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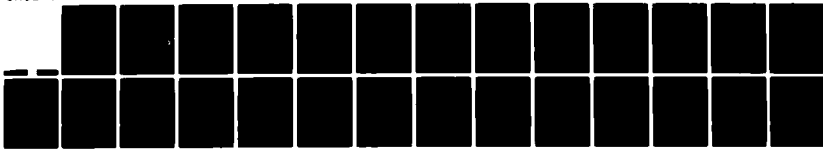
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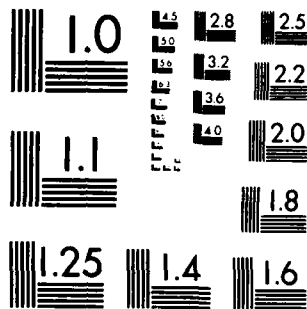
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BASIC STUDIES OF GASES FOR FAST SWITCHES

Semiannual Status Report

by

L. G. Christophorou and S. R. Hunter  
Health and Safety Research Division

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April 1983

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## BASIC STUDIES OF GASES FOR FAST SWITCHES

L. G. Christophorou and S. R. Hunter

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### I. INTRODUCTION

There has been increasing interest in recent years in the possibility of using inductive energy storage devices as a means of storing and transferring energy in numerous repetitive, pulsed-power applications. The major advantages to be realized using this technology are that the intrinsic energy density of these devices are of the order of  $10^2$  to  $10^3$  times those for capacitive systems<sup>1</sup> and that this energy can be transferred to the load on the very short-time scale of a few nanoseconds. The major technological problem to be faced when using this type of energy-storage system is in the design of a repetitive opening switch. A leading contender for this switching concept is an externally sustained diffuse gas discharge operating at gas pressures of one to several atmospheres. Two possible electron sources have been proposed for the external control of the discharge current. They are by means of gas ionization by pulsed electron beams (e-beams)<sup>2</sup> or by resonant ionization processes of the gaseous medium using a pulsed high power laser.<sup>3</sup> A number of operating parameters may be defined for these types of switches, which are common to both switching concepts. These parameters can then form a basis for tailoring specific gases and gas mixtures to optimize these operating conditions as nearly as possible.

The operating principle of the diffuse switch in the energy-storage cycle is given in Fig. 1 (Ref. 1). In the *conducting* stage, the switch

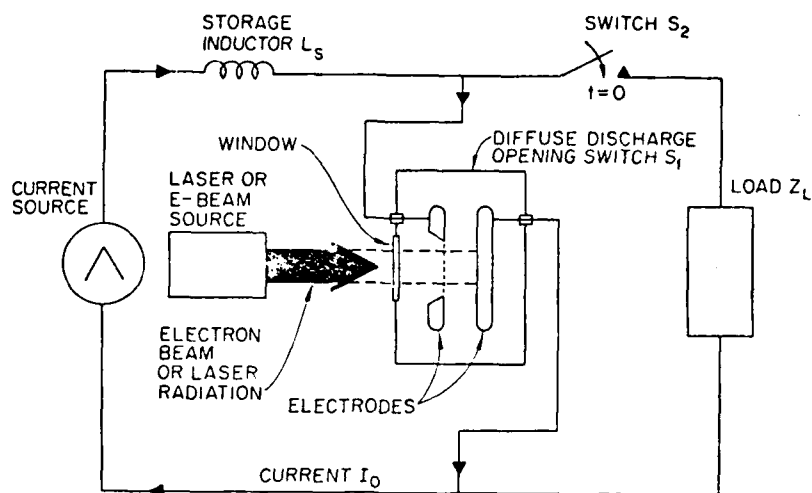


Fig. 1. Inductive energy discharge circuit (from Ref. 1).

$S_2$  is open, and the switch  $S_1$  is conducting by means of a diffuse discharge, which is sustained by ionization of the gas mixture using either an e-beam or a laser. In the opening stage, the external ionization source is removed, thus opening  $S_1$ , and the switch  $S_2$  is closed to allow the energy stored in the inductor,  $L_s$ , to be transferred to the load,  $Z_L$ . It is known, however, that in an inductive system where one attempts to rapidly open the conducting switch, a very large voltage is induced across the switch due to the term  $V_i = -L di/dt$  ( $L$  is the inductance of  $L_s$  in Fig. 1, and  $i$  is the current). This induced voltage tends to maintain a conducting arc between the electrodes of the switch  $S_1$  and to quote Kristiansen *et al.*,<sup>1</sup> "How to interrupt the conduction process against a high driving voltage is the essence of an opening switch."

The circuit equation governing the electron density,  $n_e$ , in the diffuse-discharge switch,  $S_1$ , which is driven by an external electron beam flux  $J_b$  at a given  $E/N$ , is

$$\frac{dn_e}{dt} = \langle ds/ds \rangle J_b w^{-1} - k_a n_e N_a - k_{R1} n_e n_+ \quad (1)$$

where  $\langle d\varepsilon/dx \rangle$  is the mean energy loss in the direction of the beam,  $W$  is the average energy required to produce an ion pair,<sup>4</sup>  $k_a$  is the electron attachment rate constant,  $N_a$  is the attaching gas number density,  $k_{R1}$  is the two-body recombination coefficient, and  $n_+$  is the positive ion number density. A similar expression may be written when the current in the switch is sustained by resonance (laser) photoionization of the gas mixtures. The current density in the switch  $J_s$  is given by Ohm's law, i.e.,

$$J_s = en_e w \quad , \quad (2)$$

where  $w$  is the electron drift velocity.

In the conducting stage, the electron current density in the switch must be as large as possible for a given e-beam current. In order for the switch to be as effective as possible, the electron loss terms in Eq. (1) must be minimized. Along with the minimization of the electron attachment rate constant  $k_a$ , the electron ionization rate constant  $k_i$  resulting from the applied electric field must be small,<sup>2</sup> otherwise the switch opening time will be increased considerably. This source of ionization can be ignored provided that  $k_i \ll k_a$  during the conducting and opening stages of the switch.

Conversely, the electron gain term  $\langle d\varepsilon/dx \rangle J_b W^{-1}$  is maximized so as to enhance the current gain in the discharge by minimizing the nonionizing inelastic processes in the gas constituents, while attempting to maximize their ionization cross sections. To maximize the efficiency of ion pair production, and hence the current in the switch,  $W$  must be minimized for a given gas mixture. A further criterion for enhancing the switch current,  $J_s$ , from Eq. (2) is to maximize the electron drift velocity (or

mobility) at the given electric field strength during the conduction stage. The desirable characteristics of the gaseous medium during the conduction stage may thus be summarized as follows: (1) maximum electron drift velocity,  $w$ ; (2) minimum e-beam ionization energy,  $W$ ; (3) minimum electron loss terms  $k_a$  and  $k_{R_1}$ ; and (4)  $k_i \ll k_a$ .

In the opening stage, the voltage across the switch increases rapidly due to the induced voltage across the inductor, causing an accompanying increase in  $E/N$  across the discharge gap. This basic difference between the conducting stage, where the applied conduction voltage is comparatively small ( $E/N \approx 3 \times 10^{-17} \text{ V cm}^2$ ),<sup>3</sup> and the opening stage, where the  $E/N$  across the gap may increase to values of  $\approx 120 \times 10^{-17} \text{ V cm}^2$ , is the key to tailoring gas mixtures with the desired operating characteristics.

In the opening stage, the external electron source is ceased, and the largest rate of decrease in the current of switch  $S_1$  occurs when  $k_a$  is as large as possible. Similarly, the response time of the switch is improved from Eq. (2) by choosing a gas mixture in which the electron drift velocity decreases when the  $E/N$  across the discharge gap increases. The gas mixture must also be able to withstand a high breakdown field ( $\approx 120 \times 10^{-17} \text{ V cm}^2$ ) for successful operation of the switch at very short opening times.

A further desirable characteristic of the gas mixture which becomes important when it is proposed to operate the switch at high repetition frequencies and a closed gas system is that the gas mixture be "self-healing." That is, the composition of the gas mixture is unaffected by the repetitive operation of the switch.<sup>3</sup> This characteristic is unobtainable when using a gas which attaches electrons dissociatively to



form negative ion and neutral fragments. Repetitive operation of the switch will eventually alter the composition of the gas and a possible degradation in performance will result unless one employs a flowing rather than a closed gas system. It is desirable in these circumstances that electron attachment proceeds via stabilization of the parent negative ion. This attachment mechanism does not lead to ion fragmentation and thus increases the operating life of the gas mixture in the switch.

The desirable characteristics of the gaseous medium during the opening stage may now be summarized:

1. Minimum electron mobility,  $\mu$ ;
2. Maximum electron attachment rate,  $k_a$ ;
3. High breakdown strength ( $E/N_{lim} > 120 \times 10^{-17} \text{ V cm}^2$ );
4. Self-healing gas mixtures for static gas-filled switches.

The desirable characteristics of the gas mixture in terms of the electron drift velocity  $w(E/N)$  and  $k_a(E/N)$  are shown in Fig. 2. The drift velocity must be a maximum at the  $E/N$  values (indicated by the shaded region characteristic of the conduction stage), and  $k_a$  must be as small as possible in this  $E/N$  range. In the opening stage,  $w$  must be as small as possible and  $k_a$  as high as possible at the  $E/N$  values (indicated by the shaded region in Fig. 2) characteristic of this stage.

## II. TECHNIQUES

We have used experimental techniques that have been developed in this laboratory during the past 10 years to identify gases and gas mixtures which have the desirable characteristics outlined in Section I when used in diffuse discharge-opening switches. These measurements have allowed us to tailor gas mixtures which can optimize the characteristics required in a given switching configuration.

### ELECTRON DRIFT/ATTACHMENT CHARACTERISTICS DESIRED IN DIFFUSE-DISCHARGE SWITCHES

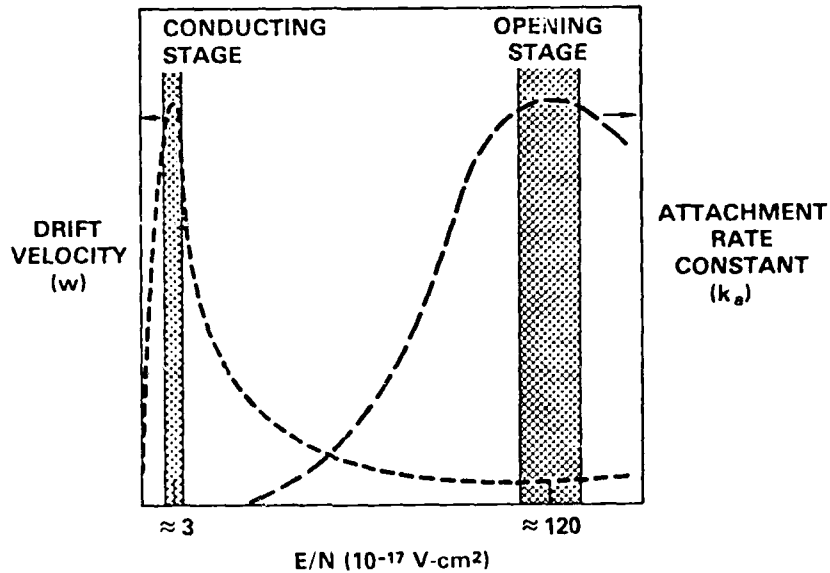


Fig. 2. Schematic illustration of the desirable characteristics of the  $w(E/N)$  and  $k_a(E/N)$  functions of the gaseous medium in an externally (e-beam-sustained) diffuse-discharge switch. Indicated in the figure are rough estimates of the  $E/N$  values for the conducting and opening stages of the switch.

Measurements of  $w$  in pure gases and gas mixtures have been made in the apparatus described by Christophorou *et al.*<sup>5,6,7</sup> This apparatus has been used to measure  $w$  in gas mixtures for use in high speed proportional counters and to study the density dependence of  $w$  in dense polar gases. Electron attachment rate constant,  $k_a$ , measurements are obtained as a function of mean electron energy,  $\langle \epsilon \rangle$ , in a high pressure electron attachment apparatus which has been described previously.<sup>4,8</sup> This apparatus has been used to screen highly electron attaching gases for

possible use as gaseous dielectrics in high voltage transmission equipment.<sup>9</sup> These measurements have enabled us to identify several gases with desirable electron attaching properties<sup>10, 11</sup> (Appendix A) for use in diffuse-discharge opening switches. Electric field breakdown strength measurements are performed in a high pressure uniform field breakdown apparatus described previously.<sup>12</sup> These measurements enable us to determine the breakdown strengths of proposed gas mixtures as a function of attaching gas concentration, thus defining the operating E/N limits of specific gas mixtures. Negative ion and neutral decomposition fragments produced under low energy electron impact have been studied using a single collision time-of-flight mass spectrometer apparatus.<sup>13, 14</sup> These studies enable us to identify the fragments produced in the gas discharge and thus estimate the possible deleterious or beneficial effects that these fragments will have on the operation of the diffuse-discharge switch.

### III. TECHNICAL PROGRESS

The measurements that have been performed during this reporting period have allowed us to identify several attaching gas/buffer gas mixtures which have very desirable electron attaching and drift velocity characteristics for possible use in diffuse-discharge opening switches. The decomposition products resulting from electron attaching collisions have been identified, and the operating E/N limits of several gases and gas mixtures have been determined.

#### A. Equipment Modifications and New Experimental Techniques

A new technique for measuring the electron attachment ( $\eta/N$ ) and ionization ( $\alpha/N$ ) coefficients has been developed using a modification of the Grünberg<sup>15</sup> method and the "state-of-the-art" data acquisition

capabilities of the Biomation 8100 transient digitizer. Electron attachment and ionization coefficient measurements in several gases and gas mixtures have been obtained over a wide range of E/N and gas pressures using this technique.

A new high-field-uniformity drift assembly has been constructed with a drift gap approximately 3 times that of our present apparatus. A new high-speed (2 ns/channel) Biomation 6500 transient digitizer has been purchased and interfaced with our data acquisition and analysis computer. With these two improvements, we can now accurately measure electron drift velocities in fast gases and gas mixtures up to  $\sim 5 \times 10^7$  cm/s (i.e., approximately 10 times faster than in the original experiment).

#### B. Basic Data

We have obtained electron attachment and ionization coefficients in  $O_2$ ,  $CF_4$ ,  $C_2F_6$ , and  $C_3F_8$  gases using the new method of analysis outlined above. The pressure dependence of the electron attachment coefficient in  $O_2$  and  $C_3F_8$  has also been analyzed. A paper describing this technique and the measurements in these gases is in preparation.

Measurements of  $\alpha/N$  and  $\eta/N$  in  $C_2F_6/Ar$  and  $C_2F_6/CH_4$  gas mixtures have been obtained over the concentration range of from 0.1 to 30% which can be used in modeling studies of diffuse-discharge switches. These measurements and their significance will be discussed in a paper to be presented at the Third International Swarm Seminar (see Part C of this section).

High-pressure electron attachment rate constant measurements ( $k_a = \eta w/N$ ) have been obtained in  $N_2$  and Ar buffer gases for the per-fluoroalkane series  $CF_4$  to  $n-C_6F_{14}$  over the mean electron energy range

from thermal energy ( $\sim 0.04$  eV) to  $\sim 4.8$  eV. Knowledge of the electron energy distribution functions for those buffer gases has enabled us to obtain the electron attachment cross sections ( $\sigma_a$ ) for these electro-negative gases from such measurements. Single collision negative ion production studies have been performed for these gases which have identified the negative ion and neutral fragments which will be produced during the operation of the switching gas discharge.

High-pressure electron attachment rate constant measurements, electron attachment cross sections, and negative ion production as a function of electron energy have also been obtained for the ethers  $(CF_3)_2O$  and  $(CF_3)_2S$ . Both  $(CF_3)_2O$  and  $(CF_3)_2S$  have desirable electron attaching properties for use in diffuse-discharge switches.

High voltage breakdown strengths ( $E/N_{lim}$ ) have been obtained for the gas mixtures  $C_2F_6/Ar$ ,  $C_2F_6/CH_4$ ,  $C_3F_8/Ar$ , and  $C_3F_8/CH_4$  as a function of the percentage of the electron attaching gas in the buffer gas. These measurements are useful in optimizing the attaching gas concentration and total gas pressure in the operation of practical diffuse-discharge switches.

High-pressure swarm studies are being performed for  $CClF_3$  in  $N_2$  and Ar buffer gases as a function of gas temperature over the temperature range 300 to 600 K. Considerable enhancement of the electron attachment rate constant has been observed in this gas over this temperature range.

### C. Publications

Preliminary results of the measurements outlined above have been published in the *Proceedings of the Workshop on Gaseous Breakdown Phenomena* sponsored by the Naval Surface Weapons Center in September 1982 (see Appendix B) and in the *Proceedings of the Tamarron (Colorado) Workshop*

on Diffuse Discharge Opening Switches in January 1983. An abstract (Appendix C) has been submitted for a presentation at the IEEE 4th International Pulsed Power Conference in June 1983, and at the Third International Swarm Seminar in August 1983, in which our latest measurements will be reported and discussed. A paper is presently in preparation for journal publication in which our electron attachment and ionization coefficient measurement technique will be outlined, and the measurements in the gases mentioned above will be analyzed.

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APPENDIX A



## Gases for possible use in diffuse-discharge switches

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Desirable electron attachment and electron drift characteristics of gases for possible use in diffuse-discharge switches are indicated. Gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches are suggested on the basis of electron attachment rate constants and electron drift velocities measured as a function of the density-normalized electric field  $E/N$ . Of particular promise are mixtures of Ar and  $C_3F_8$ .

PACS numbers: 52.80.Dy, 51.50.+v, 34.70.+e, 34.80.Gs

It has been pointed out recently<sup>1,2</sup> that in pulsed-power applications, energy storage using inductive elements could be advantageous because of the high intrinsic energy density: about  $10^2$  to  $10^4$  times that for capacitive systems. It appears<sup>1-3</sup> that the main technological problem in inductive storage systems for pulsed-power applications is the need for an opening switch—capable of repetitive operation—to transfer the energy from the storage loop to the load. In this letter we wish to suggest candidate gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches.

The requirements of a gaseous medium for use in a diffuse-discharge switch can be understood by realizing that a basic difference between the conducting (storing) and the opening (transferring) stages of the switch (at least in the *e*-beam-sustained discharge) is the effective value of the density-reduced electric field,  $E/N$  (or  $E/P$ ). In the conducting stage the  $E/N$  is low ( $\sim 3 \times 10^{-17}$  V cm<sup>2</sup>), while in the opening stage the  $E/N$  is high ( $\sim 120 \times 10^{-17}$  V cm<sup>2</sup>). This is most significant and remains a key variable in efforts to tailor gases for optimum performance in both stages. The gas, which in the conducting stage must optimize conduction (high  $w$ , no attachment, reduced recombination), in the transferring stage must serve as a high-voltage insulant in order to sustain the high driving voltage and prevent breakdown.

In Fig. 1 we show schematically the desirable characteristics of the gas in terms of the drift velocity  $w(E/N)$  and the attachment rate constant  $k_a(E/N)$ . The drift velocity  $w$  must be a maximum at the  $E/N$  values (indicated by the shaded region in Fig. 1) characteristic of the conducting stage, and  $k_a$  must be as small as possible in this  $E/N$  range. In the opening state (Fig. 1),  $w$  must be as small as possible and  $k_a$  as high as possible at the  $E/N$  values (indicated by the shaded region in Fig. 1) characteristic of this stage.

Fast gases having the general characteristics of  $w(E/N)$  shown in Fig. 1 have been reported by us<sup>4</sup> (e.g., Ar +  $CF_4$  mixtures) which are free of electron attachment at low  $E/N$ . Promising mixtures that are comprised of Ar and  $CF_4$  are shown in Fig. 2. The mixture composition and  $E/N$  can be chosen such as to maximize  $w$  in the conducting stage. It is also seen that at high  $E/N$ , the  $w$  of such mixtures falls off

considerably, a property desirable in the opening stage of the switch<sup>5</sup> (see Fig. 1).

To become effective for the opening stage of the switch, such gases must, in addition, have a high dielectric strength. To achieve this, the mixture must effectively remove electrons by electron attachment forming negative ions.<sup>6,7</sup> Since in the opening stage of the switch  $E/N$  is very high, the gas must be capable of removing electrons with energies in excess of thermal energy. It thus seems that a fast gas mixture (i.e., one with high  $w$ ) such as Ar +  $CF_4$  must be mixed with a third gas which does not attach thermal and near-thermal energy electrons but which attaches electrons at higher energies (say, from  $\sim 0.5$  to 2 eV). Candidates for such electron attaching gases to mix with the fast mixtures of Ar +  $CF_4$  are shown in Fig. 3.

Special attention is drawn to the gas  $(CF_3)_2S$  which is seen (Fig. 3) to capture electrons rather strongly above thermal energies and which itself is an excellent gas dielectric having a dc uniform field breakdown strength 1.5 times that of  $SF_6$  (Ref. 9). A mass spectrometric study of  $(CF_3)_2S$  has shown<sup>10</sup> that the dominant anion is  $CF_3S^-$  whose yield peaks at  $\sim 0.65$  eV, a finding consistent with the  $k_a$  vs  $(\epsilon)$

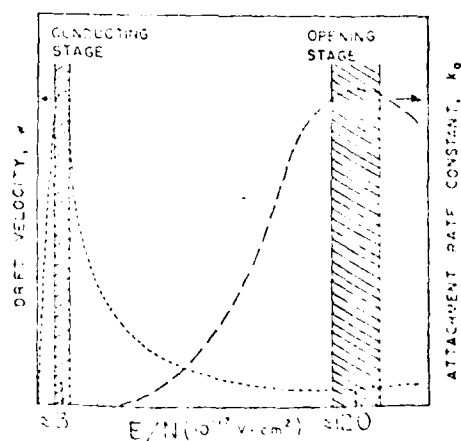


FIG. 1. Schematic illustration of the desirable characteristics of the gas  $w(E/N)$  and  $k_a(E/N)$  functions of the gaseous medium in an externally *e*-beam-sustained diffuse-discharge switch. Indicated in the figure are rough estimates of the  $E/N$  values for the conducting and the opening stage of the switch.

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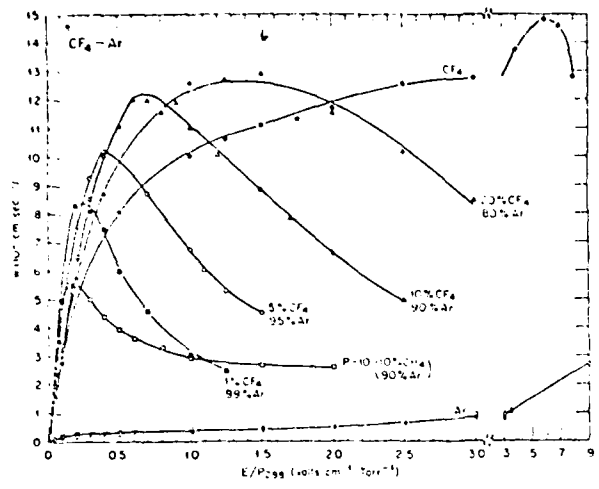


FIG. 2.  $w$  vs  $E/P_{298}$  for Ar and Ar/CF<sub>4</sub> mixtures (from Ref. 4).

lata in Fig. 3. The vapor pressure of (CF<sub>3</sub>)<sub>2</sub>S at ~20 °C is ~4.4 atm.

It follows from the above discussion that ternary mixtures comprised of Ar + CF<sub>4</sub> and (CF<sub>3</sub>)<sub>2</sub>S (or another electron attaching additive with the appropriate properties, Figs. 1 and 3) are good candidates for diffuse-discharge witches. It is, however, preferable to have a binary rather than a ternary mixture and to identify, for example, a gas which would serve the role of both CF<sub>4</sub> and (CF<sub>3</sub>)<sub>2</sub>S when mixed with Ar. In the search for such a gas we focused on C<sub>3</sub>F<sub>8</sub>. The attachment rate constant  $k_a$  as a function of  $\langle \epsilon \rangle$  or C<sub>3</sub>F<sub>8</sub> is shown in Fig. 3. Although the  $k_a$  for C<sub>3</sub>F<sub>8</sub> is lower in magnitude than that for (CF<sub>3</sub>)<sub>2</sub>S, it has a very desirable  $\langle \epsilon \rangle$

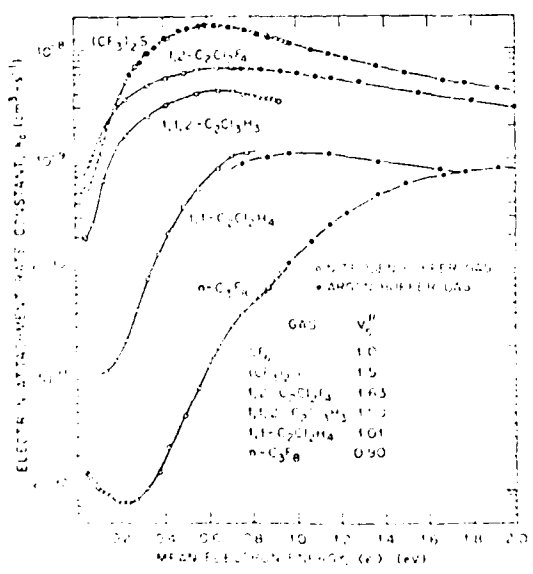


FIG. 3. Electron attachment rate constant  $k_a$  as a function of mean electron energy  $\langle \epsilon \rangle$  for (CF<sub>3</sub>)<sub>2</sub>S and C<sub>3</sub>F<sub>8</sub> (present work) and 1,1,2-C<sub>2</sub>Cl<sub>2</sub>F<sub>3</sub>, 1,1,2-C<sub>2</sub>Cl<sub>2</sub>H<sub>3</sub>, and 1,1-C<sub>2</sub>Cl<sub>2</sub>H<sub>4</sub> (from Ref. 8). The relative breakdown strengths  $V_b^0$  shown in the figure are from Ref. 7 except those for (CF<sub>3</sub>)<sub>2</sub>S, which are from Ref. 9.

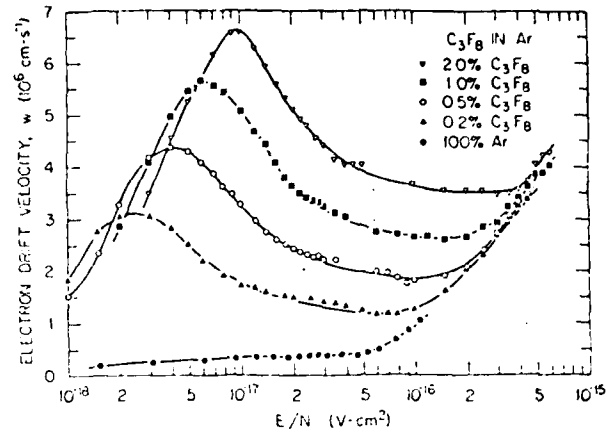


FIG. 4.  $w$  vs  $E/N$  for Ar and Ar/C<sub>3</sub>F<sub>8</sub> mixtures.

dependence (i.e., it is very small at low  $\langle \epsilon \rangle$  and large at high  $\langle \epsilon \rangle$ ). Mass spectrometric studies in a single collision experiment have shown<sup>11</sup> that the dominant anion is F<sup>-</sup> with a peak at 2.9 eV. Swarm studies at atmospheric gas pressures indicate<sup>12</sup> that the predominant electron attachment process in this gas proceeds via stabilization of the parent negative ion. This attaching gas is thus "self-healing" in that it does not fragment considerably in an electron attaching collision and may be useful in a closed-cycle switch as well.

In Fig. 4 are presented  $w$  vs  $E/N$  for Ar and Ar/C<sub>3</sub>F<sub>8</sub> mixtures. Due to apparatus limitations, we were unable to obtain data for higher percentages of C<sub>3</sub>F<sub>8</sub> in Ar (our apparatus is being modified to allow such measurements). However, based on the data on Ar + CF<sub>4</sub> (Fig. 2) and similar data on Ar + C<sub>2</sub>F<sub>6</sub> (not presented because of space limitation) we can infer that mixtures comprised of 10-20% C<sub>3</sub>F<sub>8</sub> and 90-80% Ar will have maximum values of  $w$  in excess of 10<sup>7</sup> cm s<sup>-1</sup> and  $w(E/N)$  functions maximizing in the  $E/N$  range of 2-4 × 10<sup>-17</sup> V cm<sup>2</sup>, which is roughly the range characteristic of the conductive stage of the switch.

We have conducted dc uniform field breakdown

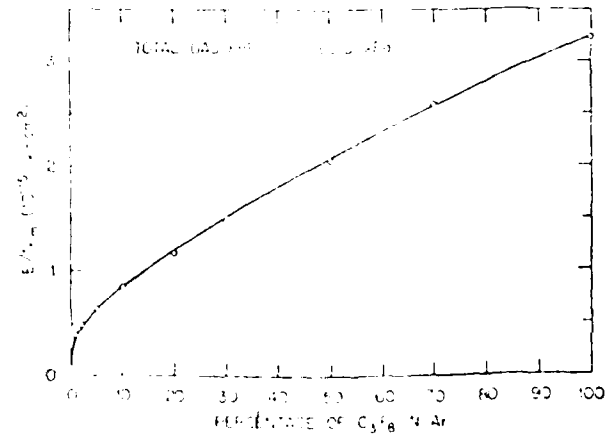


FIG. 5.  $(E/N)_{max}$  vs percentage of C<sub>3</sub>F<sub>8</sub> in Ar under dc uniform field conditions.

strength measurements on Ar/C<sub>3</sub>F<sub>8</sub> mixtures and determined (Fig. 5) the limiting value,  $(E/N)_{lim}$ , of  $E/N$  (i.e., the  $E/N$  value at which breakdown occurs) as a function of the percentage of C<sub>3</sub>F<sub>8</sub> in Ar. It can be seen from the data in Fig. 5 that for Ar/C<sub>3</sub>F<sub>8</sub> mixtures containing ~15–20% C<sub>3</sub>F<sub>8</sub>, the  $(E/N)_{lim}$  is  $\approx 120 \times 10^{-17}$  V cm<sup>2</sup>, i.e., such mixtures can withstand the voltage levels characteristic of the opening stage of the switch.

Although further work is necessary, on the basis of the preliminary data presented, it can be suggested that mixtures comprised of ~15–20% C<sub>3</sub>F<sub>8</sub> and 80–85% Ar may possess both of the required characteristics (see Fig. 1) of a switching gas and can thus be suggested as good candidates for diffuse-discharge switches.<sup>13</sup>

This research was sponsored by the Office of Health and Environmental Research and the Division of Electric Energy Systems, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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press); see also relevant papers in *IEEE Trans. Plasma Sci.* PS-8 (1980).

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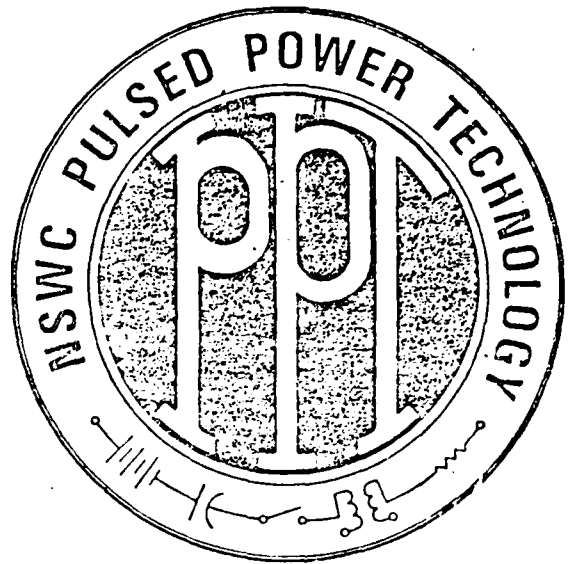
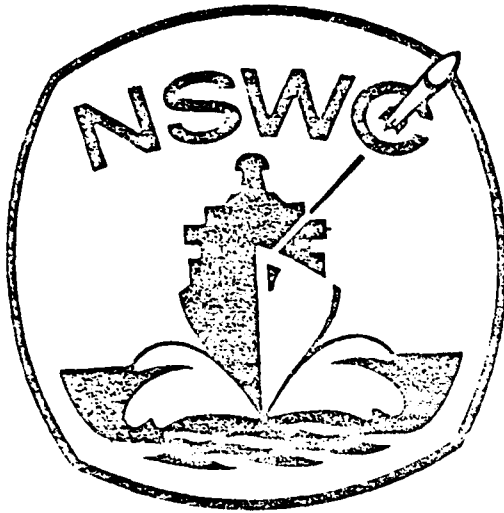
<sup>10</sup>S. M. Spyrou (private communication 1981).

<sup>11</sup>L. G. Christophorou, D. R. James, R. Y. Pai, R. A. Mathis, I. Sauer, D. H. Smith, L. C. Frees, S. R. Hunter, M. O. Pace, D. W. Bouldin, S. M. Spyrou, and A. Fatheddin, Oak Ridge National Laboratory Report ORNL/TM-7862, 1981, p. 14.

<sup>12</sup>S. R. Hunter, L. G. Christophorou, D. R. James, and R. A. Mathis, in *Gaseous Dielectrics III*, edited by L. G. Christophorou (Pergamon, to be published).

<sup>13</sup>The vapor pressure of C<sub>3</sub>F<sub>8</sub> at ~20 °C is ~7.8 atm; C<sub>3</sub>F<sub>8</sub> is listed in [*Matheson Gas Data Book*, 5th ed., edited by W. Braiker and A. L. Mossman (New Jersey, 1971), p. 467] as nontoxic, nonflammable, unreactive, and thermally stable; its dc uniform field breakdown voltage is 0.9 that of SF<sub>6</sub>.

APPENDIX B



**WORKSHOP ON GASEOUS  
BREAKDOWN PHENOMENA**

**15 SEPTEMBER 1982**

**NAVAL SURFACE WEAPONS CENTER**

## Gases for possible use in diffuse-discharge switches

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(Received 29 March 1982; accepted for publication 6 May 1982)

Desirable electron attachment and electron drift characteristics of gases for possible use in diffuse-discharge switches are indicated. Gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches are suggested on the basis of electron attachment rate constants and electron drift velocities measured as a function of the density-normalized electric field  $E/N$ . Of particular promise are mixtures of Ar and  $C_3F_8$ .

PACS numbers: 52.80.Dy, 51.50.+v, 34.70.+e, 34.80.Gs

It has been pointed out recently<sup>1,2</sup> that in pulsed-power applications, energy storage using inductive elements could be advantageous because of the high intrinsic energy density: about  $10^2$  to  $10^4$  times that for capacitive systems. It appears<sup>1-3</sup> that the main technological problem in inductive storage systems for pulsed-power applications is the need for an opening switch—capable of repetitive operation—to transfer the energy from the storage loop to the load. In this letter we wish to suggest candidate gas mixtures for possible use in externally sustained (*e*-beam) diffuse-discharge switches.

The requirements of a gaseous medium for use in a diffuse-discharge switch can be understood by realizing that a basic difference between the conducting (storing) and the opening (transferring) stages of the switch (at least in the *e*-beam-sustained discharge) is the effective value of the density-reduced electric field,  $E/N$  (or  $E/P$ ). In the conducting stage the  $E/N$  is low ( $\sim 3 \times 10^{-17}$  V cm<sup>2</sup>), while in the opening stage the  $E/N$  is high ( $\sim 120 \times 10^{-17}$  V cm<sup>2</sup>). This is most significant and remains a key variable in efforts to tailor gases for optimum performance in both stages. The gas, which in the conducting stage must optimize conduction (high  $w$ , no attachment, reduced recombination), in the transferring stage must serve as a high-voltage insulant in order to sustain the high driving voltage and prevent breakdown.

In Fig. 1 we show schematically the desirable characteristics of the gas in terms of the drift velocity  $w(E/N)$  and the attachment rate constant  $k_a(E/N)$ . The drift velocity  $w$  must be a maximum at the  $E/N$  values (indicated by the shaded region in Fig. 1) characteristic of the conducting stage, and  $k_a$  must be as small as possible in this  $E/N$  range. In the opening state (Fig. 1),  $w$  must be as small as possible and  $k_a$  as high as possible at the  $E/N$  values (indicated by the shaded region in Fig. 1) characteristic of this stage.

Fast gases having the general characteristics of  $w(E/N)$  shown in Fig. 1 have been reported by us<sup>4</sup> (e.g., Ar +  $CF_4$  mixtures) which are free of electron attachment at low  $E/N$ . Promising mixtures that are comprised of Ar and  $CF_4$  are shown in Fig. 2. The mixture composition and  $E/N$  can be chosen such as to maximize  $w$  in the conducting stage. It is also seen that at high  $E/N$ , the  $w$  of such mixtures falls off

considerably, a property desirable in the opening stage of the switch<sup>5</sup> (see Fig. 1).

To become effective for the opening stage of the switch, such gases must, in addition, have a high dielectric strength. To achieve this, the mixture must effectively remove electrons by electron attachment forming negative ions.<sup>6,7</sup> Since in the opening stage of the switch  $E/N$  is very high, the gas must be capable of removing electrons with energies in excess of thermal energy. It thus seems that a fast gas mixture (i.e., one with high  $w$ ) such as Ar +  $CF_4$  must be mixed with a third gas which does not attach thermal and near-thermal energy electrons but which attaches electrons at higher energies (say, from  $\sim 0.5$  to 2 eV). Candidates for such electron attaching gases to mix with the fast mixtures of Ar +  $CF_4$  are shown in Fig. 3.

Special attention is drawn to the gas  $(CF_3)_2S$  which is seen (Fig. 3) to capture electrons rather strongly above thermal energies and which itself is an excellent gas dielectric having a de uniform field breakdown strength 1.2 times that of  $SF_6$  (Ref. 9). A mass spectrometric study of  $(CF_3)_2S$  has shown<sup>10</sup> that the dominant anion is  $CF_3S^-$  whose yield peaks at  $\sim 0.65$  eV, a finding consistent with the  $k_a$  vs  $(\epsilon)$

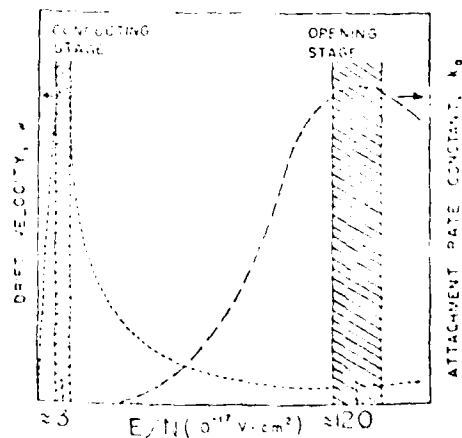


FIG. 1. Schematic illustration of the desirable characteristics of the  $w(E/N)$  and  $k_a(E/N)$  functions of the gaseous medium in an externally (*e*-beam-sustained) diffuse-discharge switch. Indicated in the figure are rough estimates of the  $E/N$  values for the conducting and the opening stage of the switch.

<sup>a)</sup> Also, Department of Physics, The University of Tennessee, Knoxville, Tennessee 37916.

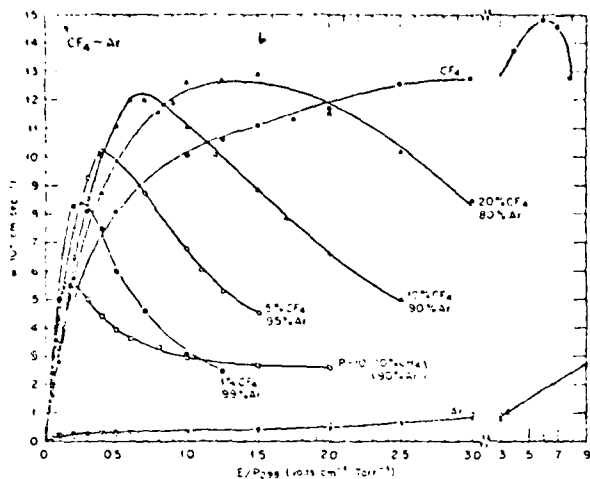


FIG. 2.  $w$  vs  $E/P_{298}$  for Ar and Ar/ $CF_4$  mixtures (from Ref. 4).

lata in Fig. 3. The vapor pressure of  $(CF_3)_2S$  at  $\sim 20^\circ C$  is  $\sim 4.4$  atm.

It follows from the above discussion that ternary mixtures comprised of Ar +  $CF_4$  and  $(CF_3)_2S$  (or another electron attaching additive with the appropriate properties, Figs. 1 and 3) are good candidates for diffuse-discharge wickies. It is, however, preferable to have a binary rather than a ternary mixture and to identify, for example, a gas which would serve the role of both  $CF_4$  and  $(CF_3)_2S$  when mixed with Ar. In the search for such a gas we focused on  $C_3F_8$ . The attachment rate constant  $k_a$  as a function of  $\langle \epsilon \rangle$  or  $C_3F_8$  is shown in Fig. 3. Although the  $k_a$  for  $C_3F_8$  is lower in magnitude than that for  $(CF_3)_2S$ , it has a very desirable  $\langle \epsilon \rangle$

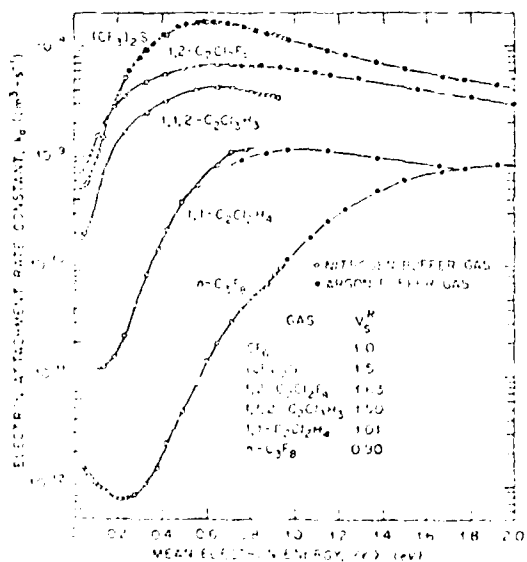


FIG. 3. Electron attachment rate constant  $k_a$  as a function of mean electron energy  $\langle \epsilon \rangle$  for  $(CF_3)_2S$  and  $C_3F_8$  (present work) and  $1,2-C_2Cl_2F_2$ ,  $1,1,2-C_2Cl_2H_2$ , and  $1,1-C_2Cl_2H_2$  (from Ref. 8). The relative breakdown strengths  $V_5^0$  shown in the figure are from Ref. 7 except those for  $(CF_3)_2S$ , which are from Ref. 9.

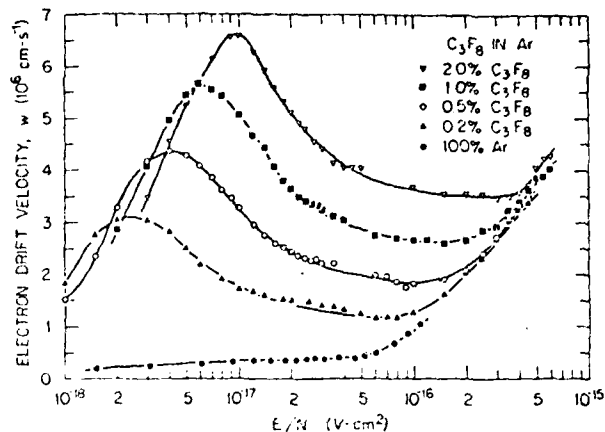


FIG. 4.  $w$  vs  $E/N$  for Ar and Ar/ $C_3F_8$  mixtures.

dependence (i.e., it is very small at low  $\langle \epsilon \rangle$  and large at high  $\langle \epsilon \rangle$ ). Mass spectrometric studies in a single collision experiment have shown<sup>11</sup> that the dominant anion is  $F^-$  with a peak at 2.9 eV. Swarm studies at atmospheric gas pressures indicate<sup>12</sup> that the predominant electron attachment process in this gas proceeds via stabilization of the parent negative ion. This attaching gas is thus "self-healing" in that it does not fragment considerably in an electron attaching collision and may be useful in a closed-cycle switch as well.

In Fig. 4 are presented  $w$  vs  $E/N$  for Ar and Ar/ $C_3F_8$  mixtures. Due to apparatus limitations, we were unable to obtain data for higher percentages of  $C_3F_8$  in Ar (our apparatus is being modified to allow such measurements). However, based on the data on Ar +  $CF_4$  (Fig. 2) and similar data on Ar +  $C_2F_6$  (not presented because of space limitation) we can infer that mixtures comprised of 10–20%  $C_3F_8$  and 90–80% Ar will have maximum values of  $w$  in excess of  $10^7$  cm s<sup>-1</sup> and  $w(E/N)$  functions maximizing in the  $E/N$  range of  $2-4 \times 10^{-17}$  V cm<sup>2</sup>, which is roughly the range characteristic of the conductive stage of the switch.

We have conducted dc uniform field breakdown

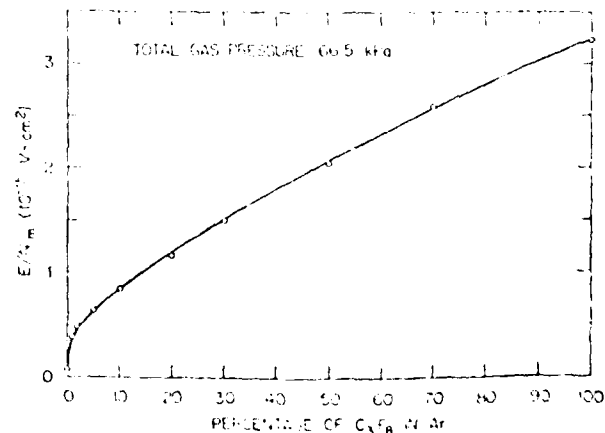


FIG. 5.  $(E/N)_m$  vs percentage of  $C_3F_8$  in Ar under dc uniform field conditions.

strength measurements on Ar/C<sub>3</sub>F<sub>8</sub> mixtures and determined (Fig. 5) the limiting value,  $(E/N)_{lim}$ , of  $E/N$  (i.e., the  $E/N$  value at which breakdown occurs) as a function of the percentage of C<sub>3</sub>F<sub>8</sub> in Ar. It can be seen from the data in Fig. 5 that for Ar/C<sub>3</sub>F<sub>8</sub> mixtures containing ~15–20% C<sub>3</sub>F<sub>8</sub>, the  $(E/N)_{lim}$  is  $\approx 120 \times 10^{-17}$  V cm<sup>2</sup>, i.e., such mixtures can withstand the voltage levels characteristic of the opening stage of the switch.

Although further work is necessary, on the basis of the preliminary data presented, it can be suggested that mixtures comprised of ~15–20% C<sub>3</sub>F<sub>8</sub> and 80–85% Ar may possess both of the required characteristics (see Fig. 1) of a switching gas and can thus be suggested as good candidates for diffuse-discharge switches.<sup>13</sup>

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<sup>10</sup>S. M. Spyrou (private communication 1981).

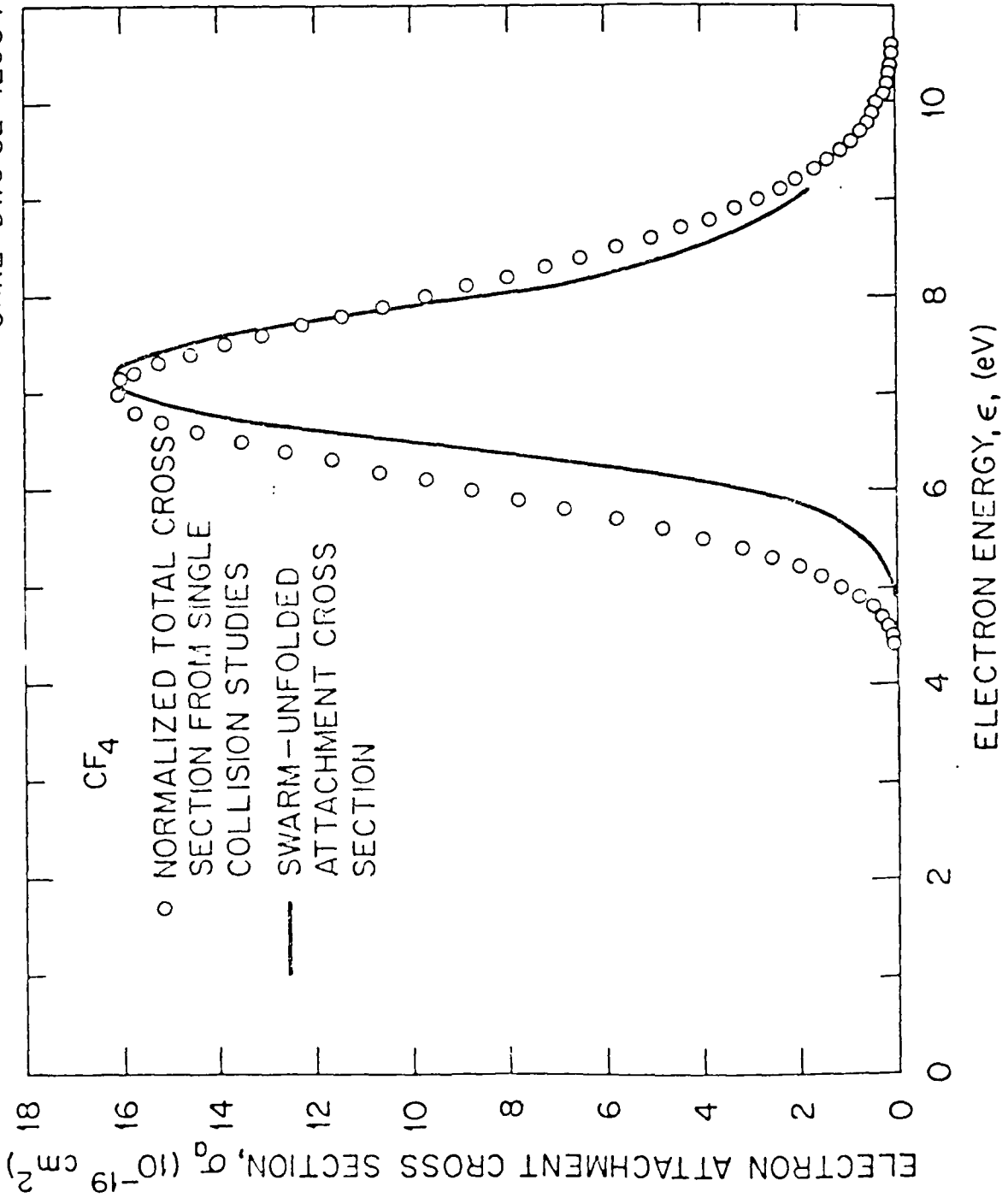
<sup>11</sup>L. G. Christophorou, D. R. James, R. Y. Pai, R. A. Mathis, I. Sauer, D. H. Smith, L. C. Frees, S. R. Hunter, M. O. Pace, D. W. Bouldin, S. M. Spyrou, and A. Fatheddin, *Oak Ridge National Laboratory Report ORNL/TM-7862*, 1981, p. 14.

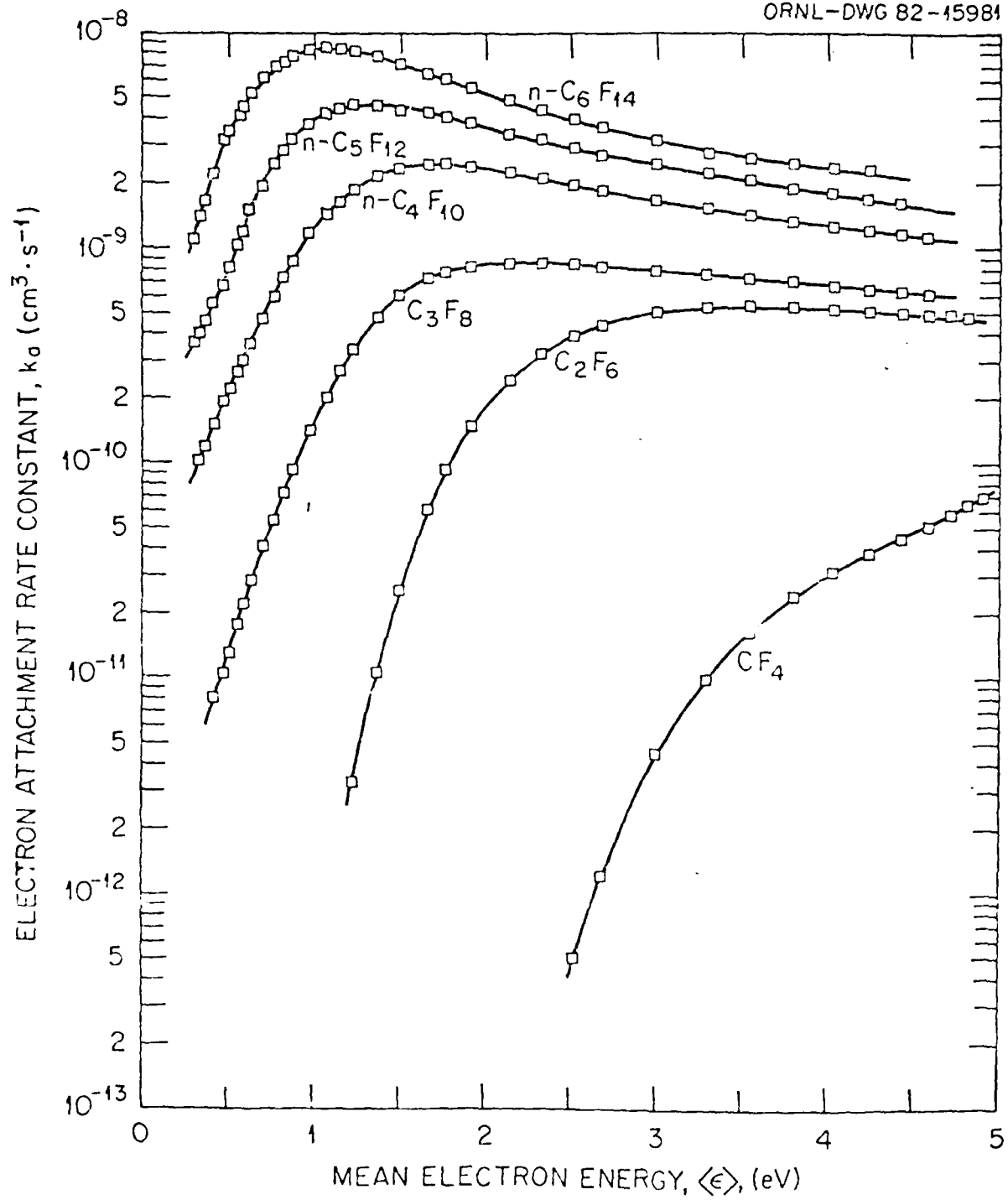
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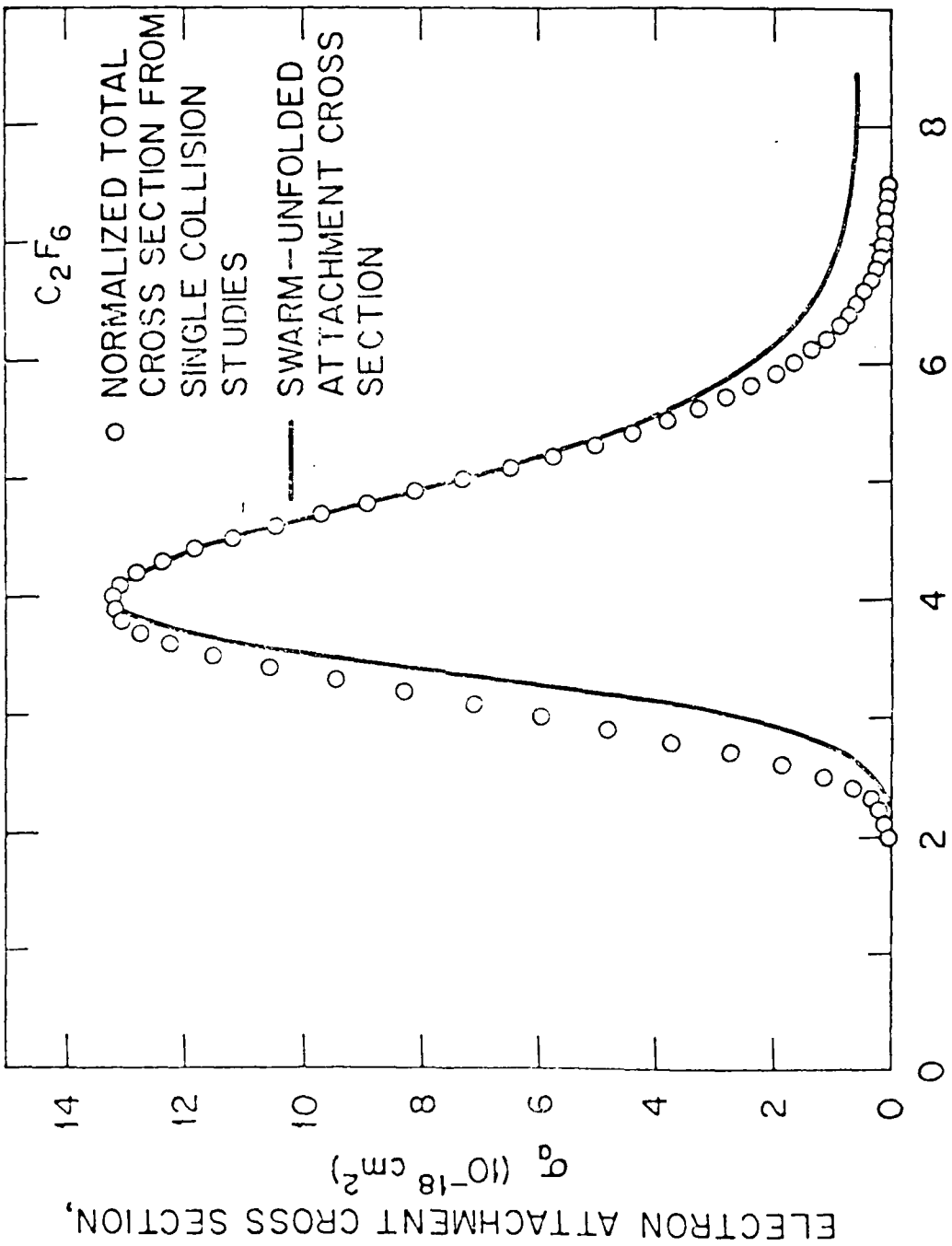


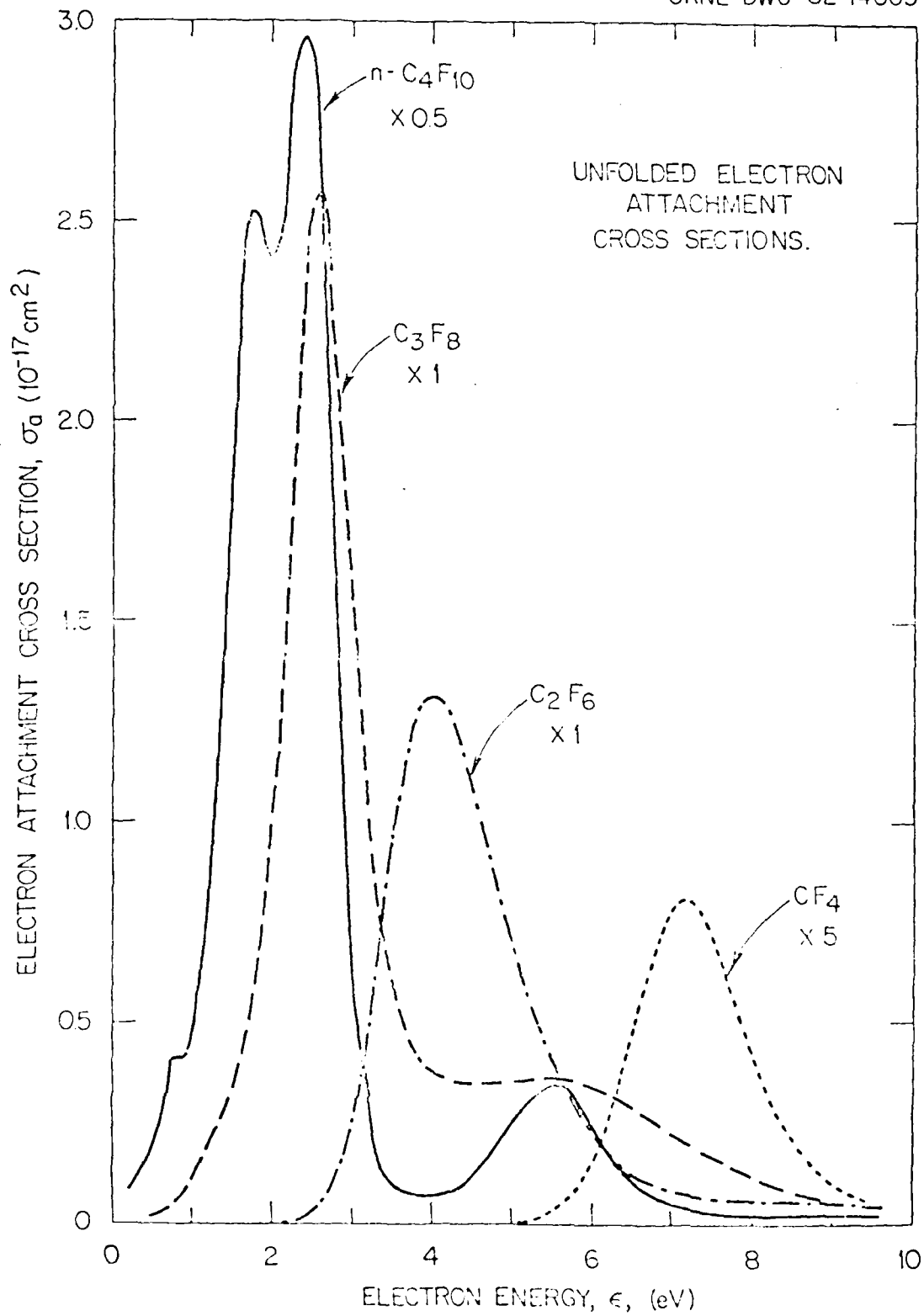
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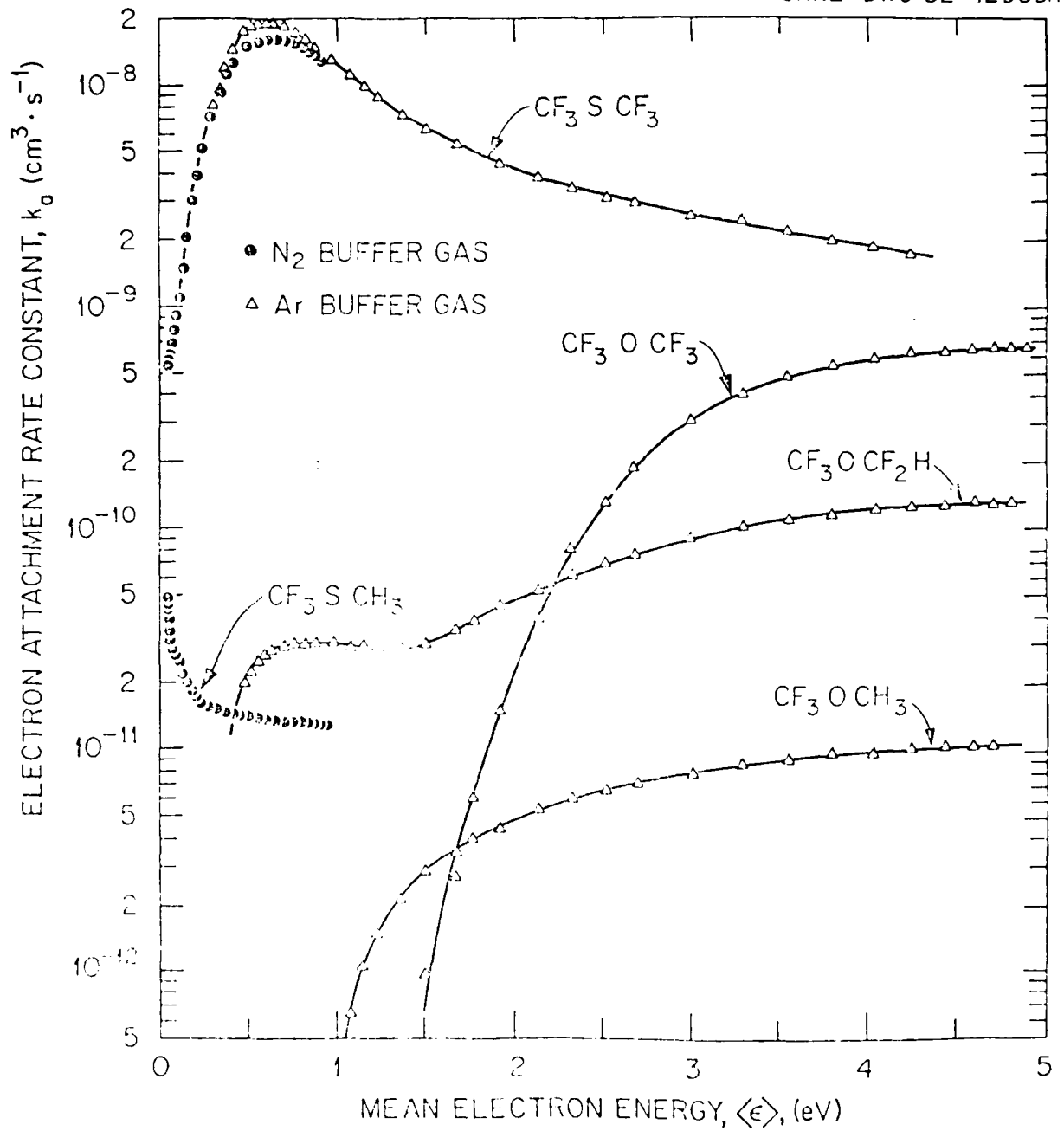


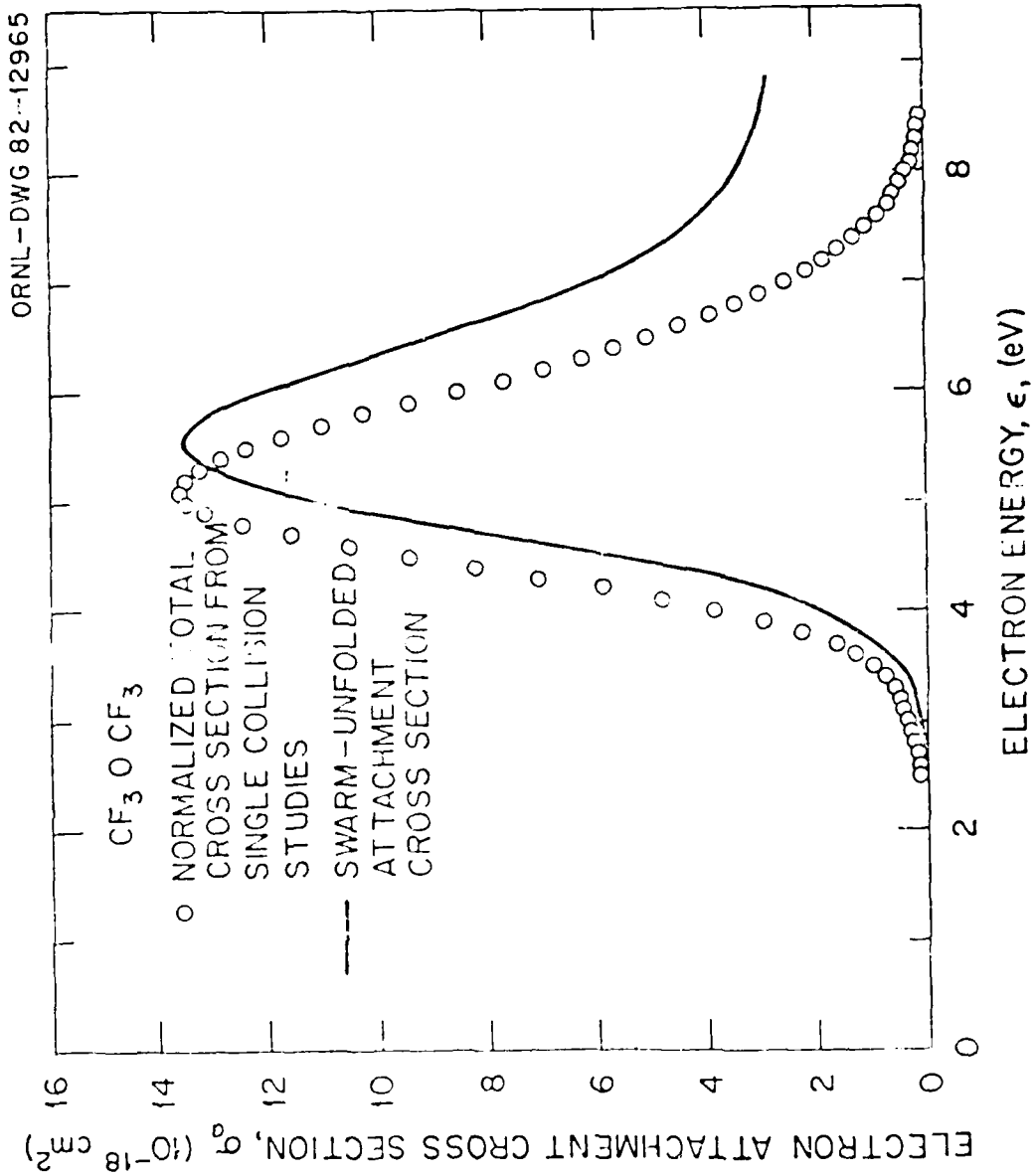


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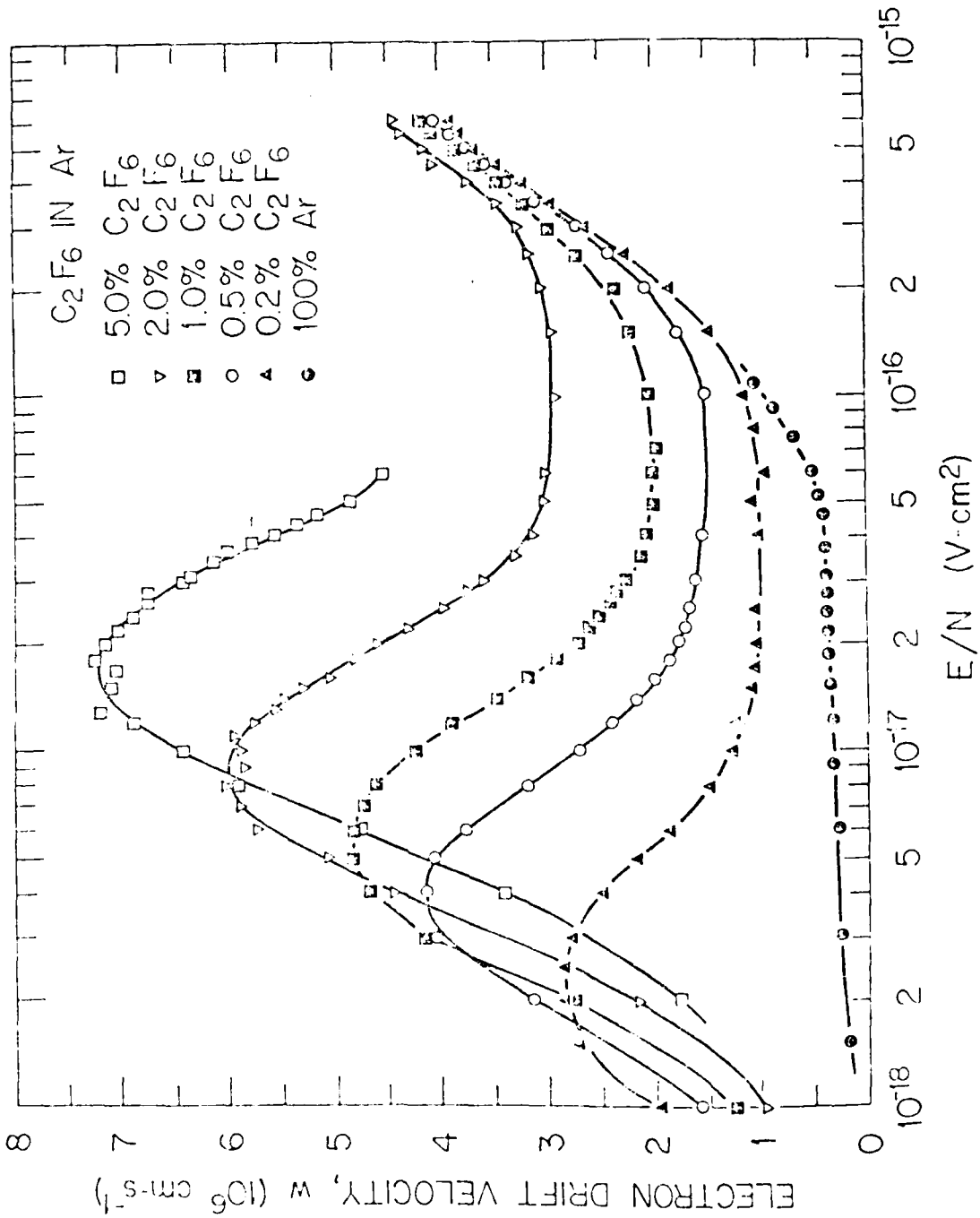








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APPENDIX C



## BASIC STUDIES OF GASES FOR DIFFUSE-DISCHARGE SWITCHING APPLICATIONS\*

L. G. Christophorou,<sup>†</sup> S. R. Hunter,<sup>†</sup> J. G. Carter, and S. M. Spyrou<sup>†</sup>

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Oak Ridge, Tennessee 37830

The basic processes which underlie the successful tailoring of gases/mixtures with high dielectric strengths and appropriate conduction characteristics for diffuse-discharge switching applications will be discussed. Recent results on electron attachment rate constants and cross sections as well as on the fragmentation by electron impact of  $CF_4$ ,  $C_2F_6$ ,  $C_3F_8$ ,  $CF_3OCF_3$ , and  $CF_3SCF_3$  which are of potential interest in diffuse-discharge technologies will be presented. Recent findings on the electron attachment, electron drift velocity, and breakdown properties of a number of mixtures comprised of electron attaching and electron drift-velocity-enhancing components (e.g.,  $CF_3OCF_3/Ar$ ,  $C_3F_8/Ar$ ,  $C_2F_6/Ar$ ,  $C_2F_6/CH_4$ ) will be reported. The observed increase in the electron attachment rate constant of  $CO_2F_2$  with temperature over a wide mean energy range (0.5 to 4.0 eV) and its implications for diffuse-discharge switching applications will be reported also.

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\*Research sponsored in part by the Office of Naval Research and in part by the Division of Electric Energy Systems, U.S. Department of Energy, under contract no. W-7405-eng-26 with the Union Carbide Corporation.

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