AD-A198 641

ornl

ORNL/TM-10844

DTIC FILE COPY

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

Basic Studies of Gases for Fast Switches

Final Report

S. R. Hunter
L. G. Christophorou

DTIC
ELECTE
S AUG 9 1988 D

This document has been approved for public release and sale; its distribution is unlimited.

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A06; Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-10844

Interagency Agreement DOE No. 1246-1246-A1
Navy No. N00014-82-F-0123

Office of Naval Research
Physics Division
Arlington, Virginia 22217

BASIC STUDIES OF GASES FOR FAST SWITCHES

Final Report
by
S. R. Hunter and L. G. Christophorou

Health and Safety Research Division
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6123

and

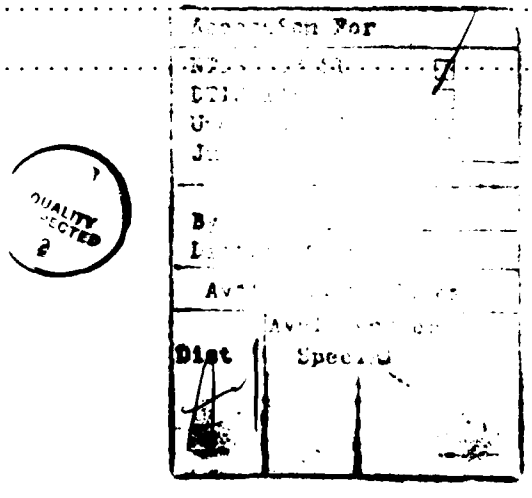
Department of Physics
The University of Tennessee
Knoxville, Tennessee 37996

Date Published - August 1988

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. Department of Energy
Under Contract No. DE-AC05-84OR21400

Contents

Section			Page
I.		Introduction	3
	1.1	Background	3
	1.2	Operating Parameters for a Diffuse Discharge Opening Switch	5
	1.3	Program Objectives	13
	1.4	Summary of Accomplishments	14
	1.5	Publications and Presentations	17
II.		Experimental Approach	23
	2.1	High Pressure Swarm Experiment	23
	2.2	High Temperature Swarm Experiment	26
	2.3	Pulsed Townsend Experiment	26
	2.4	Gas Ionizing W Value Experiment	29
	2.5	High Voltage Breakdown Experiment	31
III.		Experimental Techniques and Selected Results	33
	3.1	Room Temperature Electron Attachment Rate Constants and Attachment Cross Sections	33
	3.2	Elevated Temperature Electron Attachment Rate Constant Measurements	38
	3.3	Room Temperature Electron Drift Velocity Measurements	42
	3.4	Room Temperature Electron Attachment and Ionization Coefficients	50
	3.5	Elevated Temperature Gas Mixture Studies	64
	3.6	W-Value Measurements	75
	3.7	High Voltage Breakdown Field Strength Studies	84
IV		Relevance to Switching Experiments	91
	4.1	C_2F_6/Ar Gas Mixtures	95
	4.2	C_2F_6/CH_4 Gas Mixtures	95
	4.3	Enhanced Discharge Current Characteristics	99
	4.4	Operation at Elevated Gas Temperatures	101
	4.5	Diffuse Discharge Closing Switch Experiments	103
V.		Conclusions	108
		References	110



I. Introduction

This final report covers the contract period October 1, 1982 to March 31, 1988, and includes an outline of the operation of diffuse discharge switches in pulsed power energy storage circuits, the methods by which the operation of these switches may be optimized, and the measurements we have performed on several gas mixtures which exhibit these optimized characteristics. The goal of the program has been to identify these optimization procedures, and using basic data on electron-atom and electron-molecule collision processes, to find gas mixtures in which the transport properties of the electrons in the gas discharges are "tailored" to match these optimization requirements. Using these criteria, we have found several gas mixtures which have very desirable characteristics for use in these switches. The potential of these gas mixtures has been demonstrated in recent switching experiments which have shown considerable operational improvements when these gases were used.

The following outline for this report has been adopted in which the accomplishments of this program are highlighted. For the remainder of Section I, a brief background description of the operation of a diffuse discharge switch in an inductive energy storage circuit is outlined. The electron transport and other parameters of the gas mixtures to be optimized are identified, and the specific objectives of this program are discussed along with a summary of the accomplishments and publications which have resulted from this contract. In Section II, the experimental techniques used to obtain the electron transport and breakdown measurements are outlined; the basic experimental measurements are presented in Section III, while in Section IV, we discuss some of the implications of these data in the operation of both diffuse discharge closing and opening switches. The results of switching experiments using our new gas mixtures will also be presented along with a discussion of the strengths and limitations of these switches in pulsed power energy storage circuits. Finally in Section V some general conclusions are presented.

1.1 Background

There has been considerable interest in recent years in the possibility of using inductive energy storage devices as a means of storing and rapidly transferring electrical energy in repetitive pulsed power applications. The primary advantage to be gained from the use of these energy storage devices is

that they have potential energy storage densities 100 to 1000 times that of comparable capacitive storage systems and that this energy can be transferred to the load on the very short time scale of nanoseconds.[1-3] One of the major problems to be faced with this technology before it can be introduced in a number of applications is that these inductive energy storage systems require a switching device that can repetitively switch (repetition rates > 10^4 pps and more than 10^6 shots) high currents (e.g., 100 kA for inertial fusion confinement) with opening times of the order of a few ns and being capable of withstanding high voltages (>100 kV) during the opening stage without breakdown.[3,4]

One of the most promising contenders for fast repetitive switching is an externally sustained diffuse gas discharge operating at gas pressures of one to several atmospheres. Two different types of external electron sources have been proposed for the control of the discharge current. They are by means of volume gas ionization by a pulsed high energy electron beam ("e-beam controlled"[5,6]) or by resonance ionization of the gaseous medium using a pulsed high power laser ("optically controlled"[7,8]).

The first experiments using e-beam controlled discharges were performed in the early 1970s in an effort to improve the efficiency of high pressure CO_2 discharge lasers, where the efficient operation of these devices requires that they be operated at electric fields below the self-sustained discharge voltage.[9] Early researchers in this field noticed that at high electric fields the discharge becomes unstable, and oscillations in the discharge current occur.[10] These oscillations have been shown to be due to an electron attachment instability because the electron attachment coefficient in CO_2 increases in magnitude with increasing field strength over a range of E/N values.[11] A small, local reduction in the electron concentration causes a small increase in the local electric field in the space-charge dominated diffuse discharge, which results in increased electron attachment and a further reduction in the electron concentration, etc.[11] As a consequence, the discharge becomes unstable and waves of plasma current travel between the electrodes in the discharge. Although this is an undesirable process in e-beam sustained lasers, this mechanism forms the basis of most present schemes for rapidly extinguishing the discharge in opening switching applications. Early experiments using e-beam sustained diffuse discharges

were mainly conducted in Russia for use in fast closing switch applications.[12] Hunter[5] and Koval'chuk and Mesyats[13] were the first to realize that e-beam sustained diffuse discharges could also be used in rapid opening switch applications where switching times $<10^{-7}$ s are required.

1.2 Operating Parameters for a Diffuse Discharge Opening Switch

Several operating parameters may be defined for externally sustained diffuse discharge opening switches, most of which are common to both e-beam and optically controlled diffuse discharges. Knowledge of these parameters can then form a basis for tailoring specific gases and gas mixtures to optimize the switch operating conditions as nearly as possible. The relevant basic physical quantities include the electron attachment, recombination, ionization and diffusion coefficients, and the electron drift velocity as a function of E/N (the electric field strength to gas number density ratio), N and gas temperature T, and the high voltage breakdown field strengths of these gas mixtures.

The operating principle of the diffuse discharge switch in an inductive energy storage circuit is given in Fig. 1. In the *conducting* stage, the switch S_2 is opened, and the switch S_1 is closed (conducting) by means of a diffuse discharge which is sustained by ionization of the gas mixture using either a high energy electron beam or laser radiation, causing a current I to flow in the circuit through the storage inductor L_S. In the *transferring* stage, the switch S_1 is opened by removing the external source of ionization, and the current in the circuit rapidly decreases. In an inductive current loop, a voltage is induced across the inductor and, hence, across the opening switch, which is proportional to the rate of change in the current through the inductor (i..e., $V_L = -L\ dI/dt$, where L is the inductance of L_S and I is the current). At the same time that S_1 is opened, the switch S_2 is closed, and the current path flows through the load Z_L. The faster S_1 is opened, the larger the induced voltage that appears across L_S, and the more rapidly is the electrical energy stored in L_S transferred to the load Z_L. The major problem to be faced before this switching concept is accepted is to design the diffuse discharge switch S_1 such that it will open very rapidly and not form

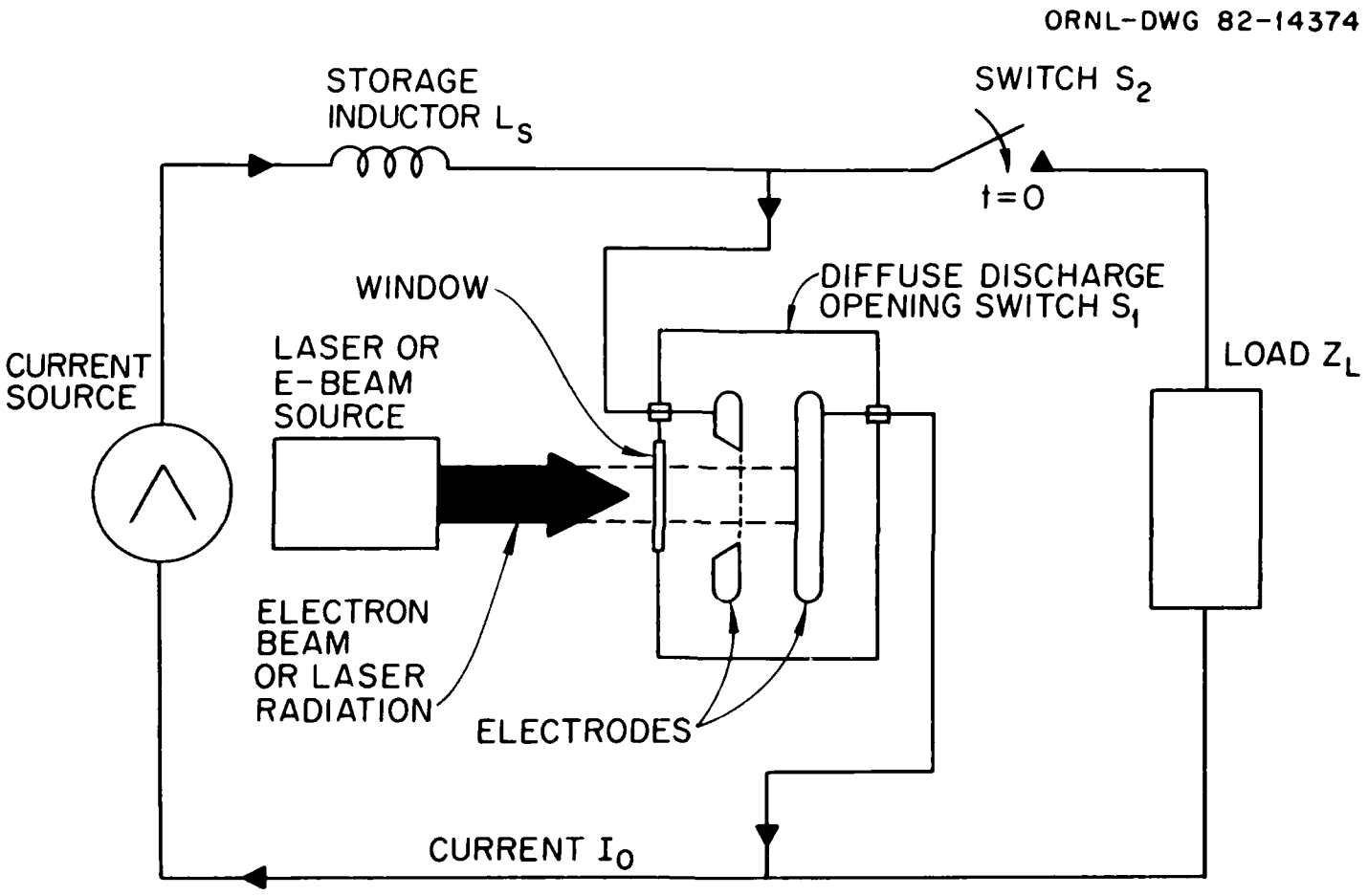


Fig. 1. Inductive energy storage circuit (based on original diagram in Ref.3).

conducting arcs between the electrodes due to the high induced voltages which appear across the switch during the rapid opening stage.

The electron number density n_e in the diffuse discharge, which is driven by an external source of ionization at a given E/N value is given by the following continuity equation:

$$\frac{dn_e}{dt} = S + k_i n_e N_T - k_a n_e N_a - k_{R_1} n_e n_+ - k_{R_2} n_e N_+ N_T \quad , \qquad (1)$$

where k_i is the electron impact ionization rate constant, k_a is the electron attachment rate constant, k_{R_1} and k_{R_2} are the two- and three-body electron-positive ion recombination rate constants, respectively, n_e, n_+, N_a, and N_T are, respectively, the electron, positive ion, attaching gas, and total gas number densities. The electron production rate by the external high energy electron beam in the discharge, S, is given by

$$S = \left\langle \frac{d\epsilon}{dx} \right\rangle J_B \, W^{-1} \quad , \qquad (2)$$

where $(d\epsilon/dx)$ is the average energy deposited in the gas by the electrons in the e-beam of flux J_B in traveling a distance dx, and W is the average energy required to produce an electron-positive ion pair (and includes a contribution to the volume ionization by excited state ionization of a lower ionization potential gas additive in the case of Penning gas mixtures and direct electron impact ionization of metastable species). Similar continuity equations may be written for the positive and negative ion number densities in the discharge, i.e.,

$$\frac{dn_+}{dt} = S + k_i n_e N_T - k_{R_1} n_e n_+ - k_{R_2} n_e n_+ N_T - k_{R_+} n_+ n_- \quad , \qquad (3)$$

where k_{R_+} is the positive ion-negative ion recombination rate constant and n_- is the negative ion number density. The negative ion number density continuity equation is

$$\frac{dn_-}{dt} = k_a n_e N_a - k_{R_+} n_+ n_- \quad . \tag{4}$$

When the electron and the ion loss processes from the discharge are negligible and the current gain in the switch is large,

$$n_+ \simeq n_e + n_- \quad . \tag{5}$$

The electron current density J_e in the discharge is given by

$$J_e(r,x) = e\left[n_e w - D_L \frac{\partial n_e}{\partial x} - D_T \frac{\partial n_e}{\partial r}\right] \tag{6}$$

and is dependent on the electron drift velocity w, the longitudinal diffusion coefficient D_L, and the transverse diffusion coefficient D_T (r is the radial direction perpendicular to the applied electric field). At the gas pressures proposed for most switching applications (1 to 10 atm[1]), the diffusion terms in Eq. (6) are negligibly small in comparison with w, i.e.,

$$J_e \simeq e n_e w = \frac{e n_e \mu V_s}{d} \quad , \tag{7}$$

where μ is the electron mobility ($\mu = w/E$), V_s is the voltage appearing across the switch electrodes, and d is the electrode spacing in the switch. The maximum voltage $(V_s)_{\ell im}$ that can appear across the switch electrodes before the diffuse discharge collapses into an arc discharge (which is undesirable as, for example, it greatly increases the opening time of the switch) is given--for a uniform field electrode configuration and a space charge free discharge--by the static high voltage breakdown field strength $(E/N)_{\ell im}$ of the gas mixture in the switch

$$(V_s)_{\ell im} = (E/N)_{\ell im} \times (N_T d) \tag{8}$$

An important parameter, which may be derived from the electron current density J_e and which significantly affects the switch efficiency, is the switch resistivity ρ given by

$$\rho = E/J_e \simeq (en_e \mu)^{-1} \quad . \tag{9}$$

The positive and negative ion current densities in the discharge are given by $J_+ = en_+w_+$ and $J_- = en_-w_-$, respectively, where the ion diffusion terms are negligible in comparison with the ion drift terms. The positive (and negative) ion fluxes do not play a significant role in the conductivity of the transient stage (i.e., in the opening stage) of the switching action of the discharge. However, they do cause significant space-charge distortion, such that the electric field E(x) within the discharge is spatially dependent, and Poisson's equation must be solved in order to determine the field, i.e.,

$$\frac{\partial^2 V}{\partial x^2} = - \frac{e}{\epsilon_o} (n_+ - n_- - n_e)$$

and

$$E = - \frac{\partial V}{\partial x} \quad . \tag{10}$$

where ϵ_o is the permitivity of the gaseous medium.

With the aid of Eqs. (1) to (9), it is possible to establish several requirements of a gas mixture in the diffuse discharge which will optimize the performance of the switch. The conductivity of the discharge must be maximized while the switch is conducting [i.e., the voltage drop, and hence the E/N, across the discharge should be low ($E/N \lesssim 3 \times 10^{-17}$ V cm^2) to minimize power losses and, consequently, gas heating effects in the switch]. The opening time of the switch must be as short as possible (i.e., largest rate of decrease in the discharge current) once the e-beam has been switched off in order to maximize the voltage developed across the inductive energy storage device. Consequently, the electron conductivity in the discharge must be minimized during the opening stage, and the gas mixture must be able to

withstand high *transient* voltage levels ($E/N > 10^{-15}$ V cm^2) while the switch is opening.

These operating conditions allow us to define several desirable characteristics of the gaseous medium in the conducting (low E/N) and opening (high E/N) stages of the switching action. In the conducting stage, the requirements are:

1. Maximum electron drift velocity w - the larger w is, the higher the conductivity of the discharge and the greater the current density in the diffuse discharge and the lower the switch resistivity.
2. Minimum e-beam "ionization energy" W - the smaller W is, the greater the current gain in the discharge with a consequent increase in the efficiency of the coupling of the e-beam to the discharge and a greater control of the resultant discharge current.
3. Minimum electron loss terms k_a, k_{R_1}, k_{R_2}, and k_{R_+} - the conductivity of the discharge drastically decreases and space-charge problems increase when the highly mobile electrons are converted into relatively immobile negative ions. Similarly, the conductivity will decrease if the electron and negative ion-positive ion recombination in the discharge is large due to the loss of the charge carriers. Another problem that results from large recombination coefficients is that the current gain in the switch will decrease, and the energy released in the recombination process will result in increased gas kinetic energy causing heating problems in the gas under repetitive operation.
4. Minimum ionization rate constant k_i - the conductivity of the gas is required to be completely controlled by the external ionization source, otherwise the opening time of the switch will be considerably increased due to additional gas ionization when the e-beam is switched off.[6]

In the opening stage the requirements of the gas mixture as as follows:

1. Minimum electron drift velocity w - i.e., reduce the electron mobility and hence lower the electron conductivity in the gas mixture.

2. Maximum electron attachment rate constant k_a - i.e., lower the gas conductivity by converting highly mobile electrons into relatively immobile negative ions and by removing free electrons from the discharge, reducing the current density due to additional ionization processes as the E/N increases.
3. High breakdown strength $(E/N)_{\ell im}$ (for uniform fields defined as the E/N at which $k_i = k_a$) $> 10^{-15}$ V cm^2 - the higher the value of $(E/N)_{\ell im}$, the faster the permissible rate of decrease in the electron conductivity in the discharge, and hence the shorter the opening time of the switch.
4. Self-healing gas mixtures - for closed cycle operation without a time dependent degradation in the performance of the switch, it is required that the gas mixture composition not change with time. The molecular gases in the switch can be fragmented either by collisions with high energy electrons from the e-beam or by electron impact-induced dissociation and dissociative attachment processes occurring during the diffuse discharge, particularly during the opening phase where the E/N quickly rises to very large values (E/N $\gtrsim 10^{-15}$ V cm^2). This problem can be reduced by using gases that attach electrons nondissociatively at energies well in excess of thermal energy and also have low electron impact dissociation cross sections and large neutral-neutral and negative ion-positive ion recombination coefficients at high E/N values.
5. In photoexcited and photoionized gas discharges (required for laser-controlled discharges) it is desirable to have an electron attaching gas in which electron attachment can be increased by photoexcitation of the molecules by the laser radiation.[7,8]

The desirable characteristics for the E/N dependence of w and k_a for the gas mixture in the diffuse discharge are shown in Fig. 2.[14,15] When the switch S_1 is closed or conducting (i.e., when the electric field across the switch electrodes is small), electron conduction in the discharge is optimized by using gas mixtures which have large electron drift velocities and small electron loss processes (e.g., electron attachment and recombination) at the

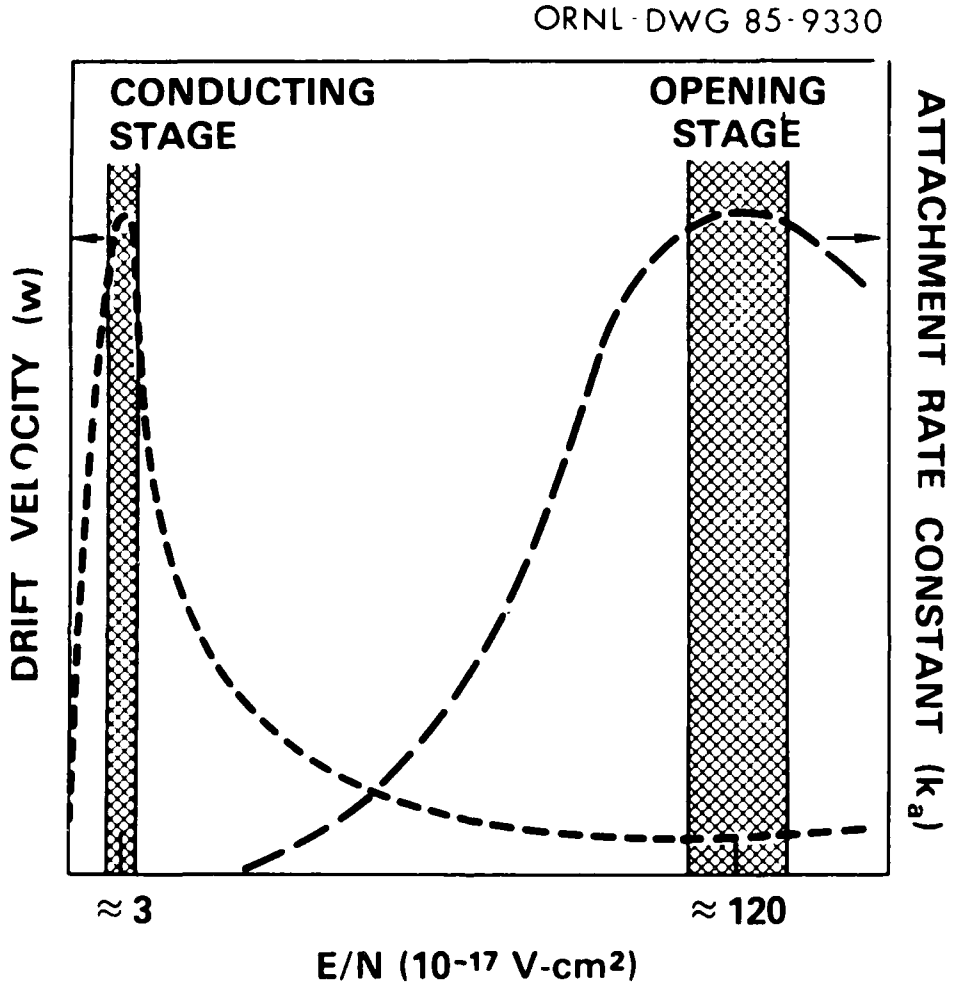


Fig. 2. Schematic illustration of the electron attachment rate constant $k_a(E/N)$ and the electron drift velocity $w(E/N)$ characteristics required of a gas mixture for use in a diffuse discharge opening switch. Approximate values of E/N for the discharge in the conducting and opening stages of the switch are shown in the figure (from Ref. 14).

electric field strengths characteristic of this stage of the switching action (indicated by the shaded region in Fig. 2). Conversely, during the opening stage (i.e., when the electric field strengths are large, indicated by the shaded region in Fig. 2), the electron drift velocity should now be low, and the electron attachment rate constant large in order to reduce the electron conduction in the discharge as quickly as possible.

1.3 Program Objectives

The aim of this research program has been to find gas mixtures which would optimize the gas discharge requirements outlined above in both the conduction and opening stages of the switching action. This has been accomplished by performing the following measurements on potential gases and gas mixtures.

1. Measurements of the room temperature electron attachment rate constant k_a were performed on selected electronegative gases in both N_2 and Ar buffer gases as a function of E/N (or mean electron energy $\langle\epsilon\rangle$) and gas pressure in an effort to find the energy dependence and electron attachment mechanisms of these candidate gases. If any of these gases possessed the required characteristics (i.e., low k_a at thermal and near thermal electron energies, and high k_a at $\langle\epsilon\rangle > 2$ eV) then the following measurements were performed.
2. Room temperature electron drift velocity w measurements were performed on the candidate gases in gas mixtures with both Ar and CH_4 over a wide range of concentrations (typically varying from 0.1% to 100% of the attaching gas) to observe any enhancement in w that may occur at low E/N values, and to give additional insights into the electron scattering processes which may be occurring in these electronegative gases.
3. Electron attachment coefficient η/N and electron ionization coefficient α/N measurements were also performed on a few selected gas mixtures with Ar and CH_4 over a similarly wide range of concentrations in an effort to understand how these gases would perform in switching gas mixtures.

4. High voltage breakdown field strength $(E/N)_{\ell im}$ measurements were performed on selected gas mixtures in order to determine if these gases were able to withstand the transient high voltages that occur when the switch is opened. These measurements enabled us to determine the minimum concentration of the attaching gas that was required to sustain these voltage transients without breakdown.
5. For repetitively operated switches, the gas temperature within the switch is expected to rise several hundred degrees centigrade, and under these circumstances, the electron transport and rate coefficients are expected to be functions of the gas temperature T. Knowledge of these parameters as a function of T is desirable for modeling the operation of the diffuse discharge switch in practical applications. Consequently, the above measurements (namely $k_a(\langle\epsilon\rangle)$, w (E/N), α/N (E/N), η/N (E/N) and $(E/N)_{\ell im}$) were performed as a function of T on selected gas mixtures to simulate the environment found in repetitively operated switches.
6. Finally, the W value (the average energy to produce an electron-positive ion pair from the energy decay of a high energy ionizing particle) of several gases and gas mixtures was measured in an effort to find gas mixtures which would maximize the electron current density in the switch during switch conduction (i.e., minimize the "resistivity" of the discharge and consequently maximize the current switching efficiency).

1.4 Summary of Accomplishments

The following is a list of the most significant accomplishments achieved during the course of this program.

1. Measurement of the room temperature electron attachment rate constant k_a as a function of $\langle\epsilon\rangle$ from thermal electron energy ($\approx$ 0.04 eV) to $\langle\epsilon\rangle \approx 5$ eV in N_2 and Ar buffer gases for several molecules (many of which have been found to possess very desirable electron attachment characteristics for use in diffuse discharge opening switches). These molecules include CF_4, C_2F_6, C_3F_8, c-C_3F_6, l-C_3F_6, c-C_4F_8, n-C_4F_{10}, n-C_5F_{12}, i-C_5F_{12}, n-C_6F_{14}, $OClF_3$, $(CF_3)_2O$, $(CF_3)_2S$, NF_3, N_2O and SO_2.

2. Measurement of the room temperature electron drift velocity over a wide E/N range ($0.002 \leq E/N \leq 400 \times 10^{-17}$ V cm^2) in the following pure gases; CF_4, C_2F_6, C_3F_8, n-C_4F_{10}, $(CF_3)_2O$, SiF_4, BF_3, Ar, CH_4 and N_2.
3. Measurement of the room temperature w in the following gas mixtures which were proposed for use in diffuse discharge opening and closing switches; Ar/CH_4, CF_4/Ar, CF_4/CH_4, C_2F_6/Ar, C_2F_6/CH_4, C_3F_8/Ar, C_3F_8/CH_4, $(CF_3)_2O/Ar$, $(CF_3)_2S/CH_4$, SiF_4/He.
4. Developed a new procedure for the measurment of electron attachment and ionization coefficients in a pulsed Townsend experiment where both electron ionization and attachment processes are present.
5. Measurement of the electron attachment coefficient η/N as a function of E/N and gas pressure in the following pure gases; CF_4, C_2F_6, C_3F_8, n-C_4F_{10}, O_2, SiF_4 and BF_3. With the exception of O_2 (which was measured to test the accuracy of the experimental technique), all these molecules only attach electrons efficiently at high electric field strengths.
6. Measurement of the electron ionization coefficient α/N as a function of E/N in the following gases; CF_4, C_2F_6, C_3F_8, n-C_4F_{10}, SiF_4, BF_3 and CH_4.
7. Room temperature η/N and α/N measurements were also performed in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures, as these mixtures were chosen to represent the expected E/N and concentration dependence of these coefficients in typical diffuse discharge opening switch applications.
8. Room temperature α/N and η/N measurements were also performed in the following mixtures; SiF_4/He, $SiF_4/He/TEA$ and $SiF_4/He/TMAE$. These mixtures were chosen for study as they possessed almost ideal characteristics for self-sustained diffuse discharge closing switch applications.
9. The high voltage breakdown field strength measurements were performed at room temperature in the following mixtures; C_2F_6/Ar, C_2F_6/CH_4, C_3F_8/Ar, C_3F_8/CH_4 and c-C_4F_8/He.
10. The average energy to produce an electron-positive ion pair W was measured for the following pure gases; CF_4, C_2F_6, C_3F_8, n-C_4F_{10}, CH_4, Ar, N_2, C_2H_2 and 2-C_4H_8.

11. The W values were measured in the following binary gas mixtures; CF_4/Ar, C_2F_6/Ar, C_3F_8/Ar, CF_4/CH_4, CF_4/C_2H_2, C_2F_6/C_2H_2, C_3F_8/C_2H_2, $C_2F_6/2\text{-}C_4H_8$, C_3F_8/C_2H_2, Ar/C_2H_2 and $Ar/2\text{-}C_4H_8$.
12. The W values were also measured in the following ternary gas mixtures; $CF_4/Ar/C_2H_2$, $C_2F_6/Ar/C_2H_2$, $C_2F_6/Ar/2\text{-}C_4H_8$ and $C_3F_8/Ar/C_2H_2$. These mixtures have not only been found to possess excellent w, α/N and η/N characteristics, but also for specific C_2H_2 or $2\text{-}C_4H_8$ concentrations, can also considerably enhance the electron production in the discharge by the external electron beam, thereby maximizing the current switching efficiency.
13. Electron attachment rate constant k_a measurements were performed over the gas temperature range $300 \lesssim T \lesssim 700$ K in $CClF_3$, C_2F_6, C_3F_8, $n\text{-}C_4F_{10}$, $c\text{-}C_4F_8$, $c\text{-}C_4F_6$, and $c\text{-}C_6F_6$. These measurements helped to elucidate the electron attachment mechanisms in these molecules.
14. Electron drift velocity, α/N and η/N measurements were also performed in pure C_2F_6 and CH_4, and the gas mixtures C_2F_6/Ar and C_2F_6/CH_4 at the gas temperatures 300 K, 500 K and 700 K. These measurements have shown that the operation of repetitively pulsed opening switches will not be seriously degraded by operation at these gas temperatures.
15. High voltage breakdown field strength measurements $(E/N)_{\ell im}$ were performed in the following gases over the temperature range $300\text{ K} < T < \approx 600\text{ K}$ at atmospheric gas pressures; CF_3Cl, C_2F_6, C_3F_8, $1\text{-}C_3F_6$, $c\text{-}C_4F_8$ and $n\text{-}C_4F_{10}$. These measurements have shown that for C_2F_6 (which is considered a prime candidate for use in diffuse discharge opening switches) operation of the switch at these temperatures does not degrade the dielectric properties of this gas, and in fact, the dielectric strength increases slightly over this temperature range.

1.5 Publications and Presentations

A. Journal Publications

The following journal papers were published under full or partial support of this contract.

1. S. M. Spyrou, S. R. Hunter, and L. G. Christophorou, "Studies of Negative Ion Formation in Fluoroethers and Fluorosulphides Using Low-Energy ($\leq$10 eV) Electron Beam and Electron Swarm Techniques," *J. Chem. Phys.* **81**, 4481-4493 (1984).

2. K. Nakanishi, L. G. Christophorou, J. G. Carter, and S. R. Hunter, "Penning Ionization Ternary Gas Mixtures for Diffuse Discharge Switching Applications," *J. Appl. Phys.* **58**, 633-641 (1985).

3. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Transport Studies of Gas Mixtures for Use in e-Beam Controlled Diffuse Discharge Switches," *J. Appl. Phys.* **58**, 3001-3015 (1985).

4. S. M. Spyrou and L. G. Christophorou, "Effect of Temperature on the Dissociative Electron Attachment to $OClF_3$ and C_2F_6," *J. Chem. Phys.* **82**, 2620-2629 (1985).

5. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Transport Measurements in Methane Using Improved Pulsed Townsend Experimental Techniques," *J. Appl. Phys.* **60**, 24-35 (1986).

6. G. F. Reinking, L. G. Christophorou, and S. R. Hunter, "Studies of Total Ionization in Gases/Mixtures of Interest to Pulsed Power Applications," *J. Appl. Phys.* **60**, 499-508 (1986).

7. P. G. Datskos and L. G. Christophorou, "Variation of the Electron Attachment to n-C_4F_{10} with Temperature," *J. Chem. Phys.* **86**, 1982-1990 (1987).

8. S. R. Hunter, "Comment on Shortening of Electron Conduction Pulses by Electron Attachers O_2, N_2O, and CF_4," *J. Appl. Phys.* **60**, 4335-4337 (1986).

9. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Attachment and Ionization Processes in CF_4, C_2F_6, C_3F_8, and n-C_4F_{10}," *J. Chem. Phys.* **86**, 693-703 (1987).

10. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Motion in CF_4, C_2F_6, C_3F_8, and n-C_4F_{10}," *Phys. Rev. A*, in press.

11. L. G. Christophorou, R. A. Mathis, S. R. Hunter, and J. G. Carter, "Effect of Temperature on the Uniform Field Breakdown Strength of Electronegative Gases," *J. Appl. Phys.* **63**, 52-59 (1988).

12. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Attachment, Ionization and Drift in SiF_4 and BF_3," *J. Appl. Phys.*, in preparation.

13. S. R. Hunter, "Electron Attachment to NF_3," *J. Appl. Phys.*, in preparation.

14. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Transport in C_2F_6/Ar and C_2F_6/CH_4 Gas Mixtures at Elevated Temperatures," *J. Appl. Phys.*, in preparation.

B. Conference Proceedings

The following papers were published in conference proceedings under full or partial support of this contract.

1. L. G. Christophorou, S. R. Hunter, J. G. Carter, and S. M. Spyrou, "Gases for Possible Use in Diffuse-Discharge Switches," In *Proceedings of the Workshop on "Diffuse Discharge Opening Switches"* (M. Kristiansen and K. M. Schoenbach, Eds.), Texas Tech University, Lubbock, Texas, 1982, pp. 236-251.

2. J. G. Carter, S. R. Hunter, L. G. Christophorou, and V. K. Lakdawala, "Electron Drift Velocity and Ionization and Attachment Coefficients in Gases/Mixtures for Diffuse-Discharge Opening Switches," In *Proceedings of the 3rd International Swarm Seminar* (W. Lindinger, H. Villinger, and W. Federer, Eds.), Innsbruck, Austria, 1983, pp. 30-36.

3. L. G. Christophorou, S. R. Hunter, J. G. Carter, S. M. Spyrou, and V. K. Lakdawala, "Basic Studies of Gases for Diffuse-Discharge Switching Applications," In *Proceedings of the U.S.-F.R.G. Joint Seminar on Externally Controlled Diffuse Discharges*, Texas Tech University, Lubbock, Texas, 1983, pp. 104-133.

4. L. G. Christophorou, S. R. Hunter, J. G. Carter, S. M. Spyrou, and V. K. Lakdawala, "Basic Studies of Gases for Diffuse-Discharge Switching Applications," In *Proceedings of the 4th IEEE Pulsed Power Conference* (T. H. Martin and M. F. Rose, Eds.), The Texas Tech Press, Lubbock, Texas, 1983, pp. 702-708.

5. S. R. Hunter, J. G. Carter, L. G. Christophorou, and V. K. Lakdawala, "Transport Properties and Dielectric Strengths of Gas Mixtures for Use in Diffuse Discharge Opening Switches," In *Gaseous Dielectrics IV* (L. G. Christophorou and M. O. Pace, Eds.), Pergamon Press, New York, 1984, pp. 224-237.

6. K. Nakanishi, L. G. Christophorou, J. G. Carter, and S. R. Hunter, "Penning Ionization Ternary Gas Mixtures for Diffuse Discharge Switching Applications," In *Proceedings of the 5th IEEE Pulsed Power Conference* (M. F. Rose and P. J. Turchi, Eds.), IEEE, New York, 1986, pp. 40-43.

7. S. R. Hunter, J. G. Carter, L. G. Christophorou, and S. M. Spyrou, "Temperature Dependent Electron Transport Studies for Diffuse Discharge Switching Applications," In *Proceedings of the 5th IEEE Pulsed Power Conference* (M. F. Rose and p. J. Turchi, Eds.), IEEE, New York, 1986, pp. 402-409.

8. L. G. Christophorou, S. R. Hunter, J. G. Carter, and S. M. Spyrou, "Effects of Temperature on Dissociative and Nondissociative Electron Attachment," In *Swarm Studies and Inelastic Electron-Molecule Collisions* (L. C. Pitchford, V. McKoy, A. Chutjian, and S. Trajmar, Eds.), Springer-Verlag, New York, 1986, pp. 303-308.

9. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Drift Velocity and Attachment and Ionization Coefficients in CH_4, CF_4, C_2F_6, C_3F_8, and n-C_4F_{10}," In *Swarm Studies and Inelastic Electron-Molecule Collisions* (L. C. Pitchford, V. McKoy, A. Chutjian, and S. Trajmar, Eds.), Springer-Verlag, New York, 1986, pp. 93-94.

10. S. R. Hunter, "Gas Engineering for Pulsed Power and Switching," In *Gaseous Dielectrics V* (L. G. Christophorou and D. W. Bouldin, Eds.), Pergamon Press, New York, 1987, pp. 363-372.

11. S. R. Hunter, L. G. Christophorou, and J. G. Carter, "Gas Engineering Studies for High Pressure Self-Sustained Diffuse Discharge Closing Switches," In *Gaseous Dielectrics V* (L. G. Christophorou and D. W. Bouldin, Eds.), Pergamon Press, New York, 1987, pp. 404-411.

12. J. G. Carter, S. R. Hunter, and L. G. Christophorou, "Temperature Dependent Electron Transport and Rate Coefficient Studies for e-Beam-Sustained Diffuse Gas Discharge Switching," In *Gaseous Dielectrics V* (L. G. Christophorou and D. W. Bouldin, Eds.), Pergamon Press, New York, 1987, pp. 47-54.

13. L. G. Christophorou, R. A. Mathis, S. R. Hunter, and J. G. Carter, "Effect of Temperature on the Uniform Field Breakdown Strength of Electronegative Gases," In *Gaseous Dielectrics V* (L. G. Christophorou and D. W. Bouldin, Eds.), Pergamon Press, New York, 1987, pp. 88-95.

14. S. R. Hunter, J. G. Carter, and L. G. Christophorou, "Electron Transport Studies in Gaseous Media for Diffuse Discharge Closing Switches," In *Proceedings of the International Conference on Phenomena in Ionized Gases (ICPIG XVIII)*, Swansea, United Kingdom, July 13-17, 1987.

15. S. R. Hunter, L. G. Christophorou, J. G. Carter, and P. G. Datskos, "New Concepts in High Current Self-Sustained Diffuse Discharge Closing Switches," In *Proceedings of the 6th IEEE Pulsed Power Conference*, Arlington, Virginia, June 29-July 1, 1987, pp. 1-8.

C. Book Chapter

The following book chapter was published under the partial support of this contract.

L. G. Christophorou and S. R. Hunter, "Electrons in Dense Gases," In *Swarms of Ions and Electrons in Gases* (W. Lindinger, T. D. Mark, and F. Howorka, Eds.), Springer-Verlag/Wien, Austria, 1984, pp. 241-264.

D. Patents and Patent Applications

The following patents and patent disclosures were developed under partial support of this contract.

1. L. G. Christophorou, S. R. Hunter, and J. G. Carter, Gas Mixtures for Diffuse-Discharge Switches, Patent No. 4,490,650 (December 25, 1984).

2. L. G. Christophorou and S. R. Hunter, Penning Ionization Ternary Gas Mixtures for Diffuse-Discharge Switch (granted).

3. S. R. Hunter and L. G. Christophorou, Binary and Ternary Gas Mixtures for Diffuse Glow Discharge Closing Switches.

4. L. G. Christophorou and S. R. Hunter, Binary and Ternary Gas Mixtures with Temperature Enhanced Characteristics for Use in Diffuse Glow Discharge Closing Switches.

E. Presentations

The following invited and contributed talks and lectures were presented on the work developed during this contract.

1. L. G. Christophorou, S. R. Hunter, J. G. Carter, and S. M. Spyrou (invited), "Gases for Possible Use in Diffuse-Discharge Switches," Workshop on "Diffuse Discharge Opening Switches," Tamarron, Colorado, January 13-15, 1982.

2. L. G. Christophorou (invited), "Gases for High Voltage Insulation and Pulsed-Power Technologies," Sandia National Laboratories, Albuquerque, New Mexico, January 21, 1983.

3. S. R. Hunter (invited), "Electron Transport Studies for Diffuse Discharge Switching Applications," Chemical Physics Seminar, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 9, 1983.

4. L. G. Christophorou, S. R. Hunter, J. G. Carter, S. M. Spyrou, and V. K. Lakdawala (invited), "Basic Studies of Gases for Diffuse-Discharge Switching Applications," 4th IEEE Pulsed Power Conference, Albuquerque, New Mexico, June 6-8, 1983.

5. J. G. Carter, S. R. Hunter, L. G. Christophorou, and V. K. Lakdawala (contributed), "Electron Drift Velocity and Ionization and Attachment Coefficients in Gases/Mixtures for Diffuse-Discharge Opening Switches," 3rd International Swarm Seminar, Innsbruck, Austria, August 3-5, 1983.

6. L. G. Christophorou (invited), "Development of New Gases for Diffuse Discharge Opening Switches," Workshop on "Externally-Controlled Diffuse Discharges," Bad Honnef, West Germany, August 15-19, 1983.

7. L. G. Christophorou, S. R. Hunter, J. G. Carter, S. M. Spyrou, and V. K. Lakdawala (invited), "Basic Studies of Gases for Diffuse-Discharge Switching Applications," U.S.-F.R.G. Joint Seminar on Externally Controlled Diffuse Discharges, Bad Honnef, West Germany, August 15-19, 1983.

8. L. G. Christophorou (invited), "Electron-Molecule Interactions and the Development of Gases for High Voltage Insulation and Pulsed Power Technologies," Department of Electrical Engineering, Old Dominion University, Norfolk, Virginia, March 23, 1984.

9. S. R. Hunter, J. G. Carter, L. G. Christophorou, and V. K. Lakdawala (contributed), "Transport Properties and Dielectric Strengths of Gas Mixtures for Use in Diffuse-Discharge Opening Switches," Fourth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, April 29-May 3. 1984.

10. S. R. Hunter (invited), "Electron Transport Studies of Gas Mixtures for Pulsed Power Diffuse Discharge Switching Applications," Health and Safety Research Division Information Meeting, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 3-5, 1984.

11. L. G. Christophorou (invited), "Basic Physics of Gases for Pulsed Power," Ecole Superieure d'Electricite de France, Gif-sur-Yvette, France, July 5, 1984.

12. L. G. Christophorou (invited), "Basic Physics of Gases for Pulsed Power Technologies," Naval Research Laboratory, Washington, D.C., October 24, 1984.

13. S. R. Hunter, J. G. Carter, L. G. Christophorou, and S. M. Spyrou (invited), "Temperature Dependent Electron Transport Studies for Diffuse Discharge Switching Applications," 5th IEEE Pulsed Power Conference, Arlington, Virginia, June 10-12, 1985.

14. R. Nakanishi, L. G. Christophorou, J. G. Carter, and S. R. Hunter (contributed), "Penning Ionization Ternary Gas Mixtures for Diffuse Discharge Switching Applications," 5th IEEE Pulsed Power Conference, Arlington, Virginia, June 10-12, 1985.

15. L. G. Christophorou, S. R. Hunter, J. G. Carter, and S. M. Spyrou (invited), "Effects of Temperature on Dissociative and Nondissociative Electron Attachment," Joint Symposium on Swarm Studies and Inelastic Electron-Molecule Collisions, Tahoe City, California, July 19-23, 1985.

16. S. R. Hunter, J. C. Carter, and L. G. Christophorou (contributed), "Electron Drift Velocity and Attachment and Ionization Coefficients in CH_4, CF_4, C_2F_6, C_3F_8, and n-C_4F_{10}," Joint Symposium on Swarm Studies and Inelastic Electron-Molecule Collisions, Tahoe City, California, July 19-23, 1986.

17. J. G. Carter, S. R. Hunter, and L. G. Christophorou (contributed), "Electron Drift Velocity and Attachment and Ionization Coefficients in C_2F_6/Ar and C_2F_6/CH_4 Gas Mixtures at Elevated Gas Temperatures," 38th Annual Gaseous Electronics Conference, Monterey, California, October 15-18, 1985.

18. L. G. Christophorou (invited), "From Basic Research to Application: Gas Engineering for High Voltage Insulation and Pulsed Power Technologies," Department of Electrical Engineering, Mississippi State University, Mississippi State, Mississippi, November 21, 1985.

19. S. R. Hunter (invited), "Electron Transport Studies in Vibrationally and Electronically Excited Gases/Mixtures for Use in e-Beam Controlled Diffuse Gas Discharge Switches," Department of Electrical Engineering, Old Dominion University, Norfolk, Virginia, March 21, 1986.

20. S. R. Hunter, L. G. Christophorou, and J. G. Carter (contributed), "Electron Drift Velocity and Attachment and Ionization Coefficients for Gases/Mixtures for Use in Diffuse Discharge Switching Applications," 1986 IEEE International Conference on Plasma Science, Saskatoon, Saskatchewan, Canada, May 19-21, 1986; abstract published in *IEEE Conference Record - Abstracts*, IEEE Catalog No. 86CH2317-6, IEEE, New York, 1986, pp. 7-8.

21. S. R. Hunter (contributed), "Electron Attachment to NF_3 Revisited," Thirty-ninth Annual Gaseous Electronics Conference, Madison, Wisconsin, October 7-10, 1986.

22. S. R. Hunter and L. G. Christophorou (contributed), "Gas Engineering Studies for High Pressure Self-Sustained Diffuse Discharge Closing Switches," Fifth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, May 3-7, 1987.

23. L. G. Christophorou, D. L. McCorkle, and S. R. Hunter (contributed), "Gas Mixtures for Spark Gap Closing Switches with Emphasis on Efficiency of Operations," Fifth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, May 3-7, 1987.

24. S. R. Hunter (invited), "Gas Engineering for Pulsed Power Switching," Fifth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, May 3-7, 1987.

25. J. G. Carter, S. R. Hunter, and L. G. Christophorou (contributed), "Electron Transport and Rate Coefficient Studies for e-Beam-Sustained Diffuse Gas Discharge Switching," Fifth International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, May 3-7, 1987.

26. S. R. Hunter, L. G. Christophorou, J. G. Carter, and P. G. Datskos (invited), "New Concepts in High Current Self-Sustained Diffuse Discharge Closing Switches," 6th IEEE Pulsed Power Conference, Arlington, Virginia, June 29-July 1, 1987.

27. S. R. Hunter, J. G. Carter, and L. G. Christophorou (contributed), "Electron Transport Studies of Gaseous Media for Diffuse Discharge Closing Switches," International Conference on Phenomena in Ionized Gases (ICPIG XVIII), Swansea, Wales, United Kingdom, July 13-17, 1987.

28. L. G. Christophorou, S. R. Hunter, L. A. Pinnaduwage, J. G. Carter, and P. G. Datskos (contributed), "Electron Attachment Properties of Excited Dielectric-Gas Molecules and their Possible Use for Pulsed Power Switching," IX International Conference on Gas Discharges and their Applications, Venice, Italy, September 19-23, 1988.

II. Experimental Techniques

Several different experimental techniques were employed to obtain the data discussed in this report. Most of these experiments existed before the commencement of this program, but some were modified during the course of the present research program. These experiments are described briefly in this section.

2.1 High Pressure Swarm Experiment

The technique used to obtain the electron attachment rate constants in the present swarm studies was originally devised by Bortner and Hurst.[16,17] In Fig. 3 is shown the schematic diagram of the present apparatus. Electrons are produced in a plane at the source electrode, perpendicular to the applied electric field, $\underline{E}$, by the passage through the gas of high energy alpha particles. The alpha particle trajectories are well collimated such that the electron swarms produced by the energy decay of the alpha particles lie in a well-defined plane at the source. Each alpha particle (produced by the decay of Cf^{252}, energy $\approx$ 6.1 MeV) produces a swarm of $\approx 2.3 \times 10^5$ electrons in N_2 within $\approx 5 \times 10^{-9}$s at 133 kPa to 2×10^{-10} s at 3.2 MPa. These swarms of electrons then drift to the anode under the influence of a uniform electric field established between the cathode and anode.

The change in the number n(t) of electrons in the swarm during the time interval dt is

$$\frac{dn(t)}{dt} = - \eta w n(t) \quad , \tag{11}$$

where η is the average number of attaching collisions per centimeter of drift, and w is the drift velocity of the swarm. The measurements were performed at high total gas pressures (133 kPa $\leq P_T \leq$ 3.9 MPa) such that the influence of

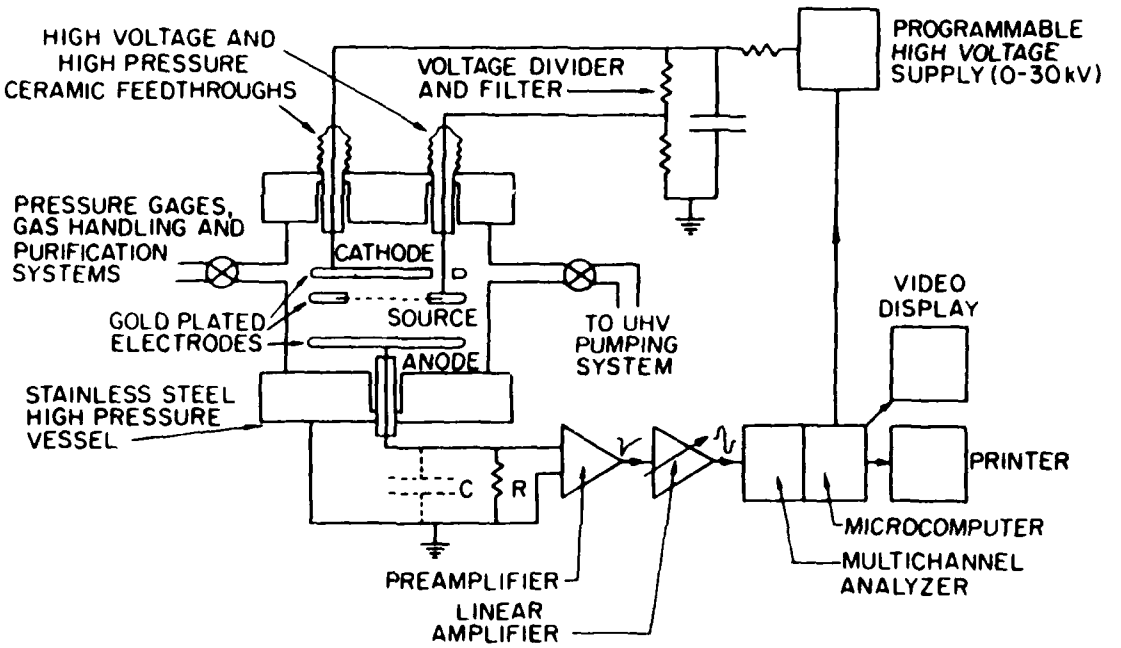


Fig. 3. Schematic diagram of the electron attachment apparatus and signal conditioning electronics used in the room temperature electron attachment rate constant measurements (Ref. 18).

diffusion upon the drift of the swarm was negligibie. Equation (11) has the following solution

$$n(t) = n_o \exp[-(\eta/N_a)N_a\ wt] \quad , \tag{12}$$

where η/N_a is defined as the attachment coefficient with the units of cm^2, N_a is the partial attaching gas number density, and n_o is the initial number of electrons produced by each α-particle at the beginning of the drift space.

To obtain the attachment coefficients, the experiment is performed as follows: A pure buffer gas sample is admitted into the vessel at a given pressure, and a distribution of voltage pulse heights are obtained at a given E/N, which are accumulated in a multichannel analyzer (MCA) operating in the pulse height analysis mode. The most probable pulse height is recorded. The E/N is changed and a series of most probable pulse heights is obtained as a function of E/N. If the pressure dependence of the attachment process is to be studied, then the above set of measurements are performed over a range of buffer gas pressures as well. A small quantity of attaching gas is then added to the drift vessel (usually one part in 10^5 to 10^8 of the total gas pressure in the present study), the chamber refilled with the buffer gas, and a new series of most probable pulse heights obtained as a function of E/N and P_T. The ratio of the pulse heights with and without the attaching gas is obtained. The electron attachment coefficient η/N_a is then obtained from this ratio.

The drift region electrodes of the experimental apparatus shown in Fig. 3 are housed in a stainless steel high pressure vessel, capable of operating at total gas pressures up to 10 MPa. The chamber is pumped by a UHV pumping system with a base pressure of a few parts in 10^{-6} Pa and an outgassing rate of 10^{-3} Pa per hour. All electrodes in the chamber are gold plated, and enameled insulators are used to reduce possible surface reactions with reactive attaching gases. The alpha paticle source used in these studies was Cf^{252} which was electroplated onto a thin platinum ribbon and housed within the source electrode. This source produced $\approx 10^4$ detectable swarms per second. The induced anode voltages, produced by the motion of the swarm, are detected and amplified by a preamplifier and linear amplifier and passed into a microprocessor based, 2048 channel multichannel analyzer (MCA), where the

distribution of the resultant peak pulse heights are stored. The pulse height histogram is analyzed by the microprocessor to find the most probable pulse height, which is then used to obtain η/N_a, and thus k_a using a simple numerical iterative procedure. The microprocessor then resets the programmable voltage supply and hence the E/N value, and a new histogram is obtained, and the whole procedure repeated. Further details of the experimental technique are given in Ref. 18.

2.2 High Temperature Swarm Experiment

The high temperature swarm apparatus is shown schematically in Fig. 4. The operation of this experiment is very similar to that described above, except that a number of modifications were made to the basic design to facilitate the measurements at high gas temperatures. In contrast to our other swarm apparatus, the swarm chamber was made ~100 cm long, and the distances of the two end flanges from the middle of the chamber are ~50 cm. To avoid leaks at the flanges when heating or cooling, the region around the flanges was water cooled and was kept at a much lower temperature than the collision region (the region between the anode and cathode; see Fig. 4). This arrangement also allowed the high voltage and signal feedthroughs to be kept at a low T. Special care was also taken in the construction of the long supporting stands holding the anode and the cathode (the Cf^{252} alpha particle source used to produce the electron swarms by the energy decay of the alpha particles was mounted on a plate supported on the cathode), which consist of a stainless steel rod with insulating rods at its two ends.

A furnace and temperature control system (0-1000°C, resolution 1°C, Applied Test System, Inc.) was used to heat the central region of the chamber. The temperature in the collision region was measured by six thermocouples (chromel-alumel, type KX) located as close to the drift region as possible. With the aid of two independently controlled heating elements embedded in the insulating walls of the furnace, the gas temperature between the electrodes was controlled to within 1-2°C. Further details of the experimental technique are given in Ref. 19.

2.3 Pulsed Townsend Experiment

The electron drift apparatus used to obtain the room temperature and high temperature electron drift velocity and attachment and ionization coefficient data is shown schematically in Fig. 5. The high pressure chamber was designed

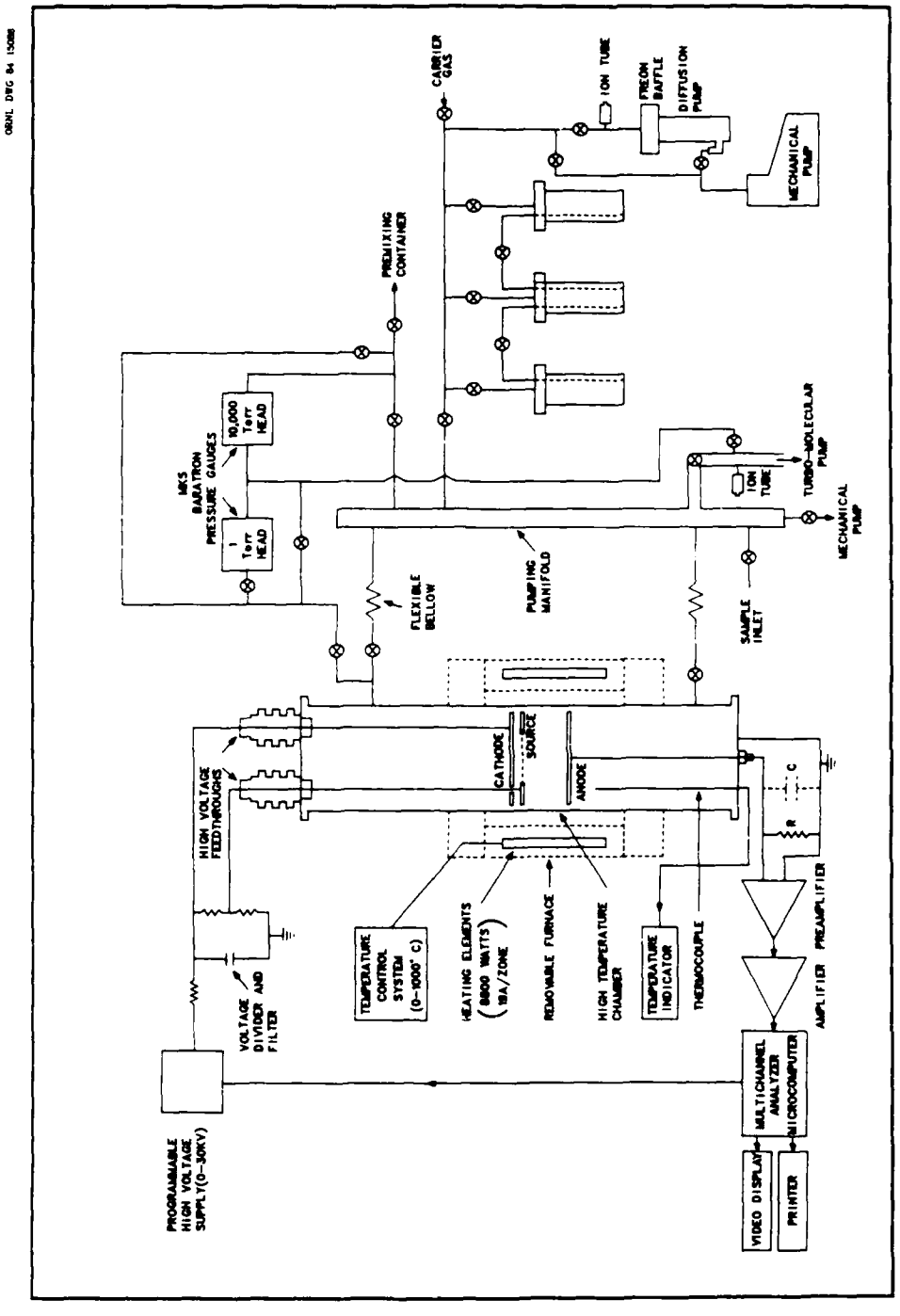


Fig. 4. Schematic diagram of the high temperature electron attachment rate constant experimental appratus (Ref. 19).

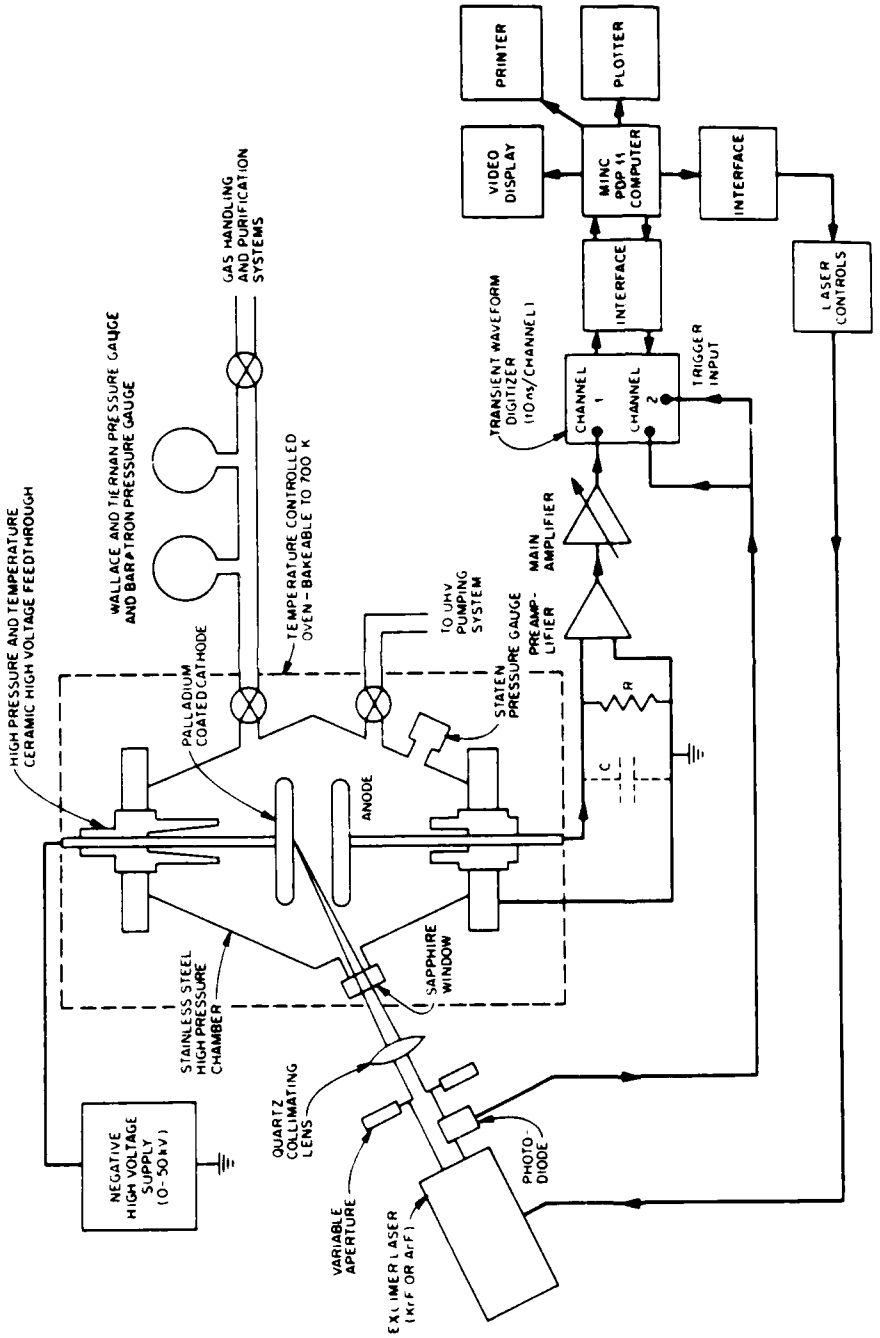


Fig. 5. Schematic diagram of the pulsed Townsend experimental apparatus used to obtain the room temperature and high temperature w, α/N and η/N coefficients (Ref. 20).

and tested to a pressure of 8 MPa and a temperature of 750 K and pumped by an ultrahigh vacuum system having a base pressure of $\simeq 5 \times 10^{-6}$ Pa. This chamber housed the two stainless steel electrodes 7 cm in diameter at a gap separation which could be varied from 1.5 to 4 cm. Electrons were produced photoelectrically at the palladium-coated photocathode by a pulsed excimer laser using argon fluoride (λ = 193 nm, full width at half maximum $\approx$ 5 ns) as the lasing medium. The voltage induced in the anode circuit by the motion of the electrons and ions in the drift gap was detected by a fast (risetime $\approx$ 1 ns), high impedance ($Z_i \approx 10^{11}$ Ω) unitary gain emitter-follower preamplifier. For the electron drift velocity measurements, the voltage transient was digitized by a Biomation model 6500 waveform recorder (2 ns per channel, 6 bits vertical resolution), which was triggered by a variable delay synchronization pulse from the laser firing control circuit. This technique allowed the waveform recorder to be triggered before the laser was fired. For the electron attachment and ionization measurements, the voltage transient was digitized by a Biomation model 8100 waveform recorder (10 ns per channel, 9 bit vertical resolution) operating in the "pretrigger" mode which allowed the signal immediately preceding the trigger pulse to also be recorded. In this case the waveform recorder was triggered by an electronic pulse produced by a fast UV photodiode ($\approx$1 ns risetime). This waveform digitizer has the capability of capturing the voltage transient on two different time scales. The first part of the waveform was digitized at 10 ns per channel in order to capture the distinct break in the waveform between the electron and ion voltage components. The second part of the waveform was digitized at a much slower rate (usually 50 ns to 1 μs per channel) in order to capture the total ion voltage transient. The digitized waveforms were transferred to a PDP 11 computer where multiple waveforms could be averaged, and the resultant waveform analyzed to determine w_m, α_T/N, and η_T/N. Further experimental details of the pulsed Townsend experimental technique are given in Ref. 20.

2.4 Gas Ionizing W Value Experiment

Figure 6 shows the block diagram of the system employed for the measurement of the W values of the gases. The parallel electrodes, which have a 5 cm gap separation, are supported by ceramic insulators mounted on the top

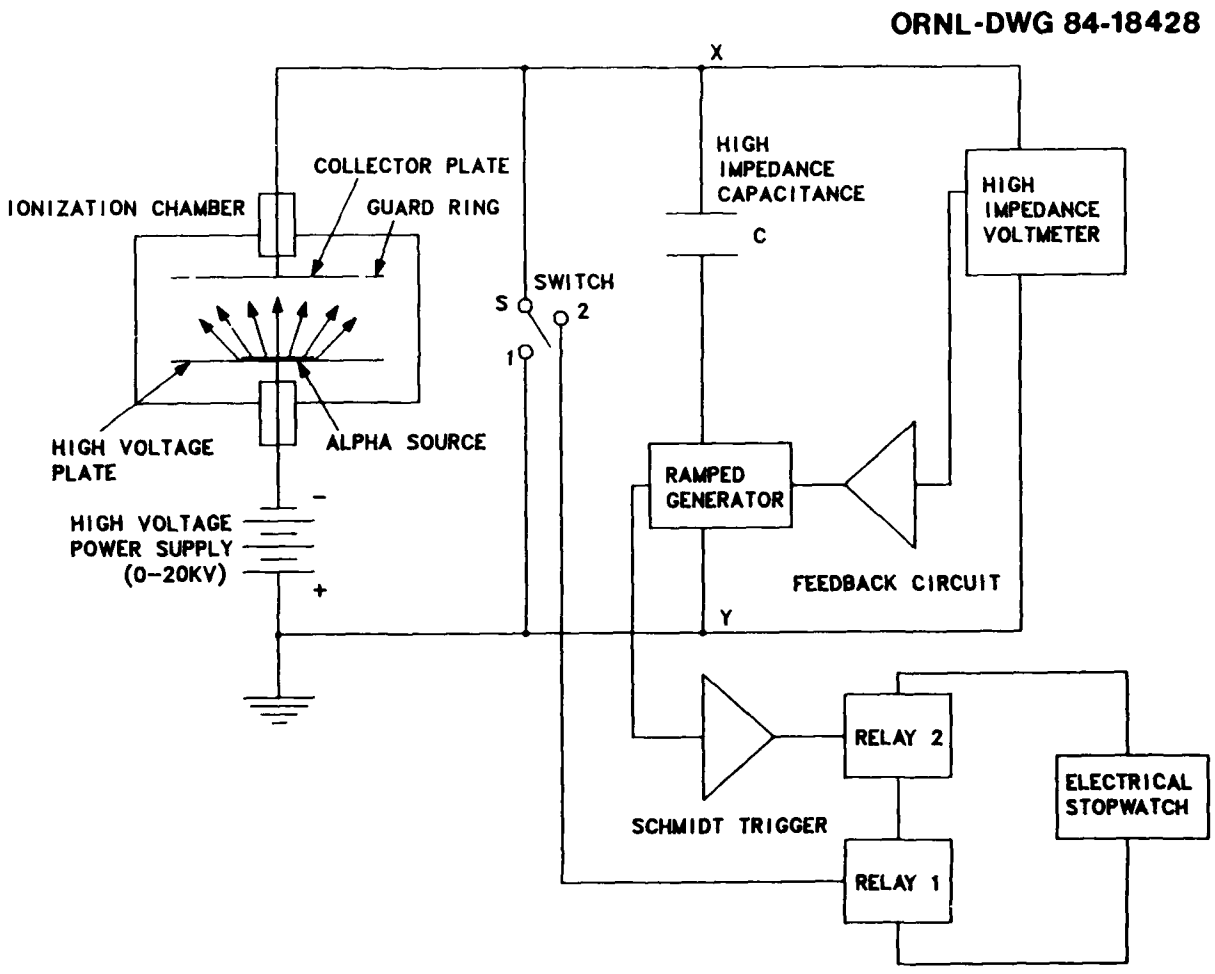


Fig. 6. Schematic diagram of the apparatus used to measure the W values of α-particles (Ref. 22).

and bottom flanges of the vacuum chamber. The collector plate is 11.9 cm in diameter and is surrounded by a guard ring with a gap of 0.1 cm. As an ionization source, an uncollimated Pu^{239} source deposited on a platinum plate of 2.5 cm in diameter and 0.16 cm in thickness is flush mounted in the center of the high voltage electrode, itself 15.4 cm in diameter. The ionization source produces ~ 6×10^4 α particles per second; each α particle has an initial energy of ~ 5.1 MeV.

In order to eliminate impurities, especially water vapor, all gases were passed through a liquid nitrogen trap. Prior to introducing the gas into the chamber, the gas system was pumped to a pressure of less than 5×10^{-6} Torr. Direct current voltages up to 12 kV were applied to the test chamber. Above this voltage, corona discharges in the vacuum chamber disturbed the measurements.

The principle of the measurement circuit is the same as that used by Bortner *et al.*[21] In our system, the accuracy of the measurement is improved by using an automatically controlled feedback circuit. When the switch (Fig. 6) is closed (contact 2 closed), electrons and ions produced by the α particle energy decay in the gas produce a current in the collector circuit which is collected as charge on the low loss capacitor C. Simultaneously, an electrical stopwatch starts counting the time by closing relay 1. The ramped generator in the circuit was used as a source of bucking voltage to the capacitor. The voltage of the ramped generator was controlled through a feedback circuit by the output of a high impedance voltmeter (~10^{14} Ω) which monitored the potential between X and Y (see Fig. 6). Further details of the experimental apparatus are discussed in Refs. 22 and 23, while the principle of the experimental technique is given in Section III.

2.5 High Voltage Breakdown Experiment

The experimental procedure and breakdown chamber employed in the present study have been described previously.[24,25] A schematic of the apparatus is shown in Fig. 7. The uniform field was maintained with two stainless steel plane electrodes having 4.8" (12.2 cm) diameter and a Bruce profile [1.6" (4.1 cm) diameter flat surfaces]; the dc voltage was provided by a 100 kV Spellman power supply. The stainless steel chamber was heated with a three-zone electrical strip heater enclosure. The temperature was sensed by thermocouples attached to the test chamber and was indicated and controlled by three Barber-Coleman model 560 controllers; it could be measured to within $\pm$ 1°C over the temperature range investigated (~22 to 300°C).

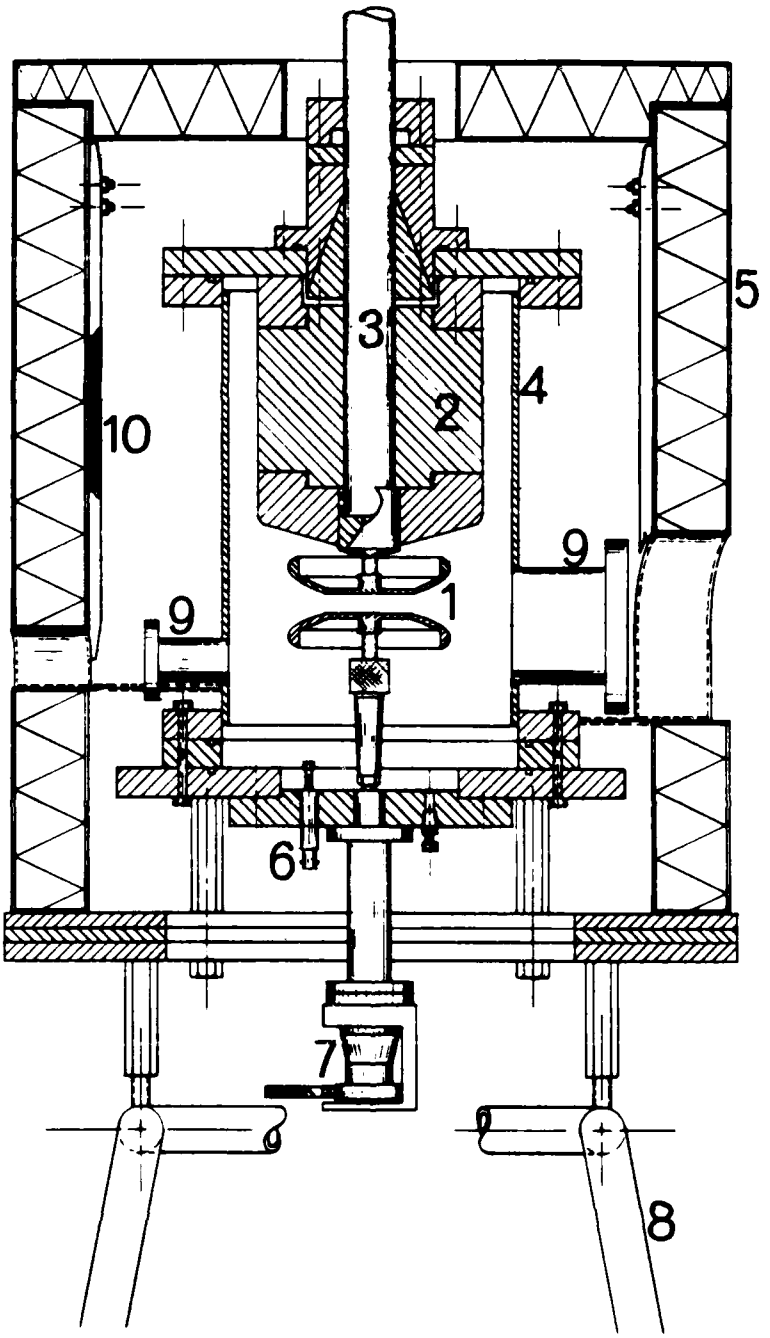


Fig. 7. Cross sectional view of the high pressure, variable temperature high voltage breakdown chamber: (1) uniform field electrodes, (2) Teflon spacer, (3) high voltage cable, (4) high pressure chamber, (5) oven, (6) ground feedthrough, (7) linear motion drive, (8) support stand, (9) ports, (10) resistance heaters (Ref. 24).

III. Experimental Techniques and Selected Results

In this section we present selected results of our measurements of the electron attachment rate constant, electron attachment and ionization coefficients, electron drift velocities, high voltage breakdown field strengths and W values in several gases and gas mixtures which have been shown to be good candidates for use in diffuse discharge switch applications. Detailed discussions of these measurements are to be found in the publications listed in Section I.

3.1 Room Temperature Electron Attachment Rate Constants and Attachment Cross Sections

High pressure (>1 atm) electron attachment studies of the perfluoroalkanes[18] and several fluorinated ethers[26] have shown that several of these molecules possess electron attachment rate constants which have desirable energy dependences for diffuse discharge switching applications (i.e., they attach electrons efficiently at high energies and have much reduced electron attachment rate constants at near-thermal energies). These measurements are summarized in Fig. 8a and have been obtained using a high pressure swarm technique.[18,26-27] The molecules C_2F_6 and CF_3OCF_3 are of considerable interest for opening switch applications due to their very low rates of thermal electron attachment and that the peak in $k_a(\langle\epsilon\rangle)$ occurs at comparatively high electron energies for both molecules. These two molecules, along with CF_4 and CF_3SCF_3 attach electrons dissociatively. On the other hand, molecule C_3F_8 (and $n\text{-}C_4F_{10}$) is particularly noteworthy in that electron attachment to this molecule at atmospheric pressures and ambient temperatures is predominantly by parent negative ion stabilization,[18] and thus this molecule could possibly be used in closed-cycle switches.

The electron attachment rate constant for NF_3 is plotted in Fig. 9 as a function of $\langle\epsilon\rangle$ along with several previous electron attachment measurements.[28,29] This molecule was previously thought to possess a comparatively high thermal electron attachment rate constant [$(k_a)_{th} \approx 10^{-10} - 10^{-9}$ cm^3 s^{-1}] and consequently to be unsuitable for use in opening switch applications. The present measurements show that the thermal electron attachment in NF_3 is up to two orders of magnitude lower than these estimates [$(k_a)_{th} \approx 3 \times 10^{-12}$ cm^3 s^{-1}], making this molecule a suitable candidate for study in switching applications.

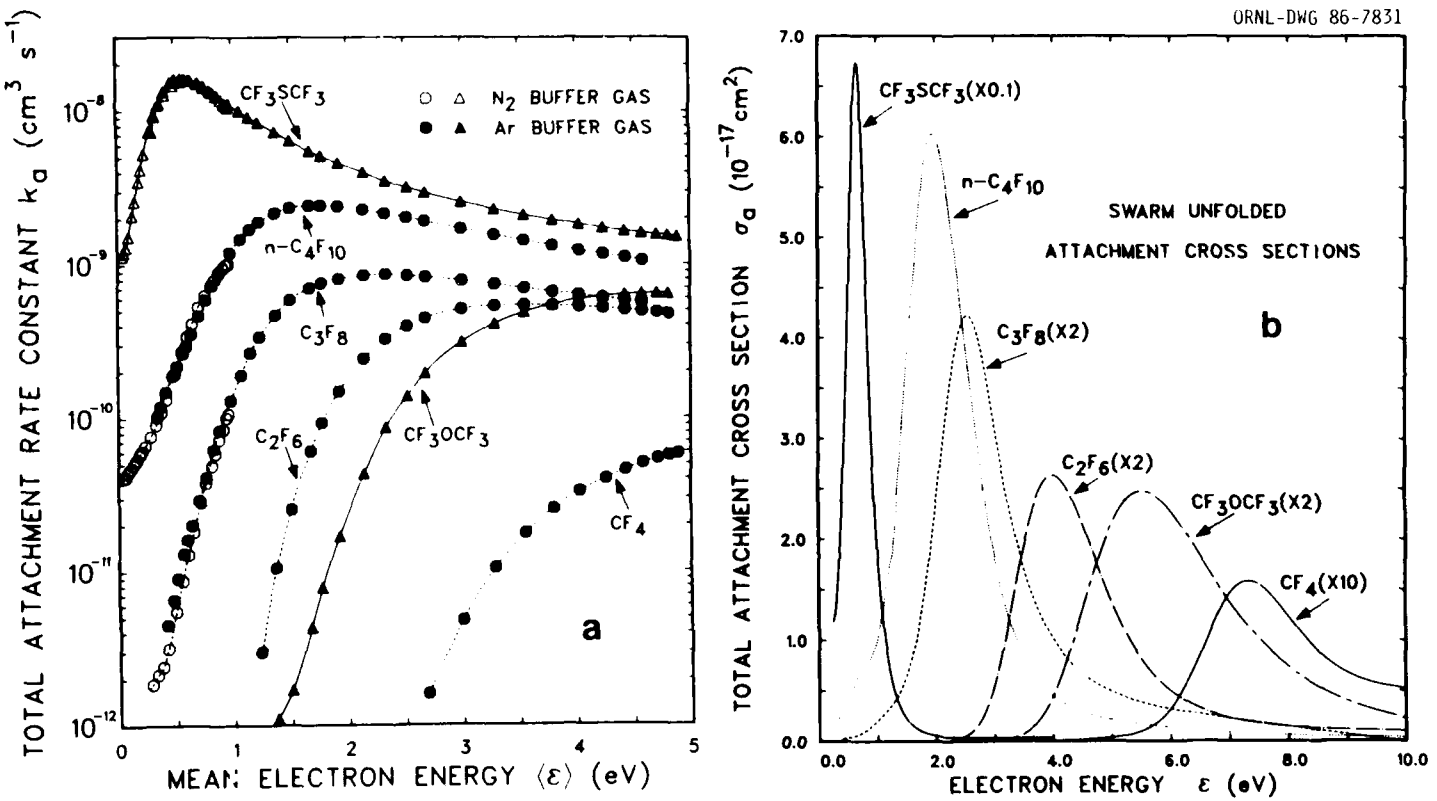


Fig. 8. a) The total electron attachment rate constant k_a as a function of the mean electron energy ⟨ε⟩ for several perfluoroalkanes[18] and perfluoroethers[26] measured in buffer gases of N_2 and Ar, and b) The total electron attachment cross section σ_a as a function of the electron energy ε for several perfluoroalkanes and perfluoroethers determined from k_a (⟨ε⟩) measurements in Ar (Refs. 18 and 26).

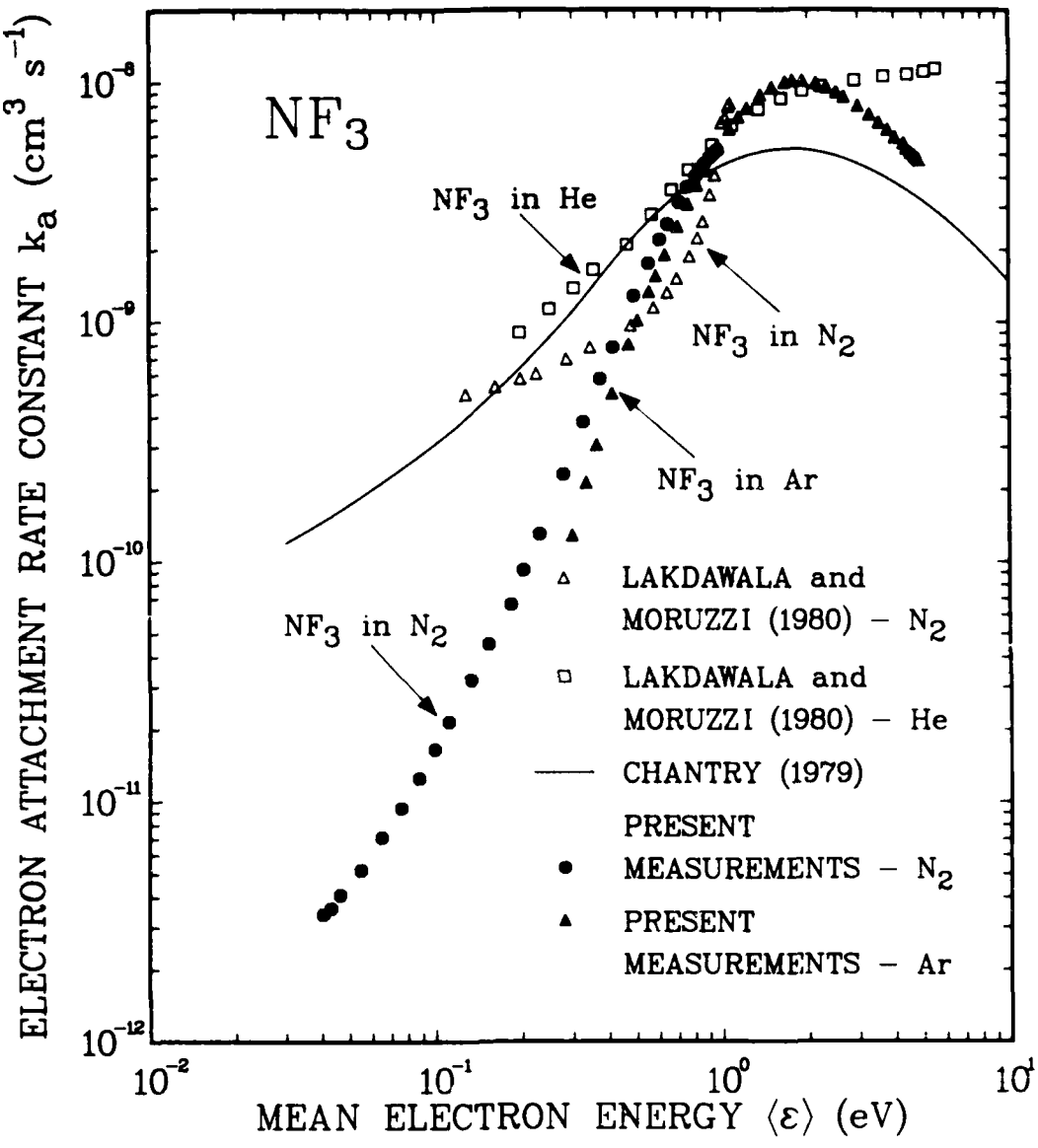


Fig. 9. The electron attachment rate constant k_a as a function of mean electron energy $\langle\epsilon\rangle$ for NF_3 in comparison with the previous measurements of Chantry (Ref. 28) and Lakdawala and Moruzzi (Ref. 29).

The total electron attachment cross section $\sigma_a(\epsilon)$ for each of these molecules is related to the attachment rate constant k_a as a function of $\langle\epsilon\rangle$ (or E/N) and the electron energy distribution function $f(\epsilon,E/N)$ of the gas mixture by

$$k_a(E/N) = \frac{\eta(E/N)\ w(E/N)}{N_a} = \left[\frac{2}{m}\right]^{1/2} \int_0^\infty \epsilon^{1/2}\ \sigma_a(\epsilon)\ f(\epsilon,E/N)\ d\epsilon \quad , \quad (13)$$

where η/N_a is the normalized electron attachment coefficient and m is the electron mass. The electron energy distribution function is normalized by

$$\int_0^\infty f(\epsilon,E/N)\ d\epsilon = 1 \quad . \quad (14)$$

If both $k_a(E/N)$ and $f(\epsilon,E/N)$ are known over a wide range of E/N values, then $\sigma_a(\epsilon)$ can be determined over a wide range of electron energies using a swarm unfolding technique.[30] The attachment rate constant measurements given in Figs. 8a and 9 have been obtained for these electronegative gases by performing the measurements in gas mixtures composed of traces (one part in 10^6 to 10^8) of the attaching gas in the high pressure buffer gas of argon. The electron energy distribution functions $f(\epsilon,E/N)$ and $w(E/N)$ values used in Eq. (13) are those for pure Ar,[18] as we have made the justifiable assumption that the electron transport parameters and hence $f(\epsilon,E/N)$ are unaffected by the addition of minute quantities of the attaching gas to the Ar.[18,26] (Any observed dependence of k_a on the attaching gas partial pressure can be removed by extrapolating the measurements to zero attaching gas pressure.)[18,26]

The electron attachment cross sections $\sigma_a(\epsilon)$ obtained from these analyses are plotted in Figs. 8b and 10 and these measurments, along with the $k_a(\langle\epsilon\rangle)$ values given in Figs. 8a and 9, indicate that we indeed have found several electronegative gases which attach electrons over a wide energy range at electron energies well in excess of thermal energies ($\epsilon > 0.3$ eV). Consequently, the electron attachment processes in a potential switching gas

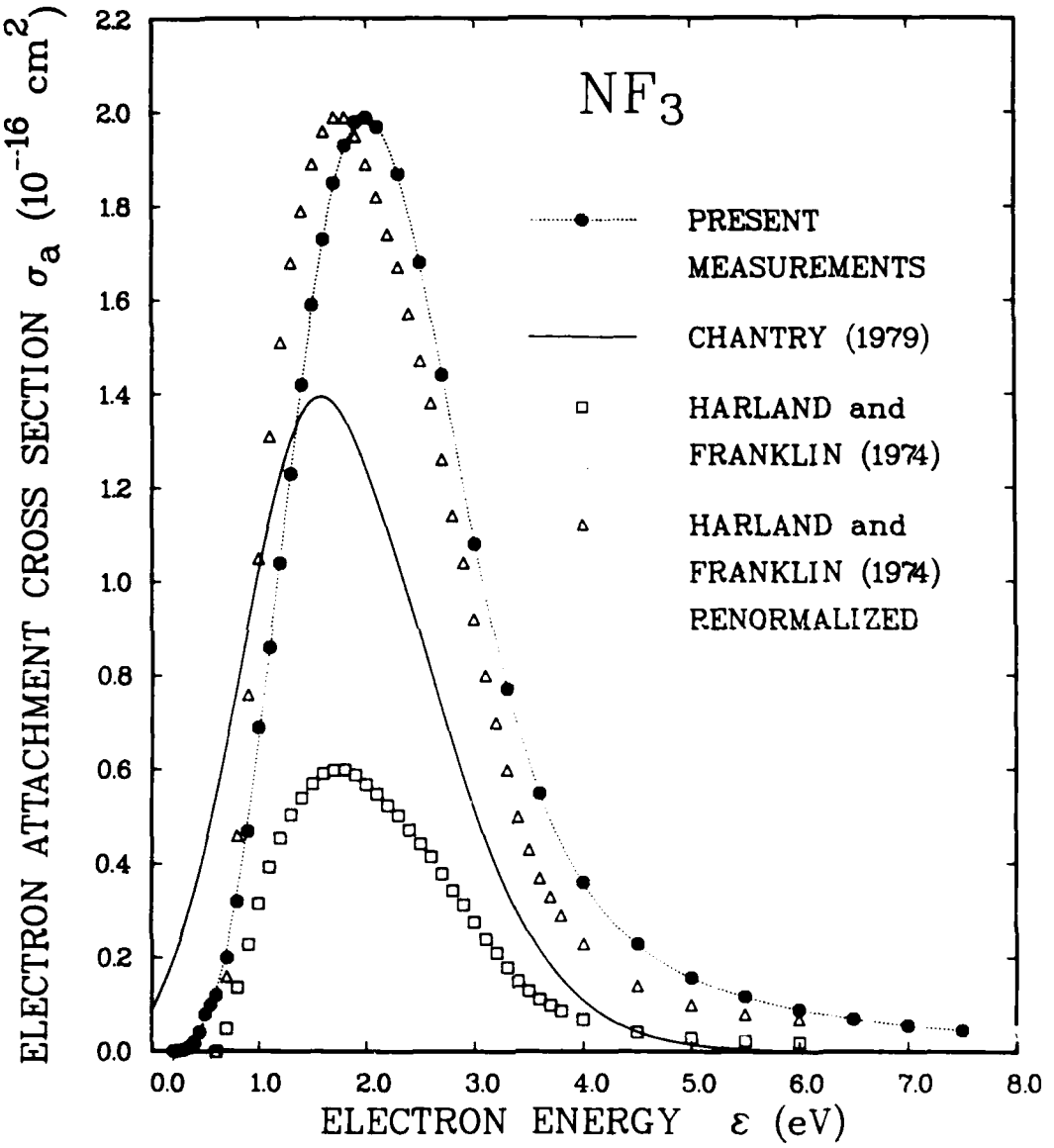


Fig. 10. The electron attachment cross section $\sigma_a(\epsilon)$ for NF_3 in comparison with the previous measurements of Chantry (Ref. 28) and Harland and Franklin (Ref. 31).

mixture using these gases can be positioned at appropriate $\langle\epsilon\rangle$ or E/N values by choosing a gas which efficiently attaches electrons in that E/N range.

3.2 Elevated Temperature Electron Attachment Rate Constant Measurements

Whenever the diffuse discharge switch in an inductive energy storage circuit is fired, the gas temperature within the switch is expected to rise several degrees centigrade, and operating temperatures of several hundred degrees are likely for repetitively operated switches. An understanding of the factors that affect the operation of the switch under these conditions can be obtained by performing the electron transport and rate coefficient measurements at gas temperatures above room temperature.

The electron attachment rate constant $k_a(\langle\epsilon\rangle)$ has been measured for C_2F_6 over the temperature range $300 \leq T \leq 750$ K in order to investigate the influence of gas heating on the electron attaching properties of this molecule (Fig. 11). As the gas temperature increases, $k_a(\langle\epsilon\rangle)$ increases, and this increase is progressively larger at lower energies such that the threshold and the peak in the $k_a(\langle\epsilon\rangle)$ shift to lower energies at higher gas temperatures. The $k_a(\langle\epsilon\rangle)$ increases by $\approx$30% over this temperature range near its peak at $\langle\epsilon\rangle \approx 3$ eV (Fig. 11).

Measurements of $k_a(\langle\epsilon\rangle)$ have also been performed in C_3F_8 and n-C_4F_{10} as a function of gas temperature up to 750 K in Ar buffer gas (over the mean electron energy range $0.76 \leq \langle\epsilon\rangle \leq 4.8$ eV). These measurements are given in Figs. 12 and 13 and show that at a given value of $\langle\epsilon\rangle$, k_a decreases only slightly up to $T \sim 400$ K, then rapidly decreases with increasing T up to $T \sim 450$ K, and finally significantly increases with increasing T above this temperature. The lower temperature measurements ($T < 450$ K) have been found to be strongly dependent on total gas pressure, indicating that parent negative ion formation processes are significant electron attachment processes at these temperatures. At higher gas temperatures ($T \geq 450$ K) pressure dependent electron attachment processes are negligible indicating that electron attachment to C_3F_8 and n-C_4F_{10} at these temperatures is predominantly dissociative. These measurements indicate that relatively small changes in the gas kinetic energy (and hence in the vibrational populations of the attaching gas) can have a large influence on the electron attaching properties of C_3F_8 and n-C_4F_{10} which could, in turn, significantly affect the performance

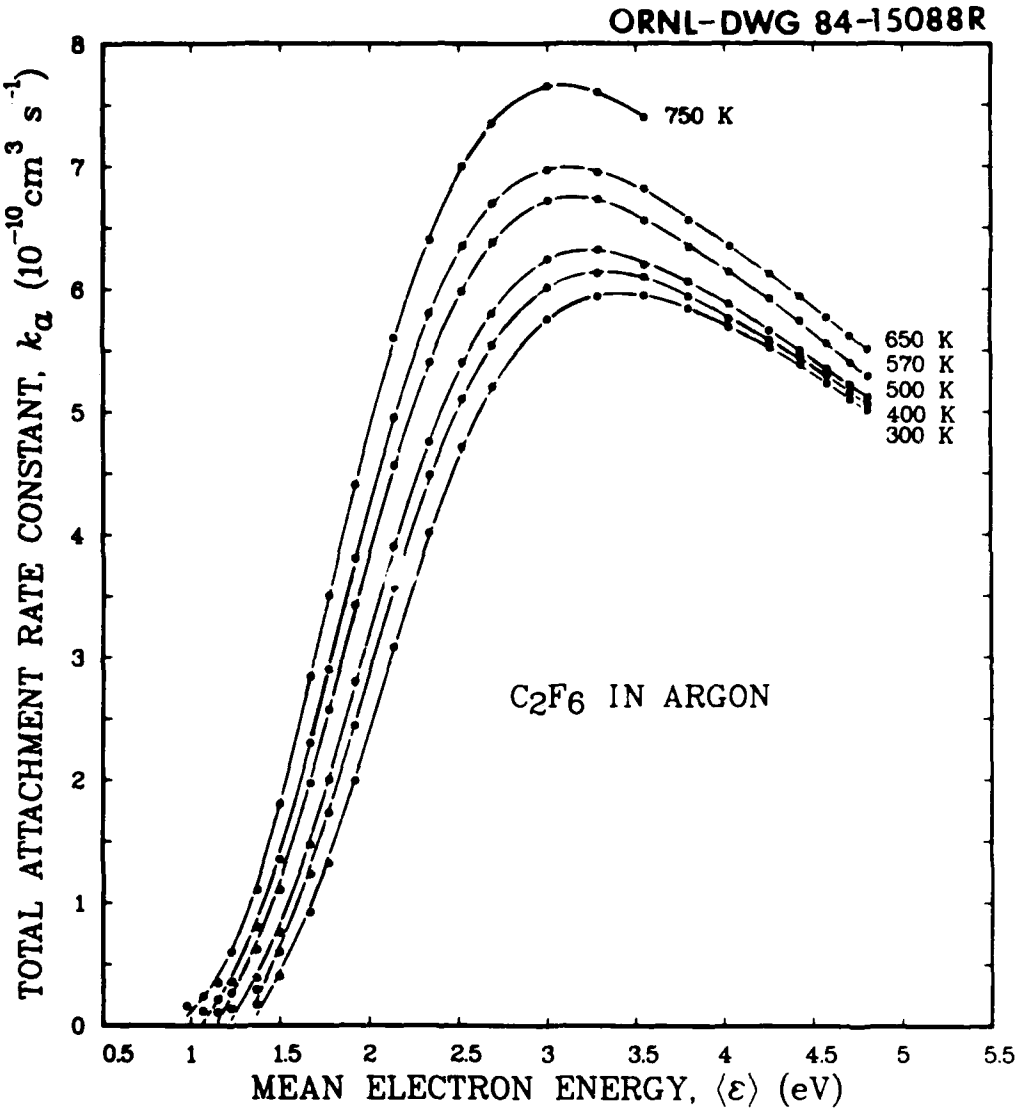


Fig. 11. The total electron attachment rate constant k_a as a function of the mean electron energy ⟨ε⟩ for C_2F_6 at several gas temperatures between 300 K and 750 K (Ref. 19).

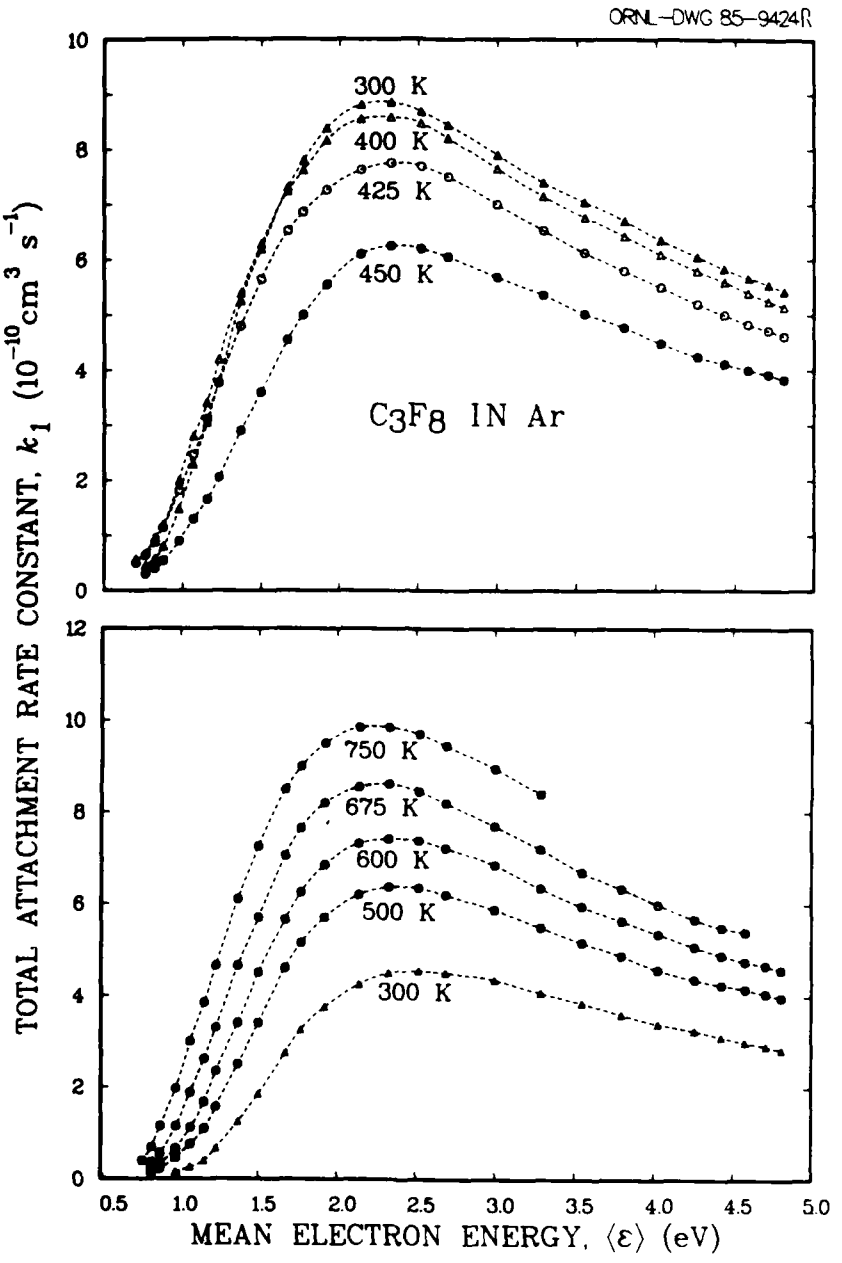


Fig. 12. Electron attachment rate constant k_1 for $N_T \rightarrow \infty$ (and $N_a \rightarrow 0$) for C_3F_8 as functions of mean electron energy $\langle \epsilon \rangle$ in a buffer gas of Ar at the gas temperatures given in the figure. The curve at 300 K in Fig. 12b is the dissociative attachment component to the total rate of electron attachment at this temperature (see Ref. 19 for full discussion).

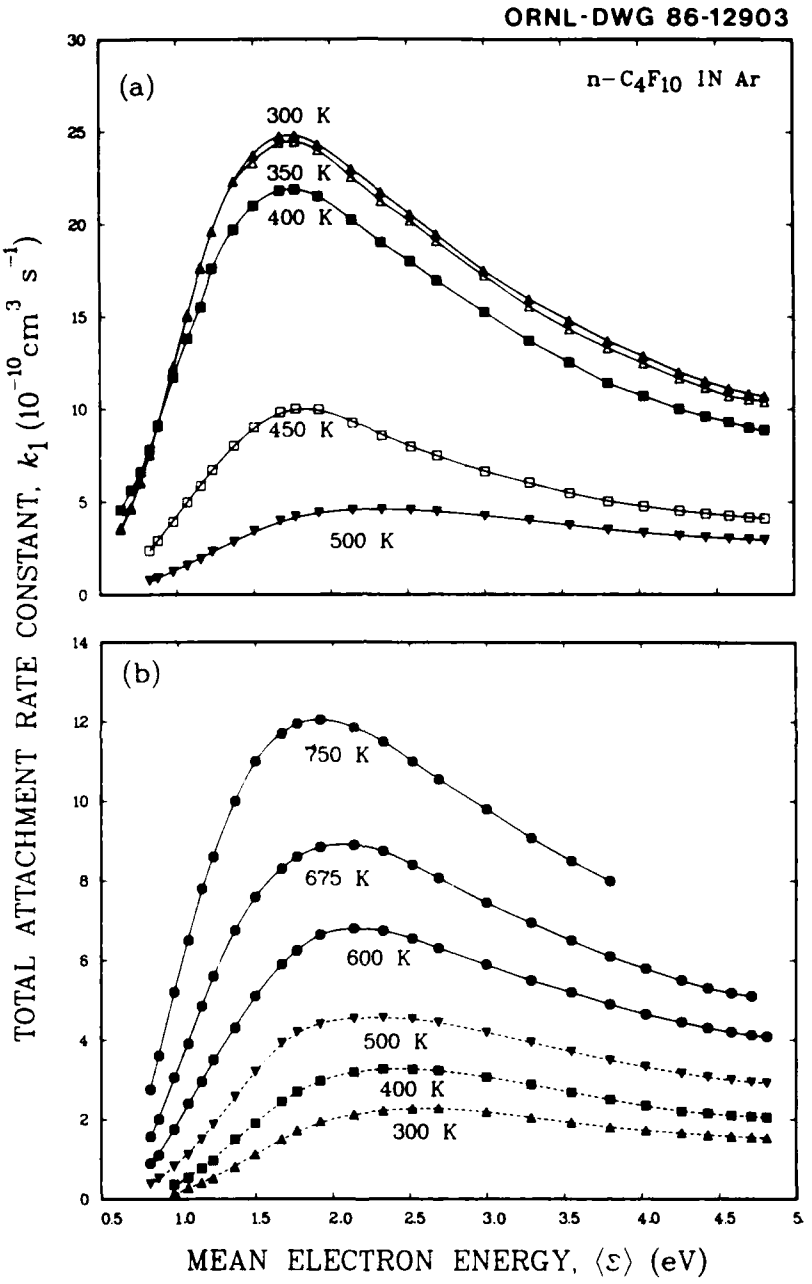


Fig. 13. Electron attachment rate constant k_1 for n-C_4F_{10} obtained under the same conditions as those for C_3F_8 in Fig. 12.

of repetitively operated switches operating at elevated gas temperatures using C_3F_8 or $n\text{-}C_4F_{10}$.

3.3 Room Temperature Electron Drift Velocity Measurements

A. Pure Gases

The electron drift velocity w has been measured in several pure gases using our pulsed Townsend experimental apparatus. The w measurements in gases which are potentially useful in diffuse discharge opening and closing switches are given in Figs. 14 and 15, respectively. All these gases (with the exception of $n\text{-}C_4F_{10}$) possess significantly enhanced w values (i.e. regions of negative differential conductivity [NDC]) at comparatively low E/N values, which as indicated in Fig. 2 is a very desirable characteristic of gases for use in diffuse discharge opening switches.

B. Gas Mixtures

The electron drift velocity w has been measured in several gas mixtures composed of the attaching gases shown in Fig. 8a using either Ar or CH_4 as buffer gases in an attempt to combine the electron mobility enhancement afforded by the NDC effect at low E/N observed in gas mixtures using Ar and CH_4, with the very desirable electron attaching properties of the electronegative gases given in Fig. 8a at high E/N (or$\langle\epsilon\rangle$). These measurements are plotted in Figs. 16 to 19 over the concentration range of 0.1 to 100% of the attaching gas in the buffer gas. The measurement technique and accuracy of the resultant data have been discussed in Ref. 32. These gas mixtures all possess pronounced regions of NDC over a range of E/N values. The NDC effects observed in several of these gas mixtures are among the largest that have been observed in any gas mixture and are the result of large vibrational inelastic energy loss processes in these electronegative gases at comparatively low electron energies [$0.1 < \epsilon \lesssim 1.0$ eV].

Electron drift velocity measurements in several SiF_4/He gas mixtures are plotted in Fig. 20. These gas mixtures have been found to possess the very desirable characteristics outlined later in this section for use in diffuse discharge closing switches. They have the added advantage of possessing high w values at E/N values near the operating E/N value of the discharge when the switch is closed.

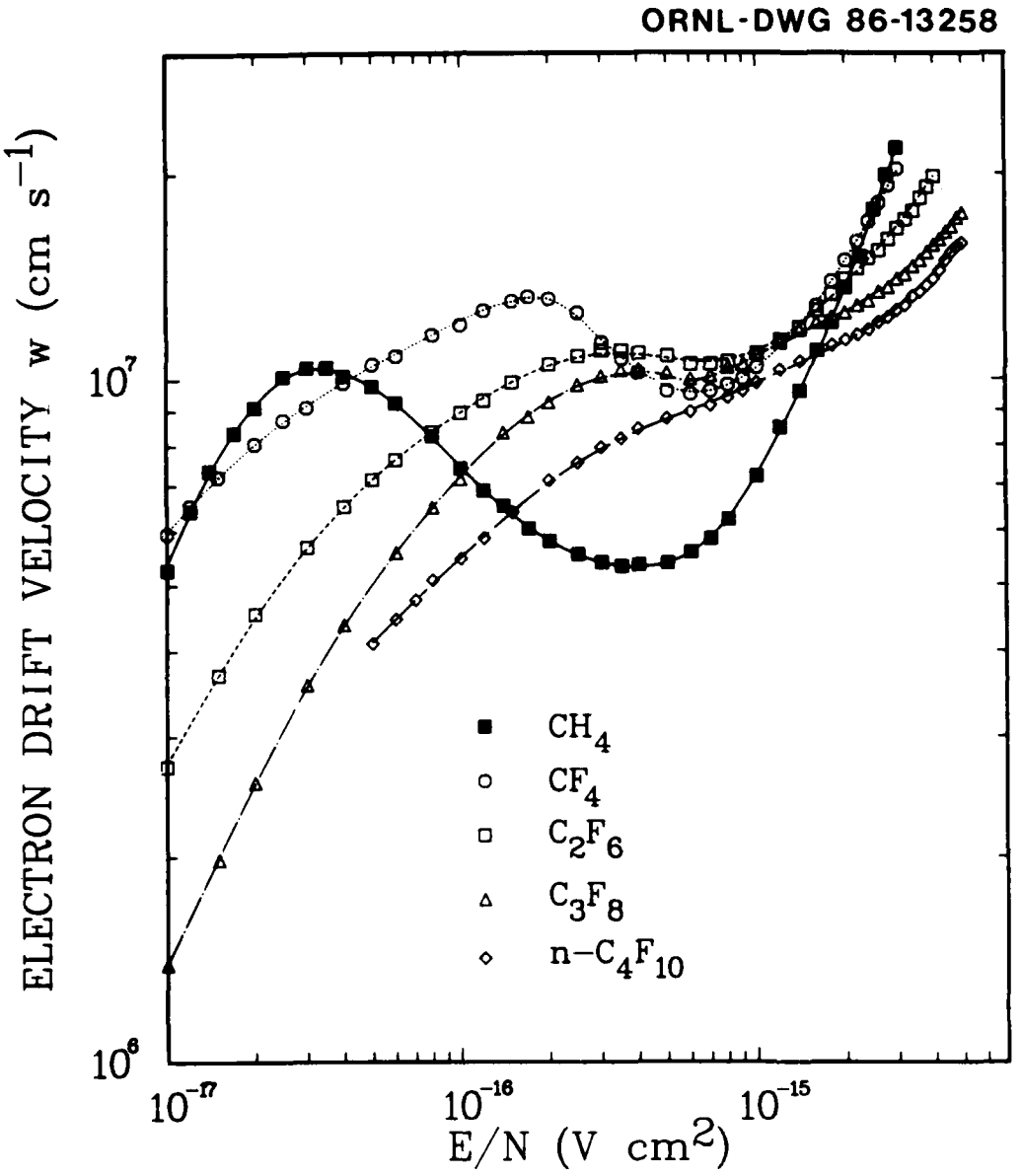


Fig. 14. Electron drift velocity w versus E/N for CH_4, CF_4, C_2F_6, C_3F_8 and n-C_4F_{10}.

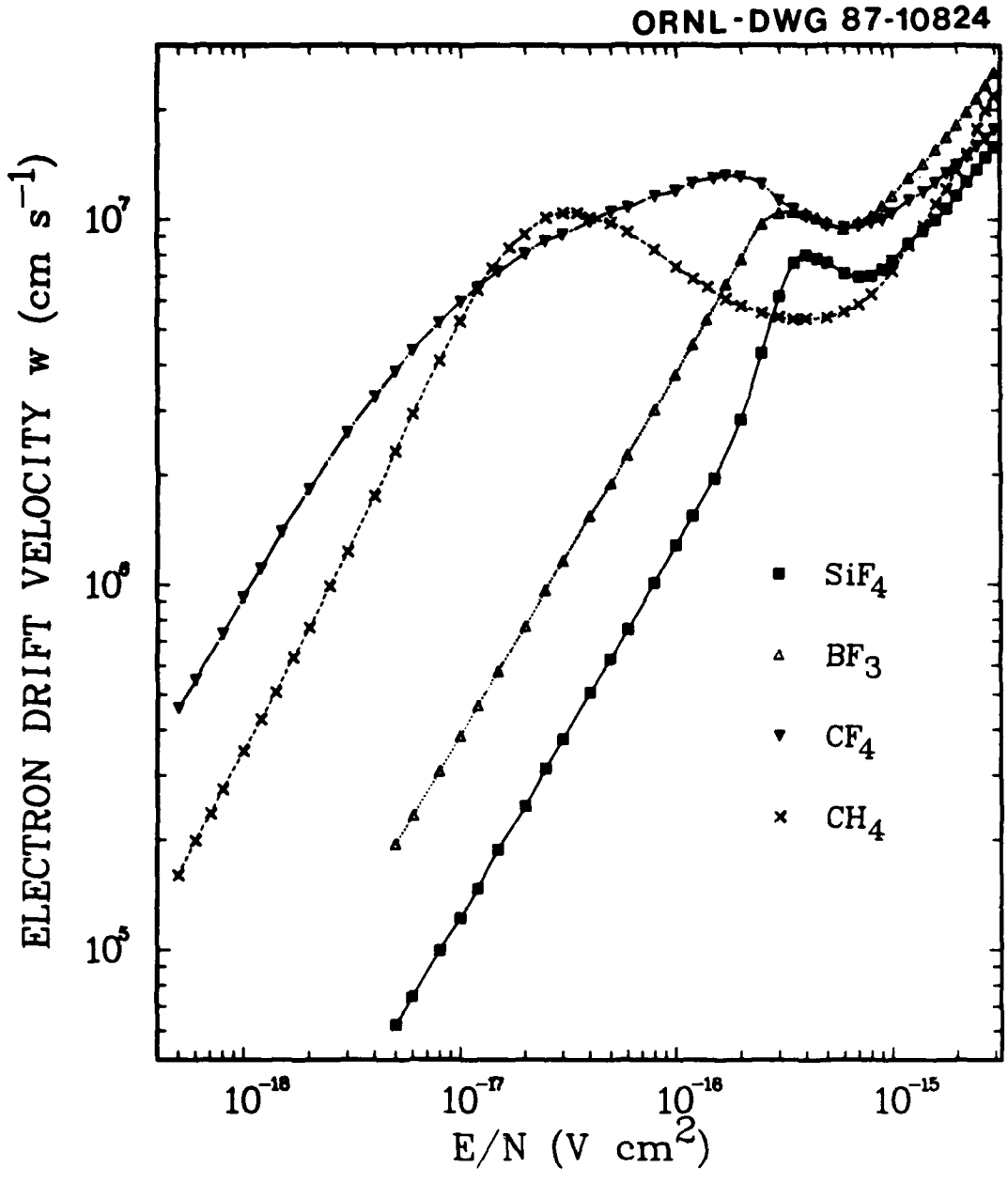


Fig. 15. Electron drift velocity w versus E/N for CH_4, CF_4, SiF_4 and BF_3.

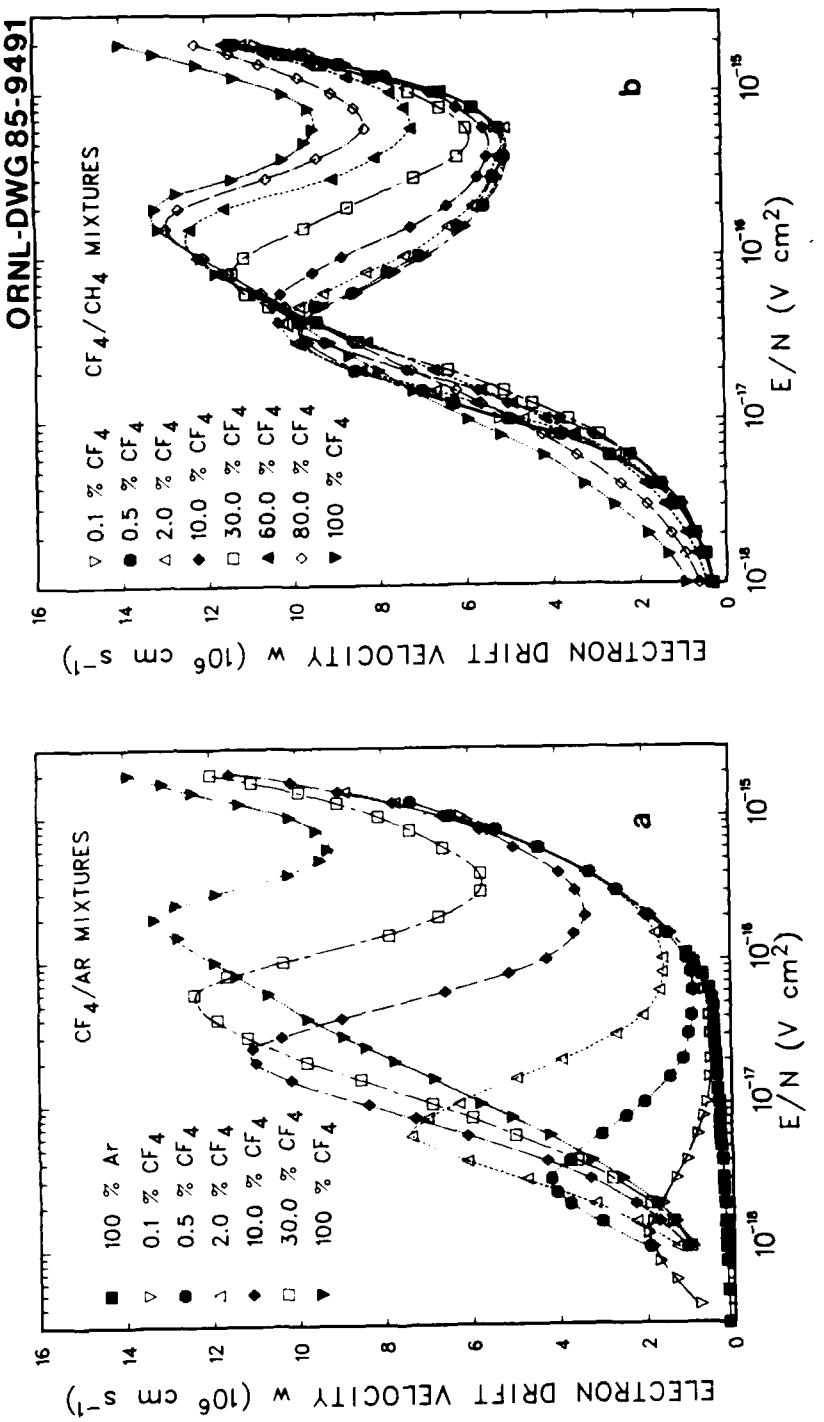


Fig. 16. Electron drift velocity w versus E/N for several (a) CF_4/Ar and (b) CF_4/CH_4 gas mixtures.

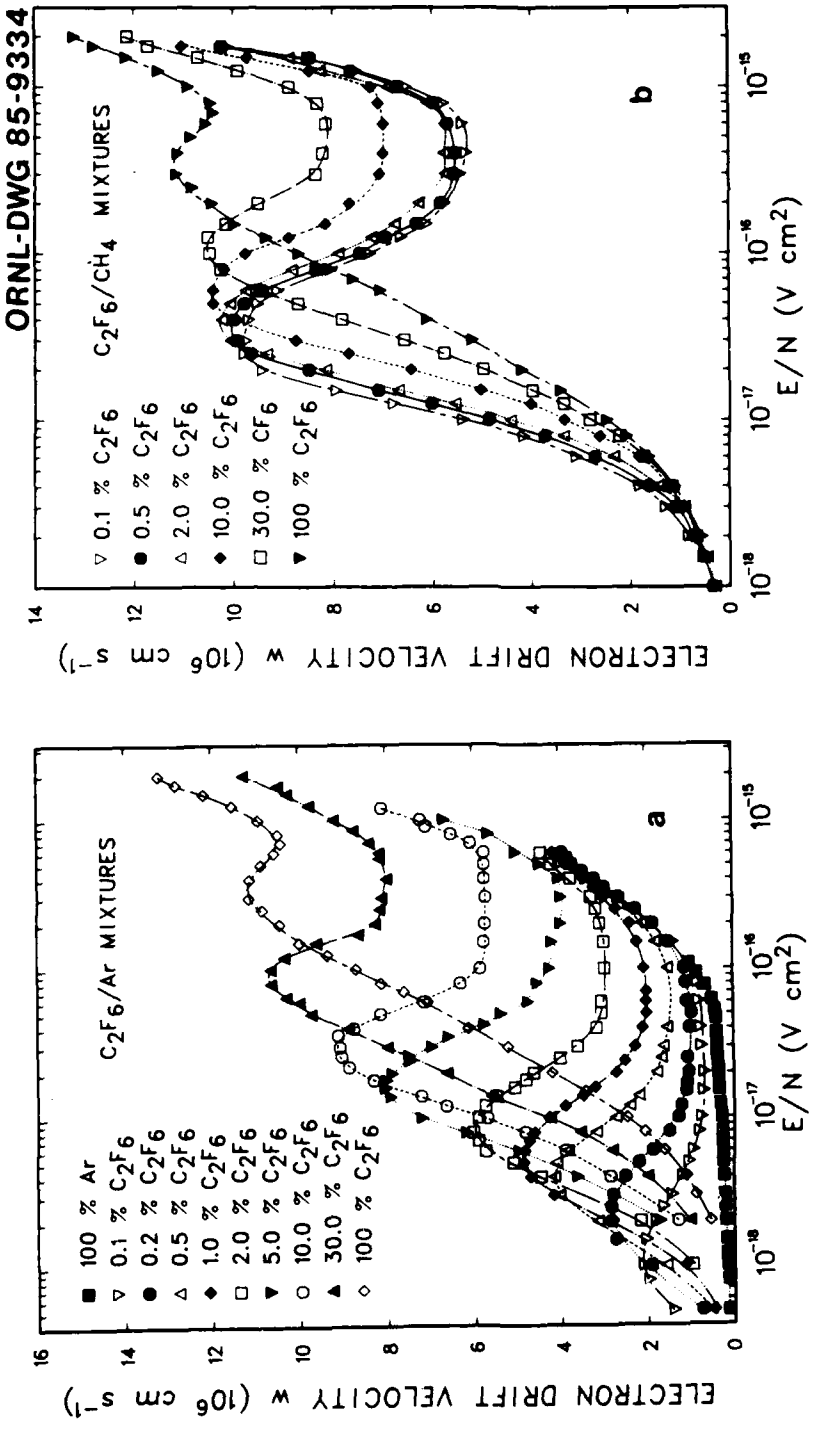


Fig. 17. Electron drift velocity w versus E/N for several (a) C_2F_6 /Ar and (b) C_2F_6/CH_4 gas mixtures.

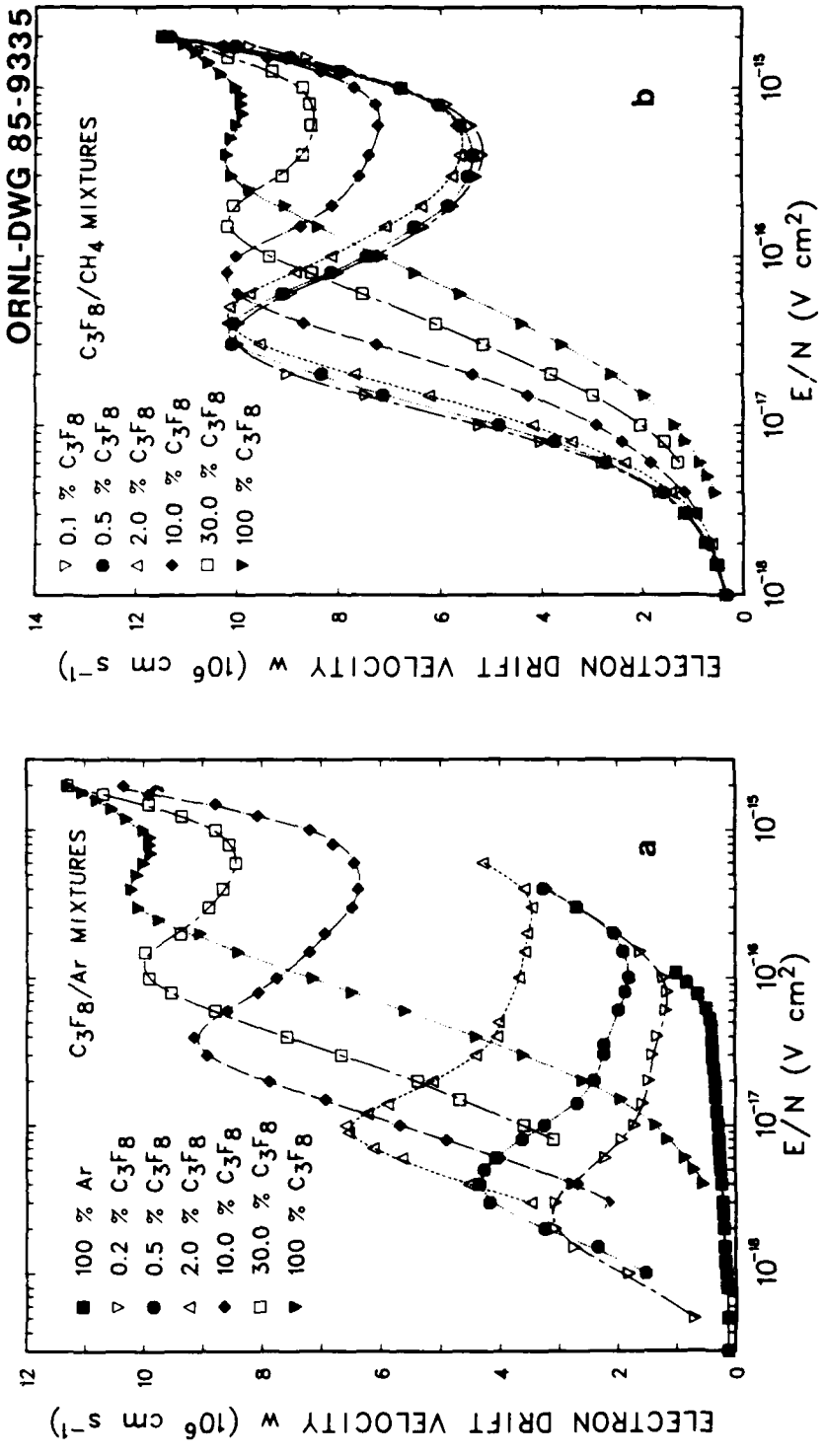


Fig. 18. Electron drift velocity w versus E/N for several (a) C_3F_8/Ar and (b) C_3F_8/CH_4 gas mixtures.

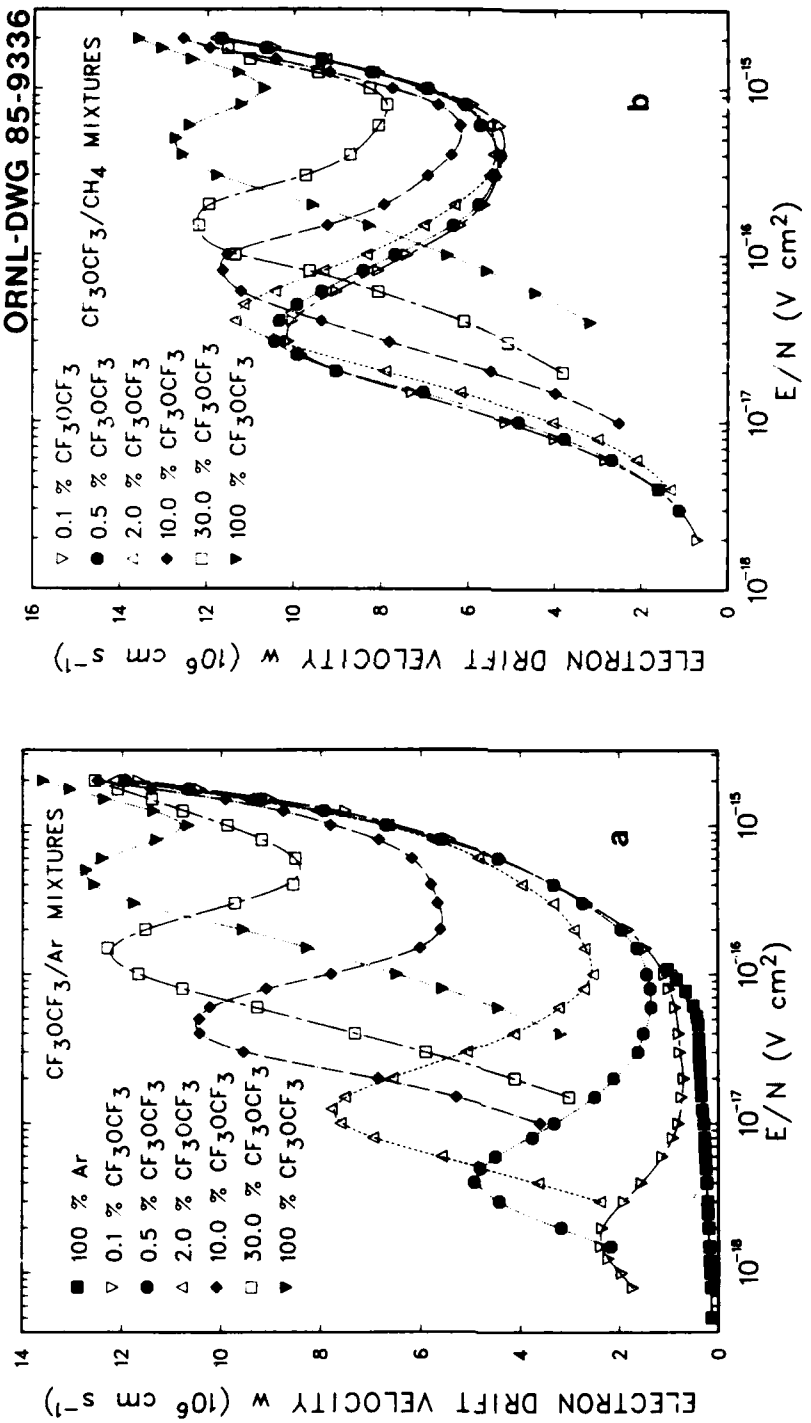


Fig. 19. Electron drift velocity w versus E/N for several (a) CF_3OCF_3/Ar and (b) CF_3OCF_3/CH_4 gas mixtures.

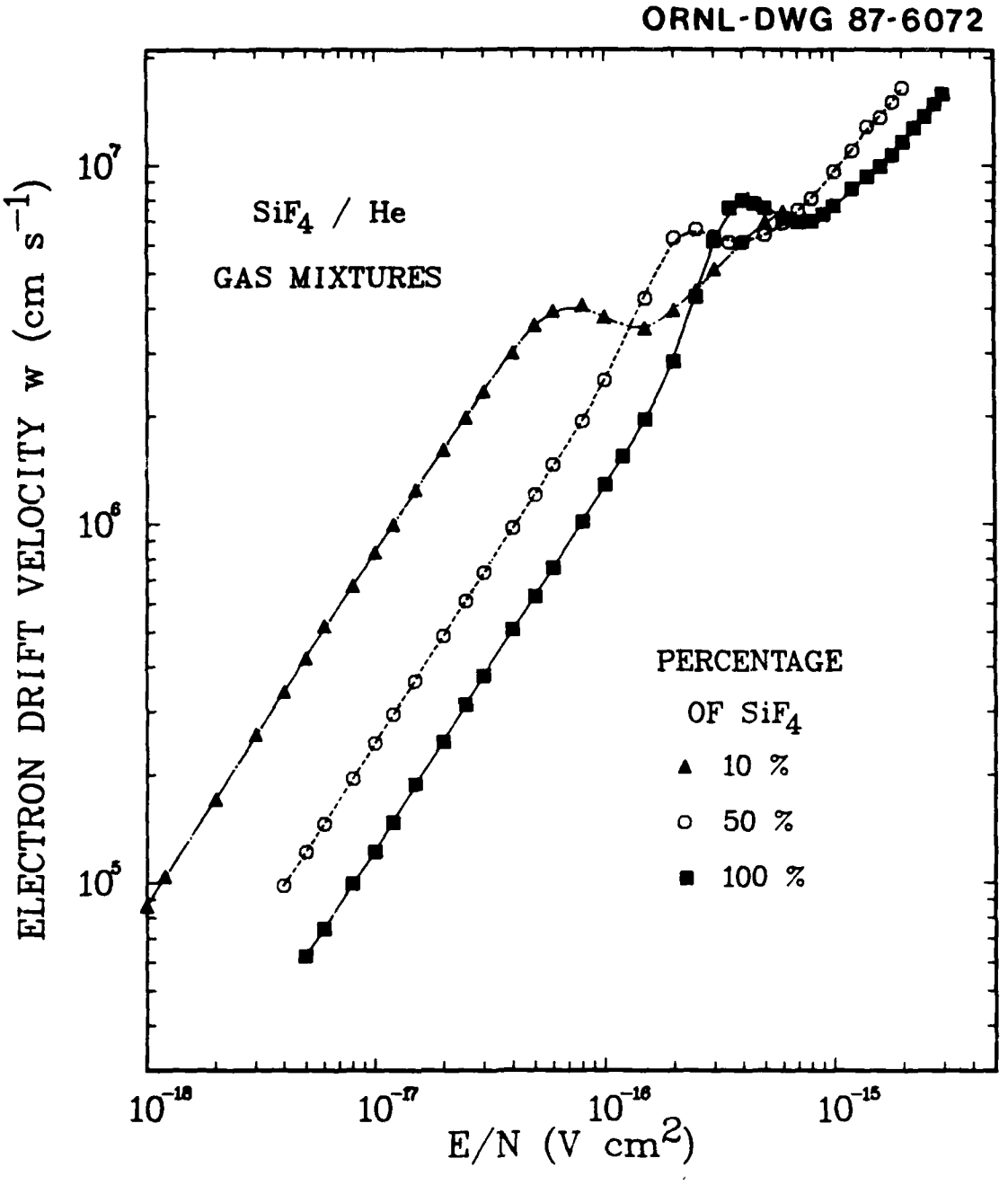


Fig. 20. Electron drift velocity w versus E/N for several SiF_4/He gas mixtures.

3.4 Room Temperature Electron Attachment and Ionization Coefficients

The electron attachment and ionization coefficients can be obtained from the pulsed Townsend (PT) experiment using the following analysis. A schematic diagram showing the operating principle of the PT technique[20] is given in Fig. 21. In the PT method, a small group or swarm of electrons is produced photoelectrically from a source on the cathode of a drift chamber by irradiating the cathode with a short duration ultraviolet (UV) laser radiation light pulse. The electrons diffuse as they drift to the anode under the influence of the applied uniform electric field. In the presence of an electronegative gas or at high fields, the swarm may experience electron attachment and/or ionization collision processes with the gas.

The present experiments were performed with the detection circuit operating in the voltage integrating mode. The motion of the electrons and ions in the drift gap induces a charge on the anode, and hence across C, and thereby establishing an increasing potential V(t) across R (Fig. 21). The time constant of the preamplifier input (τ = RC $\approx$ 1 s) in the present experiments was much greater than those of the electron ($T_e \approx 10^{-7}$ -10^{-5} s) or positive and negative ion transit times ($T_+ \approx T_- \approx 10^{-4}$ -10^{-2} s). Since $T_e << T_+ \approx T_-$, the voltage drop across R due to the drift of the positive and negative ions is negligible during the electron swarm transit time T_e. Consequently, a break will occur in the voltage transient as shown in Fig. 22 for CF_4, allowing T_e, and hence, the measured electron drift velocity $w_m = d/T_e$, to be obtained from the discontinuity in the waveform.

The absolute values of the attachment and ionization coefficients may be obtained from the ratio of the voltage transients shown in Fig. 22. When the time constant of the detection circuit τ = RC >> $T_- \approx T_+$ (i.e., the charge depletion from C is negligible during the positive and negative ion transit times), then the potential drop across R will rise to a constant value when all of the ions have drifted to the anode of the drift gap, i.e.,

$$V_T(t \gtrsim T_- \text{ and } T_+) = \frac{n_o e}{C} \text{ , when RC >> } T_- \text{ or } T_+ \quad . \qquad (15)$$

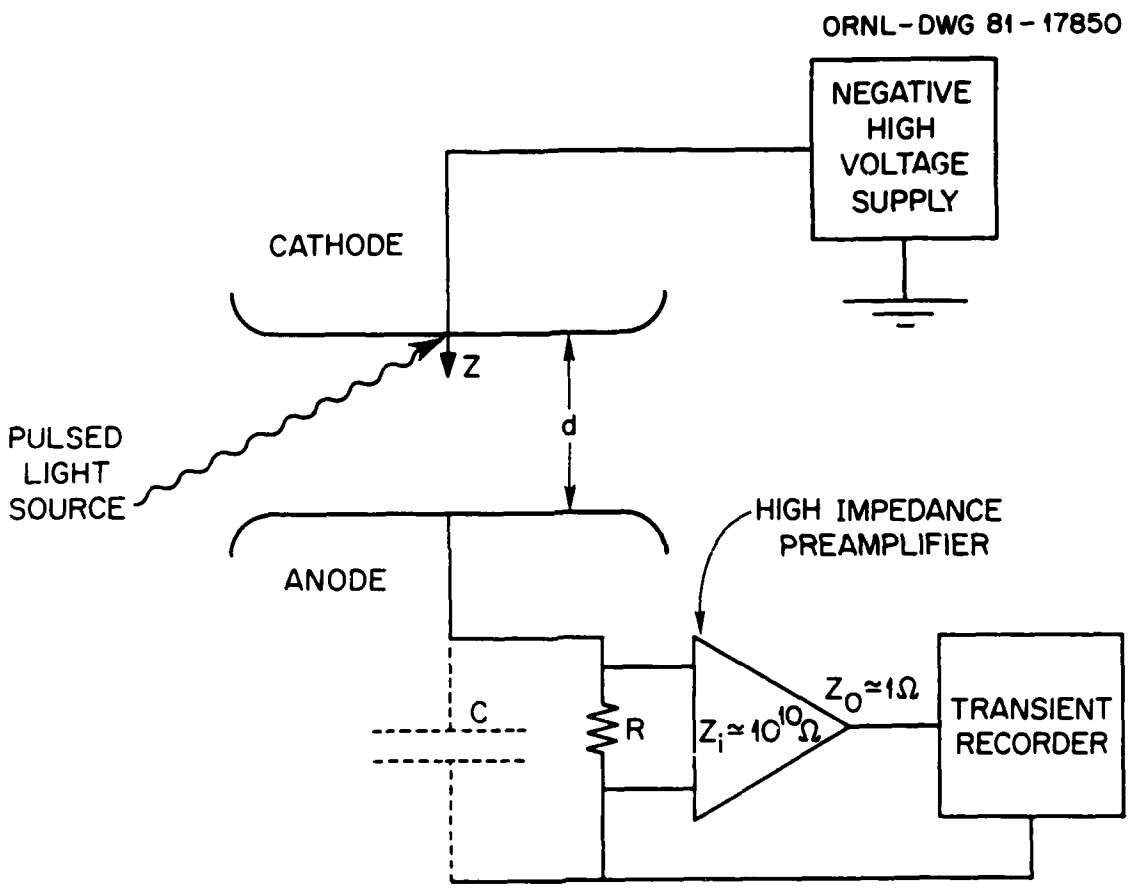


Fig. 21. Schematic diagram showing the principle of the pulsed Townsend (PT) technique for measuring the electron drift velocity and electron attachment and ionization coefficients.

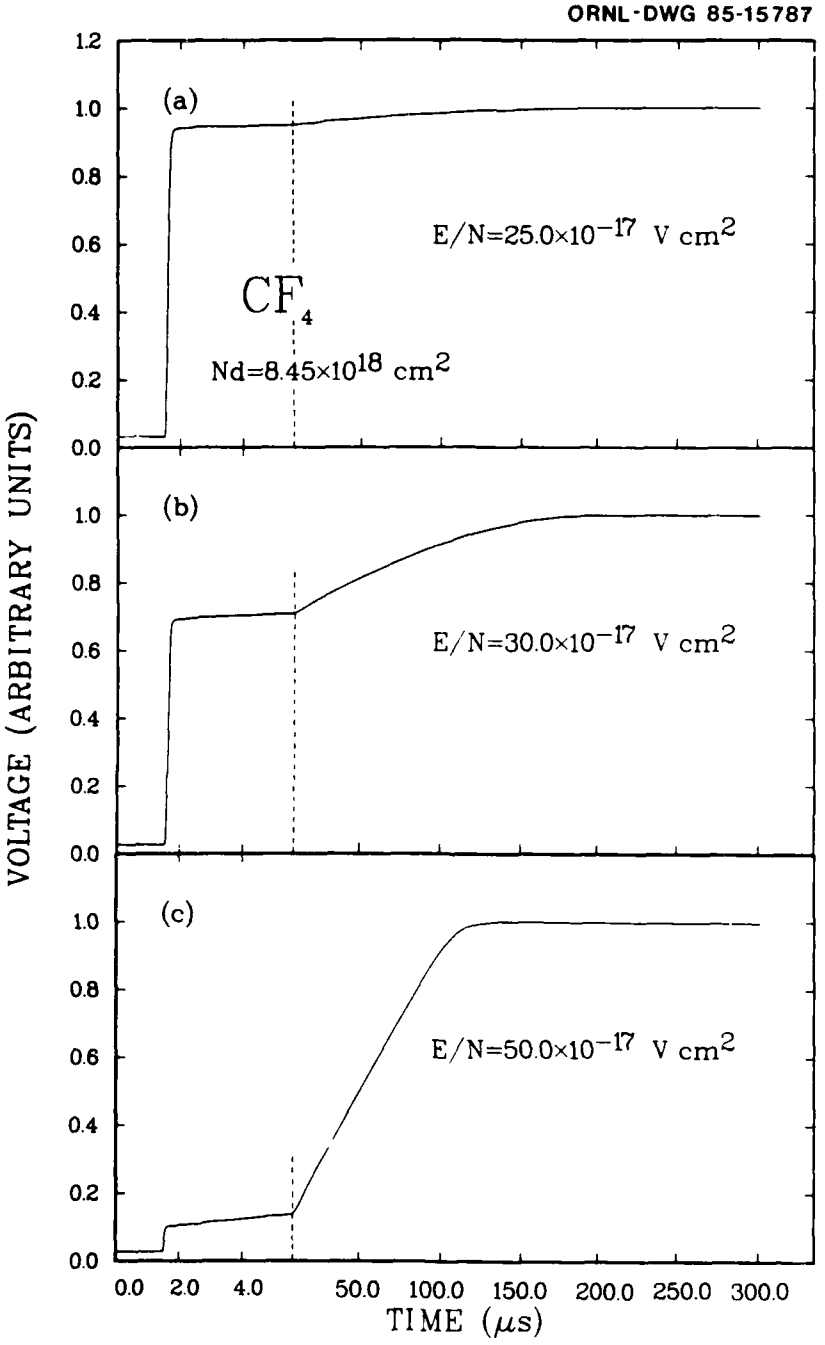


Fig. 22. Digitized voltage waveforms obtained in CF_4 for three values of E/N, corresponding to (a) low, (b) moderate, and (c) high rates of electron attachment. The first segments of the waveforms were digitized at 10 ns/channel, and the second segments (occurring after the vertical dashed lines) were digitized at 50 ns/channel.

We define the voltage ratio as

$$R_v = \frac{V_e(T_e) + V_-(t) + V_+(t)}{V_e(T_e)} \text{ , when } t \geq T_- \text{ or } T_+ \quad , \tag{16}$$

In the presence of significant electron attachment and ionization, the voltage ratio R_v is given by

$$R_v = \frac{\eta d - \alpha d \exp[\bar{\alpha} d]}{(1 - \exp[\bar{\alpha} d])} \tag{17}$$

$$= \frac{\eta d \exp[\eta d] - \alpha d \exp[\alpha d]}{(\exp[\eta d] - \exp[\alpha d])} \quad . \tag{18}$$

When electron ionization is negligibly small, Eq. (17) further reduces to

$$R_v = \frac{\eta d}{1 - \exp[-\eta d]} \quad , \tag{19}$$

or when electron attachment is negligible, Eq. (17) reduces to

$$R_v = \frac{\alpha d}{1 - \exp[-\alpha d]} \quad . \tag{20}$$

A. Pure Gases

We have performed an extensive series of measurements of η/N and α/N in O_2, CF_4, C_2F_6, C_3F_8 and n-C_4F_{10} over the gas pressure range $0.03 \leq P \leq 100$ kPa. The present measurements in O_2 are shown in Fig. 23 in comparison with the previous literature data.[33,34] Low energy electron attachment to O_2 is due to three body parent anion formation, which is very strongly dependent on gas pressure. The measured η/N values are consequently very sensitive to changes in the experimental parameters and the good agreement between the present and previous measurements in this gas indicates that the present technique is capable of obtaining reliable measurements with good accuracy.

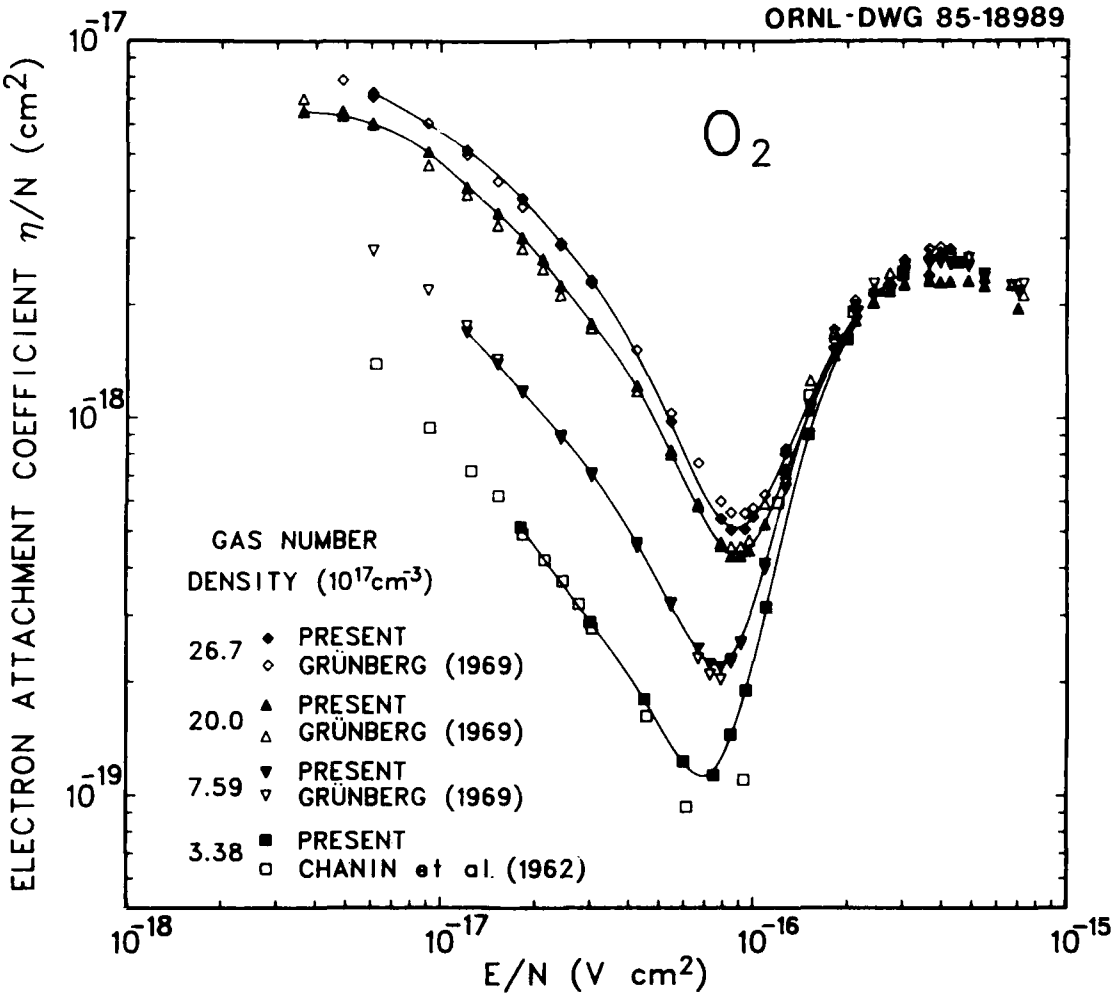


Fig. 23. Electron attachment coefficient η/N in O_2 as a function of E/N at selected gas number densities in comparison with the previous measurements of Grünberg (Ref. 33) and Chanin et al. (Ref. 34).

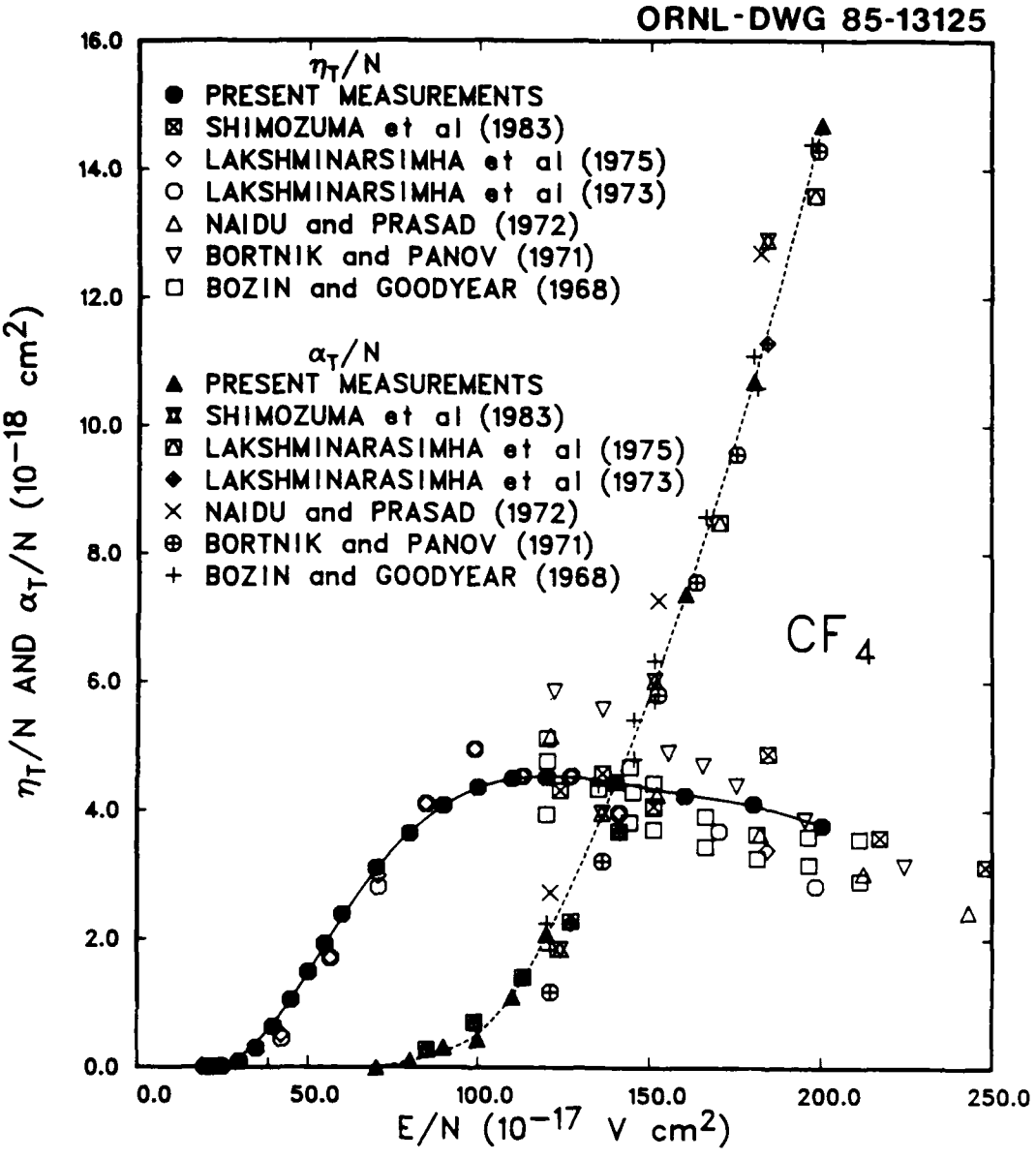


Fig. 24a. Present measurements of the diffusion-modified electron attachment coefficient η_T/N and diffusion-modified ionization coefficient α_T/N as a function of E/N for CF_4 in comparison with the measurements of Shimozuma et al. (Ref. 37), Lakshminarasimha et al. (Refs. 35 and 36), Naidu and Prasad (Ref. 39), Bortnik and Panov (Ref. 38), and Bozin and Goodyear (Ref. 40).

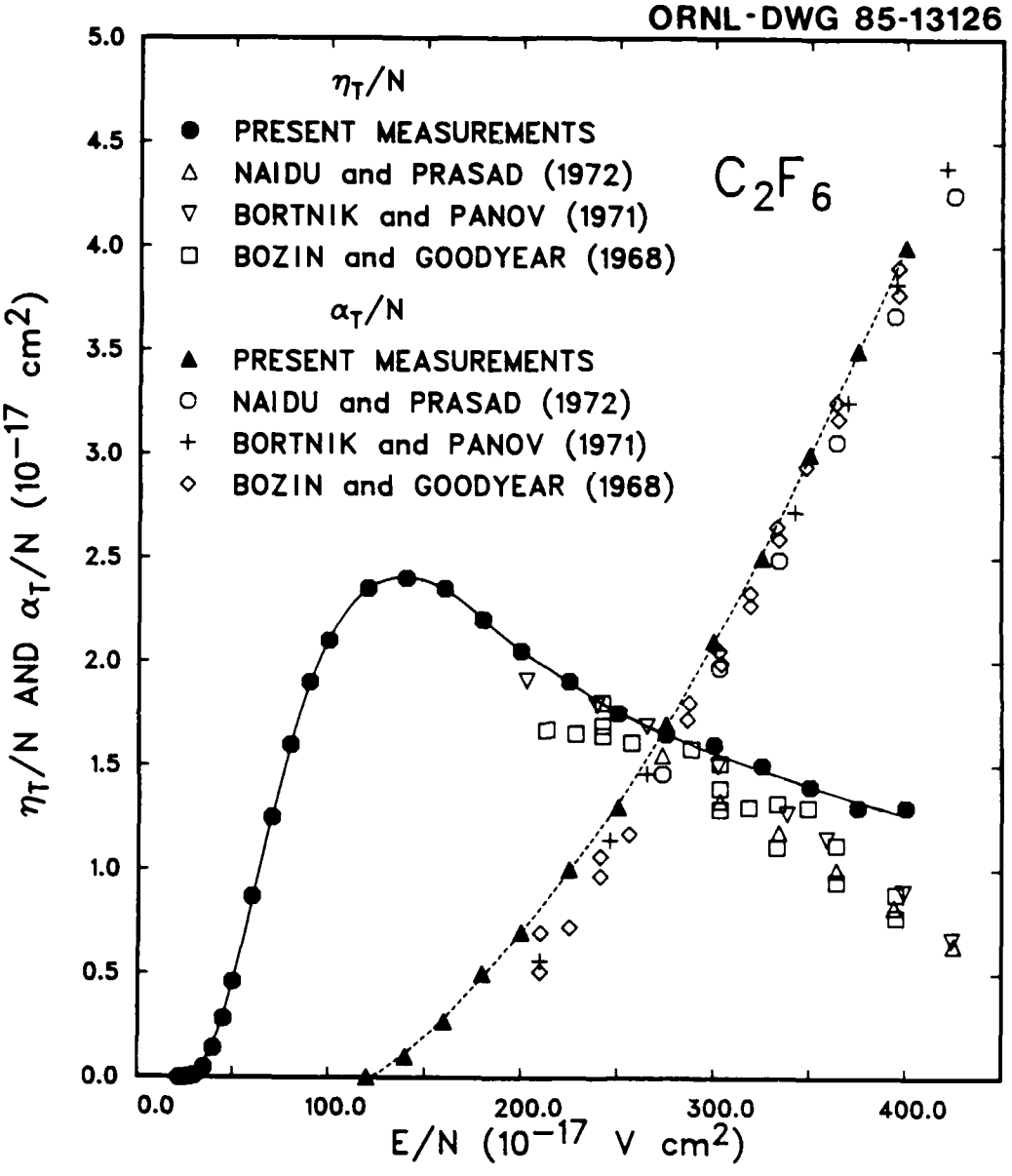


Fig. 24b. Present measurements of the diffusion-modified electron attachment coefficient η_T/N and diffusion-modified ionization coefficient α_T/N as a function of E/N for C_2F_6 in comparison with the mesurements of Naidu and Prasad (Ref. 39), Bortnik and Panov (Ref. 38) and Bozin and Goodyear (Ref. 40).

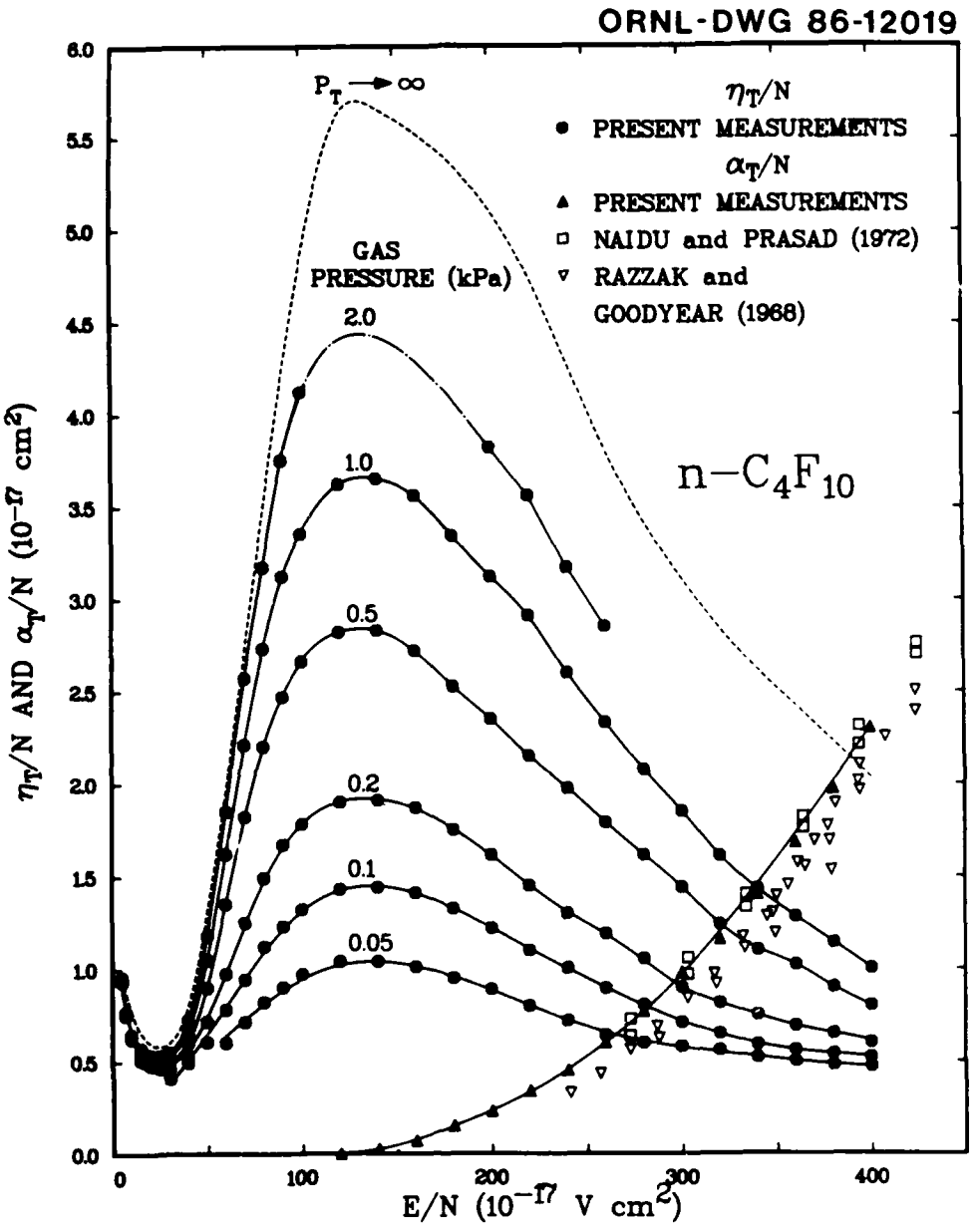


Fig. 25. Present measurements of the diffusion-modified electron attachment coefficient η_T/N and the diffusion-modified ionization coefficient α_T/N as a function of E/N and gas pressure for n-C_4F_{10} in comparison with the measurements of Naidu and Prasad (Ref. 39) and Razzak and Goodyear (Ref. 41). The dashed line is the resultant attachment coefficient when the present measurements are extrapolated to infinite gas pressure using the method of analysis given in the text.

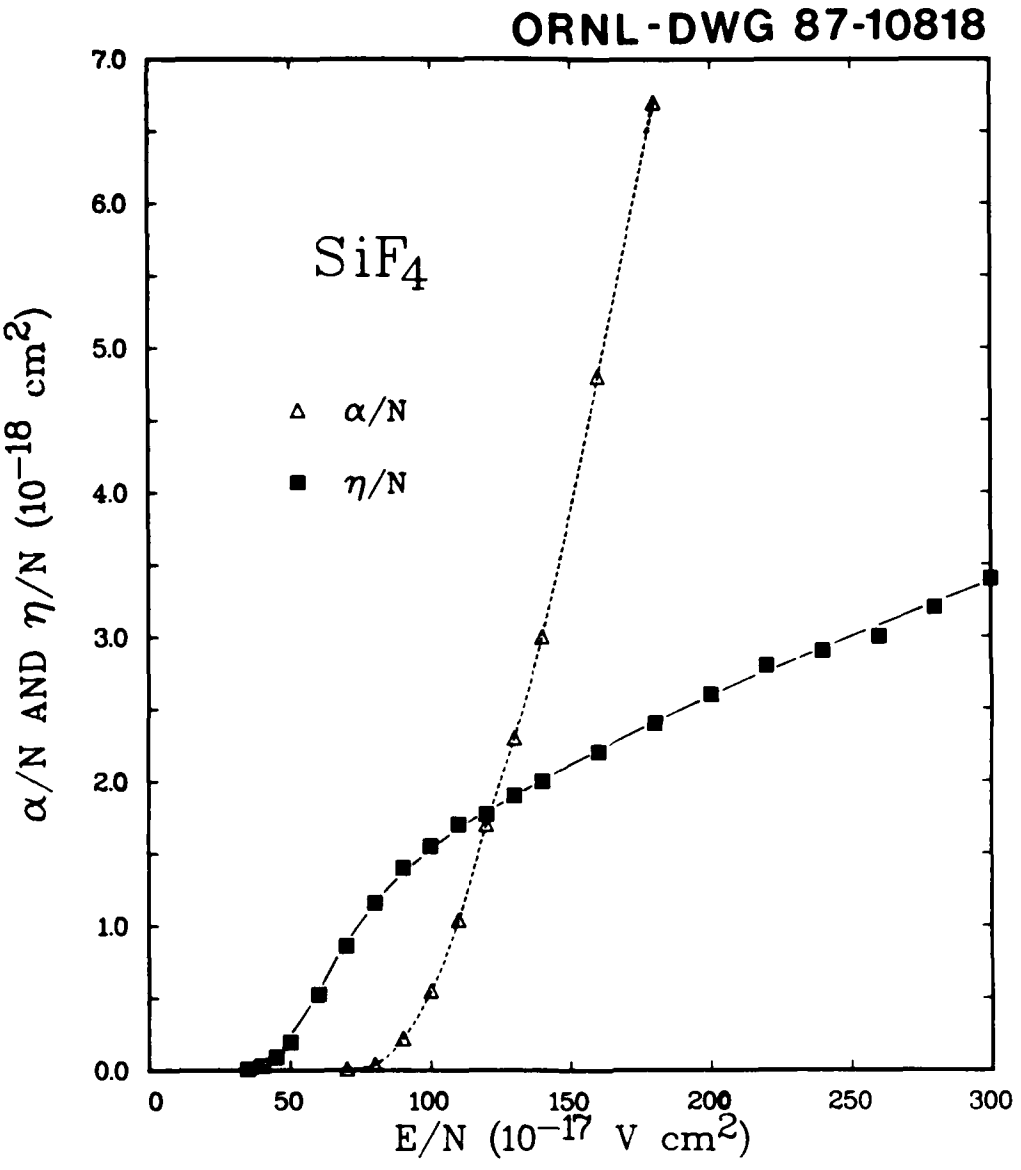


Fig. 26. Electron attachment η/N and ionization α/N coefficient in SiF_4 as a function of E/N.

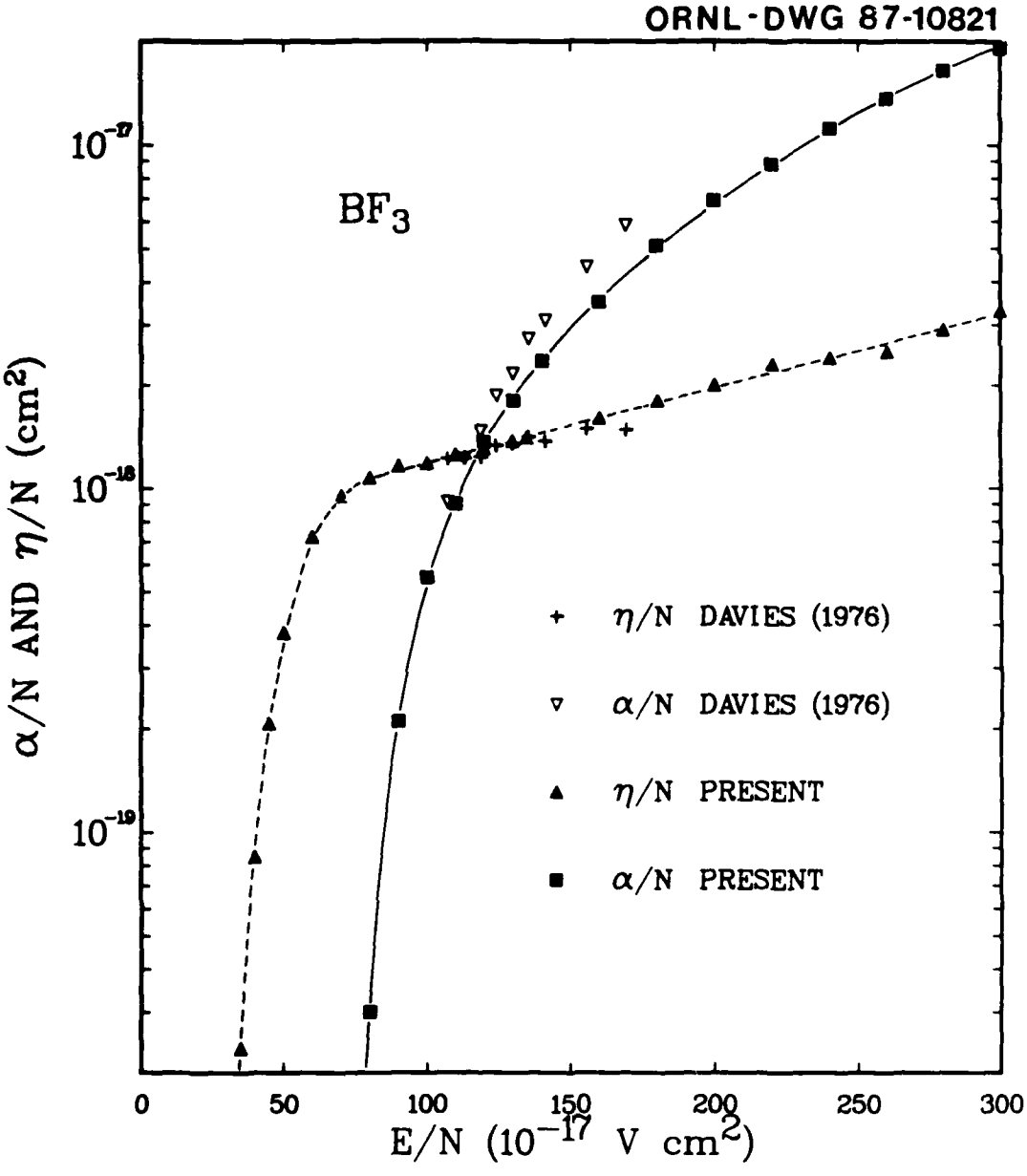


Fig. 27. Electron attachment η/N and ionization α/N coefficients in BF_3 as a function of E/N.

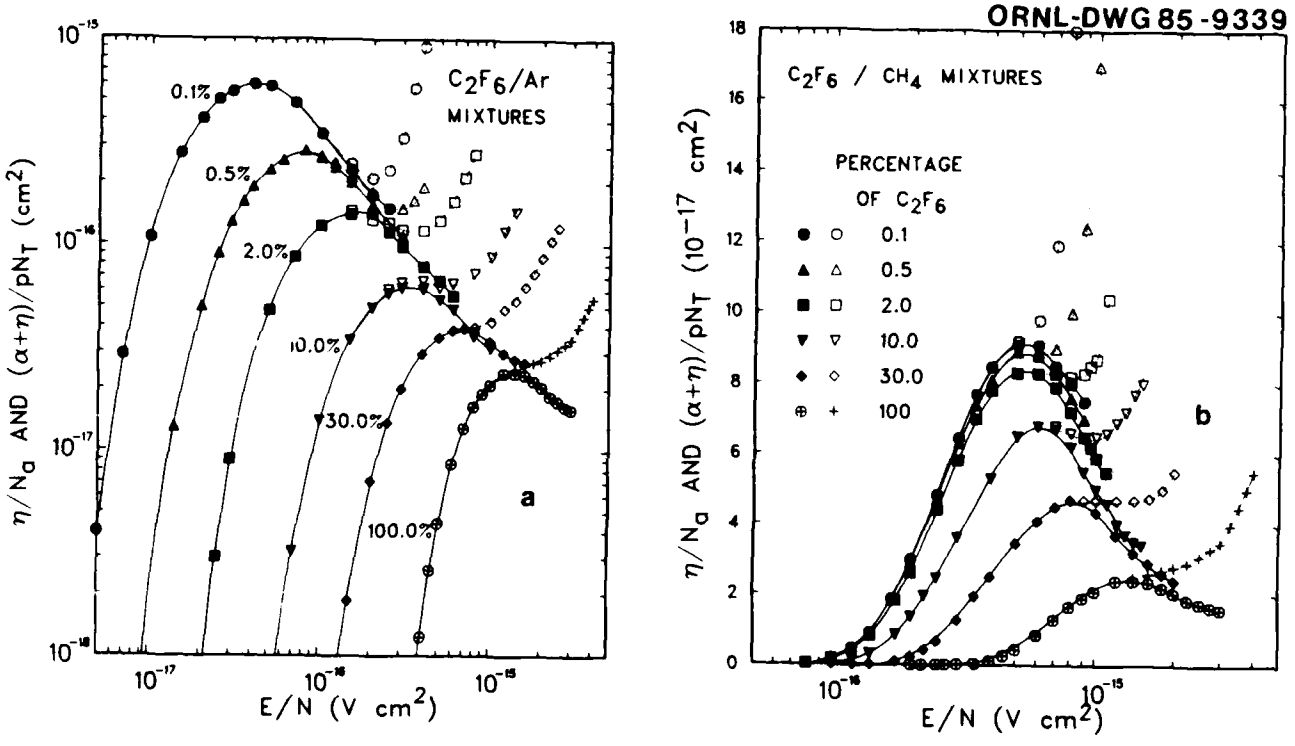


Fig. 28. The electron attachment coefficient η/N_a for C_2F_6 and the effective ionization coefficient $(\alpha + \eta)/pN_T$ (where p is the fractional concentration of C_2F_6 in the buffer gas) for the gas mixtures (a) C_2F_6/Ar and (b) C_2F_6/CH_4. the actual parameter measured in the electron attachment experiment is $(\alpha + \eta)$ (in units of cm^{-1}). This measurement can be either normalized to the attaching gas number density N_a, when $\alpha = 0$ to obtain the normalized attachment coefficient of the attaching gas constituent of the mixture (shown in the figure by the solid lines for various percentages of C_2F_6 in Ar or CH_4), or it can be normalized to pN_T to find the effective ionization coefficient of the mixture as a whole (shown in the figure by the broken lines for various percentages of C_2F_6 in Ar or CH_4).

The present measurements of η_T/N and α_T/N in CF_4 and C_2F_6 obtained using this technique are given in Figs. 24a and 24b, respectively, in comparison with previous literature values using steady state Townsend techniques (SST) which measure α_T/N and η_T/N directly.[35-41] In general there is good agreement between the present measurements and those obtained previously using both SST[38-40] and time-of-flight (TOF) techniques,[35,36] although we believe that the uncertainty in our results is considerably less than that obtained using conventional SST techniques. At E/N values > 200 × 10^{-17} V cm^2 for C_2F_6 (Fig. 24b), our attachment measurements appear to be significantly higher than the previous measurements.

In contrast to CF_4 and C_2F_6, the electron attachment coefficients for C_3F_8 and n-C_4F_{10} depend on gas pressure, particularly for n-C_4F_{10} (Fig. 25). We have previously argued that electron attachment to CF_4 and C_2F_6 is dissociative in nature (and, consequently, independent of gas pressure),[18,19] whereas at room temperature electron attachment to C_3F_8 and n-C_4F_{10} is largely due to nondissociative parent anion formation.

The stability of self-sustained diffuse discharge closing switches may be enhanced by tailoring the electron attachment (η/N) and ionization (α/N) coefficients of the gas mixture in such a way that the rate of change in the electron production and loss is minimal during small perturbations of the applied electric field beyond the glow discharge operating voltage level V_S.[42] Gases and gas mixtures which possess low $(E/N)_{\ell im}$ values and $\bar{\alpha}/N$ (= α/N - η/N) which vary slowly with E/N near $(E/N)_{\ell im}$ lead to lower voltage operation with increased discharge stability. This characteristic can be achieved by choosing electronegative gases which only attach electrons at energies well above thermal energy. Both SiF_4 and BF_3 only attach electrons at high electron energies (>10 eV) and as a consequence, are good candidates for use in these types of switches. The present α/N and η/N measurements in SiF_4 and BF_3 are given in Figs. 26 and 27, respectively, and show that $\bar{\alpha}/N$ does vary slowly near $(E/N)_{\ell im}$ for both of these gases.

B. Gas Mixtures

In practical e-beam sustained diffuse discharge opening switch applications, several percent of an attaching gas must be added to the buffer gas in order to effectively remove the free electrons in the discharge when

the switch opens. Consequently, to model these discharge conditions, measurements of the attachment coefficient normalized to the attaching gas number density N_a, η/N_a and the ionization coefficient normalized to the total gas number density N_T, α/N_T are required as a function of the concentration of the attaching gas in the buffer gas. Measurements of η/N_a and the *effective* ionization coefficient $(\alpha + \eta)/pN_T$ (where p is the fractional concentration of the attaching gas in the buffer gas) in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures, obtained using the technique outlined by Hunter *et al.*,[20] are given in Figs. 28a and 28b, respectively.

When Ar is used as the buffer gas, the magnitude of the electron drift velocity and attachment coefficient and the positions of the maxima of these quantities when plotted as a function of E/N are very sensitive functions of the percentage of the attaching gas in the buffer gas. The peak positions move to higher E/N values and the magnitude of the attachment coefficient decreases by over one order of magnitude in going from 0.1% to 100% of the C_2F_6 (Fig. 18a). Similar changes are observed for w in these mixtures, except that w increases with increasing concentration of the attaching gas (Figs. 16a and 19a). In contrast to the measurements in argon, the attachment coefficient and electron drift velocity in the attaching gas/methane gas mixtures are not nearly as sensitive to the attaching gas concentration as are the argon mixtures, particularly at low attaching gas concentrations (Fig. 28b). The reason for this is that the addition of even small amounts of a molecular gas to argon drastically shifts the electron energy distribution function of the mixture to lower energies,[17] lowering the mean electron energy $\langle\epsilon\rangle$ and, consequently, increasing the E/N value which corresponds to the $\langle\epsilon\rangle$ value for which w and η/N_a maximize. The addition of small amounts of a molecular gas to CH_4 has only a small influence on the w(E/N) and η/N_a(E/N) for the mixture as CH_4 itself already possesses sizeable inelastic loss processes at low electron energies.

We have also performed α/N and η/N measurements in several gas mixtures which show promise for use in self-sustained diffuse discharge closing switches.[42] In order to reduce the operating $(E/N)_{\ell im}$ in these switches to as low a value as possible (and thereby increase the current switching efficiency

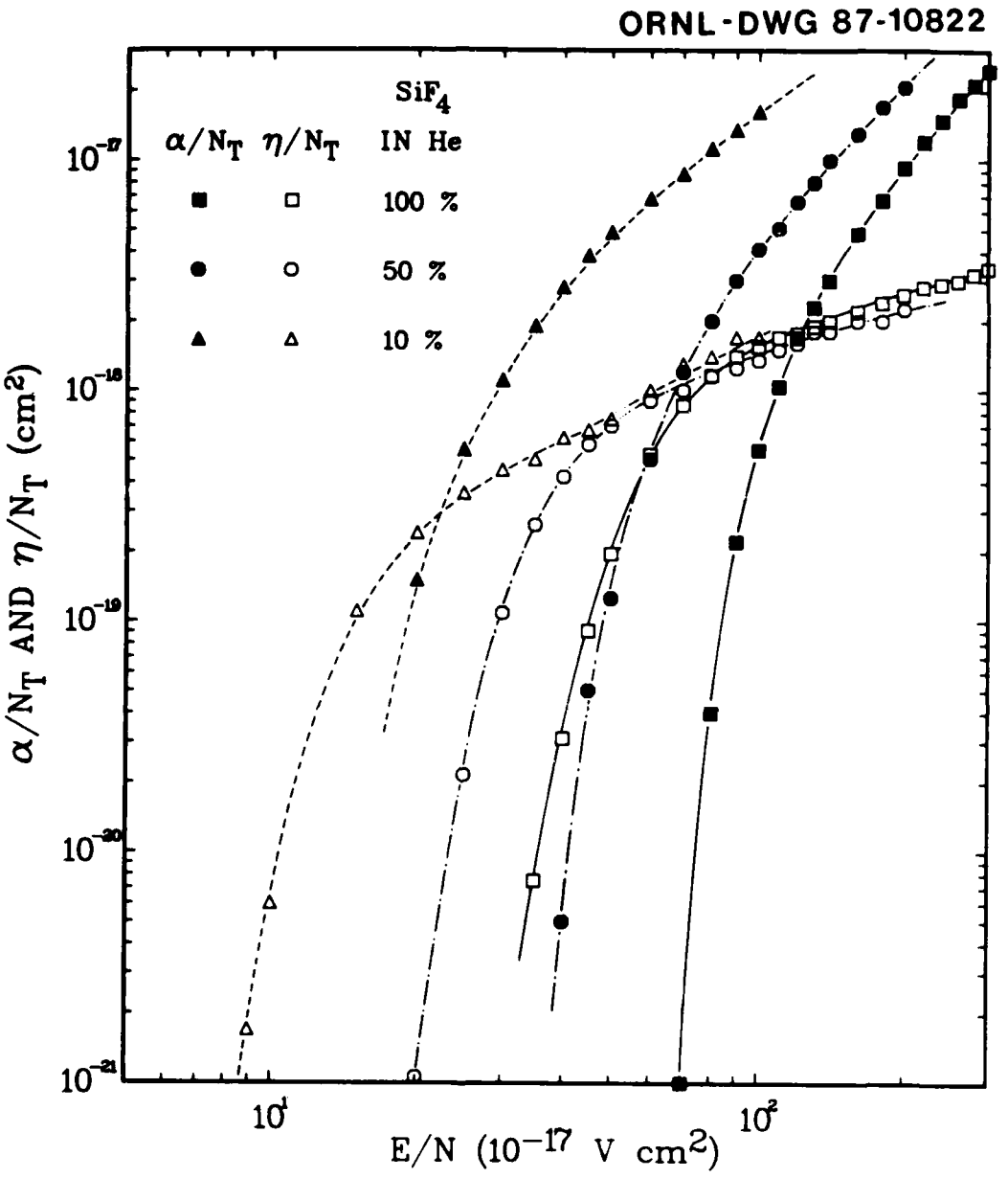


Fig. 29. The electron attachment coefficient η/N_T and ionization coefficient α/N_T in several SiF_4/He gas mixtures.

of the discharge), it is necessary to add to an electronegative gas with the desirable $\bar{\alpha}/N$ ($= \alpha/N - \eta/N$) (described earlier in this section) characteristics, a rare gas buffer gas. Two electronegative gases with the desirable $\bar{\alpha}/N$ characteristics are SiF_4 and BF_3 and are shown in Figs. 26 and 27, respectively. Using He or Ne as the rare gas buffer gas will tend to preserve the relative changes in $\bar{\alpha}/N$ near $(E/N)_{\ell im}$ for low concentrations of the attaching gas (<20%), even when $(E/N)_{\ell im}$ is decreased with decreasing attaching gas concentration. An example of this behavior is given in Fig. 29 which shows our present measurements of α/N_T and η/N_T in several SiF_4/He gas mixtures. The present measurements indicate that for all concentrations of SiF_4 in He, $\bar{\alpha}/N$ does vary slowly with E/N around the $(E/N)_{\ell im}$ value for each gas mixture, and that the $(E/N)_{\ell im}$ of the discharge can be reduced considerably by reducing the concentration of the SiF_4 in the buffer gas [i.e., $(E/N)_{\ell im} \approx 22 \times 10^{-17}$ V cm^2 for 10% SiF_4 in He, $(E/N)_{\ell im} \approx 67 \times 10^{-17}$ V cm^2 for 50% SiF_4 in He, and $(E/N)_{\ell im} \approx 122 \times 10^{-17}$ V cm^2 for pure SiF_4 (Fig. 29)].

When small concentrations of the low ionization threshold gas additive triethylamine (TEA; ionization threshold $\approx$ 7.5 eV) are added to the SiF_4/He gas mixtures, large increases in the ionization coefficient occur in the gas mixture while η/N is relatively unchanged by low concentrations ($\lesssim$ 0.5%) of the TEA. The present measurements in the SiF_4/He/TEA gas mixtures are given in Fig. 30 and show that the addition of 0.2% of TEA to a 50:50 gas mixture of SiF_4/He significantly increases the rate of ionization, thereby minimizing the variation in $\bar{\alpha}/N$ around $(E/N)_{\ell im}$ and also significantly reducing $(E/N)_{\ell im}$. These are very desirable characteristics for diffuse discharge closing switches.[42]

3.5 Elevated Temperature Gas Mixture Studies

A. Electron Drift Velocity and Mobility

The influence of changes in gas temperature on w in several C_2F_6/Ar and C_2F_6/CH_4 gas mixtures is shown in Figs. 31 and 32, respectively, at room temperature (300 K) and 500 K for several C_2F_6 concentrations from 0.1% to 100% C_2F_6. At low C_2F_6 concentrations ($\lesssim$1%), w near the peak in the curves in Figs. 31 and 32 is hardly affected by increases in T, but at large C_2F_6

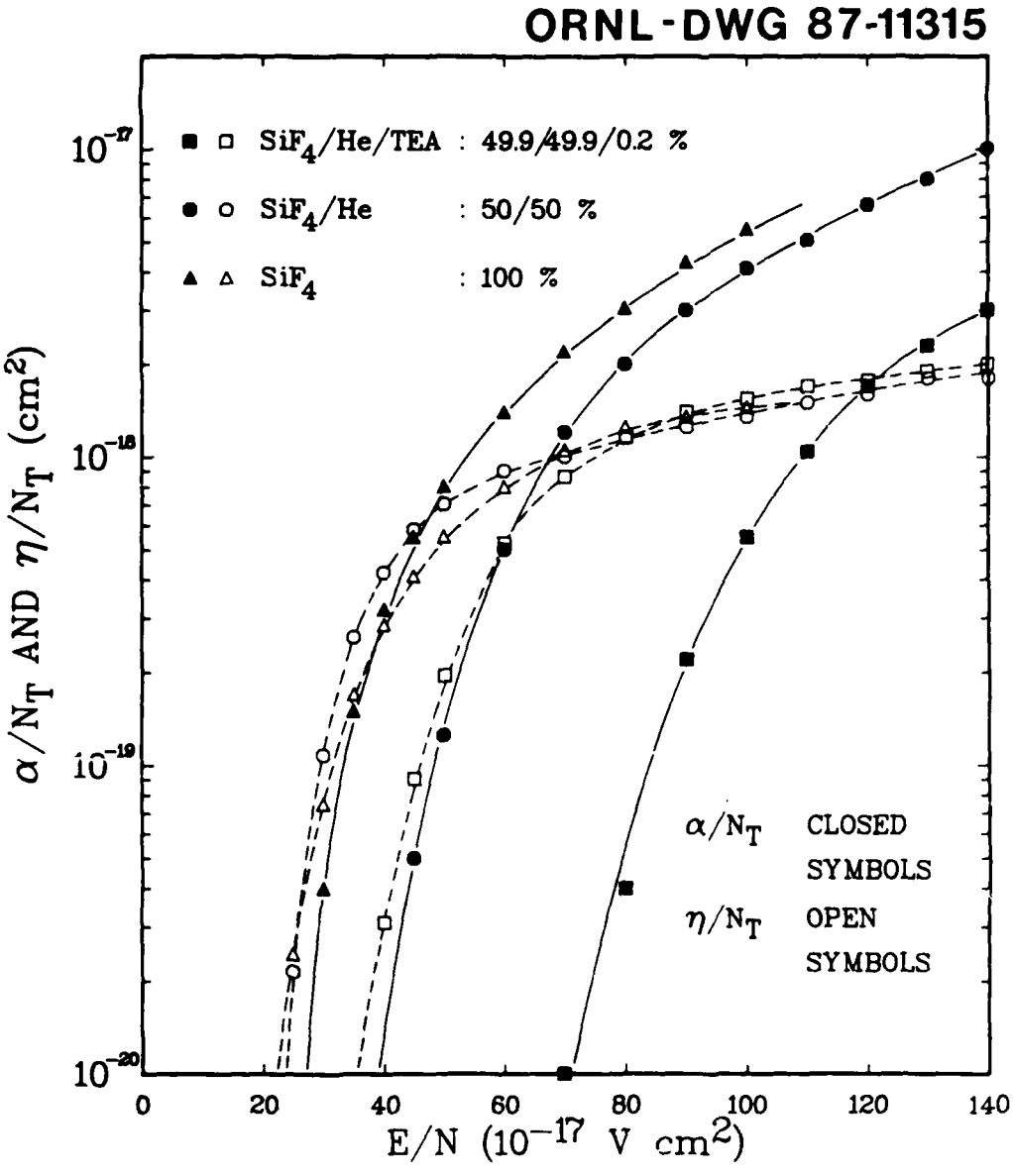


Fig. 30. The electron attachment coefficient η/N_T and ionization coefficient α/N_T in SiF_4, SiF_4/He and SiF_4/He/TEA gas mixtures.

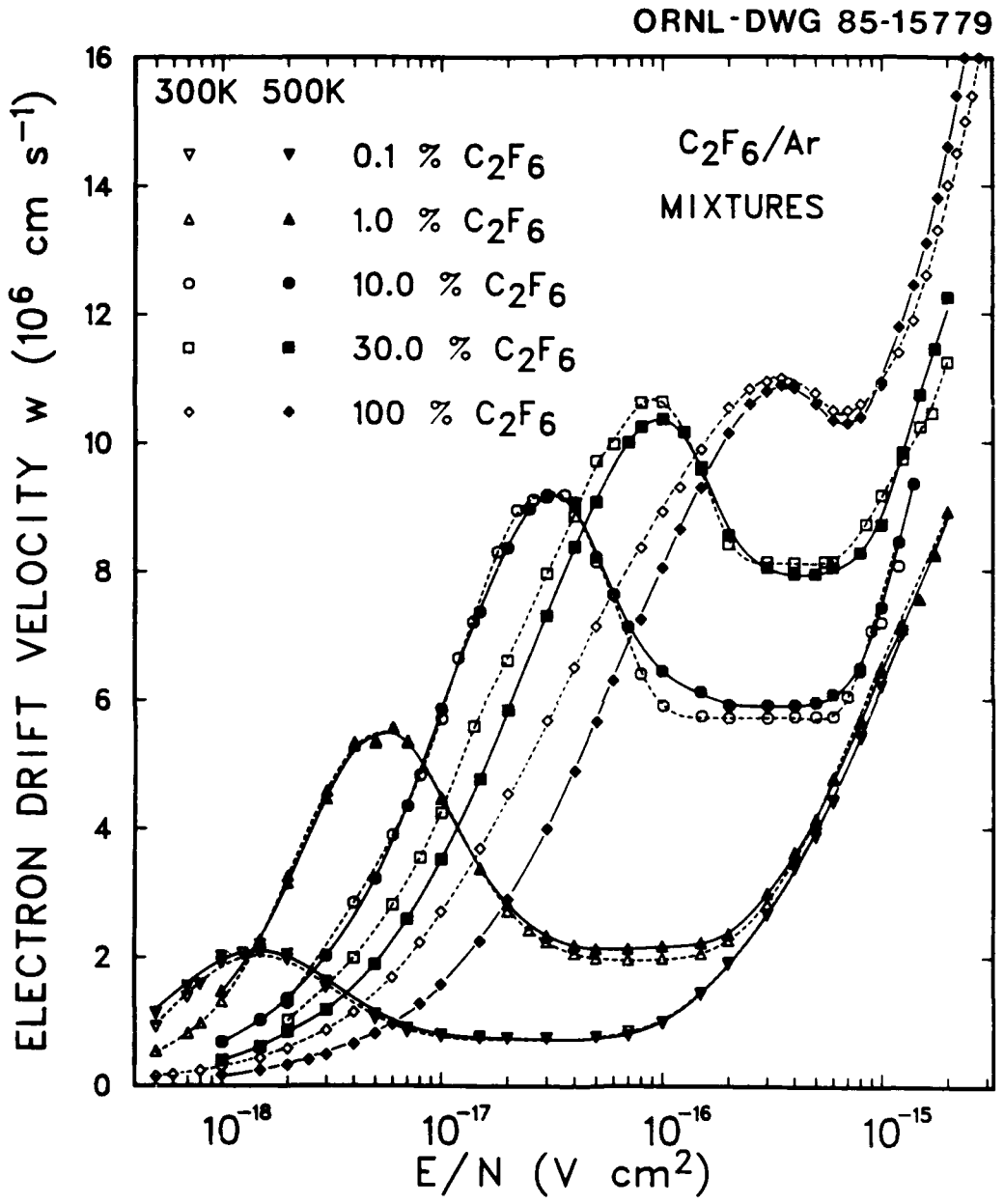


Fig. 31. Electron drift velocities as a function of E/N for several concentrations of C_2F_6 in Ar at gas temperatures of 300 and 500 K.

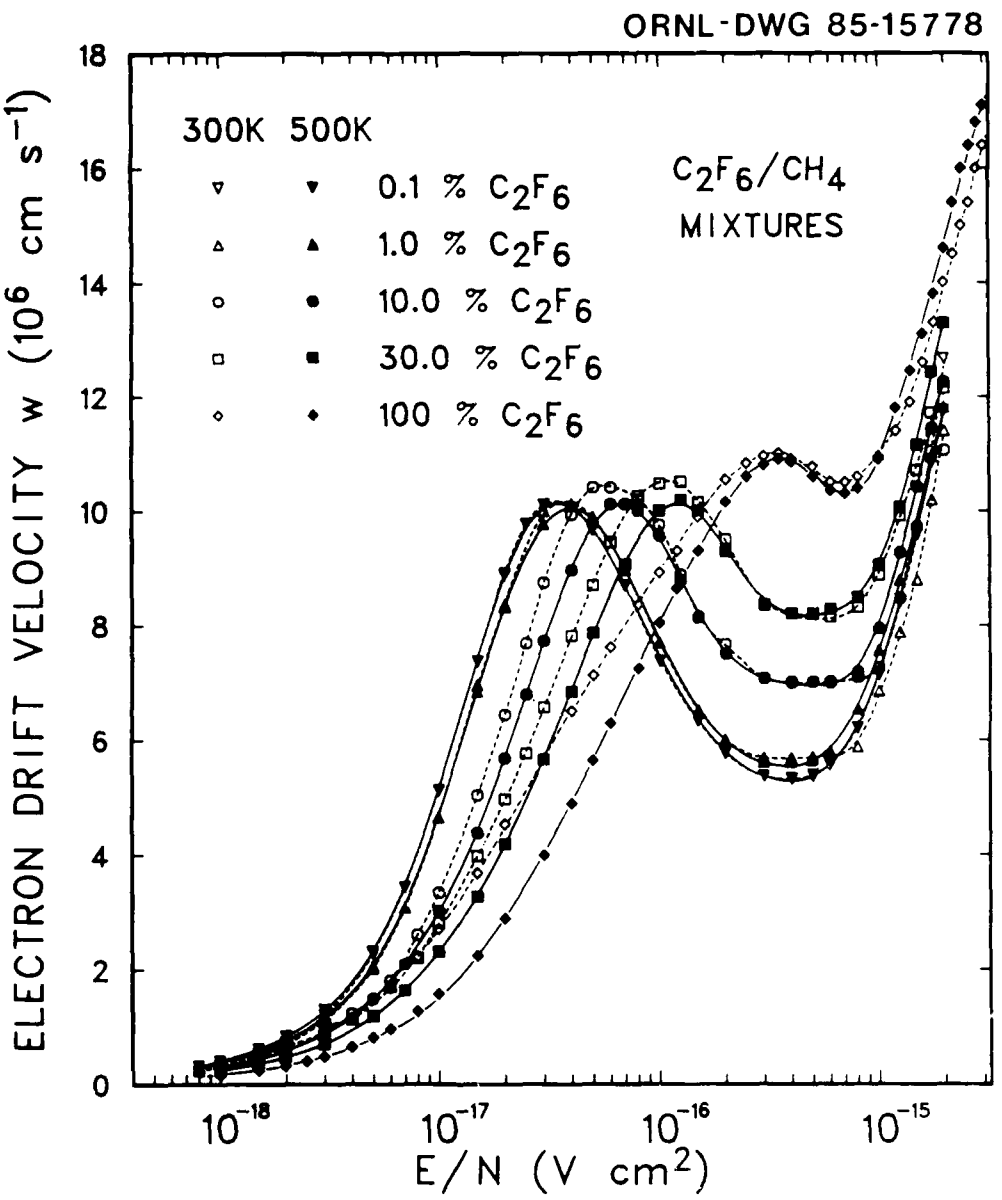


Fig. 32. Electron drift velocities as a function of E/N for several concentrations of C_2F_6 in CH_4 at gas temperatures of 300 and 500 K.

concentrations ($\gtrsim$10%) significant increases in w are observed at low and high E/N values. At high field strengths (E/N $>$ 10^{-16} V cm^2) changes in the electron non-conservation processes (i.e. electron loss by attachment and electron gain by ionization) in C_2F_6 as a function of gas temperature influence the measured electron transport parameters. At low E/N values ($<10^{-16}$ V cm^2) the changes in w with T are due to changes in the electron energy distribution functions in the C_2F_6/(Ar or CH_4) gas mixtures. These effects are the result of changes in the translational energy and the vibrational populations of the ground electronic state C_2F_6 molecules, leading to large changes with T in the fractional power exchange for superelastic and vibrational excitation collisions.

The influence of changes in T on the low electric field w measurements can be seen more clearly by plotting the density normalized electron mobility $\mu N = w(E/N)^{-1}$ as a function of E/N. The electron mobility μN in C_2F_6/CH_4 gas mixtures is given in Fig. 33 as a function of E/N at T = 300 and 500 K. At room temperature, the low electric field strength (E/N $\lesssim$ 10^{-18} V cm^2) μN values are considerably modified by changes in T, with the high C_2F_6 concentration (>10%) mixtures decreasing, and the low C_2F_6 concentration mixtures (<10%) increasing with increasing T. In Fig. 34 the density normalized thermal electron mobility $(\mu N)_{TH}$ is plotted as a function of the percentage concentration of C_2F_6 in CH_4.

The thermal electron mobility is obtained by extrapolating μN to low electric fields where, when the electrons are in thermal equilibrium with the surrounding gas, μN is independent of E/N. At T = 300 K, $(\mu N)_{TH}$ is very weakly dependent on the C_2F_6 concentration, but at higher T large changes in the low and high C_2F_6 concentration $(\mu N)_{TH}$ occur (Fig. 34), which are again the result of the increase in the translational energy of the C_2F_6 and CH_4, and also due to the changing inelastic and superelastic collisions with the vibrationally excited ground state C_2F_6 molecules.

The electron drift velocity measurements indicate that, especially for low C_2F_6 concentrations (<10%) in the buffer gas, operation of the switch at higher gas temperatures will not adversely affect the electron conductivity when the switch is closed.

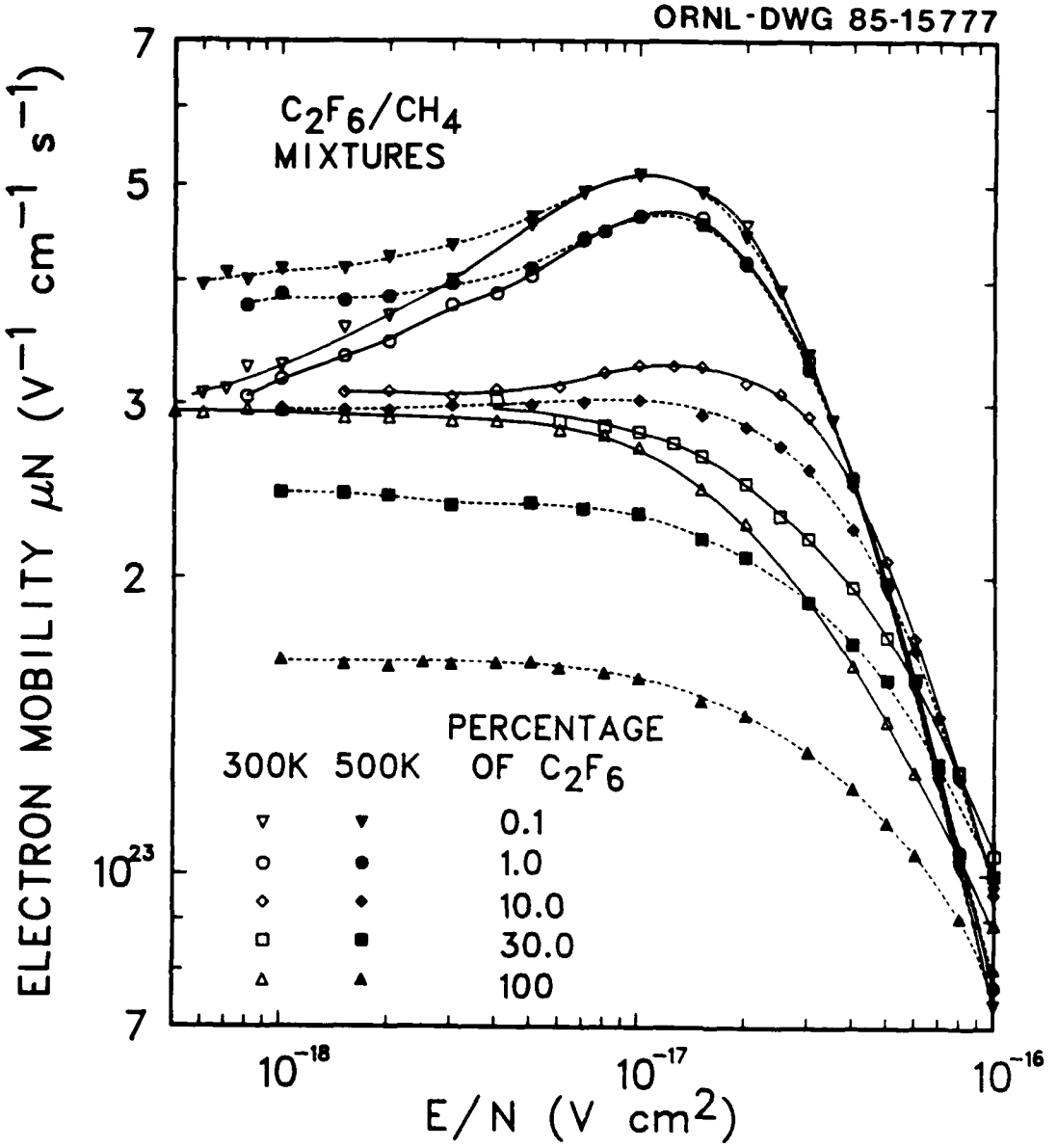


Fig. 33. The density normalized electron mobility μN in C_2F_6/CH_4 gas mixtures for low E/N values at gas temperatures of 300 and 500 K.

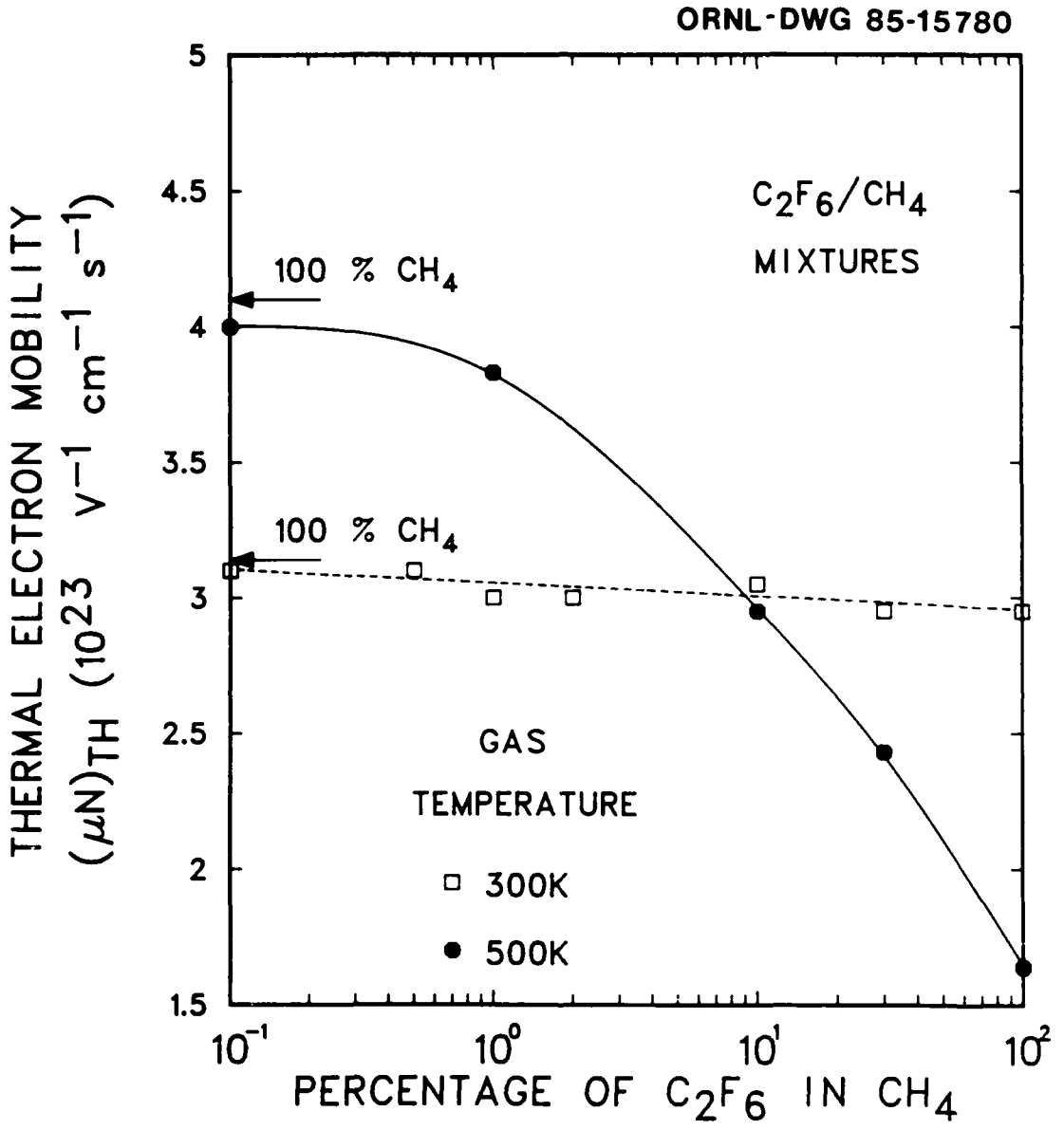


Fig. 34. Thermal electron mobilities in C_2F_6/CH_4 gas mixtures at gas tempertures of 300 and 500 K.

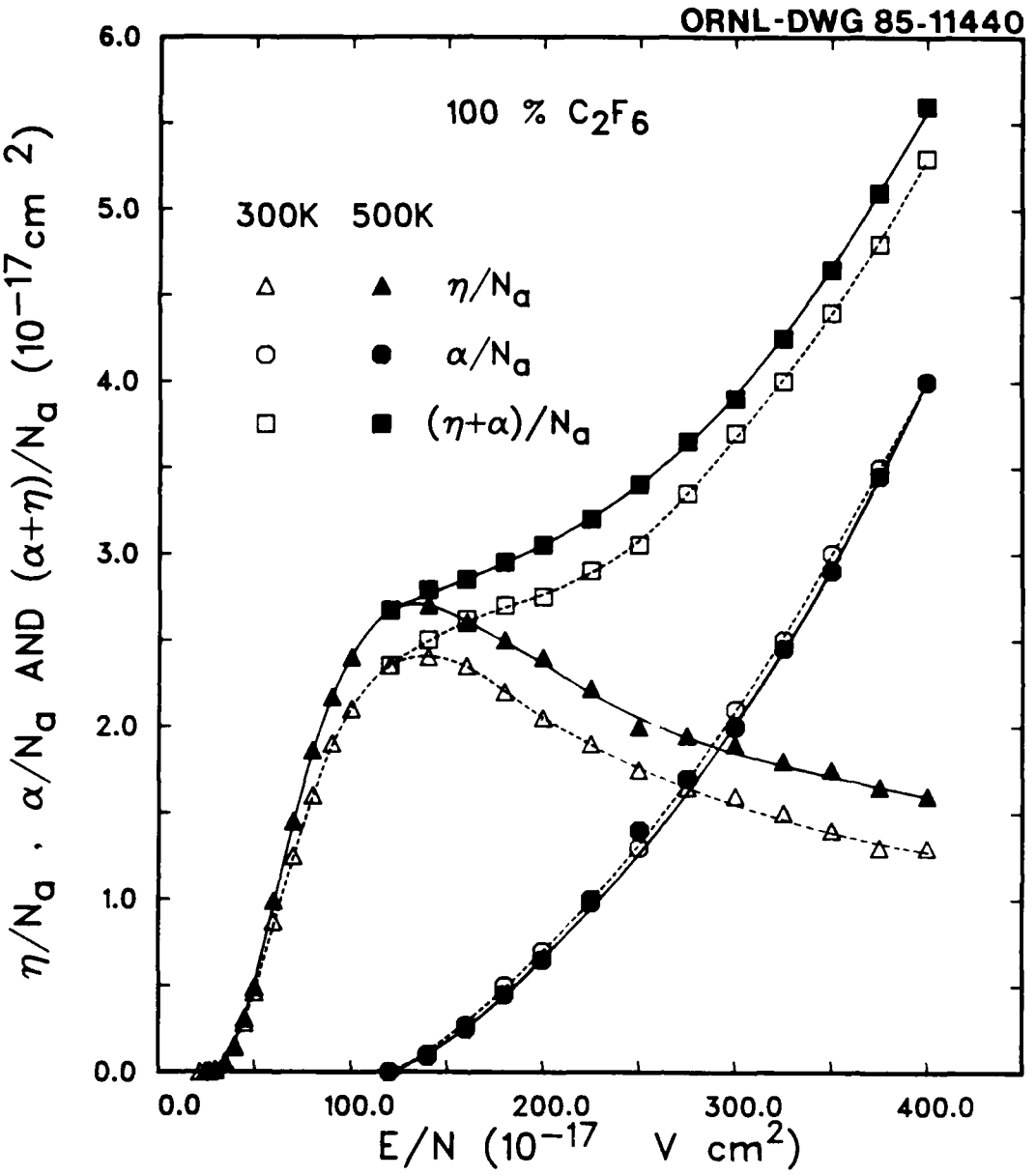


Fig. 35. Electron attachment coefficient η/N_a, electron ionization coefficient α/N_a and total ion production coefficient $(\alpha + \eta)/N_a$ of pure C_2F_6 at 300 and 500 K as a function of E/N.

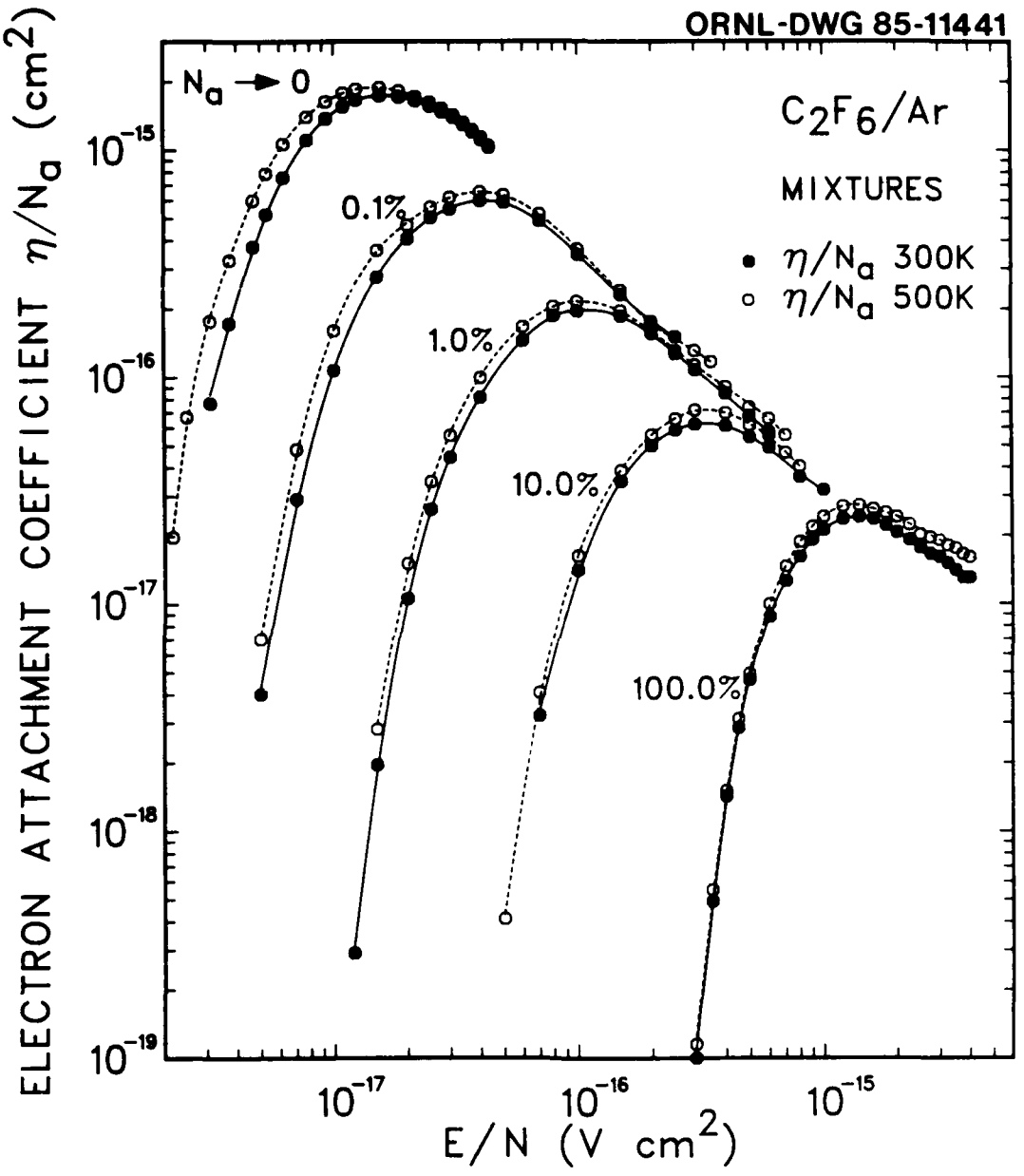


Fig. 36. Electron attachment coefficient η/N_a for several C_2F_6/Ar gas mixtures as a function of E/N at gas temperatures of 300 and 500 K.

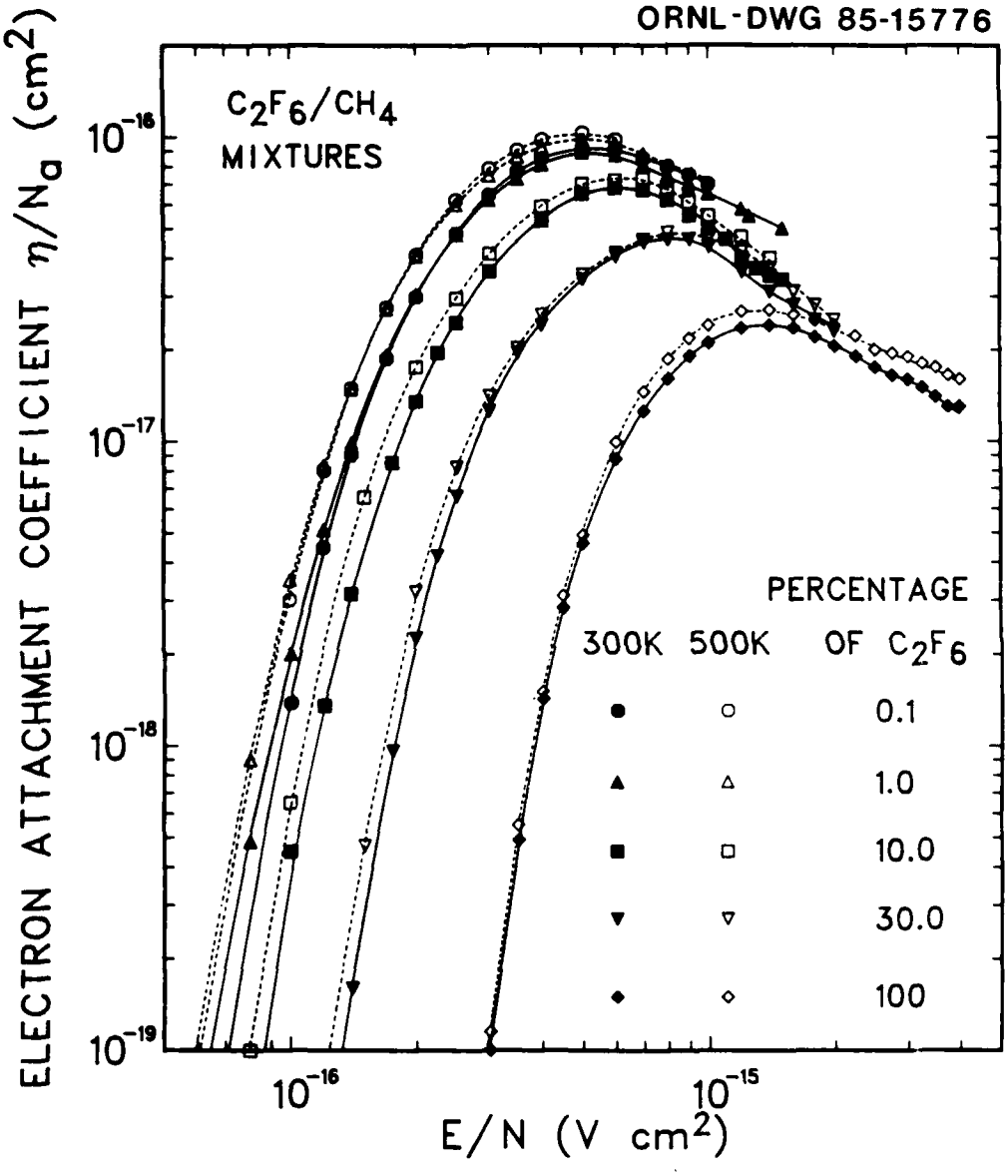


Fig. 37. Electron attachment coefficient η/N_a for several C_2F_6/CH_4 gas mixtures as a function of E/N at gas temperatures of 300 and 500 K.

B. Electron Attachment in C_2F_6 Gas Mixtures

We have measured the electron attachment coefficient η/N_a and the ionization coefficient α/N in pure C_2F_6 (Fig. 35) and in gas mixtures of C_2F_6 in Ar (Fig. 36) and C_2F_6 in CH_4 (Fig. 37) at T = 300 and 500 K in order to understand the influence of elevated gas temperatures on the transport and rate coefficients of gas mixtures in practical switching devices. It is apparent from the measurements given in Fig. 35 that over the temperature range $300 \lesssim T \lesssim 500$ K the ionization coefficient is practically unchanged [to within the uncertainty of the present measurements ($\approx \pm$ 10%)] by increases in the gas temperature. The electron attachment coefficient in contrast increases considerably (by $\approx$ 25%) at higher E/N values with a much smaller increase in η/N_a occurring at E/N values close to the threshold for the attachment process ($E/N \approx 3 \times 10^{-16}$ V cm^2). The percentage increase in the rate of electron attachment to C_2F_6 in both the rate constant [k_a ($\langle\epsilon\rangle$)] and the attachment coefficient [$\eta/N_a(E/N)$] studies (Figs. 11 and 35) near the peak in the attachment process are similar (being $\approx$10% increase at 500 K), but for the $k_a(\langle\epsilon\rangle)$ measurements [where the percentage of C_2F_6 in the Ar buffer gas is negligibly small (<1 part in 10^{-6})], the greatest increase in k_a occurs near the threshold, while for the η/N_a measurements in pure C_2F_6, the greatest change occurs at the higher E/N values near the tail of the attachment coefficient. This behavior can be more clearly seen in Fig. 36 where the attachment coefficient obtained from the rate constant measurements for C_2F_6 ($\eta/N_a = k_a/w$, where w is the electron drift velocity in Ar) is plotted along with the measurements obtained for varying concentrations of C_2F_6 in Ar. These measurements indicate that as the percentage of C_2F_6 in Ar is increased, the change in η/N_a at threshold decreases, while the percentage increase in the electron attachment at the high energy tail increases with increasing C_2F_6 concentration. A similar observation may be made in the C_2F_6/CH_4 gas mixture measurements given in Fig. 37. This observation is believed to be the result of changes in the electron energy distribution function in the swarm measurements with increasing C_2F_6 concentration, rather than to actual changes in the attachment processes to C_2F_6.

3.6 W-Value Measurements

The apparatus used to obtain the W-value measurements was described in Section 2.4. The W-values can be obtained from the following analysis. The charge Q collected at the capacitor is expressed as the product of the capacitance C and the voltage across the capacitor V. The number n of ion pairs produced per second is then given by

$$n = (1/e)\ (dQ/dt) = (C/e)\ (dV/dt) \quad . \tag{21}$$

where e is the electron charge.

The total energy deposited in the gas per second by the α particles is $\epsilon_0 N_0$, where ϵ_0 is the energy of each α particle and N_0 is the number of α particles which are completely stopped in the gas per second. Since W is the average energy required to produce an electron-ion pair, it is equal to

$$W = \epsilon_0 N_0/n = \epsilon_0 N_0/(C/e)\ (\Delta V/\Delta t) \quad . \tag{22}$$

In Eq. (22) C, ϵ_0, and N_0 are constant during the experiment; hence, the W value can be determined by measuring ΔV and Δt for the gas under investigation and comparing these values with those for a reference standard gas. In the present experiments, we measured the time Δt required to charge C to a fixed value (1.824 V) which was the threshold voltage of the Schmidt trigger circuit. When the voltage across the capacitor reached the fixed voltage, the electrical stopwatch was stopped by the signal from the Schmidt circuit (i.e., relay 2 was opened, Fig. 6). Since the W value for pure argon is well known,[17] we used Ar as the standard reference gas in our study. The unknown W value for the gas mixture, W_m, was obtained from

$$W_{Ar}/\Delta t_{Ar} = W_m/\Delta t_m \quad . \tag{23}$$

using the measured times Δt_{Ar} and Δt_m required to charge C to a fixed value when the chamber was filled, respectively, with Ar and the gas mixture. The accuracy of the technique was checked by measuring Δt_{Ar} in Ar and Δt_{N_2} in N_2;

the W values of both gases are well established.[17] We have obtained for the ratio W_{Ar}/W_{N_2} the value 0.727 which compares well with the value 0.725 obtained from the literature.[17] Measurements of W were also obtained in Ar and N_2 over a wide range of gas pressures (10 kPa $\leq P_T \leq$ 270 kPa) to ensure that the α particles were completely stopped in the gas over the range of gas pressures used in these experiments and at sufficiently high voltages such that electron-positive ion recombination was negligibly small. In these circumstances, the W values were independent of gas pressure as expected.

A. Unary Gases

The W values for the unary gases studied are given in Table I. The present W values for C_2F_6, N_2, CH_4, and C_2H_2 agree well with earlier data (see Table I). To our knowledge, no measurements of the W value of CF_4, C_3F_8, and $n\text{-}C_4F_{10}$ have been reported previously. The W values of all four perfluorocarbons (PFCs) studied are large and almost identical.

TABLE I. W Values for Unary Gases.

Gas	W (eV/i.p.)[a]
CF_4	34.3
C_2F_6	34.5; 34.7[b]
C_3F_8	34.4
$n\text{-}C_4F_{10}$	34.2
Ar	26.4[c]
N_2	36.4; 36.39[d]
CH_4	29.2; 29.1[d]
C_2H_2	27.6; 27.5;[d] 27.7[b]

[a] Present values unless otherwise indicated (Ref. 23).
[b] Ref. 22.
[c] Reference value (Ref. 27).
[d] Ref. 27.

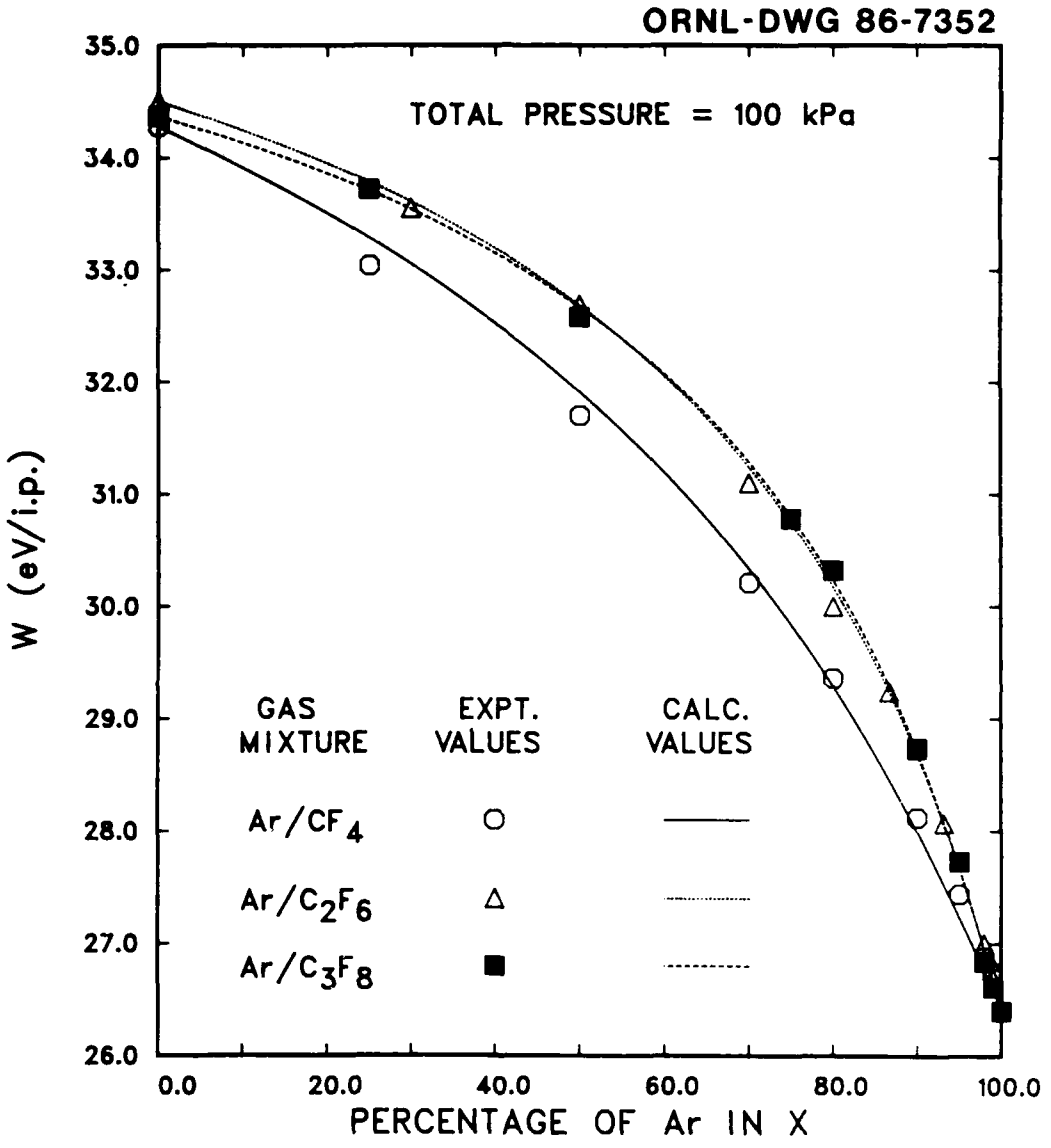


Fig. 38. Experimental W values for the Ar/CF_4, Ar/C_2F_6, and Ar/C_3F_8 binary gas mixtures as a function of the percentage of Ar in CF_4 or C_2F_6 or C_3F_8 and their comparison with the calculated data. The symbols are the experimental values; the lines are the calculated results.

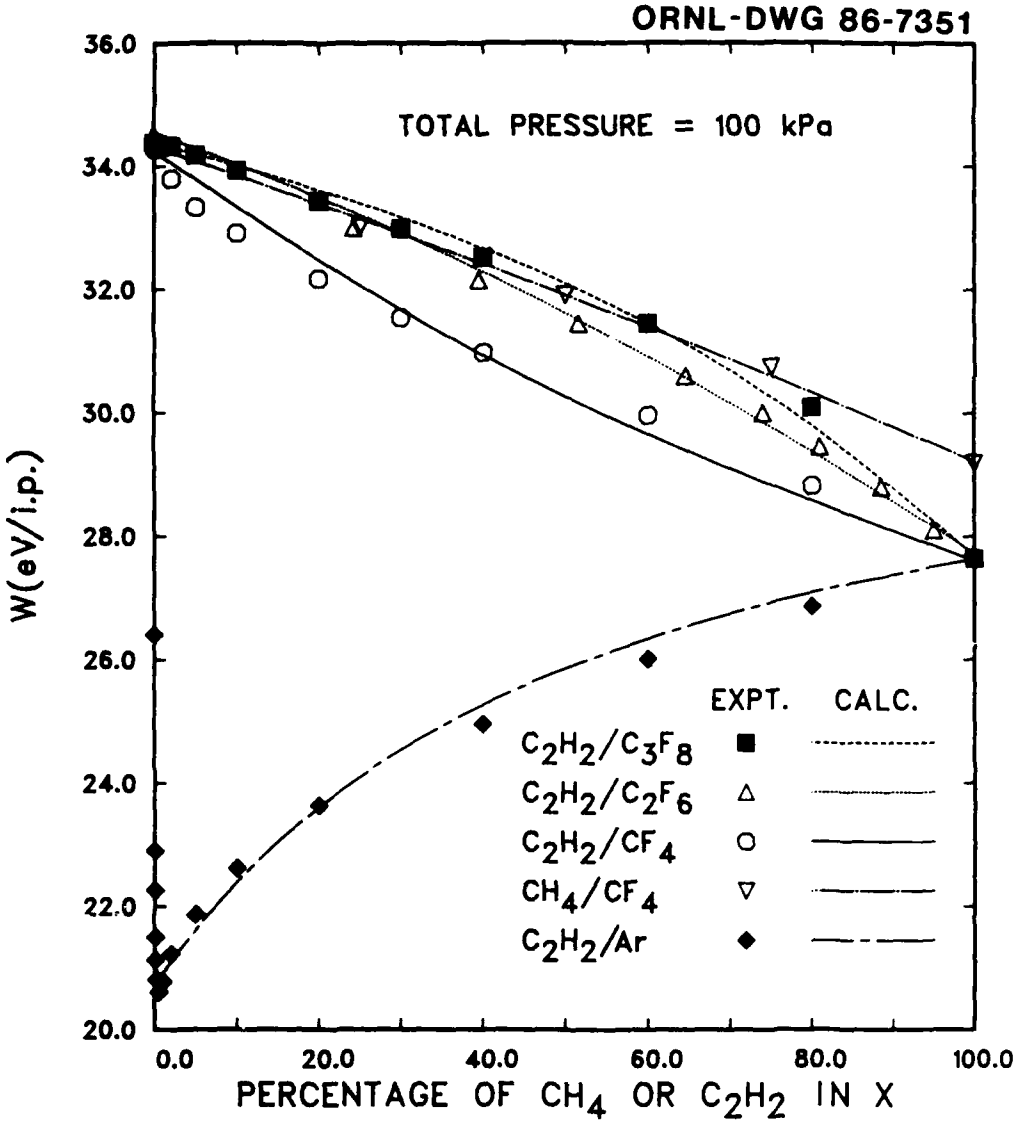


Fig. 39. Experimental W values for the C_2H_2/CF_4, C_2H_2/C_2F_6, C_2H_2/C_3F_8, CH_4/CF_4, and C_2H_2/Ar binary gas mixtures as a function of the percentage of CH_4 or C_2H_2 in CF_4 or C_2F_6 or C_3F_8 or Ar. The symbols are the experimental values; the lines are the calculated results.

B. Binary Gas Mixtures

The W values that we measured for the binary gas mixtures for various partial pressures of the constituent gases are plotted in Figs. 38 and 39. None of the perfluorocarbon-containing binary gas mixtures showed a "Jesse effect"[27] [i.e., an abrupt decrease in the W_m (the W value of the gas mixture) as small amounts of the PFC were added to Ar or as small amounts of C_2H_2 were added to the PFC], although a number of excited electronic states of the PFC molecules exist above the ionization onset energy of C_2H_2. This is attributed (see Ref. 21) to the fast dissociation of the electronically excited PFC molecules. A distinct example[27,21] of a binary gas mixture which exhibits a pronounced Jesse effect is the Ar/C_2H_2 binary gas mixture shown in Fig. 39. As discussed earlier,[27,21] the reduction in the W_m of the Ar/C_2H_2 mixtures compared with the W of the individual components is due to increased ionization resulting from collisions of excited Ar atoms with unexcited C_2H_2 molecules.

C. Ternary Gas Mixtures

The W values, W_m'', for the ternary gas mixtures $CF_4/Ar/C_2H_2$, $C_2F_6/Ar/C_2H_2$ and $C_3F_8/Ar/C_2H_2$--measured at a total pressure of 100 kPa--are shown, respectively, in Figs. 40, 41, and 42. The experimental data were obtained by adding the C_2H_2 gas to the CF_4/Ar, C_2F_6/Ar and C_3F_8/Ar binary mixtures having the composition ratios 99/1, 49/1, 19/1, 9/1, and 4/1. Addition of C_2H_2 to the Ar/PFC mixture substantially decreases W (i.e., increases ionization). The W_m'' of the ternary mixtures goes through a minimum for ternary mixtures containing $\lesssim$10% of the PFC in the Ar/PFC binary. The smaller the percentage of the PFC in the binary Ar/PFC mixture used, the lower the concentration of C_2H_2 in the respective ternary gas mixture for which the minimum value of W_m'' (maximum ionization) is realized. The observed increase in W_m'' with increasing PFC/Ar ratio is considered to be due to the quenching of the excited Ar atoms by the PFC, leading to the dissociation of the latter into neutral species.

A comparison of the values of W_m'' for ternary mixtures containing various percentages of C_2H_2 in 99% Ar/1% PFC clearly shows that the total ionization in the gas mixture increases (W_m'' decreases) in the order $CF_4 > C_2F_6 > C_3F_8$ and that the amount of C_2H_2 in 99% Ar/1% PFC for which the maximum ionization (minimum W_m'') is realized increases in the order $C_3F_8 > C_2F_6 > CF_4$.

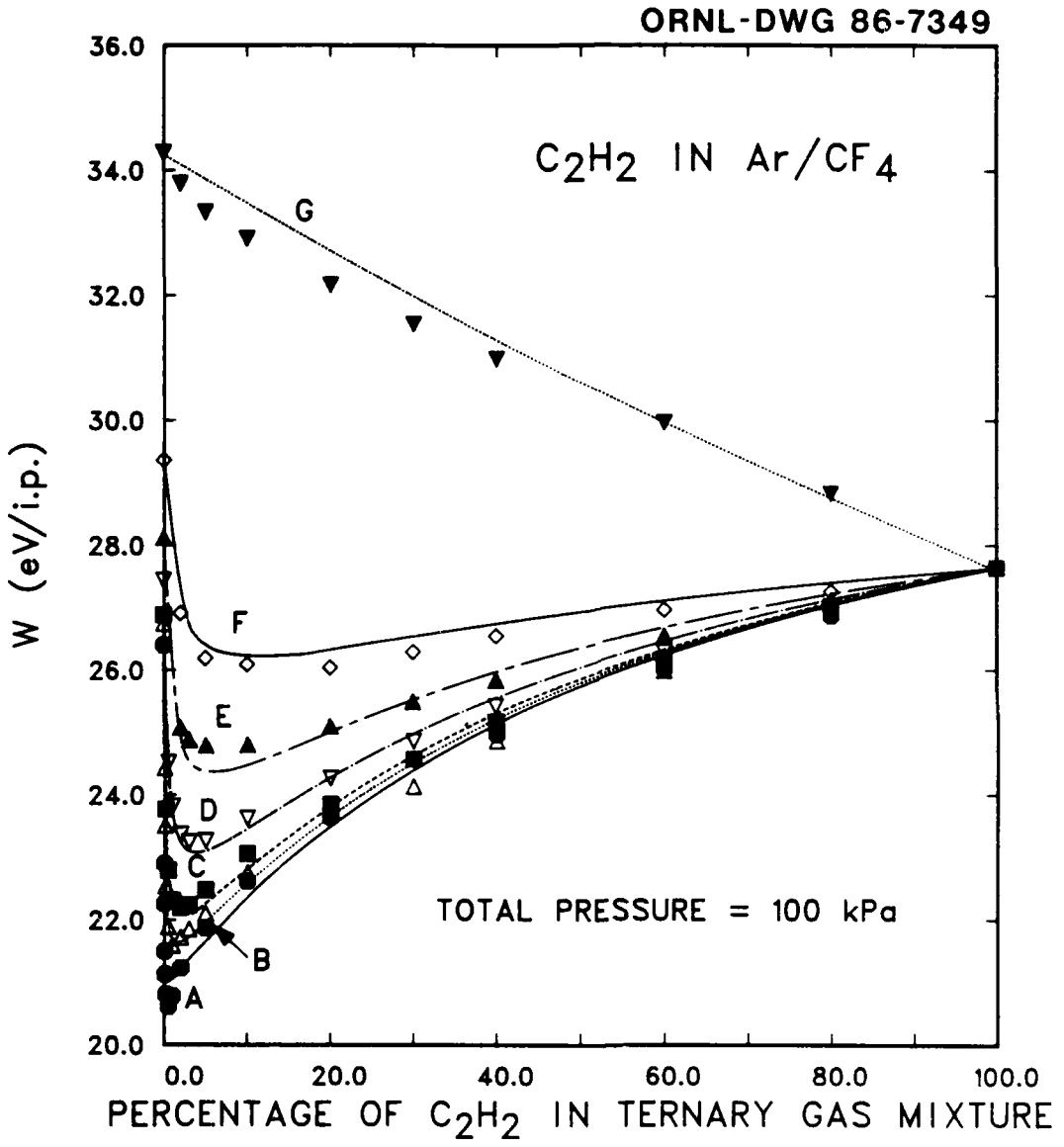


Fig. 40. Experimental W values for $Ar/CF_4/C_2H_2$ ternary gas mixtures as a function of the percentage of C_2H_2 in the Ar/CF_4 mixtures at high concentrations of C_2H_2 having the following Ar/CF_4 composition: A - 1/0, B - 99/1, C - 49/1, D - 19/1, E - 9/1, F - 4/1, G - 0/1. The symbols are the experimental values; the lines are the calculated values.

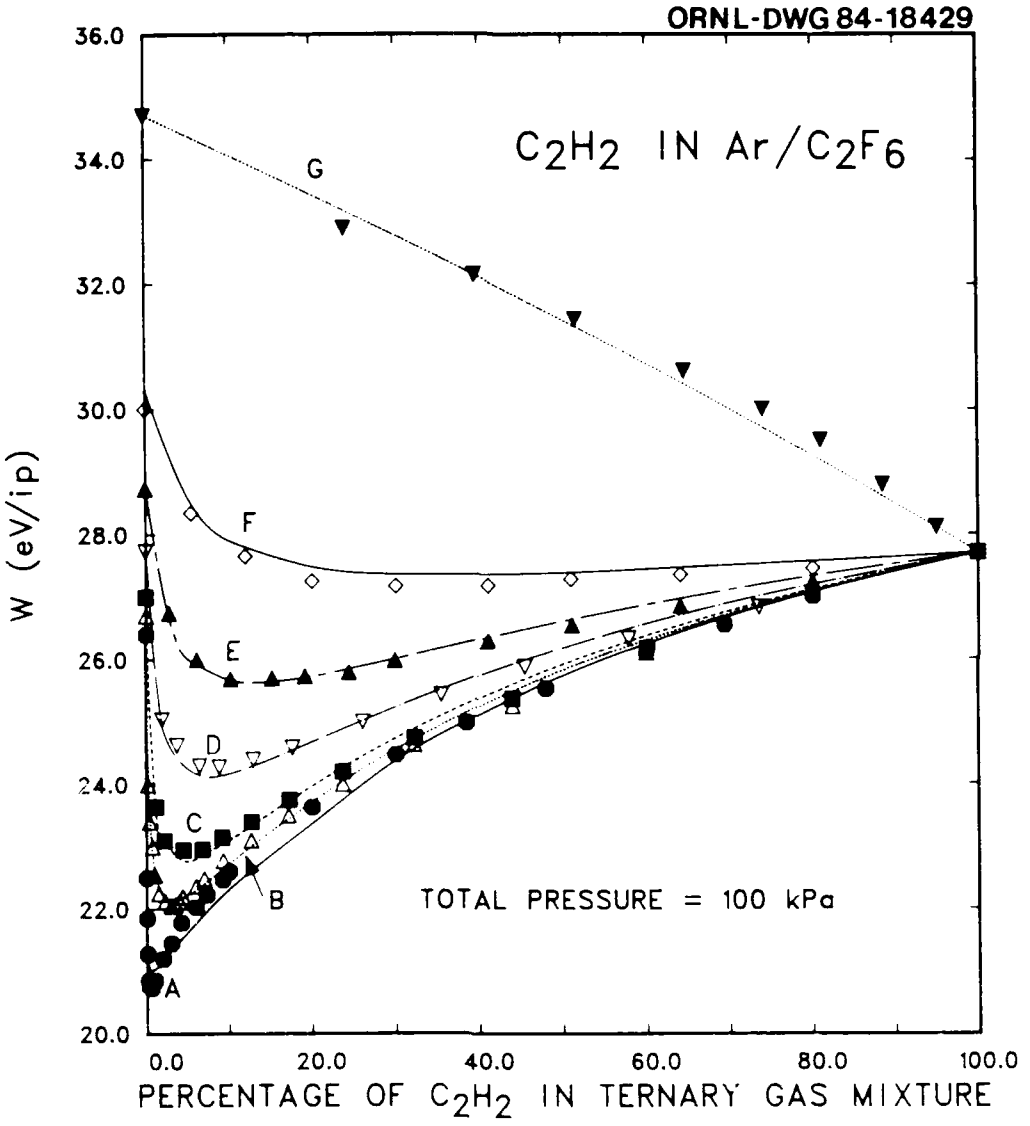


Fig. 41. Experimental W values of $Ar/C_2F_6/C_2H_2$ ternary gas mixtures as a function of the percentage of C_2H_2 in Ar/C_2F_6 mixtures at high concentrations of C_2H_2, having the following compositions: A, Ar/C_2F_6 = 1/0; B, Ar/C_2F_6 = 99/1; C, Ar/C_2F_6 = 49/1; D, Ar/C_2F_6 = 19/1; E, Ar/C_2F_6 = 9/1; F, Ar/C_2F_6 = 4/1; G, Ar/C_2F_6 = 0/1. The symbols are the experimental values and the lines are the calculated values.

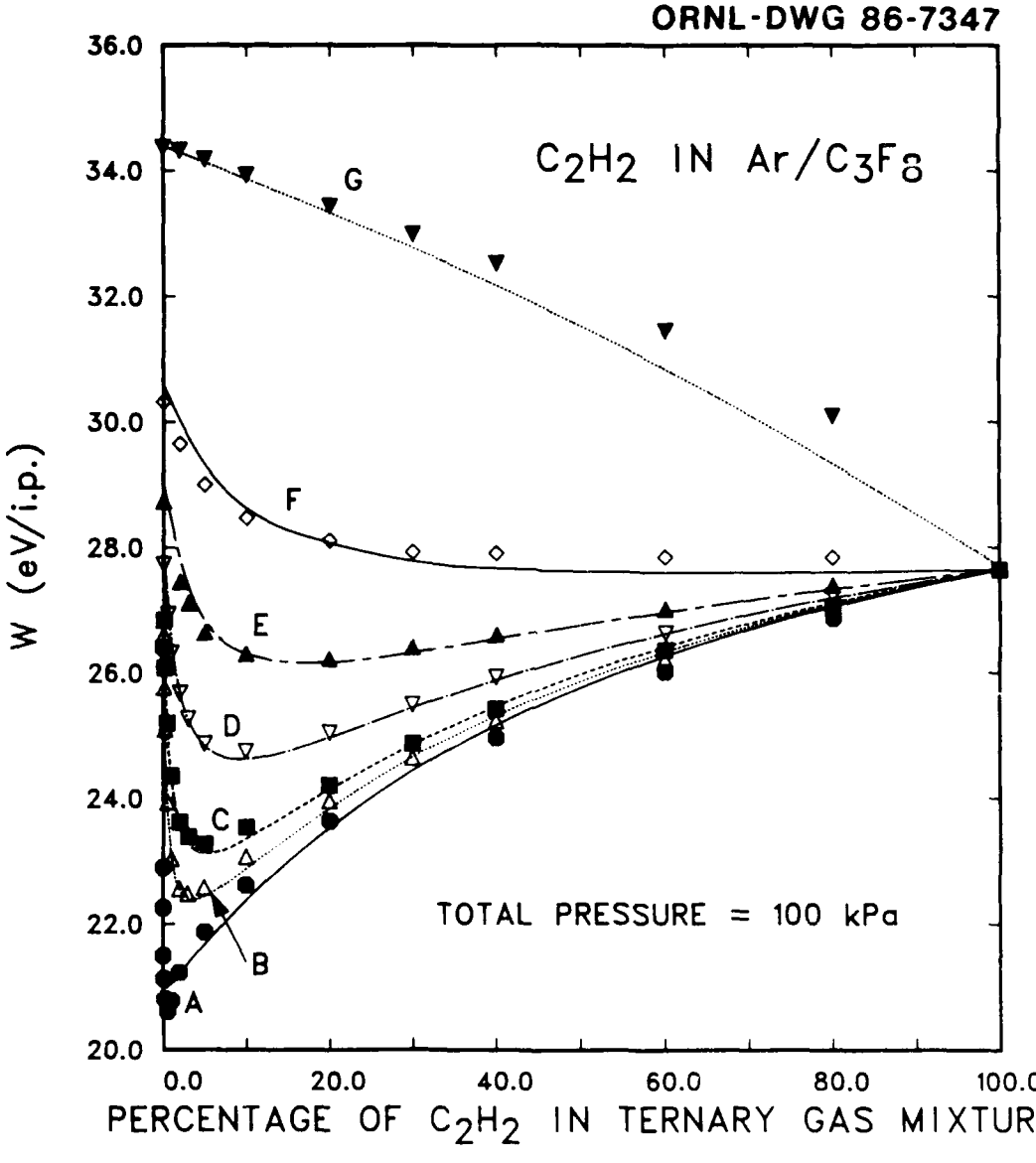


Fig. 42. Experimental W values for $Ar/C_3F_8/C_2H_2$ ternary gas mixtures as a function of the percentage of C_2H_2 in the Ar/C_3F_8 mixtures at high concentrations of C_2H_2 having the following Ar/C_3F_8 compositions: A = 1/0, B = 99/1, C = 49/1, D = 19/1, E = 9/1, F = 4/1, G = 0/1. The symbols are the experimental values; the lines are the calculated values.

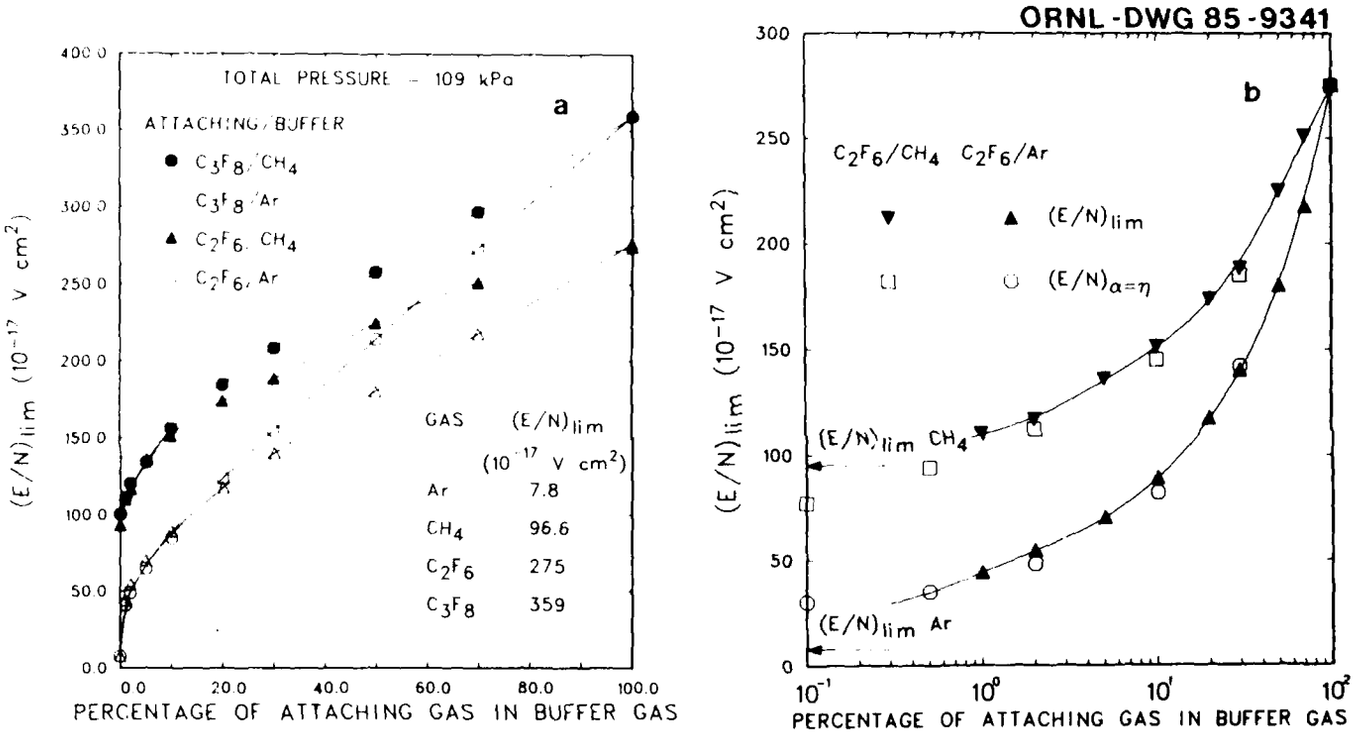


Fig. 43. (a) Measured $(E/N)_{\ell im}$ versus percentage of C_2F_6 or C_3F_8 in Ar and C_2F_6 or C_3F_8 in CH_4. The measurements were made using 12 cm Bruce profiled electrodes, and the estimated uncertainty in the measurements is ± 3%. (b) Comparison of measured $(E/N)_{\ell im}$ and calculated $(E/N)_{\alpha=\eta}$ for C_2F_6/CH_4 and C_2F_6/Ar mixtures.

The quantitative measurements on the W values of the perfluorocarbons CF_4, C_2F_6, and C_3F_8, on their binary mixtures with Ar, and on their ternary mixtures with Ar + C_2H_2 are of direct interest to diffuse discharge switching applications. They form the basis for achieving substantial current increases--by the proper choice of the gas components and their properties in the ternary gas mixtures--in the gaseous media (Ar/PFC) which otherwise possess the desirable conduction/insulation characteristics for pulsed power opening switches.[21,22]

3.7 High Voltage Breakdown Field Strength Studies

A. Room Temperature Measurements

The high voltage direct current (dc) uniform field strength $(E/N)_{\ell im}$ has been measured in mixtures of the attaching gases C_2F_6 and C_3F_8 in buffer gases of Ar and CH_4[15] and are given in Fig. 43a. The apparatus and measurement technique have been described previously.[24,25] The $(E/N)_{\ell im}$ values were determined from the slope of the breakdown voltage V_s versus Nd functions, where d is the uniform field electrode gap spacing at a total gas pressure of 109 kPa.

The measurements in Fig. 43a indicate that gas mixtures composed of $\gtrsim$20% of C_2F_6 or C_3F_8 in Ar have $(E/N)_{\ell im}$ values in excess of 10^{-15} V cm^2 and can thus withstand the voltage levels characteristic of the opening stage of the switch.[1,3] The C_2F_6/CH_4 and C_3F_8/CH_4 mixtures possess high breakdown strengths over a wider (and lower) range of concentrations of the attaching gas in CH_4 enabling a wider choice of gas mixtures to be made while still maintaining high breakdown field strengths.

It is interesting to note that in an electronegative gas at sufficiently high gas pressures, the high voltage breakdown field strength may also be defined as the E/N value at which $(\alpha-\eta) = 0$. The E/N values $[(E/N)_{\alpha=\eta}]$ at which this occurs have been determined from the electron attachment and ionization measurements for the C_2F_6/Ar and C_2F_6/CH_4 gas mixtures and have been plotted in Fig. 43b along with the measured $(E/N)_{\ell im}$ values (Fig. 43a) for these mixtures. The $(E/N)_{\alpha=\eta}$ value for pure C_2F_6 has been found to be 2.75×10^{-15} V cm^2 in excellent agreement with the measured $(E/N)_{\ell im}$ value. At lower concentrations of C_2F_6 in both Ar and CH_4, but particularly the

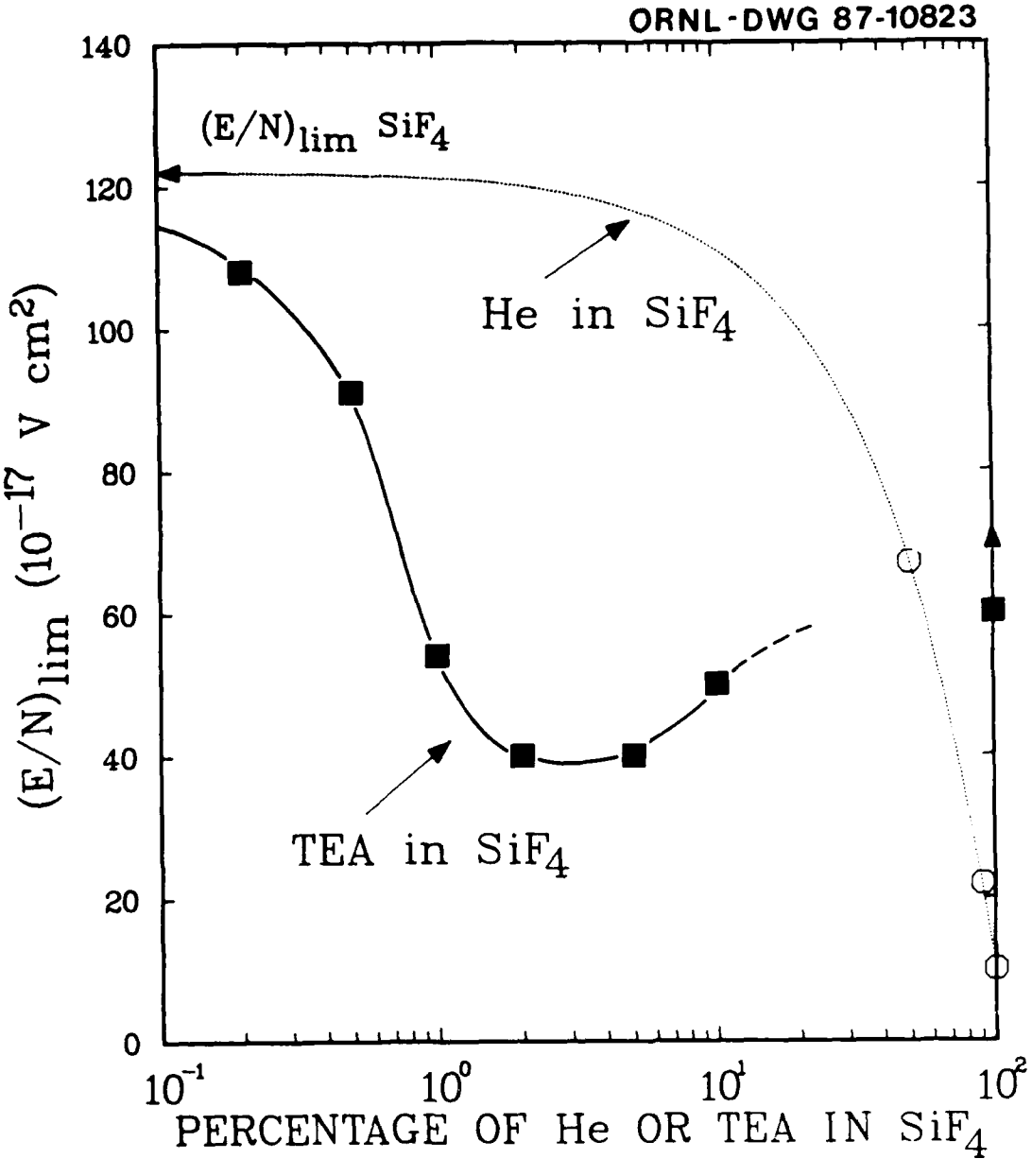


Fig. 44. The $(E/N)_{\ell im}$ (defined as the E/N value at which $\alpha/N = \eta/N$) as a function of the concentration of either TEA (triethylamine) or He in SiF_4.

C_2F_6/CH_4 gas mixtures, the $(E/N)_{\alpha=\eta}$ values are somewhat lower than the measured $(E/N)_{\ell im}$ values. In weakly electronegative gases (i.e., gases and gas mixtures where the electron attachment processes are small), the $(E/N)_{\ell im}$ value of the gas is determined by other processes, such as secondary electron generation and the streamer growth in the discharge, and is no longer simply given by the E/N value for which the attachment and ionization processes are equal. Such effects are evident in these measurements, particularly at low concentrations of C_2F_6 in CH_4.

The $(E/N)_{\ell im}$ (obtained when $\alpha=\eta$) for several SiF_4/He and SiF_4/TEA gas mixtures have also been obtained from the electron attachment and ionization coefficient measurements described earlier in this section. These values are plotted in Fig. 44 These gas mixtures have been proposed as possible candidates for use in diffuse discharge closing switches.[42] These measurements show that the addition of 1% of TEA to SiF_4 reduces the $(E/N)_{\ell im}$ of pure SiF_4 by a factor of 3. This is the result of the variation of η/N with E/N near $(E/N)_{\ell im}$ for SiF_4 and is only exhibited in gas mixtures in which the threshold for electron attachment occurs at high electron energies (>8 eV), where, because of the small variation in $\bar{\alpha}/N$ near $(E/N)_{\ell im}$ minor increases in α/N lead to considerable reductions in $(E/N)_{\ell im}$.

B. Elevated Temperature Measurements

The $(E/N)_{\ell im}$ characteristics of several gases which may be useful in diffuse discharge opening (i.e., $CClF_3$, C_2F_6, C_3F_8 and $n\text{-}C_4F_{10}$) and closing (i.e., $1\text{-}C_3F_6$, C_3F_8, $c\text{-}C_4F_8$ and $n\text{-}C_4F_{10}$) switches have been studied as a function of gas temperature from room temperature ($T \approx 300$ K) up to $T \approx 600$ K. The dielectric properties of the gas mixtures within these switches may be beneficially or adversely affected by changes in the gas temperature of this magnitude. For the present measurements, 10 breakdown values to determine V_s (the breakdown voltage) were made at each value of the electrode gap separation d which was varied from $\approx$ 1.9 to 10.8 mm in steps of 1.27 mm.

We found that the $V_s(T)$ vs Nd measurements could best be presented as measured $(E/N)_m$ vs Nd for various values of $T(\leq 575$ K). Examples of such plots are shown in Figs. 45 and 46 for $c\text{-}C_4F_8$ and CF_3Cl, respectively. For

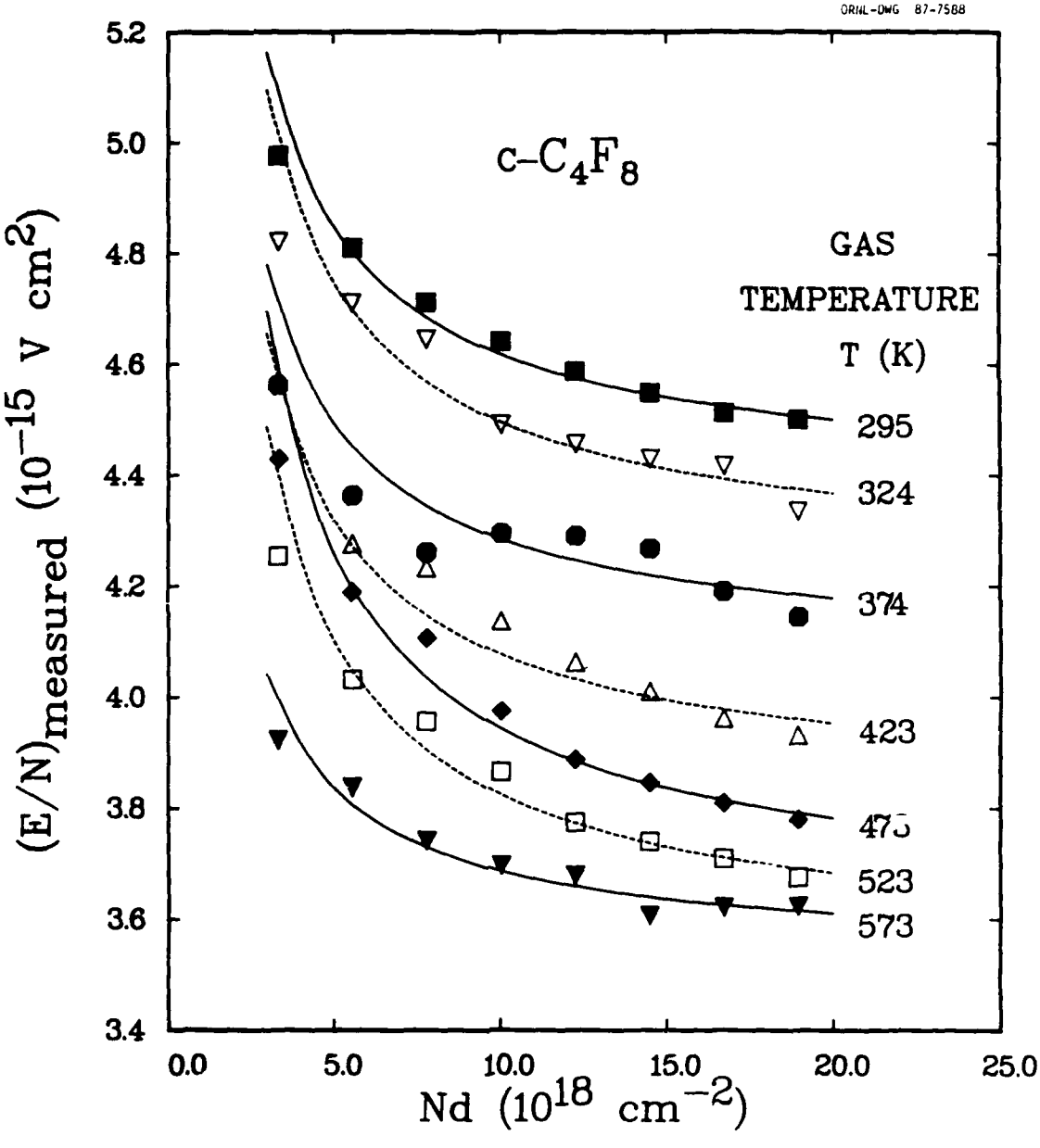


Fig. 45. $(E/N)_{measured}$ versus Nd at various T for c-C_4F_8.

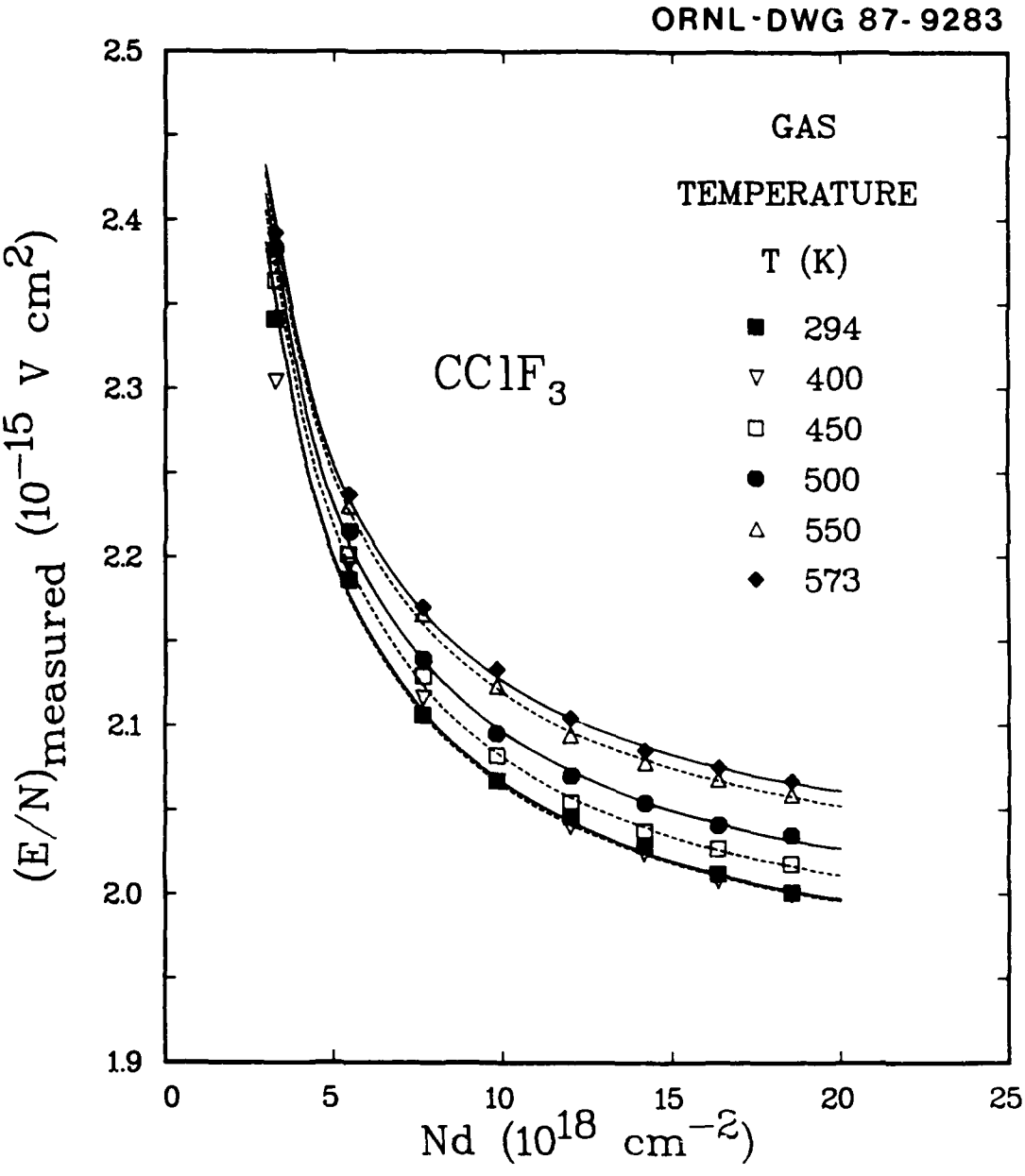


Fig. 46. $(E/N)_{measured}$ versus Nd at various T for CCl_3F.

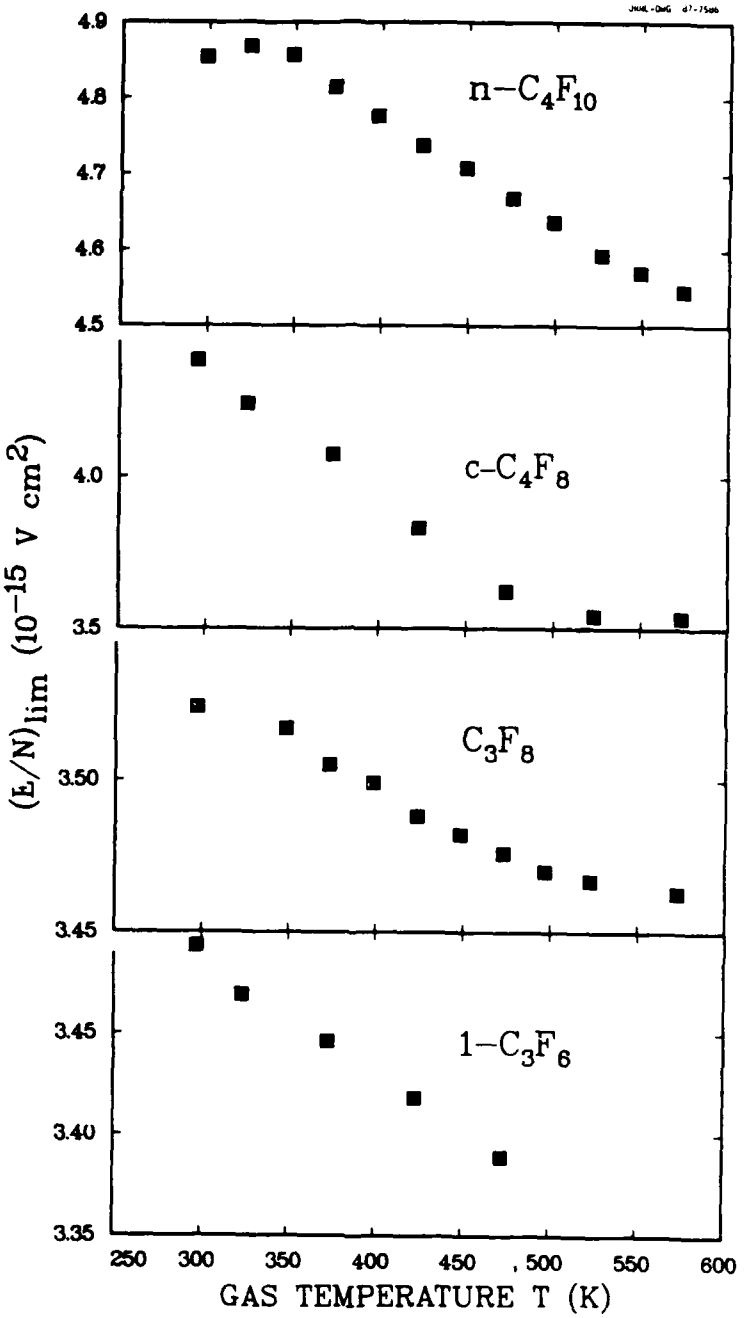


Fig. 47. $(E/N)_{\ell im}$ versus T for n-C_4F_{10}, c-C_4F_8, C_3F_8, and 1-C_3F_6.

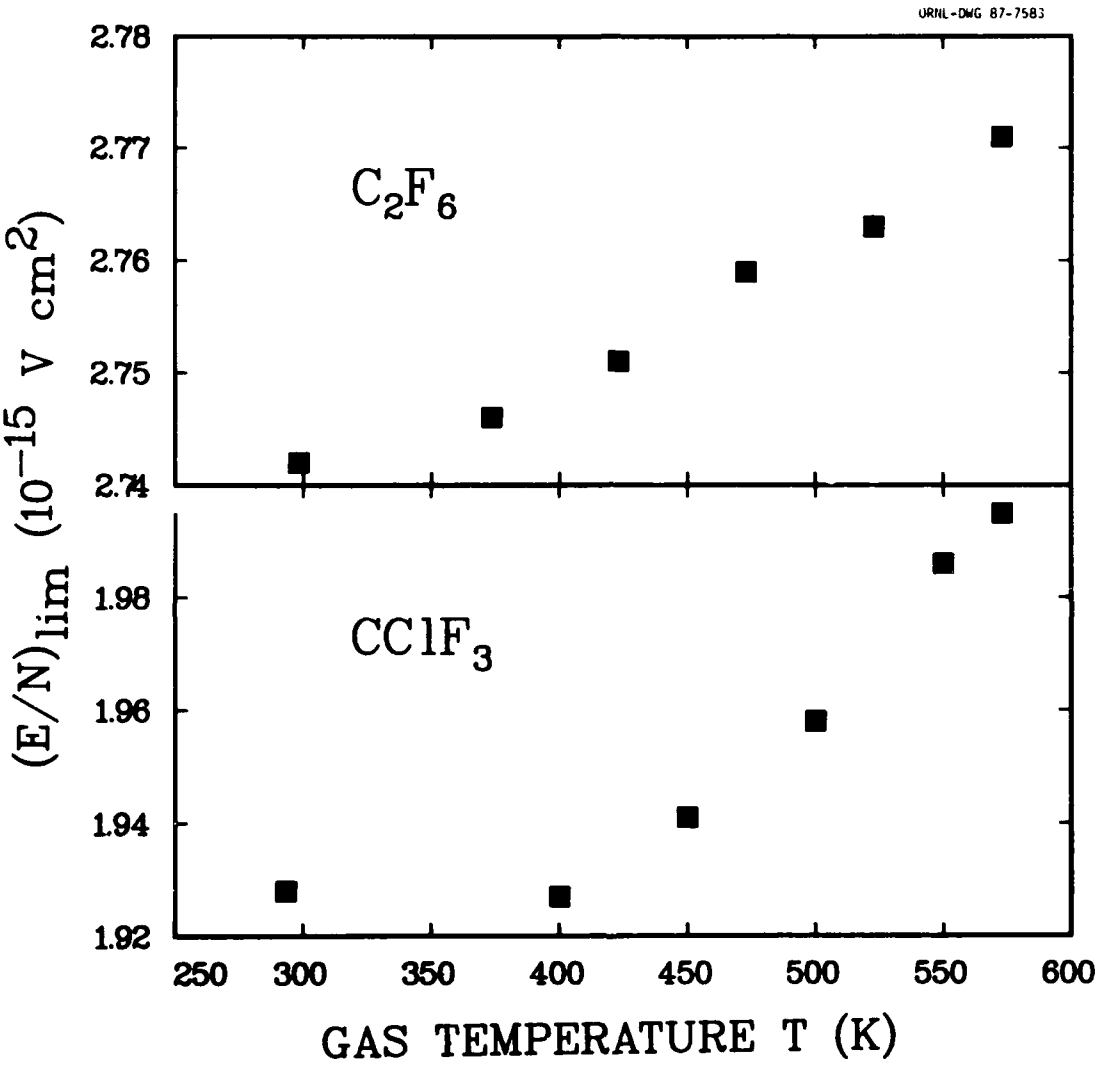


Fig. 48. $(E/N)_{\ell im}$ versus T for C_2F_6 and $CClF_3$.

each value of T, the measurements in Figs. 45 and 46 (and similar measurements on the rest of the gases investigated) were fitted to the expression

$$(E/N)_m = (E/N)_{\ell im} + A/Nd \qquad (24)$$

(where A is a constant) and the limiting value, $(E/N)_{\ell im}$, of E/N was obtained. The values of $(E/N)_{\ell im}$ at various T are plotted in Figs. 47 and 48 for all six gases studied.

These measurements indicate that the effect of increasing gas temperature on the hold-off voltage in opening switch applications will be minimal for gas temperatures $T \leq 600$ K for most of these gases. Specifically, for $OClF_3$ and C_2F_6, the gas dielectric properties increase slightly ($\approx$ 3.6% and $\approx$ 1.0%, respectively) with increasing T, while for 1-C_3F_6 and C_3F_8, $(E/N)_{\ell im}$ decreases slightly ($\approx$ 2.6% and 3.0%, respectively) over this temperature range. On the other hand, there are larger decreases in $(E/N)_{\ell im}$ for c-C_4F_8 ($\approx$25%) and n-C_4F_{10} ($\approx$ 8%) (and c-C_4F_6 [?]) over this temperature range. Although these reductions in $(E/N)_{\ell im}$ are not beneficial for opening switch applicaitons, they can be used to enhance the conductivity in self-sustained closing switches, and thereby increasing the current switching efficiency of this type of switch.[42]

IV. Relevance to Switching Experiments

From the measurements given in Section III, it is clear that we have developed several gas mixtures with the optimized w(E/N) and k_a(E/N) characteristics shown in Fig. 2. These gas mixtures contain a low percentage perfluorocarbon (0.1% to 30% in the total gas mixture) and either Ar[14,15] or CH_4[20] as a buffer gas. The E/N dependence of w and the density normalized electron attachment coefficient η/N_a of gas mixtures containing C_2F_6 in Ar and C_2F_6 in CH_4 are given in Figs. 49a and 49b, respectively. These measurements (e.g. the 2% C_2F_6 mixture in Fig. 49a and the 10% C_2F_6 mixture in Fig. 49b) indicate that these mixtures have the near ideal characteristics required to optimize $J_{SW}(E/N)$ [and hence $J_{SW}(t)$] shown in Fig. 2. Small scale e-beam sustained switching studies have been performed using these gas mixtures and have shown that switch opening times $\geq$ 50 ns are achievable.[43-46]

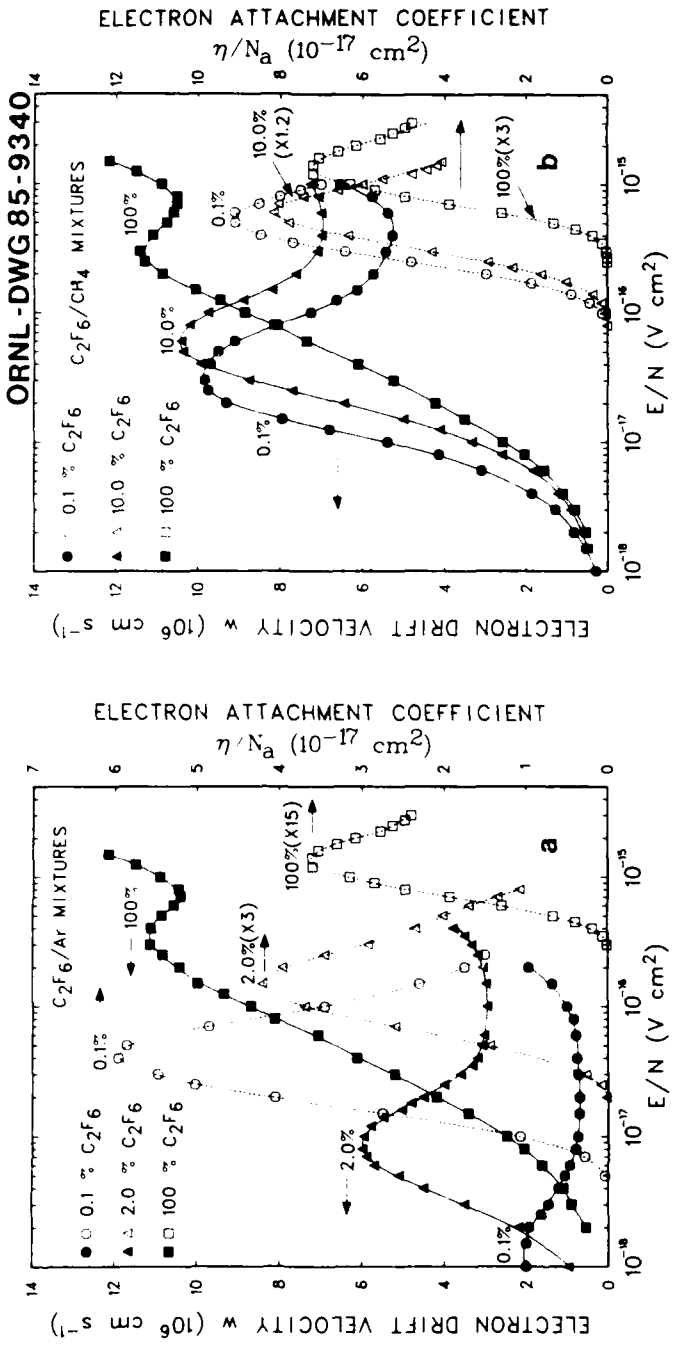


Fig. 49. a) Comparison of the electron attachment coefficient η/N_a and drift velocity w for C_2F_6/Ar gas mixtures and b) Comparison of the electron attachment coefficient η/N_a and drift velocity w for C_2F_6/CH_4 (Ref. 20).

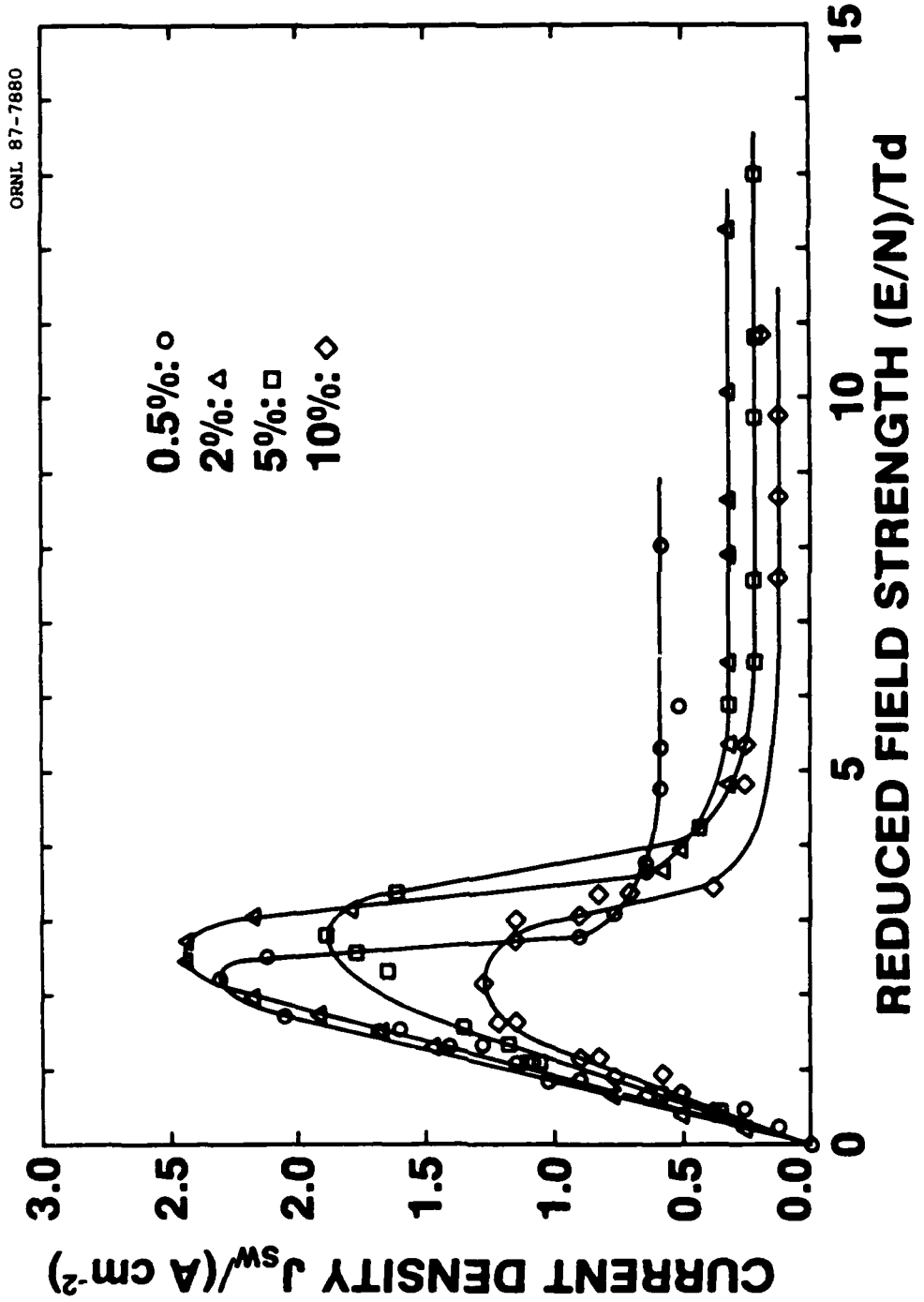


Fig. 50. The switch current density J_{SW} vs E/N for an e-beam sustained diffuse discharge in several C_2F_6/Ar gas mixtures (Ref. 44).

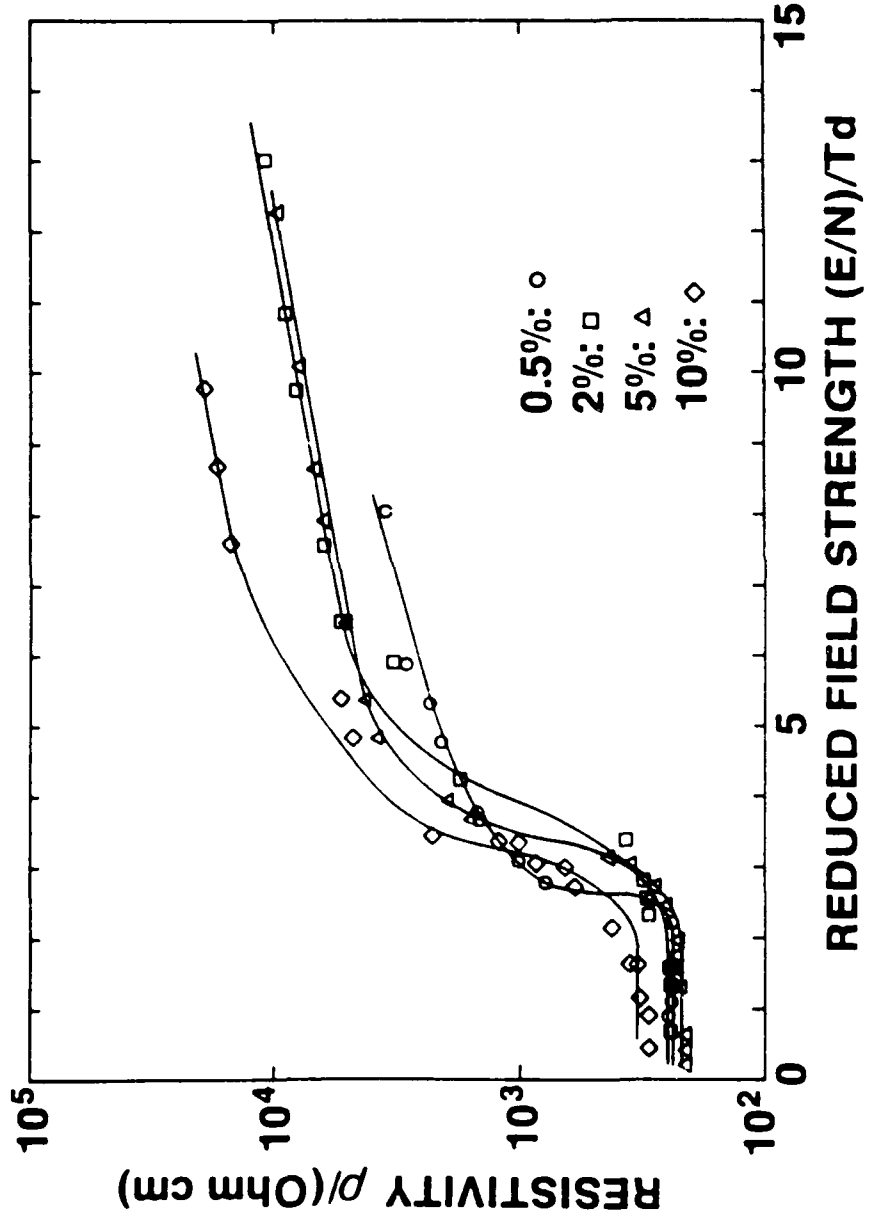


Fig. 51. The switch resistivity ρ versus E/N for an e-beam sustained discharge in several C_2F_6/Ar gas mixtures (Ref. 44).

4.1 C_2F_6/Ar Gas Mixtures

The current density J_{SW} and discharge resistivity ρ measurements obtained as a function of E/N in the e-beam switching experiments of Schaeffer and colleagues (Ref. 44, 45) are given in Figs. 50 and 51, respectively, for several concentrations of C_2F_6 in Ar. A strong negative differential conductivity is seen in the measurements given in Fig. 50, with the peaks in J_{SW} occurring at E/N $\approx$ 2-3 $\times$ 10^{-17} V cm^2 (1 Td $\equiv$ 10^{-17} V cm^2). Similarly, the resistivity measurements given in Fig. 51 indicate that over the E/N range 2.5 < E/N < 5 $\times$ 10^{-17} V cm^2, the resistivity of the discharge increases by over an order of magnitude. These measurements indicate that a mixture composed of approximately 2% C_2F_6 in Ar has the best electrical conductivity characteristics at low E/N (i.e. during switch conduction), and the largest decrease in conductivity (i.e. increase in resistivity) at high E/N values which occur during switch opening. The reduction in conductivity was found to be primarily due to the onset of electron attachment at E/N = 2-3 $\times$ 10^{-17} V cm^2 (Fig. 49a) rather than due to the reduction in w at high E/N. At low E/N, the discharge is recombination dominated and the magnitude of the peak in J_{SW} was found to be controlled by the maximum in the electron mobility μ(= w/E) at these E/N values (Fig. 5, Ref. 44). Studies of the switching characteristics of opening switches using a UV light source to provide a source of electrons in the discharge by photoionization of the gas mixture have obtained similar results.[45]

4.2 C_2F_6/CH_4 Gas Mixtures

The transient electron beam current I_b, the switch discharge current I_{SW} and the switch voltage V_{SW} obtained in the e-beam switching measurements of Commisso and colleagues (Ref. 43) using a mixture composed of 1% C_2F_6 in CH_4 are given in Fig. 52. These measurements indicate that the mixtures shown in Fig. 49b give rapid switch opening upon termination of the discharge sustaining source, with switch opening times an order of magnitude faster than those for pure CH_4. This can be seen in Fig. 53 where the switch voltage obtained in pure N_2, CH_4 and a 1% C_2F_6 in CH_4 gas mixture are compared (Ref. 43). Even at the lower total gas pressure, the C_2F_6/CH_4 gas mixture exhibits a larger voltage transient with a much faster decay than pure CH_4. The switch opening time in pure N_2 is also orders of magnitude slower than for the

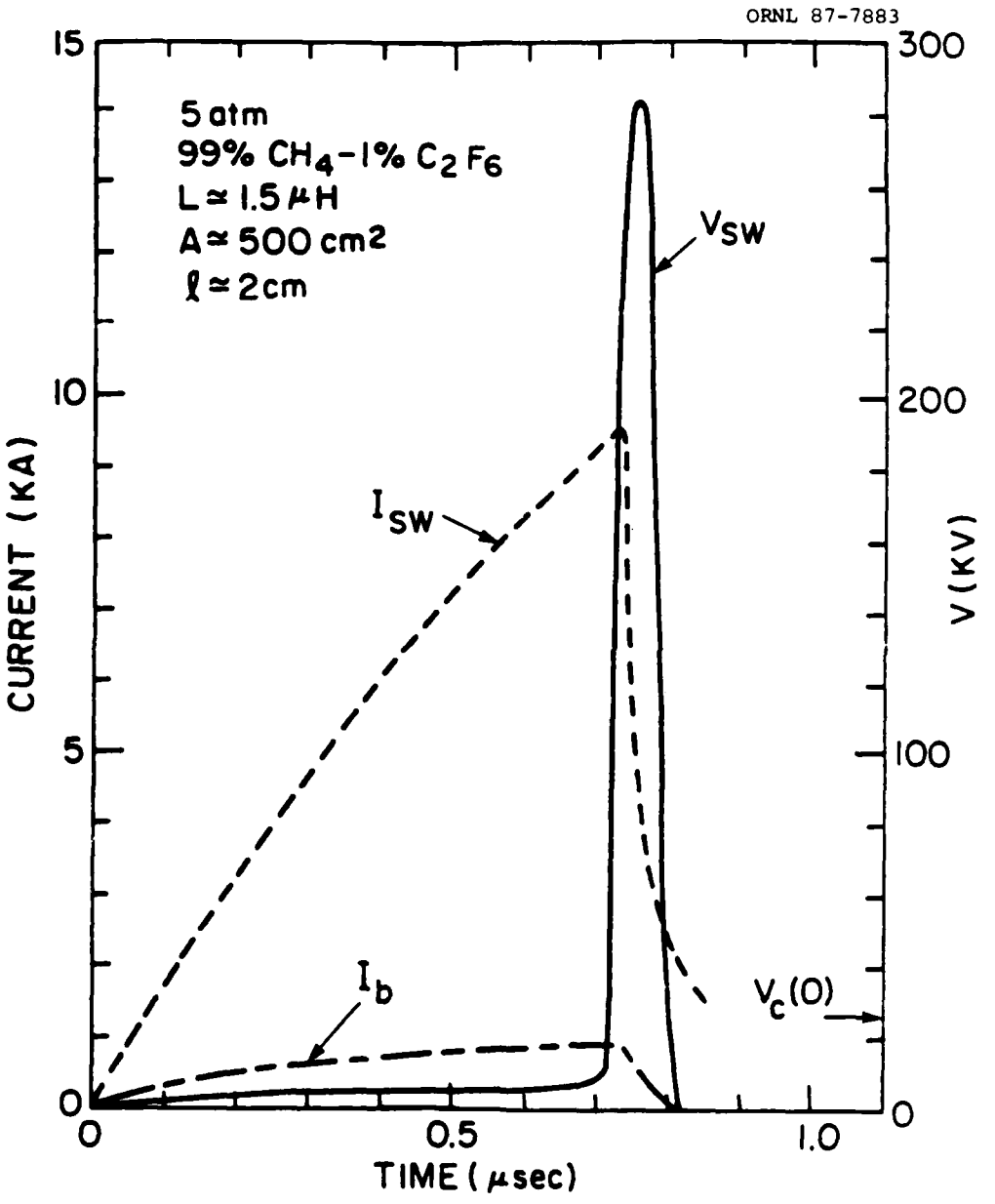


Fig. 52. The diffuse discharge switch current I_{SW}, the sustaining e-beam current I_b, and the voltage transient developed across the switch V_{SW} during switch opening using a gas mixture of CH_4 containing 1% of C_2F_6 (Ref. 43).

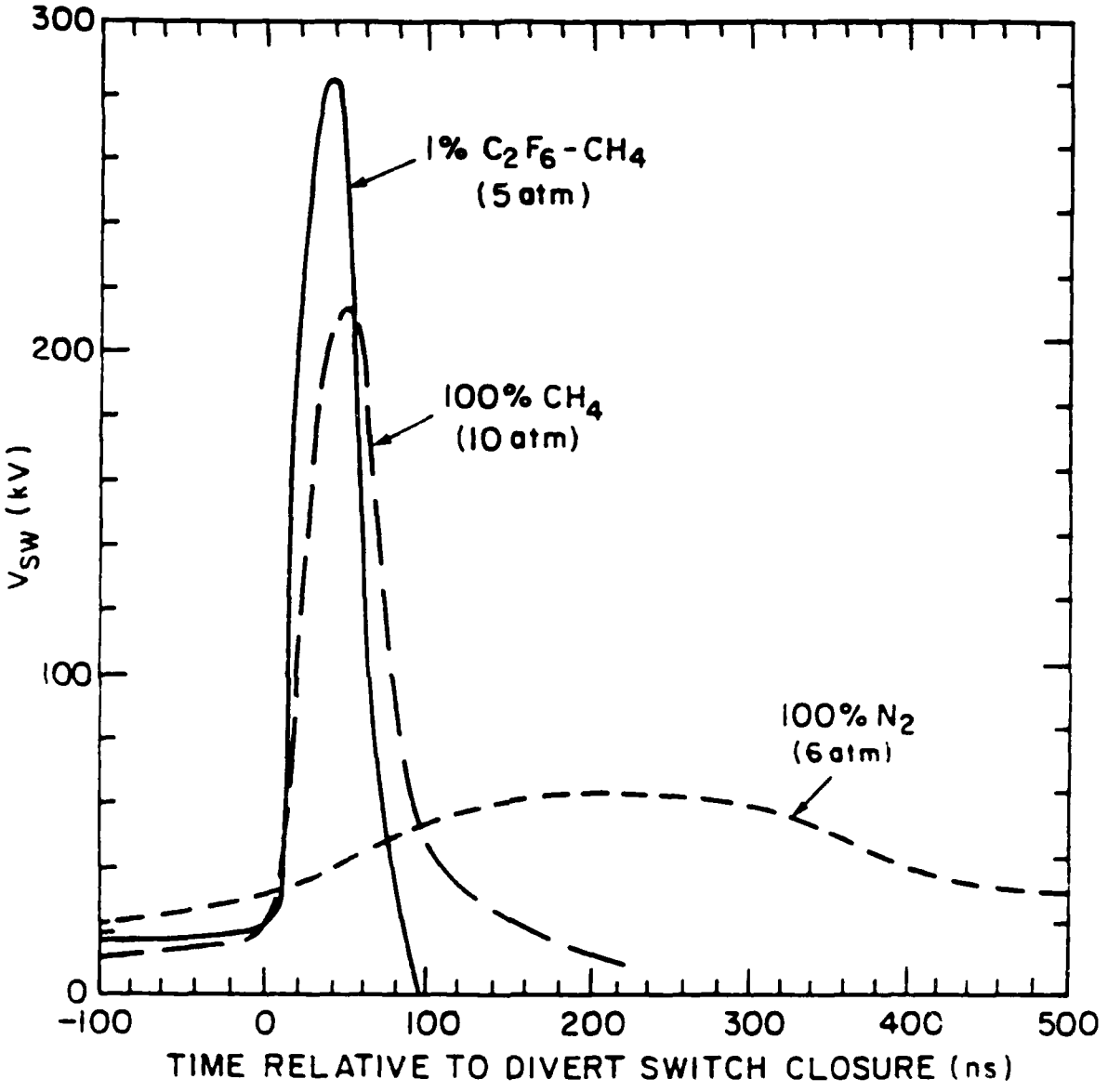


Fig. 53. Comparison of the switch opening times and switch voltage V_{SW} for pure N_2, pure CH_4 and a gas mixture of CH_4 containing 1% of C_2F_6 (Ref. 43).

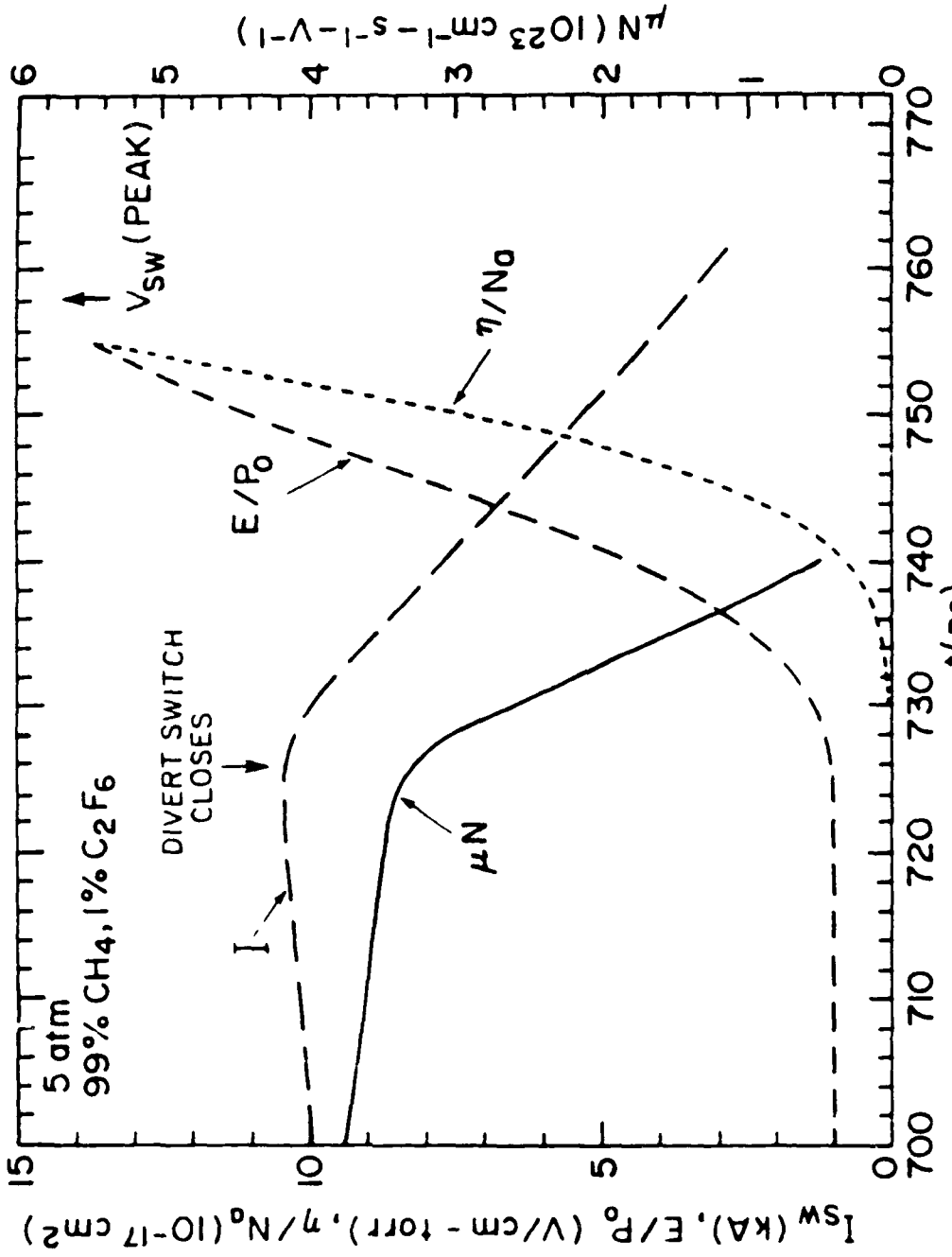


Fig. 54. Plot of the gas discharge parameters (i.e. the density normalized electron mobility μN, electron attachment coefficient η/N_a and E/P) and the switch current I_{SW}, as a function of time at switch opening (Ref. 43).

C_2F_6/CH_4 gas mixture. The calculated discharge parameters (density normalized electron mobility μN, η/N_a and E/P) in the C_2F_6/CH_4 gas mixture are shown in Fig. 54 in comparison with the discharge current I_{SW}. These calculations show that the rapid decrease in the discharge current (i.e. rapid increase in the discharge resistivity) in this mixture is due initially to the reduction in μN, and at later times, the rapid increase in η/N_a at the higher switch voltages (i.e. high E/P values) causes a further rapid reduction in I_{SW}.

4.3 Enhanced Discharge Current Characteristics

Although the discussion given above has indicated the feasibility of using externally sustained diffuse gas discharges as an opening switch concept, several problems have been identified which may potentially limit the usefulness of these switches. Of primary concern are the energy losses by the e-beam electrons in the switching gas (i.e. reduced current switching efficiency) and the lack of precise timing control of the opening of the switch. Possible gas engineering solutions to these problems are outlined in the following discussion.

The electron source function S in an e-beam sustained diffuse gas discharge is

$$S = \left\langle \frac{d\epsilon}{dx} \right\rangle J_B \, W^{-1} \qquad (25)$$

where $\langle d\epsilon/dx \rangle$ is the average energy deposited in the gas by each primary electron in the e-beam, J_B is the flux of the e-beam, and W is the average energy required to produce an electron-positive ion pair by the high energy electrons in the e-beam. The W value of a gas is usually approximately twice the value of the ionization onset energy, with the remaining electron energy being used in vibrational (for molecular gases) and electronic excitation processes in the gas. The excitation energy is a loss process in the discharge, but a sizeable fraction of the electronic excitation energy can be recovered (i.e., J_{SW} increased) during switch conduction by seeding the gas mixture with a low ionization onset gas additive. If the ionization onset energy is less than the energy of any metastable or resonant electronic states of the predominant gas then extra electrons can be generated in the discharge

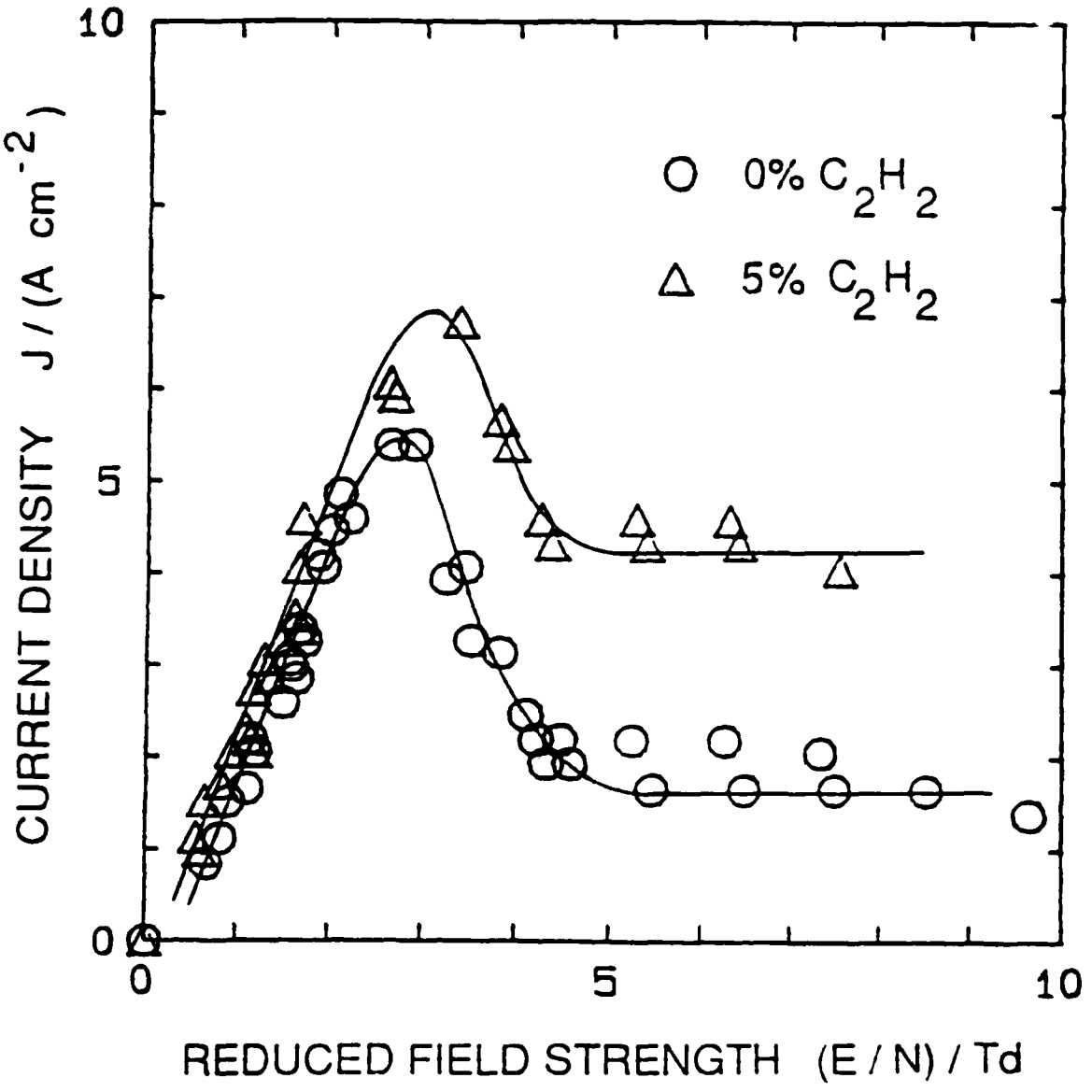


Fig. 55. Current density J vs E/N for an e-beam sustainted discharge in a mixture of 2% C_2F_6 in Ar and a varying admixture of C_2H_2 (Ref. 46).

by Penning ionization processes.[21,22] Measurements of the W value have been performed in several $Ar/C_2F_6/C_2H_2$ and $Ar/C_2F_6/2\text{-}C_4H_8$ ternary gas mixtures by Nakanishi and colleagues[21] and in $Ar/CF_4/C_2H_2$ and $Ar/C_3F_8/C_2H_2$ ternary gas mixtures by Reinking and colleagues[22] in an attempt to optimize the electron production (and hence J_{SW}) in the discharge by the external e-beam. The measurements obtained by Nakanishi and colleagues in the $Ar/C_2F_6/C_2H_2$ gas mixture are given in Fig. 41 and show that there is a significant reduction in W (i.e. increase in the electron production) when small quantities ($\lesssim$ 5%) of C_2H_2 are added to the C_2F_6/Ar binary gas mixtures. Reductions in W up to $\simeq$ 25% were found in the ternary gas mixture composed of 5% C_2H_2 and 2% C_2F_6 in Ar.[21] This gas mixture has recently been studied in e-beam switching experiments by Schaefer and colleagues.[45,46] The switch current density obtained in these experiments using a 2% C_2F_6 in Ar gas mixture with and without the addition of 5% C_2H_2 to the gas mixture is given in Fig. 55. These measurements indicate that there is a considerable enhancement of the electron current density (by $\approx$ 25% at the maximum in J_{SW}) when the C_2H_2 is added to the gas mixture, thereby improving the efficiency of the switch.

4.4 Operation at Elevated Gas Temperatures

A considerable effort was expended during the course of this project in obtaining electron transport and high voltage breakdown mesurements as a function of gas temperature in an attempt to understand the influence of elevated gas temperatures on the operation of both diffuse discharge opening and closing switches. The changes in the electron drift velocity and low field electron mobilities shown in Figs. 31 to 34, and the increase in the rate of electron attachment that we have observed in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures (Figs. 36 and 37, respectively) with increasing gas temperature are not expected to seriously alter the switching characteristics of the diffuse discharge and may in fact be beneficial to the operation of the switch at these temperatures. On the other hand, the change in the rate of electron attachment and the type of electron attachment processes (i.e. either parent anion formation or dissociative attachment) are significantly affected by the gas temperature in C_3F_8 and $n\text{-}C_4F_{10}$ (Fig. 56) and may significantly modify the response characteristics of a repetitively operated diffuse discharge switch at elevated gas temperatures. In contrast, this large decrease in the rate of electron attachment (and hence in the operating electric field strength) in

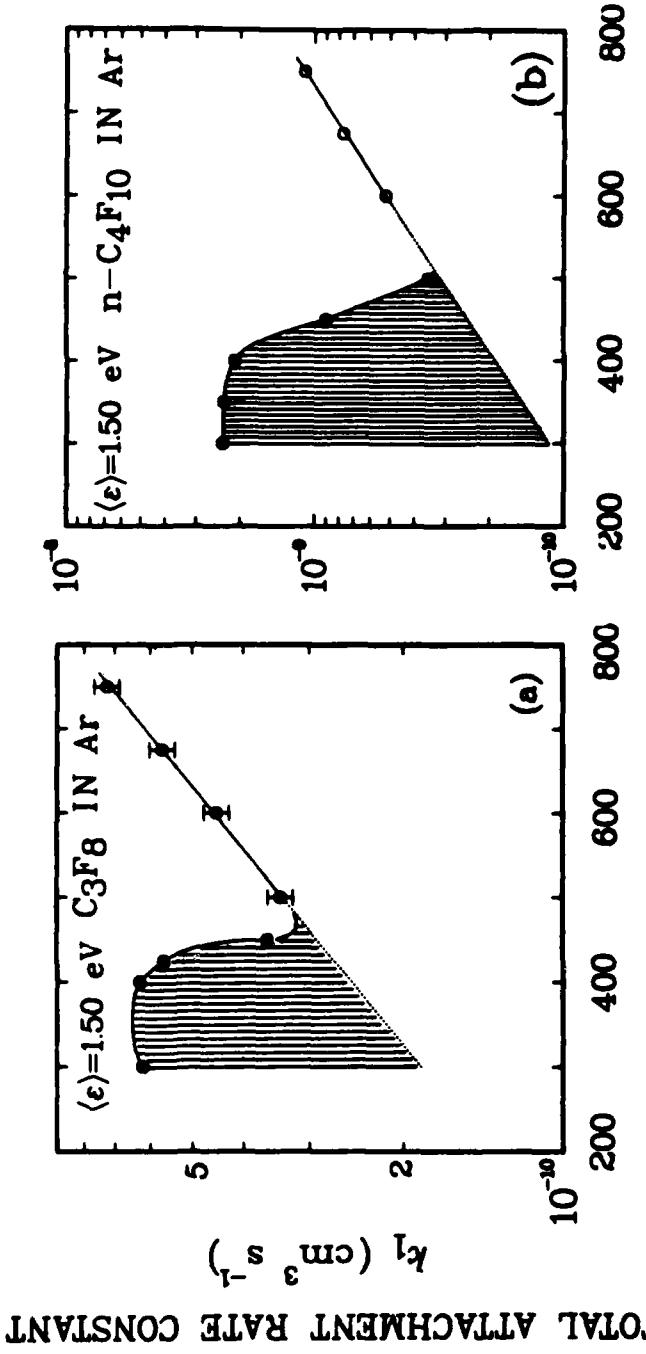


Fig. 56. Electron attachment rate constant k_a for (a) C_3F_8 and (b) n-C_4F_{10} versus gas temperature T at a mean electron energy (ϵ) = 1.50 eV. The shaded area under each curve indicates the contribution of parent anion formation to the total rate of electron attachment.

these molecules [along with $1\text{-}C_3F_6$, $c\text{-}C_4F_8$ and $c\text{-}C_4F_6$] may be useful in improving the current switching efficiency of diffuse discharge closing switches, while maintaining the high withstand voltage when the switch is open.

Our studies of the effect of gas temperature on the withstand voltage of repetitively operated diffuse discharge switches have shown that increases in the gas temperature lead to small increases in $(E/N)_{\ell im}$ for C_2F_6 (due primarily to the increase in η/N with T in C_2F_6), and to a sizeable decrease in $(E/N)_{\ell im}$ for C_3F_8 and $n\text{-}C_4F_{10}$ (due to the decrease in η/N with T in these two gases). These findings also support the conclusion that the C_2F_6 mixtures discussed above may be used in repetitively operated switches with little likelihood of degraded performance from temperature modified electron transport and rate coefficients. Further work is required to determine the long term stability of these gas mixtures under repetitive discharge operation. Further improvements in switch performance can be expected from continuing studies of the basic electron-molecule interaction processes which occur in these discharges.

4.5 Diffuse Discharge Closing Switch Experiments

The main problems to be addressed in diffuse discharge closing switch studies before these switches find widespread acceptance are as follows.

A. Discharge Stability

A self-sustained glow discharge is inherently unstable and short lived (<100 ns). The diffuse discharge quickly becomes constricted and a hot, low impedance arc discharge is observed. This situation must be avoided since repetitive operation of the switch is degraded considerably under arc discharge conditions. Arc formation is believed to be due to small perturbations in the electric field within the discharge between the switch electrodes. The stability of the discharge may be enhanced by tailoring the electron attachment (η/N) and ionization (α/N) coefficients of the gas mixtu e in such a way that the rate of change in the electron production and loss is minimal during small perturbations of the applied electric field beyond the glow discharge operating voltage level V_S.

B. Discharge Impedance

The impedance of self-sustained diffuse discharges is necessarily high (i.e. the current switching efficiency is low) as the voltage fall across the

switch gap necessarily approaches the static breakdown voltage (i.e. the $(E/N)_{\ell im}$) of the gas. Gases and gas mixtures which possess low $(E/N)_{\ell im}$ values and $\bar{\alpha}/N$ which vary slowly with E/N near $(E/N)_{\ell im}$ consequently lead to lower voltage operation (higher efficiency) with increased discharge stability. These characteristics can be achieved by choosing electronegative gases which only attach electrons at energies well above thermal and adding a rare gas buffer gas to these electronegative gases to reduce the $(E/N)_{\ell im}$ of the mixture. Such gas mixtures have been discussed in Section III.

C. Gas Recovery

The gas recovery after a diffuse discharge with a high current density is crucially important in switching applications. This is especially important in that spark gaps (which are presently the major types of switches used in these applications) perform exceptionally well in terms of impedance and energy transfer but have considerable shortcomings in the recovery phase (switch repetition rates < 10 kHz). Gas mixtures which contain a strongly electronegative gas additive are attractive in this regard as free electrons remaining in the gas after the cessation of the discharge are quickly converted to negative ions and will not subsequently ionize the gas (causing gas breakdown) when the high voltage is reapplied across the discharge gap in the switch.

These topics have been discussed in detail in the work reported by colleagues at GTE Laboratories in Waltham, Massachusetts.[47-50] This group has utilized our measurements in several of the gas mixtures discussed in the report to explore these problems using highly overvolted self-sustained diffuse discharge switches. The switching current waveform of a self-sustained discharge obtained in their studies, using pure C_3F_8 as the gaseous medium and an external UV light source to initiate the discharge is given in Fig. 57.[48] These mesurements show that it is possible to initiate the discharge very rapidly ($\lesssim$ 5 ns) and produce a diffuse discharge with a comparatively long discharge maintenance time ($\approx$ 60 ns) at high discharge currents (~ 200 A). These results are obtained in electronegative gases with the desirable α/N and η/N characteristics outlined in Section III.

At longer times (T > 80 ns), the discharge does become constricted and a high current spark discharge results which has inherently poor discharge

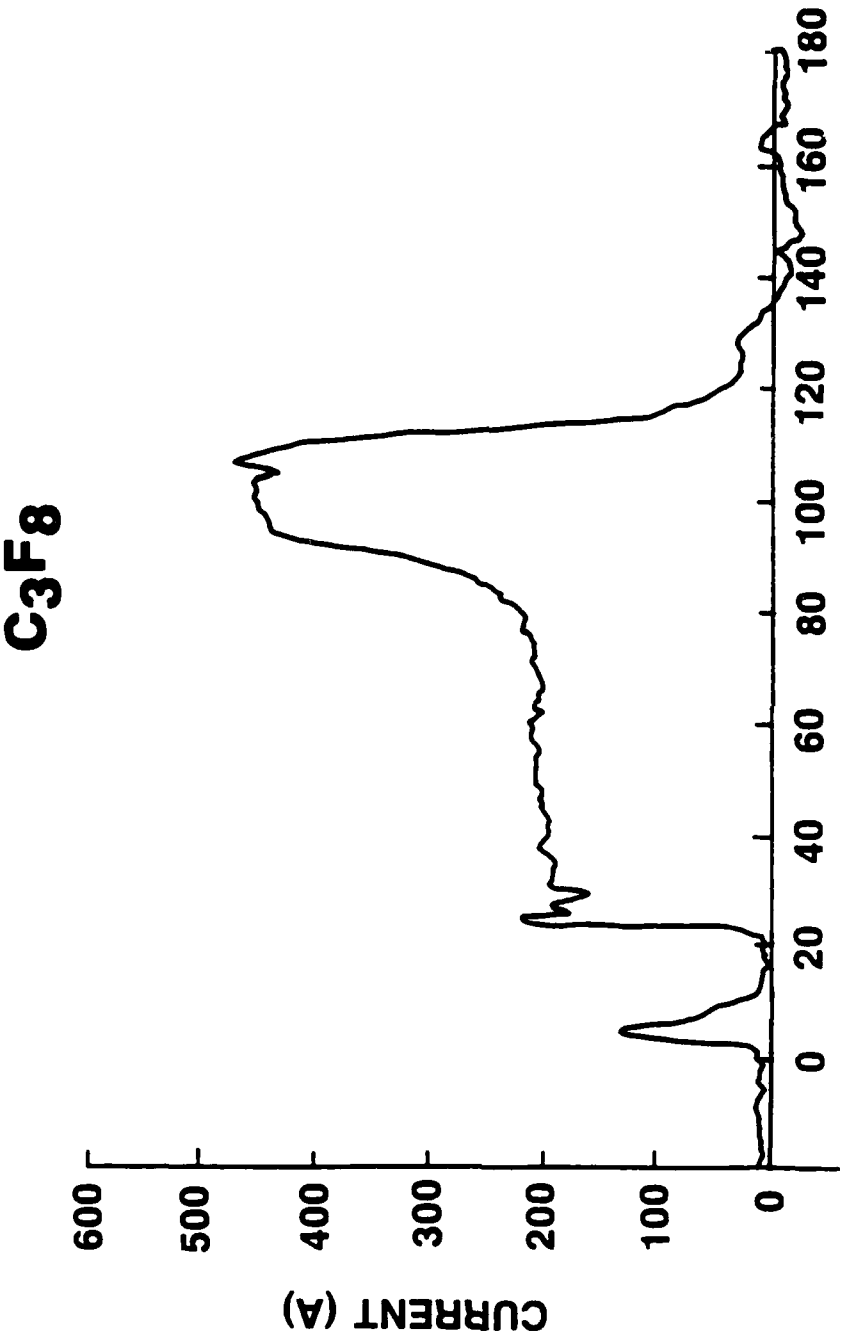


Fig. 57. Current switching waveform in C_3F_8 obtained using an external UV flashlamp triggered at T = 0, with an applied voltage V = 50 V, gap separation d = 1 cm and gas pressure P = 300 Torr. The discharge becomes constricted at T = 90 ns (Ref. 48).

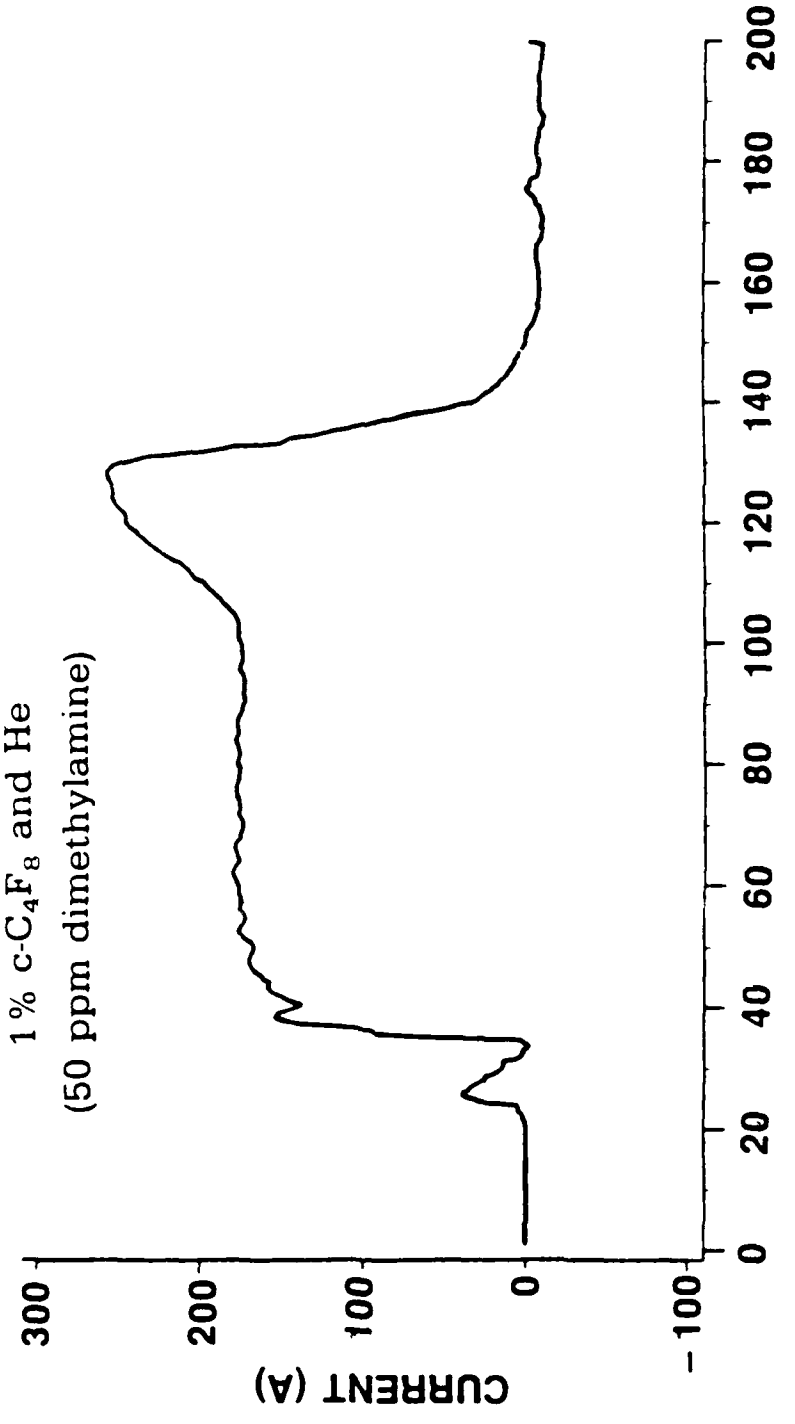


Fig. 58. Current switching waveform in a mixture of 1% c-C_4F_8 in He with 50 ppm of dimethylamine as the photoionization gas additive. The applied voltage V = 30 kV, d = 1.5 cm and the gas pressure P = 600 Torr (Ref. 49).

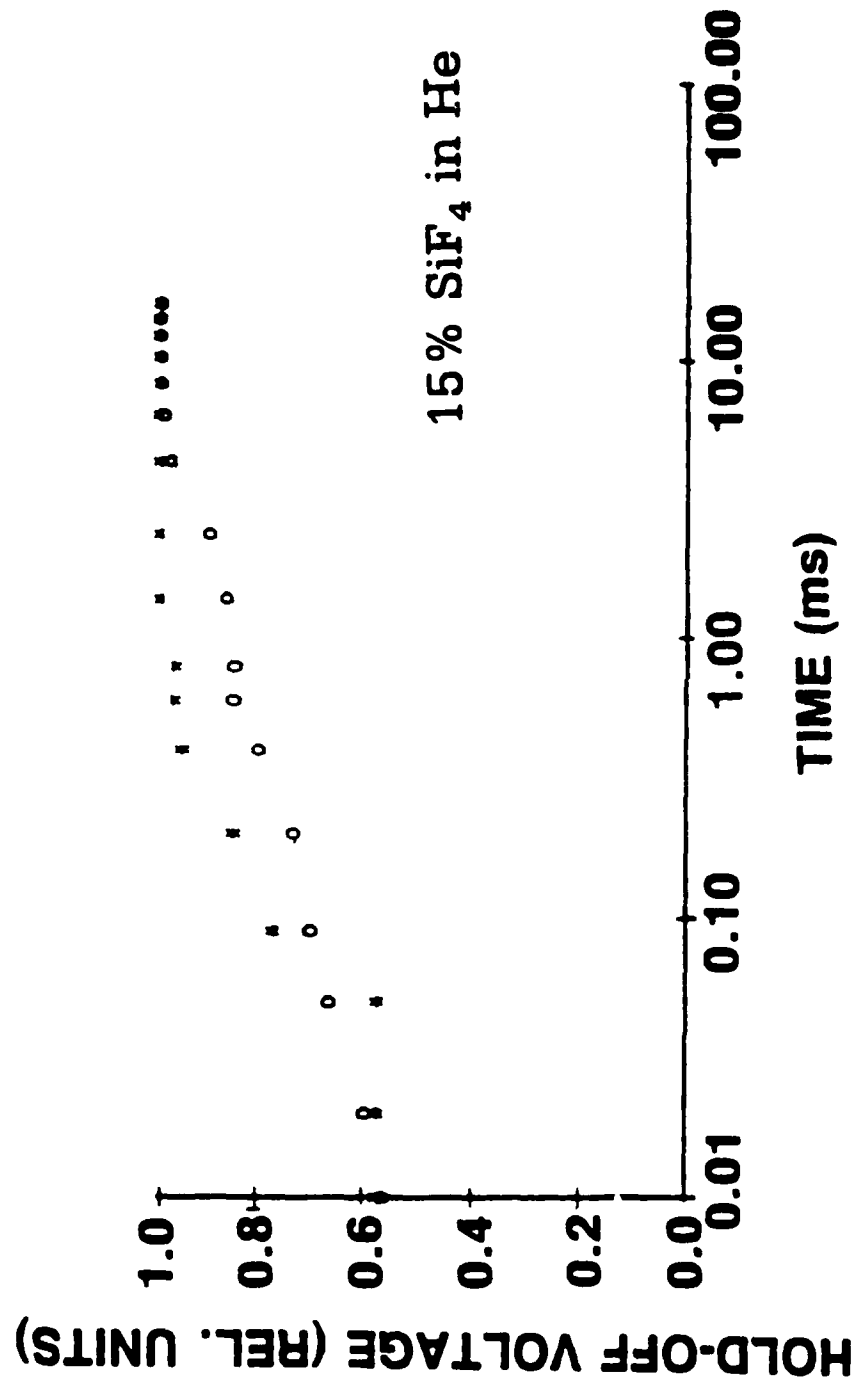


Fig. 59. The hold-off voltage recovery vs. the time after the cessation of the current switching pulse in a gas mixture of 15% SiF_4 in He. The total gas pressure P = 50 Torr (Ref. 50).

recovery characteristics. The current switching efficiency of the discharge may be improved, as shown in Fig. 58, by using a rare gas buffer gas to reduce the operating voltage (and hence $(E/N)_{\ell im}$) of the discharge. Figure 58 shows the resultant current switching waveform in a 1% mixture of $c\text{-}C_4F_8$ in He using 50 ppm of dimethylamine as a photoionization source. The switch discharge voltage is considerably lower (i.e. switch efficiency higher) than in Fig. 57, while good discharge stability is maintained ($T \gtrsim 70$ ns).

The switch recovery characteristics are shown in Fig. 59 for a gas mixture composed of 15% SiF_4 in He using tripropylamine as a photoionization source. This figure indicates the time required for the discharge to recover to a given fraction of the initial applied voltage after the cessation of the diffuse discharge switching pulse. These results show that for this gas mixture (i.e. 15% SiF_4 in He), full gas recovery did not occur until after $\approx$ 10 ms. On the other hand, partial gas recovery to >50% of the initial applied voltage occurs very rapidly in <10 μs, due to the fast removal of the free electrons in the gas by electron attachment. Long term recovery was limited by collisional detachment and diffusion processes. These measurements indicate that it should be possible to optimize the gas mixture constituents and composition such that efficient, stable and high repetition rate current switching is achievable using self-sustained diffuse discharge closing switches.

V. Conclusions

Several of the gas mixtures discussed in this report are considered to be good candidates for e-beam sustained diffuse discharge closing switch applications. These gas mixtures possess the desirable electron attachment and drift velocity characteristics displayed in Fig. 2 which are required to enhance the electron conduction when the switch is closed and then reduce the electron conduction as rapidly as possible when the switch is opened. The present studies indicate that several of these gas mixtures have the further desirable characteristics of possessing relatively high breakdown field strengths ($E/N > 10^{-15}$ V cm^2) and have stable electron attachment and low impurity product formation characteristics at high gas temperatures which are desirable for repetitive discharge operation. These conclusions are supported by the recent e-beam switching studies discussed in Section IV where considerable improvements in switch opening time and current switching efficiency were reported.[43-46]

The analyses and results discussed in this report have also shown that there are several mechanisms by which the efficiency and stability of high current self-sustained diffuse discharge closing switches can be improved. Firstly, the use of electronegative gases in which the variation in $\bar{\alpha}/N$ near the $(E/N)_{\ell im}$ of the gas is minimal will lead to an enhancement in the stability of the discharge while the addition of a rare gas buffer gas to the gas mixture will lead to lower $(E/N)_S$ and, therefore, more efficient current switching. Secondly, the energy deposited in the gas of a power loaded discharge can be used to reduce the electron attachment coefficient of specific electronegative gases, such that the $(E/N)_{\ell im}$ of the gas mixture decreases with increasing gas temperature, and again increasing the discharge efficiency. Thirdly, it may be possible to tailor the electron attachment and ionization processes of a gas mixture, such that electron impact ionization is greater than attachment at low E/N values. In gas mixtures of this type, it may be possible to switch the discharge from a low to a high conductivity state. Further work is required on these and other switching schemes to demonstrate their utility.

The studies outlined in this report and our continuing investigations will allow accurate modeling of the often complex and interrelated phenomena that occur within diffuse gas discharges. This, in turn, will allow the overall performance of these switching devices to be predicted accurately, and as a consequence, the tailoring of the gaseous constituents and operating parameters of the discharge to achieve optimum performance.

REFERENCES

1. M. F. Rose and A. K. Hyder, Jr., *Final Report on Workshop on Diffuse Discharge Opening Switches* (Texas Tech University, Lubbock, 1928), pp. 18-42.
2. J. K. Burton, D. Conte, R. D. Ford, W. H. Lupton, V. E. Scherrer, and I. M. Vitkovitsky, *Proc. 2nd IEEE Int. Pulsed Power Conf.*, June 12-14, 1979, Lubbock, Texas, p. 284.
3. M. Kristiansen and K. H. Schoenbach, *Final Report on Workshop on Repetitive Opening Switches* (Department of Electrical Engineering, Texas Tech University, Lubbock, 1981).
4. M. Kristiansen and K. H. Schoenbach (Eds.), *Final Report on Workshop on Diffuse Discharge Opening Switches* (Texas Tech University, Lubbock, 1982).
5. R. O. Hunter, *Proc. IEEE Int. Pulsed Power Conf.*, November 9-11, 1976, Lubbock, Texas, p. IC8-1.
6. R. F. Fernsler, D. Conte, and I. M. Vitkovitsky, *IEEE Trans. Plasma Sci.* PS-8, 176 (1980); R. J. Commisso, R. F. Fernsler, V. E. Scherrer, and I. M. Vitkovitsky, *Rev. Sci. Instrum.* 55, 1834 (1984).
7. K. H. Schoenbach, G. Schaefer, M. Kristiansen, L. L. Hatfield, and A. H. Guenther, *IEEE Trans. Plasma Sci.* PS-10, 246 (1982).
8. G. Schaefer, K. H. Schoenbach, A. H. Guenther, and W. K. Pendleton, *Proc. 4th IEEE Pulsed Power Conf.*, June 6-8, 1983, Albuquerque, New Mexico, p. 602.
9. A. J. DeMaria, in *Principles of Laser Plasmas* (G. Bekefi, Ed.) (Wiley, New York, 1974), Chapt. 8, p. 315.
10. D. H. Douglas-Hamilton and Sira A. Mani, *Appl. Phys. Lett.* 23, 508 (1973); D. H. Douglas-Hamilton and Sira A. Mani, *J. Appl. Phys.* 45, 4406 (1974).
11. J. D. Daugherty, in *Principles of Laser Plasmas* (G. Bekefi, Ed.) (Wiley, New York, 1974), Chapt. 9, p. 369.
12. E.g., B. M. Koval'chuk, V. V. Kremnev, and G. A. Mesyats, *Sov. Phys.-Doklady* 15, 267 (1970); N. G. Basov, E. M. Belenov, V. A. Danilychev, O. M. Kerimov, I. B. Kovsh, and A. F. Suchkov, *Sov. Phys. - Tech. Phys.* 17, 1976 (1973); A. S. El'chaninov, V. G. Emel'yanov, B. M. Koval'chuk, G. A. Mesyats, and Yu. F. Potalitsyn, *Sov. Phys. - Tech. Phys.* 20, 51 (1975).

13. B. M. Koval'chuk and G. A. Mesyats, *Sov. Phys. - Tech. Phys.* 2, 252 (1976).

14. L. G. Christophorou, S. R. Hunter, J. G. Carter, and R. A. Mathis, *Appl. Phys. Lett.* 41, 147 (1982).

15. L. G. Christophorou, S. R. Hunter, J. G. Carter, and V. K. Lakdawala, *Proc. 4th IEEE Pulsed Power Conf.*, June 6-8, 1983, Albuquerque, New Mexico, p. 702.

16. T. E. Bortner and G. S. Hurst, *Health Phys.* 1, 39 (1958).

17. L. G. Christophorou, *Atomic and Molecular Radiation Physics* (Wiley-Interscience, New York, 1971), Chapt. 4.

18. S. R. Hunter and L. G. Christophorou, *J. Chem. Phys.* 80, 6150 (1984).

19. S. M. Spyrou and L. G. Christophorou, *J. Chem. Phys.* 82, 2620 (1985); S. M. Spyrou and L. G. Christophorou, *J. Chem. Phys.* 83, 2829 (1985).

20. S. R. Hunter, J. G. Carter, and L. G. Christophorou, *J. Appl. Phys.* 60, 24 (1986).

21. T. E. Bortner, G. S. Hurst, M. Edmundson, and J. E. Parks, Oak Ridge National Laboratory Report ORNL TM-3422 (1955).

22. K. Nakanishi, L. G. Christophorou, J. G. Carter, and S. R. Hunter, *J. Appl. Phys.* 58, 633 (1985).

23. G. F. Reinking, L. G. Christophorou, and S. R. Hunter, *J. Appl. Phys.* 60, 499 (1986).

24. L. G. Christophorou, D. R. James, R. Y. Pai, R. A. Mathis, M. O. Pace, D. W. Bouldin, A. A. Christodoulides, and C. C. Chan, Oak Ridge National Laboratory Report ORNL/TM-6113, 1977.

25. L. G. Christophorou, D. R. James, and R. A. Mathis, *J. Phys. D* 14, 675 (1981).

26. S. M. Spyrou, S. R. Hunter, and L. G. Christophorou, *J. Chem. Phys.* 81, 4481 (1984).

27. L. G. Christophorou, *Atomic and Molecular Radiation Physics* (Wiley-Interscience, New York, 1971).

28. P. J. Chantry, Westinghouse Technical Report 78-926 ATACH-R1 (1978).

29. V. K. Lakdawala and J. L. Moruzzi, *J. Phys. D* 13, 377-385 (1982).

30. L. G. Christophorou, D. L. McCorkle, and V. E. Anderson, *J. Phys. B* 4, 1163 (1971).

31. P. W. Harland and J. L. Franklin, *J. Chem. Phys.* 61, 918 (1974).

32. L. G. Christophorou, J. G. Carter, and D. V. Maxey, *J. Chem. Phys.* 76, 2653 (1982).

33. R. Grünberg, *Z. Naturforsch.* 24a, 1039 (1969).

34. L. M. Chanin, A. V. Phelps, and M. A. Biondi, *Phys. Rev.* 128, 219 (1962).

35. C. S. Lakshminarasimha, J. Lucas, and D. A. Price, *Proc. IEE* 120, 1044 (1973).

36. C. S. Lakshminarasimha, J. Lucas, and R. A. Snelson, *Proc. IEE* 122, 1162 (1975).

37. M. Shimozuma, H. Tagashira, and H. Hasegawa, *J. Phys. D* 16, 971 (1983).

38. I. M. Bortnik and A. A. Panov, *Sov. Phys. - Tech. Phys.* 16, 571 (1971).

39. M. S. Naidu and A. N. Prasad, *J. Phys. D* 5, 983 (1972).

40. S. E. Bozin and C. C. Goodyear, *J. Phys. D* 1, 327 (1968).

41. S.A.A. Razzak and C. C. Goodyear, *J. Phys. D* 1, 1215 (1968).

42. S. R. Hunter, L. G. Christophorou, J. G. Carter, and P. G. Datskos, in *Proc. 6th IEEE Pulsed Power Conf.*, Arlington, Virginia, June 29-July 1, 1987, pp. 1-8.

43. R. J. Commisso, R. F. Fernsler, V. E. Scherrer, and I. M. Vitkovitsky, *Appl. Phys. Lett.* 47, 1056 (1985).

44. G. Schaefer, K. H. Schoenbach, M. Kristiansen, B. Strickland, R. A. Korzekwa, and G. Z. Hutcheson, *Appl. Phys. Lett.* 48, 1776 (1986a).

45. G. Schaefer, K. H. Schoenbach, M. Kristiansen, R. A. Korzekwa, and G. Z. Hutcheson, *Proc. XVII Power Modulator Symposium*, Seattle, Washington, p. 1 (1986b).

46. G. Schaefer, K. H. Schoenbach, R. A. Korzekwa, and M. Kristiansen, in *Gaseous Dielectrics V*, L. G. Christophorou and D. W. Bouldin (Eds.), Pergamon Press, New York, p. 374 (1987).

47. W. W. Byszewski, M. J. Enright, and J. M. Proud, *Proc. 4th IEEE Pulsed Power Conf.*, Albuquerque, New Mexico, June 6-8, 1983, p. 718.

48. W. W. Byszewski, R. B. Piejak, L. C. Pitchford, and J. M. Proud, *Investigation of Diffuse Discharges for Fast Recovery Gas Discharge Switching*, GTE Contract Report No. N60921-83-C-(F) (1985).

49. W. W. Byszewski and J. R. Veale, in *Gaseous Dielectrics V*, L. G. Christophorou and D. W. Bouldin (Eds.), Pergamon Press, New York, p. 412 (1987).

50. R. B. Piejak, W. W. Byszewski, J. R. Veale, and J. M. Proud, *Experimental and Theoretical Investigations of Diffuse Discharges*, GTE Contract Report No. N60921-86-C-A340-(F) (1987).

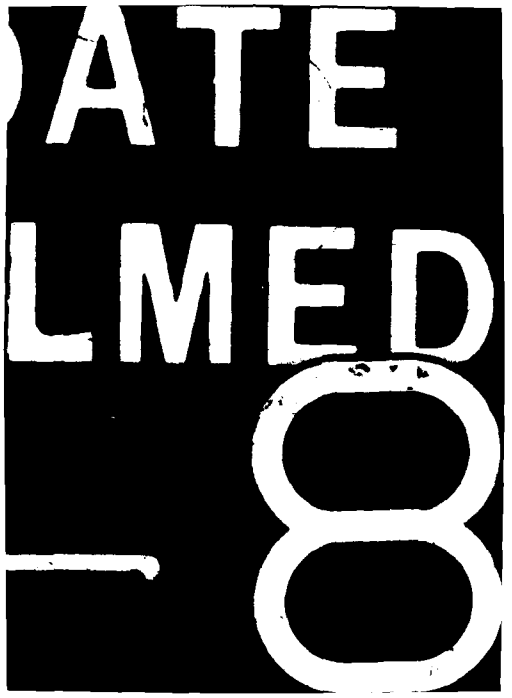
ORNL/TM-10844

INTERNAL DISTRIBUTION

1. J. G. Carter
2- 6. L. G. Christophorou
7. P. G. Datskos
8-10. S. R. Hunter
11. S. V. Kaye
12. L. A. Pinnaduwage
13. Central Research Library
14. Document Reference Section
15-16. Laboratory Records Department
17. Laboratory Records Department-RC
18. ORNL Patent Office

EXTERNAL DISTRIBUTION

19. T. A. Bryant, Office of Naval Research, Resident Representative, Georgia Institute of Technology, 206 O'Keefe Building, Atlanta, Georgia 30332-0490
20. W. M. Bugg, Department of Physics, University of Tennessee, Knoxville, Tennessee 37996
21. B. R. Junker, Director, Physics Division, Office of Naval Research, Department of the Navy, 800 North Quincy, Arlington, Virginia 22217-5000
22. Steve Ramberg, Ocean Engineering Division, Office of Naval Research, 800 North Quincy Avenue, Arlington, Virginia 22217-5000
23. F. D. Shultz, Controller's Office, 201 Andy Holt Tower, University of Tennessee, Knoxville, Tennessee 37996-0100
24-29. Director, Naval Research Laboratory, ATTN: Code 2627, Washington, DC 20375
30-41. Defense Technical Information Center, Building 5, Cameron Station, Alexandria, Virginia 22314
42-51. Technical Information Center, Oak Ridge, Tennessee 37831
52. Assistant Manager, Energy Research and Development
DOE/ORO, P.O. Box 2001, Oak Ridge, TN. 37831


ATE
LMED
8