated as before and then filled with $(He\text{-}Xe)_{84}$ to a predetermined pressure (<1270 torr). Pure helium was then added to bring the pressure up to 1270 torr. Samples were taken and tested to verify that the correct molecular weight had been obtained.

Corona measurements were made with a commercial corona tester. The test set included a manually adjustable 60-hertz high-voltage supply and corona detection circuitry. The smallest corona discharge detectable on the oscilloscope of the corona tester is 0.1 picocoulomb.

The complete test setup, but without the test specimen, was tested in air at atmospheric pressure and found to be corona free to an rms voltage of at least 6000 volts.

At each pressure and gas combination three measurements of CIV were made. As shown in the following table, the three measurements differed in the manner in which the corona tester was connected to the test specimen:

| Measurement	Top conductor	Bottom conductor
1	High voltage	Grounded
2	Floating	High voltage
3	High voltage	Floating

The block was grounded for all measurements.

The alternator stator was too large to place inside the vacuum tank. The CIV was therefore measured with the alternator placed inside a shielded test enclosure which was an integral part of the corona tester. This test enclosure could not be pressurized, and thus the test was limited to ambient air conditions. Measurements of the CIV were made between the terminal of each phase and ground and between neutral and ground. All four of these measurements would be expected to give the same result within experimental error.

To measure the CIV the test voltage was manually increased very slowly from zero volts until characteristic corona pulses were observed on the oscilloscope display of the corona test set. The voltage at which this occurred is the CIV. Throughout the test, the corona tester was adjusted to maximum sensitivity.

TEST RESULTS AND DISCUSSION

The CIV test results for the three statorettes are shown in figures 8 and 9. The curves for air, argon, and helium (fig. 8) show the same general trends as the theoret-
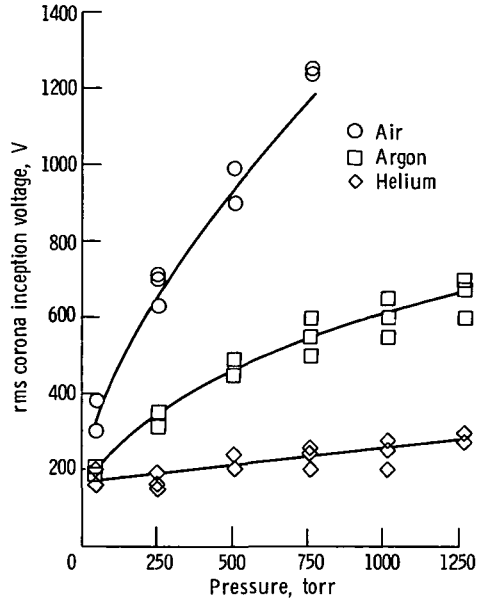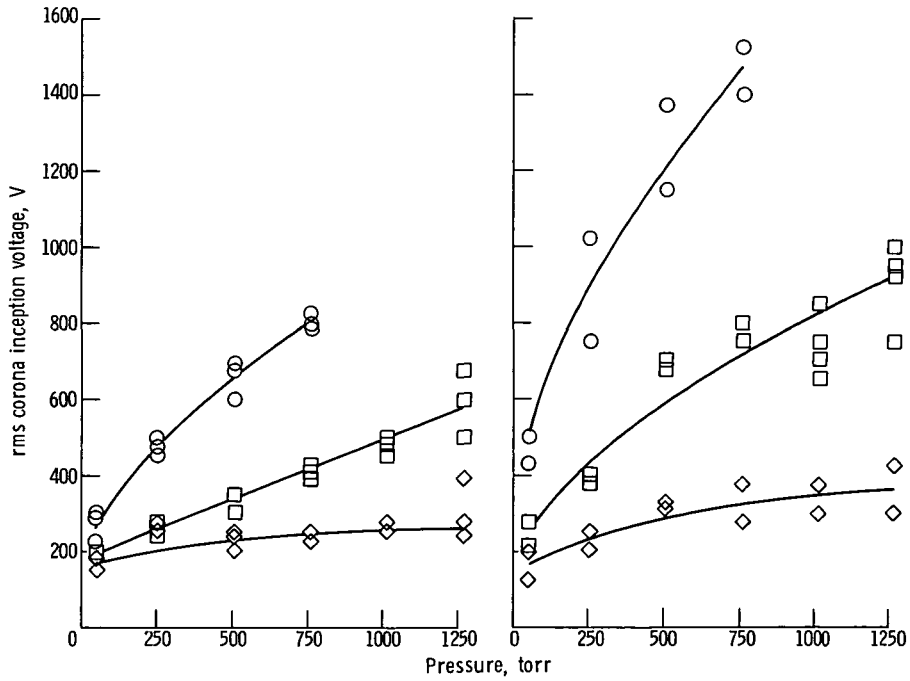
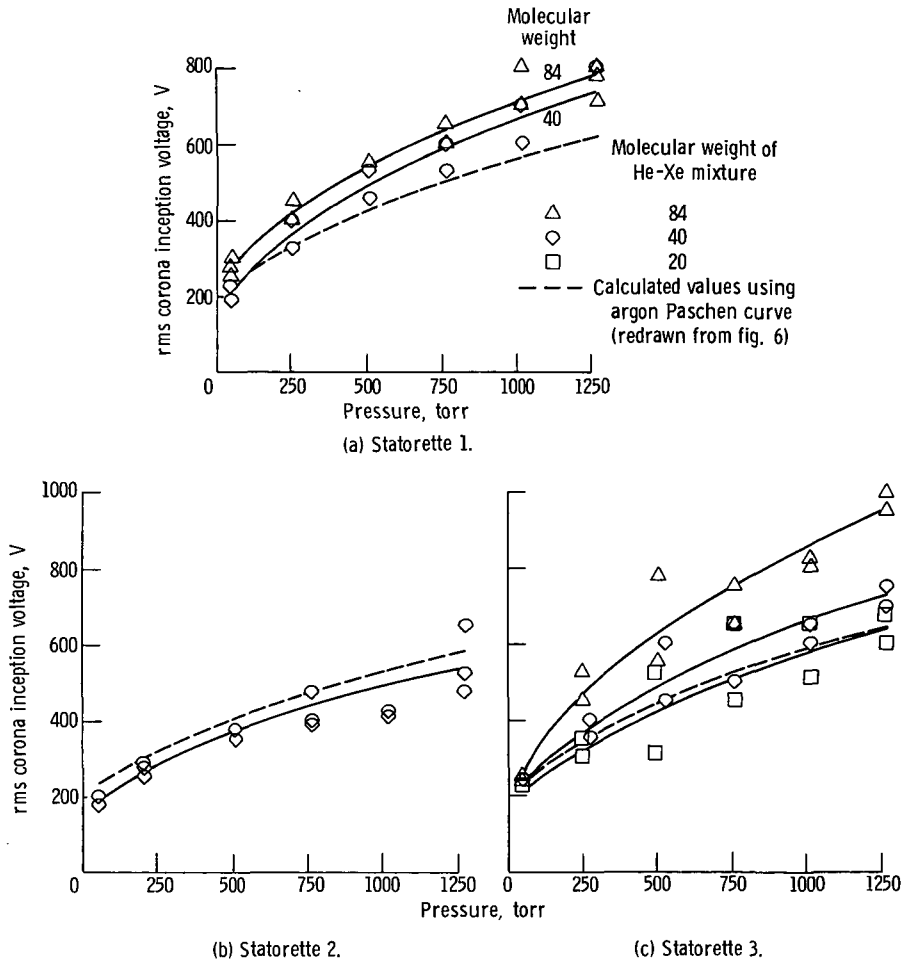Figure 8. – Measured values of corona inception voltage for three statorettes in air, argon, and helium.

Figure 9. - Measured values of corona inception voltage for three statorettes in He-Xe mixtures.

ical curves in figure 6, namely,

(1) The CIV increases with pressure.

(2) Of the three gases shown in figures 6 and 8, air exhibits the highest corona inception voltage, helium the lowest voltage, and argon intermediate voltage.

(3) The effect of pressure is most pronounced for air and least for helium.

Comparison of figures 8 and 9 shows that the CIV for the He-Xe is closer to that of argon than either air or helium. This suggests that, since Paschen curves for He-Xe are not available for calculations, a fair approximation can be obtained by using the Paschen curve for argon. This is more clearly demonstrated by the superposition of the calculated argon curves in figure 6 on the He-Xe curves in figure 9. Examination of figure 9 justifies the use of argon Paschen curves to calculate the CIV for He-Xe mixtures with molecular weights between 20 and 40. For He-Xe mixtures of higher molecular weight the argon approximation is less accurate but is nevertheless a useful guide in some applications.
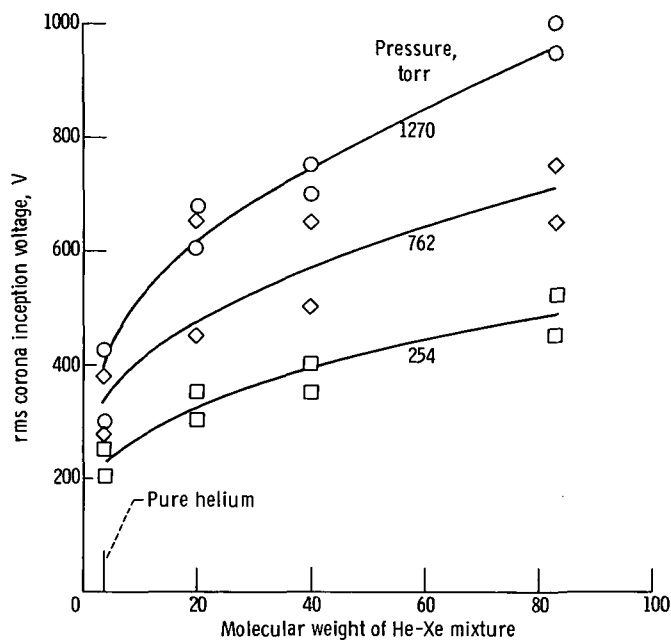
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Figure 10. – Measured corona inception voltage for statorette 3 as function of molecular weight of He-Xe mixture.

The effect of the molecular weight of the He-Xe mixture on the CIV is illustrated in figure 10. The data in figure 10 have been replotted from figures 8(c) and 9(c). It is evident that a decrease in the molecular weight of the mixture lowers the CIV until at a molecular weight of 4 the CIV of helium is reached.

Figure 11 compares selected calculated curves of figure 6 with the corresponding experimental curves in figure 8. The comparison is representative of all the curves and shows that good general agreement exists between calculated and measured results.

Except for two cases, the difference is always less than 130 volts with the largest difference generally occurring at the higher pressures. Expressed as percentages of measured values, the difference between measured and computed results ranges from 0 to 45 percent. The two exceptional cases are statorette 2 in air and statorette 3 in argon. No explanation for the large discrepancy in these two cases has been found.

The results of measuring the CIV of the existing alternator stator are as follows. The four measurements made ranged from 1100 to 1220 volts for an average of 1145 volts. This compares with the previously calculated value of 1370 volts (see p. 9) for a difference of 225 volts or 18 percent.
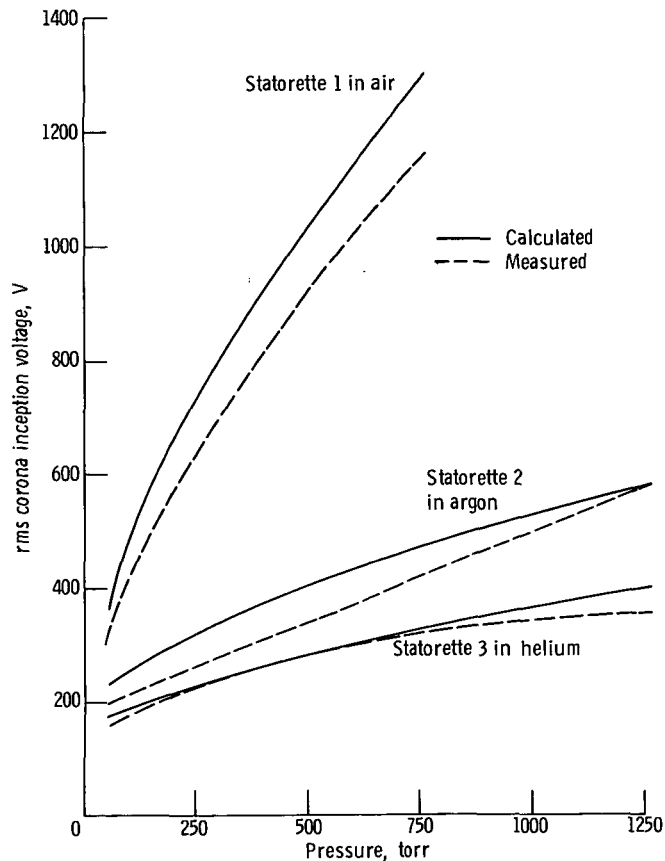
Figure 11. – Representative comparison of calculated and measured values of corona inception voltage.

CONCLUSIONS

Corona inception voltages obtained from statorette tests with various gas-solid dielectric systems and comparison with calculated data support the following conclusions:

1. Of the gases tested, air gives the highest corona inception voltage and helium the lowest. Argon and mixtures of helium and xenon are intermediate.

2. Increasing the gas pressure increases the corona inception voltage.

3. Corona inception voltage for an armature winding can be calculated by using Paschen curves for a uniform field. The results of the calculations give a good approximation to the observed values of corona inception voltage.

4. To calculate the corona inception voltage for mixtures of helium and xenon, for which Paschen curves are not available, Paschen curves for argon can be used. The resultant approximation is most accurate for helium-xenon mixtures of molecular weight between 20 and 40.

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In addition, theory indicates that to increase the corona inception voltage the following possibilities exist:

5. Use a gas of higher breakdown strength.

6. Increase the effective insulation thickness

$$t_{eff} = \frac{t_2}{\epsilon_2} + \frac{t_3}{\epsilon_3} + \cdots$$

by either increasing the actual insulation thicknesses t_2, t_3, etc. or by decreasing the dielectric constants ϵ_2, ϵ_3, etc. A large increase in t_{eff} is needed to increase the corona inception voltage substantially.

7. Eliminate voids by filling them with a dielectric material.

8. Eliminate the voltage stress across a gaseous gap by providing a conductive path across the gap.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, October 19, 1971,
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