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TEMPERATURE DEPENDENT ELECTRON TRANSPORT AND RATE COEFFICIENT STUDIES FOR e-BEAM-SUSTAINED DIFFUSE GAS DISCHARGE SWITCHING*

J. G. Carter, S. R. Hunter, and L. G. Christophorou†

Atomic, Molecular, and High Voltage Physics Group
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6123

ABSTRACT

Measurements of the electron drift velocity, w, attachment coefficient, η/N_a, and ionization coefficient, α/N, have been made in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures at gas temperatures, T, of 300 and 500 K over the concentration range of 0.1 to 100% of the C_2F_6. These measurements are useful for modeling the expected behavior of repetitively operated electron-beam sustained diffuse gas discharge opening switches where gas temperatures within the switch are anticipated to rise several hundred degrees during switch operation.

KEYWORDS

Electron drift velocity, attachment coefficients, ionization coefficients, diffuse gas discharge, pulsed power, opening switch.

INTRODUCTION

Measurements are reported of the electron drift velocity w, electron attachment coefficient η/N_a and electron ionization coefficient α/N in several C_2F_6/Ar and C_2F_6/CH_4 gas mixtures at 300 and 500 K. The effect of changes in the gas temperature T on the electron attachment rate constant as a function of the mean electron energy $\langle\varepsilon\rangle$, $k_a(\langle\varepsilon\rangle)$ in the perfluoroalkanes C_2F_6, C_3F_8, and n-C_4F_{10} at T up to 750 K are discussed. Gas mixtures composed of C_2F_6 in Ar or CH_4 have

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[†] Also, Department of Physics, The University of Tennessee, Knoxville, Tennessee 37996.

recently been shown by Schaefer and co-workers (1986) and Commisso and co-workers (1985) respectively to possess fast opening characteristics in single shot e-beam sustained discharge switch studies. Measurement of the electron transport and rate coefficients in these mixtures as a function of T may be used to predict the influence of elevated gas temperatures on the performance of repetitively operated switches. The measurements for w, η/N_a and α/N given in the following section indicate that a rise in gas temperature of a few hundred degrees will only have a small influence on the operating parameters of the repetitively operated switch and may in fact be beneficial.

ELEVATED GAS TEMPERATURE MEASUREMENTS

Electron Drift Velocity and Mobility

The influence of changes in gas temperature on w in C_2F_6/Ar and C_2F_6/CH_4 gas mixtures is shown in Figs. 1 and 2 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$1%), w near the peak in the curves in Figs. 1 and 2 is hardly affected by increases in T, but at large C_2F_6 concentrations ($\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. Changes in the electron non-conservation processes when both processes are large have recently been shown to have a significant influence on the measured w in several perfluoroalkane molecules (Blevin and co-workers, 1985; Hunter and co-workers, 1987a).

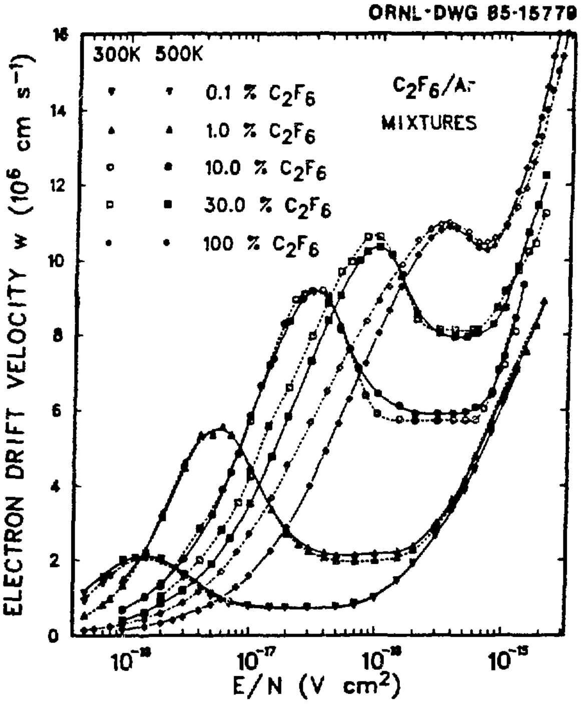

Fig. 1. Electron drift velocities as a function of E/N for several concentrations of C_2F_6 in Ar at gas temperatures of 300 and 500 K.

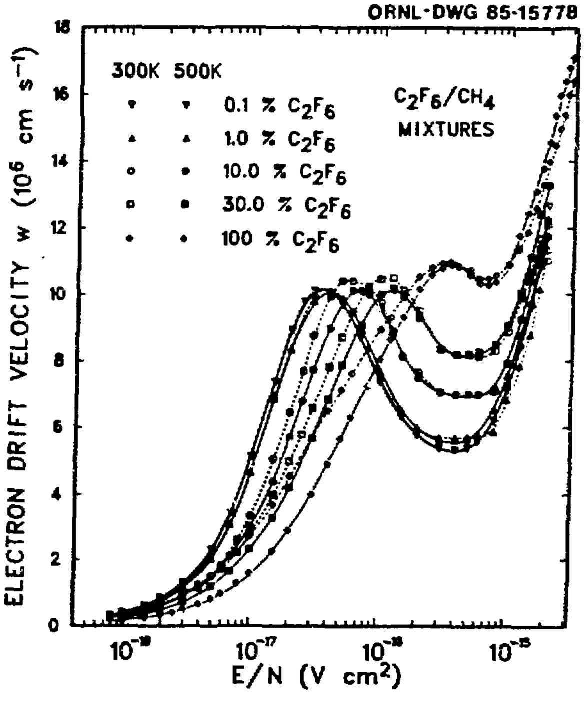

Fig. 2. Electron drift velocities as a function of E/N for several concentrations of C_2F_6 in CH_4 at gas temperatures of 300 and 500 K.

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. There are several ground state vibrational excitation modes with threshold energies $\lesssim$0.1 eV, and the relative populations of these modes are very dependent on the gas temperature (e.g. the ground electronic state ($\nu = 0$) percentage population decreases from ≈40% to ≈25% when the gas temperature T is raised from 300 K to 500 K, while for example the $\nu = 3$ [$h\nu_3 = 0.043$ eV] vibrational level increases from ≈7% to ≈10% over this temperature range).

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. 3 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. 4 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. 4), which are again the result of the increase

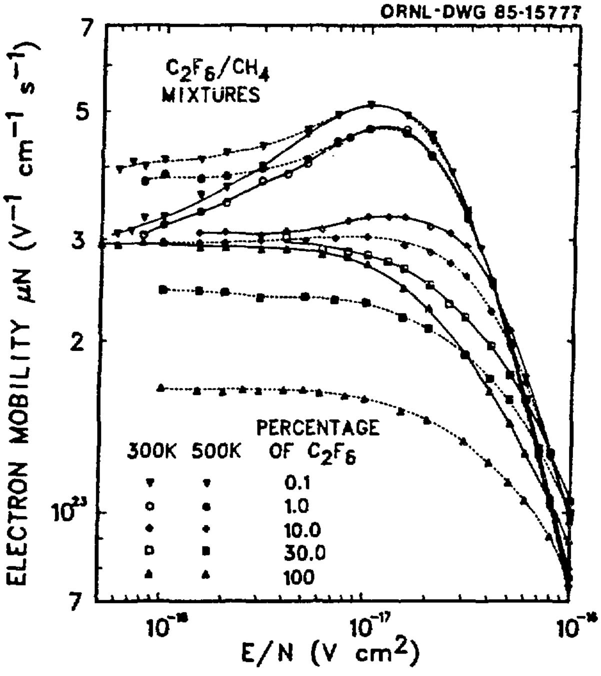

Fig. 3. The density normalized electron mobility μN in C_2F_6/CH_4 gas mixtures for low E/N values at gas temperatures of 300 and 500 K.

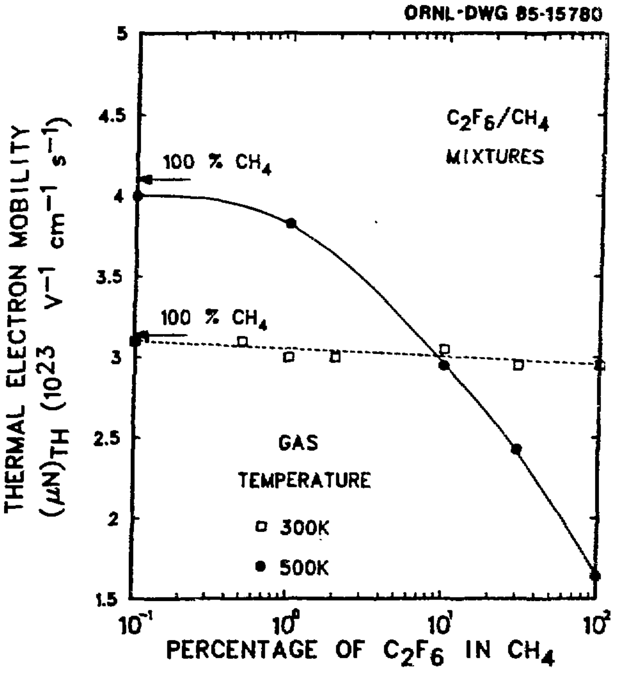

Fig. 4. Thermal electron mobilities in C_2F_6/CH_4 gas mixtures at gas temperatures of 300 and 500 K.

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.

Electron Attachment in C_2F_6 Gas Mixtures

Changes in the gas temperature can have a number of effects upon the rate of electron attachment to a gas molecule, depending on the type of electron attachment process that is involved (e.g. Christophorou and co-workers, 1986). Resonance electron attachment to a molecule is generally regarded as a two step process, in which an electron is initially captured by a parent molecule to form a transient anion. For dissociative electron attachment, the anion either autoionizes with, in general, a very short lifetime ($T < 10^{-12}$ s) or fragments to form neutral and negative ion radicals. Alternatively, in non-dissociative electron attachment, the transient parent anion may either autoionize with much longer lifetimes (typically $10^{-12} < T \lesssim 10^{-3}$ s) or form a stable parent anion usually by losing excess internal energy in a collision with a third body.

In general, increasing the gas temperature increases the rate of electron attachment in dissociative electron attachment processes due to increased attachment from the higher vibrational levels of the ground electronic state of the parent molecule. Examples of this behavior are shown in Figs. 5 and 6 for C_2F_6. The rate of electron attachment for non-dissociative processes decreases with increasing T due primarily to a decrease in the lifetime of the transient parent anion. When both dissociative and non-dissociative attachment processes are present, then the overall rate of electron attachment can increase or decrease with T depending on the relative magnitude and temperature dependence of these two processes. This phenomenon is discussed later in this section with regard to electron attachment to C_3F_8 and n-C_4F_{10}.

The electron attachment rate constant $k_a(\langle\epsilon\rangle)$ for C_2F_6 measured in a buffer gas of Ar over the temperature range $300 \lesssim T \lesssim 750$ K is given in Fig. 5 (Spyrou and Christophorou, 1985a). 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 peak in the $k_a(\langle\epsilon\rangle)$ shift to lower energies at higher gas temperatures. The $k_a(\langle\epsilon\rangle)$ increases by ≈30% over this temperature range near the peak at $\langle\epsilon\rangle \approx 3$ eV (Fig. 5).

We have measured the electron attachment coefficient η/N_a and the ionization coefficient α/N in pure C_2F_6 (Fig. 6) and in gas mixtures of C_2F_6 in Ar (Fig. 7) and C_2F_6 in CH_4 (Fig. 8) 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. 6 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 (≈±10%)] by increases in the gas temperature. The electron attachment coefficient in contrast increases considerably (by ≈25%) at higher E/N values with a much smaller increase in η/N_a occurring at E/N values

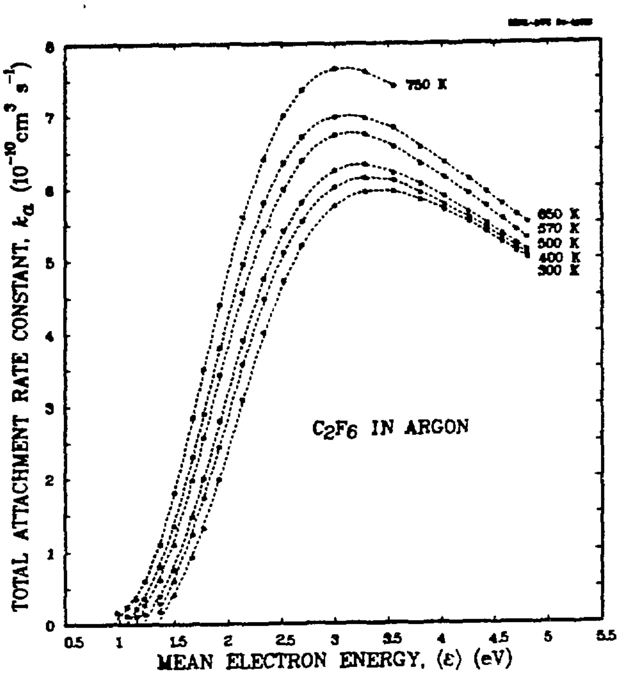

Fig. 5. Total electron attachment rate constant k_a as a function of mean electron energy ⟨ε⟩ for C_2F_6 in an argon buffer gas over a range of gas temperatures.

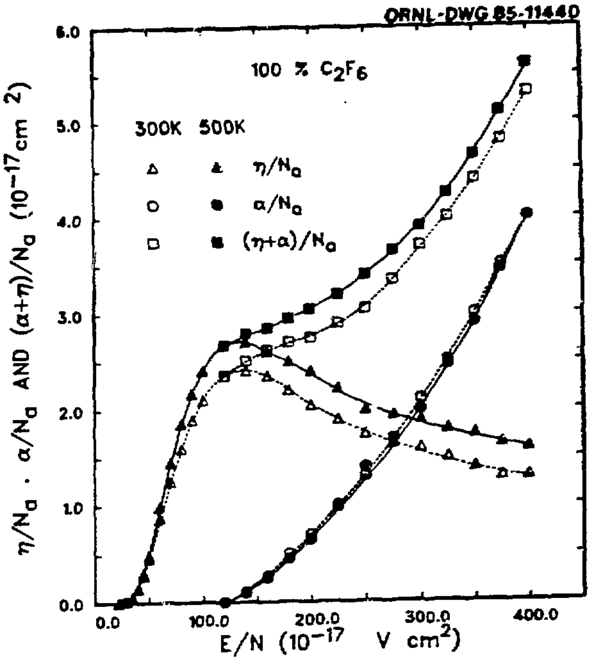

Fig. 6. Electron attachment coefficient η/N_a, electron ionization coefficient α/N_a and total ion production coefficient $(\alpha+\eta)/N_a$ of pure C_2F_6 at 300 and 500 K as a function of E/N.

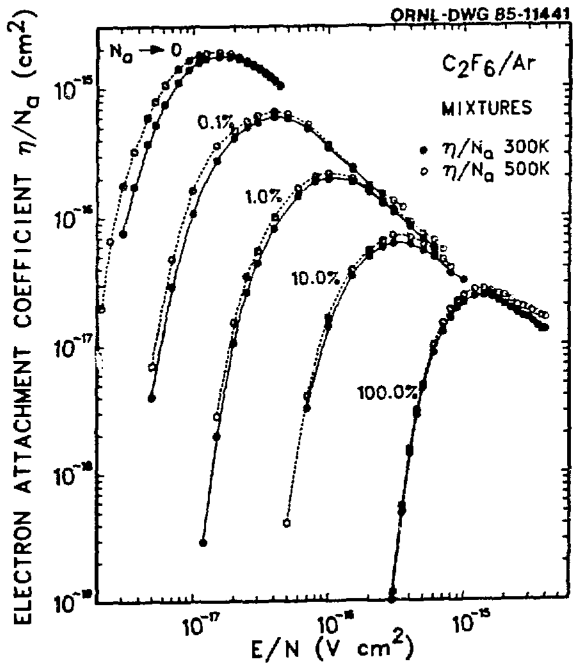

Fig. 7. Electron attachment coefficient η/N_a for several C_2F_6/Ar gas mixtures as a function of E/N at gas temperatures of 300 and 500 K.

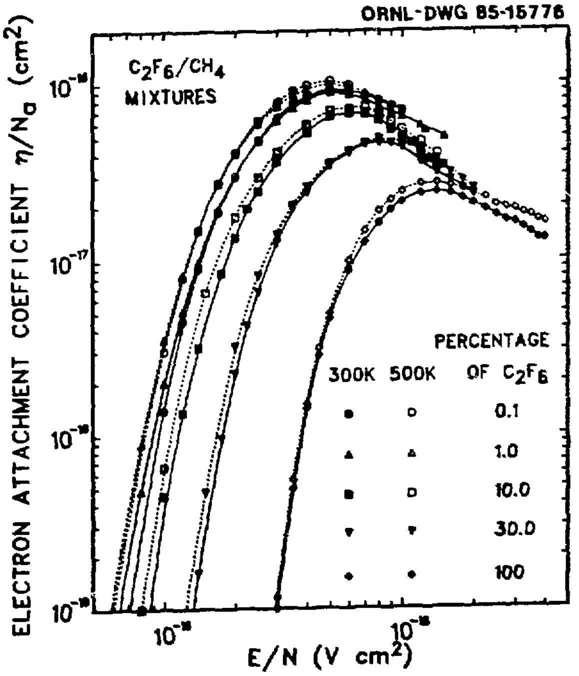

Fig. 8. Electron attachment coefficient η/N_a for several C_2F_6/CH_4 gas mixtures as a function of E/N at gas temperatures of 300 and 500 K.

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. 5 and 6) near the peak in the attachment process are similar (being ≈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. 7 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. 8. 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.

Electron Attachment Rate Constant Measurements in C_3F_8 and n-C_4F_{10}

Measurements of $k_a(\langle\epsilon\rangle)$ have recently 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 $0.76 \lesssim \langle\epsilon\rangle \lesssim 4.8$ eV) (Spyrou and Christophorou, 1985b; Datskos and Christophorou, 1987a). These measurements are plotted as a function of $\langle\epsilon\rangle$ and T in Fig. 5 of the paper by Christophorou and co-workers (1987b) in this proceedings. We show the variation in the total electron attachment rate constant k_a as a function of T at one mean electron energy $\langle\epsilon\rangle = 1.50$ eV, in Figs. 9a and 9b for C_3F_8 and n-C_4F_{10} respectively. These measurements indicate that k_a first decreases with increasing T between 400 and 500 K, and at higher T, k_a increases for both C_3F_8 and n-C_4F_{10}: the variation in k_a with T being more pronounced for n-C_4F_{10} than for C_3F_8. The contribution of non-dissociative parent anion formation to the total electron attachment rate constant is also given in Fig. 9 by the shaded area under each curve, and shows that the competition between dissociative and non-dissociative electron attachment processes is the cause of the overall variation in k_a with T. 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 of repetitively operated switches operating at elevated gas temperatures using C_3F_8 or n-C_4F_{10} as the electron attaching gas additive.

The sensitivity of the overall magnitude in k_a to small changes in gas temperature between T = 400 K and 500 K, especially for n-C_4F_{10} (Fig. 9b) may be useful as a switching mechanism in the operation of self-sustained diffuse discharge closing switches (Hunter and co-workers, 1987b).

CONCLUSION

The C_2F_6/buffer gas (either CH_4 or Ar) mixtures discussed in this paper along with other mixtures mentioned by Christophorou and co-workers (1982) and Hunter and co-workers (1985) are considered to be good candidates for diffuse discharge switching applications. These gas mixtures possess the very desirable electron attachment and drift velocity characteristics which are required to enhance the electron conduction when the switch is closed, and then reduce the electron conduction as quickly as possible when the switch is opened.

The changes in the electron drift velocity and low field electron mobilities shown in Figs. 1 to 4, 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. 7 and 8 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 changes 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-C_4F_{10} (Fig. 9) and may significantly modify the response characteristics of a repetitively operated diffuse discharge switch at elevated gas temperatures.

Other studies (Christophorou and co-workers, 1987a) have shown the influence of gas temperature on the breakdown strength ($[E/N]_{\ell im}$, defined as the E/N value in an electronegative gas at which $\alpha/N = \eta/N$) on these gases. As expected, 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-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.

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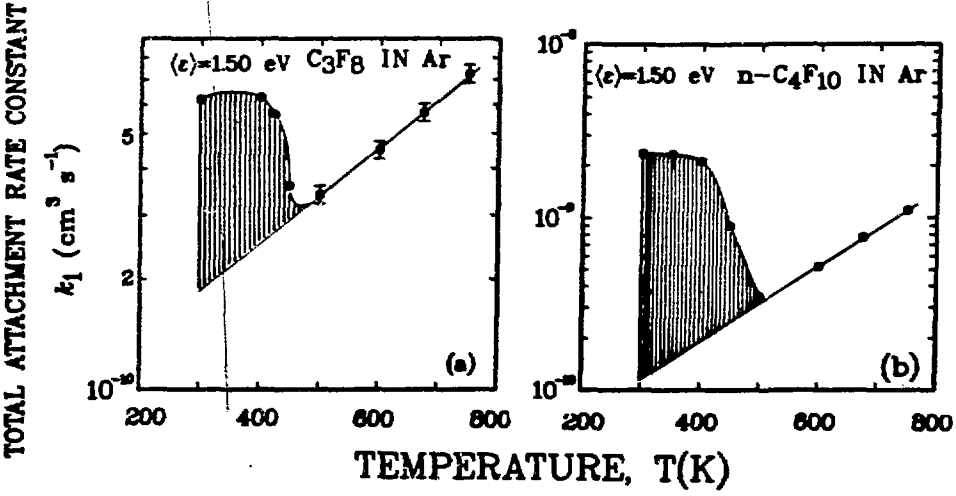

Fig. 9. Electron attachment rate constant k_a for (a) C_3F_8 and (b) n-C_4F_{10} versus gas temperature T at a mean electron energy $\langle\varepsilon\rangle = 1.50$ eV. The shaded area under each curve indicates the contribution of parent anion formation to the total rate of electron attachment (Spyrou and Christophorou, 1985b and Datskos and Christophorou, 1987).

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