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High Voltage Research (Breakdown Strengths of Gaseous and Liquid Insulators)

Fourth Quarterly Report (Period Ending March 31, 1977)

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R. Y. Pai
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OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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HIGH VOLTAGE RESEARCH (BREAKDOWN STRENGTHS OF GASEOUS AND LIQUID INSULATORS)

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(Period Ending March 31, 1977)

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ABSTRACT

The DC breakdown strengths of C_7F_{14} (perfluoromethylcyclohexane), C_7F_{14} (perfluoroheptene-1), and C_4F_6 (hexafluorobutadiene) have been found to be superior to SF_6 by a factor of 2.1, 1.2, and 1.4, respectively. Electron attachment rates and cross sections have been measured for C_6F_{10} (perfluorocyclohexene) and C_6F_{12} (perfluorodimethylcyclobutane) and were found to be very large to energies of $\sim$ 1 eV. They correlate nicely with the superior breakdown strengths of these systems which are more than twice that of SF_6. The DC breakdown voltage, V_s, for c-C_4F_8, iso-C_4F_8, and SF_6 were extended to higher voltages (to 300 kV). For the former two compounds, V_s obeys Paschen's law, but it deviates from it for SF_6.

Mixtures of our best dielectric fluorocarbon gases such as C_4F_6 and c-C_4F_8 with N_2 do not show a "saturation" effect as does SF_6 and exhibit a synergistic behavior. Very importantly, the direct effect of the inelastic scattering properties of the gas via low-lying ($\sim$ 1 to 4 eV) negative ion resonances on its breakdown strength has been demonstrated.

Construction of a new high pressure, high voltage, variable temperature test chamber continued. Fabrication of cylindrical electrodes of variable degree of surface roughness, material composition and radius for applied testing has been completed. The results of the first phase of our diverter studies are reported.

I. INTRODUCTION

This is the fourth quarterly report of a project which was begun at Oak Ridge National Laboratory (ORNL) to develop improved insulation for high voltage power transmission. The previous quarterly reports and the ends of their corresponding periods are ORNL/TM-5604,[1] to June 30, 1976; ORNL/TM-5713,[2] to September 30, 1976; and ORNL/TM-5806,[3] to December 31, 1976.

Knowledge of fundamental electron-molecule interactions is being applied to the understanding and design of improved gaseous insulators. The free electrons in a gas under an applied electric field possess a distribution of energies extending over a considerable range, and their many interactions with molecules which actually determine the breakdown characteristics are all energy-dependent,[4] so that the events of importance are quite complex.

The design of improved gaseous dielectrics is being pursued by controlling both the number and the energies of free electrons. The number is reduced by attaching the electrons to molecules found to attach electrons efficiently over a wide energy range. The free-electron energies are controlled by other molecules ("electron thermalizers"), with two benefits: electrons are not only kept from attaining sufficient energy for ionization, but they are forced into a lower energy range where attachment is more efficient than at higher energies. Thus, improved gaseous dielectrics are designed as multicomponent systems on the basis of detailed, quantitative, fundamental knowledge.

A good part of this program therefore consists of an experimental and theoretical study of fundamental electron-molecule interactions and careful breakdown measurements in DC uniform fields to correlate breakdown strength of gases and gas mixtures with fundamental processes. It also includes studies of the effects of practical conditions so that engineering design instructions can be supplied with the new insulators. At present considerable experience is being accumulated in the study of fundamental processes and DC uniform field breakdown, and hence the practical studies are being prepared to merge with those already in progress.

Our tests are being extended to higher voltages and pressures. New equipment is under construction to extend basic breakdown measurements to higher and lower temperatures from ambient, and to cylindrical electrode geometries of variable degree of roughness and material composition. Efforts are also underway for extending present DC studies to impulse testing.

II. APPARATUS

Construction is underway on the new high pressure, high voltage, variable temperature test chamber. While the chamber is in the shop, the design of the peripheral heating and cooling facilities is being completed. The larger the maximum Pd (pressure x gap) attainable in a breakdown test apparatus, the greater the range of conditions for which a gaseous insulator can be tested. Our new chamber can provide Pd values up to 150 atm-mm (P_{max} = 10 atm; d_{max} = 15 mm), a factor of approximately 4 greater than we can now attain. The power supply, electrodes, and instrumentation are ready for this new chamber.

For breakdown studies under more practical conditions a set of cylindrical electrodes has been fabricated (see Fig. 1). The outer cylinder, shown in Fig. 2, was machined from a single block of brass to effect a cylinder 10 cm long with 2 cm radius, plus 11 cm of curved ends to make a total length of 21 cm. Seven inner cylinders (Fig. 3), each 27 cm long, have been made of three materials (stainless steel, copper, and aluminum) and three radii (0.4, 0.75, and 1.4 cm) to study effects of material and radius on breakdown strength of dielectric gases. To study surface roughness, three stainless steel rods of 0.75 cm radius were made, on which the surface roughness can be varied. The mounting scheme can be seen in Fig. 1 where Plexiglas discs hold the inner cylinder ends relative to the flared ends of the outer cylinder.

The chamber for the practical studies has been fitted with a mechanical forepump, a diffusion pump, a liquid nitrogen trap, and appropriate valves and gauges. Designs have been made for a high voltage feedthrough and a quartz window; they are being fabricated. A

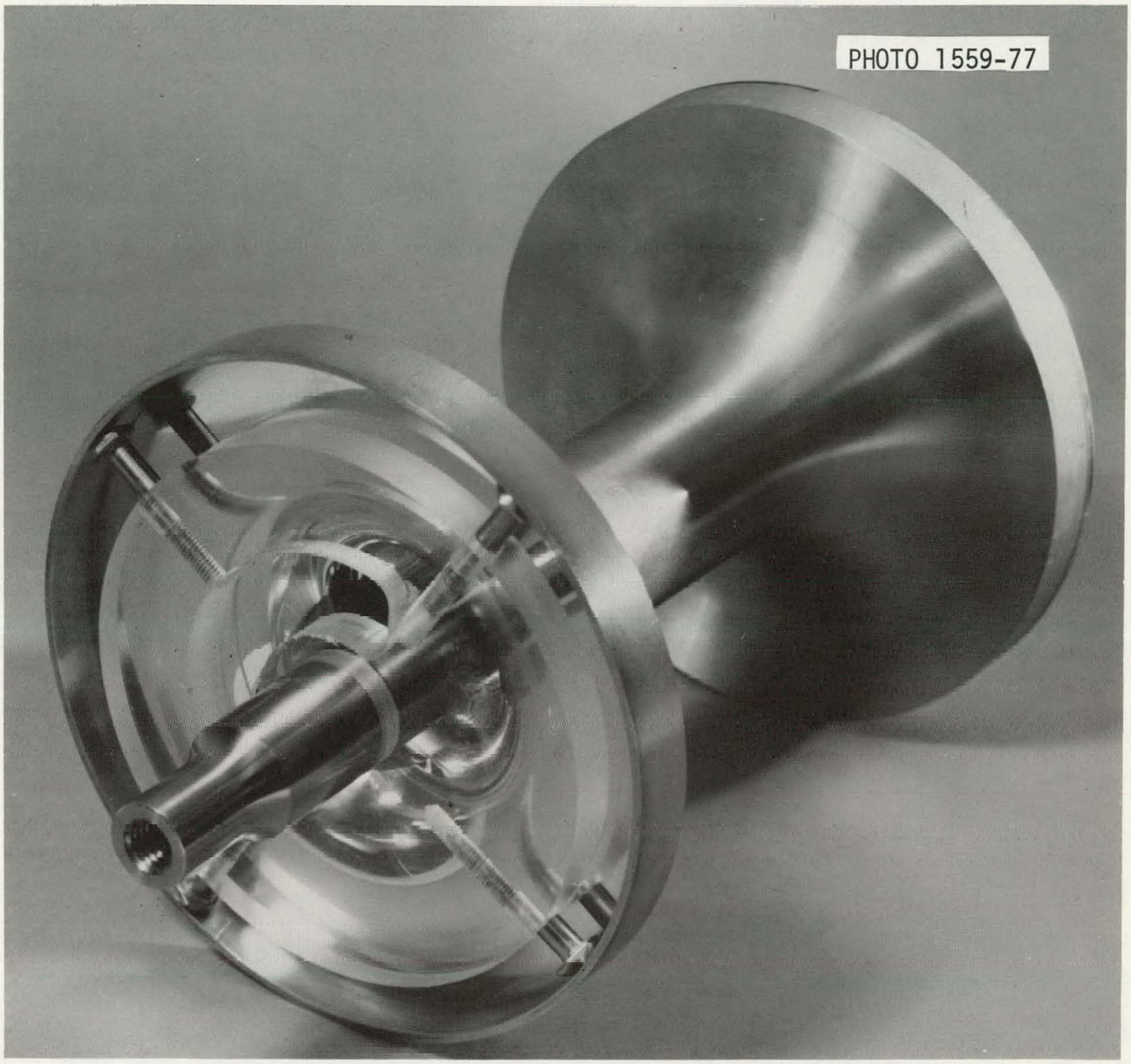

FIG. 1. Mounted concentric cylinder electrodes.

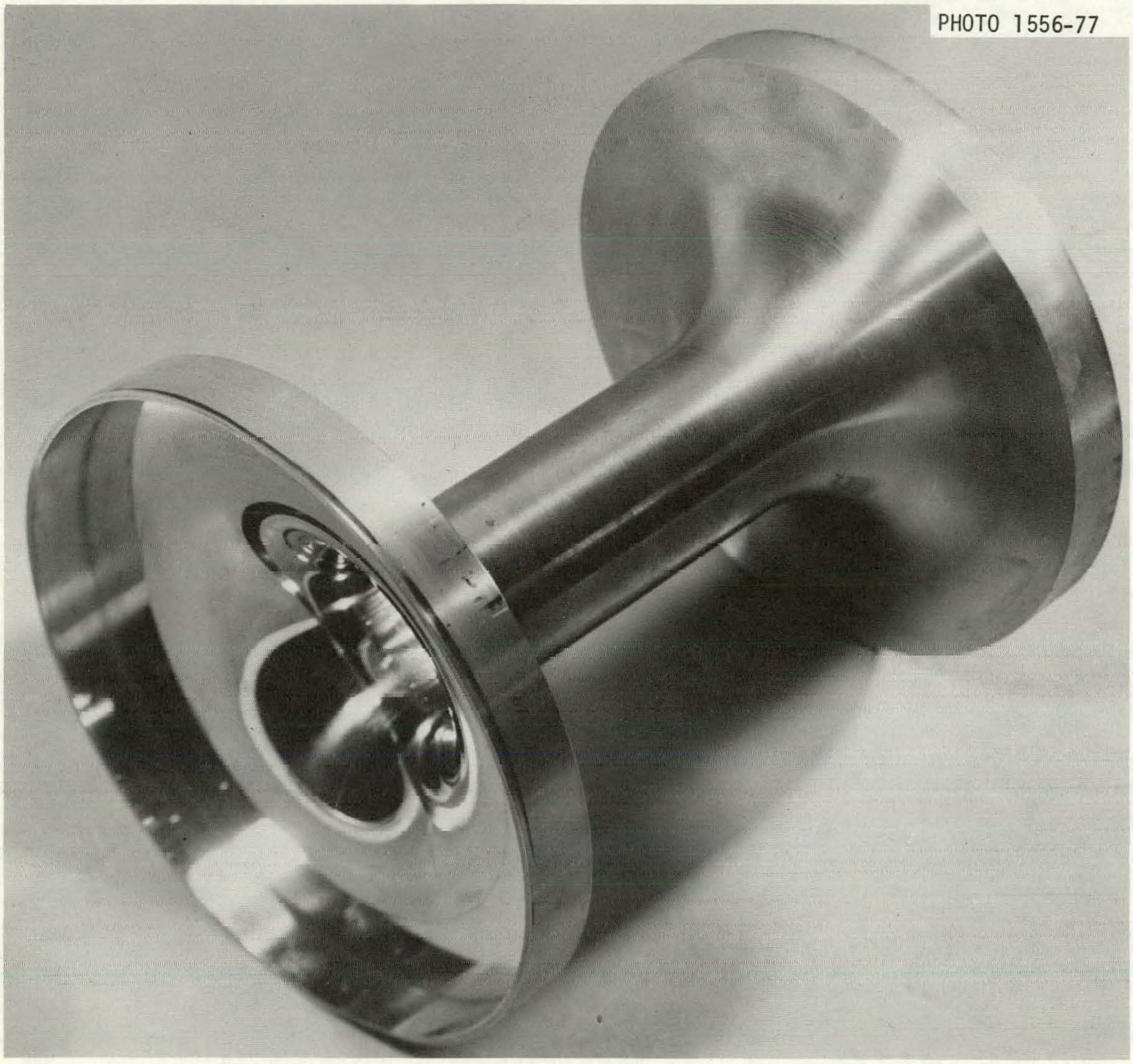

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FIG. 2. Outer electrode assembly for concentric cylinder electrode geometry.

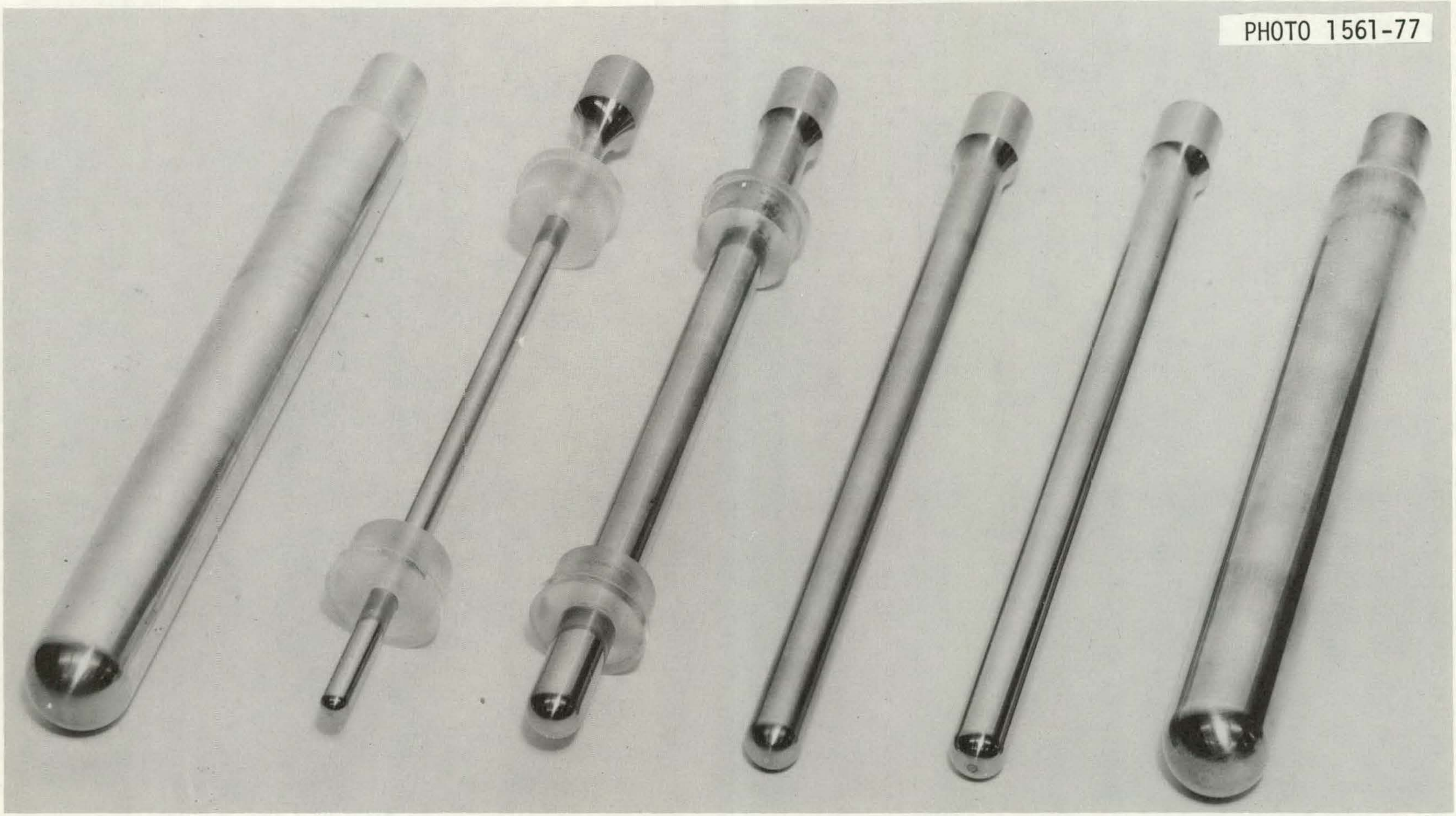

FIG. 3. Inner electrodes for concentric cylinder geometry (the smaller sizes have adapter sleeves for mounting).

shielding cage is expected from Erik A. Lindgren Company early next quarter. A 300 kV power supply for this experiment is expected from Delta Ray Corporation about September 1977; in the meantime an old 0-150 kV DC Sorenson power supply has been acquired from others at ORNL for this experiment.

A power supply was received from the Delta Ray Corporation for 0-300 kV DC, with low stored energy in the supply itself. Until the new high pressure, variable temperature chamber is completed, this power supply is being used on the larger of the two present breakdown apparatuses. For this purpose a 13-inch-long rolled pipe with appropriate end flanges was fabricated to act as an adapter between the high voltage cable feedthrough flange and the chamber flange.

Figures 4 and 5 show the effects on the uniform field electrodes of repeated sparking with the new 300 kV power supply. Although the energy stored in the power supply and cable is $\lesssim$ 30 joules, there is marked pitting of the electrodes.

The additional roughness created by the pitting is not large. Measurements in our shop of the surface roughness of these electrodes, using a Gould Surf-Indicator Model AD-20, gave the following results:

1. Residual roughness of polished electrode surface (maximum deviation from mean) was 2 micrometers.
2. Maximum roughness of grounded electrode (Fig. 4) after pitting was 8 micrometers.
3. Maximum roughness of HV electrode (Fig. 5) after pitting was 11 micrometers.

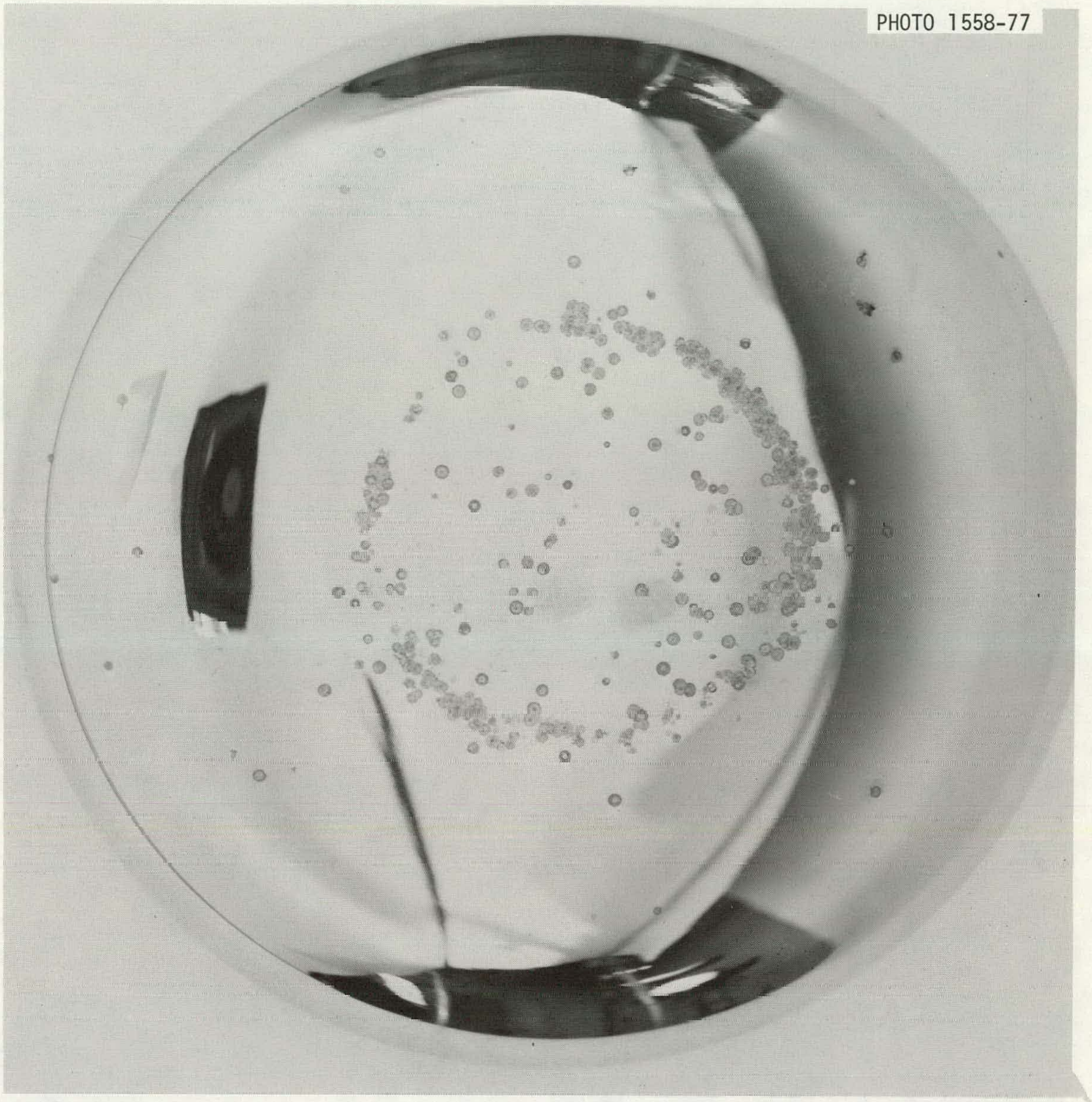

FIG. 4. Grounded uniform field electrode with pit marks made by repeated breakdowns.

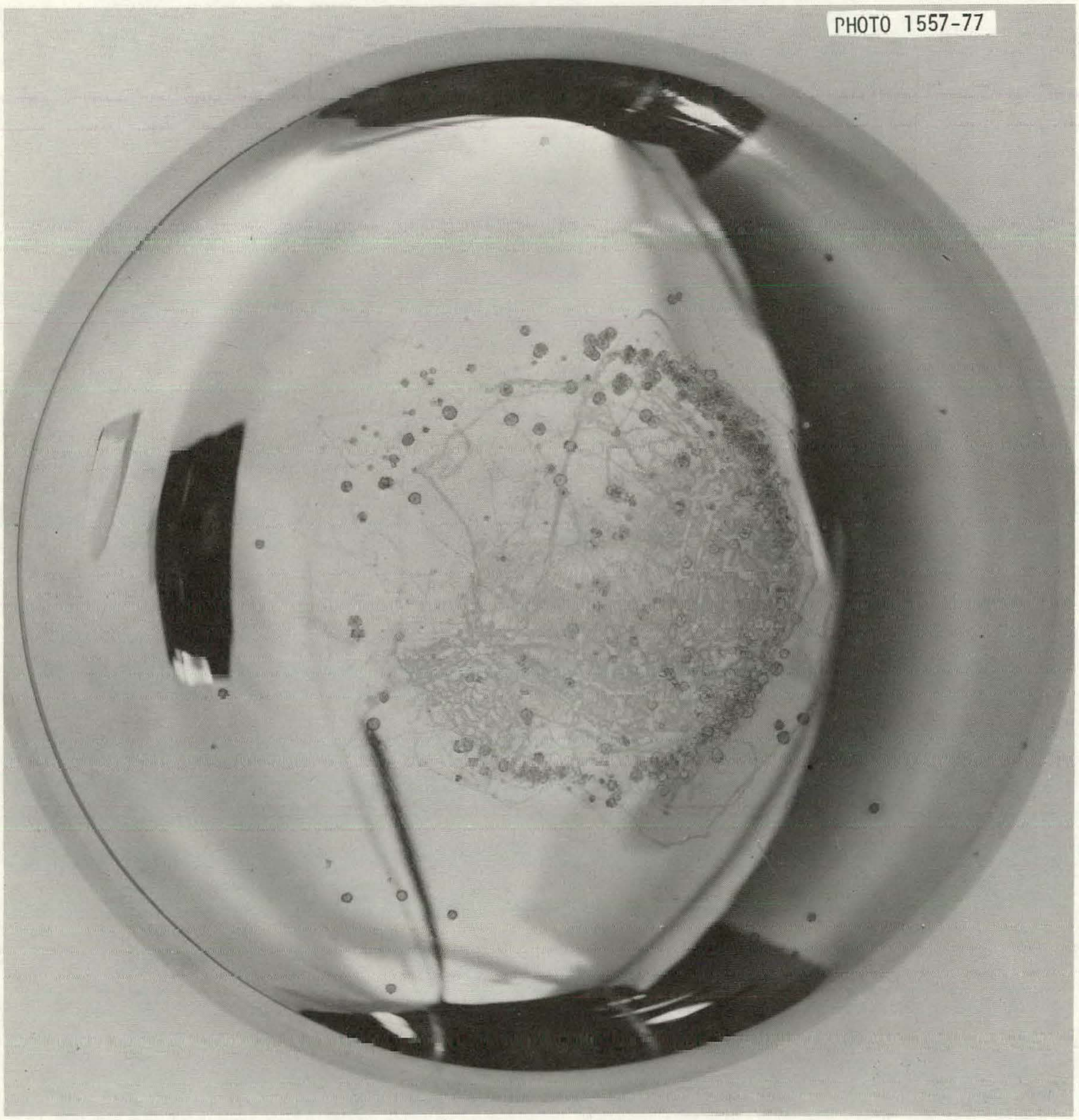

FIG. 5. Uniform field electrode (to which high voltage is applied) with pit marks caused by repeated breakdowns.

At low pressures of SF_6, these pit marks (which began to appear after the very first spark) had no effect on the breakdown strength; the breakdown voltage duplicated our earlier data using the older power supply. The roughness on even our worst-pit electrode is, of course, much less than that encountered in practical apparatuses.

It is seen from the photographs (Figs. 4 and 5) that the pitting is concentrated along the circumference of a circle and on one side. The concentration on the circumference is due to the slight nonuniformity of our electrodes. Due to the digital drive of the computer-driven lathe on which they were made, a final unavoidable step was made between the flat portion of the electrode and the curved part.

The concentration on one side is due to the ultraviolet light used to produce electrons in the electrode gap. The light comes from the side of the electrode which is most heavily pit marked. This is to be expected since more electrons will be produced on that side than on any other.

III. BREAKDOWN STRENGTHS OF UNITARY GASES

Plane-Plane Electrode Geometry

We have extended our measurements of the DC breakdown voltages of SF_6, c-C_4F_8, and iso-C_4F_8 to higher voltages (300 kV) which we can now achieve with the new power supply from Delta Ray Corporation. Figure 6 shows results for c-C_4F_8 and iso-C_4F_8 at 500 and 1000 torr pressure and for SF_6 at 1000 and 2000 torr pressure. These breakdown data agree well with our previous lower voltage measurements and obey Paschen's law for uniform field breakdown.

In Fig. 7 breakdown data are shown for SF_6 at higher pressures (see figure caption). Here the breakdown voltage begins to deviate from Paschen's law. This deviation has been reported earlier (see, for example, Ref. 5).

Sphere-Plane Electrode Geometry

Our DC breakdown measurements on unitary systems using the sphere-plane apparatus continued. The new fluorocarbons studied are C_7F_{14} (perfluoromethylcyclohexane), C_7F_{14} (perfluoroheptene-1), C_8F_{16} (perfluoro-1,3-dimethylcyclohexane), C_4F_6 (hexafluorobutadiene), and C_7F_8 (octafluorotoluene). The breakdown voltages of these gases along with SF_6 and C_4F_6 (hexafluorobutyne) are plotted as functions of Pd in Fig. 8. These measurements were conducted at the pressures indicated in the figure. With the exception of the two forms of C_4F_6 and SF_6, the remaining fluorocarbon gases all have relatively low vapor pressures at room temperature. The low pressures used (20-281 torr) necessitated large electrode gaps, often several mm in length. The electric field

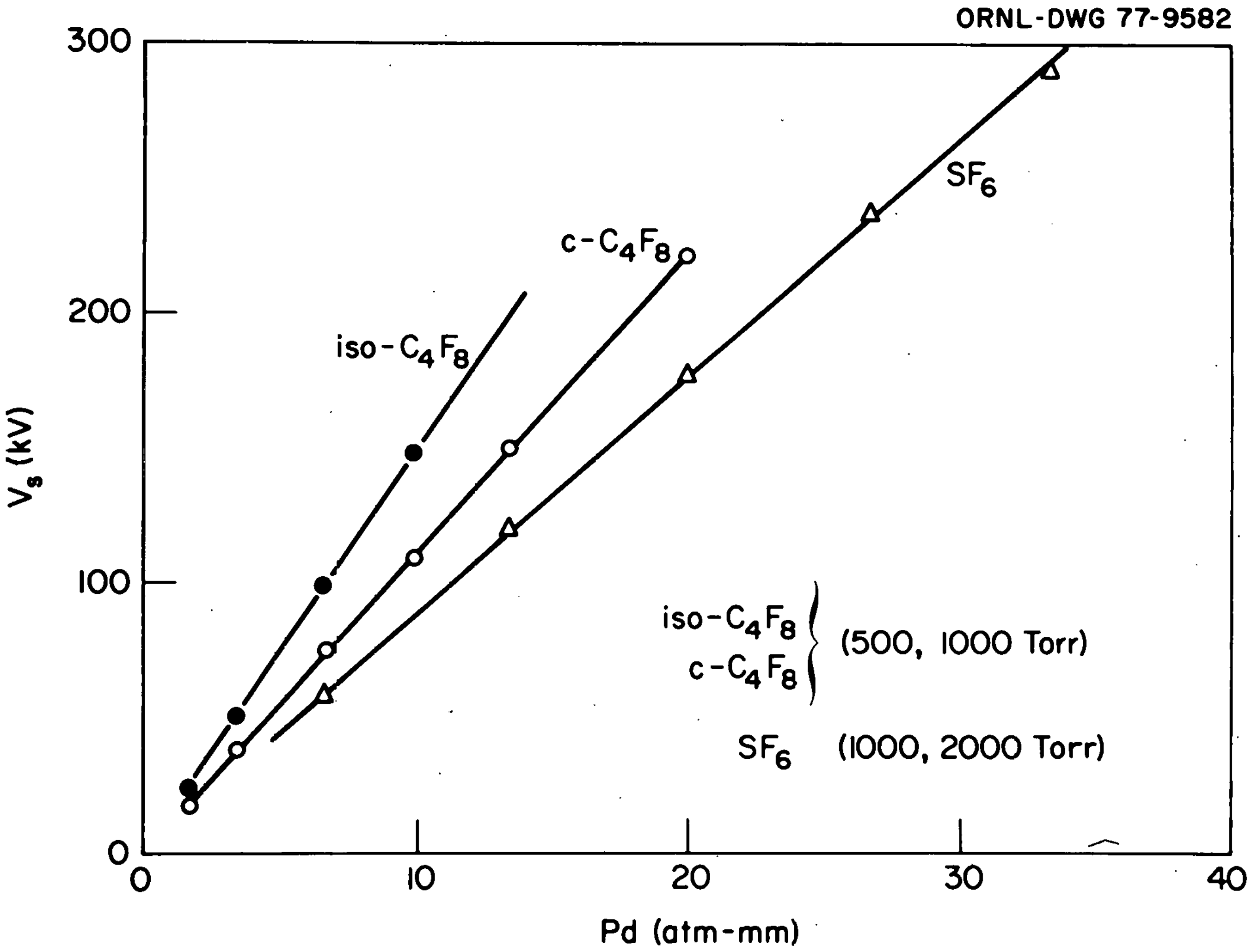

FIG. 6. Uniform field breakdown voltages, V_s, for SF_6, iso-C_4F_8, and c-C_4F_8 as a function of Pd (plane-plane electrode geometry). The pressures were 500 and 1000 torr for iso-C_4F_8 and c-C_4F_8, and 1000 and 2000 torr for SF_6.

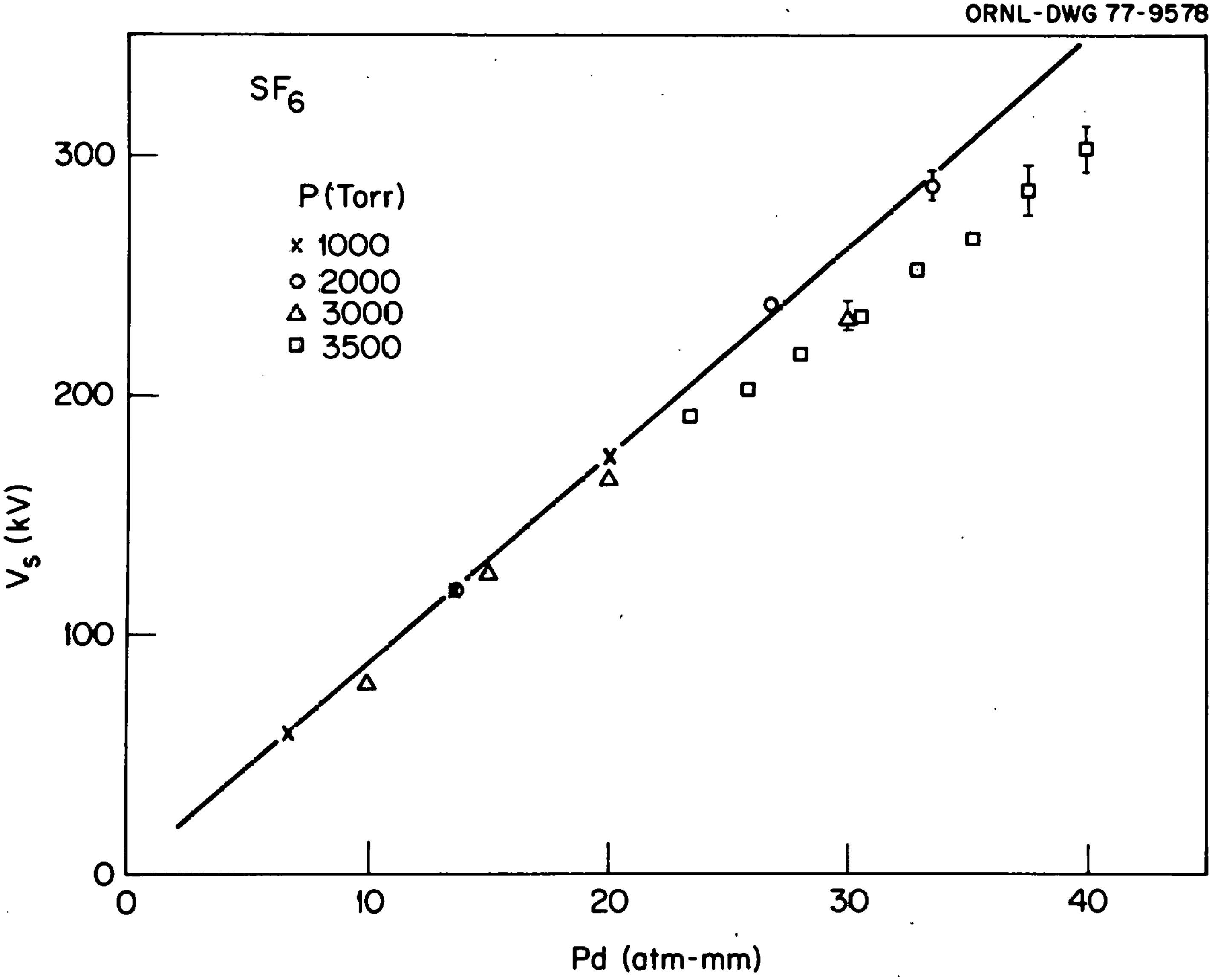

FIG. 7. Breakdown voltages, V_s, for SF_6 as a function of Pd for pressures 1000 (x), 2000 (o), 3000 (△), and 3500 (□) torr (plane-plane electrode geometry).

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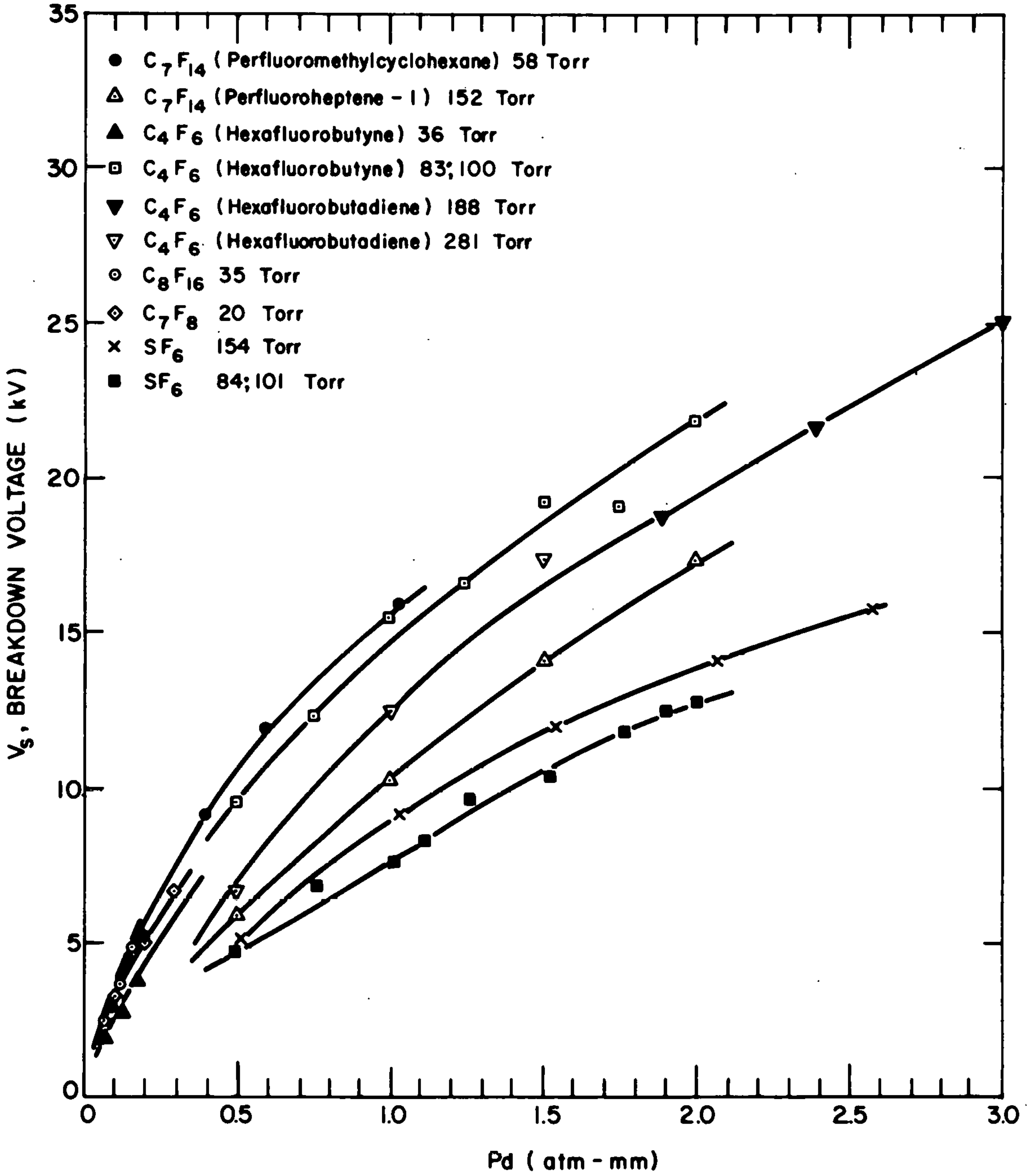

FIG. 8. Breakdown voltages as a function of Pd for several gases at the indicated pressures (sphere-plane electrode geometry) (see text).

between the sphere and plane electrodes was therefore nonuniform, as reflected by the curvature of the breakdown voltages versus Pd plots. When comparing breakdown voltages at a given Pd for sphere-plane electrodes, one must compare the gases at the same P (or d) so that the field configuration is also the same. It would be erroneous to compare the breakdown strength of two gases at widely different pressures. Of course, this is not the case for strictly uniform fields. In the case of the lowest vapor pressure gases C_8F_{16} and C_7F_8, a comparison with SF_6 (at the same P) could not be made, since SF_6 tended to form a glow discharge rather than an easily detectable spark at these low pressures. However, where the pressures are comparable, one can obtain dielectric strengths relative to SF_6. These are summarized in Table I along with some of the earlier data with sphere-plane and plane-plane electrode geometries. Some of these gases, although of limited use by themselves as dielectrics due to their low pressures, could have potential as additives to appropriate buffer gases in a multicomponent gaseous insulator.

TABLE I

Relative Breakdown Strengths of Some Unitary Gases

Gas	Relative Strength	
C_4F_6 (hexafluorobutyne)	2.1 to 2.2	(a)
iso-C_4F_8 (perfluorobutene-2)	1.7 to 1.8	
c-C_4F_8 (perfluorocyclobutane)	1.4	
N_2 (nitrogen)	0.34	
SF_6 (sulfur hexafluoride)	1.0	
C_6F_{12} (mixture of 1,2- and 1,3-perfluorodimethylcyclobutane)	2.3 to 2.4	(b)
C_6F_{10} (perfluorocyclohexene)	1.9 to 2.2	
C_7F_{14} (perfluoromethylcyclohexane)	2.1	
C_4F_6 (perfluoro-2-butyne)	1.7 to 1.9	
C_4F_6 (hexafluorobutadiene)	1.4	
C_7F_{14} (perfluoroheptene-1)	1.2	
SF_6 (sulfur hexafluoride)	1.0	

(a) High pressure; uniform field (plane-plane electrode geometry).

(b) Low pressure; nonuniform field (sphere-plane electrode geometry).

IV. BREAKDOWN STRENGTHS OF MULTICOMPONENT GAS MIXTURES

Plane-Plane Electrode Geometry

We have undertaken a systematic set of breakdown measurements with binary mixtures consisting of 5 to 40% of an electron-attaching gas and nitrogen as the remaining fraction of the mixture. Figure 9 gives the breakdown voltage for a particular value of Pd (similar results were obtained for other Pd values). Two main conclusions can be drawn from the data in Fig. 9:

1. The rate of increase of V_s with addition of SF_6 to N_2 (above ∿ 20% SF_6) is much less than for the rest of the additives in Fig. 9 indicating a marked "saturation" effect for SF_6 not evident for the rest of the electron-attaching additives.
2. If we designate by V_s, V_A, V_{N_2}, F_A, and F_{N_2}, respectively, the measured breakdown voltage of the mixture at a total pressure P_T, the breakdown voltage of the electron-attaching additive A at P_T, the breakdown voltage of N_2 at P_T, the fraction of A, and the fraction of N_2 in the mixture, we see that for all additives V_s is larger than the weighted average $F_{N_2} V_{N_2} + F_A V_A$, i.e., the breakdown voltage of the mixture had a purely additive relationship existed. This is tantamount to synergism, i.e., a cooperative effect of the component gases.

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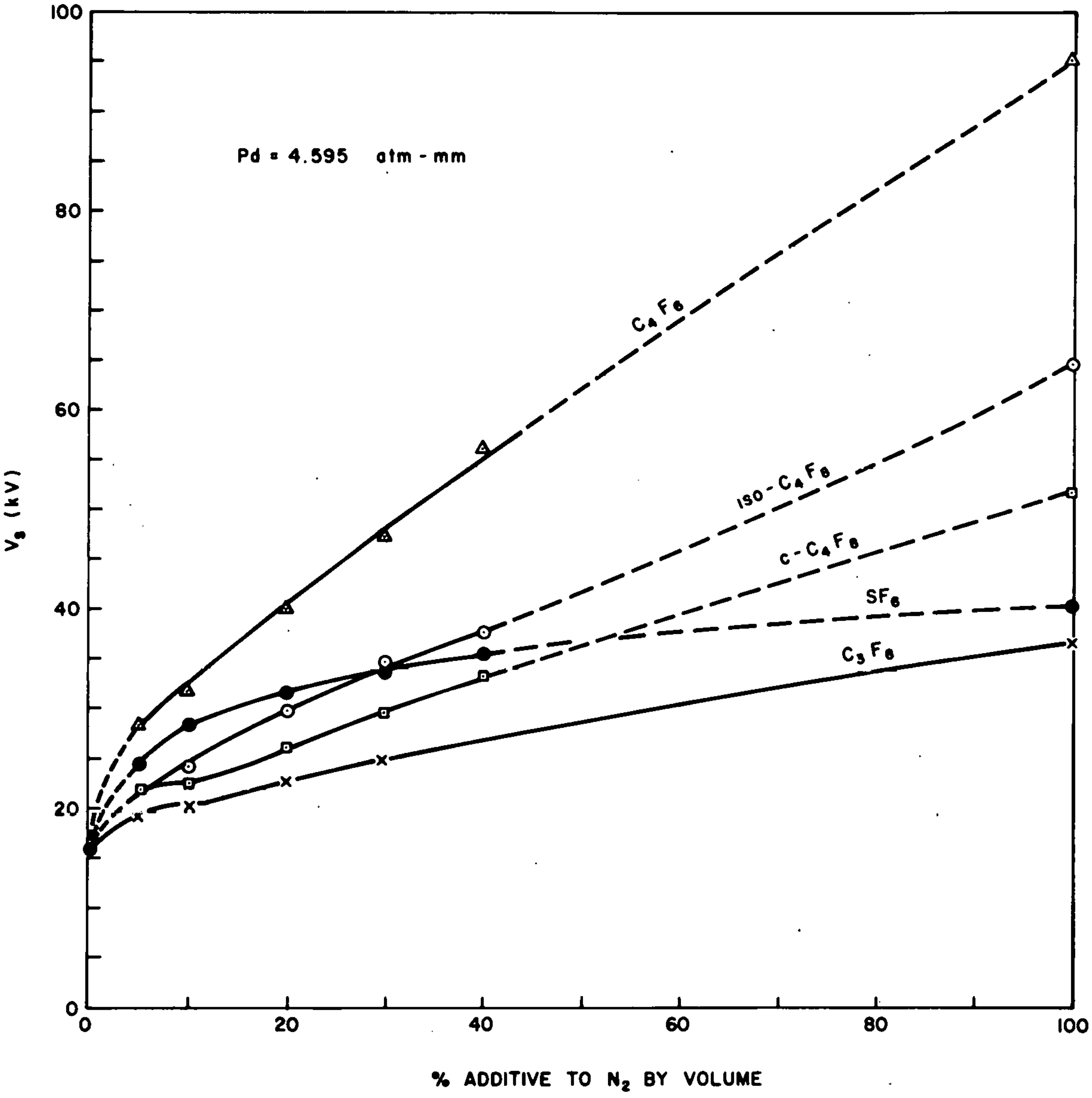

FIG. 9. Breakdown voltages, V_S, versus percent of electron-attaching additive to N_2 by volume (plane-plane electrode geometry).

Sphere-Plane Geometry

Binary Mixtures Using CO_2 as the Buffer Gas. Breakdown voltage measurements of mixtures using CO_2 as the buffer gas were also made. The electron-attaching additives mixed with CO_2 were CCl_2F_2 (Freon-12) and SF_6. We measured the breakdown strength as a function of the percentage by partial pressure of the additive. As shown in Fig. 10, the breakdown voltage, V_s, of CCl_2F_2-CO_2 mixtures is approximately a linear function of the percentage of additive for Pd's of 1 and 3 atm-mm. There is no apparent "saturation" effect for CCl_2F_2. The measured breakdown voltages for these mixtures are almost identical with the weighted average values of the breakdown strengths of the component gases. It should be noted that these measurements were made with sphere-plane electrodes at relatively small electrode gap spacings (< 1.5 mm) for which the electric field is uniform to within about 5%.

The SF_6-CO_2 mixture was investigated at only one value of Pd (atm-mm), and preliminary indications are that a slight saturation effect exists. However, before drawing any firm conclusions, it will be necessary to extend these measurements to higher Pd's as has been done for the SF_6-N_2 mixtures reported in the previous section.

Effect of Negative Ion Resonances on the Breakdown Strength of Multicomponent Mixtures. A series of breakdown measurements on the system comprising C_4F_6 (hexafluorobutyne), N_2, CO, and H_2 has been undertaken. This system is an important one from the basic point of view, since the essential electron scattering cross sections for N_2, CO, and H_2 are known. All three gases possess negative ion resonances. The positions, ε_R, of these

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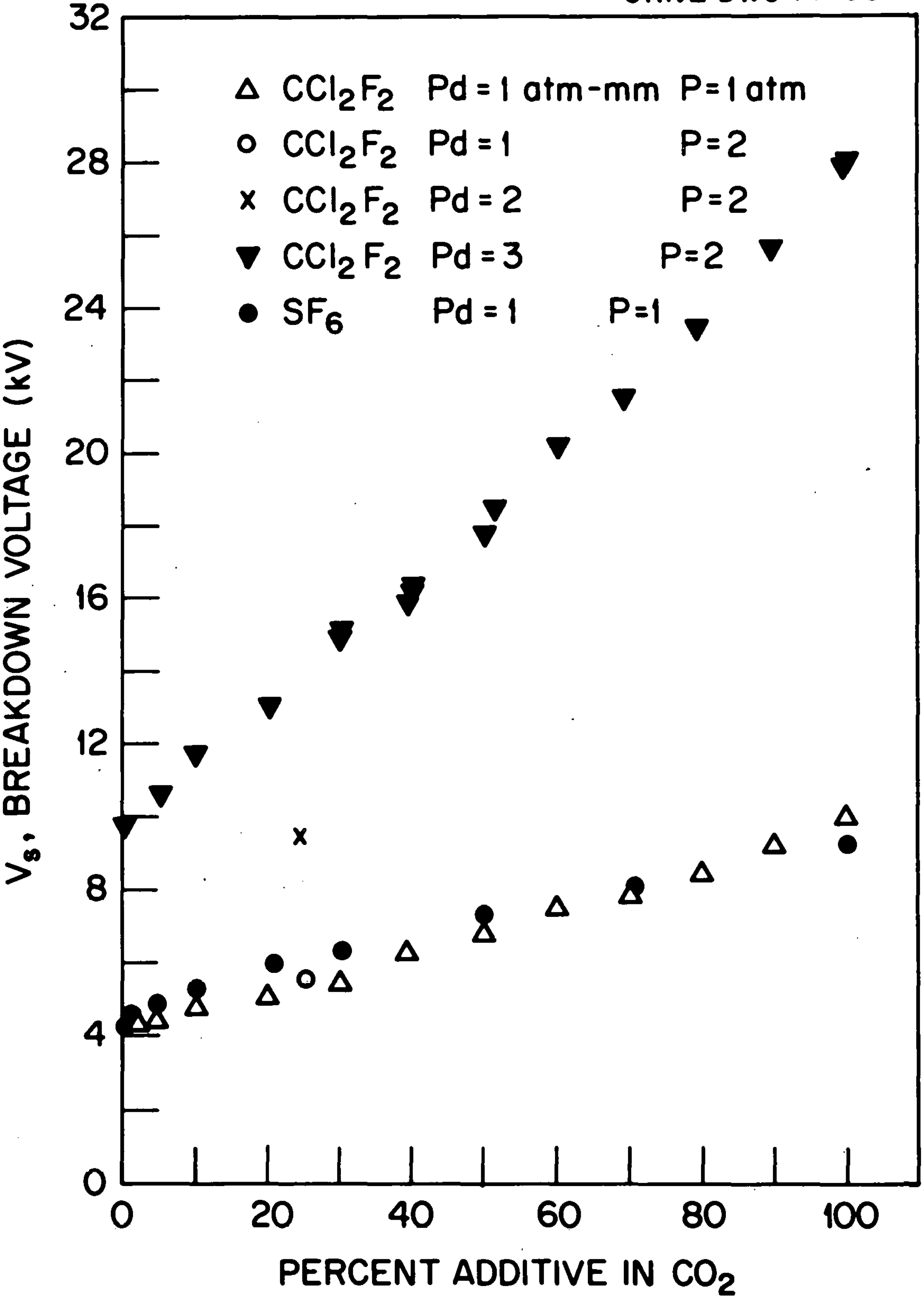

FIG. 10. Breakdown voltages, V_s, for binary mixtures CCl_2F_2-CO_2 and SF_6-CO_2 (sphere-plane electrode geometry).

are:[4] $(\varepsilon_R)_{CO}$ ($\sim$ 1.75 eV) < $(\varepsilon_R)_{N_2}$ ($\sim$ 2.3 eV) < $(\varepsilon_R)_{H_2}$ ($\sim$ 3.75 eV). The corresponding cross sections, σ_R, for indirect vibrational excitation via these negative ion resonances (see Fig. 11) are $(\sigma_R)_{CO} > (\sigma_R)_{N_2} > (\sigma_R)_{H_2}$. Similarly in the energy range below $\sim$ 4 eV, the total electron scattering cross sections, σ_T, decrease in the order $(\sigma_T)_{CO} > (\sigma_T)_{N_2} > (\sigma_T)_{H_2}$ (see Fig. 12), and the momentum transfer cross sections, σ_m, in the order $(\sigma_m)_{CO} > (\sigma_m)_{N_2} > (\sigma_m)_{H_2}$ (see Fig. 13).

As we have stressed in our previous reports, negative ion resonances constitute very effective ways of slowing down subexcitation electrons and should crucially affect the energies of the electrons in the gaseous dielectric. It is thus of utmost significance to establish what, if any, direct effect the position and the magnitude of the cross section of these negative ion resonances have on the breakdown strength. We have, therefore, begun measuring the breakdown strength of mixtures containing a fixed concentration of one of our best electron-attaching dielectric gases (C_4F_6 [hexafluorobutyne]) and varied concentrations of CO, N_2, and H_2. The first results of this study are given in Table II. In Table II are listed the percentages of the component gases as determined by partial pressure, the Pd values and the breakdown voltage values, V_s, that correspond to these, the ratio σ/V_s of the standard deviation σ to V_s for the sets of measurements at the two indicated values of Pd, and the slopes $\Delta V_s/\Delta(Pd)$.

In spite of the limited data obtained to this moment, the results in Table II clearly show that V_s and $\Delta V_s/\Delta(Pd)$ increase in the order CO > N_2 > H_2 for both the unitary systems and the binary mixtures.

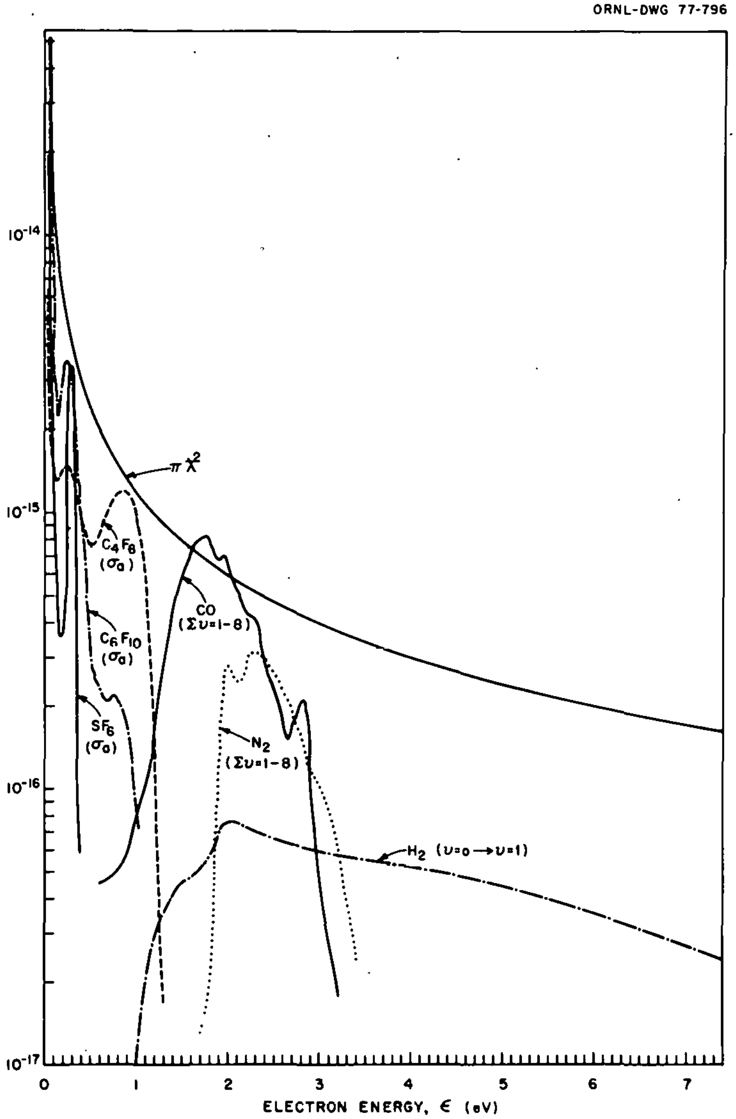

FIG. 11. Electron attachment cross sections, σ_a, as a function of electron energy, ε, for three electron-attaching gases, SF_6, C_4F_6, and C_6F_{10}. Vibrational excitation cross sections via negative ion resonances: $CO(\Sigma_{\upsilon=1-8})$ is the sum of vibrational cross sections for the first eight individual states of CO as a function of electron energies (Ref. 6); $N_2(\Sigma_{\upsilon=1-8})$ is the sum of vibrational cross sections for the first eight individual states of N_2 as a function of electron energy (Ref. 6); $H_2(\upsilon=0 \rightarrow \upsilon=1)$ is the cross section for excitation of the first vibrational level of H_2 (6) multiplied by 1.4 to correct the experimental data for nonisotropic electron scattering (see Ref. 4, p. 347). Since the cross section for excitation of higher vibrational levels of H_2 is very much lower than for the υ=1 level, one can conclude that the cross sections for vibrational excitation of CO, N_2, and H_2 via negative ion (shape) resonances decrease in the order CO > N_2 > H_2. $\pi ƛ^2$ is the maximum s-wave capture cross section.

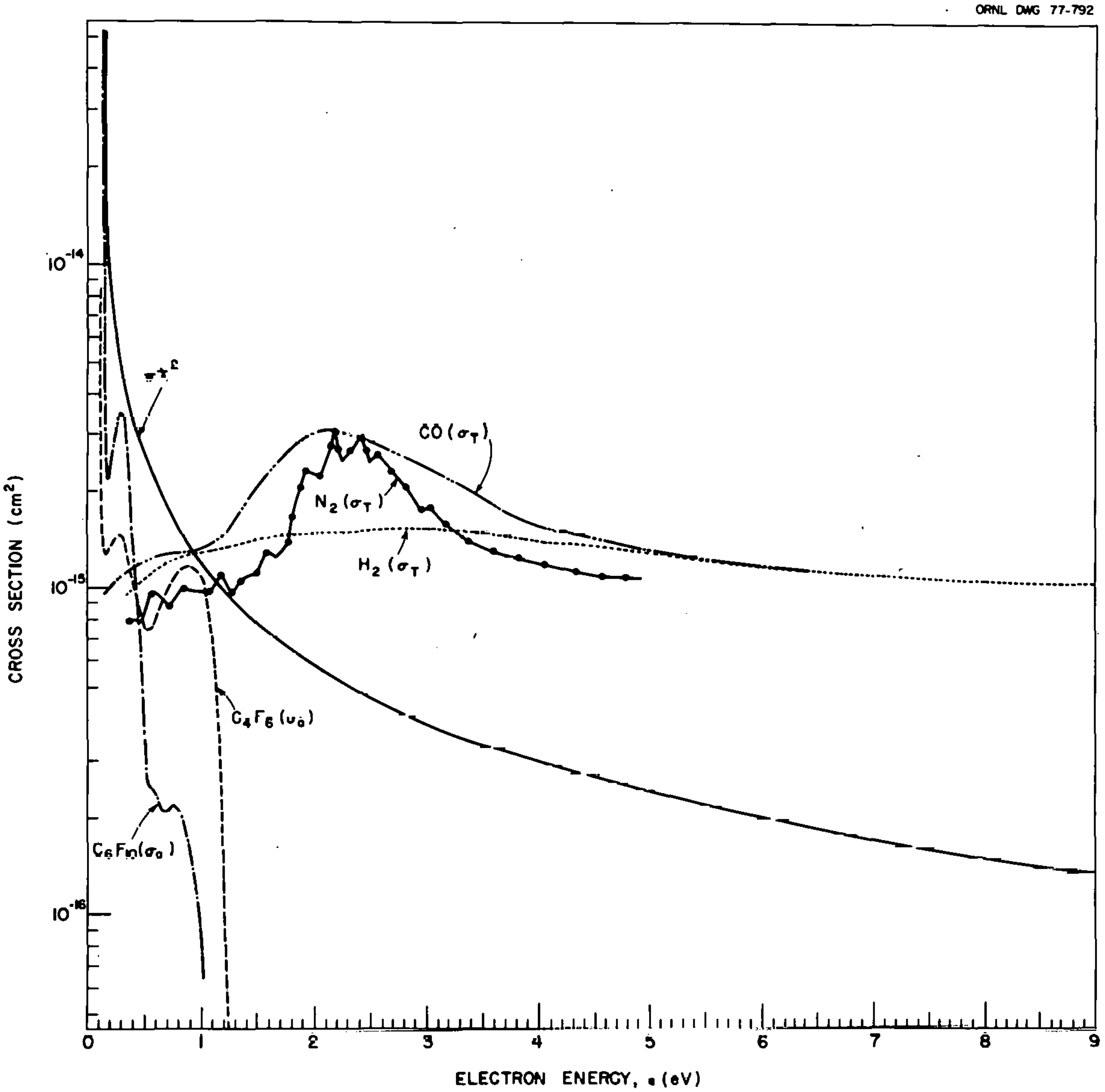

FIG. 12. Electron attachment cross sections, σ_a, as a function of electron energy, ε, for C_4F_6 and C_6F_{10} and total electron scattering cross sections, σ_T, for CO (Ref. 7), N_2 (Ref. 8), and H_2 (Ref. 9). $\pi ƛ^2$ is the maximum s-wave capture cross section.

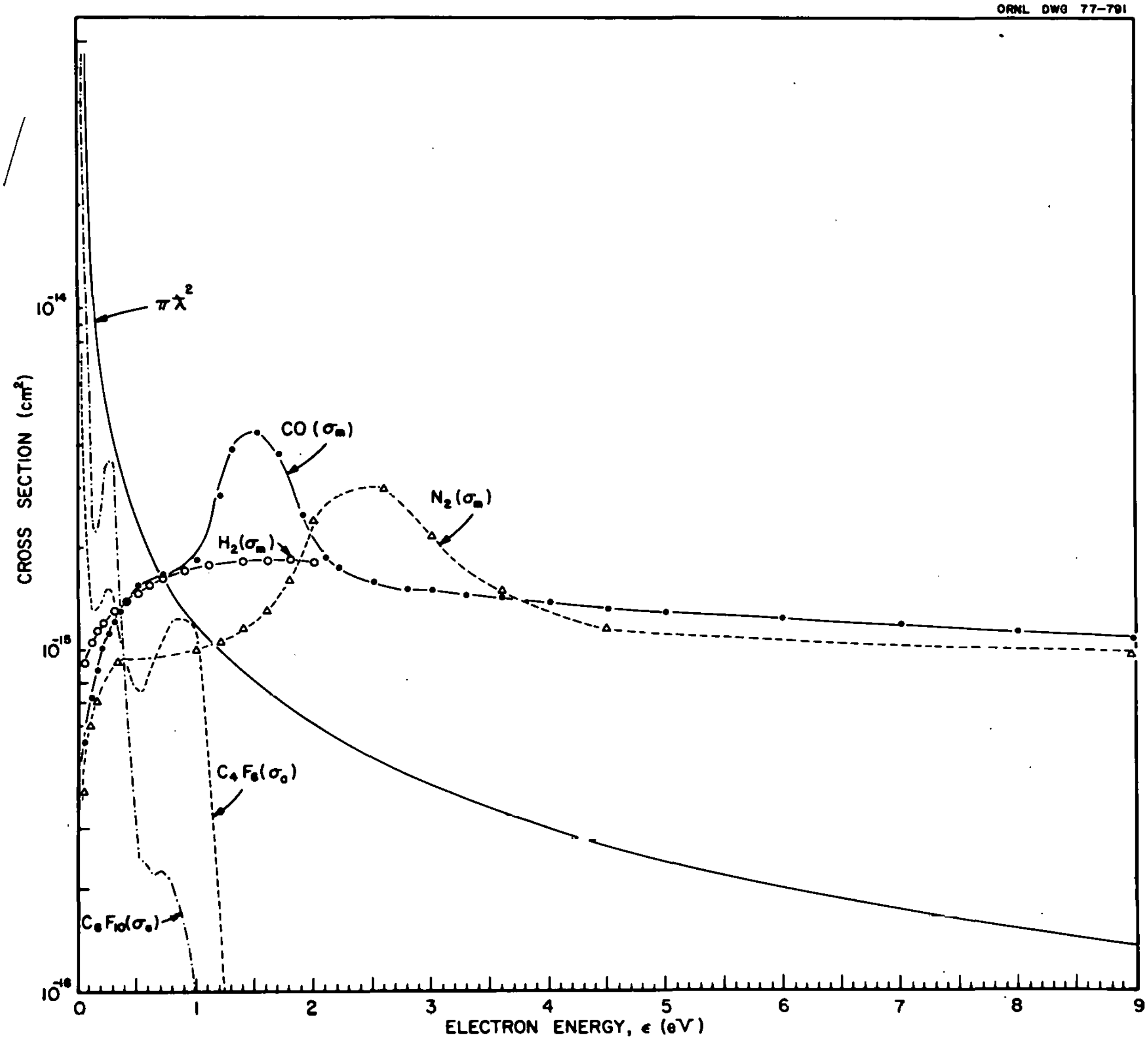

FIG. 13. Electron attachment cross sections, σ_a, as a function of electron energy, ε, for C_4F_6 and C_6F_{10} and momentum transfer cross sections, σ_m, for CO (Ref. 10), N_2 (Ref. 11), and H_2 (Ref. 12). $\pi\lambda\!\!\!^{-2}$ is the maximum s-wave capture cross section.

TABLE II

Breakdown Strengths of N_2, CO, H_2, and Binary Mixtures of These with C_4F_6*,†

C_4F_6 (%)	N_2 (%)	CO (%)	H_2 (%)	Pd (atm-mm)	V_s (kV)	$\frac{\sigma}{V_s}$ (%)	$\frac{\Delta V_s}{\Delta(Pd)}$ $\left(\frac{kV}{atm-mm}\right)$
100	—	—	—	—	—	—	17.5‡
—	100	—	—	2.04	7.54	4.1	2.97
—	100	—	—	3.05	10.54	1.1	
—	—	100	—	2.03	9.24	0.6	3.5
—	—	100	—	3.05	12.81	0.2	
—	—	—	100	2.04	4.30	4.4	1.66
—	—	—	100	3.05	5.98	2.1	
33.33	66.66	—	—	2.04	18.69	4.1	9.00
33.33	66.66	—	—	3.05	27.78	4.1	
33.33	—	66.66	—	2.04	20.90	3.9	10.08
33.33	—	66.66	—	3.05	31.08	1.9	
33.33	—	—	66.66	2.03	18.72	1.3	7.62
33.33	—	—	66.66	3.05	26.49	2.2	

*Measured using sphere-plane electrodes at a total pressure of 2 atm.

†Under identical conditions $\Delta V_s/\Delta(Pd)$ for pure SF_6 is 8 kV/atm-mm.

‡From Ref. 2.

These results are consistent with the cross section data in Figs. 11 to 13, namely that the higher the electron scattering cross section (mainly indirect through negative ion resonances) the better the breakdown strength. This statement is valid for comparisons using any set of cross section data: σ_R, σ_T, or σ_m. The direct effect of the inelastic scattering properties of the gas via negative ion resonances in the low-energy range (especially in the range $\sim$ 1 to $\sim$ 4 eV) on the breakdown strength has thus been demonstrated for the first time. Electrons in this energy range have to be slowed down for effective capture at lower energies and/or to prevent them from attaining higher energies to trigger breakdown.

These findings support our earlier conclusions[2,3] as to the high breakdown strengths we observed for unitary systems whose electron attachment cross sections are large to energies of $\sim$ 2 eV even though their cross sections at thermal energies are small. This is because the distribution of electron energies in the dielectric gas prior to breakdown is such that a large fraction of the electrons attain energies in the range $\sim$ 0.5 to $\sim$ 3 eV.

The basic experiments outlined in this section are continuing with vigor using different combinations and proportions of both the electron thermalizing gases (CO, N_2, and H_2) and the electron-attaching gases (C_4F_6, C_6F_{10}, and SF_6) (see Figs. 11 to 13).

V. BASIC STUDIES

In support of our breakdown strength studies on fluorocarbon gases, we have continued to measure the electron attachment rates as a function of mean electron energy, $\langle\varepsilon\rangle$, and to calculate from these the corresponding electron attachment cross sections as a function of electron energy, ε, for these compounds. Figure 14 shows our data for C_6F_{10} (perfluorocyclohexene). It is seen that the attachment rate (and cross section) for this molecule is very large. At each value of the mean electron energy $\langle\varepsilon\rangle$, the distribution of electron energies $f(\varepsilon,\langle\varepsilon\rangle)$ is known[4] because these studies were conducted in N_2 containing less than one part per million of C_6F_{10}. The maximum attachment rate was determined as a function of $\langle\varepsilon\rangle$ from

$$[\alpha w(\langle\varepsilon\rangle)]_{max} = N_{torr} \left(\frac{\pi^2\hbar^4}{2m^3}\right)^{1/2} \int_0^\infty \varepsilon^{-1/2} f_{N_2} (\varepsilon,\langle\varepsilon\rangle)\, d\varepsilon$$

using the known[4] electron energy distributions, f_{N_2}, in N_2 (N_{torr} is the number of attaching gas molecules per cm^3 per torr at T = 298°K). The swarm unfolded electron attachment cross section is shown in the inset of Fig. 14, where it is compared with the maximum ($\pi\lambda\!\!\!^{-2}$) s-wave capture cross section over a range of electron energies. If these experimental cross sections are used to determine the thermal attachment rate via

$$(\alpha w)_{thermal} \equiv N_{torr} \left(\frac{2}{m}\right)^{1/2} \int_0^\infty \varepsilon^{1/2} f_M(\varepsilon)\, \sigma_a(\varepsilon)\, d\varepsilon$$

where $f_M(\varepsilon)$ is a maxwellian function (T = 298°K), it is found that $(\alpha w)_{thermal} = 1.13 \times 10^{10}\ sec^{-1}\ torr^{-1}$ which is, to our knowledge, the

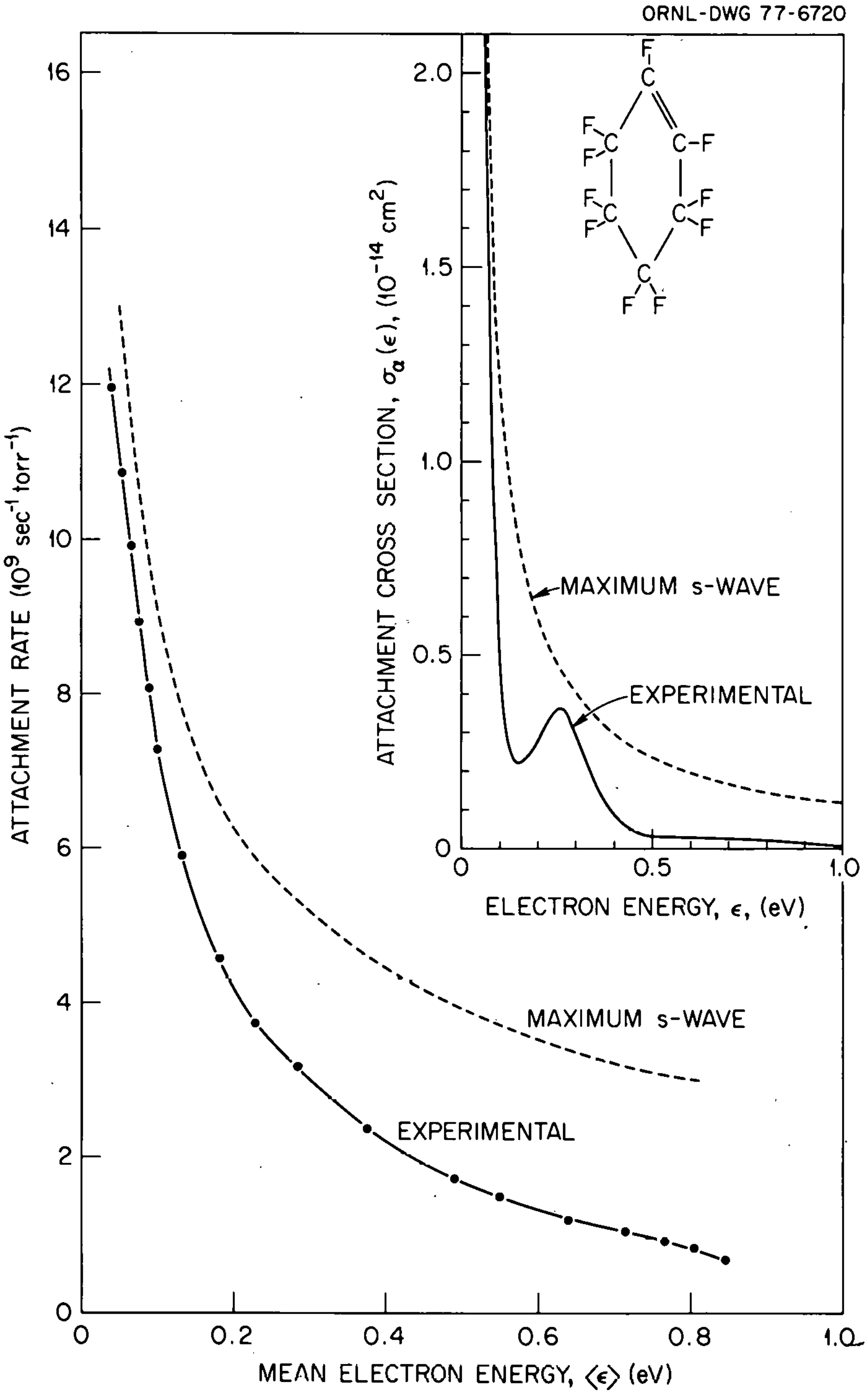

FIG. 14. Electron attachment rate as a function of the mean electron energy ⟨ε⟩ and swarm-unfolded electron attachment cross section as a function of electron energy ε for C_6F_{10} compared with maximum s-wave capture rate and cross section (see text).

largest attachment rate measured to date. It is ∿ 30% higher than that for SF_6.

The large electron attachment rates and cross sections for C_6F_{10}, extending to ∿ 1 eV and beyond correlate nicely with its very large (a factor of ∿ 2.2 larger than SF_6; see Table I) dielectric strength. They accord well with our picture that large attachment rates (cross sections) out to ∿ 1 to 2 eV increase the dielectric strength of a compound.

Additionally, we have conducted electron attachment measurements on C_6F_{12} (perfluorodimethylcyclobutane). The electron attachment cross section as a function of electron energy for this molecule is compared in Fig. 15 with those for C_6F_{10}, SF_6, and C_4F_6 (perfluorobutyne) and $\sigma_{max}(= \pi\lambda\!\!\!^{-2})$, and it is seen to be quite large to ∿ 1 eV. The dielectric strength of this fluorocarbon is more than twice that of SF_6 (see Table I).

It is readily apparent from the electron attachment cross section data in Fig. 15 that although the cross section values for these compounds at any energy are below the corresponding maximum possible cross section value at that energy, there are regions of energy in which the cross sections for these compounds approach the theoretical limit for electron attachment. If by appropriate combinations of compounds we can blanket a wide range of energies with maximal attachment cross sections we, then, may well approach the optimum dielectric material as far as electron attachment is concerned.

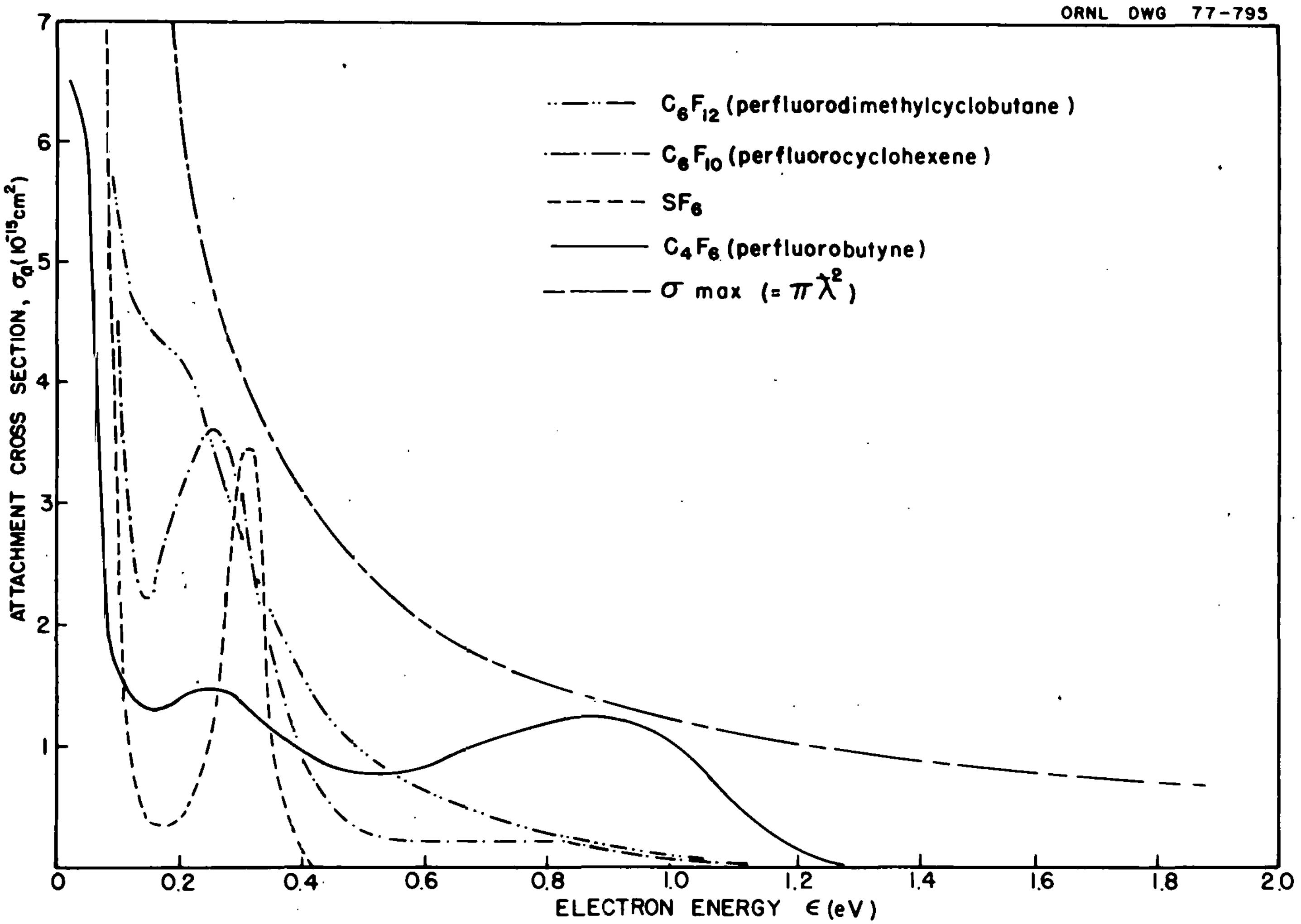

FIG. 15. Electron attachment cross sections, σ_a, as a function of electron energy, ε, for for C_6F_{12}, C_6F_{10}, C_4F_6, and SF_6 compared with $\pi\lambda\!\!\!^{-2}$.

VI. APPLIED STUDIES

As results and understanding of breakdown in DC uniform fields accrue, experiments corresponding to more practical conditions are being prepared to merge with the basic breakdown studies for gases and mixtures suggested by the DC uniform field work.

The new high pressure, variable temperature breakdown test facility will allow exploration in two new major areas: higher Pd and practical temperature ranges. This apparatus can provide Pd values up to 150 atm-mm (P = 10 atm, d = 15 mm) which is approximately an order of magnitude greater than most data taken so far and four times the maximum previously attainable; this will allow studies of breakdown at pressures near and above typical power system apparatus where the breakdown voltage may no longer vary linearly with Pd. Temperatures in the operating range of power apparatus (- 40°C to 120°C) can also be studied; essentially no reliable data is currently available over this temperature range.

The cylindrical electrodes (see Section II) for simulation of underground transmission lines have been designed to test breakdown in concentric cylinders with radii ratios $r_{outer}/r_{inner} \cong e$, 1/2e, and 2e, where e is the basis of natural logarithms. They can also be used to look for effects of electrode material and to assess dielectric tolerance to surface roughness. Analytic methods have been studied whereby the macroscopic streamer breakdown theory might be applied to breakdown measurements with these electrodes to infer the behavior of the gas large-scale parameter $\overline{\alpha} = \alpha - \eta$ with both field and pressure (where α is the ionization coefficient and η is the attachment coefficient).

The diverter studies have been completed for the present with the acquisition of data in air. Data in other gases can be obtained later using the chamber designed for practical studies.

We have made measurements of the delay time between the trigger discharge and the main gap discharge in air with the diverter apparatus using both sphere-sphere and sphere-plane geometries. Figures 16 and 17 show the delay time between the main gap discharge and the trigger discharge for + and - polarity, respectively (the triggered electrode was always at ground potential), as a function of V/V_s for sphere-sphere electrode geometry; V is the voltage across the electrode gap with the trigger and V_s is the breakdown voltage without the trigger, i.e., the self-breakdown voltage. Similar results for sphere-plane electrode geometry are presented in Figs. 18 and 19. For each value of V/V_s there was a very large spread in the measured delay times which were as a rule grouped into two regions as can be seen from the data presented in Figs. 16 to 19. In Figs. 16 to 19 the points with solid error bars are the averages of all the data within the error bars. A data point accompanied by a broken or a solid arrow indicates that a fraction of the measured delay times (shown by the number in the parentheses which accompanies the arrow) were off the graph scale in the direction of the arrow and thus the position of the point was determined by averaging the remaining fraction of the data. At times a number in parentheses accompanies an error bar. This indicates the fraction of the total delay time measurements that are within the error bar.

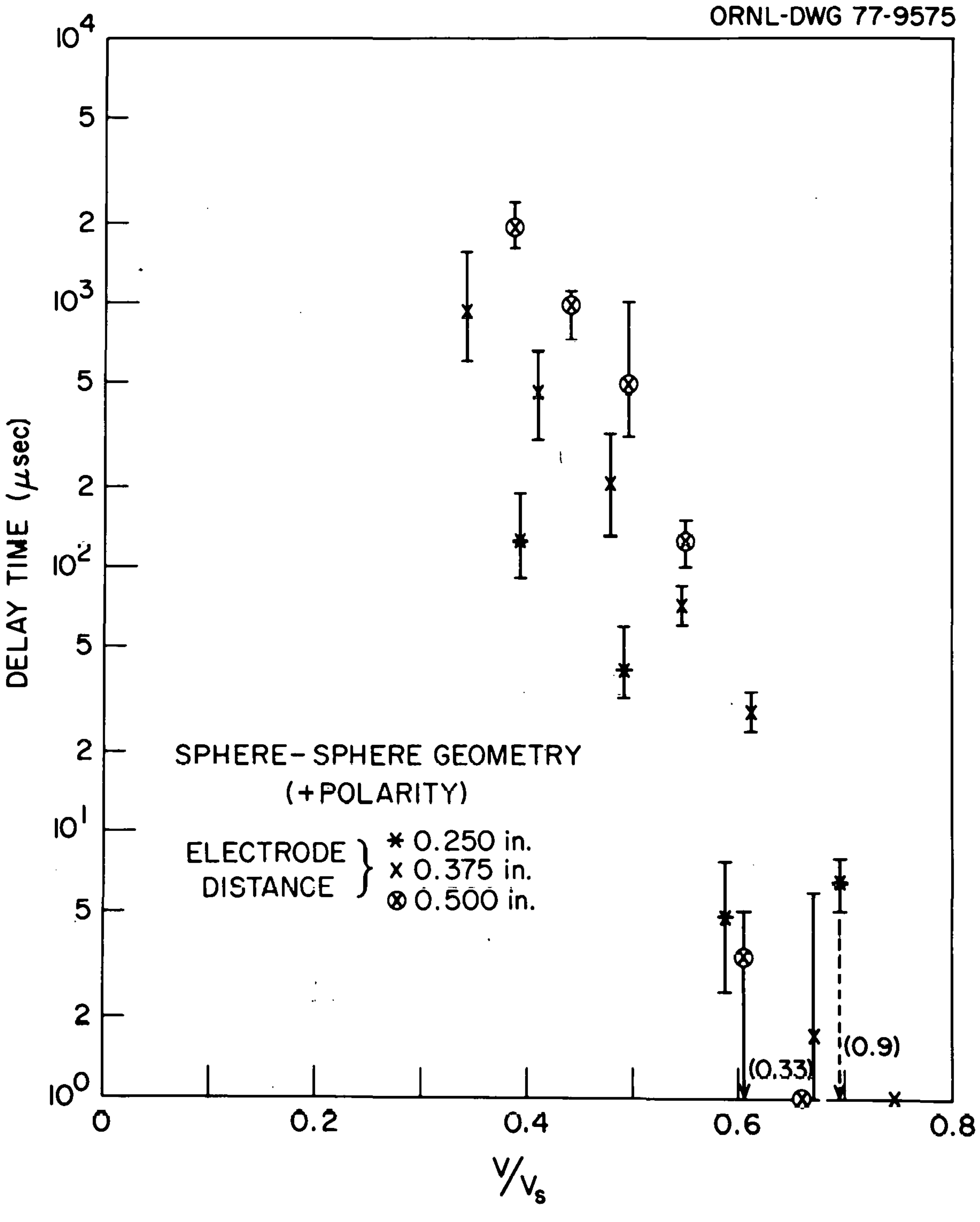

FIG. 16. Delay time as a function of V/V_S for sphere-sphere electrode geometry, positive polarity, and three electrode distances: 0.250 (*), 0.375 (x), and 0.500 (ⓧ) in.

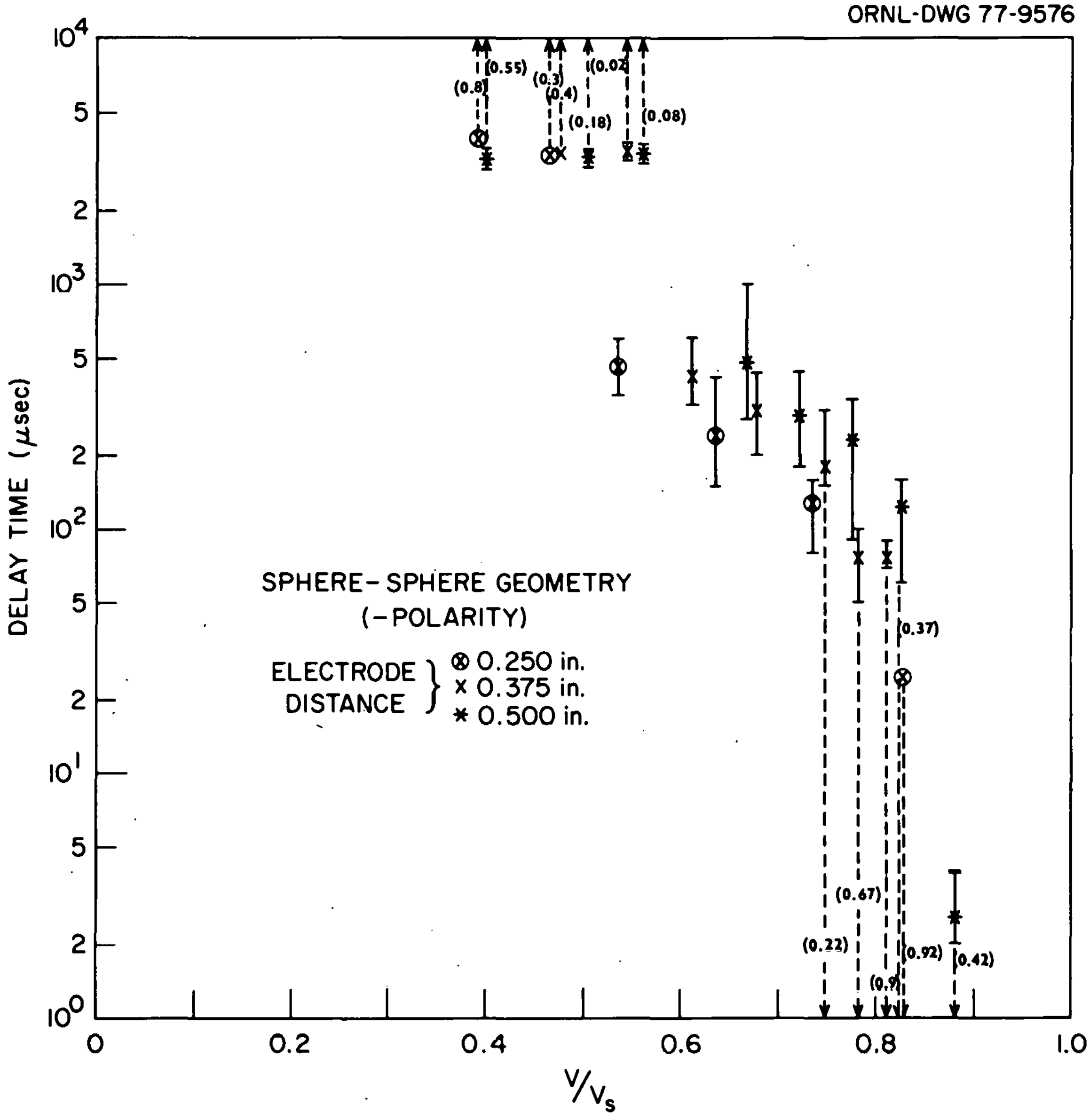

FIG. 17. Delay time as a function of V/V_S for sphere-sphere electrode geometry, negative polarity, and three electrode distances: 0.250 (⊗), 0.375 (x), and 0.500 (∗) in.

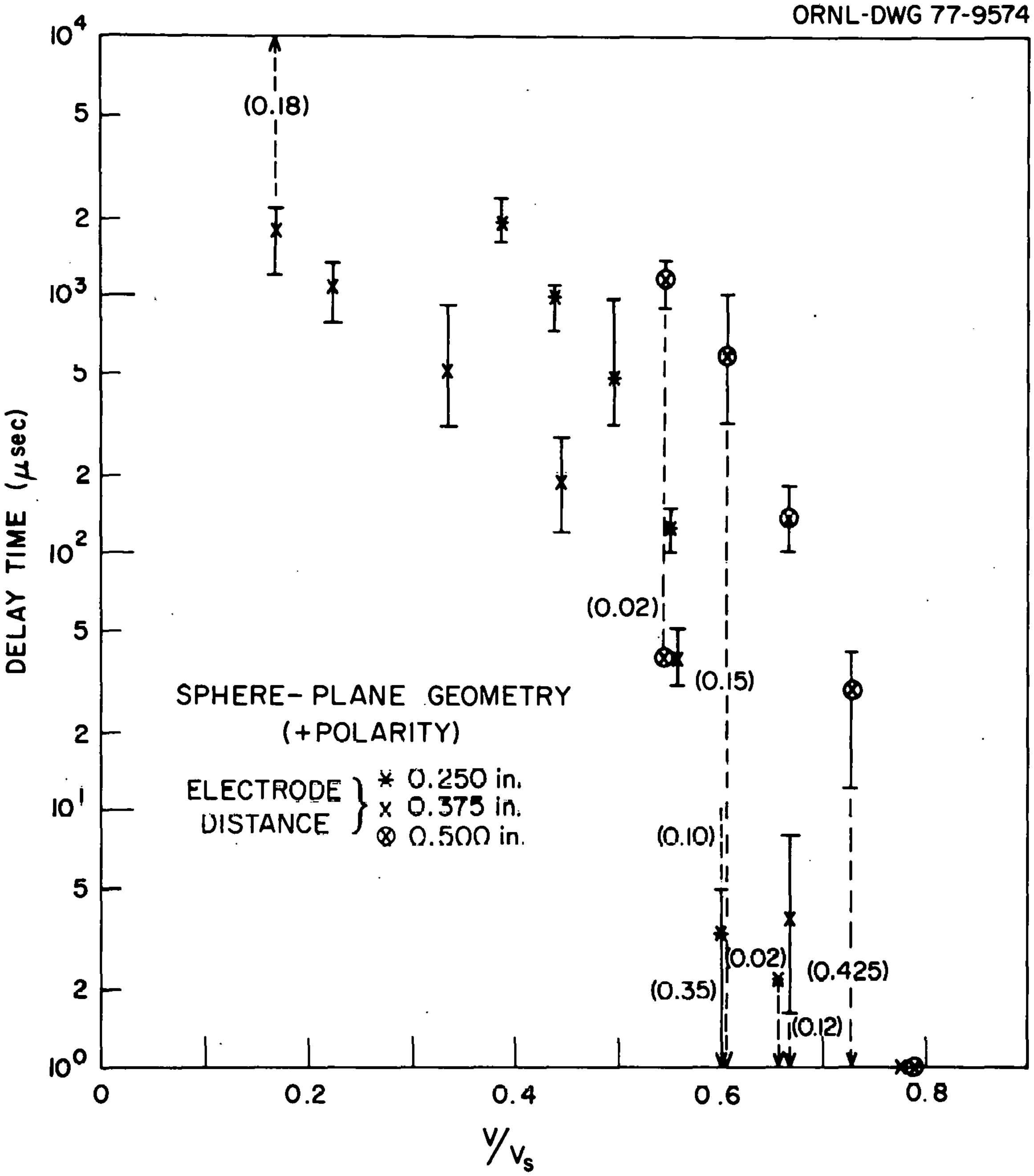

FIG. 18. Delay time as a function of V/V_s for sphere-plane electrode geometry, positive polarity, and three electrode distances: 0.250 (*), 0.375 (x), and 0.500 (ⓧ) in.

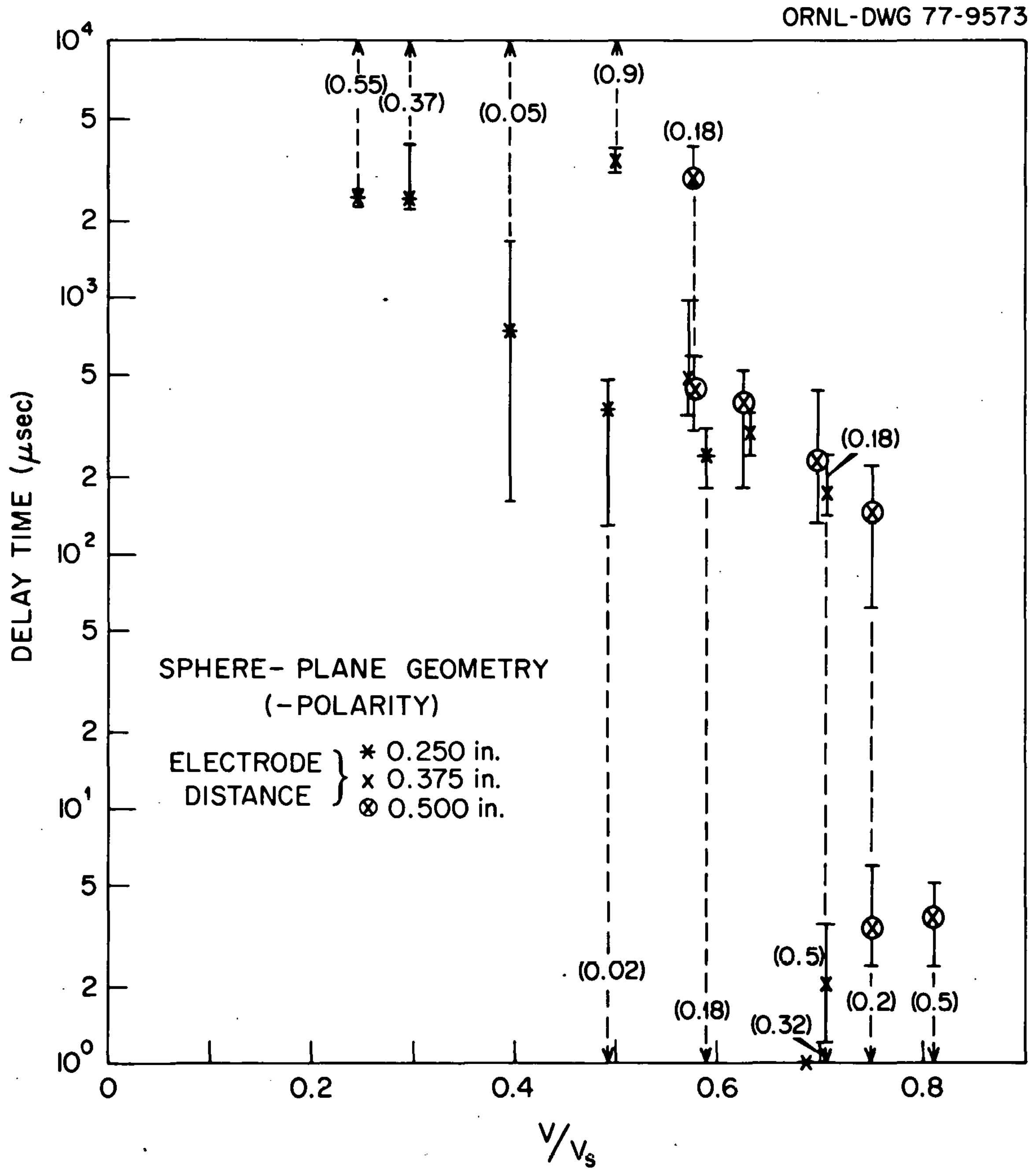

FIG. 19. Delay time as a function of V/V_S for sphere-plane electrode geometry, negative polarity, and three electrode distances: 0.250 (*), 0.375 (x), and 0.500 (⊗) in.

The salient features of these measurements are:

1. With any given electrode distance and polarity, the delay time decreases as the voltage across the electrode gap approaches the self (untriggered) breakdown.
2. Beyond a certain value of V/V_s, a fast breakdown mechanism takes over and the breakdown can proceed at much shorter times (< 1 μsec).
3. There is a region of voltage over which either of the two (fast and slow) breakdown mechanisms can occur with the probability of occurrence of the fast mechanism increasing as the voltage increases.

It should be noted that the delay times associated with the two mechanisms vary over a wide range. There is also a delay time associated with the trigger voltage itself which is of the order of 2 to 5 μsec. This is the well-known delay of breakdown in air gaps. Care must be taken when making measurements of delay times that the extra delay of the trigger electrode is properly accounted for.

As a practical matter, if diverters of this general type are used in equipment protection, both types of delay times (fast and slow) must be taken into account. Of course the use of gases other than air can change the delay time range of both mechanisms.

Our present means of acquiring data of this sort does not allow examination of the process of breakdown initiation which is fundamental to understanding the physical mechanisms involved. The use of a fast camera to observe the actual time characteristics of the spark seems to be the next natural step.

VII. INTERNATIONAL SYMPOSIUM ON GASEOUS DIELECTRICS

Arrangements are progressing well for this symposium to be convened on March 6-8, 1978, at the Hyatt Regency Hotel in Knoxville, Tennessee. ORNL will host the conference, which is sponsored by ORNL, ERDA, and EPRI. Advice of 15 experts worldwide has been solicited. Their replies were all enthusiastically in favor of such a meeting and provided valuable input to the planning of the conference and the technical program. Informal discussions were held with many other U.S. and overseas colleagues. A tentative program has been drafted.

VIII. CONTACTS

Dr. Martin Mastroianni and Mr. Larry Bobbin of Allied Chemical Company visited us in February. Dr. Mastroianni presented a seminar entitled "Dielectric Strengths of SF_6-Fluorocarbon Mixtures." Dr. John Whealton of the Fusion Energy Division of ORNL discussed theoretical simulation of breakdown with members of the group. Dr. Stephen Rice of Wayne State University visited us in March and presented a seminar entitled "Electron-Molecule Interactions in Dense Media."

A paper entitled "Improved Unitary and Multicomponent Gaseous Insulators" was accepted for the IEEE Conference on Electrical/Electronics Insulation in Chicago, Illinois, September 26-29, 1977. The paper will be published in the conference proceedings.

Contacts with researchers in the field were widened by a week-long tour of British laboratories at the Departments of Electrical Engineering at the Universities of Southampton, Liverpool, and Strathclyde, as well as Central Electricity Generating Board Laboratories at Leatherhead and Marchwood, by M. O. Pace. At Leatherhead, Dr. Brian Hampton explained his recent work on statistics of first breakdowns and on a new flexible SF_6 cable now being developed here by EPRI. At Marchwood, Mr. Roger Urwin reviewed the work of the switchgear group on SF_6 breakers. At the Electrical Engineering Department of the University of Southampton, Professor Barry Weedy explained their high voltage work, primarily on cryogenic systems. At the Electrical Engineering Department of the University of Liverpool, Professor J. D. Craggs provided visits with Professors J. Morruzzi, A. B. Parker, J. A. Rees, P. A. Chatterton, J. A. Harrison, and J. Lucas, who are active in a variety of basic aspects of breakdown. At the Electrical Engineering Department of the University of Strathclyde, Professors D. J. Tedford and Owen Farish arranged visits with Professors B. H. Crichton, A. Aked, D. T. A. Blair, I. Somerville, and R. C. Davidson, who are conducting research in most areas of high voltage engineering. The many discussions on a wide variety of topics were quite profitable. Areas of interaction and cooperation have been identified. The upcoming symposium (Section VII) was explained and universally approved.

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