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DRIFT AND DIFFUSION OF ELECTRONS IN GASES: A COMPILATION

(WITH AN INTRODUCTION TO THE USE OF COMPUTING PROGRAMS)

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ERRATUM TO CERN 84–08

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Please note that, in Fig. 35, the right-hand vertical scale (σ_T) should be multiplied by 2 (the maximum value will thus read 1000μm).

Also, in the text, the longitudinal and transverse diffusion coefficients are defined as D_L and D_T. However, in Figs. 2, 3, 6, 29, 160, 162, 166, and 173, they have been labelled as D_ℓ (longitudinal) and D_L (lateral, or transverse).

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ABSTRACT

This report is organized in two sections. The first contains an elementary introduction to the theory of electron transport in gases under the action of electric and magnetic fields, and gives indications on the use of two programs to compute drift and diffusion properties of electrons in gas mixtures. The second section contains an extensive collection of experimental and computed data on electron drift velocity and diffusion, as a function of electric field; an index allows one to find the data referring to any given gas mixture.

CONTENTS

1. INTRODUCTION

The knowledge of the drift and diffusion properties of electrons and ions in gases is primordial for the understanding of the operational characteristics of proportional gaseous detectors and for any attempt to improve their performances. A very large amount of data on drift properties of electrons and ions exist in the literature; indeed this has been one of the major research fields in the first half of the century. For a modern review of theories and a collection of data see for example Loeb (1961), Brown (1966), Massey and Burhop (1969), Christophorou (1971), McDaniel and Mason (1973), Huxley and Crompton (1974); a compilation similar in conception to the present one has been edited recently by Fehlmann and Viertel (1983).

In recent years, and for the needs of the research on detectors, drift properties have been studied in a large variety of gas mixtures used for various reasons in proportional counters. The emphasis has been, depending on experimental needs, on finding a gas mixture with low or high drift velocity, small diffusion coefficients, high proportional or semiproportional gains, and so on. The resulting data are scattered in a myriad of articles, conference proceedings, and limited circulation notes, which makes it very difficult for the user to find the gas mixture best suited to his particular needs. The frequent use of gaseous detectors in strong magnetic fields, with the modification of drift properties that results, has complicated the issue even more.

We have tried, in the present report, to collect existing data on drift velocities and diffusion of electrons both for pure gases and for mixtures, indicating the relevant properties and the reasons for preferring a given gas in a given detector in order to facilitate the experimenter's choice. It should be understood, however, that many of the recent, detector-oriented measurements may not reproduce the rigorous experimental conditions of the earlier studies. Although the purity of the component gases is generally not a concern, the construction of most modern gas detectors, dictated by feasibility and economical reasons, is not such as to guarantee the absence of unknown impurities. Even the relative concentration of the various components is sometimes poorly estimated, a fact demonstrated by discrepancies in the results obtained by different experimenters.

2. ELEMENTARY THEORY OF ELECTRON DRIFT AND DIFFUSION

The classical kinetic theory of gases can be used to estimate drift properties of electrons and provides instructive, although very approximate, relationships. In the absence of external forces, electrons in a gas at temperature T move around with a Maxwellian energy distribution with a most probable value kT (0.04 eV at room temperature). Under the action of an electric field E they acquire a net motion in the direction of the field with drift velocity w:

$$w = \frac{eE}{m}\left\langle\frac{\ell}{v}\right\rangle = \frac{eE}{m}\tau , \qquad (1)$$

where v and ℓ are, respectively, the velocity and the mean free path of the electron, and τ the average collision time. Since the mean free path ℓ is inversely proportional to the gas pressure P, and the electron energy (and therefore v) is a function of the reduced field E/P, the drift velocity is also a function of E/P as is apparent from expression (1).

The diffusion along any given direction x is described by a Gaussian distribution with a standard deviation:

$$\sigma_x = \sqrt{\frac{2Dx}{w}} , \qquad (2)$$

where D is a field-dependent diffusion coefficient.

In the ideal case, where electrons do not modify their energy at increasing values of E, the mean collision time τ is constant, the drift velocity increases linearly with the field, and the following relationship holds:

$$eE\frac{D}{w} = kT . \qquad (3)$$

By substitution in Eq. (2) one gets, in this case,

$$\sigma_x = \sqrt{\frac{2kTx}{eE}} , \qquad (4)$$

an expression often referred to as the thermal limit to electron diffusion.

Because of the very different behaviour of the molecular cross-section at increasing electron energies, in some gases the average energy remains thermal up to rather large fields, as for example in carbon dioxide (said to be a 'cool' gas); in argon, on the other hand, even at small values of E (a few V/cm·atm), the electron energy is considerably increased. As a consequence, drift velocity and diffusion properties can be very different in various gases at given values of field and pressure, and the addition of even very small quantities of one gas to another can substantially alter the electron drift behaviour; Fig. 32 is an example of such a behaviour.

Early theories of electron transport attempted to describe the process by introducing a phenomenological field-dependent quantity representing the average energy increase, thus rewriting expression (3) as

$$eE\,\frac{D}{w} = \eta kT = \varepsilon_k\ , \tag{5}$$

where ε_k, which denotes characteristic energy, is a gas-dependent function of the reduced field E/P that can be directly measured. The diffusion width can then be written:

$$\sigma_x = \sqrt{\frac{2\varepsilon_k x}{eE}} = \sqrt{\frac{2\varepsilon_k}{eE/P}}\ \sqrt{\frac{x}{P}}\ , \tag{6}$$

where the last expression shows explicitly the inverse square root dependence of σ_x on pressure at a given value of E/P. Notice that it has so far been assumed that the diffusion is uniform in all directions; this is not the case, especially at high fields, so that one has to use two distinct diffusion coefficients D_L and D_T, longitudinal and transverse with respect to the electron drift direction.

This classical approach is, however, rather unsatisfactory when applied to gas mixtures, since it requires the introduction of *ad hoc* phenomenological quantities. Only the advent of a rigorous transport theory, to be sketched in the next section, has allowed the accurate reproduction of the experimental data from the knowlege of the basic electron–molecule cross-sections for the component gases.

The presence of an external magnetic field modifies both the energy distribution (therefore the drift properties) and the average direction of drift of electrons.

Using again the elementary gas kinetic theory, and for the particular case of a magnetic field H perpendicular to E, it can be shown that the electron swarm drifts with velocity w_H along a line forming an angle α_H with the electric field according to the expressions:

$$w_H = \frac{w}{\sqrt{1 + \omega^2\tau_H^2}}\ , \qquad \omega = \frac{eH}{m} \tag{7}$$

and

$$\tan \alpha_H = \omega\tau_H\ , \tag{8}$$

where τ_H is a phenomenological mean collision time, in general a function of both E and H. Since a magnetic field having the direction of E does not affect the average electron's motion (although it does affect the diffusion properties), the general case can be treated by vectorial decomposition.

In the absence of detailed measurements, one can approximate the average collision time τ_H by its value at $H = 0$, as deduced from expression (1) if the drift velocity is known, and obtain not too bad an estimate of magnetic drift velocity and angle from expressions (7) and (8). An example of application is shown in Fig. 120 for a mixture of argon, isobutane, and methylal. The phenomenological E dependence of τ, deduced from a drift velocity measurement (Fig. 120a) has been used to compute w_H and α_H at two values of electric field; the computed value (full curves in Fig. 120b) reproduce rather well the experimental points, at least for moderate fields. Figures 38, 98, and 121 provide the phenomenological dependence of τ for other mixtures.

From the expressions one can also deduce that, in general, given the values of E and H, gases with small drift velocity have smaller variations of w and small deflections; for example, at 1 kV/cm·atm and 5 kG, Becker et al. (1983a) have measured in a CO_2–C_4H_{10} mixture a magnetic deflection of 2.2° (Fig. 203), as compared with the 18° measured for argon–isobutane–methylal (Fig. 119). A decrease of τ at high electric fields (a saturated drift velocity) similarly implies a reduction of magnetic effects.

In the case of parallel electric and magnetic fields it can be shown that the drift velocity remains unchanged and equal to the $H = 0$ value; the transverse diffusion instead can be considerably smaller at large fields, according to the expression:

$$\frac{D_T(H)}{D_T} = \frac{1}{1 + \omega^2\tau_H^2}\ . \tag{9}$$

The reduction is noticeable if $\omega\tau_H > 1$, as is the case, for example, in argon–methane mixtures (owing to the Ramsauer dip in the argon cross-section).

3. THE TRANSPORT THEORY

A rigorous statistical theory, based on the solution of transport and energy conservation equations for free electrons under the influence of external fields, has been developed by Morse, Allis and Lamar (1935), Margenau (1946), Frost and Phelps (1962), and many others. Starting with the knowledge of the appropriate elastic and inelastic cross-sections for the component gases, it allows the accurate computation of the drift properties with excellent agreement with the experimental results. Recently, in the course of development of multiwire gaseous detectors, the transport theory has been reviewed by Palladino and Sadoulet (1974, 1975), Schultz (1976), Schultz and Gresser (1978), Mathieson and El Hakeem (1979), and Ramanatsizehena (1979). These papers contain a modern formulation of the mathematics involved, and specific calculations of drift properties for several gas mixtures, both without and in the presence of strong magnetic fields. Computer programs have been written by the above authors that allow, in principle, the calculation of the drift and diffusion properties in any gas mixture, provided that the pertinent electron cross-sections are tabulated.

The most general of these programs, due to Palladino and Sadoulet, uses a numerical solution of the transport equations and has a wide domain of applicability, up to electron energies reaching inelastic excitation and ionization levels.

A more restrictive program, due to Schultz and Gresser, implements instead an analytical solution of the equations and is therefore more transparent to the user; because, however, of various approximations necessary to obtain the solution, it can only be used for a domain of electron energies well below the electronic excitation levels. As the electron energy distribution is a result of the calculation itself, one has to watch not to exceed the domain of validity of the assumptions. Both programs have recently been revised and commented at CERN by L. Ropelewski, and are available on request from one of the present authors (A. Peisert); gases for which cross-sections are already tabulated are listed in Section 7, and examples of results of the calculation are scattered throughout this work (see, for example, Figs. 16–23, 45, 48, 88, 89, 116, 117, 139–150).

Notice that in the formulation sketched here and implemented in both programs it is implicitly assumed that the space distribution of the drifting electrons is spherically symmetric; a single diffusion coefficient is therefore provided. It has been shown both theoretically and experimentally, however, that in many gases the longitudinal diffusion coefficient D_L (in the direction of the field) can be considerably smaller than the transverse D_T [Parker and Lowke (1969), Lowke and Parker (1969)]. The difference has important implications when computing the limits of the localization accuracy that can be reached in a detector; unfortunately, a theoretical estimate of the effect is mathematically difficult and data are rather scanty for gas mixtures (see, for example, Figs. 18, 30, 73). In all cases the diffusion coefficient D provided by the following theory coincides with the transverse diffusion D_T.

The starting point of the transport theory is to introduce an electron density distribution function in the six-dimensional space of positions and velocities, and to write the appropriate differential relationship describing density and energy conservation. In the stationary case and for the particular case of a magnetic field perpendicular to the electric field, one can reduce the functional dependence to only three variables, the electron energy (or velocity) and the two polar angles θ and ϕ between the instant electron velocity and the electric field. Expanding then in a series of Legendre polynomials and keeping only the first terms the distribution function is written as:

$$F(\varepsilon,\theta,\phi) = F_0(\varepsilon) + \cos\theta\ F_1(\varepsilon) + \sin\theta\ \cos\phi\ F_2(\varepsilon) + \sin\theta\ \sin\phi\ F_3(\varepsilon)\ . \tag{10}$$

Using various constraints, the conservation laws are then reduced to the following system of two differential equations in $F_0(\varepsilon)$ and $F_1(\varepsilon)$:

$$\begin{gathered} \frac{eE}{3}\frac{\partial(vF_1)}{\partial\varepsilon} - \frac{2m}{M}\frac{\partial}{\partial\varepsilon}\left(\frac{evF_0}{\ell_e}\right) - \sum_h \left[\frac{\sqrt{2(\varepsilon+\varepsilon_h)/m}}{\ell_h(\varepsilon+\varepsilon_h)} F_0(\varepsilon+\varepsilon_h) - \sqrt{\frac{2\varepsilon}{m}}\frac{F_0}{\ell_h}\right] = 0 \\ eE\frac{\partial(vF_0)}{2\varepsilon} - \frac{2eE}{mv}F_0 + \left(1 + \frac{e^2H^2\ell_e^2}{2m\varepsilon}\right)\frac{vF_1}{\ell_e} = 0\ , \end{gathered} \tag{11}$$

where the sum in brackets in the first equation describes the effect of inelastic cross-sections appearing at the energy ε_h with electron mean free path ℓ_h; ℓ_e is the elastic collision mean free path. Both are functions of ε and are obtained from the corresponding cross-sections from the expression:

$$\ell = \frac{1}{\sigma N}\ , \quad N = N_0\,\frac{P}{760}\,\frac{273}{T}\ , \quad N_0 = 2.68 \times 10^{25}\ \mathrm{m}^{-3}\ . \tag{12}$$

Solution of the system of differential equations allows $F_0(\varepsilon)$ and $F_1(\varepsilon)$ to be obtained; the transport theory then provides the following expressions for drift velocity and diffusion coefficient:

- the drift velocity in the direction of the electric field E:

$$w_{\parallel} = -\frac{2}{3}\frac{eE}{m}\int \frac{\varepsilon\ell_e[\partial(F_0/v)/\partial\varepsilon]}{1 + (e^2H^2\ell_e^2/2m\varepsilon)}\,d\varepsilon\ ; \tag{13}$$

- the drift velocity in the direction perpendicular to E and H:

$$w_\perp = \frac{eH^2}{3m} \int \frac{\ell_e^2 v[\partial(F_0/v)/\partial\varepsilon]}{1 + (e^2H^2\ell_e^2/2m\varepsilon)}\, d\varepsilon \tag{14}$$

(notice that for $H = 0$, $w_\parallel = w$ and $w_\perp = 0$);

- the symmetric (or transverse) diffusion coefficient:

$$D_H = \frac{1}{3} \int \frac{\ell_e v F_0(\varepsilon)}{1 + (e^2H^2\ell_e^2/2m\varepsilon)}\, d\varepsilon \tag{15}$$

(again, for $H = 0$, $D_H = D$, the symmetric diffusion coefficient).

The resulting drift velocity in the direction of motion and the drift angle with respect to the electric field direction are then given by

$$\begin{aligned} w_H &= \sqrt{w_\parallel^2 + w_\perp^2} \\ \mathrm{tg}\ \alpha_H &= \frac{w_\perp}{w_\parallel}\ . \end{aligned} \tag{16}$$

The system of differential equations (11) can be solved analytically using some approximations for the quantities involved, or else directly computed numerically using standard algorithms. This second method is used in the program of Palladino and Sadoulet and is, in principle, applicable for any complexity of the cross-sections involved (including inelastic) as far as they are properly tabulated and taken into account.

We will reproduce here some of the analytic solutions used in the program of Schultz and Gresser, indicating the limits of validity of the approximations. Taking into account only elastic (momentum transfer) cross-sections, i.e. for electron energies well below any electronic excitation or ionization level, a solution of Eqs. (11) can be written as

$$F_0(\varepsilon) = c\sqrt{\varepsilon}\ \exp - \int \frac{3\varepsilon\Lambda(\varepsilon)}{(eE\ell_e)^2 + 3\Lambda(\varepsilon)\,[1 + (e^2H^2\ell_e^2/2m\varepsilon)]\cdot kT}\, d\varepsilon\ , \tag{17}$$

where $\Lambda(\varepsilon)$ is the average energy lost in an electron–molecule collision at the energy ε (see below). The approximation is valid, for example, in argon up to electron energies of several electronvolts, since the first inelastic excitation level is above 10 eV. In this case the energy loss Λ is simply given by $2m/M$.

The molecular gases used as quenchers — CO_2, CH_4, and so on — have, however, inelastic rotational and vibrational excitation levels at energies between 0.1 and 1 eV that cannot be neglected. Again limiting the validity of the solution to energies up to a few electronvolts, one can write the following expression for $\Lambda(\varepsilon)$:

$$\Lambda(\varepsilon) = \frac{2m}{M} + \sum_h \frac{\varepsilon_h}{\varepsilon}\frac{\ell_e}{\ell_h} = \frac{2m}{M} + \sum_h \frac{\varepsilon_h}{\varepsilon}\frac{\sigma_h}{\sigma_e}\ , \tag{18}$$

where $\sigma_e(\varepsilon)$ and $\sigma_h(\varepsilon)$ are the elastic (momentum transfer) and inelastic cross-sections, and ε_h the excitation energy of state h; the sum is extended to all excited states.

The approximate analytic solution has been applied with satisfactory results to several gas mixtures, and provides values very close to those obtained with the numerical solution as long as the average electron energy (computed by the program itself) remains well below the lower electronic excitation levels (2.5 eV in CO_2). For even moderately quenched gases, in which the electron energy remains low, this corresponds to a practical limitation on the applied field of a few kV/cm • atm. As indicated, the numerical solution is instead, in principle, capable of reproducing the experimental results up to the ionization region.

For gas mixtures, one can use the same expressions, substituting for cross-sections and energy losses the following composite values:

$$\sigma_e(\varepsilon) = \sum_i p_i\sigma_i(\varepsilon) \quad \text{and} \quad \Lambda(\varepsilon) = \frac{1}{\sigma_e(\varepsilon)} \sum_i p_i\, \sigma_i(\varepsilon)\, \Lambda_i(\varepsilon)\ , \tag{19}$$

where p_i is the fraction of gas i in the mixture, and $\sigma_i(\varepsilon)$ and $\Lambda_i(\varepsilon)$ are, respectively, its elastic cross-section and energy loss estimated through expression (18).

4. EXPERIMENTAL DETERMINATION OF DRIFT VELOCITY AND DIFFUSION COEFFICIENT

Different methods have been used to determine experimentally the drift and diffusion properties of electrons; they are extensively described in the textbooks quoted in the Introduction, and in particular by Loeb (1961). We will here only recall some of them.

The magnetic deflection method, devised by Townsend and used by many authors with various improvements, consists in measuring the lateral deflection and transverse profile of a continuous swarm of electrons emitted by a localized discharge, in the presence of a small magnetic field perpendicular to the direction of motion. Suitably shaped collecting electrodes allow the measurement of the current ratio as a function of electric and magnetic field, and therefore of the magnetic deflection angle and the transverse width of the swarm. The drift velocity for $H = 0$ is then computed using expressions (7) and (8), and the diffusion coefficient through expressions (5) and (6). This approach is only valid under the assumption that the energy distribution of electrons is not modified by the (small) magnetic field.

A second method, introduced by Bradbury and Nielsen (1936) and developed by many others, relies on an electrical shutter grid. In a multi-electrode gas cell, a continuous stream of electrons is extracted from the cathode by ultraviolet photons. Under the action of the electric field, the swarm drifts towards a first shutter grid where an applied pulse restores transparency for a short time. A second pulse, suitably delayed, and applied on a second grid, allows the bucket of electrons to reach the collection electrode; the value of the delay provides the drift velocity.

Both drift velocity and (longitudinal) diffusion coefficient can be determined with the time-of-flight method devised by Hurst et al. (1963). A flash of light extracts, at a known instant, single electrons from a metal surface in a parallel-plate ionization chamber. After drifting, electrons are detected by a Geiger counter, and their time distribution is recorded. A modified time-of-flight method has been used recently by Piuz (1983) and by Farilla, Ropelewski and Sauli (1984) to determine drift velocity and longitudinal diffusion in various gas mixtures.

Most of the recent measurements of drift velocity have been realized using a drift chamber and a collimated charged particle beam, of which both the position and the timing can be accurately known with external scintillation counters [see, for example, Breskin et al. (1974)]. Because of the large ionization yield of the tracks (around a hundred electrons per centimetre at normal gas conditions) the average of the recorded time distribution provides a very good estimate of the drift velocity; its width (the localization accuracy), however, is not a good measurement of diffusion because of the large (and varying) number of electrons. The drift properties in strong magnetic fields can be determined with a similar device; in a drift cell, a magnetic field perpendicular to the plane of drift deflects the drifting swarm by a given angle α. Only for a particular position in the detection volume are charges allowed into the detecting part through a narrow slit, and the drift-time provides the magnetic velocity.

Drift velocity and diffusion coefficient are obtained in all large systems of multiwire drift chambers or time projection chambers as the direct outcome of tracking analysis; they refer, in general, however, to specific values of electric and magnetic fields, and have not been used for the present compilation.

5. FACTORS AFFECTING THE DRIFT OF ELECTRONS

We have, so far, discussed the dependence of drift properties on the external fields (electric and magnetic) and on the nature of the gas. Other factors may, however, affect the drift of electrons; in particular, the presence of polluting impurities, especially if electronegative, and variations of the gas pressure and temperature.

The effect of impurities on drift velocity for pure gases was already mentioned, and illustrated for example in Fig. 32. For heavily quenched mixtures, the effect is much reduced although precise measurements seem not to exist. However, Fig. 122 shows as an example the variation of drift velocity computed for two mixtures with a constant fraction of argon and addition of a few per cent of methylal, a product used to reduce polymerization effects of isobutane [Schultz and Gresser (1978)].

The drift velocity in mixtures depends, of course, on the relative concentration of components. This dependence is, however, minimal in some mixtures and in the region of electric field where the velocity is saturated and the curves for various mixtures are tangential; examples are given in Figs. 115–117. In argon–isobutane at 1 kV/cm, Breskin et al. (1975) measured a relative drift velocity change of about 1.2×10^{-3} for 1% variation in the isobutane concentration. Inspection of similar measurements in other mixtures shows that a similar behaviour appears in many gases.

The presence of electronegative pollutants (such as oxygen and water) has as a direct consequence a loss of electrons by capture, but can also affect the drift velocity. As attachment is often accompanied by a non-negligible detachment probability, it is suspected that even unnoticeable quantities of pollutant may affect sensibly the drift velocity since the process has the net effect of slowing down the electron motion.

As discussed in the previous sections, drift velocity is E/P dependent, and pressure variations at constant field have an obvious effect on w. Again, in mixtures having a pronounced velocity saturation the pressure dependence is minimal, a fact exploited in high-accuracy drift chambers operated at atmospheric pressure.

The gas temperature has two distinct effects on drifting electrons. In the region of field where the electrons are still thermal (for 'cool' gases such as carbon dioxide, up to rather high fields) the average electron energy is proportional to the absolute temperature T, and it can be shown [see, for example, Schultz and Gresser (1978)] that $\Delta w/w = \Delta T/T$, or 3.4×10^{-3} per °K at room temperature. For non-thermal gases the dependence invervenes mainly through the density variation, and depends on the detailed E/P dependence; it can even be negative, as shown in Figs. 123 and 124. Figures 58 and 59 show the measured relative variation of w for two argon–methane mixtures.

6. COMPILATION OF DRIFT VELOCITIES AND DIFFUSIONS

We have restricted our compilation to computed or directly measured drift velocities and single-electron diffusion widths, excluding indirect data such as space–time relationships and localization accuracies measured for ionizing radiation using drift chambers, since most of these measurements are instrument-dependent and cannot easily be related to the basic drift properties. Figures are collected in groups having a main constituent (in the order H_2, N_2, the noble gases, other gases); in each group the various mixtures are arranged in an approximate order of increasing molecular weight and complexity.

Drift velocities are generally given in cm/s or cm/μs as a function of electric field in V/cm at normal conditions (20 °C, 1 atm) or of reduced field E/P in V/cm · Torr; sometimes the reduced field is given in terms of E/N, N being the number of molecules per unit volume [see expression (12)]. To deduce the drift velocity in different conditions one should remember that $w = w(E/P)$.

The standard deviation of the linear single electron diffusion is generally given at normal conditions and for 1 cm of drift. To deduce the space diffusion in different conditions one should use the scaling law of expression (6), i.e. multiply by the square root of the ratio between distance of drift in centimetres and pressure in atmospheres. In some curves either the diffusion coefficient D or its ratio to the mobility μ is given; to compute the equivalent space diffusion one should use expression (2) and recall that $\mu = w/E$. Experimental data are given both for the transverse diffusion σ_T and for the longitudinal diffusion σ_L; curves computed with the programs only refer to the (symmetric) transverse diffusion.

For their practical use in single-wire or multiwire gas detectors some mixtures are more suitable than others, depending on the experimental needs. Often several requirements have to be simultaneously satisfied and this explains the continuing search for new gas mixtures. Below are given a few examples of gas mixtures classified according to their main property:

High specific mass: Mixtures with high concentrations of Xe. Used to increase specific energy losses of charged particles and photon detection efficiencies (Figs. 63, 135–158).

Low specific mass: Mixtures of H_2 and He with a small addition of quenchers. Used to minimize multiple scattering of detected tracks, or to reduce the specific ionization of charged particles when detecting neutral radiation as ultraviolet photons releasing single photoelectrons (Figs. 7–12, 77).

High drift velocity: Pure CH_4, CF_4, or their mixtures with other gases. Used for high-rate detectors (Figs. 52–74, 125, 128, 174–180).

Low drift velocities: All gases have low drift velocity at small values of the electric field. However, some gases, such as CO_2, dimethylether, and He–C_2H_6, have low and sometimes saturated drift velocity also at high fields (Figs. 10, 11, 193–196, 200, 204).

Small diffusion: All gases in which electrons remain thermal at high values of the electric field. Hydrocarbons, CO_2, dimethylether, NH_3, mixtures of noble gases with large fractions of these quenchers [Figs. 31, 49, 50, 75, 87, 100–105, 163, 196, 200, 204).

Small magnetic deflection angles: CO_2, CO_2–isoC_4H_{10} (Fig. 203).

Electron capture: Most gases listed in the present compilation do not have an appreciable electron attachment coefficient. This is not the case for O_2, H_2O, CF_3Br and other freons where electron capture is considerable. Extended tables of attachment coefficients can be found, for example, in Christophorou (1971).

Avalanche multiplication properties: This subject is outside the scope of the present work; we will only mention that various gas mixtures have rather different behaviour in this respect. Pure noble gases allow proportional amplification up to gains of 10^3–10^4; mixed with CO_2, hydrocarbons, or other quenchers they allow proportional gains above 10^5 and semi-proportional (saturated) gains in excess of 10^6 to be reached. Small fractions of some quenchers (methylal, ethyl bromide) in noble gases induce Geiger operation, while using large concentrations of hydrocarbons one can reach the very high gains of the limited streamer mode.

7. SOURCES USED IN THE COMPUTATIONS

Gases for which, at the present date, cross-sections are tabulated in the programs, and the sources of the data are the following:

Helium: Elastic cross-sections from Huxley and Crompton (1974); excitation from Bowman and Miller (1965), Lassettre et al. (1968), Christophorou (1971).

Neon: Elastic cross-sections from Huxley and Crompton (1974); excitation cross-sections from Bowman and Miller (1965), Lassettre et al. (1968), Christophorou (1971).

Argon: Elastic and excitation cross-sections, approximation by Palladino and Sadoulet (1974) from data of Engelhardt and Phelps (1964).

Xenon: Approximation of Ramanantsizehena (1979) from Pack et al. (1962).

Methane: Elastic and inelastic cross-sections approximated by Palladino and Sadoulet (1974) from Brüche (1930).

Ethane: Elastic cross-section approximated by Ramanantsizehena (1979) from experimental points by Bowman and Gordon (1967) and Brüche (1930); excitation cross-section from Bowman and Miller (1965) and Lassettre et al. (1968).

Isobutane: Elastic and excitation cross-sections approximated by Palladino and Sadoulet from Brüche (1930).

Carbon dioxide: Elastic, rotational and vibrational cross-sections approximated by Schultz and Gresser (1978) from Hake and Phelps (1967). Excitation cross-sections from Watanabe (1957).

Nitrogen: Elastic and excitation cross-sections from Huxley and Crompton (1974).

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INDEX TO THE FIGURES

The figures are collected in groups corresponding to a main constitutent (H_2, D_2, the noble gases, other gases) with various mixtures in an approximate order of increasing complexity. As each mixture only appears once in the index, the reader is invited to search for the various combinations of the constituents.

Constituent(s)	Fig. No(s).
H_2	1, 2, 7
D_2	3, 4
He	5, 6, 7, 8, 9, 12
He–Xe–CO_2	12
He–CO_2–N_2	9
He–CH_4–TMAE*)	77
He–C_2H_6	10, 11
He–isoC_4H_{10}–TMAE*)	77
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Ne–C_2H_4	25
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Ne–C_2H_6–N_2	22, 23
Ne–C_3H_8	24
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*) TMAE: tetrakis(dimethylamine)ethylene $[(CH_3)_2N]_2C = C[N(CH_3)_2]_2$

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Ar-C_3H_8O	47
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CH_4-C_2H_6	201
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*) TMAE: tetrakis(dimethylamine)ethylene $[(CH_3)_2N]_2C = C[N(CH_3)_2]_2$

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C_4H_9Br	187
C_4H_9Cl	187
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C_3H_7Cl	187
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$(CH_3)_2NH$	188
$C_2H_5NH_2$	188
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*) TMAE: tetrakis(dimethylamine)ethylene $[(CH_3)_2N]_2C = C[N(CH_3)_2]_2$

X) DME: Dimethylether $(CH_3)_2O$

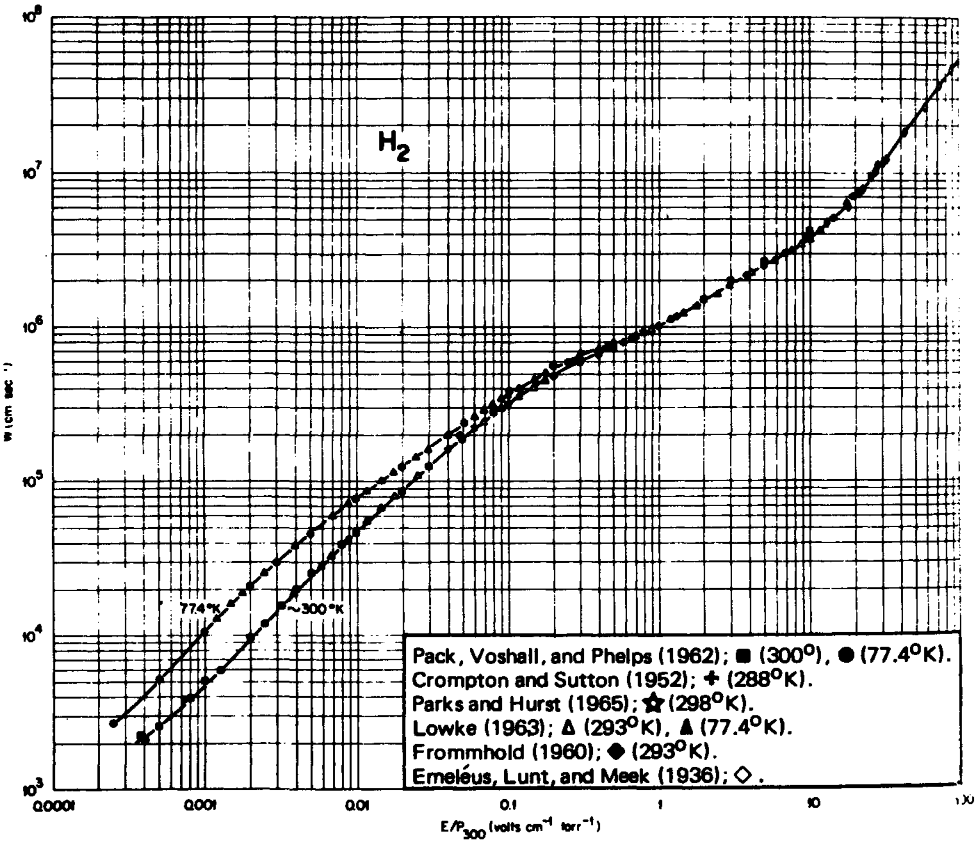


Fig. 1 Christophorou (1971)

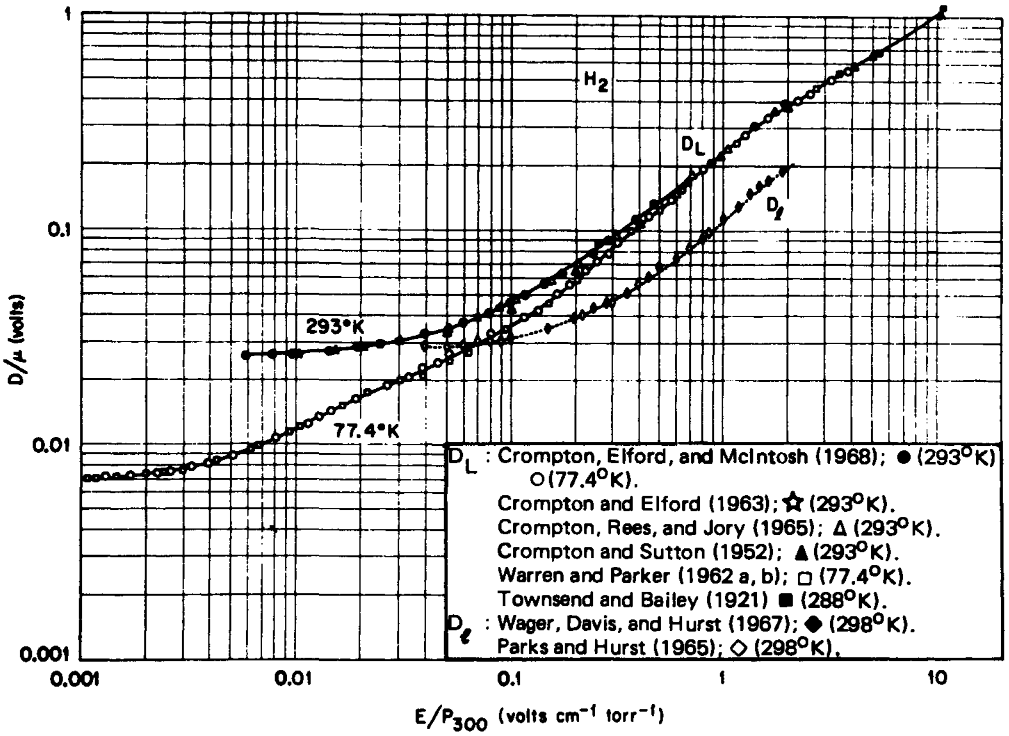


Fig. 2 Christophorou (1971)

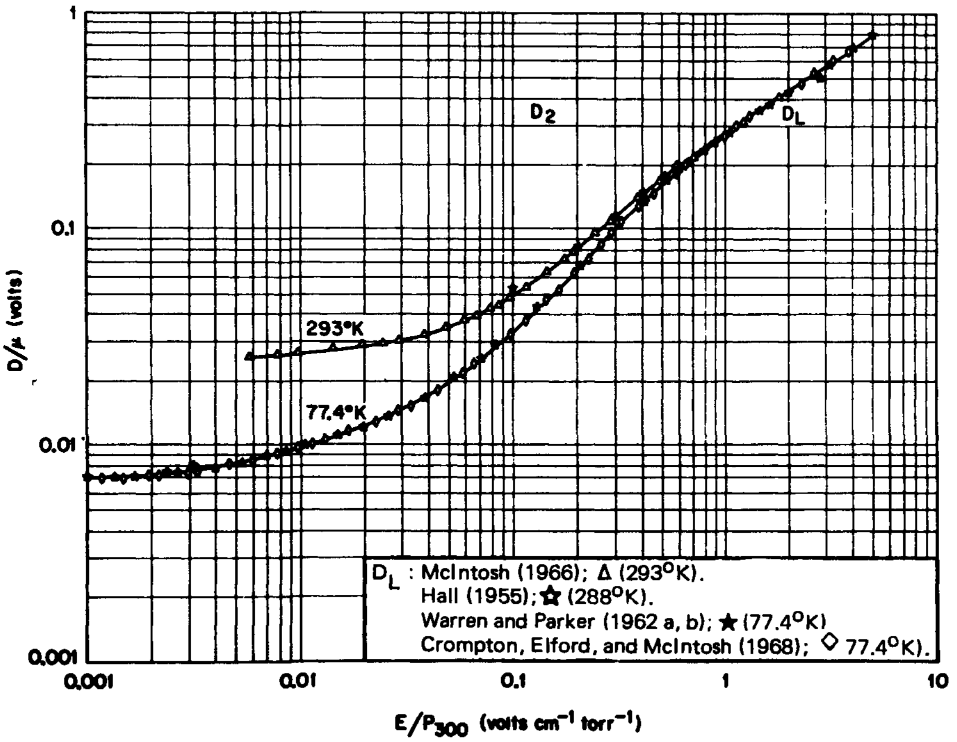


Fig. 3 Christophorou (1971)

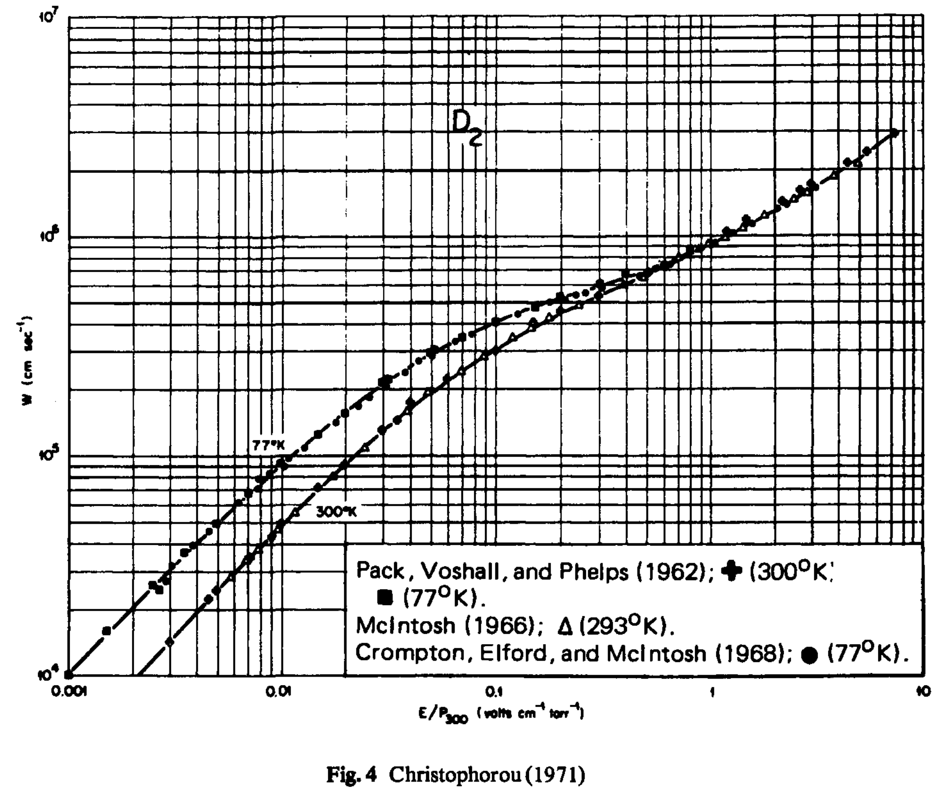


Fig. 4 Christophorou (1971)

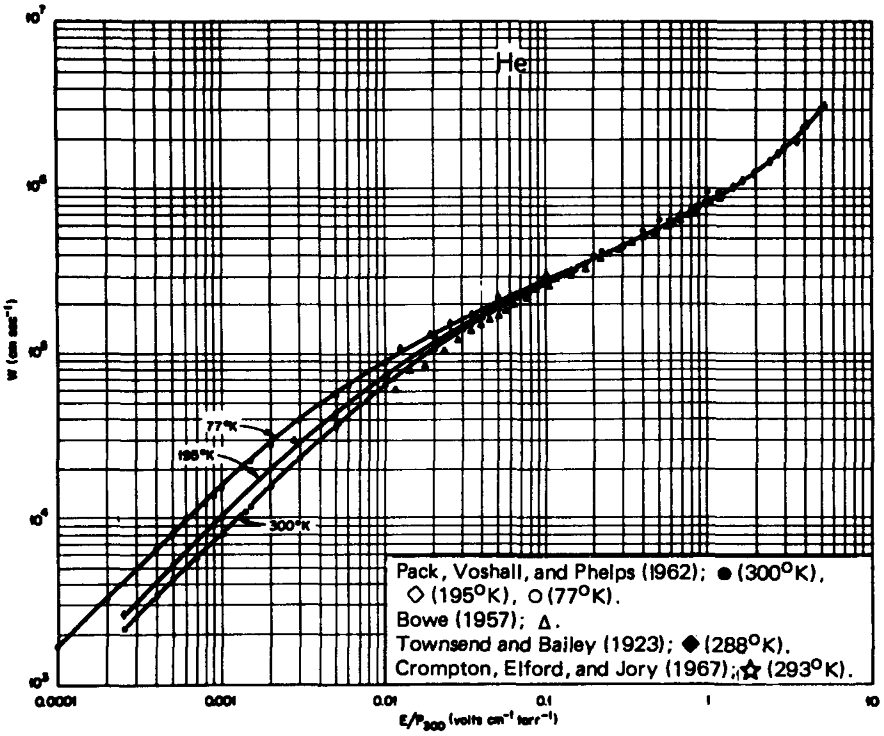


Fig. 5 Christophorou (1971)

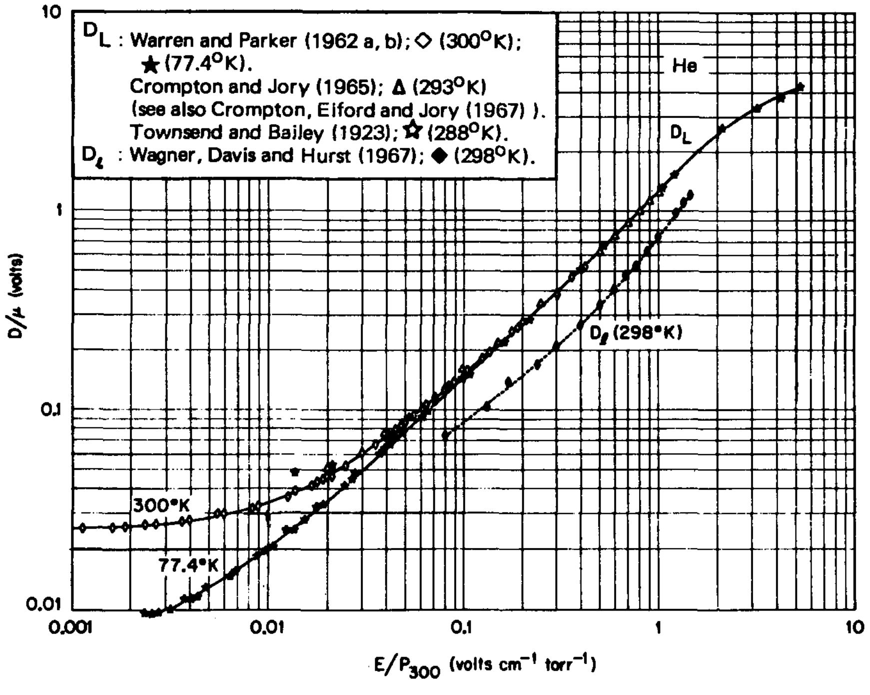


Fig. 6 Christophorou (1971)

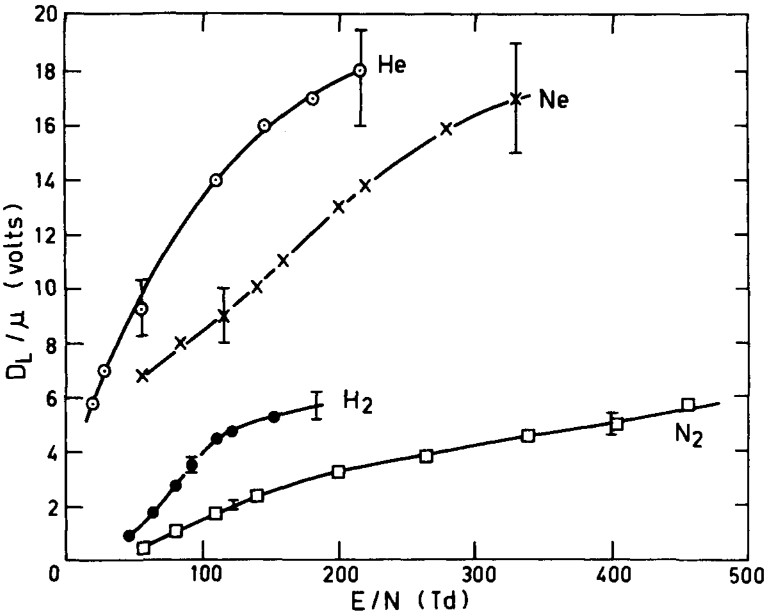


Fig. 7 Fletscher (1981)

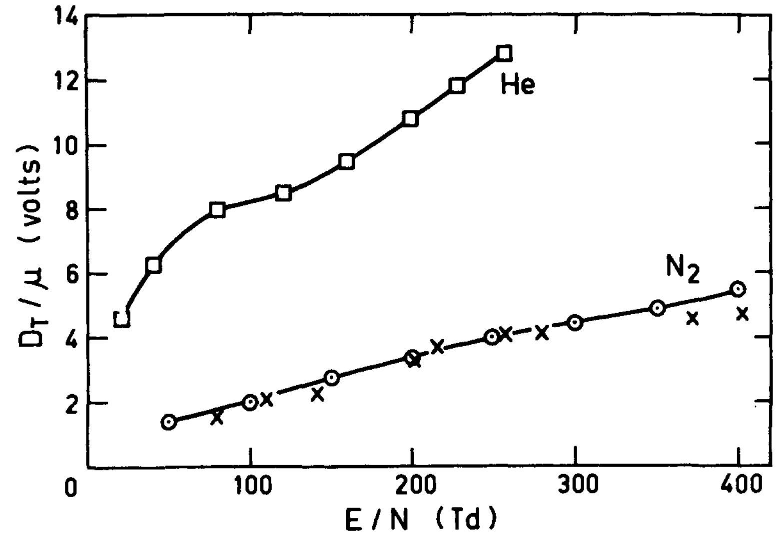


Fig. 8 Fletscher (1981)

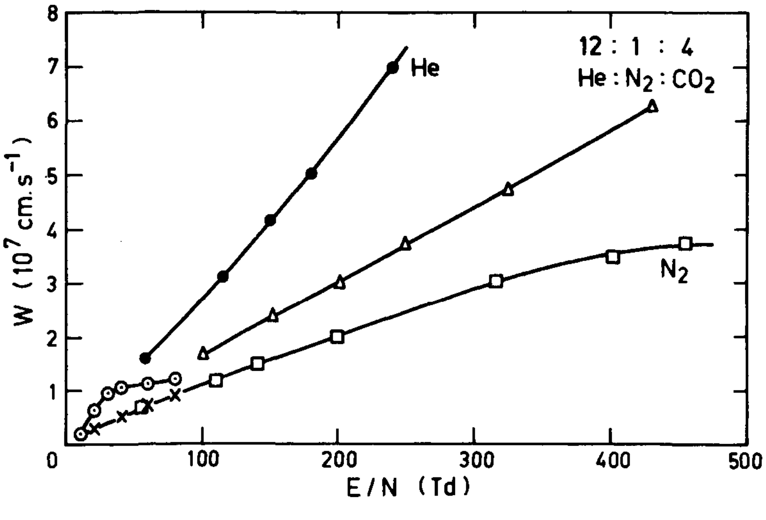


Fig. 9 Fletscher (1981)

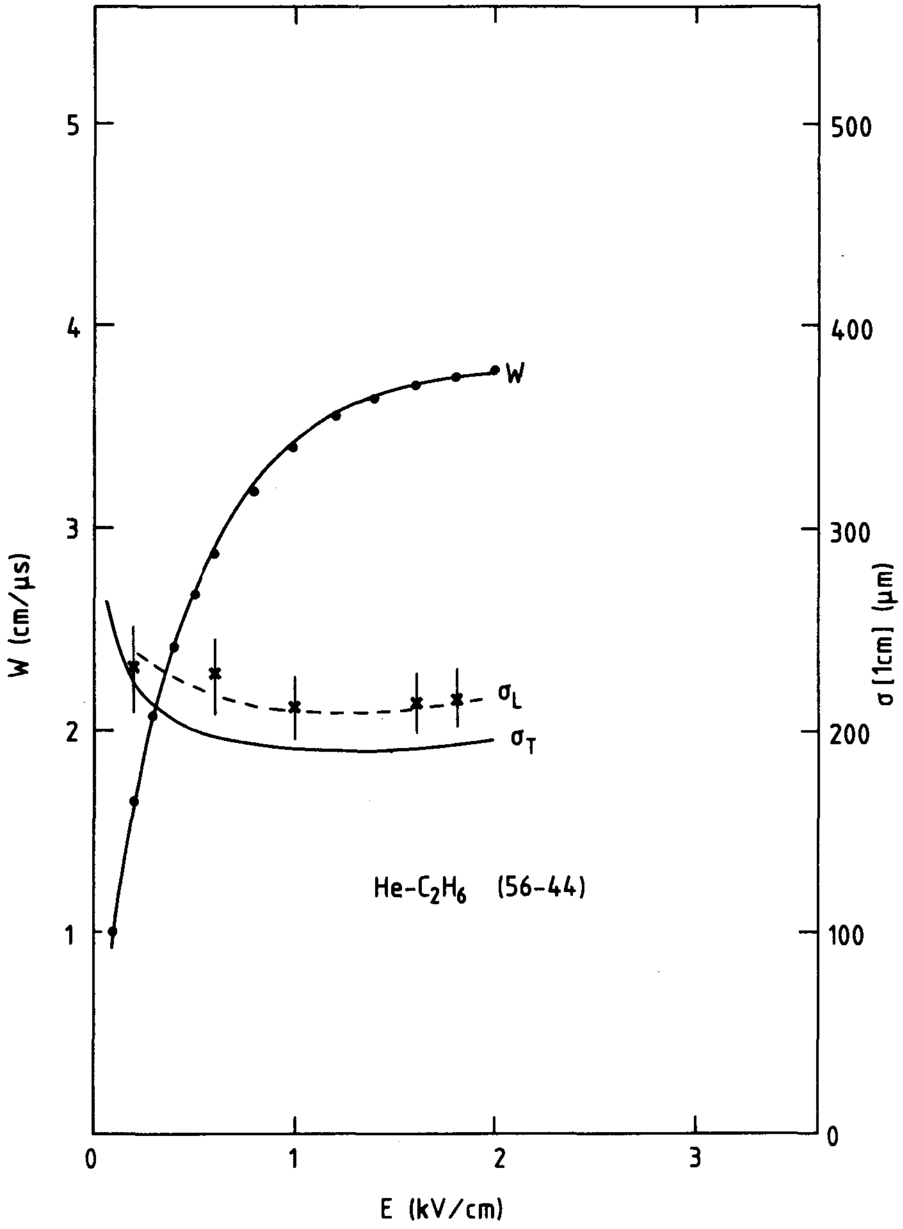


Fig. 10 Peisert and Sauli (1984)

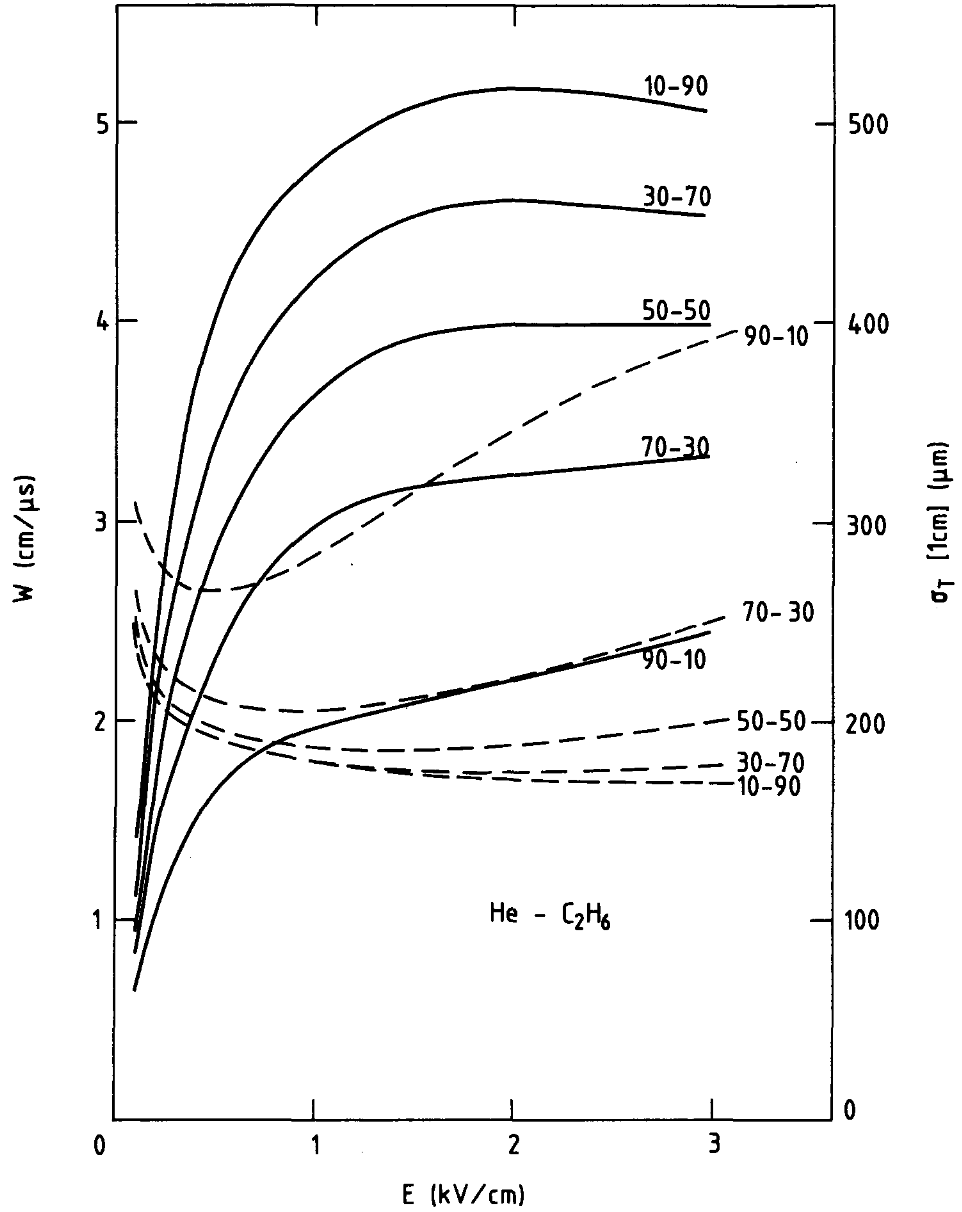


Fig. 11 Peisert and Sauli (1984)

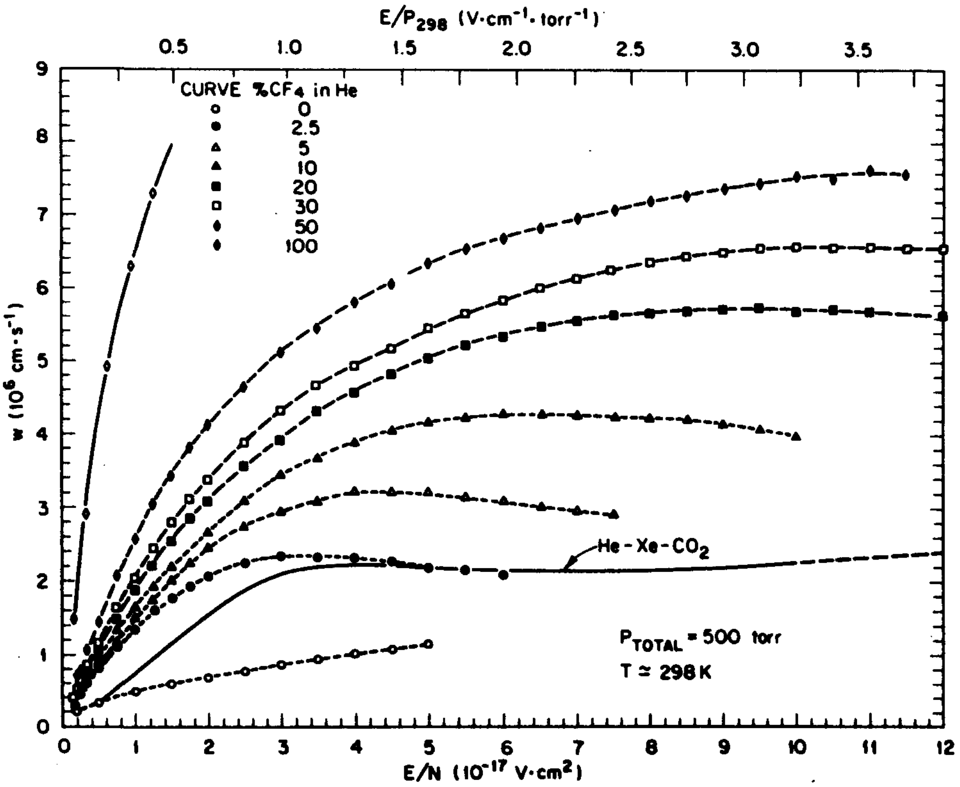


Fig. 12 Kopp et al. (1982)

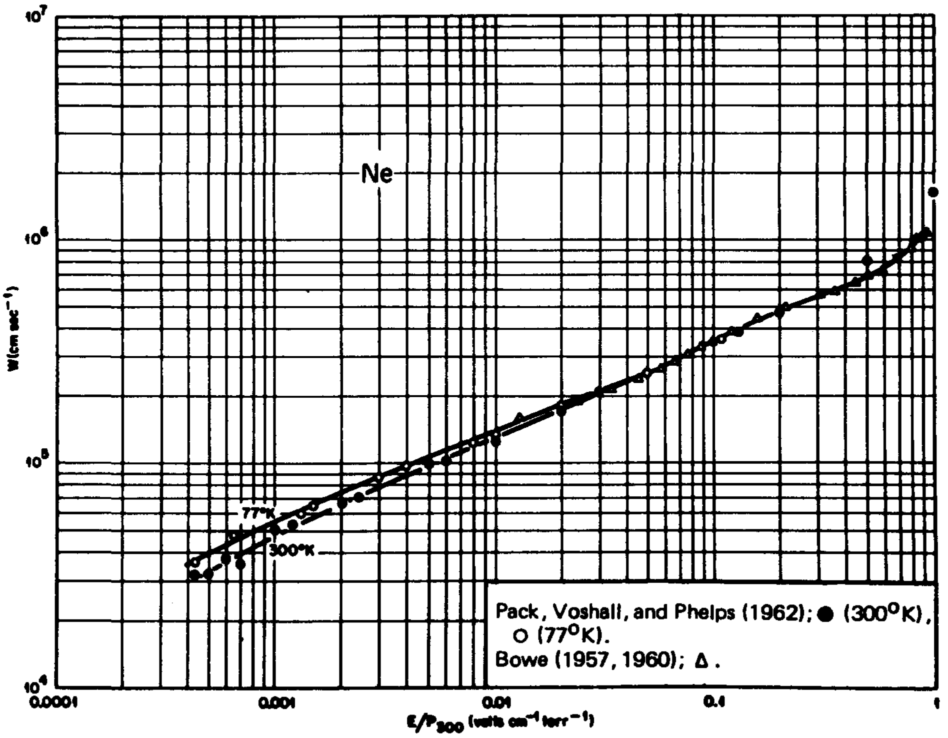


Fig. 13 Christophorou (1971)

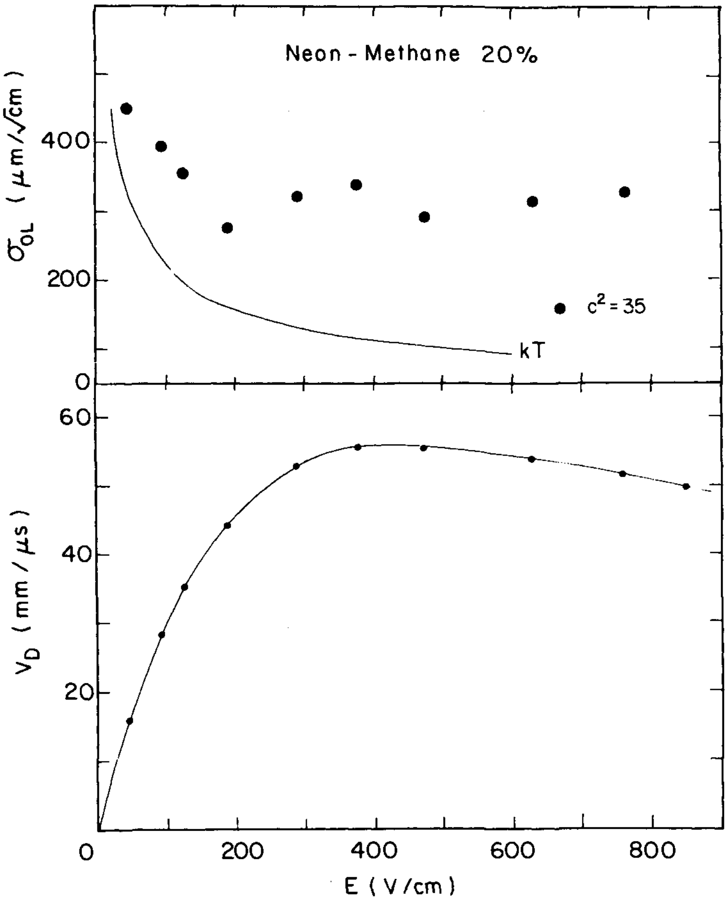


Fig. 14 Piuz (1983)

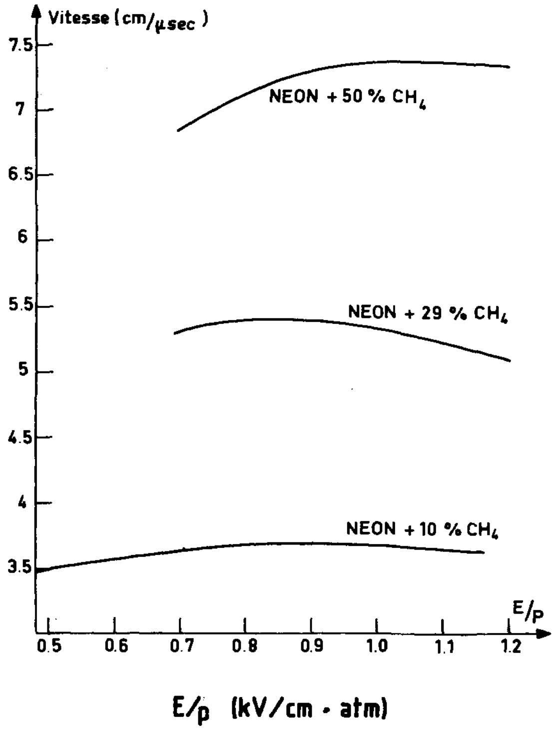


Fig. 15 Saudinos et al. (1973)

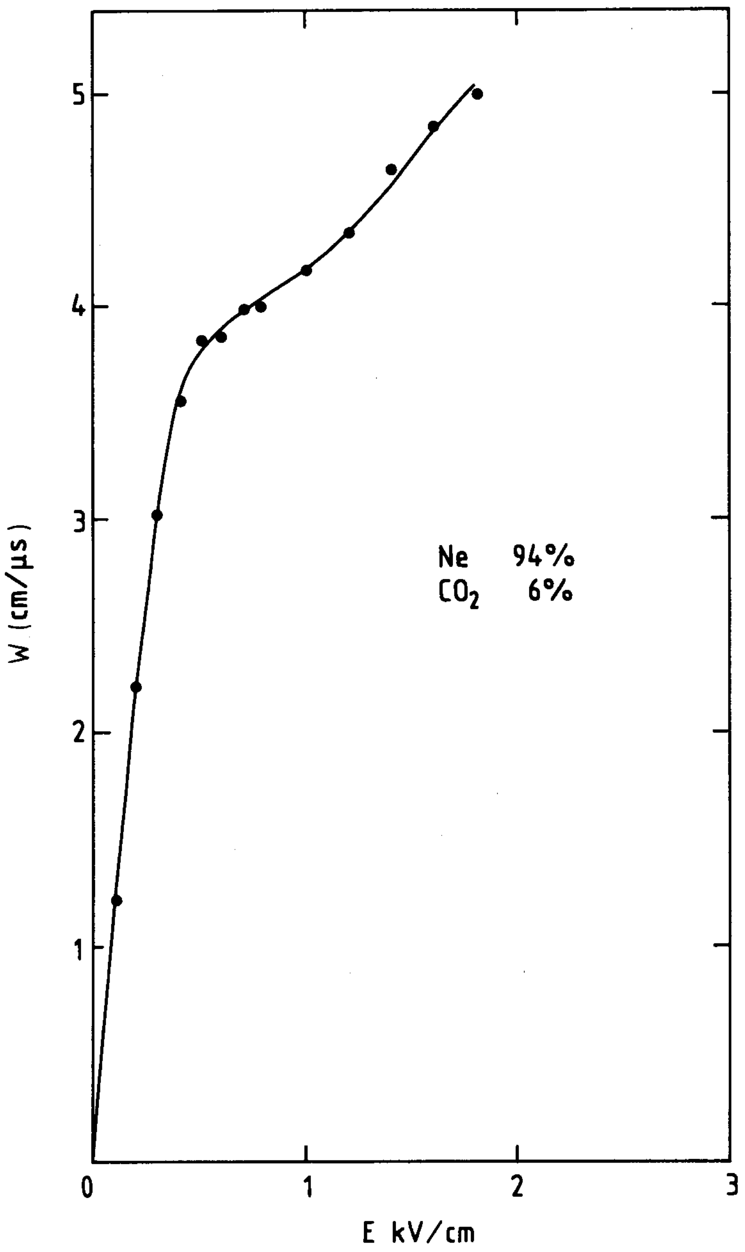
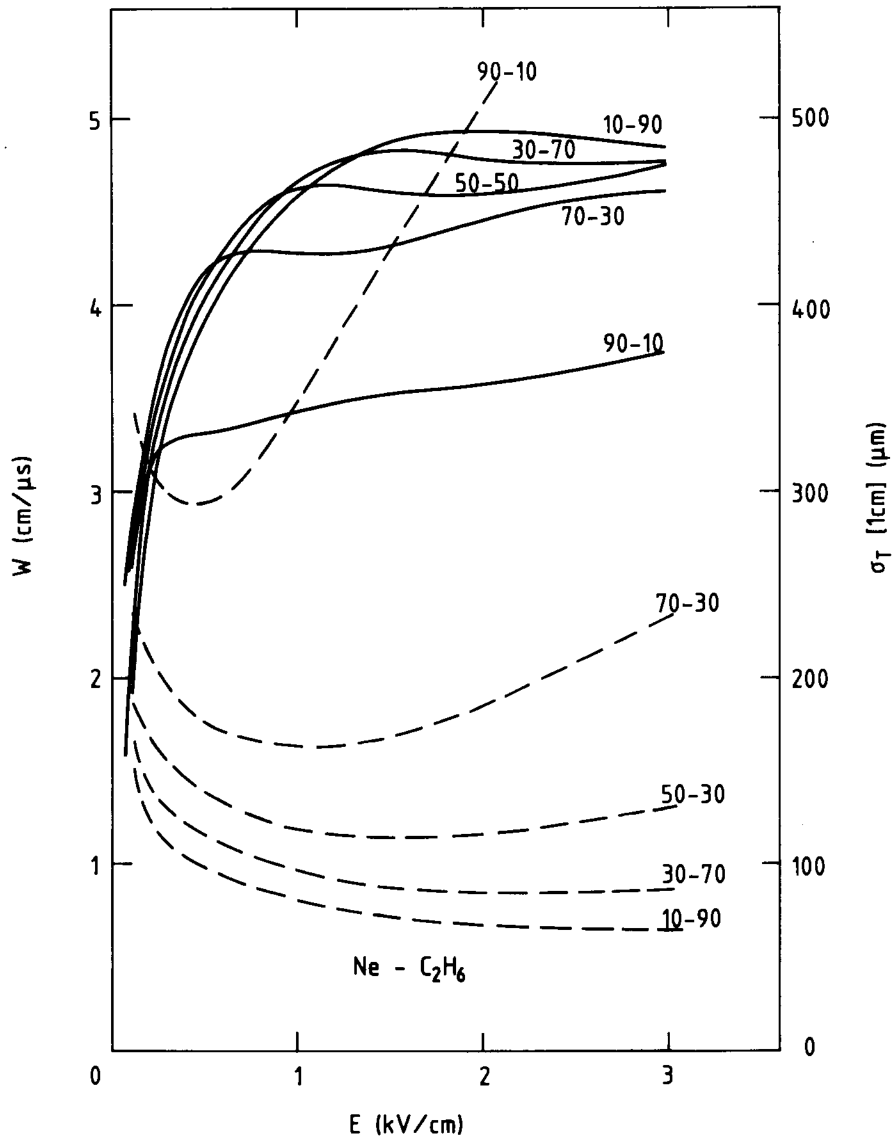


Fig. 16 Peisert and Sauli (1984)



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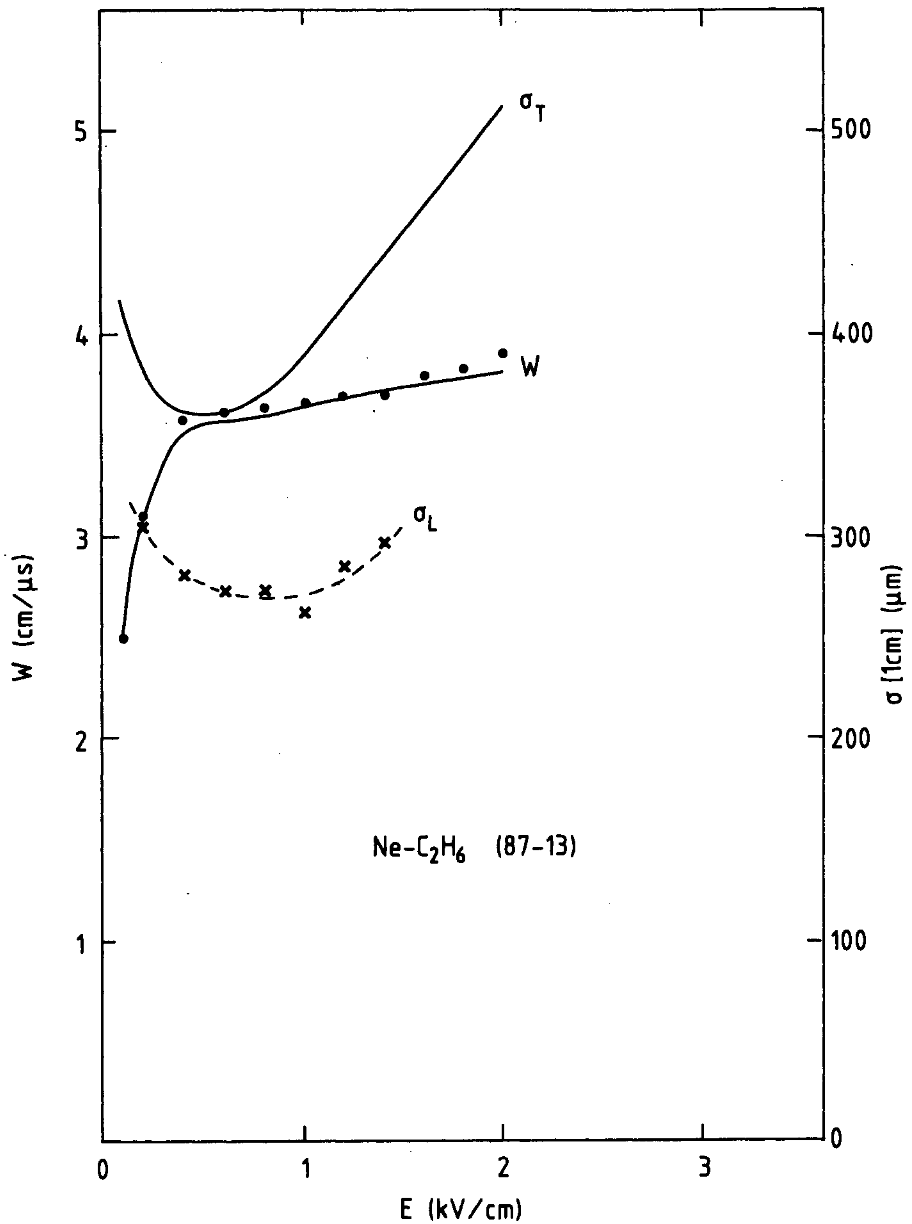

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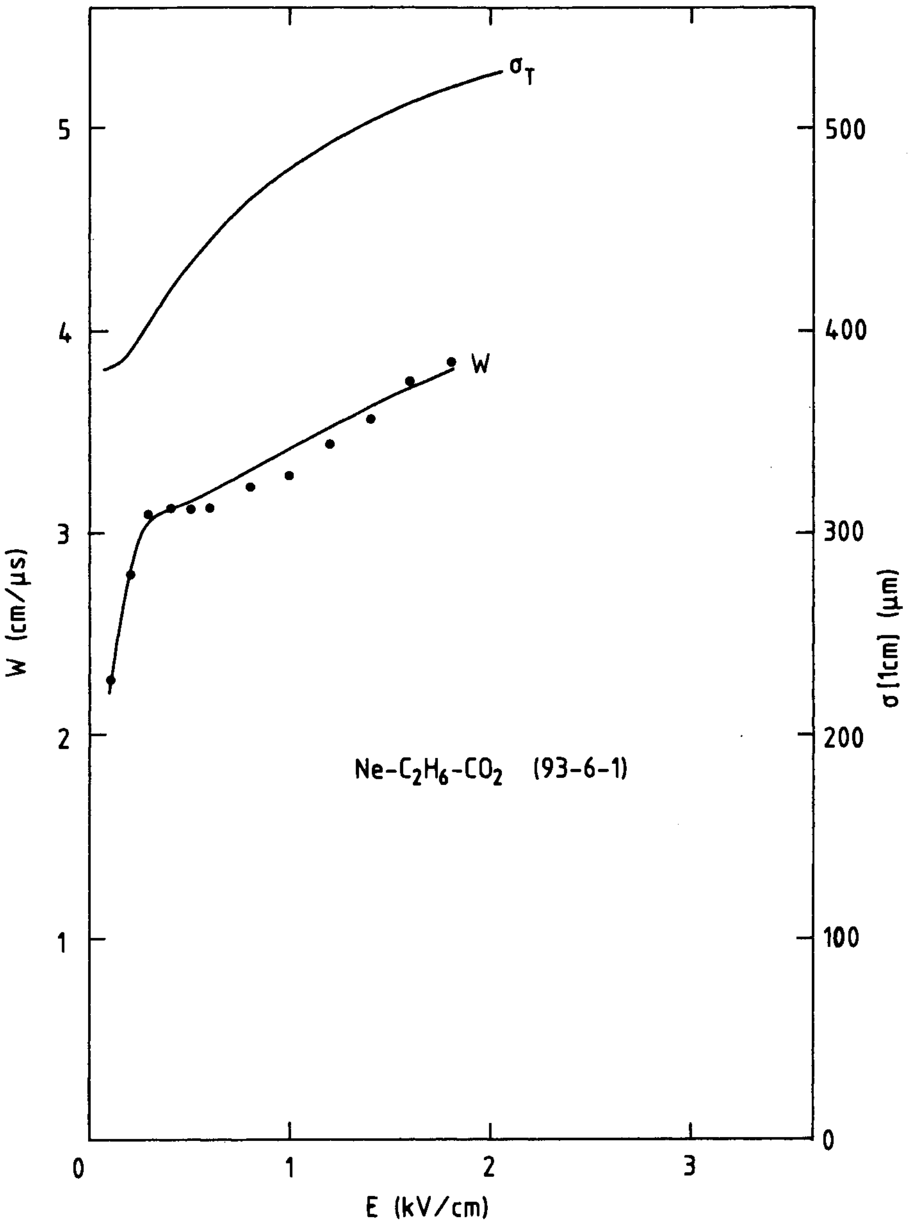

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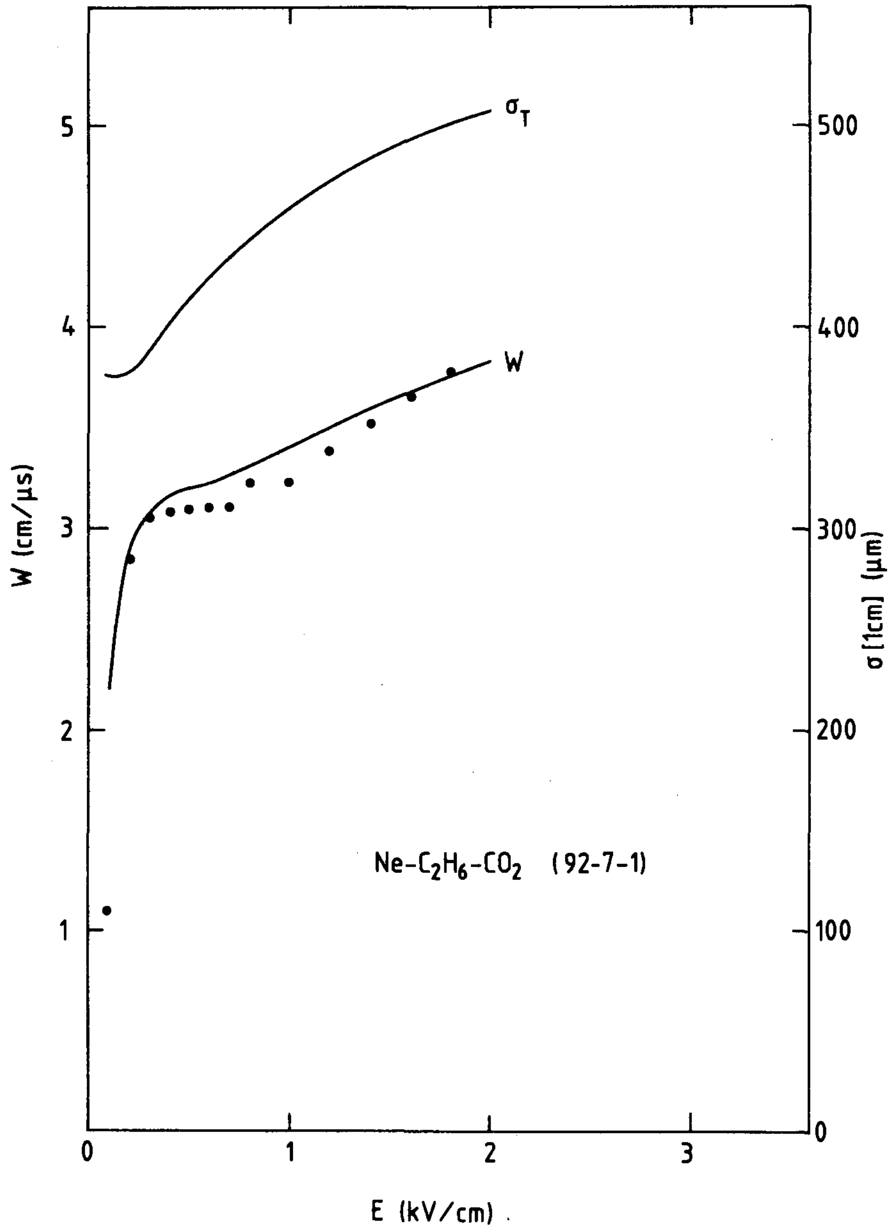

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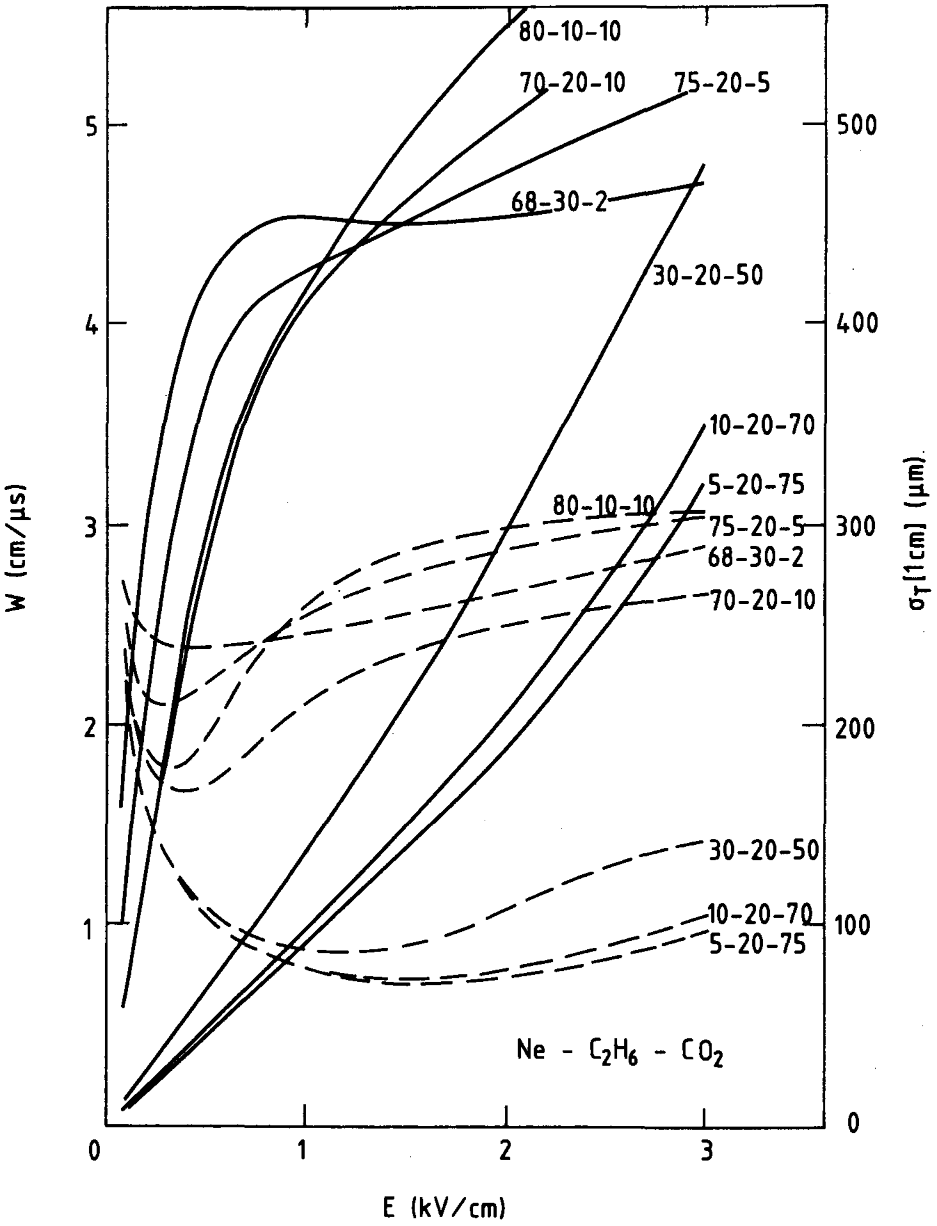


Fig. 21 Peisert and Sauli (1984)

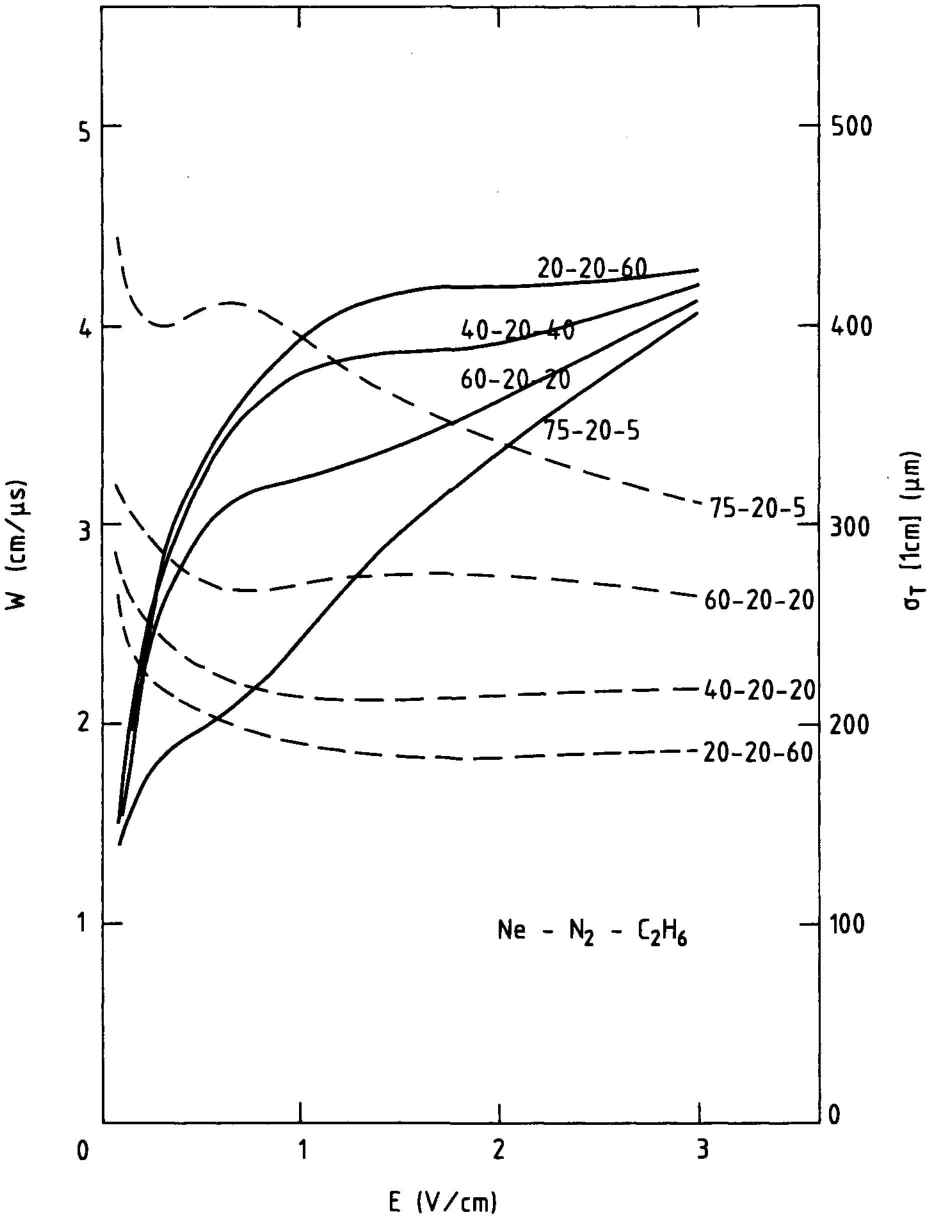


Fig. 22 Peisert and Sauli (1984)

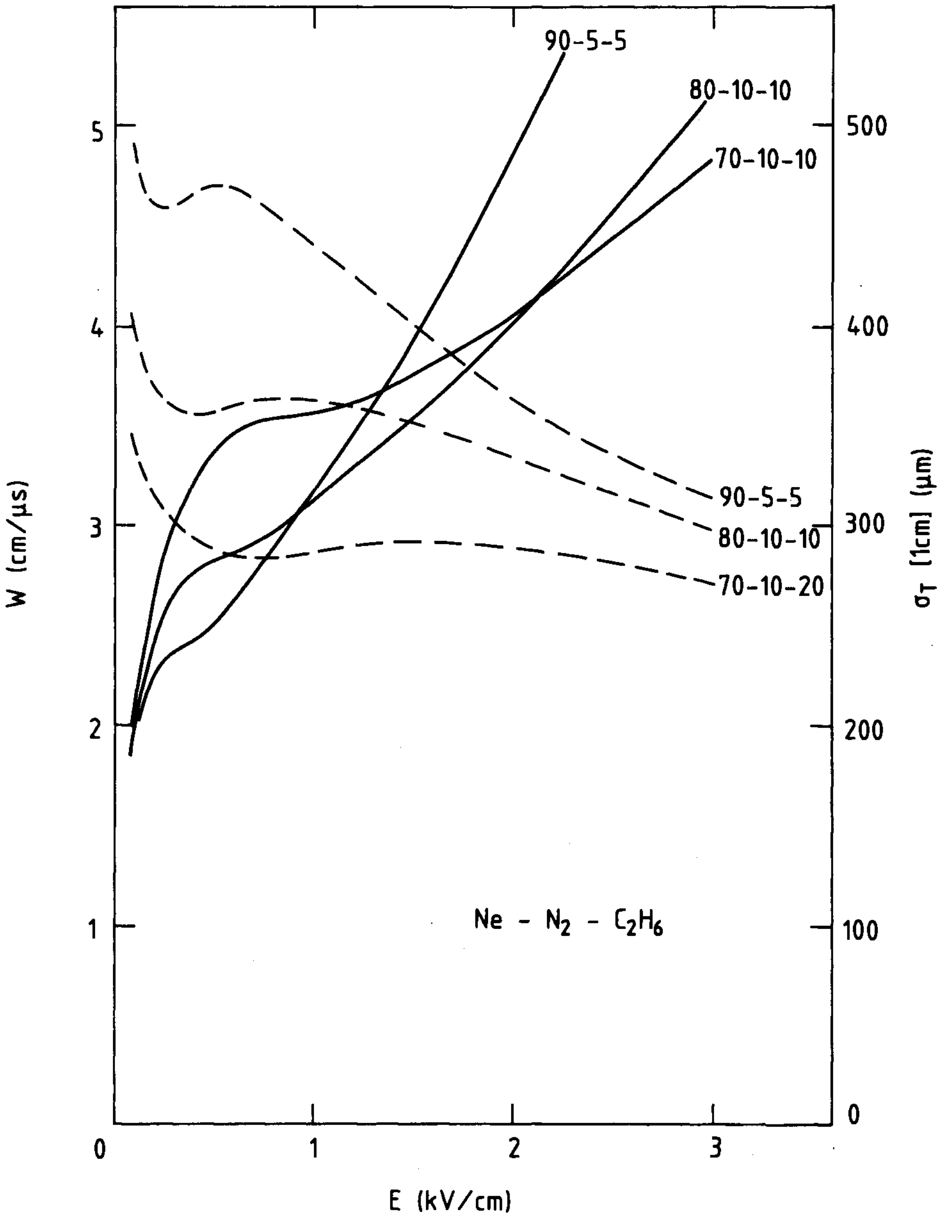


Fig. 23 Peisert and Sauli (1984)

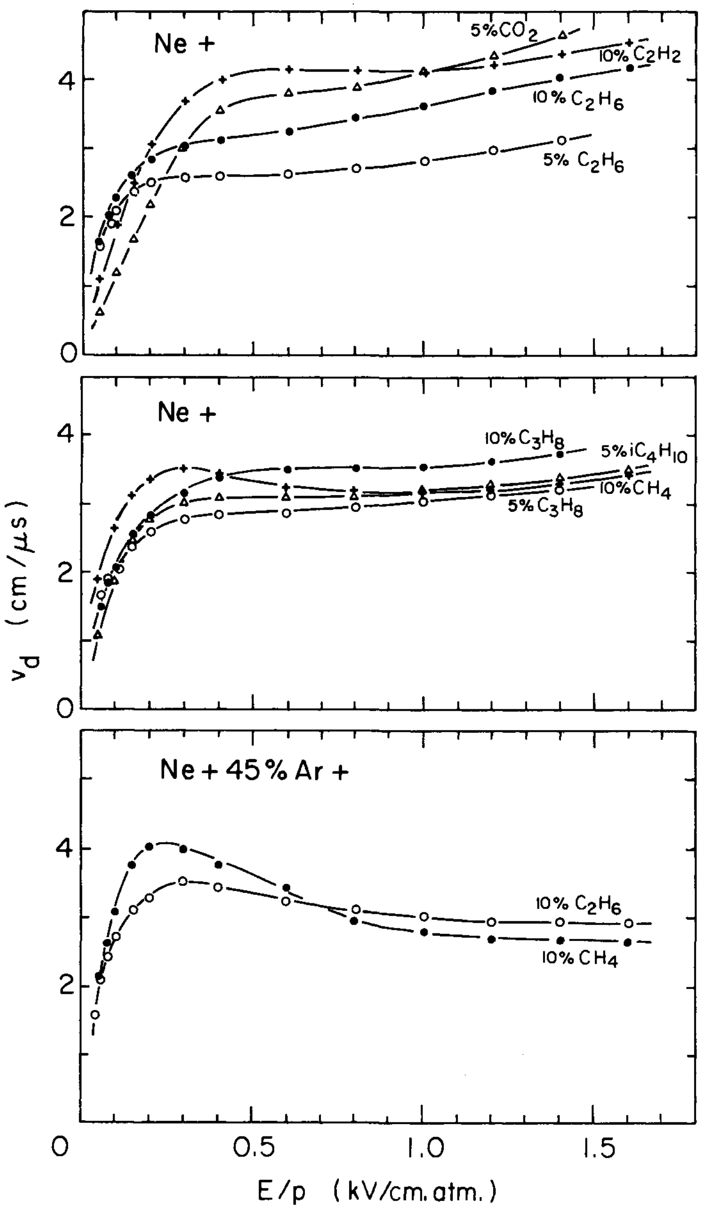


Fig. 24 Lehraus et al. (1982)

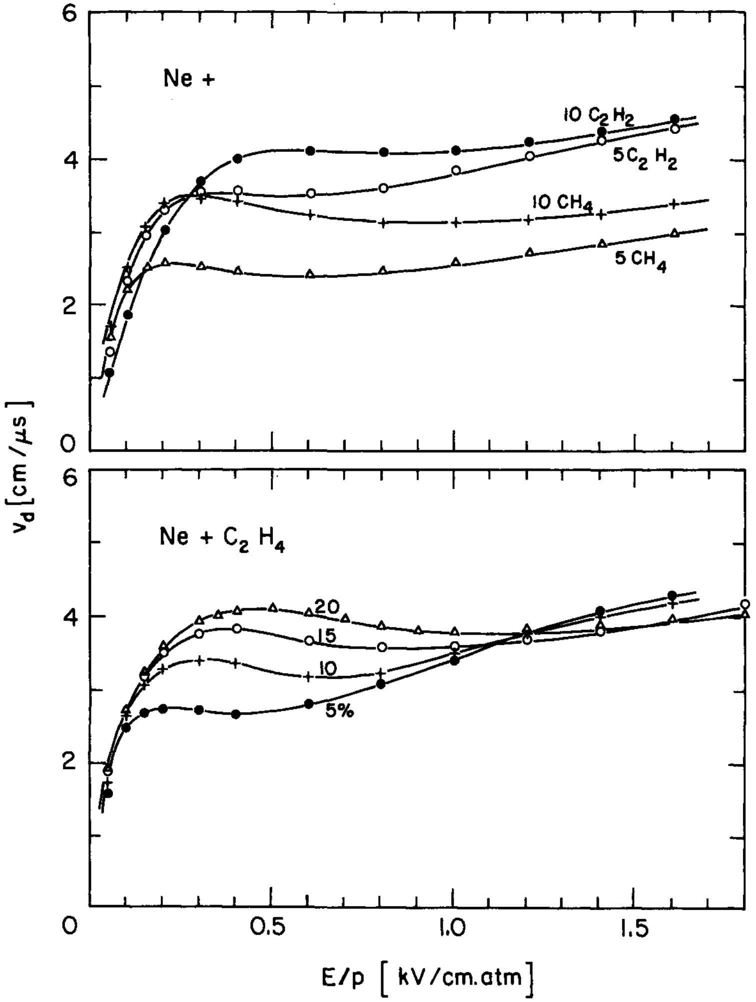


Fig. 25 Lehraus et al. (1982)

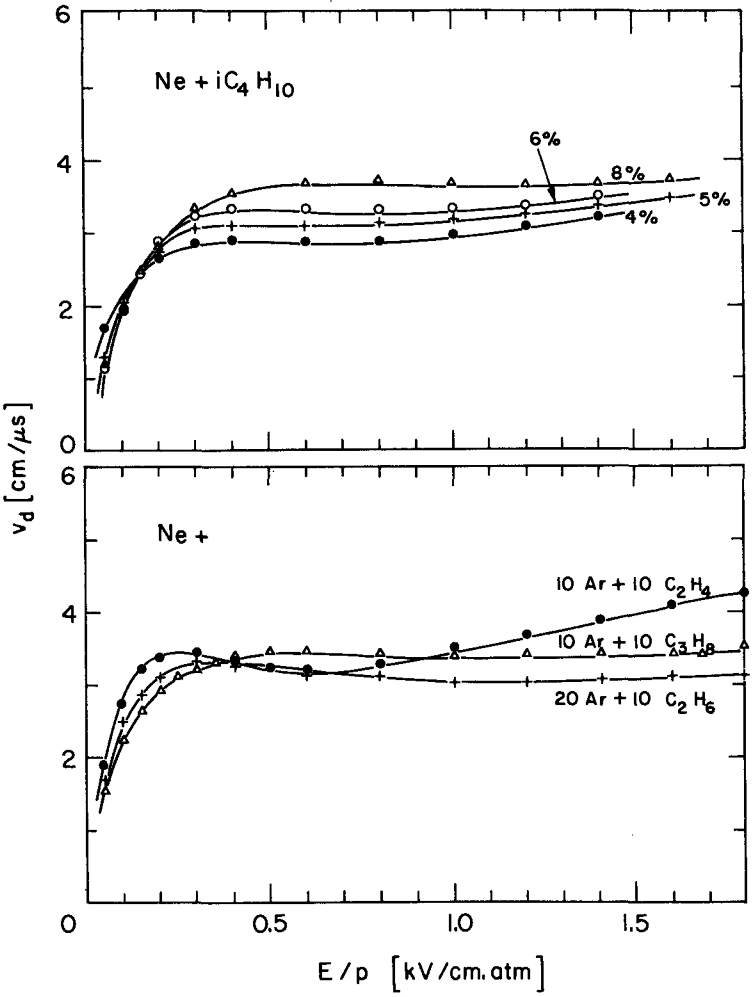


Fig. 26 Lehraus et al. (1983)

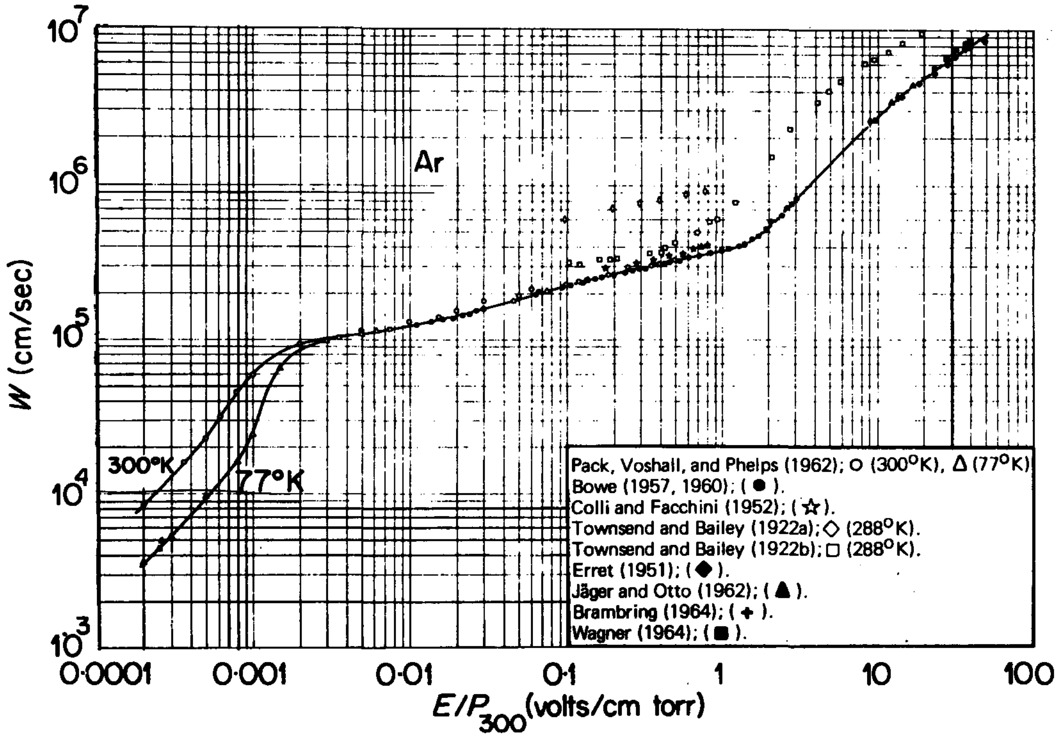


Fig. 27 Christophorou (1971)

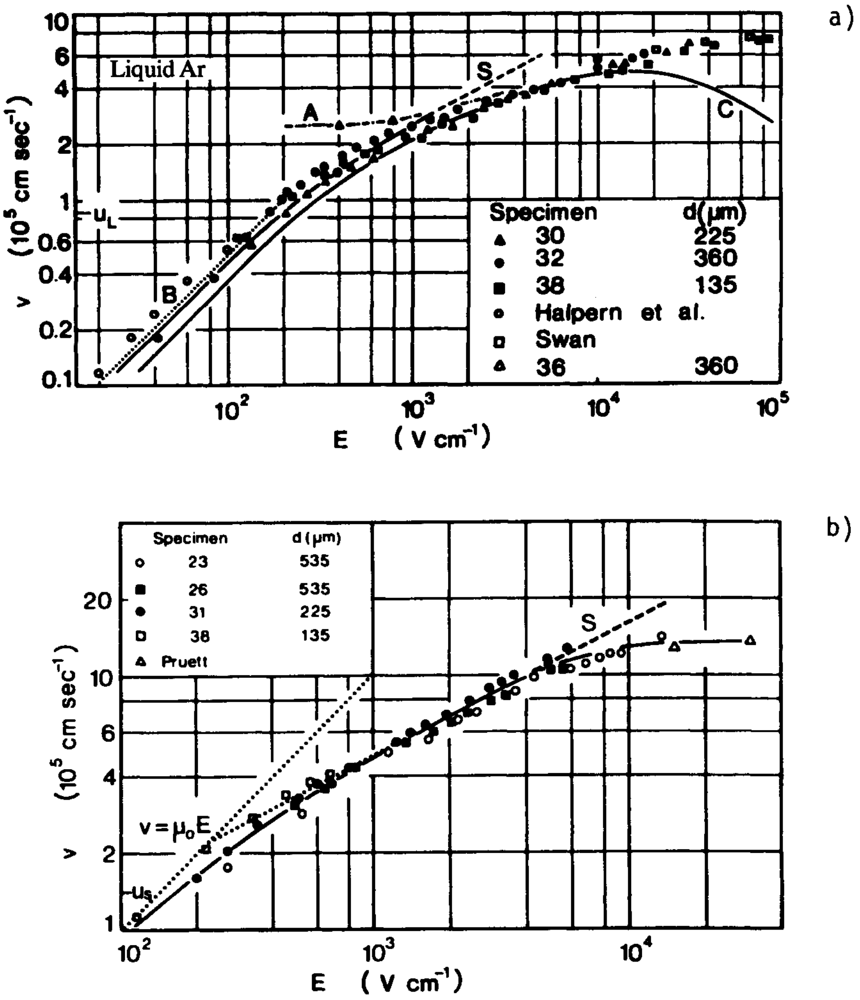


Fig. 28 Rubbia (1977)

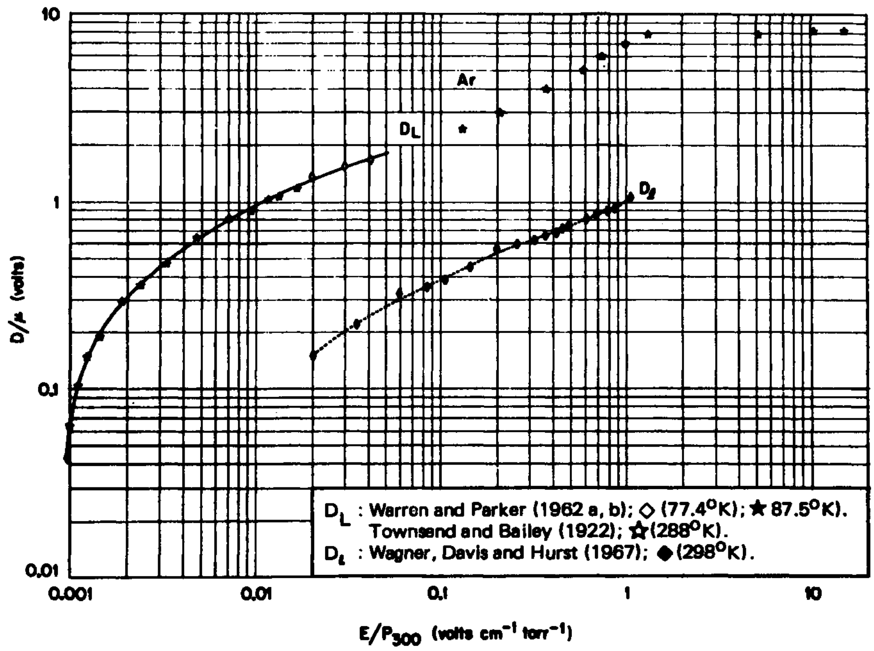


Fig. 29 Christophorou (1971)

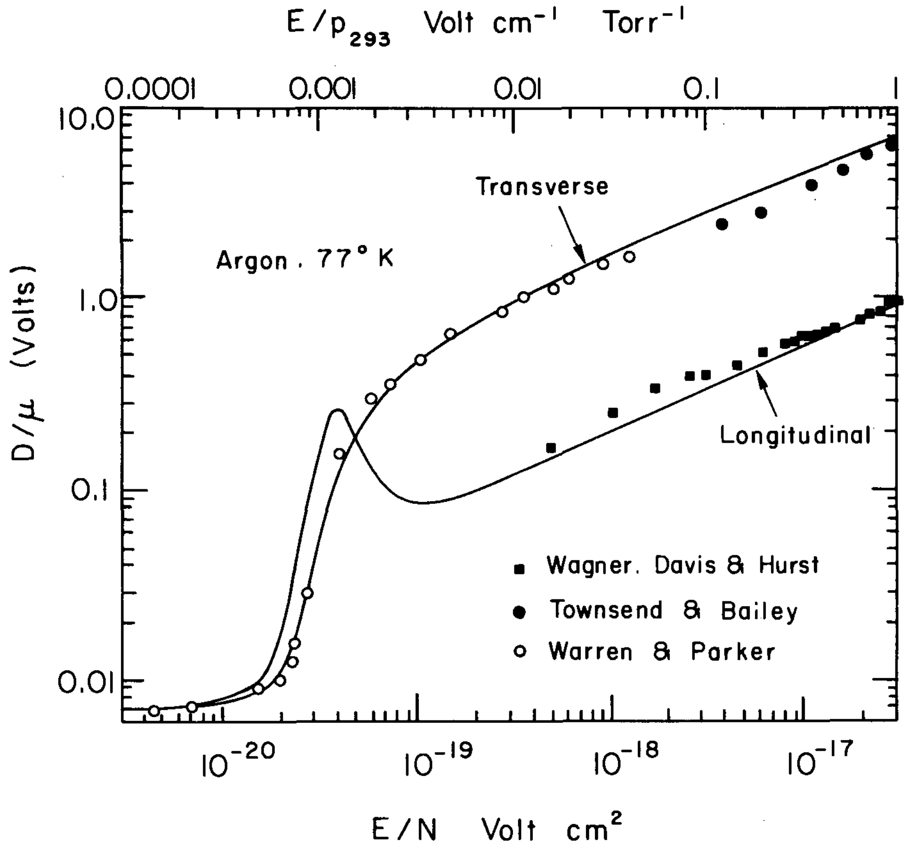


Fig. 30 Lowke and Parker (1969)

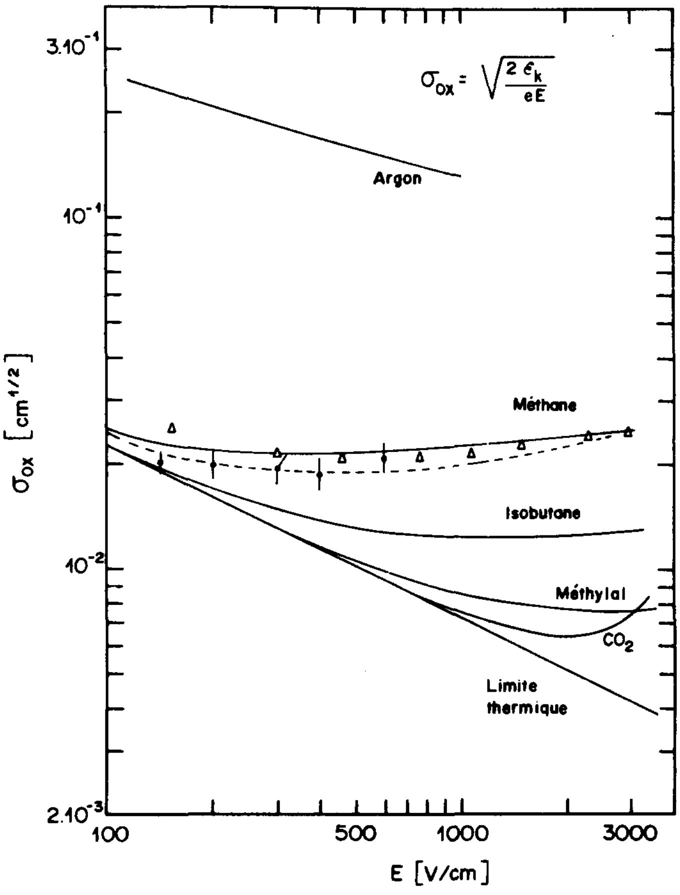


Fig. 31 Schultz (1976)

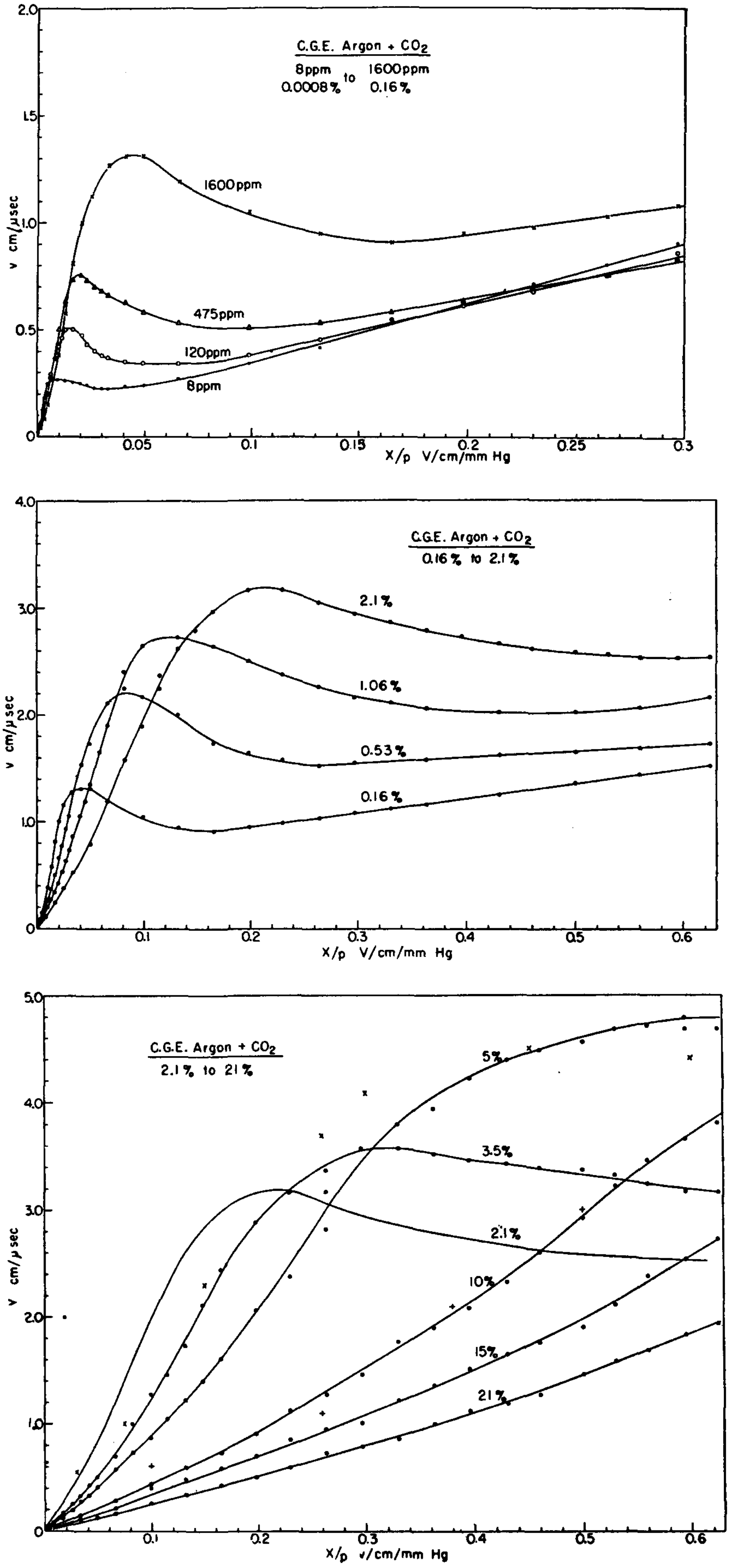


Fig. 32 English and Hanna (1953)

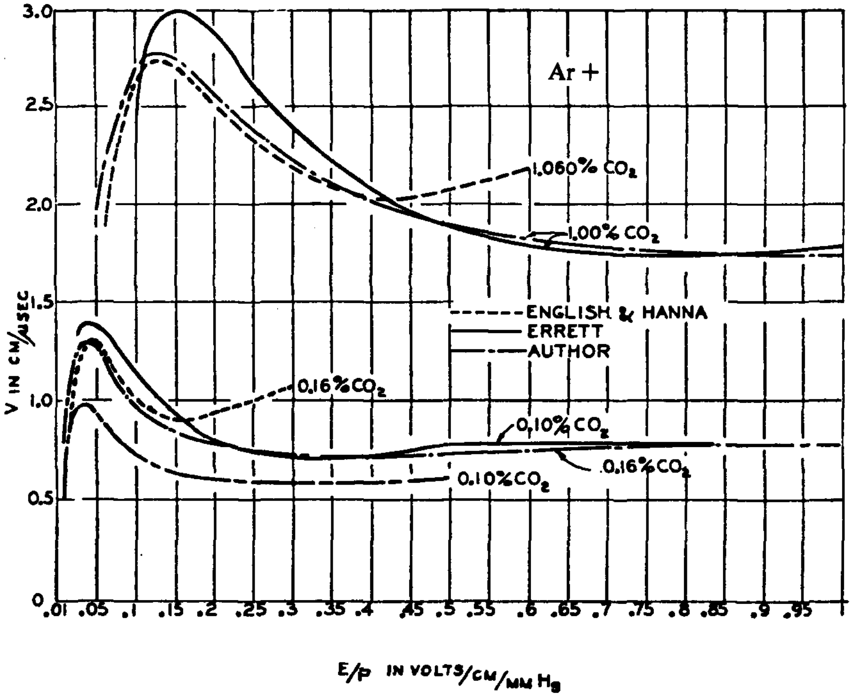


Fig. 33 Uman and Warfield (1960)

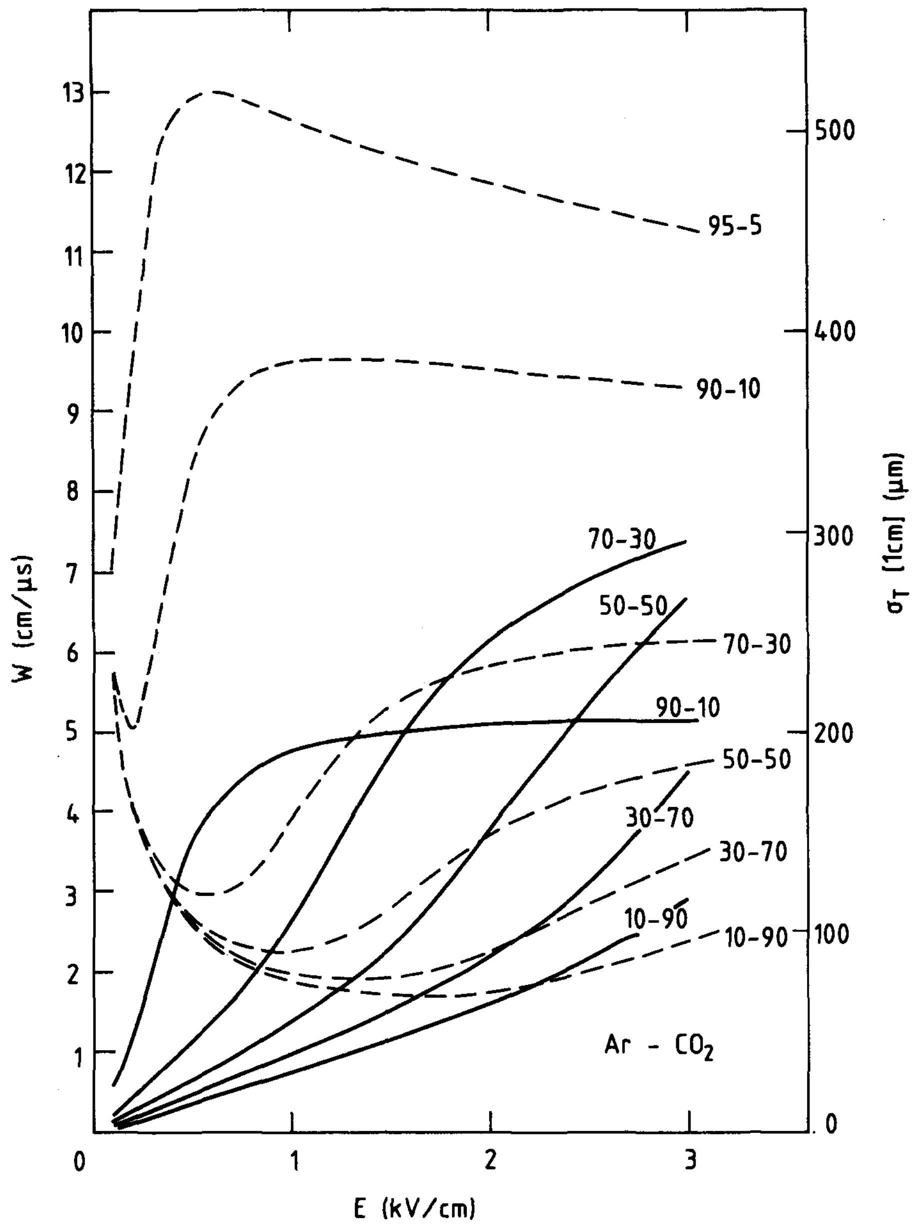


Fig. 34 Peisert and Sauli (1984)

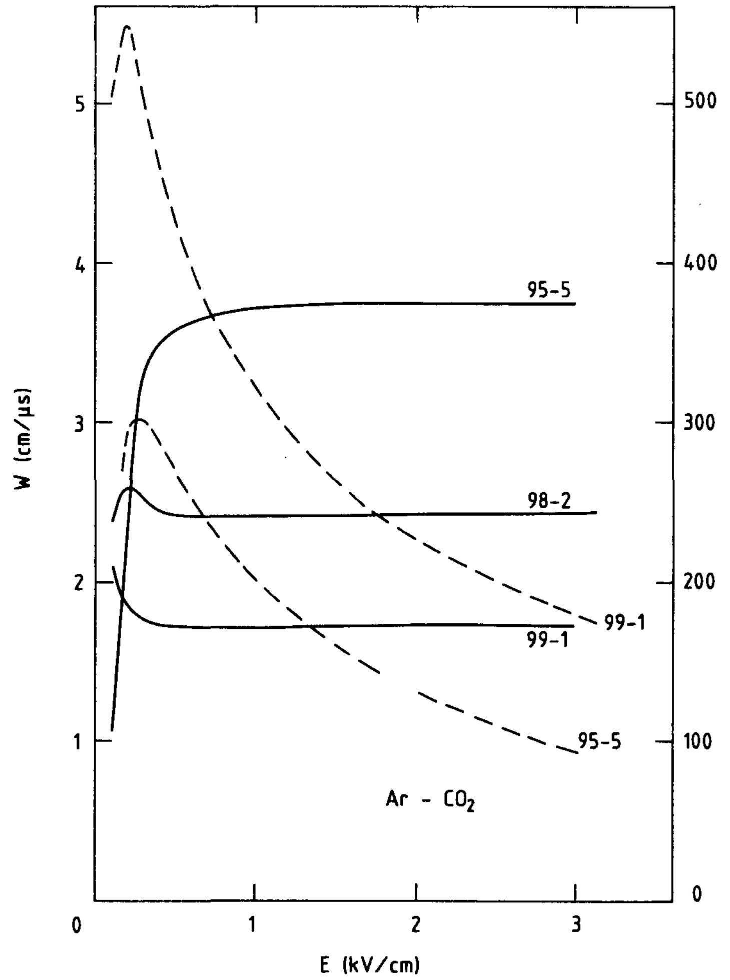


Fig. 35 Peisert and Sauli (1984)

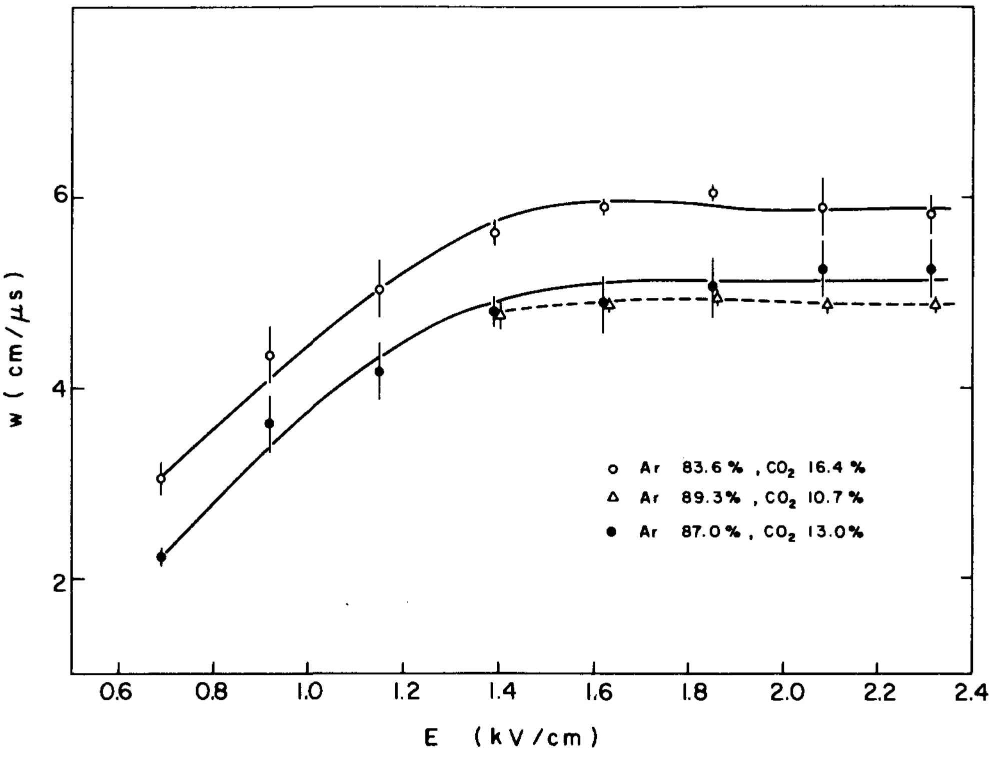


Fig. 36 Ezban and Morganti (1974)

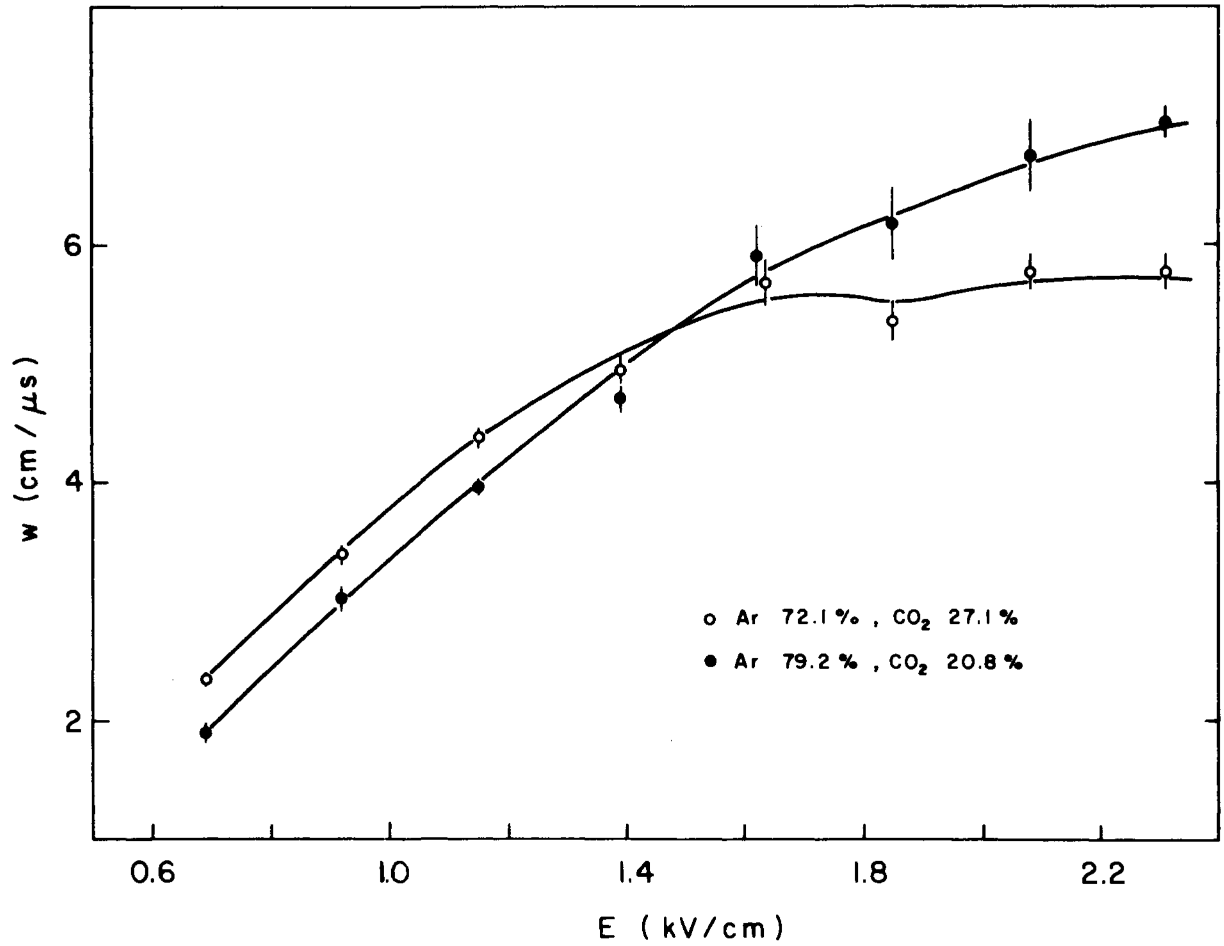


Fig. 37 Ezban and Morganti (1974)

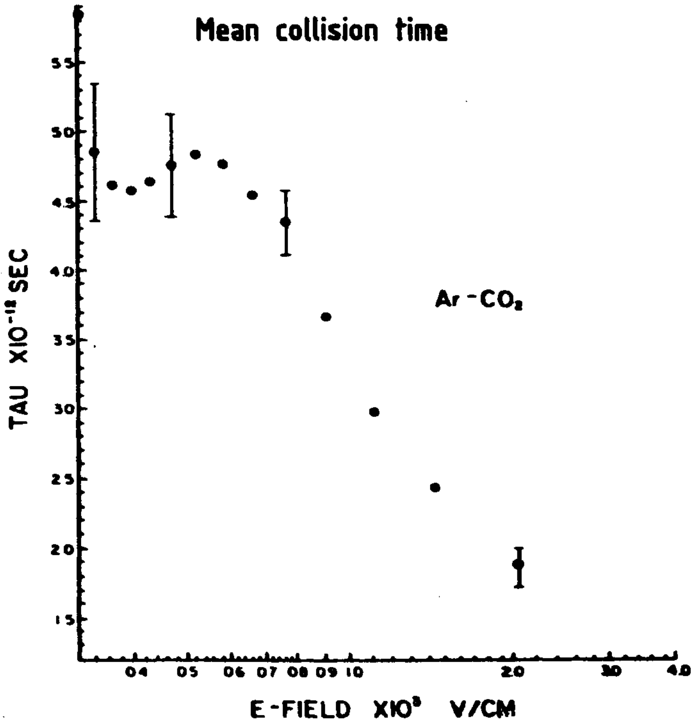


Fig. 38 Baranko et al. (1980)

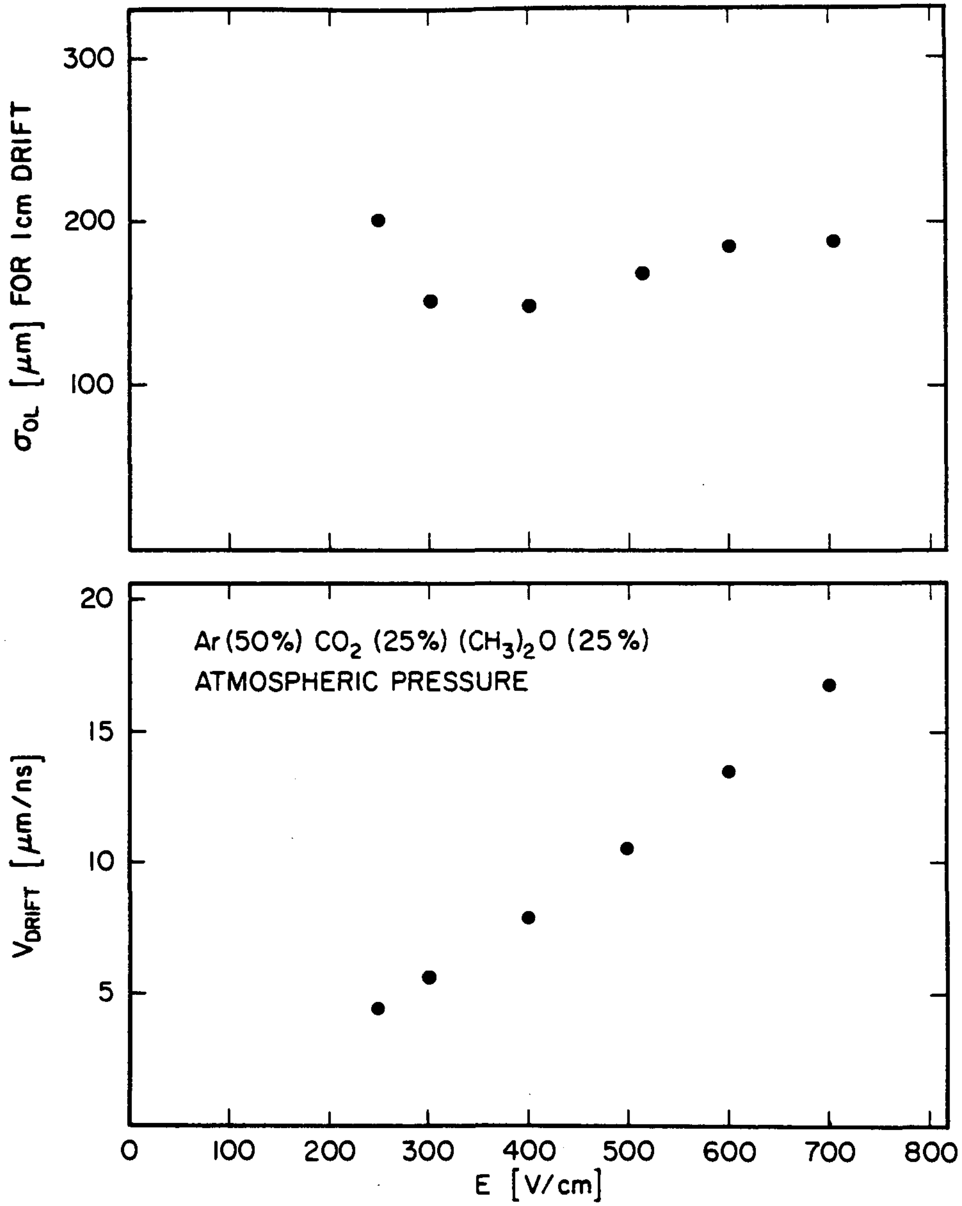


Fig. 39 Fehlmann et al. (1983)

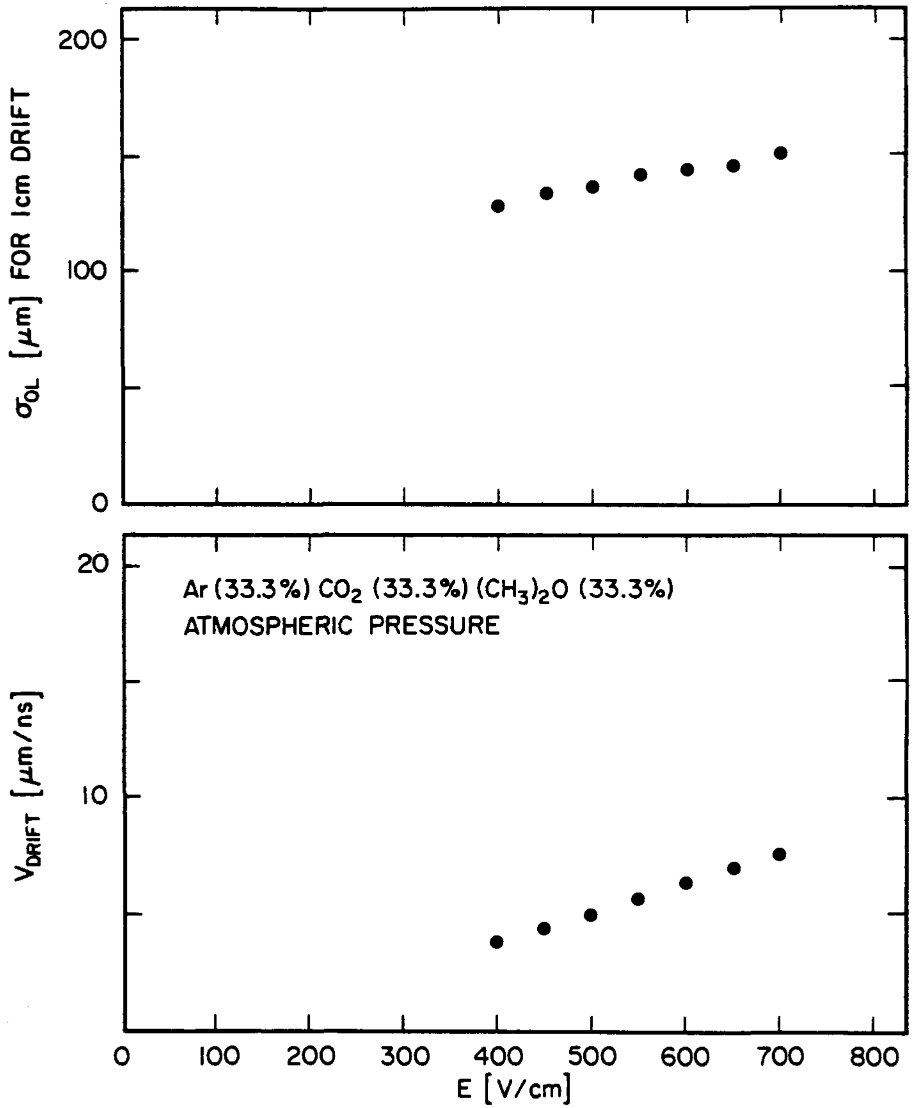


Fig. 40 Fehlman et al. (1983)

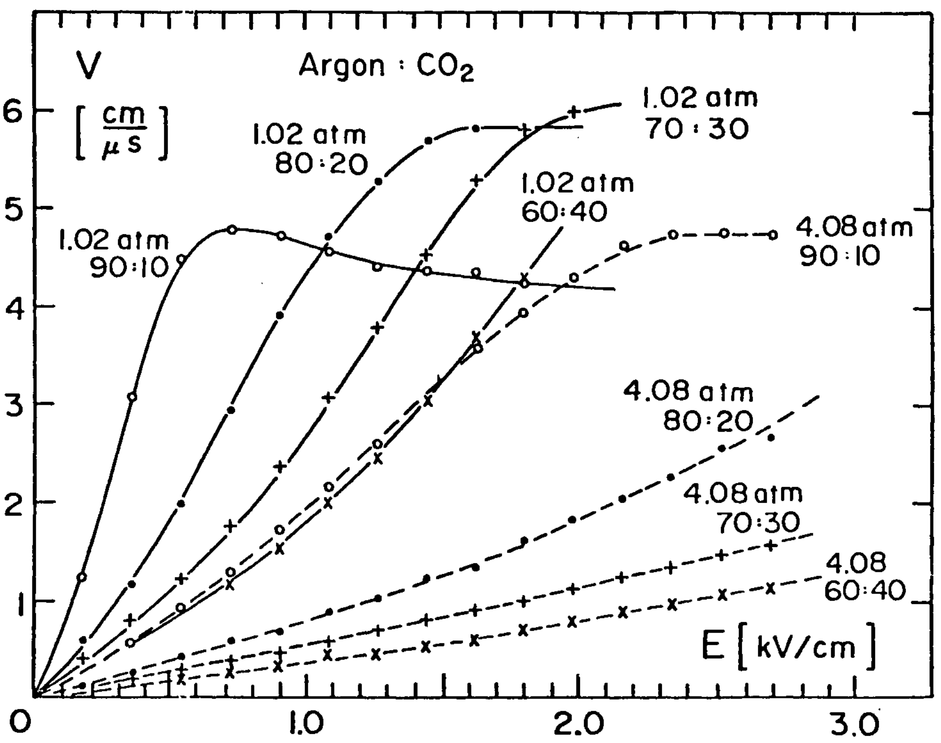


Fig. 41 Ma et al. (1982)

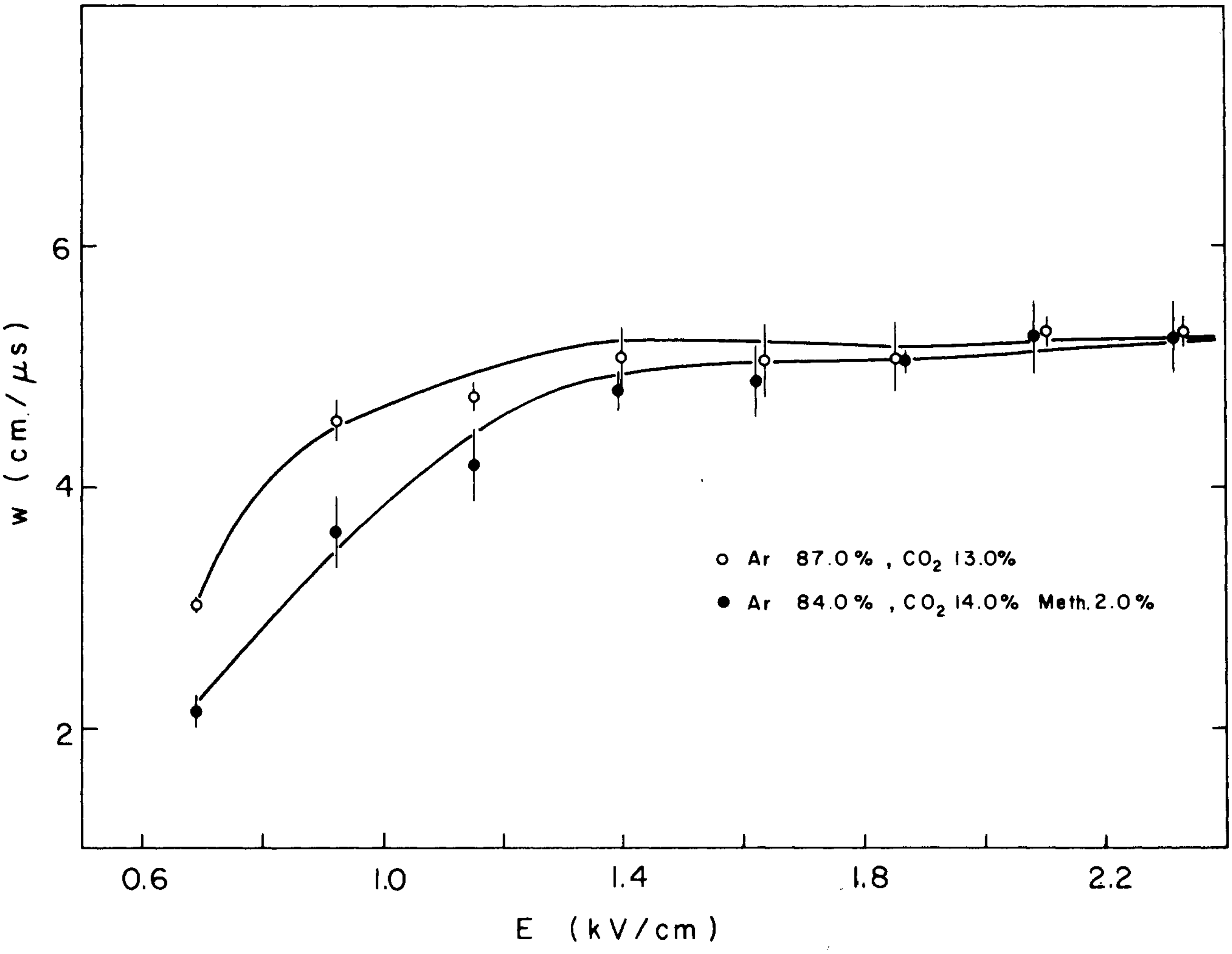


Fig. 42 Ezban and Morganti (1974)

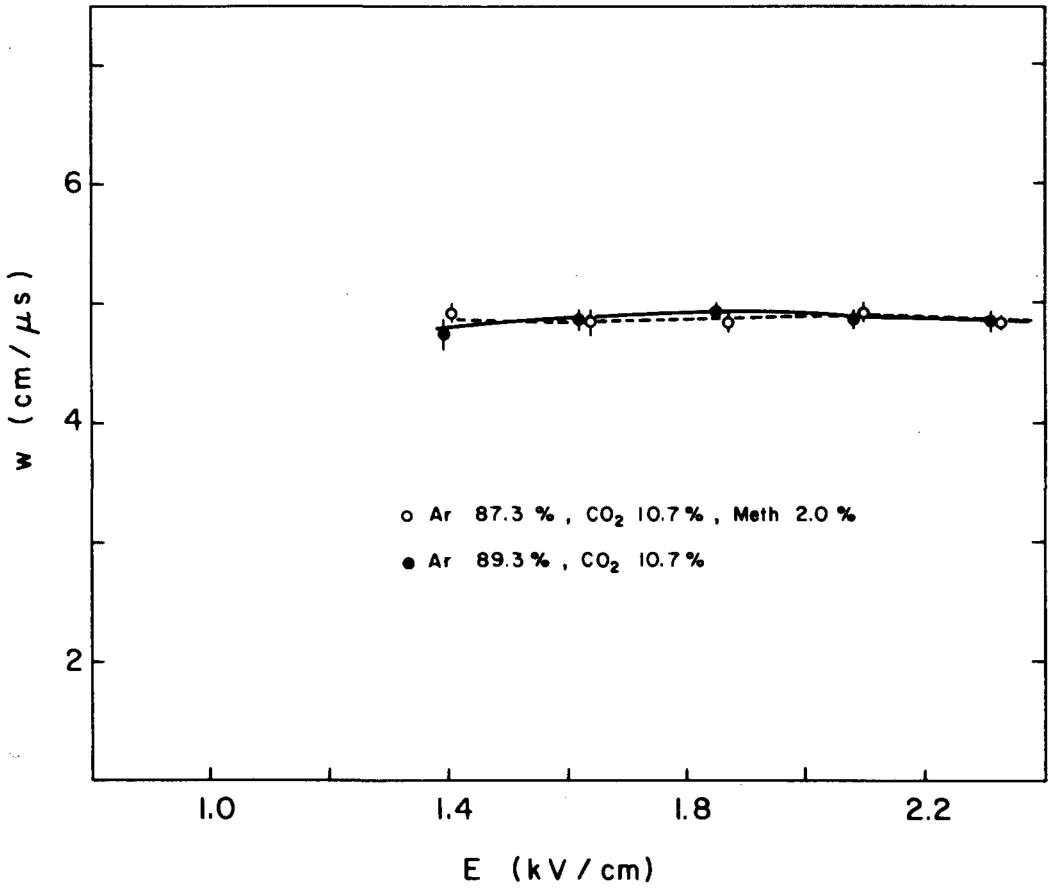


Fig. 43 Ezban and Morganti (1974)

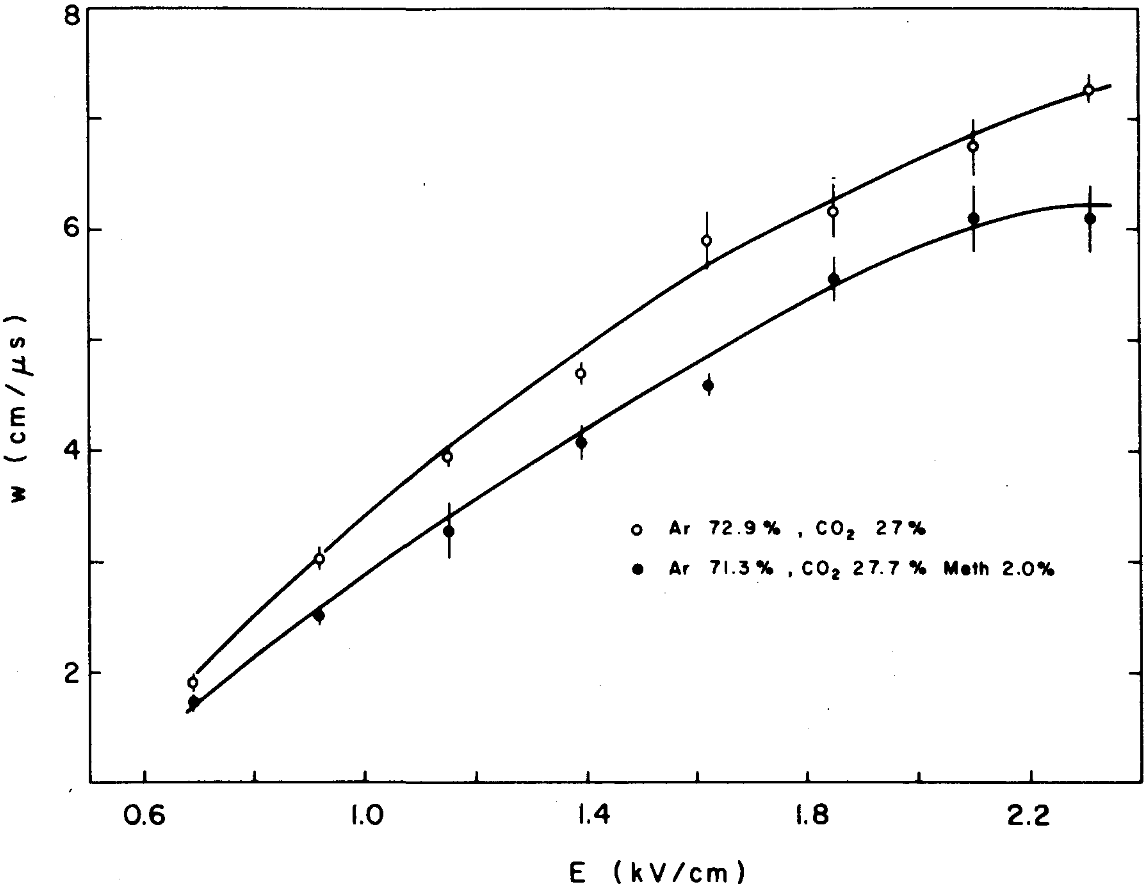


Fig. 44 Ezban and Morganti (1974)

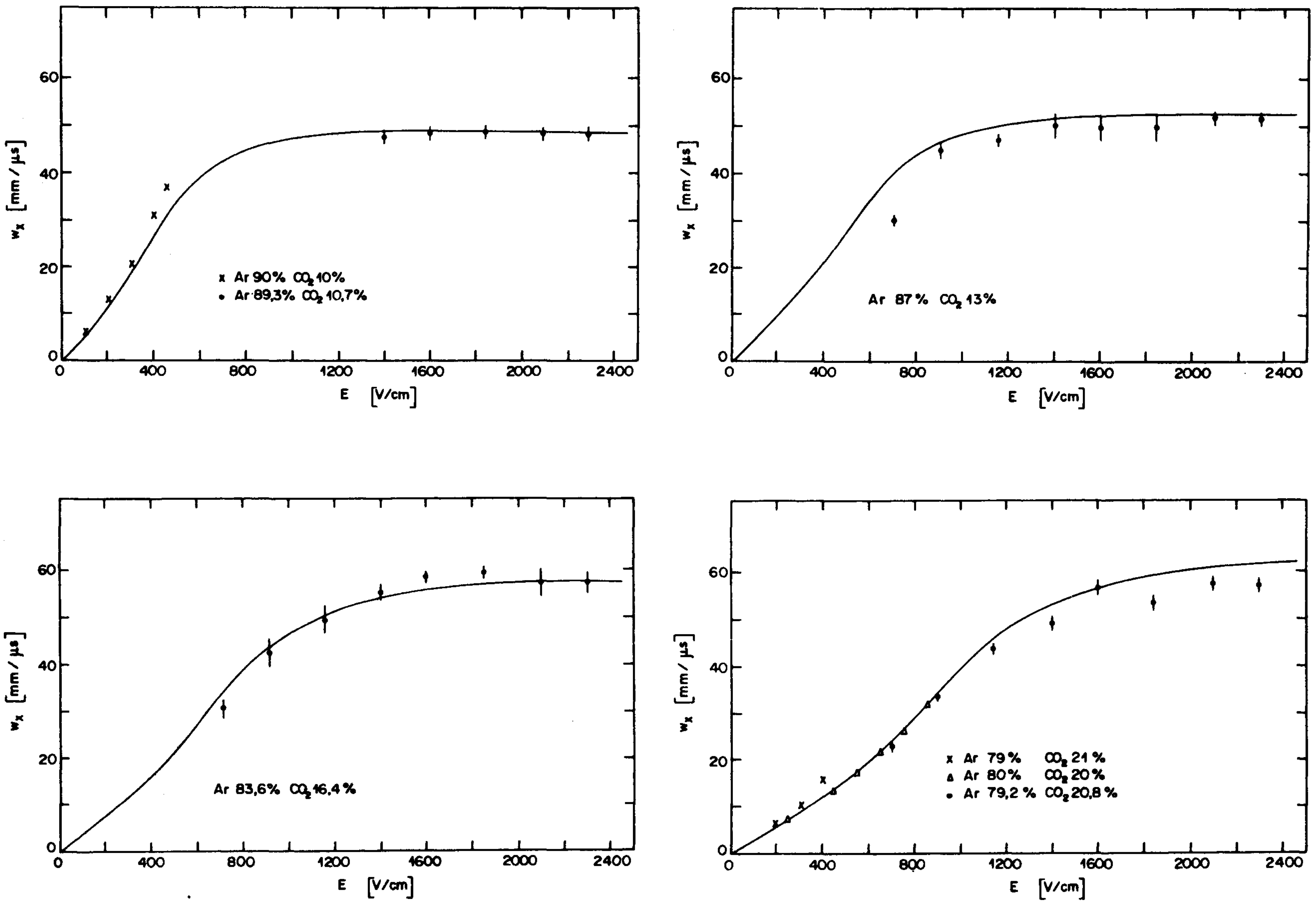


Fig. 45 Schultz (1976)

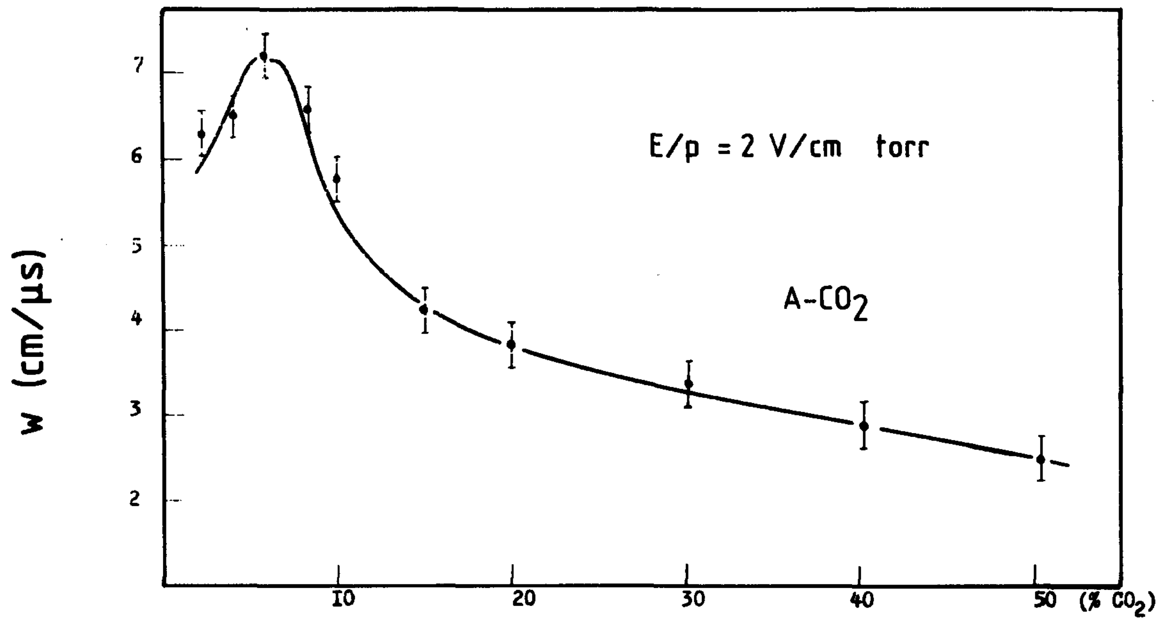


Fig. 46 Krasnow et al. (1976)

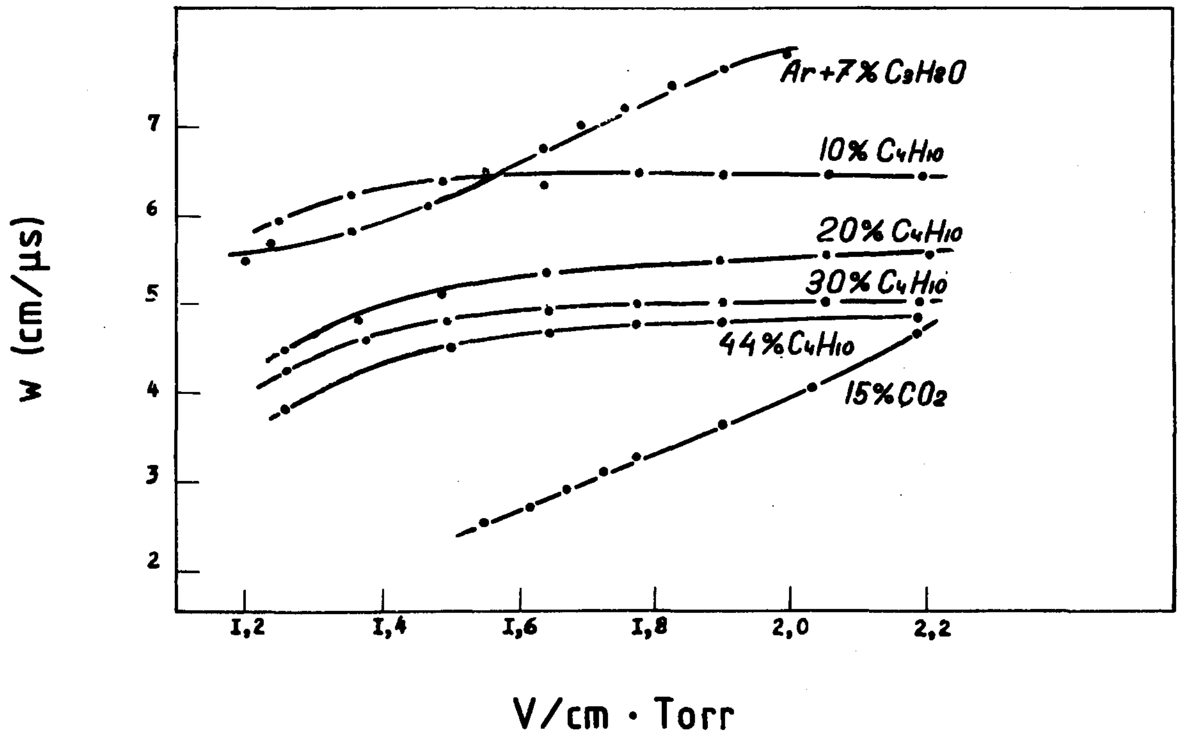


Fig. 47 Krasnow et al. (1976)

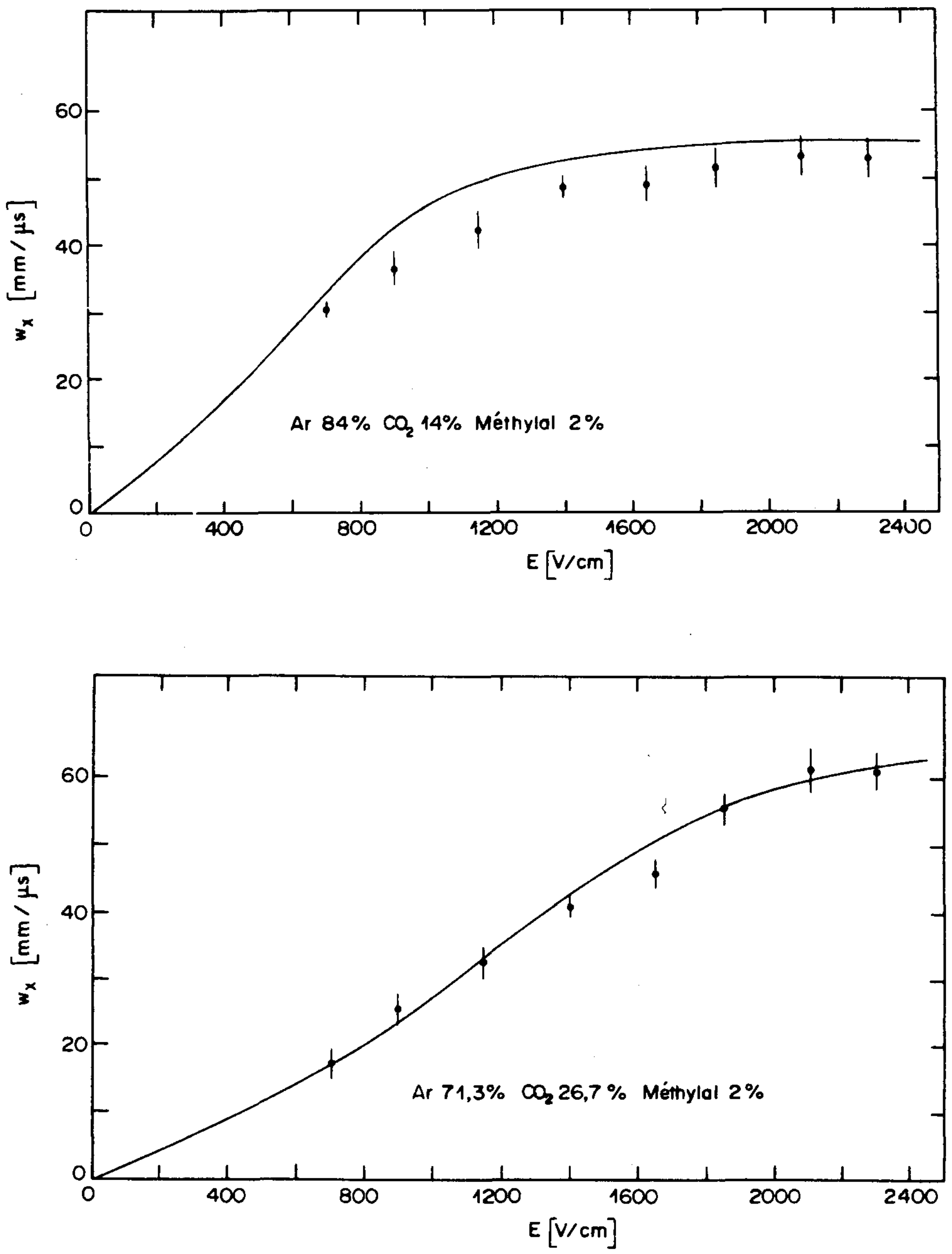


Fig. 48 Schultz (1976)

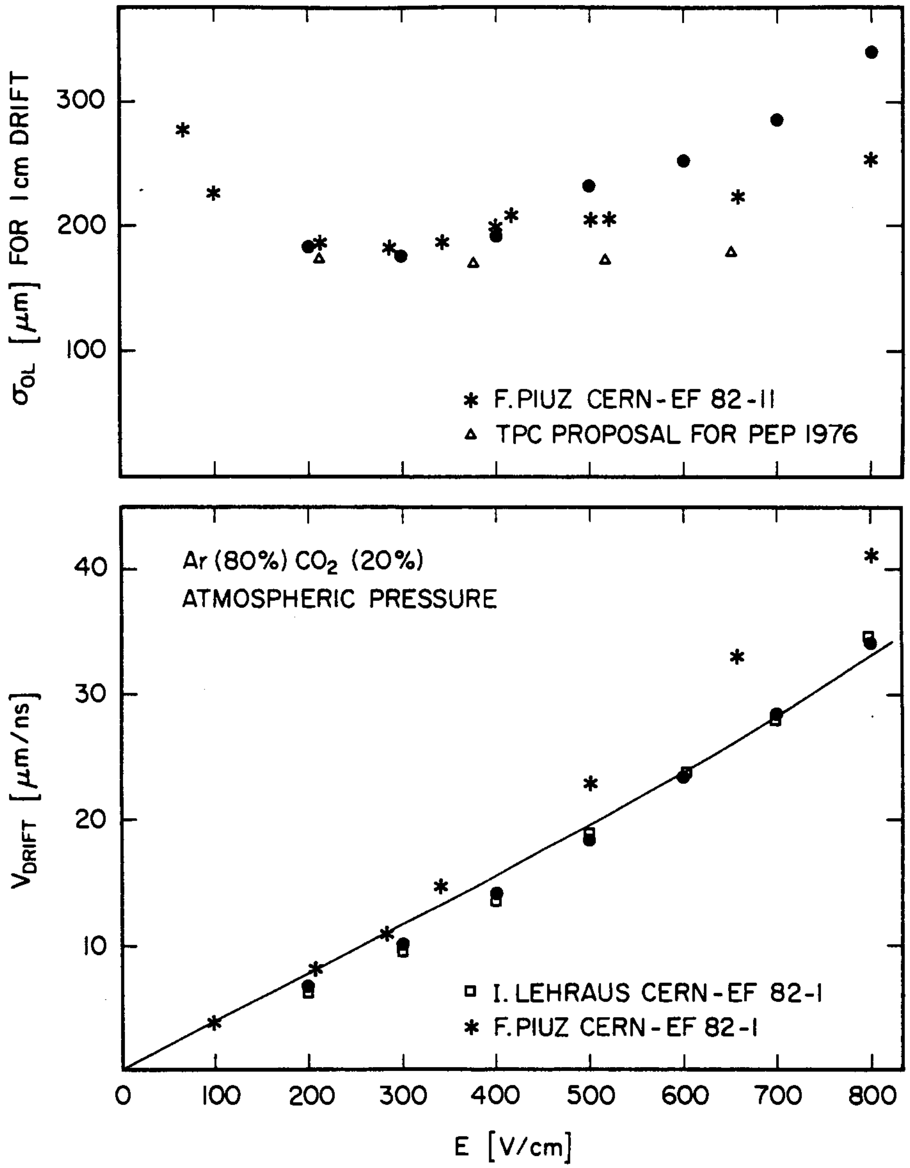


Fig. 49 Fehlman et al. (1983)

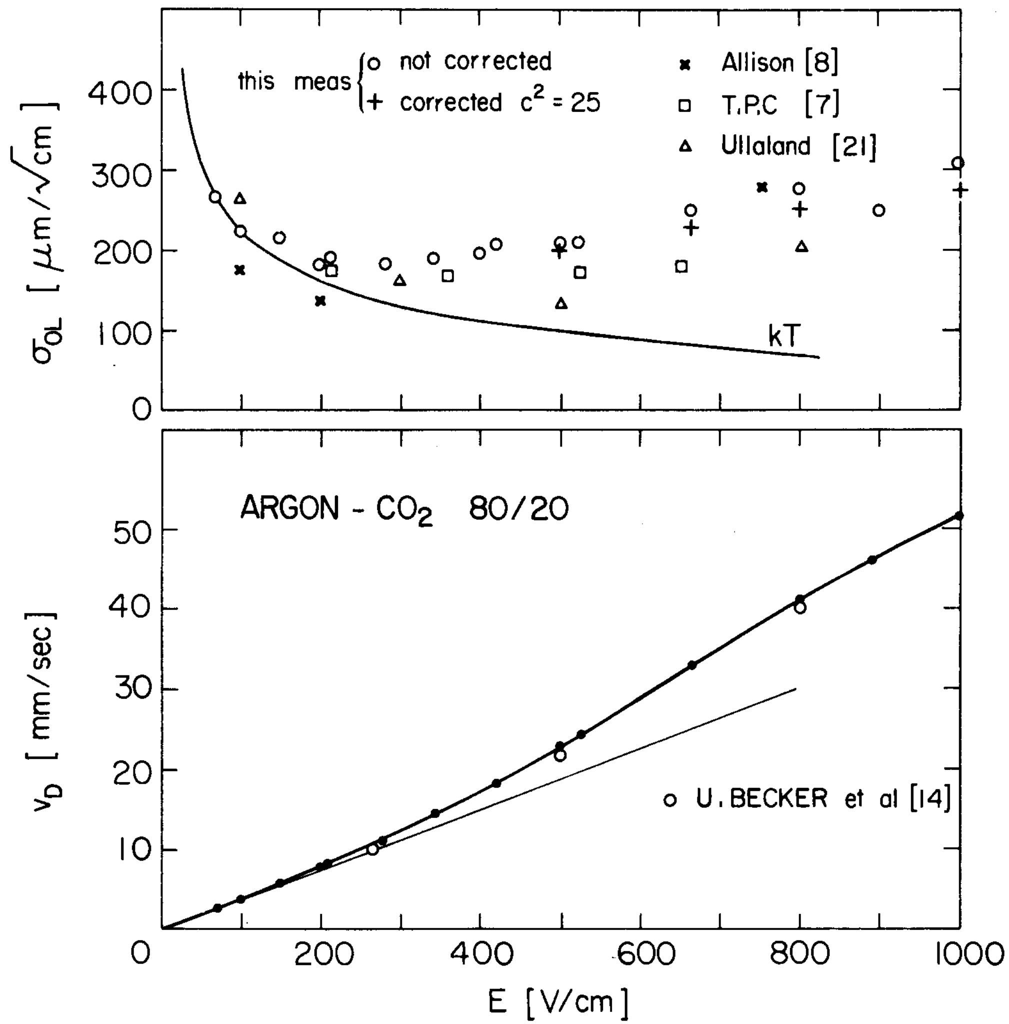


Fig. 50 Piuz (1983)

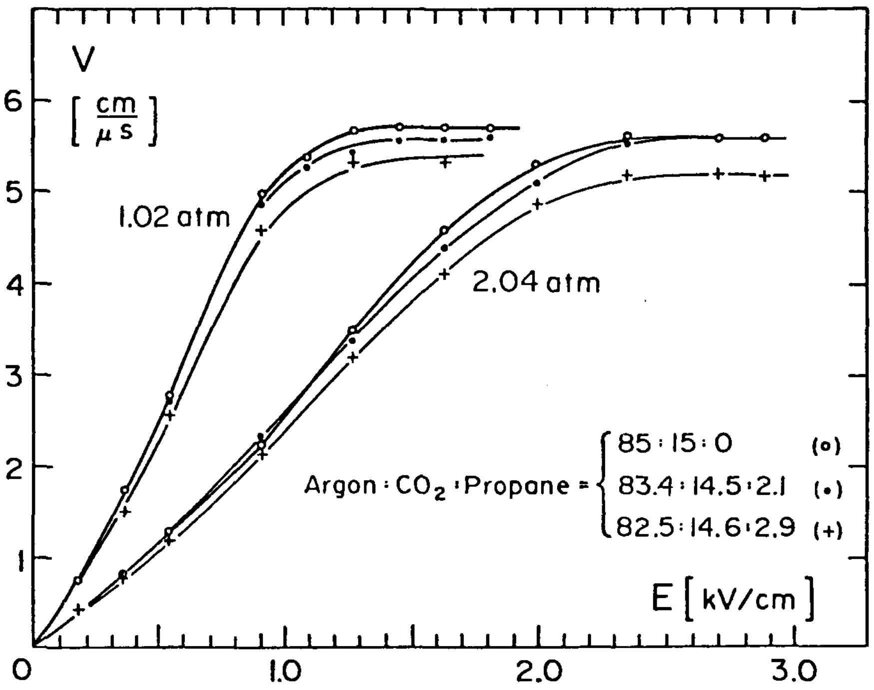


Fig. 51 Ma et al. (1982)

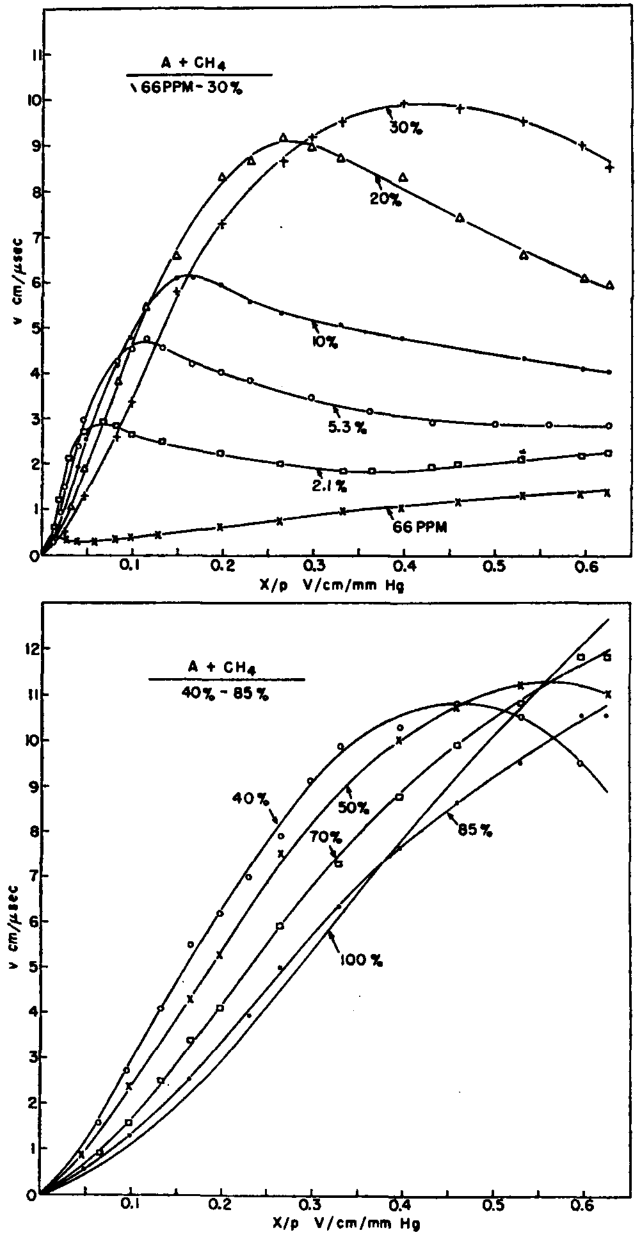
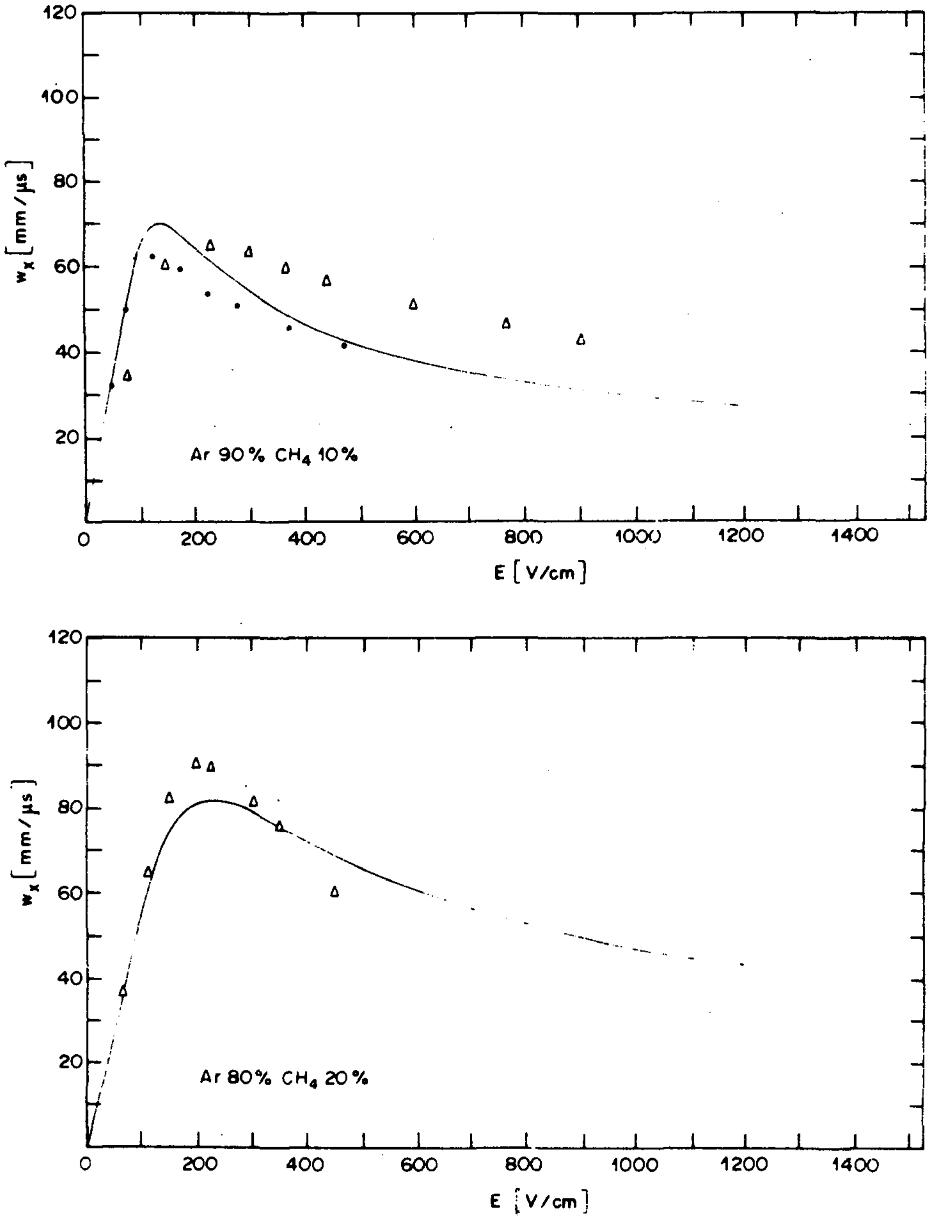


Fig. 52 English and Hanna (1953)



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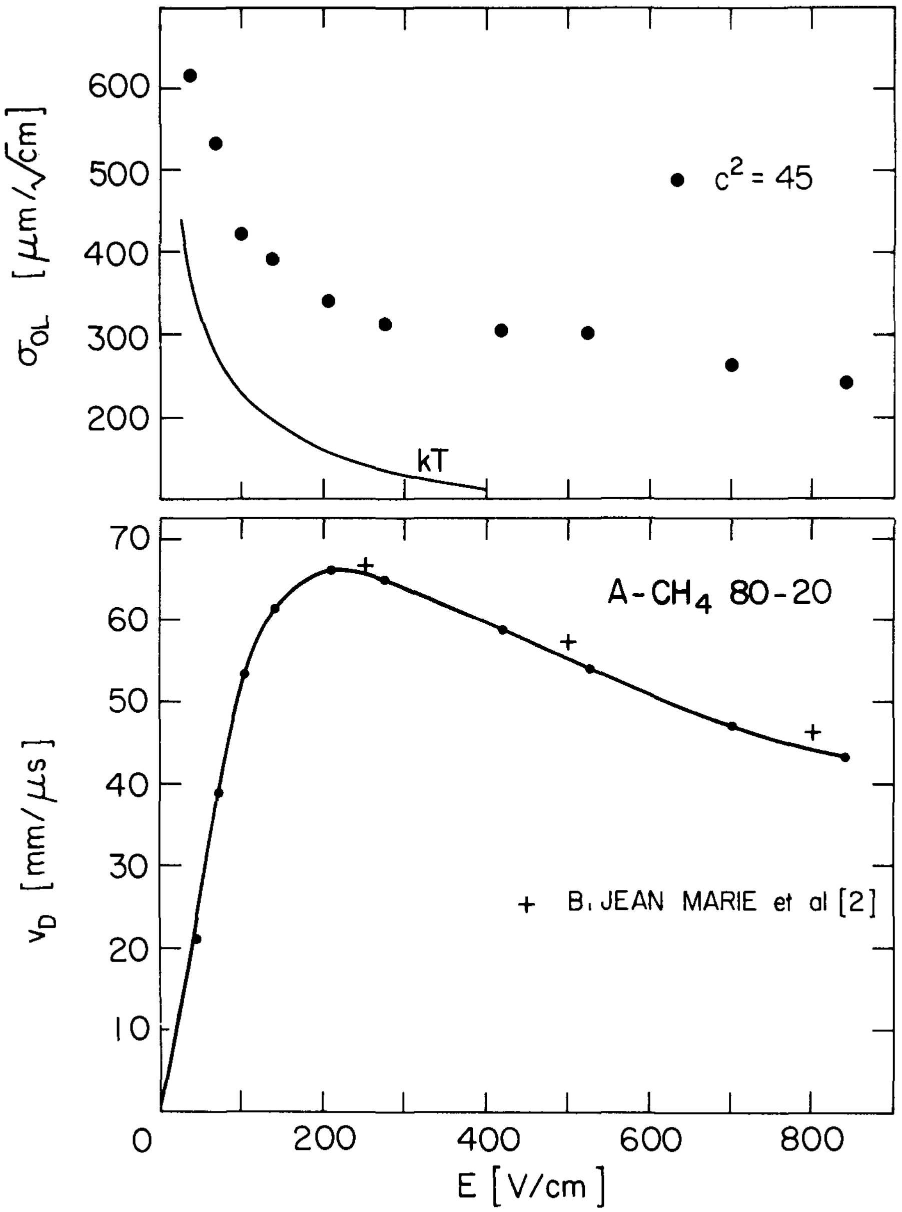

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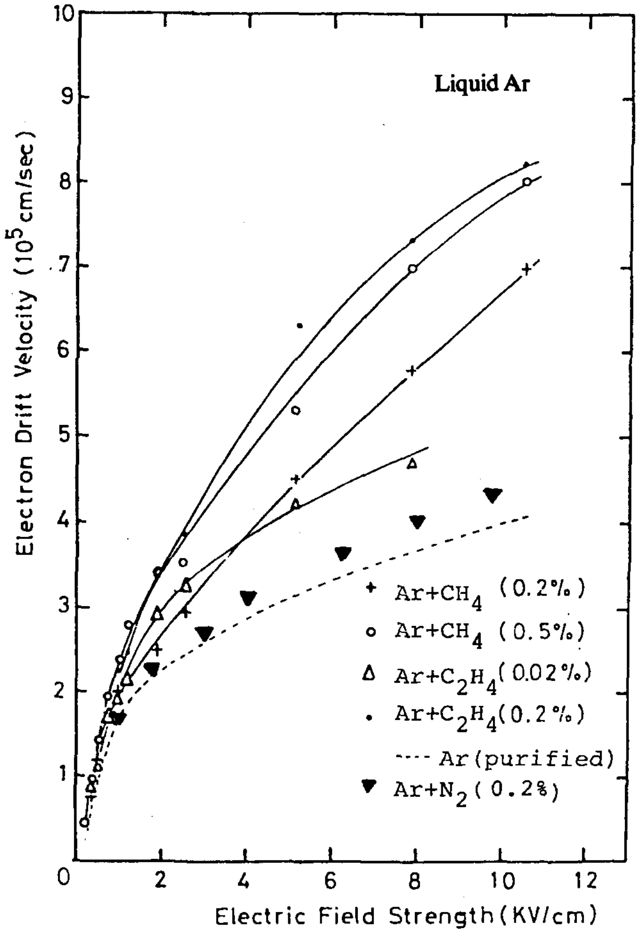


Fig. 55 Doke (1981)

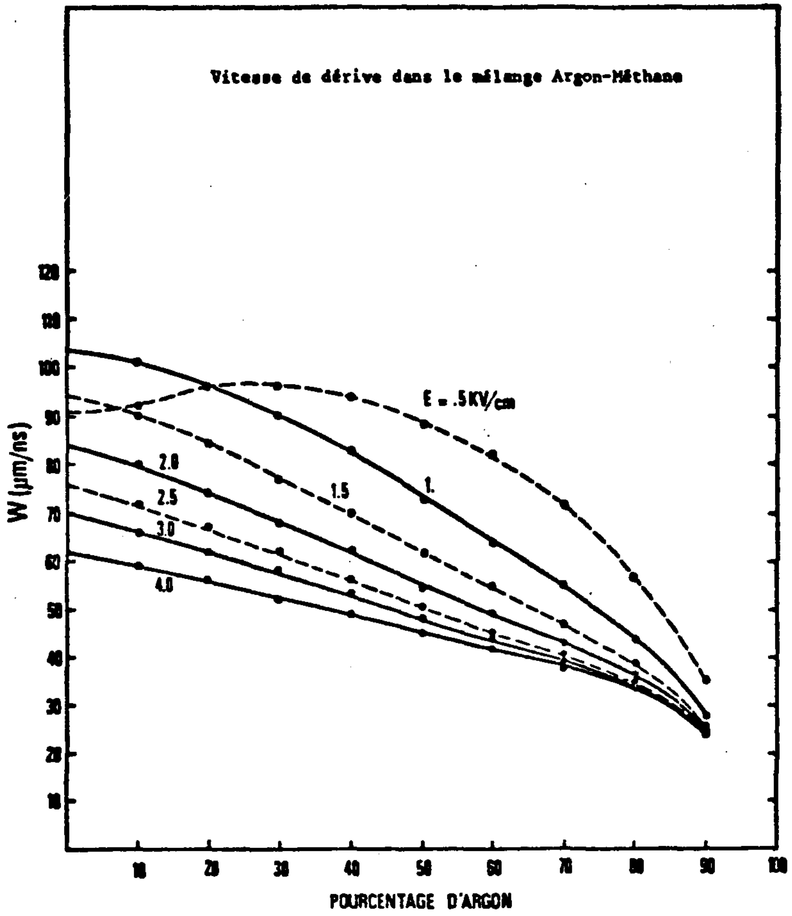


Fig. 56 L'Hôte (1978)

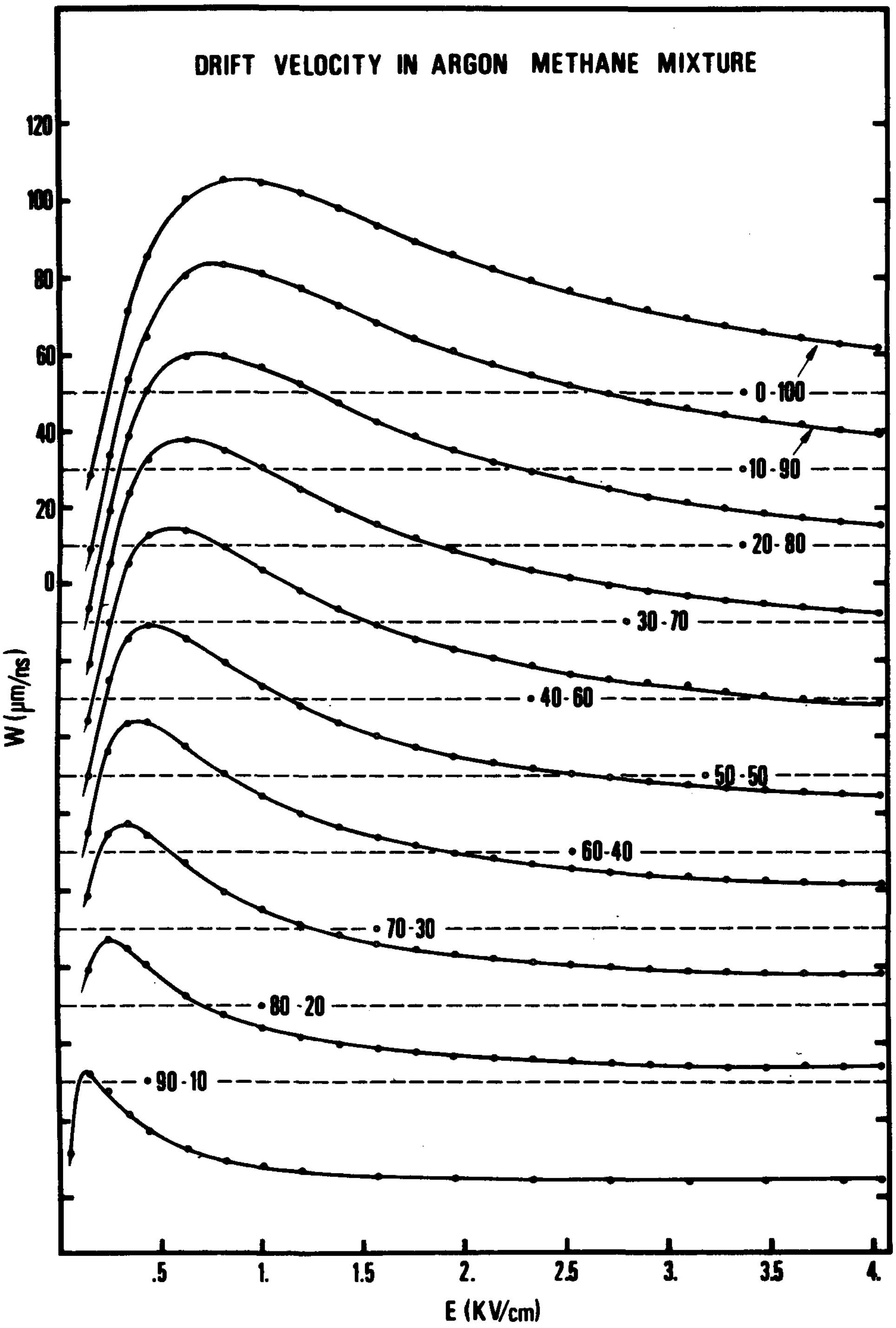


Fig. 57 Jean-Marie et al. (1979)

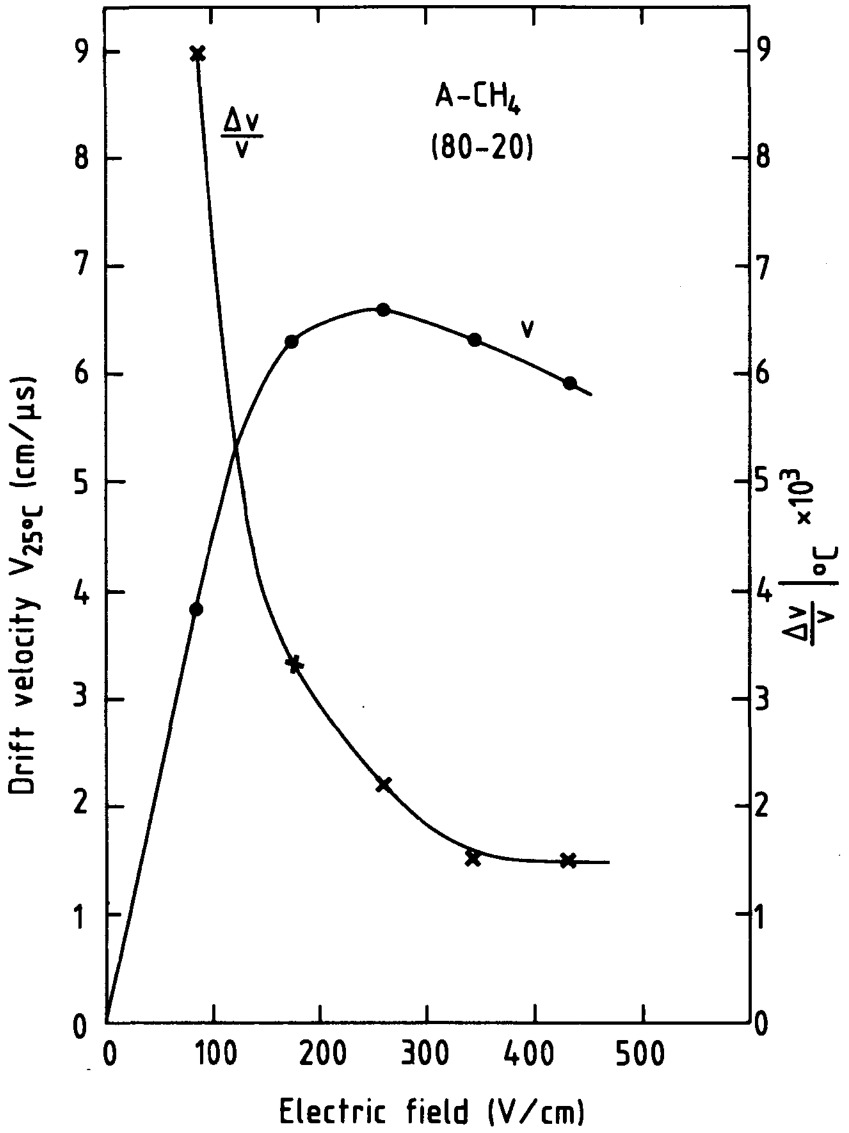
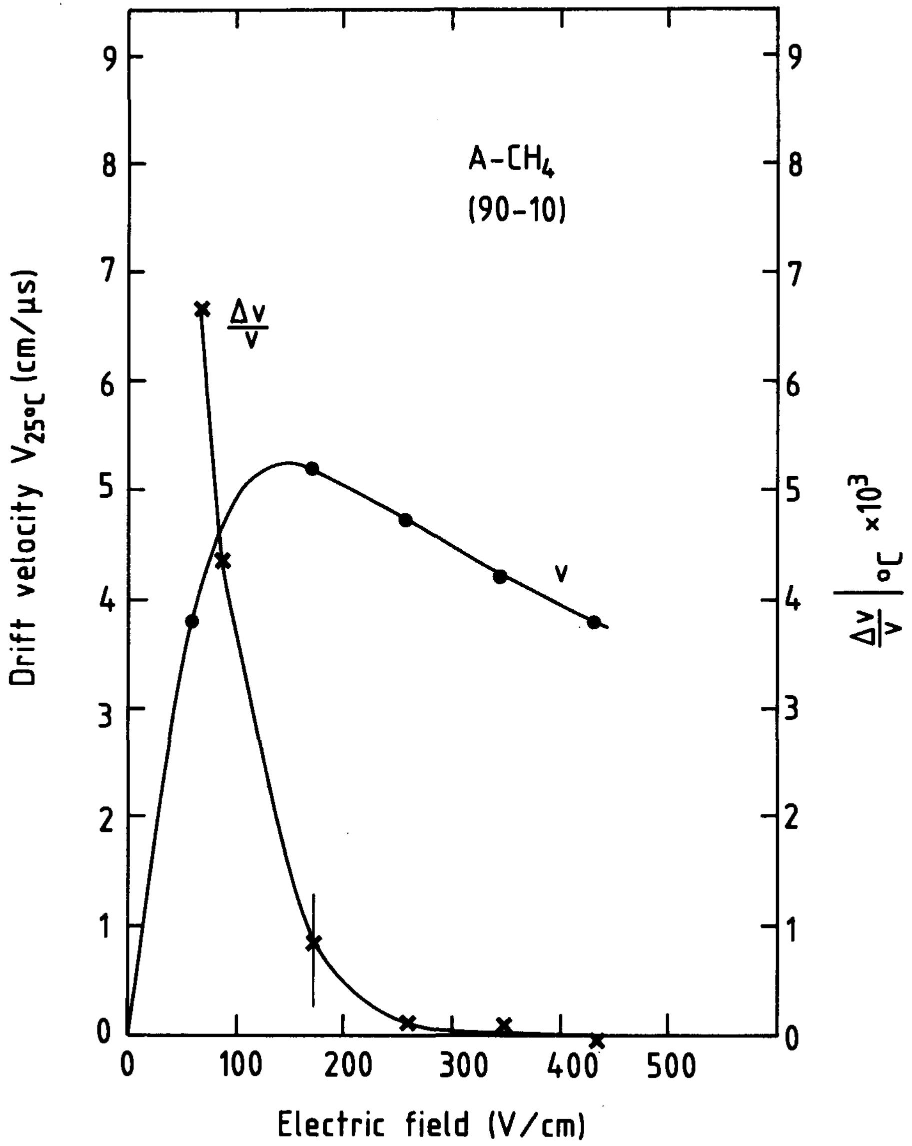


Fig. 58 Peisert and Sauli (1984)



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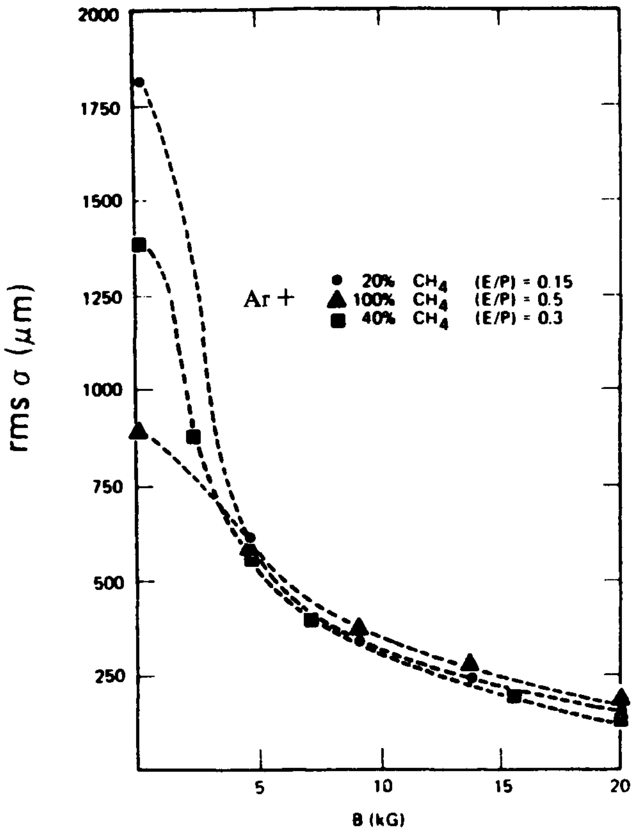
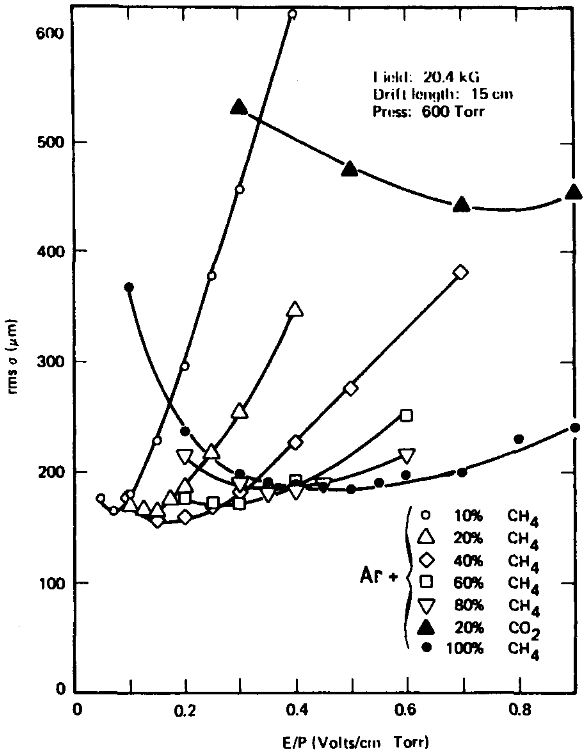


Fig. 60 Clark et al. (1974)



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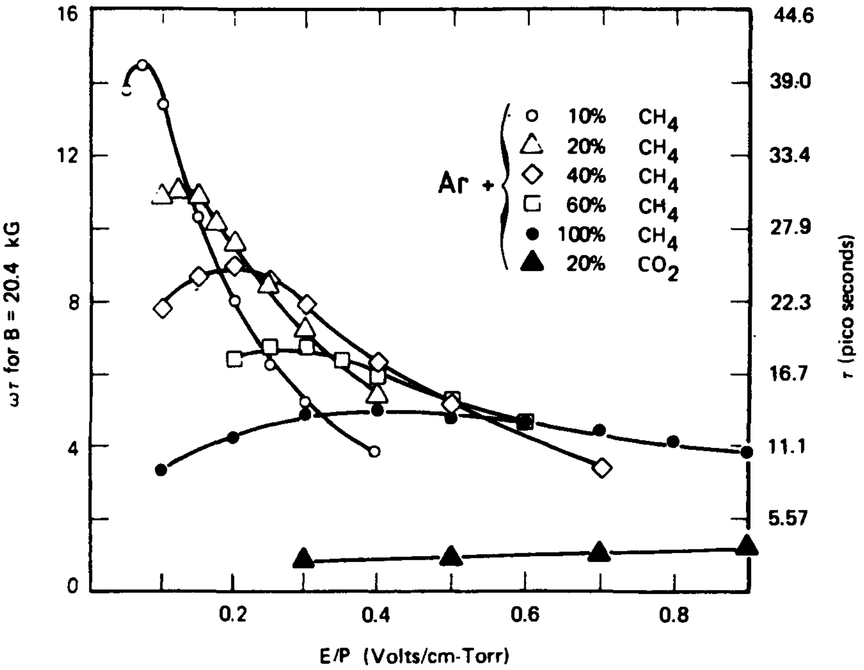

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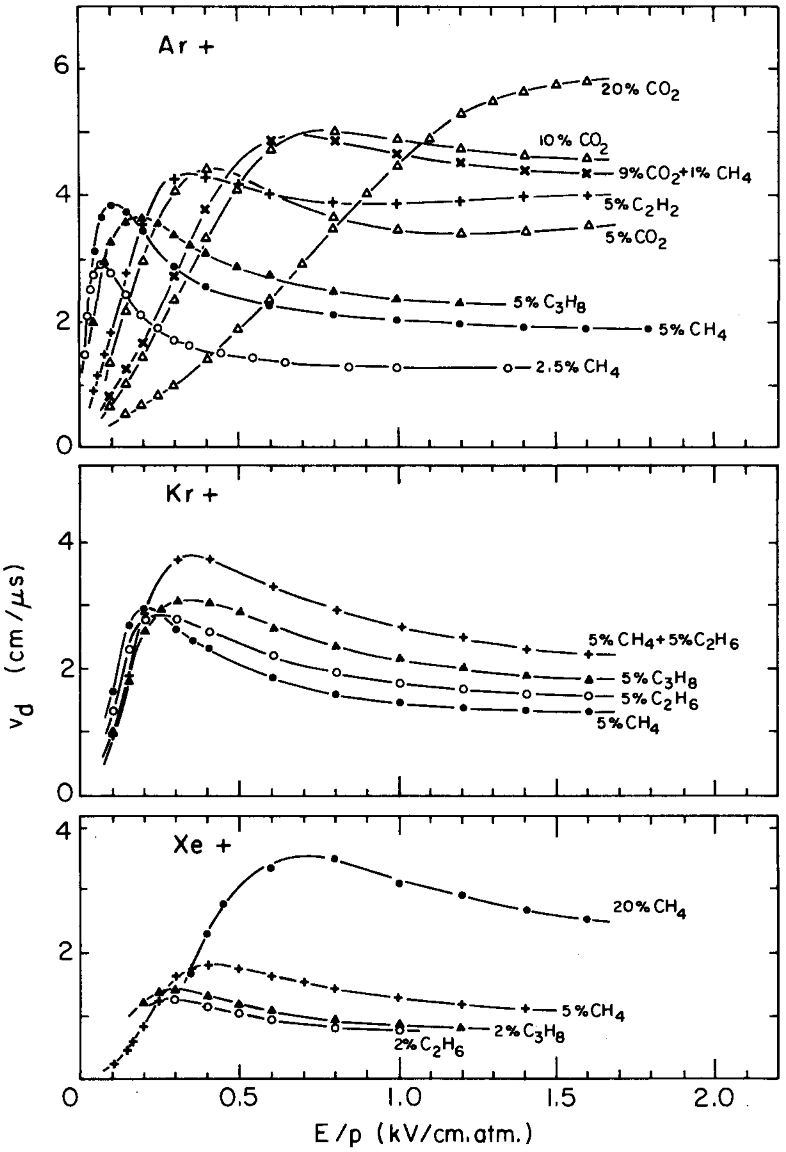


Fig. 63 Lehraus et al. (1983)

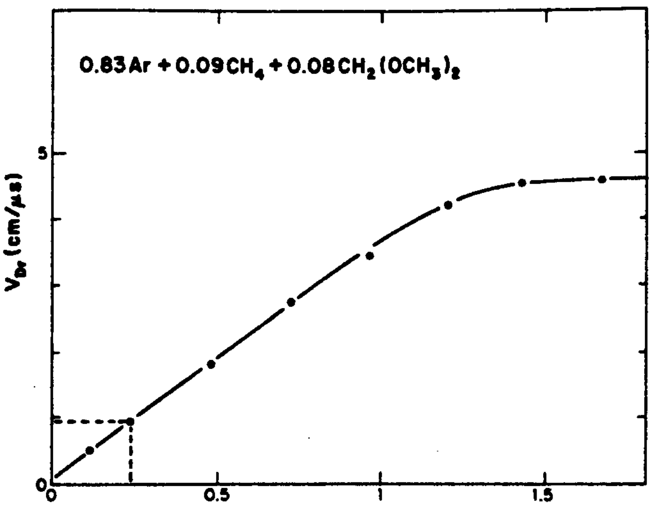


Fig. 64 Walenta (1979)

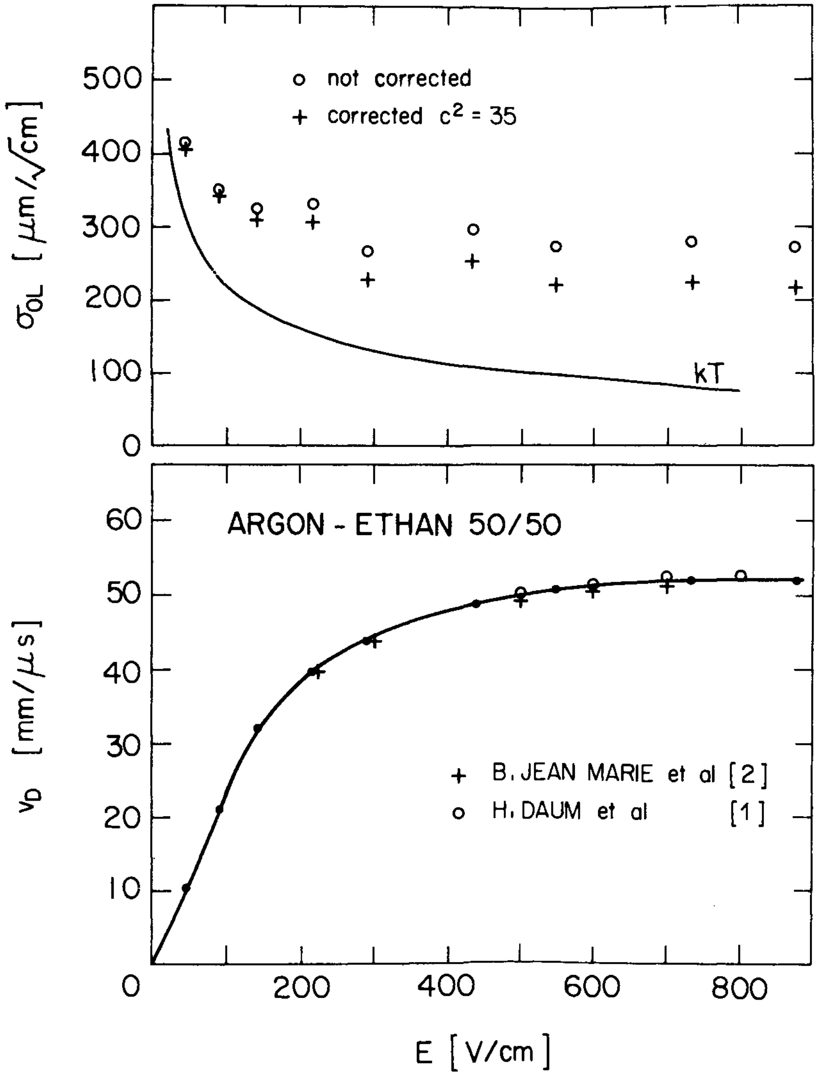


Fig. 65 Piuz (1983)

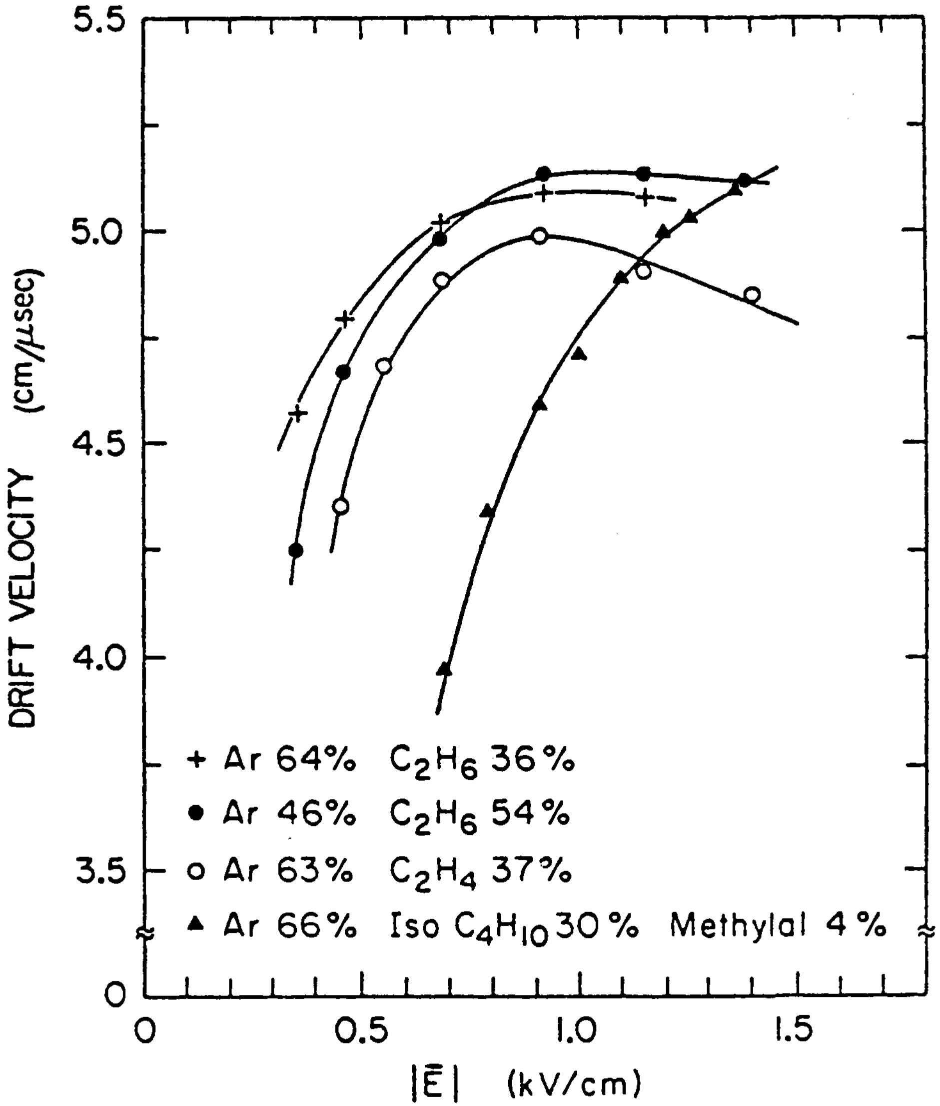


Fig. 66 Jaros (1980)

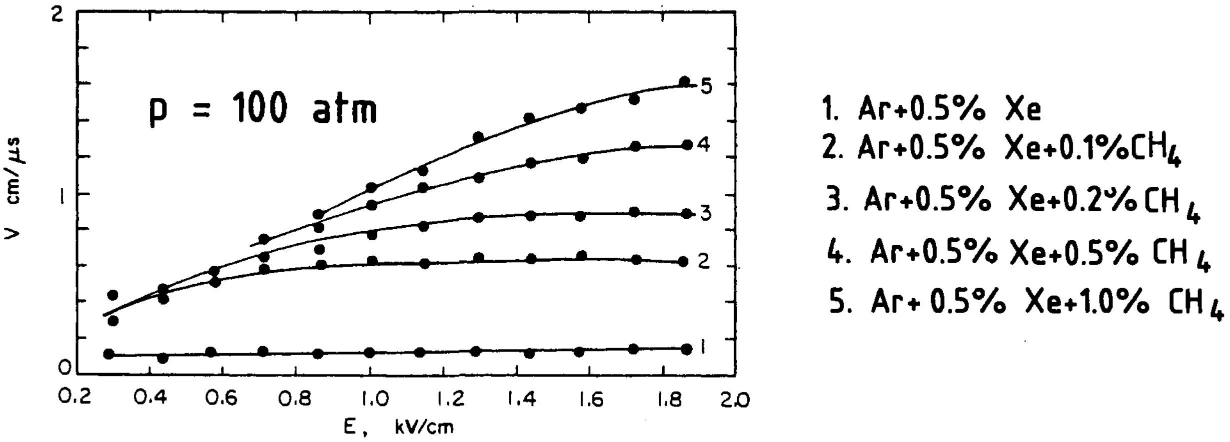


Fig. 67 Chernyatin (1979)

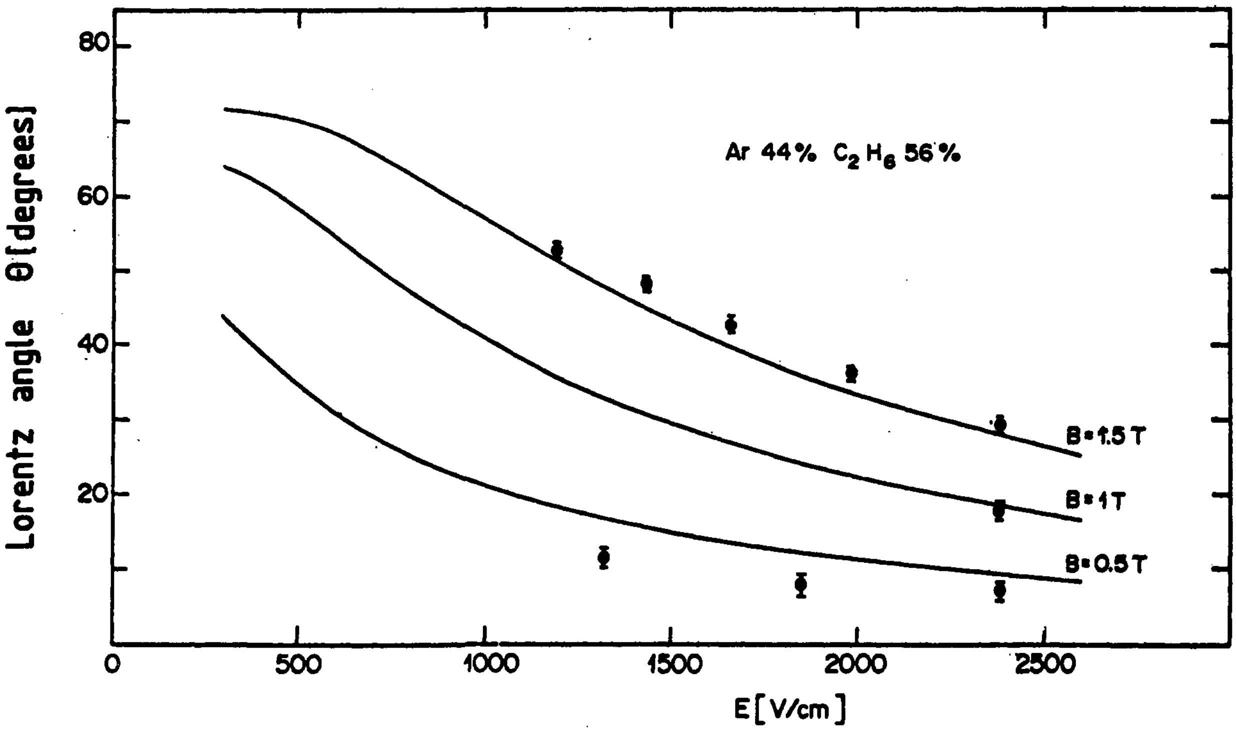


Fig. 68 Ramanantsizehena (1979)

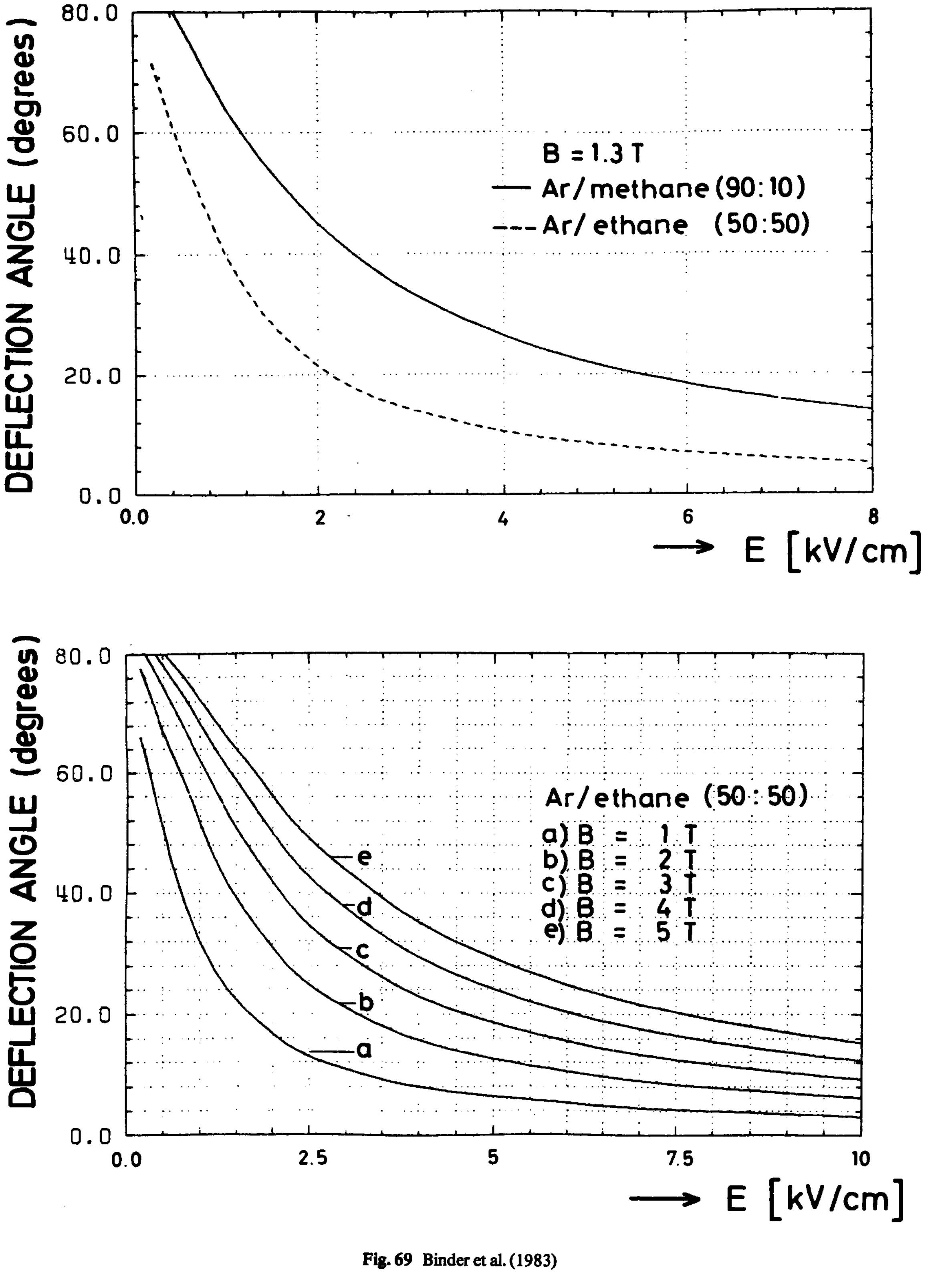
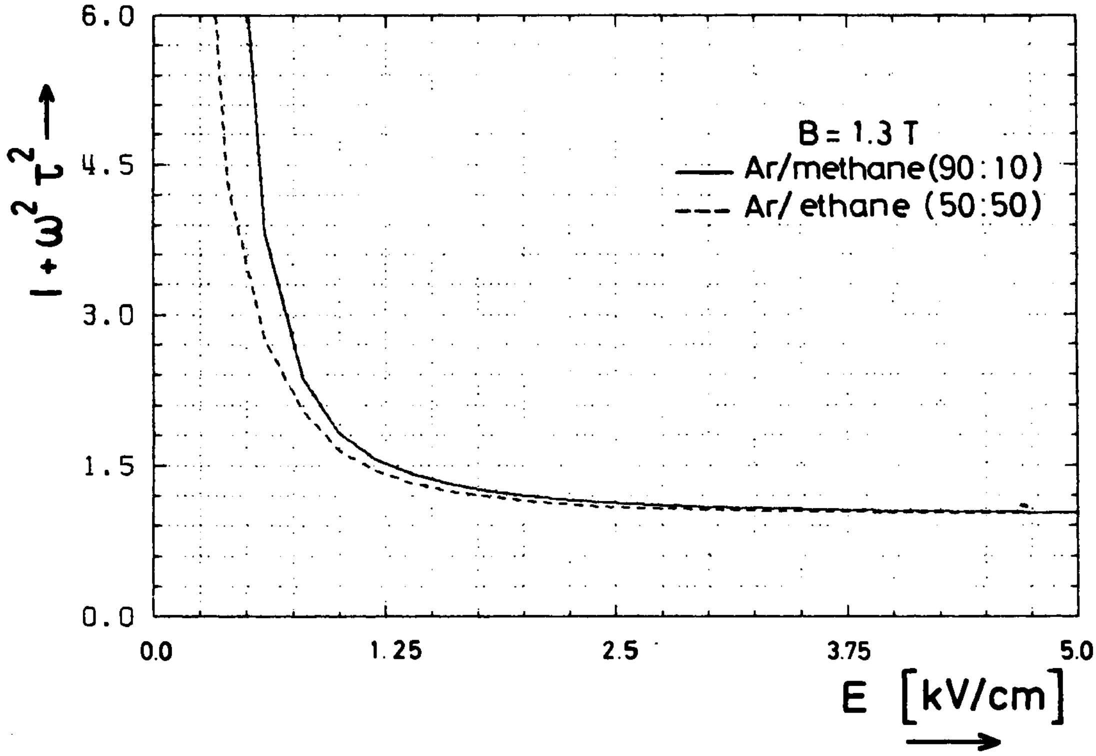


Fig. 69 Binder et al. (1983)



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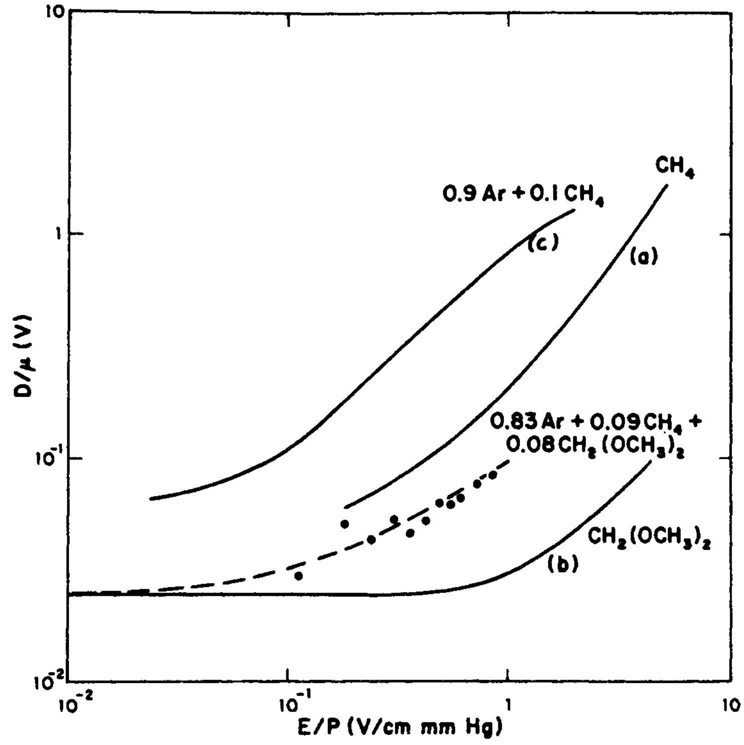

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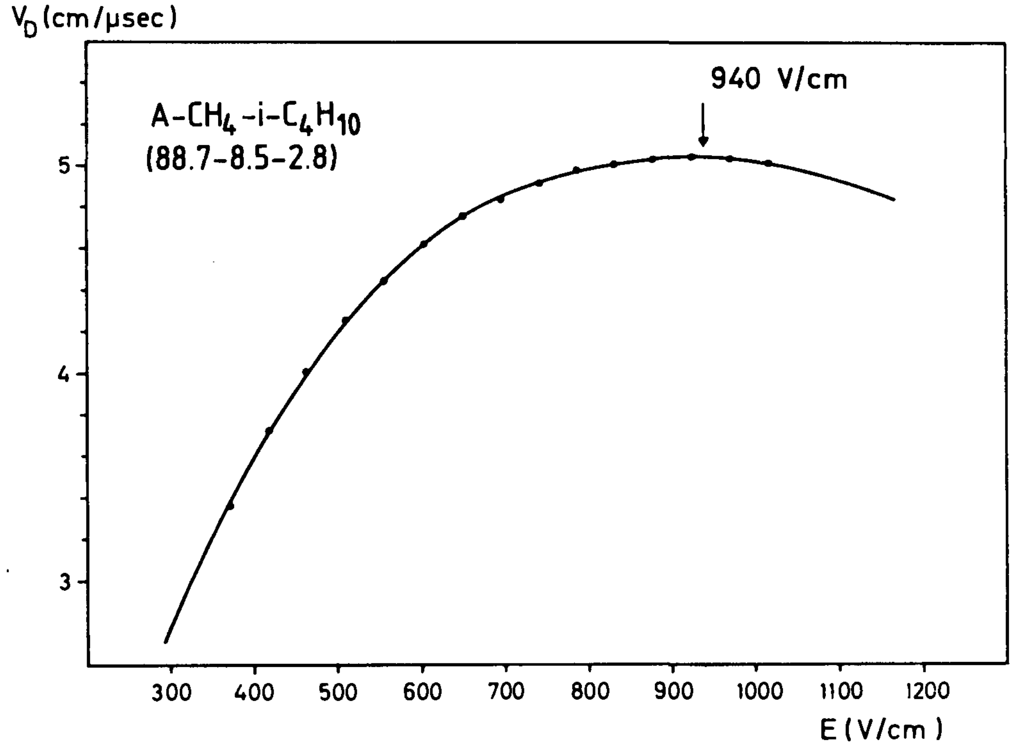

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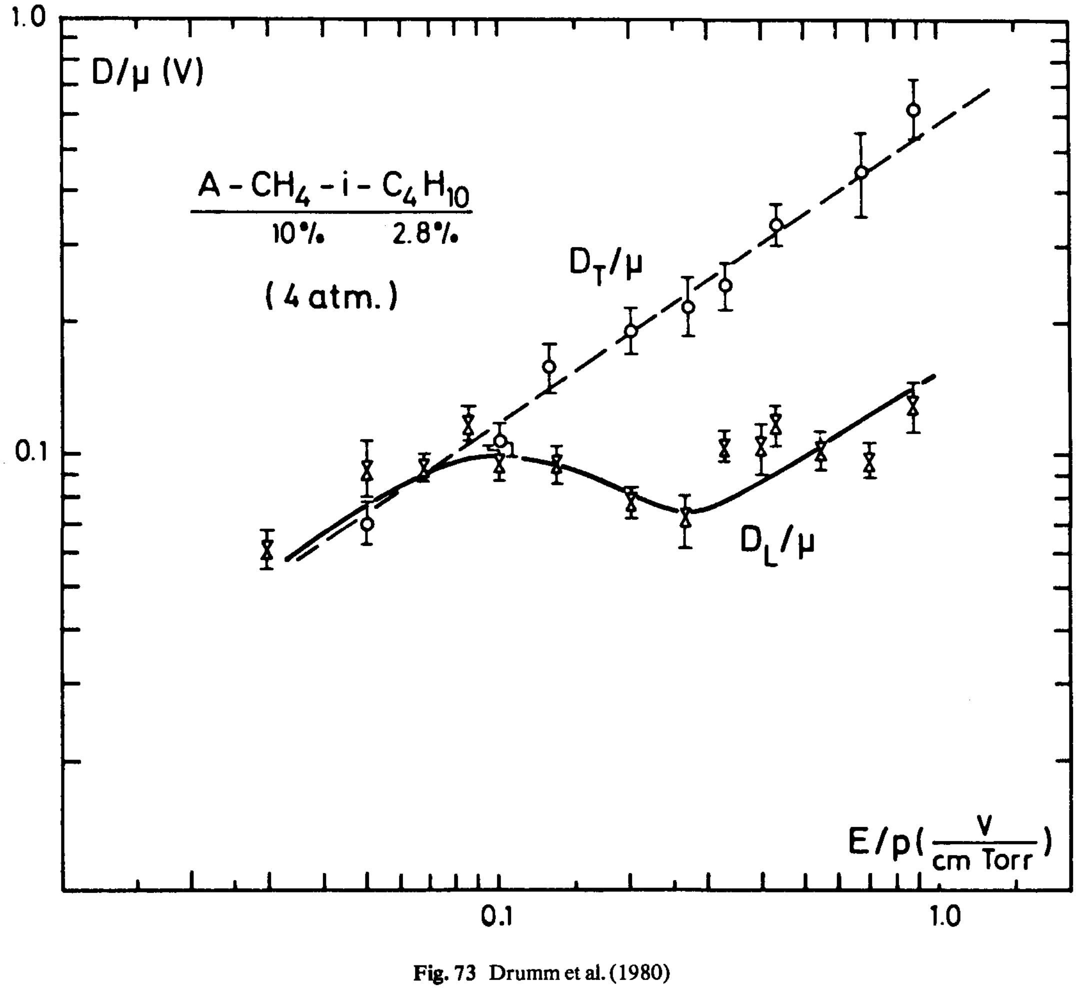

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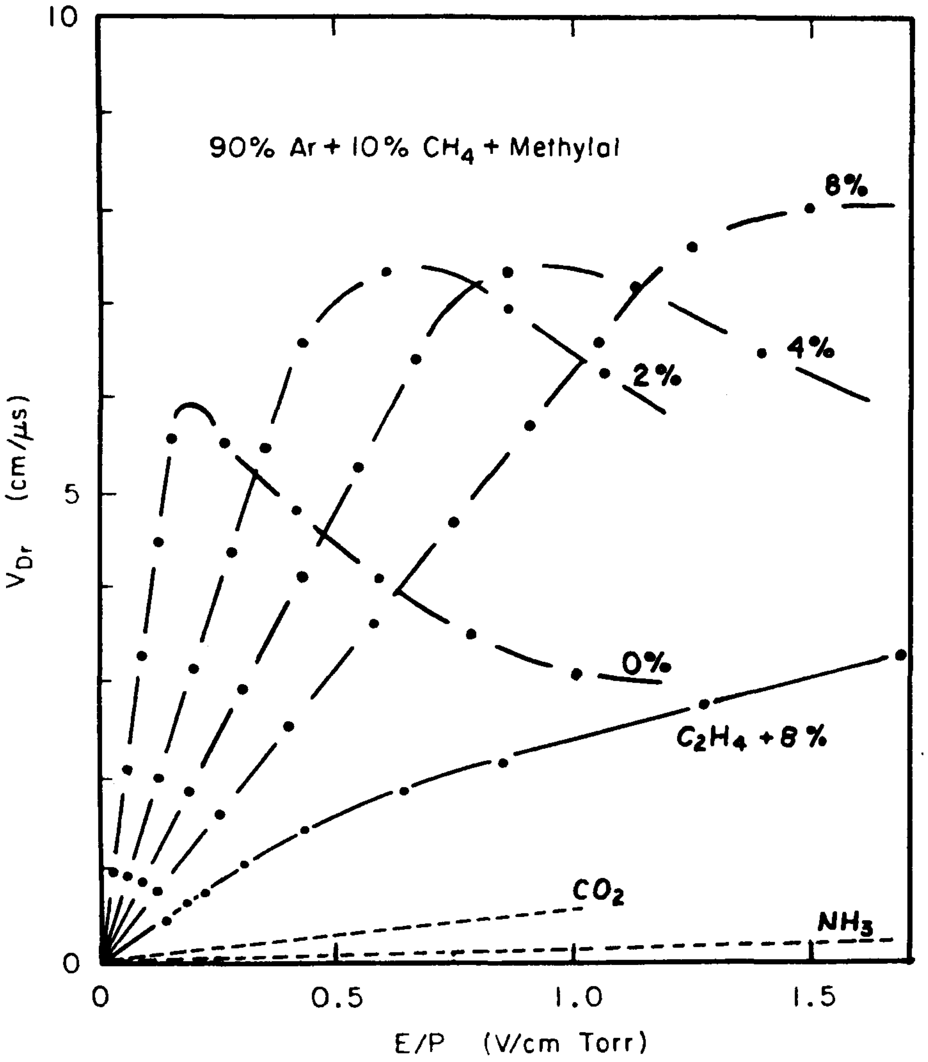

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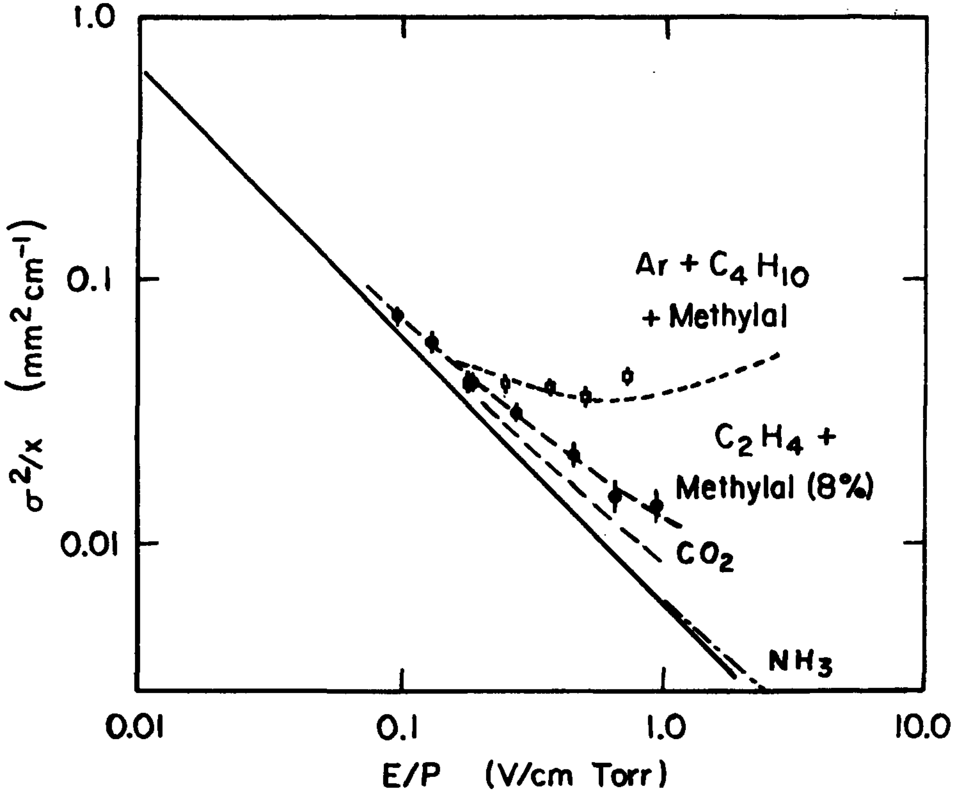

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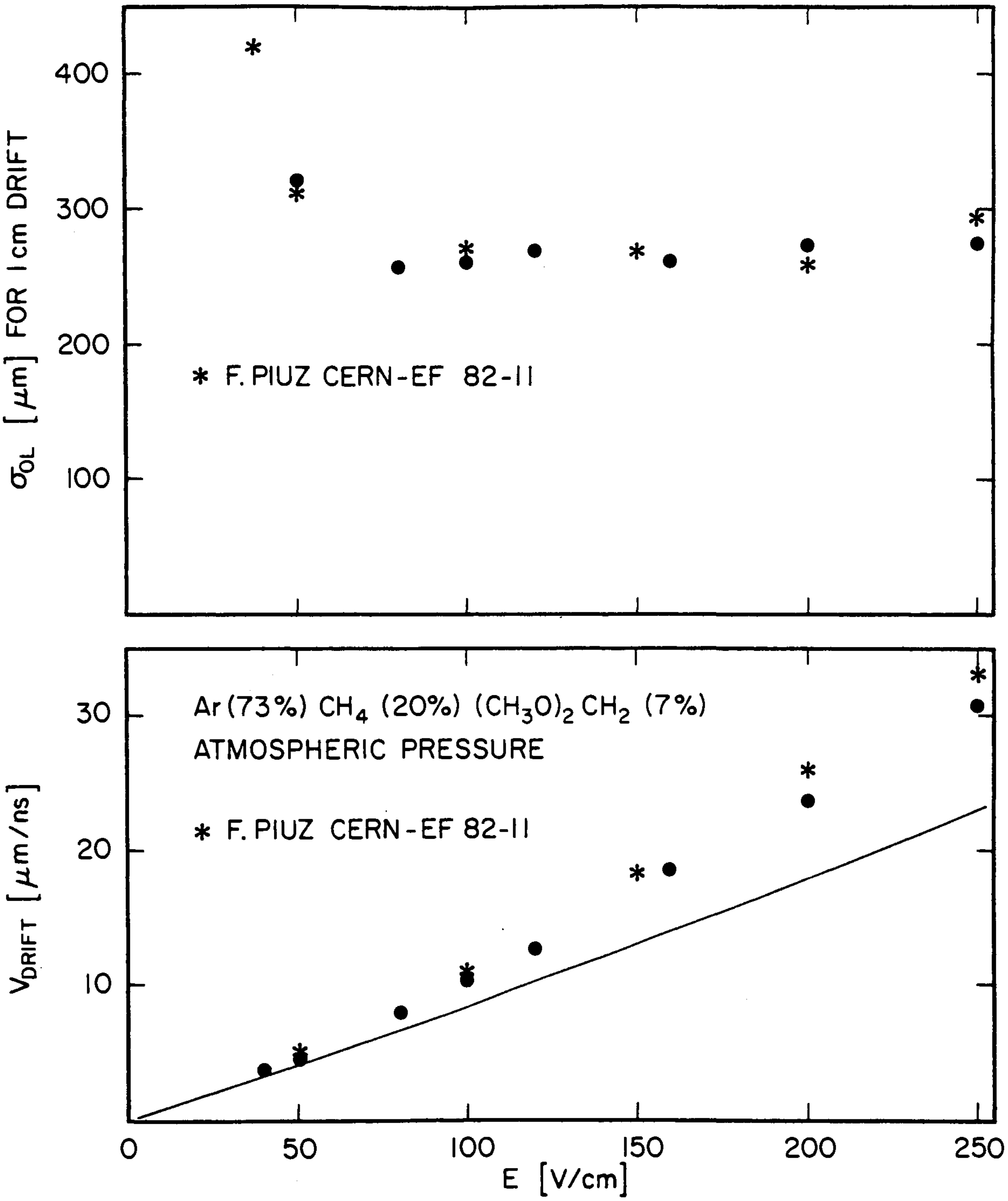


Fig. 76 Fehlman et al. (1983)

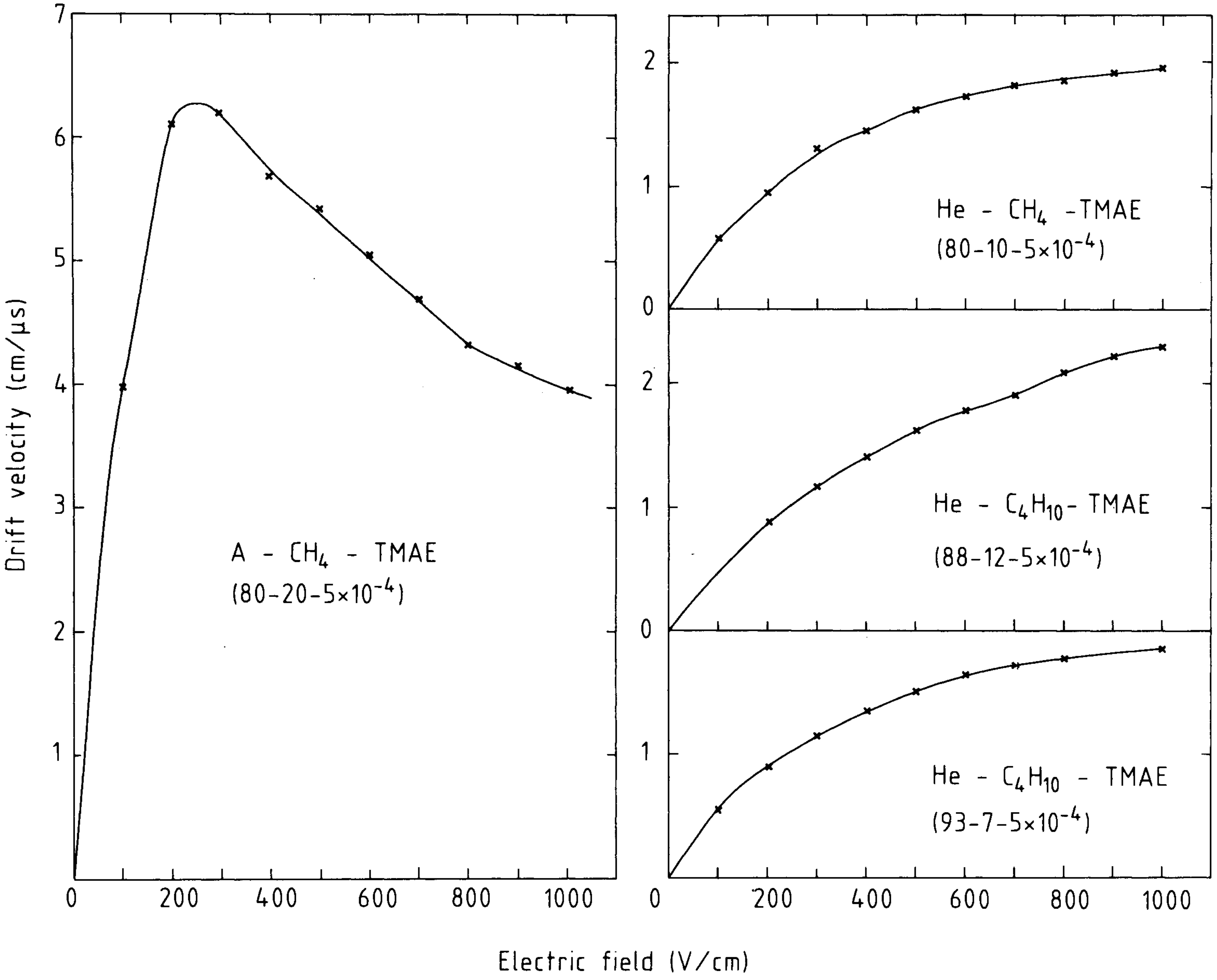
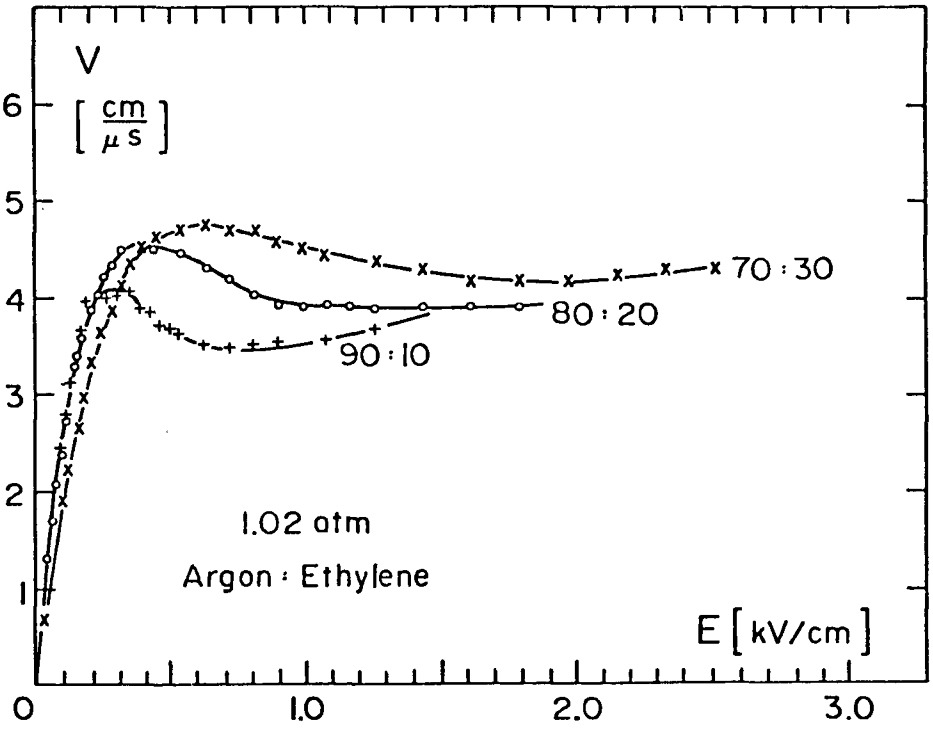


Fig. 77 Charpak and Sauli (1983)



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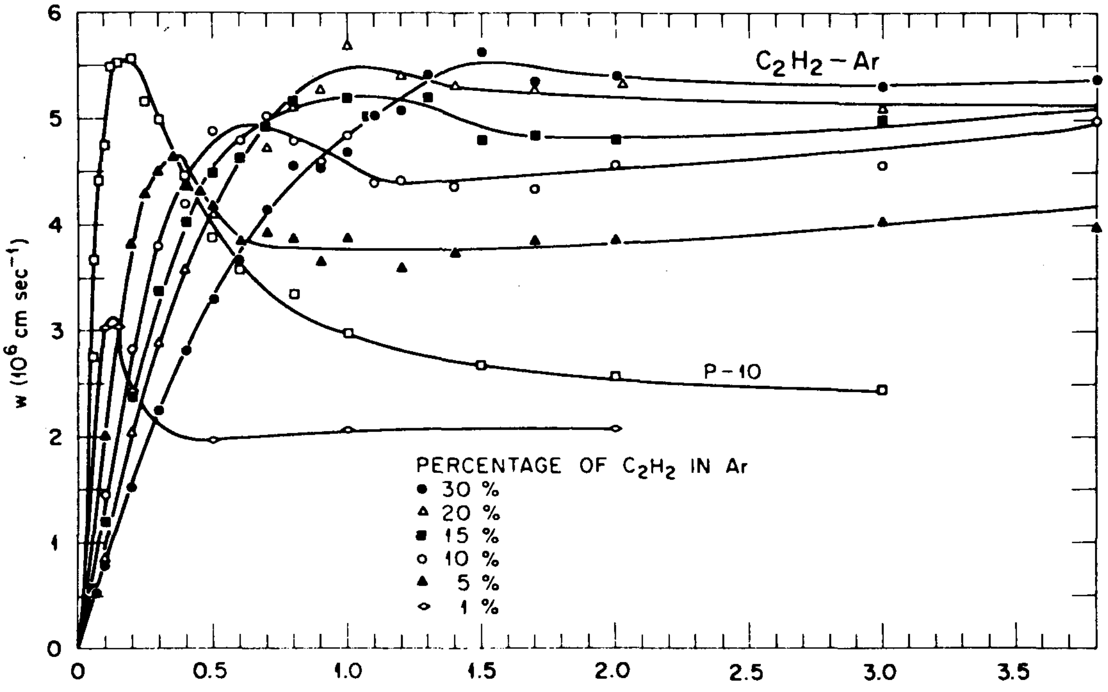


Fig. 79 Christophorou et al. (1979)

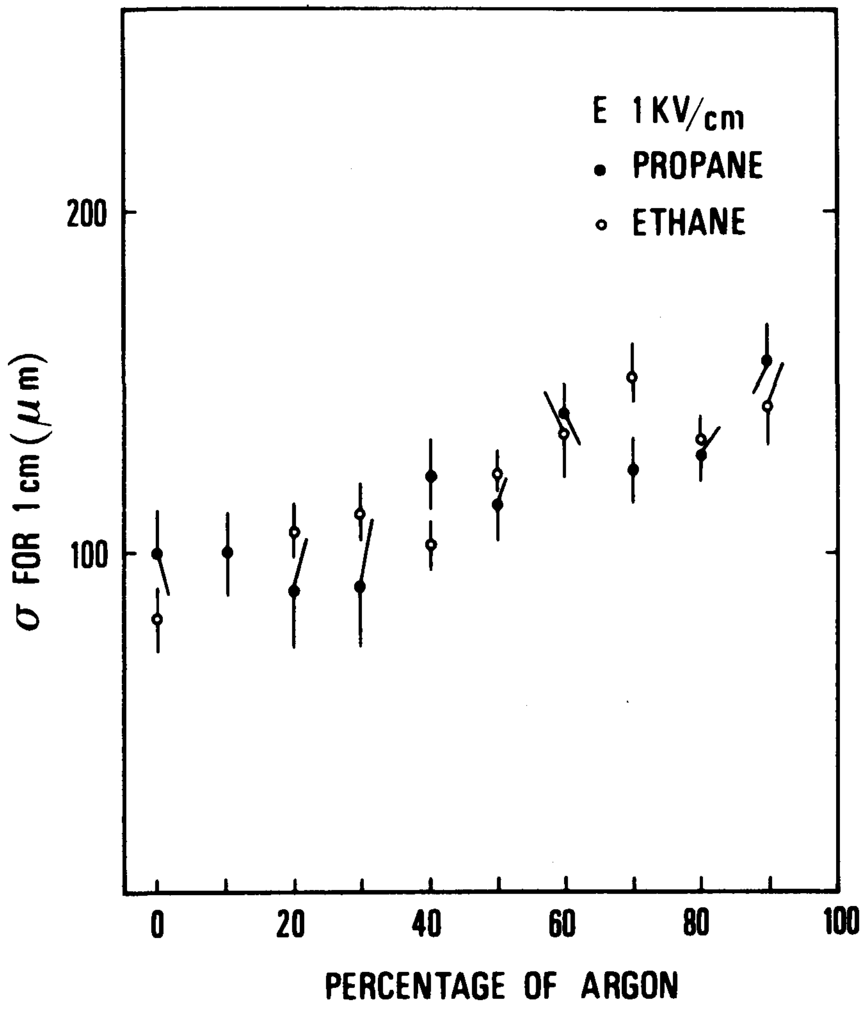
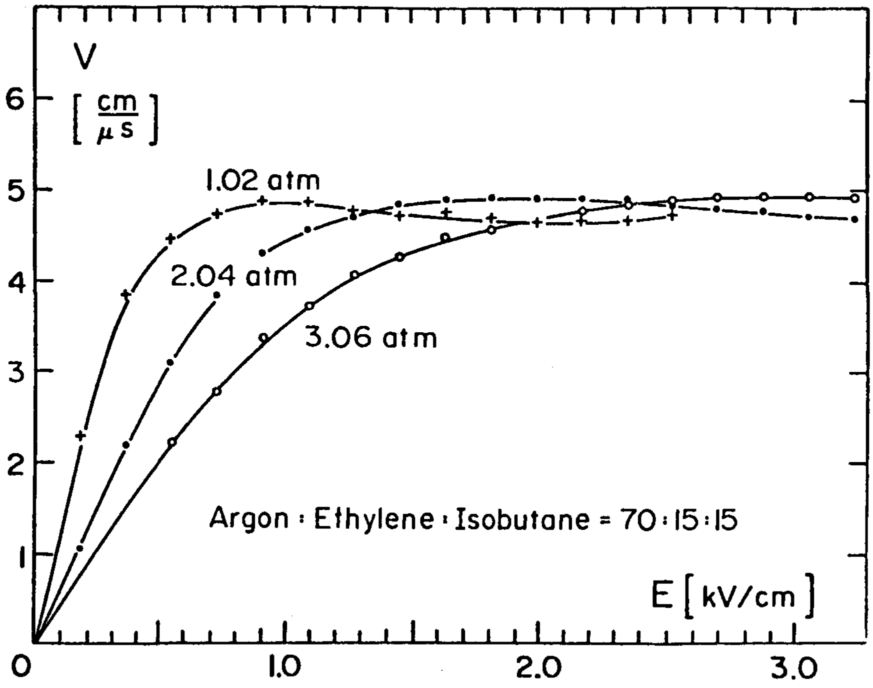


Fig. 80 Jean-Marie et al. (1979)



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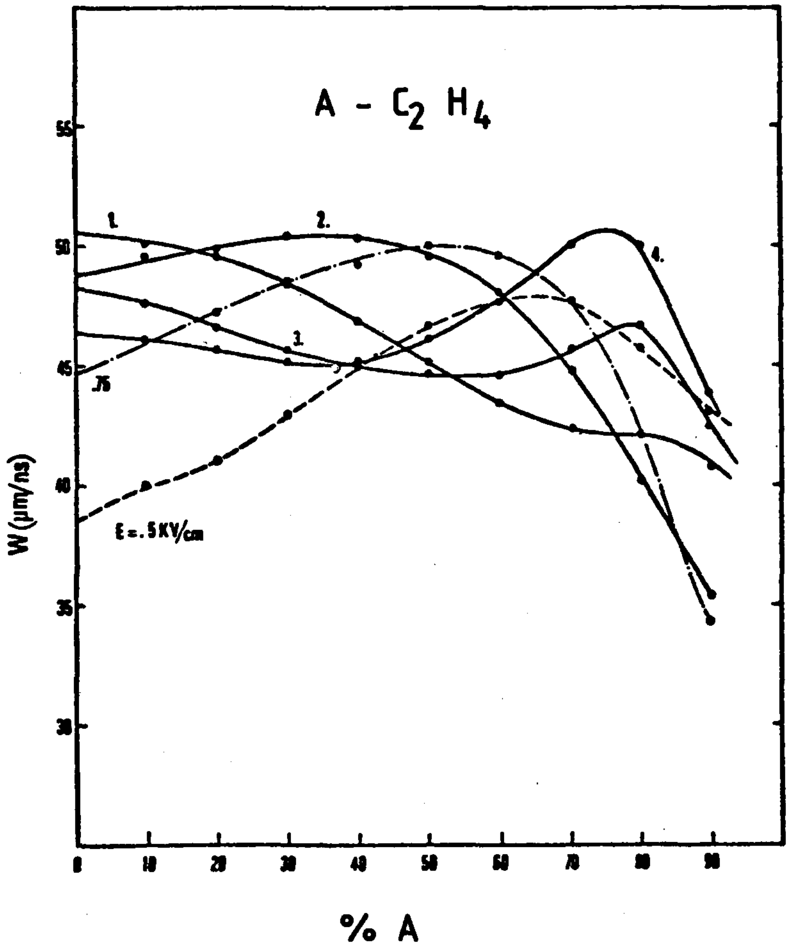
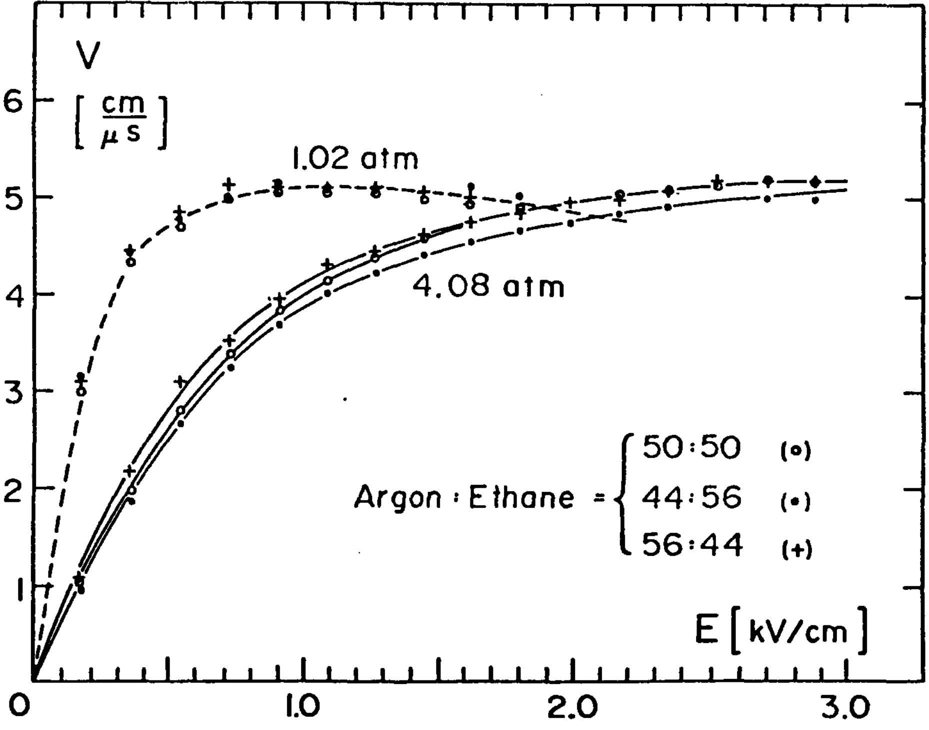


Fig. 82 L'Hôte (1978)



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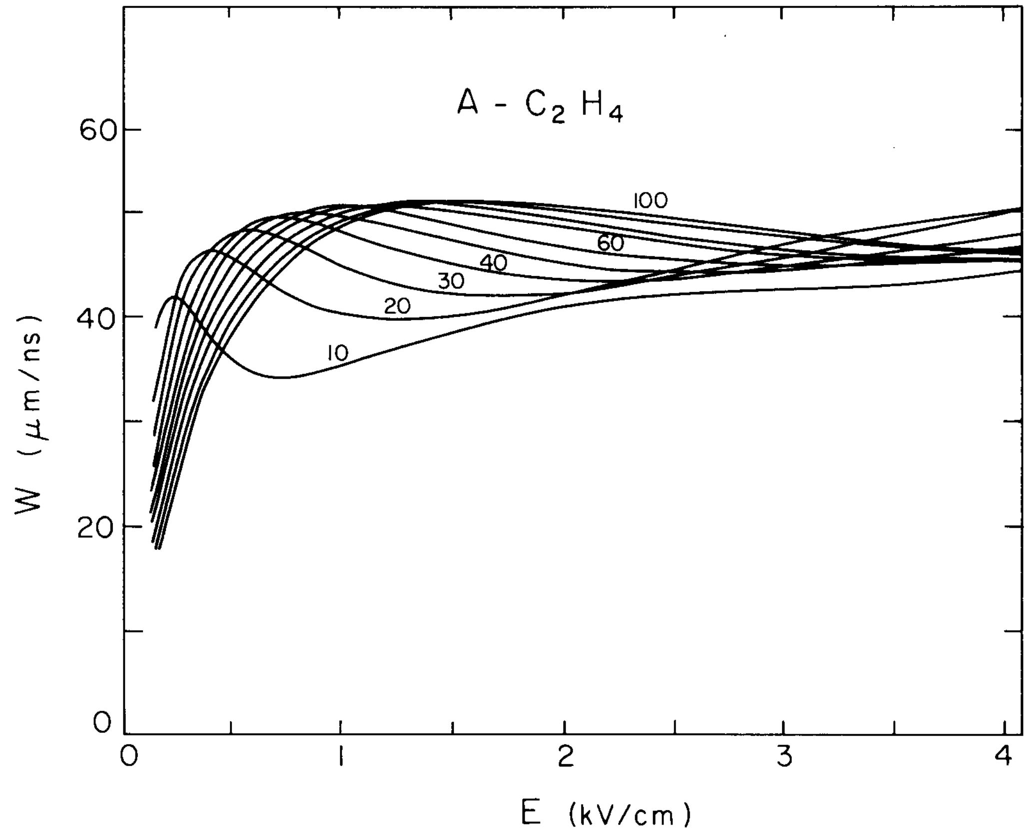

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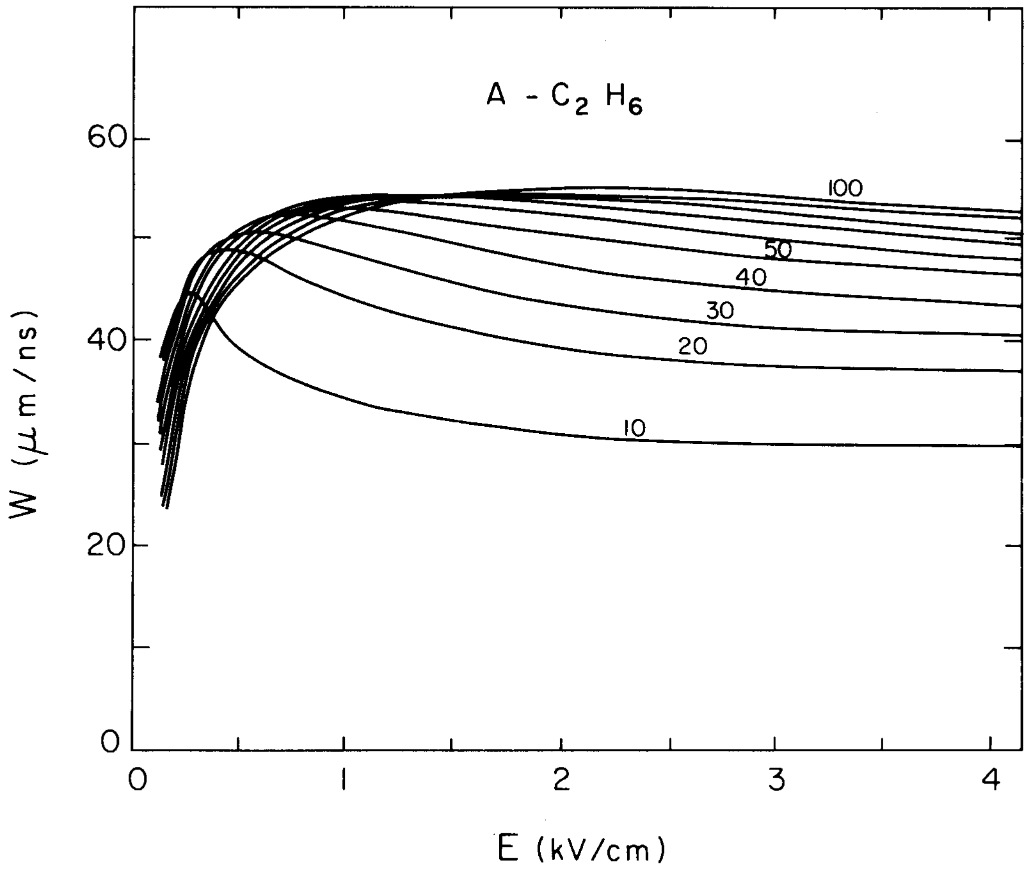

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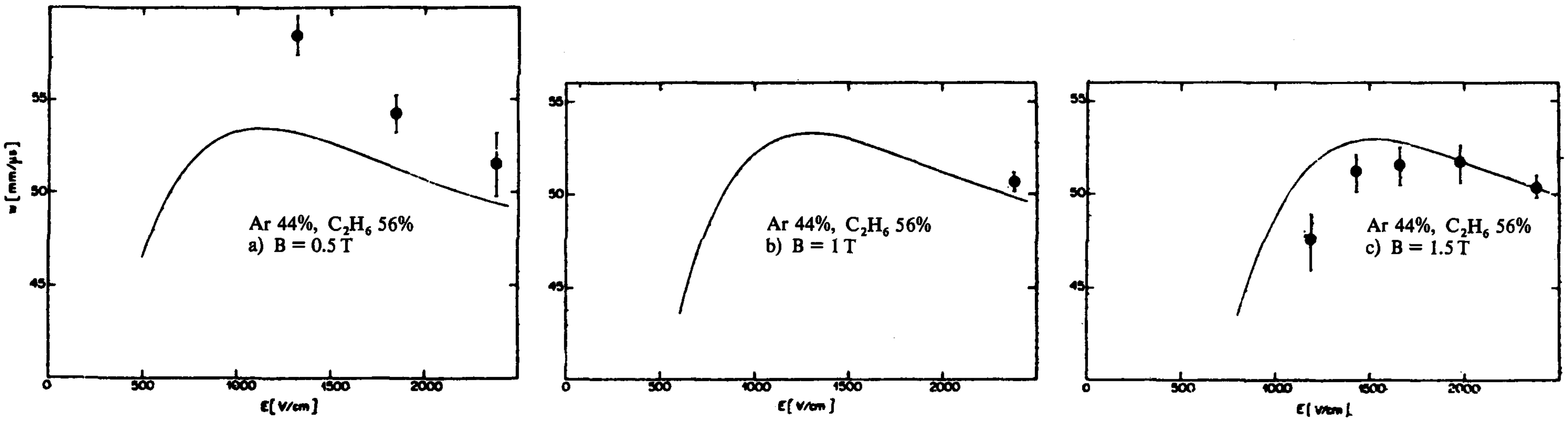

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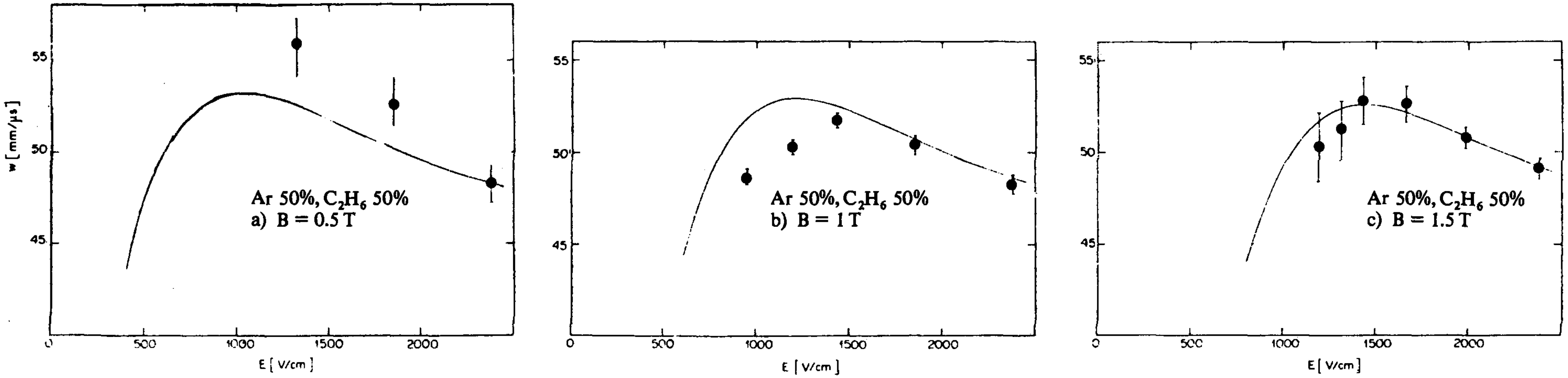

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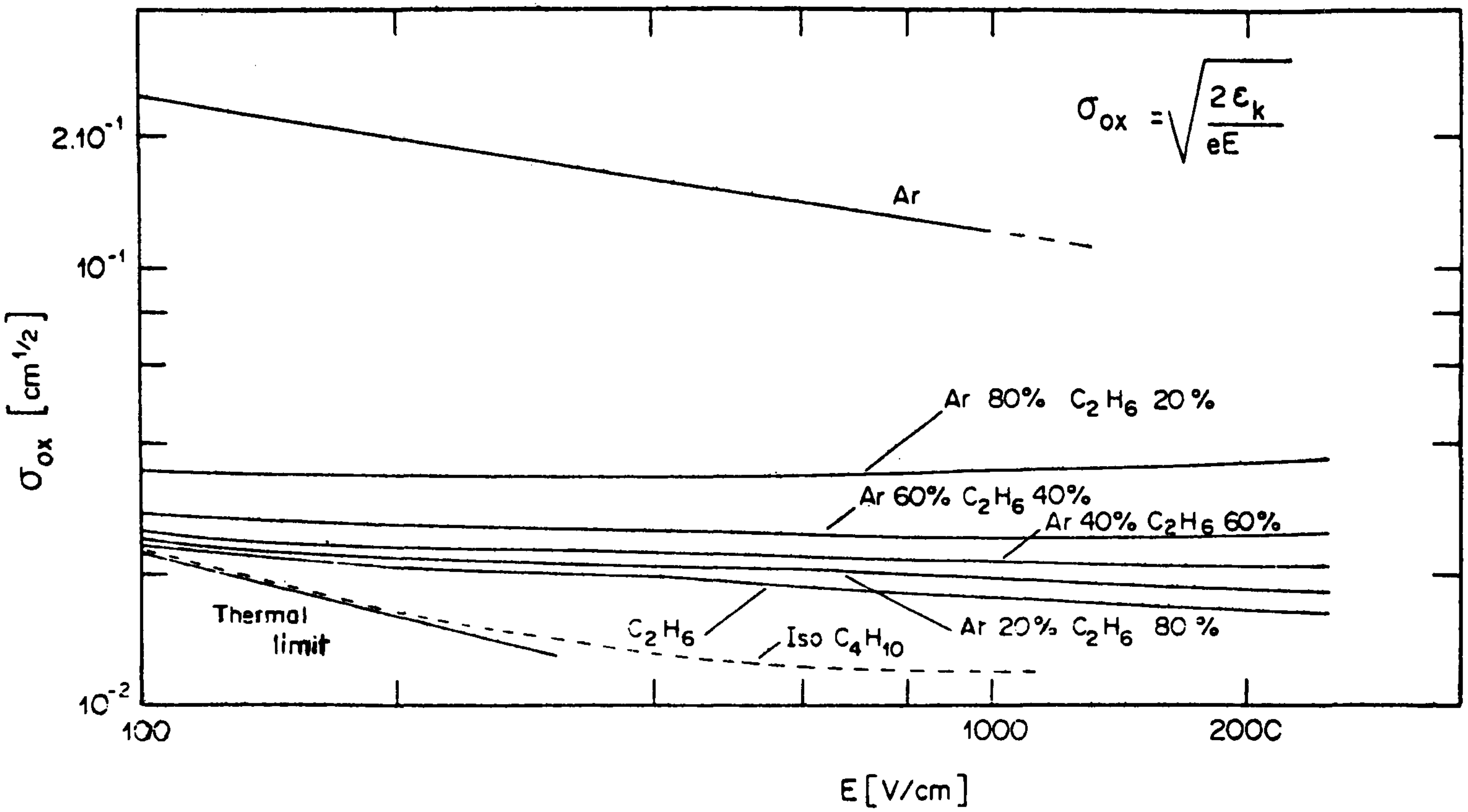

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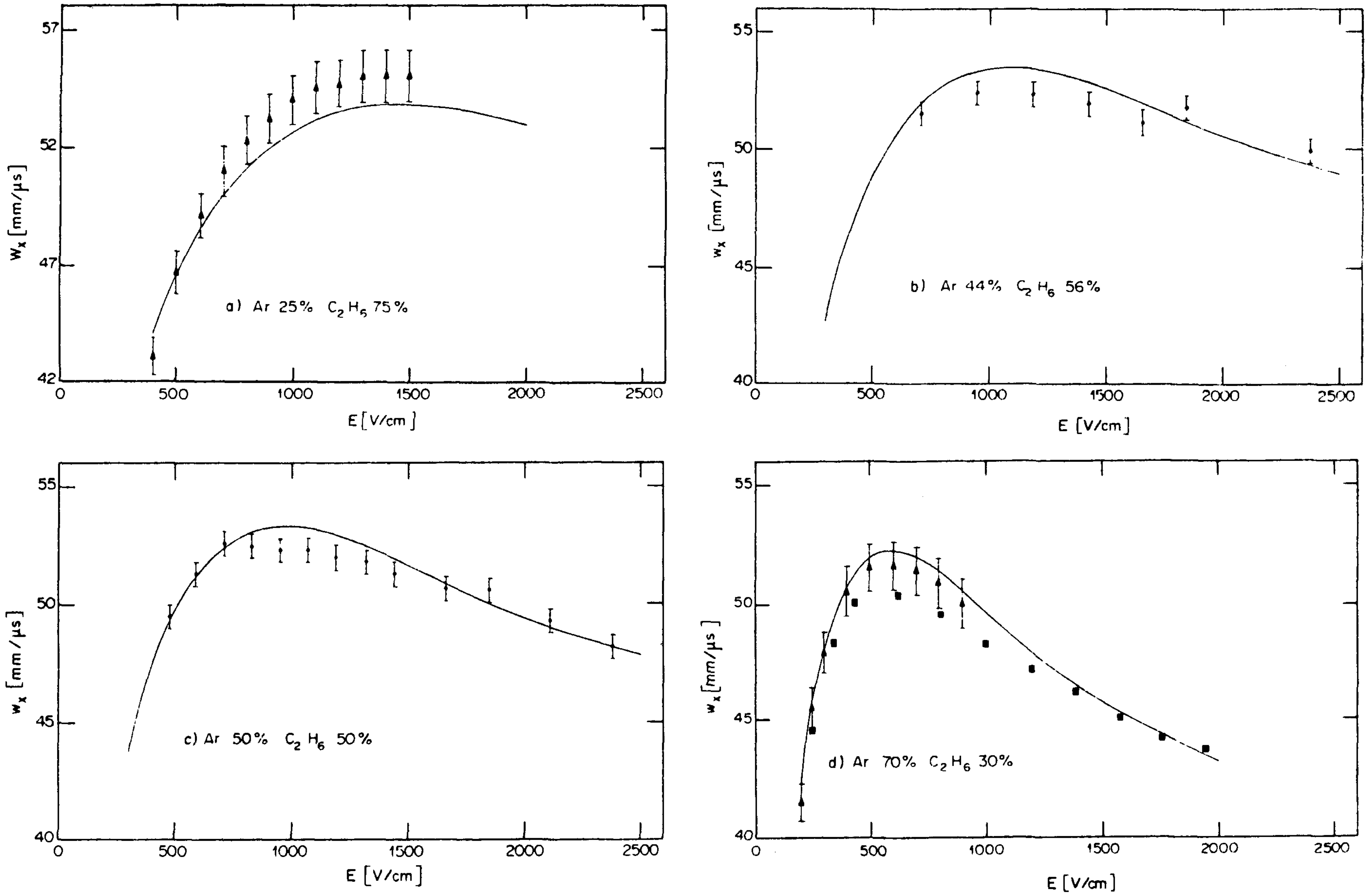

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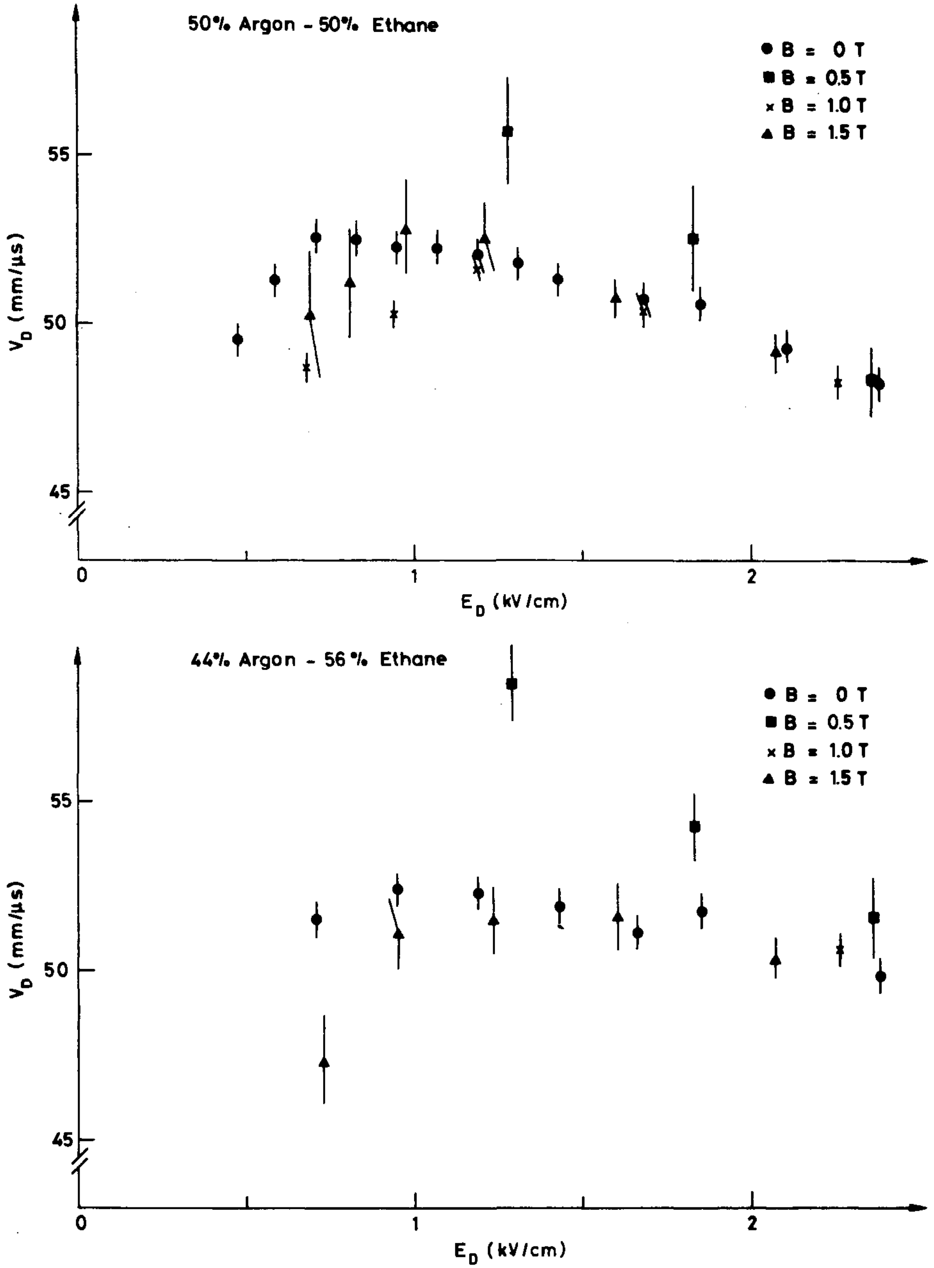


Fig. 90 Daum et al. (1978)

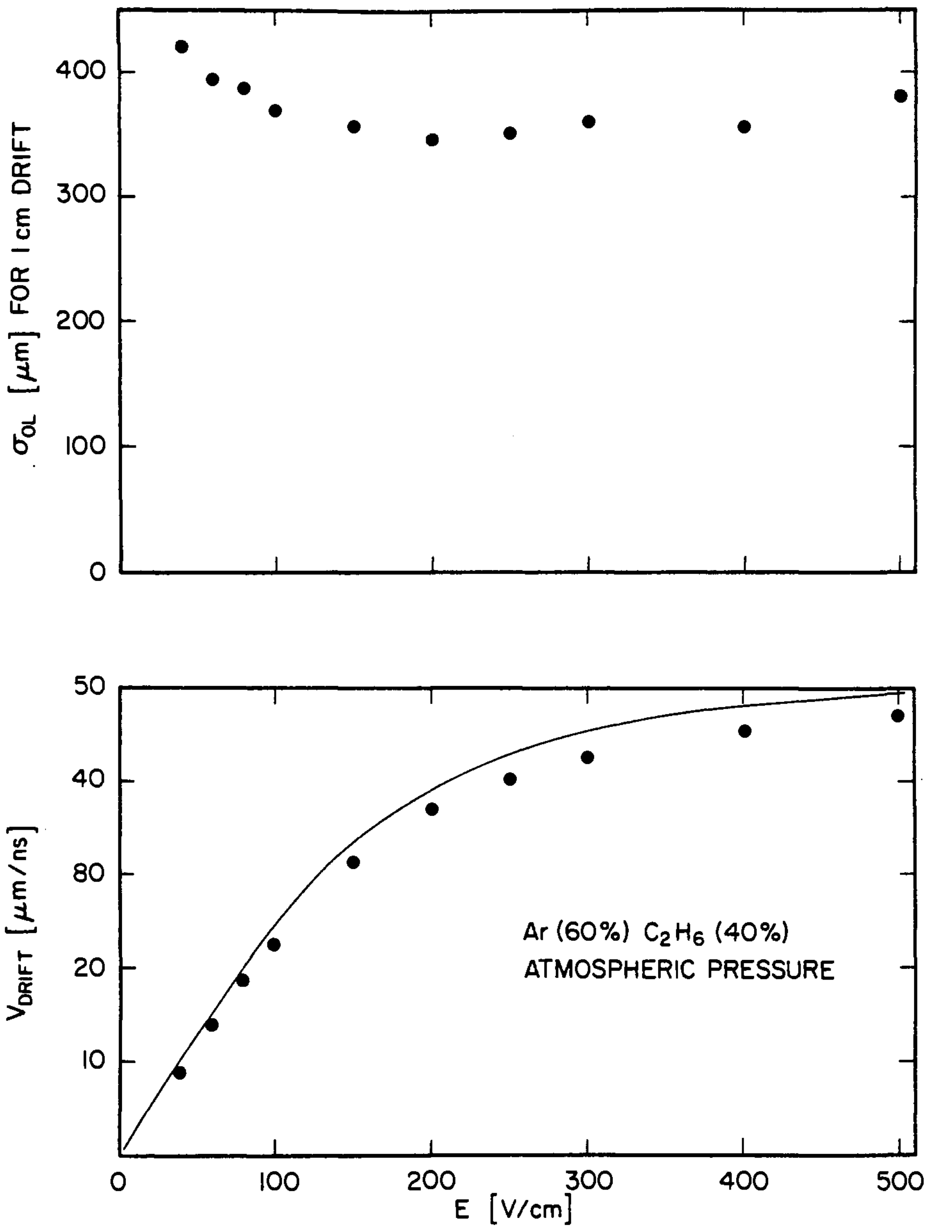


Fig. 91 Fehlman et al. (1983)

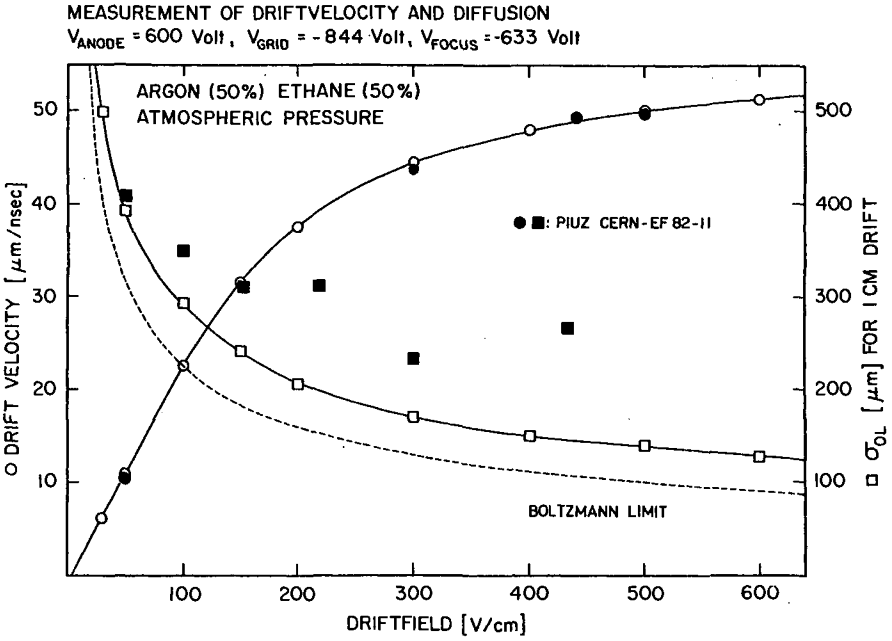


Fig. 92 Fehlman et al. (1983)

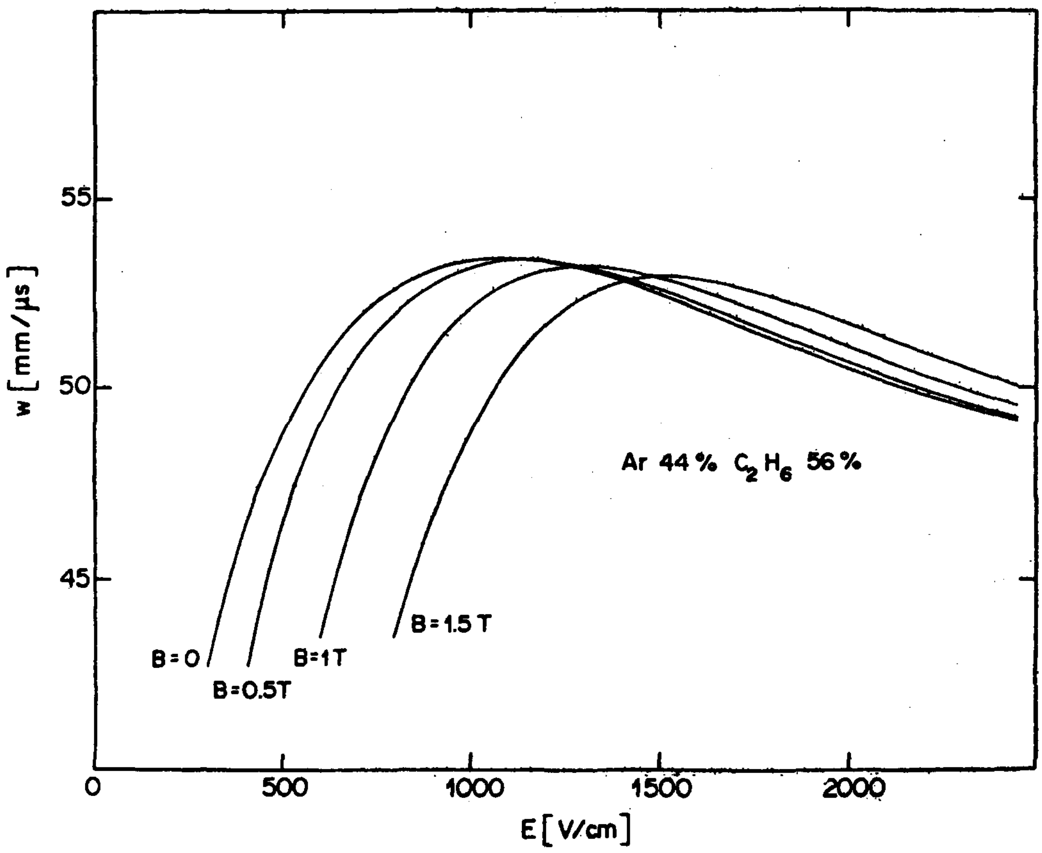


Fig. 93 Ramanantsizehena (1979)

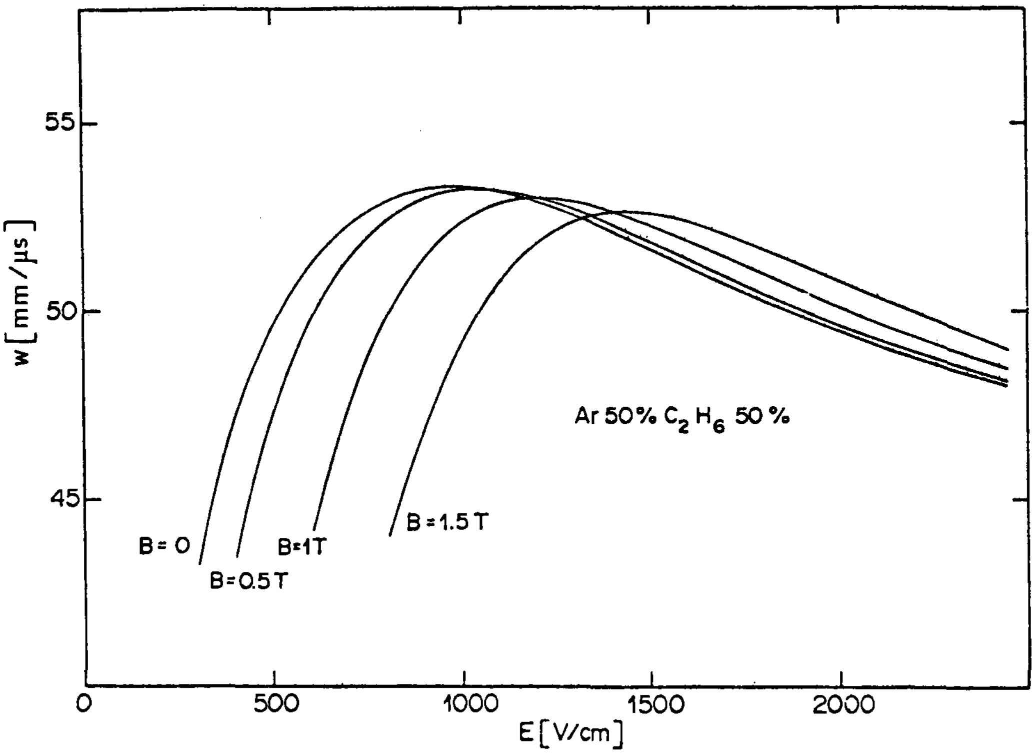


Fig. 94 Ramanantsizehena (1979)

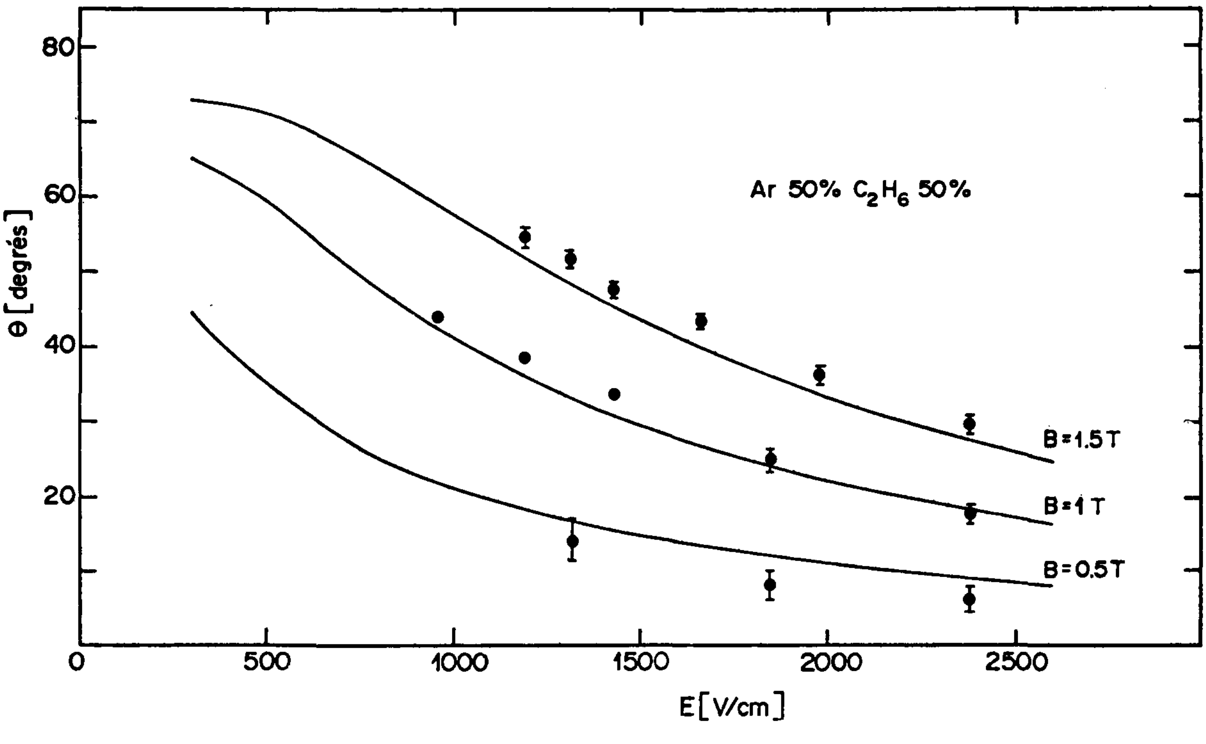
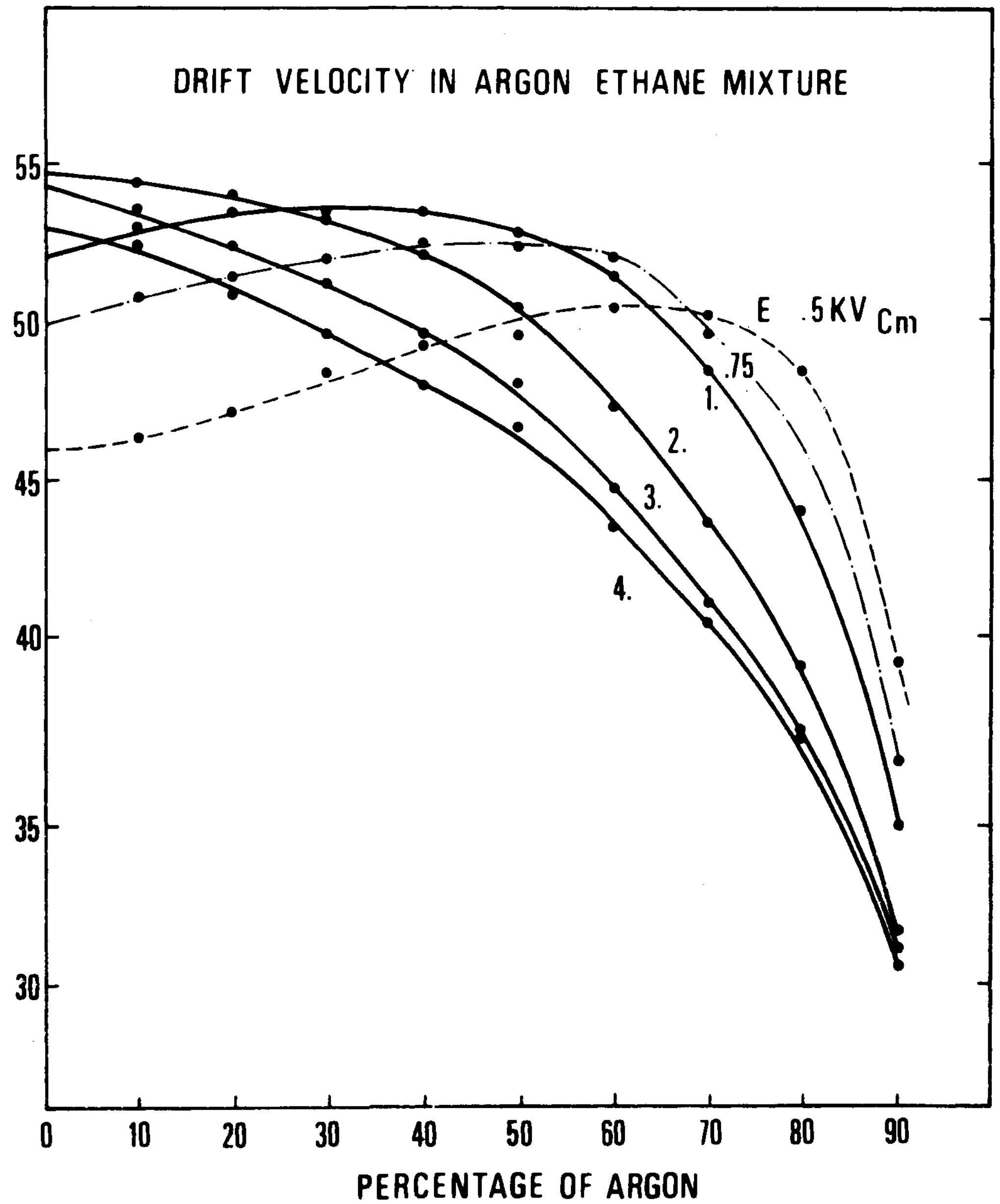


Fig. 95 Ramanantsizehena (1979)



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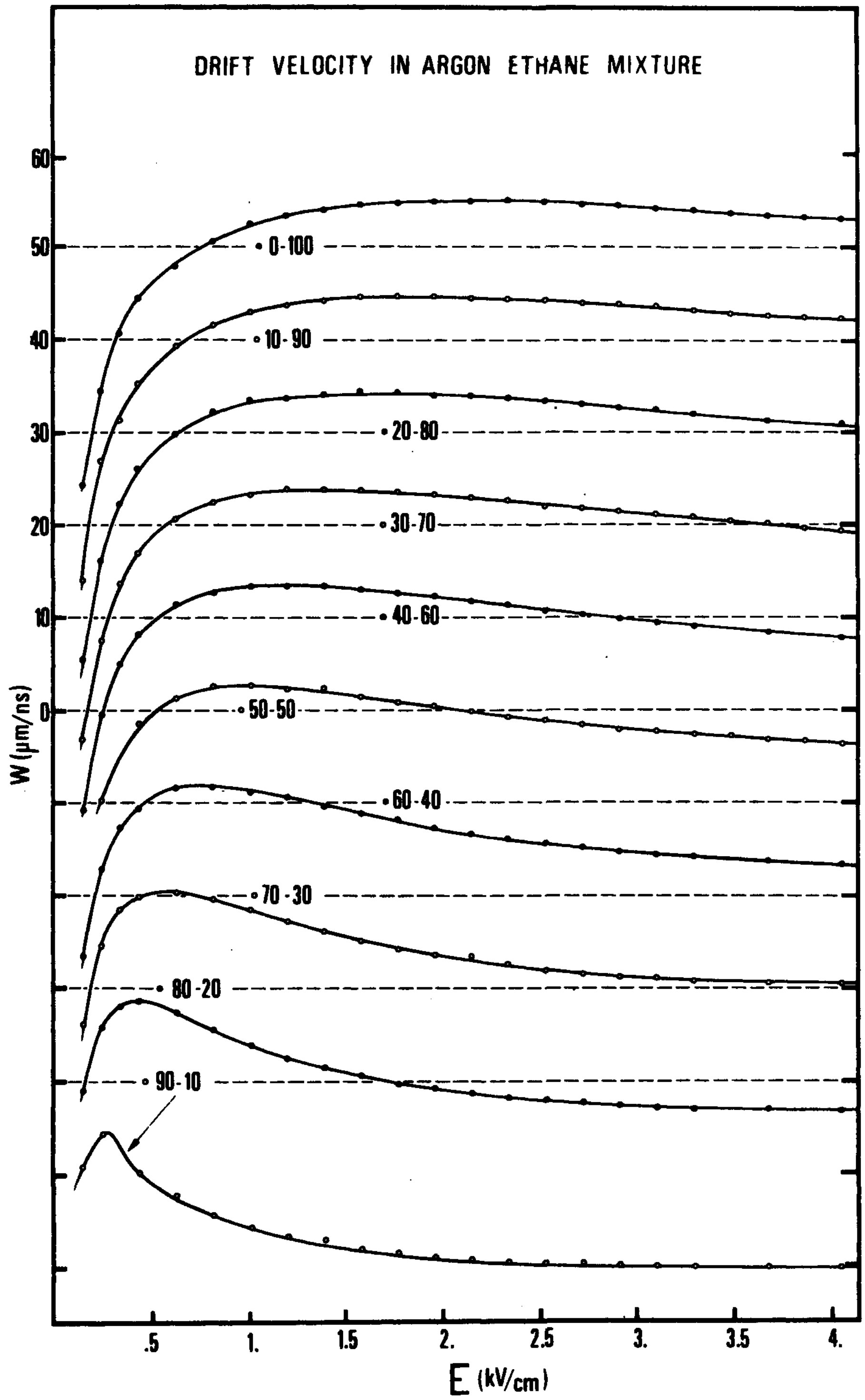

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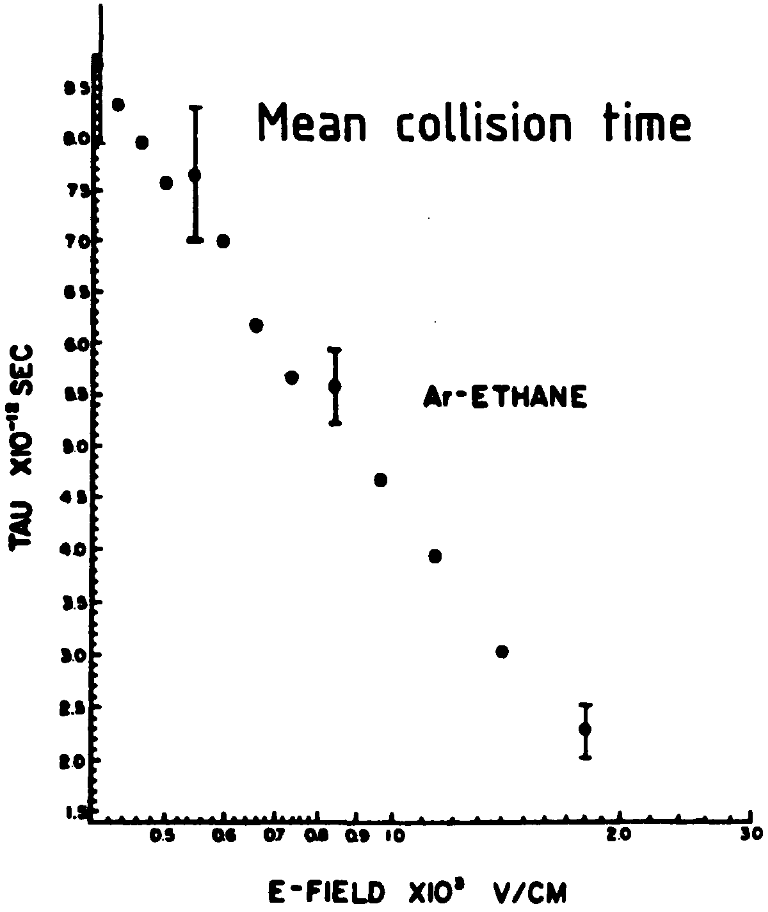


Fig. 98 Baranko et al. (1980)

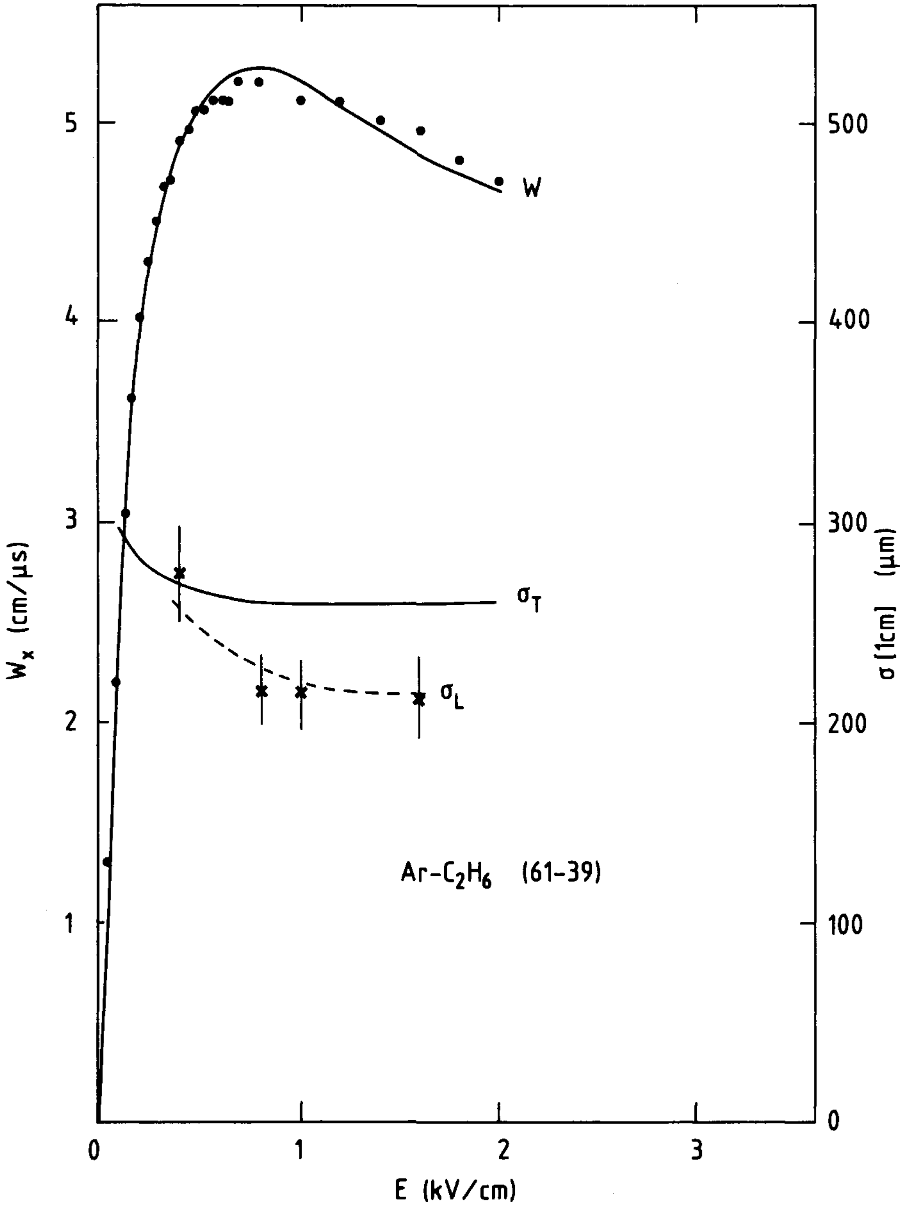
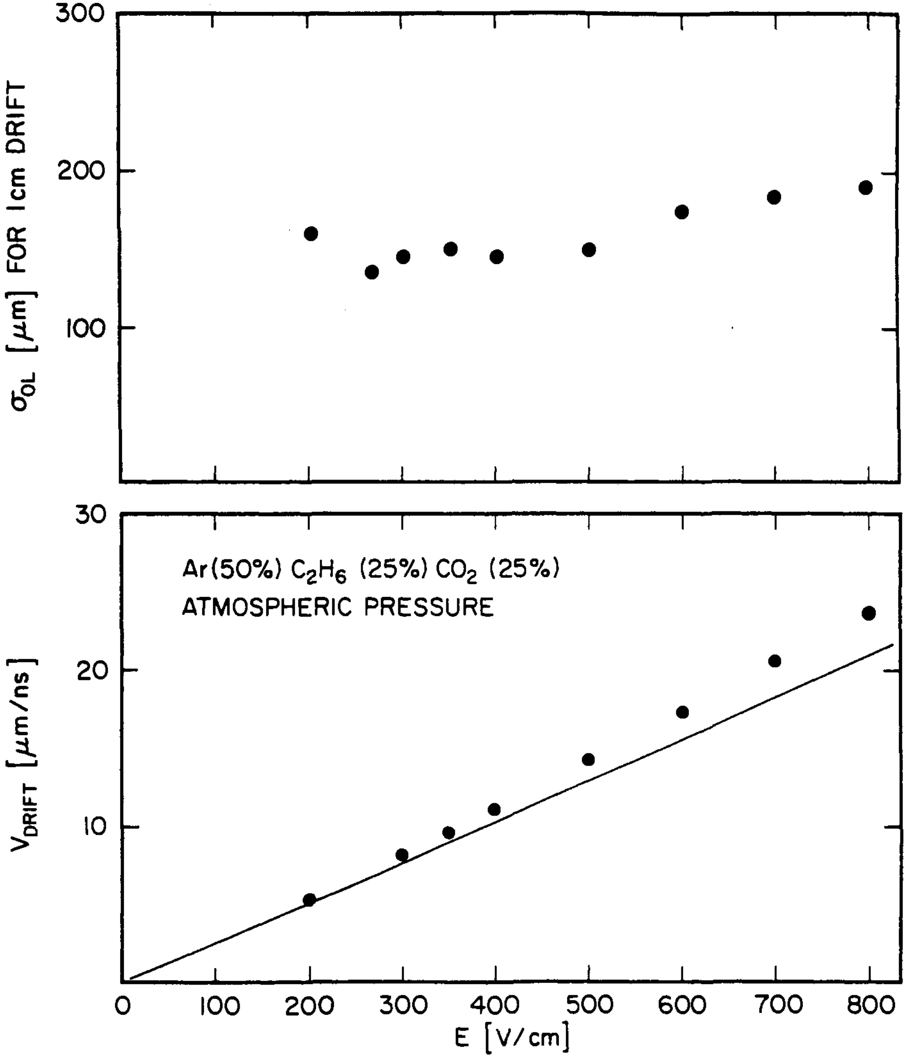


Fig. 99 Peisert and Sauli (1984)



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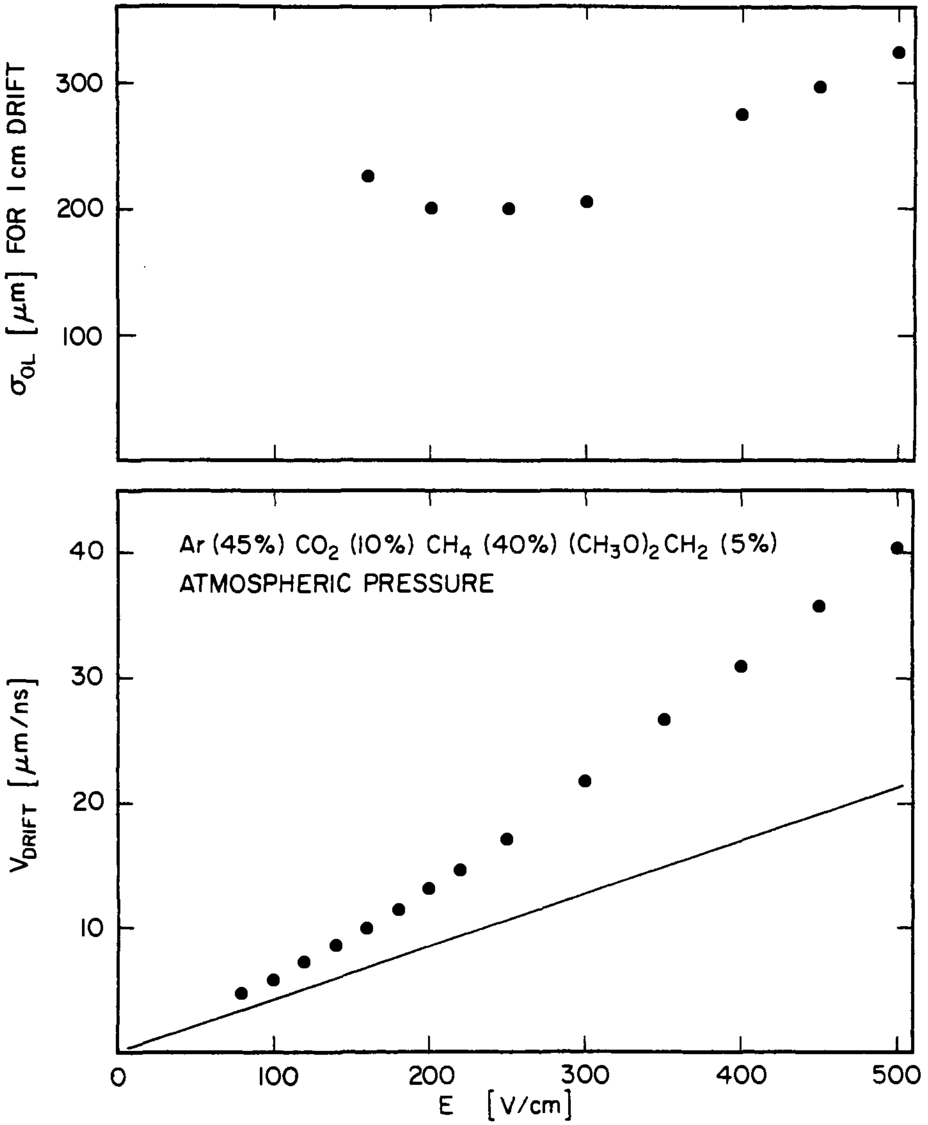

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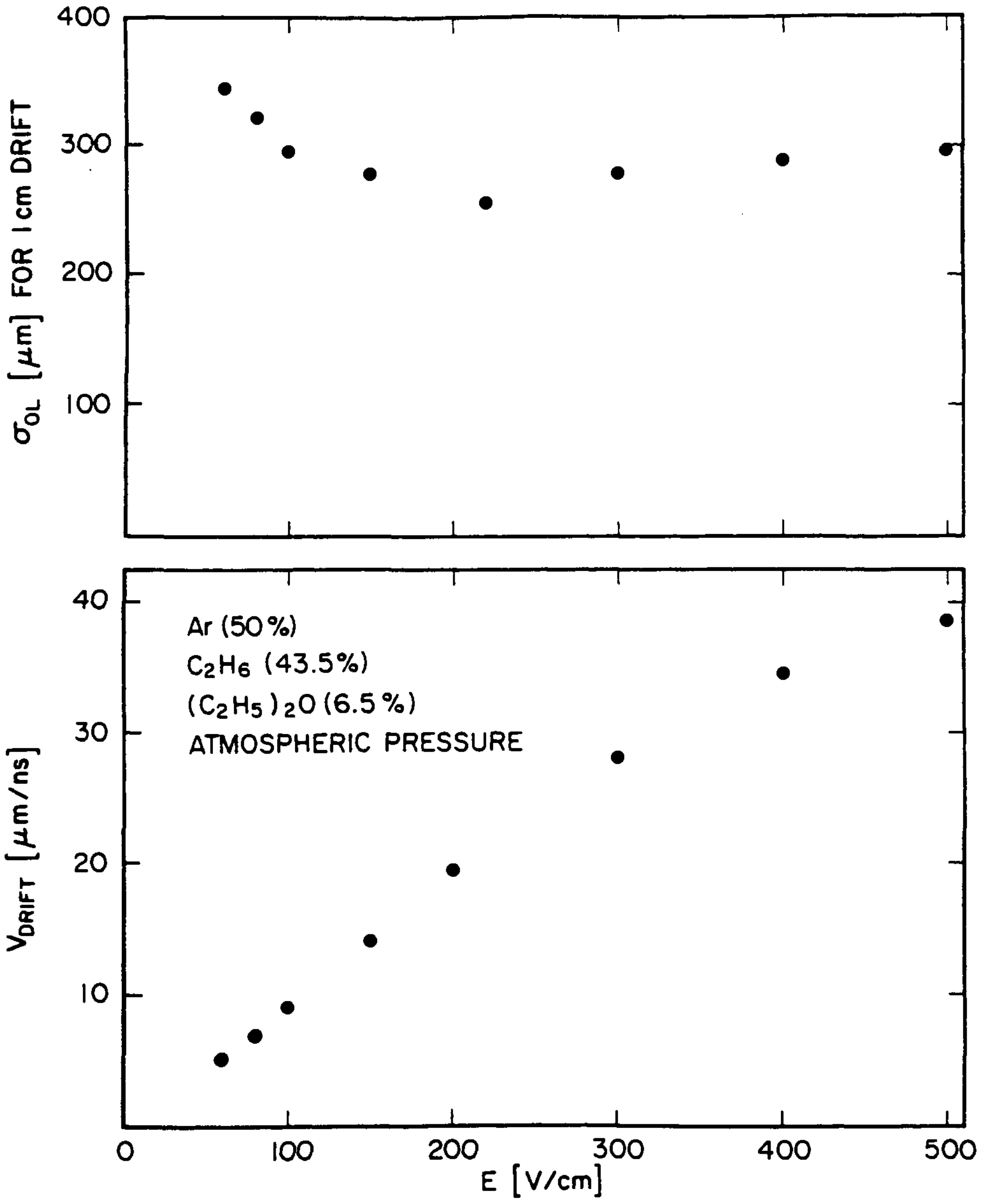

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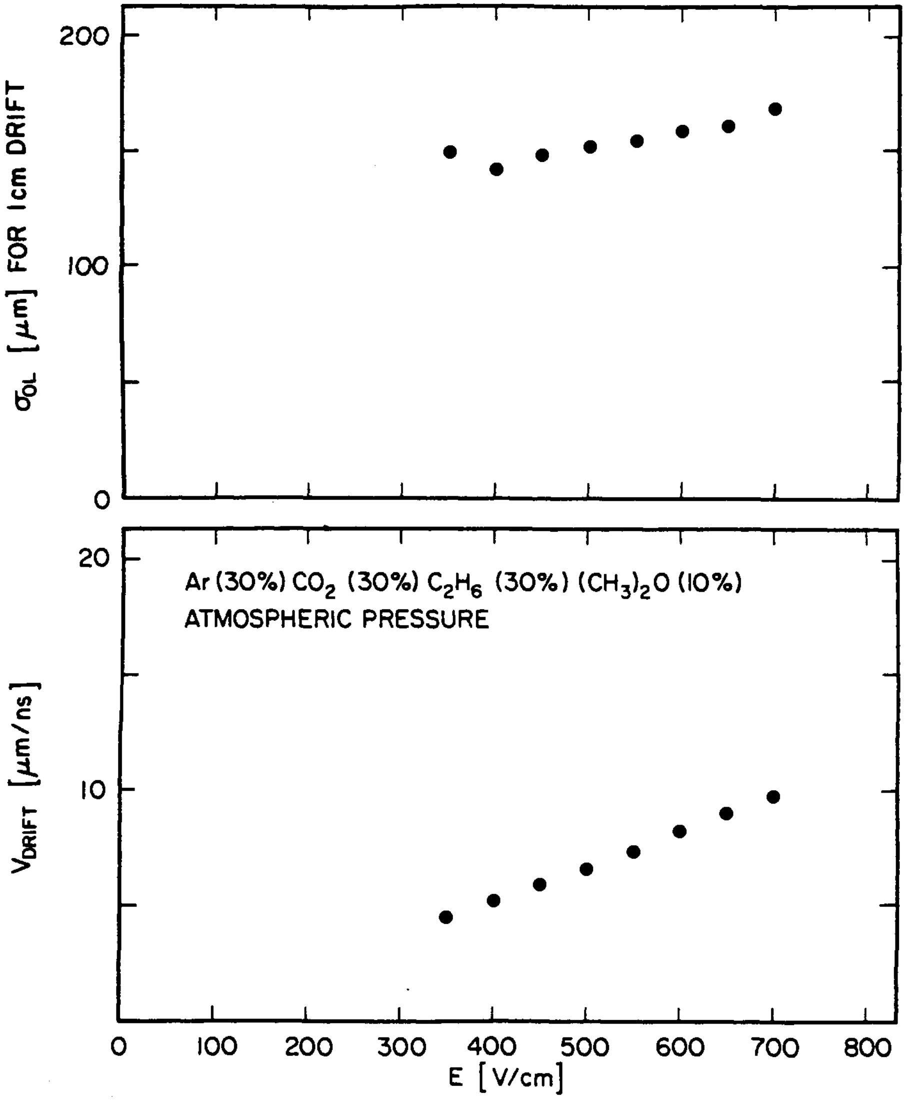

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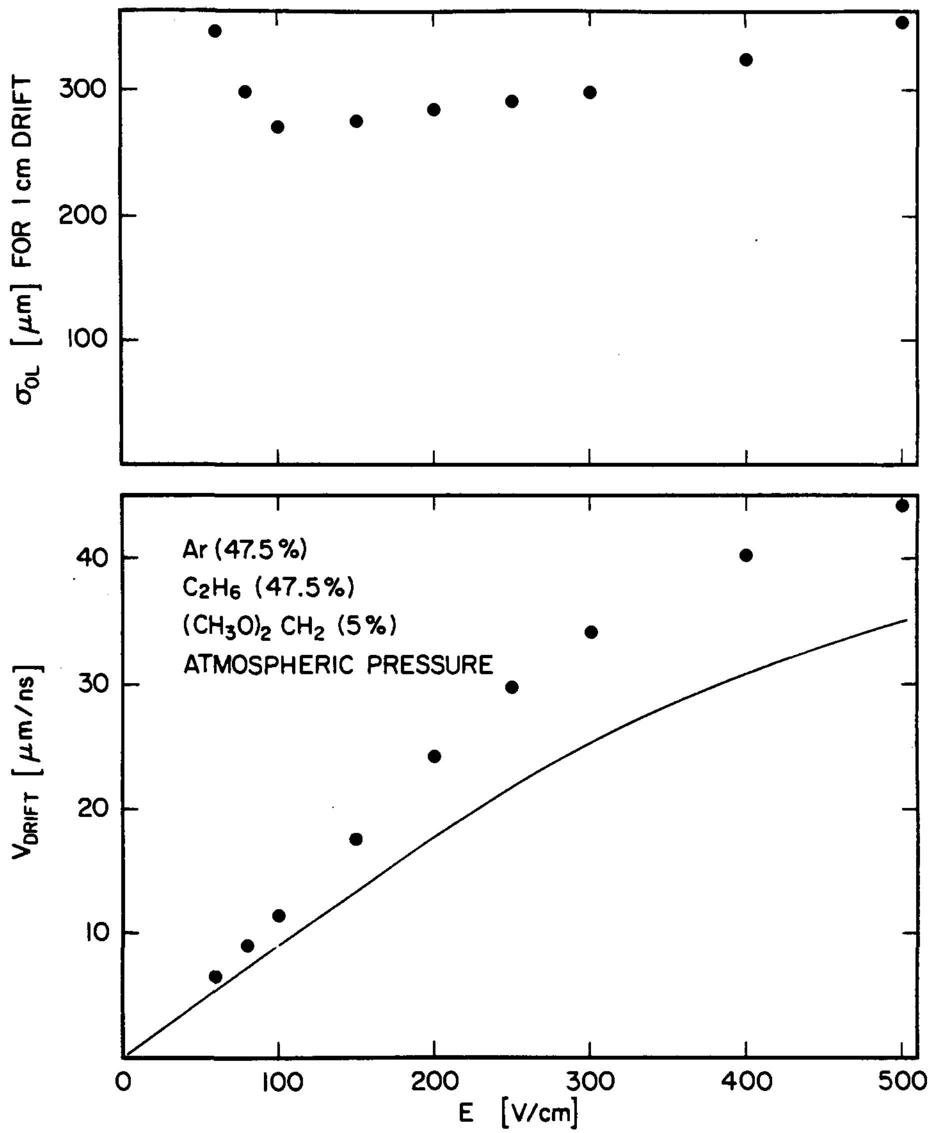

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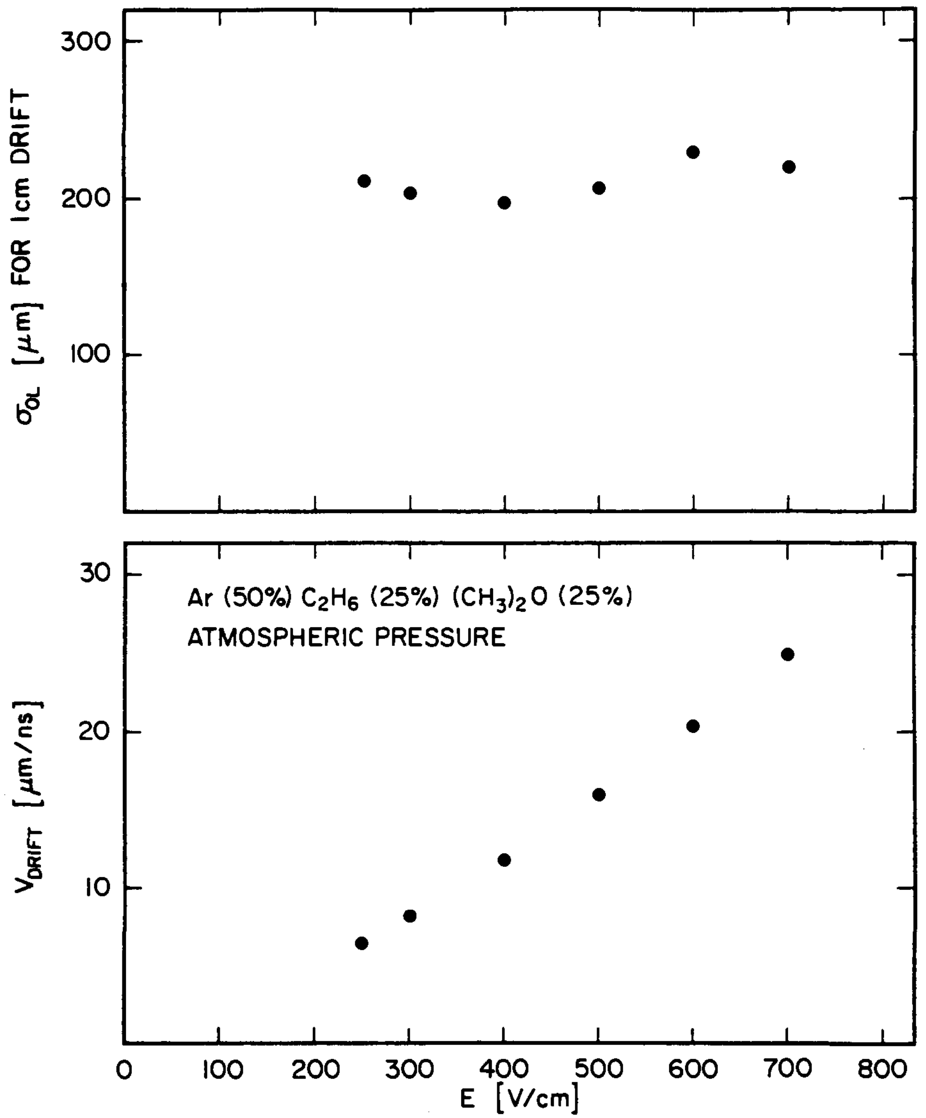

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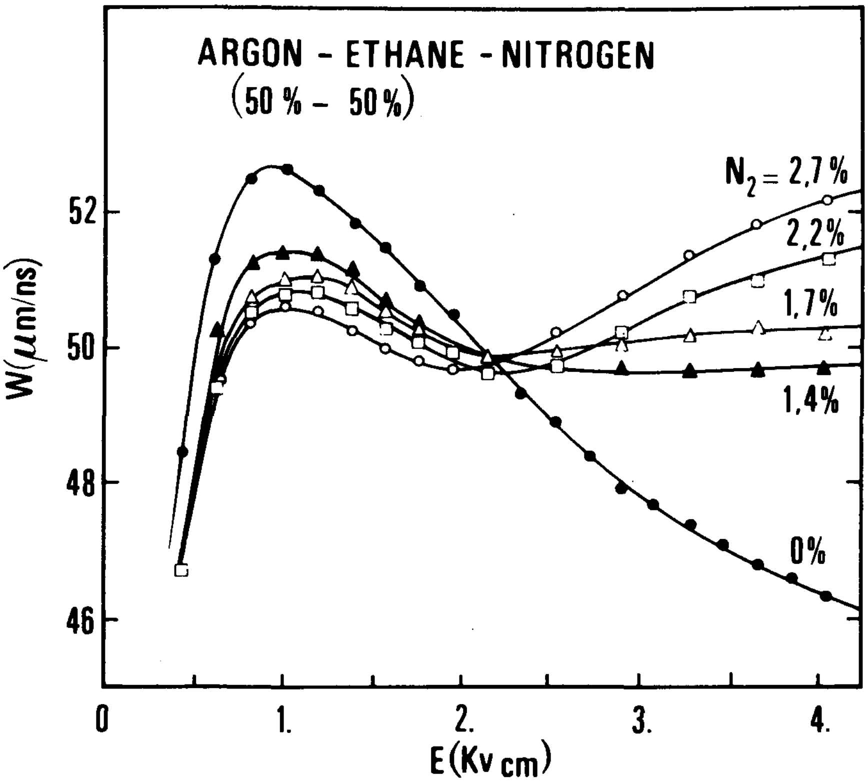

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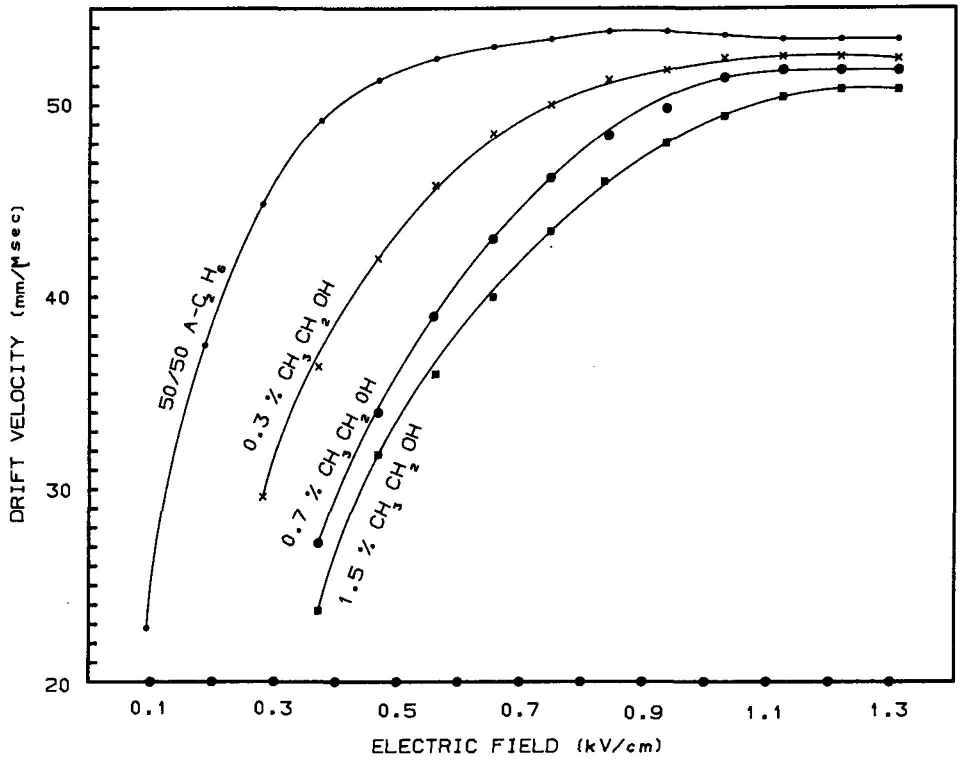


Fig. 107 M. Atac, private communication (1983)

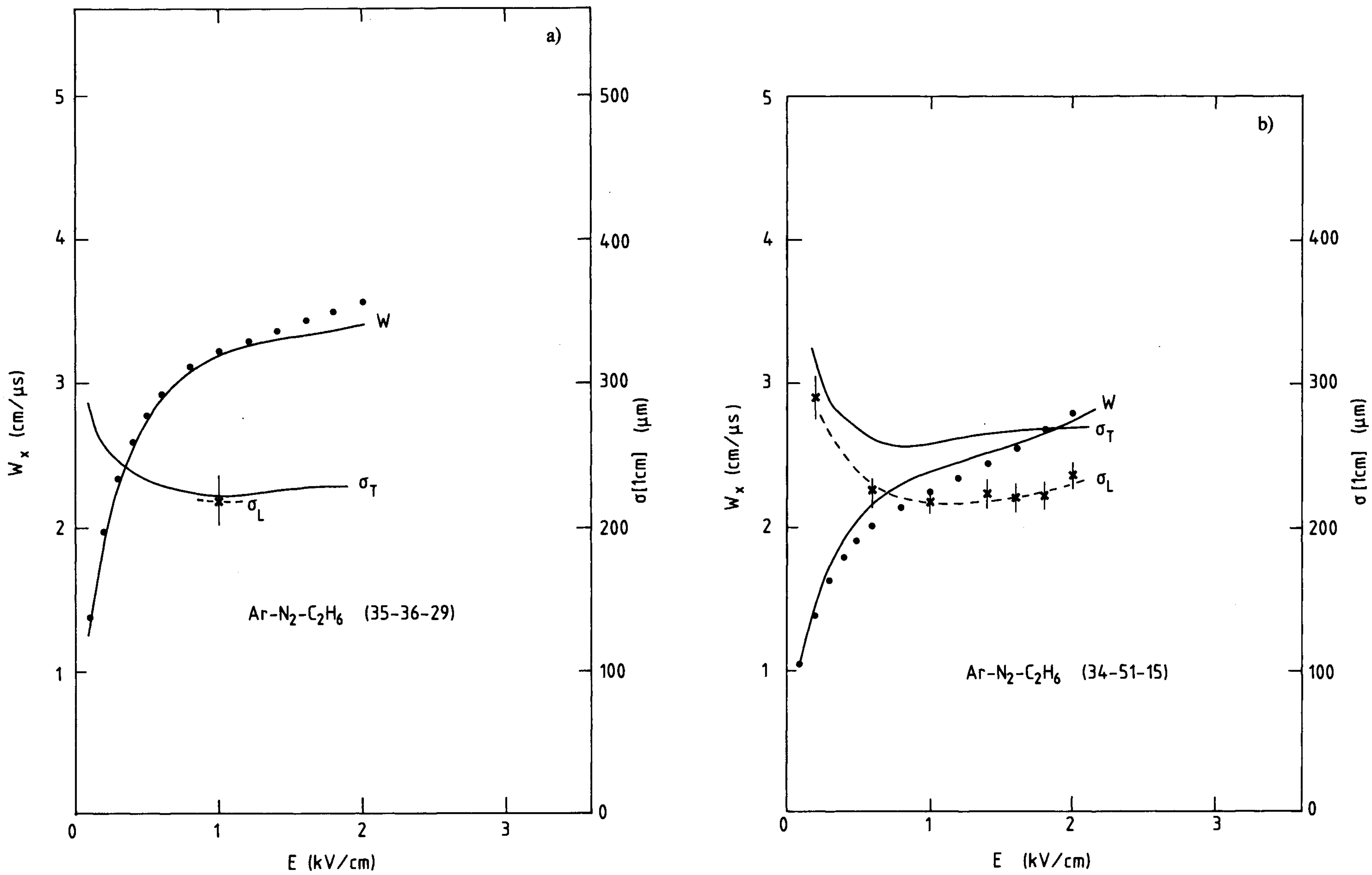
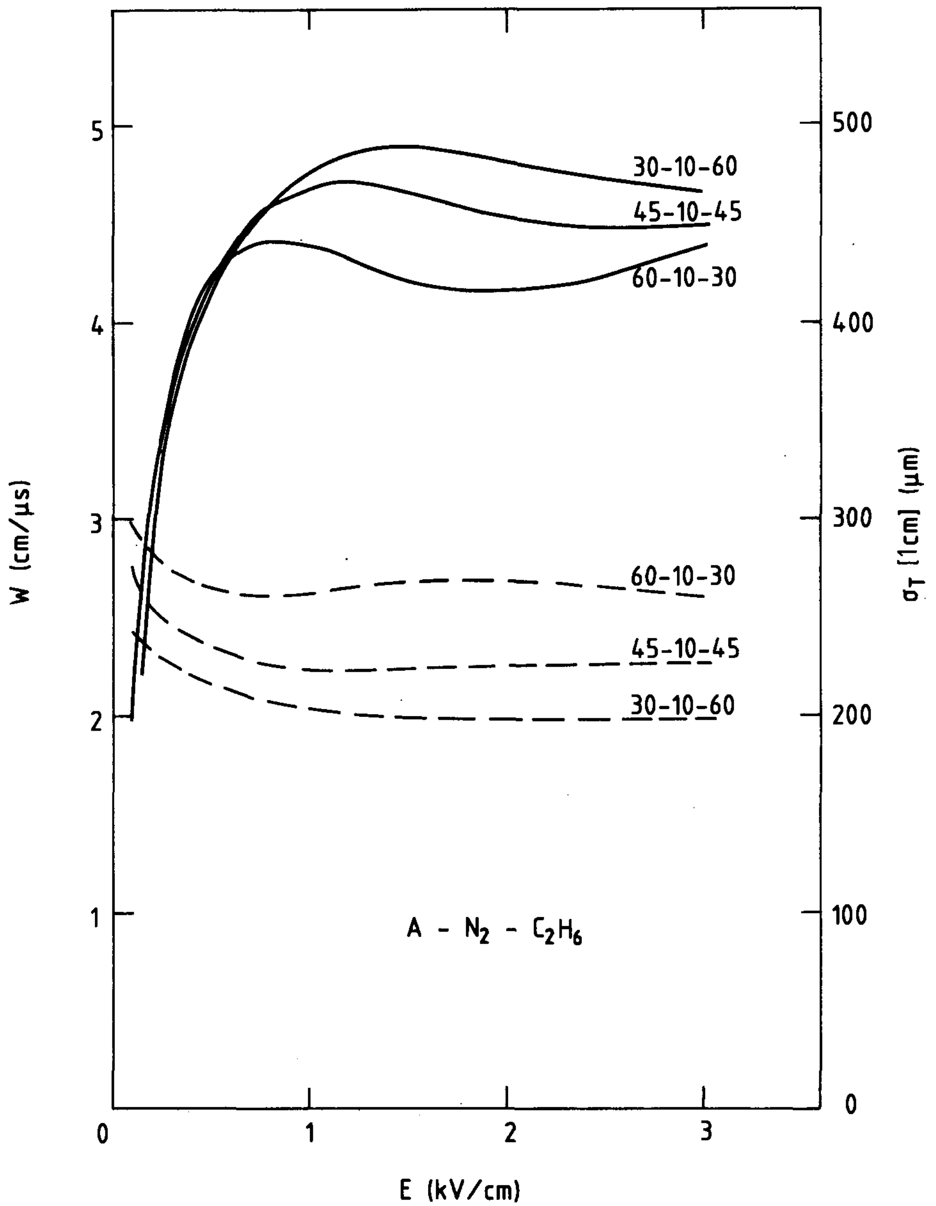


Fig. 108 Peisert and Sauli (1984)



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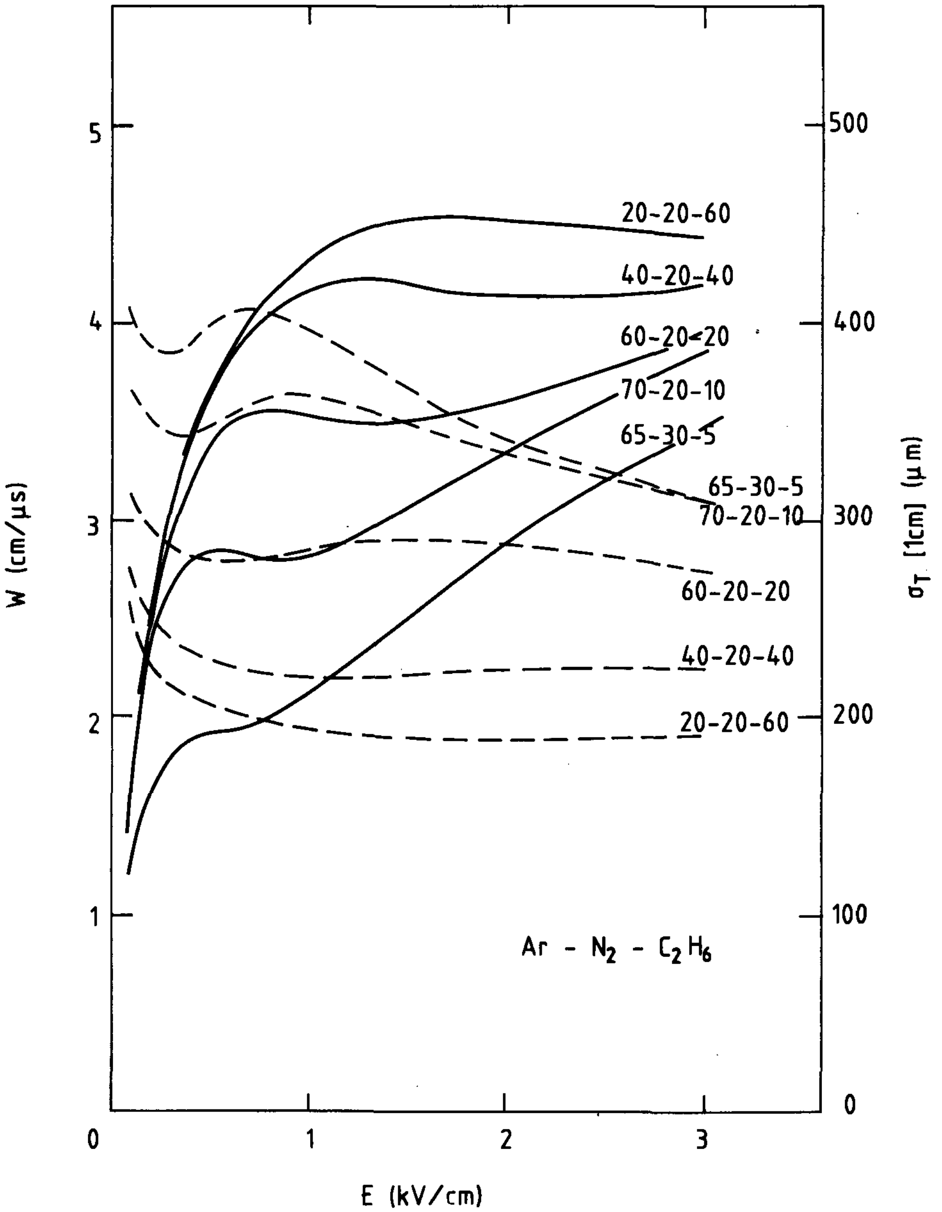

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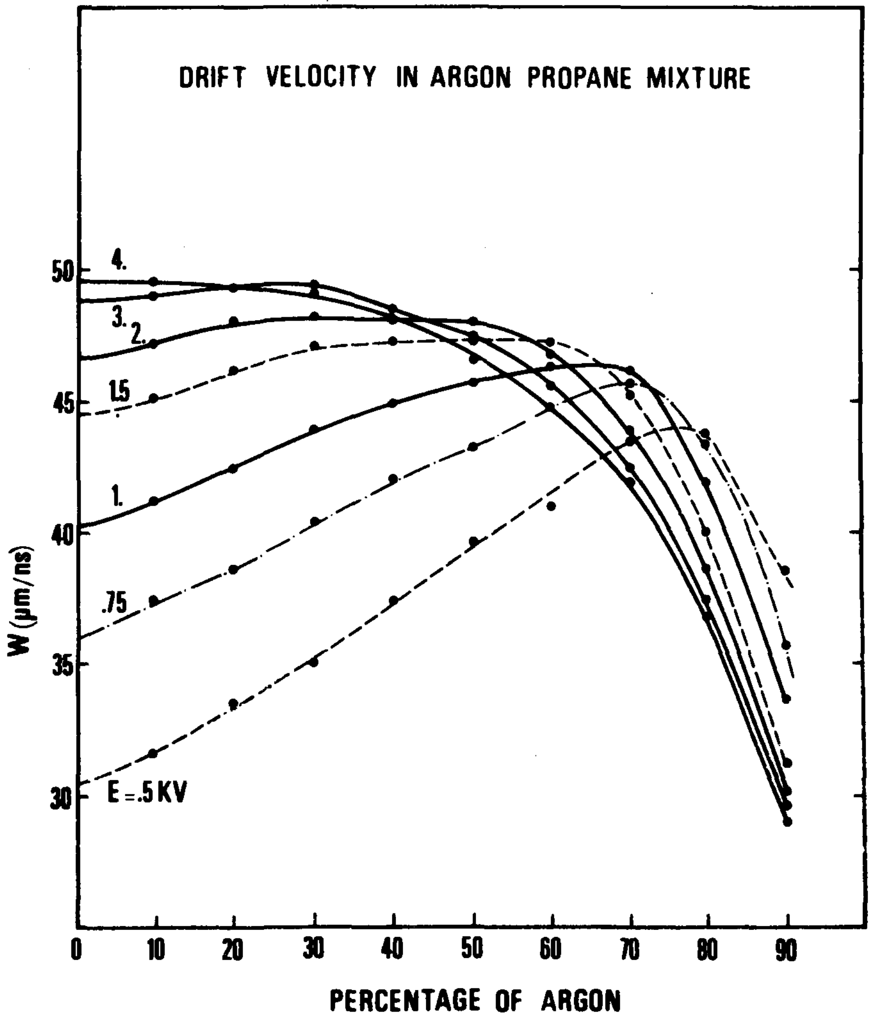

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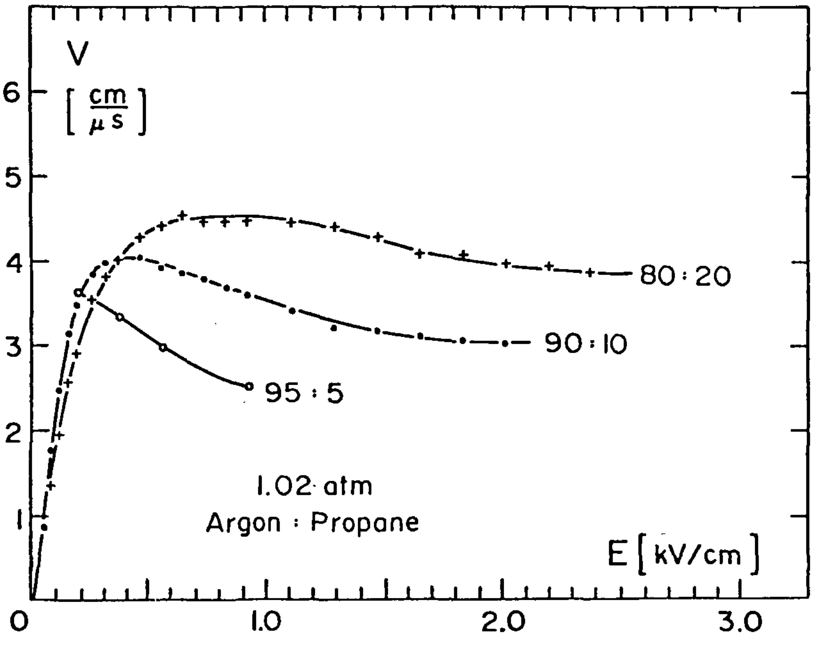
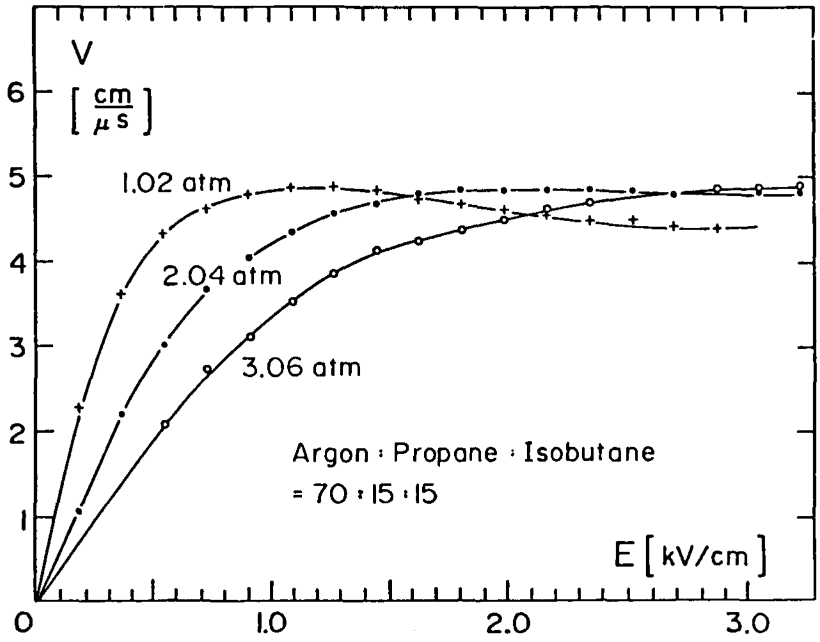


Fig. 112 Ma et al. (1982)



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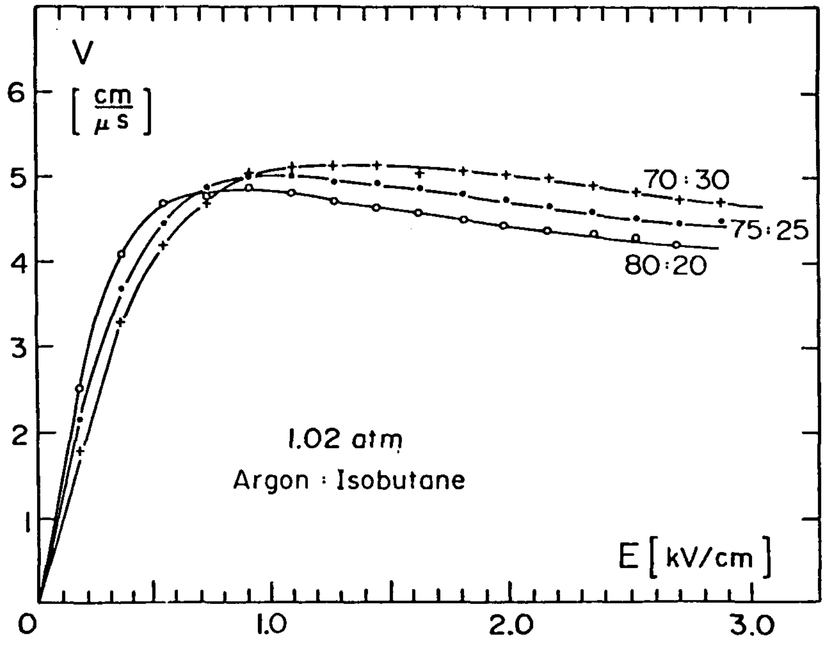

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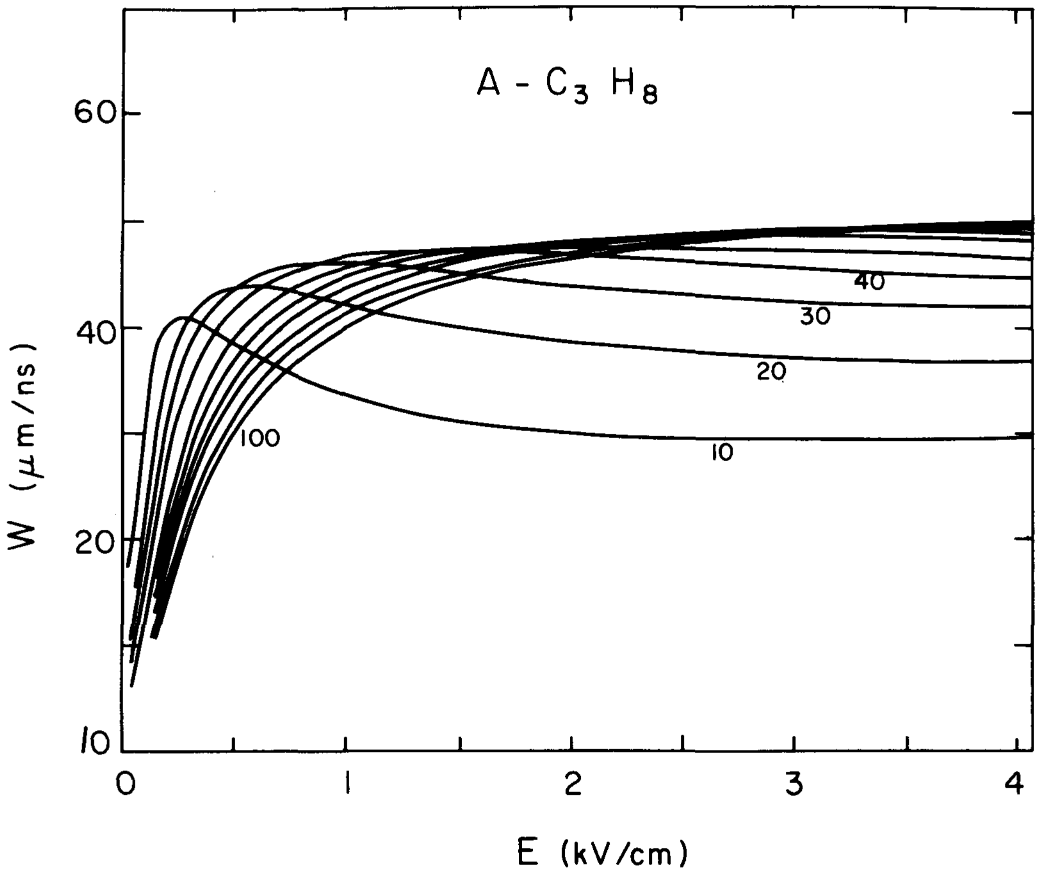

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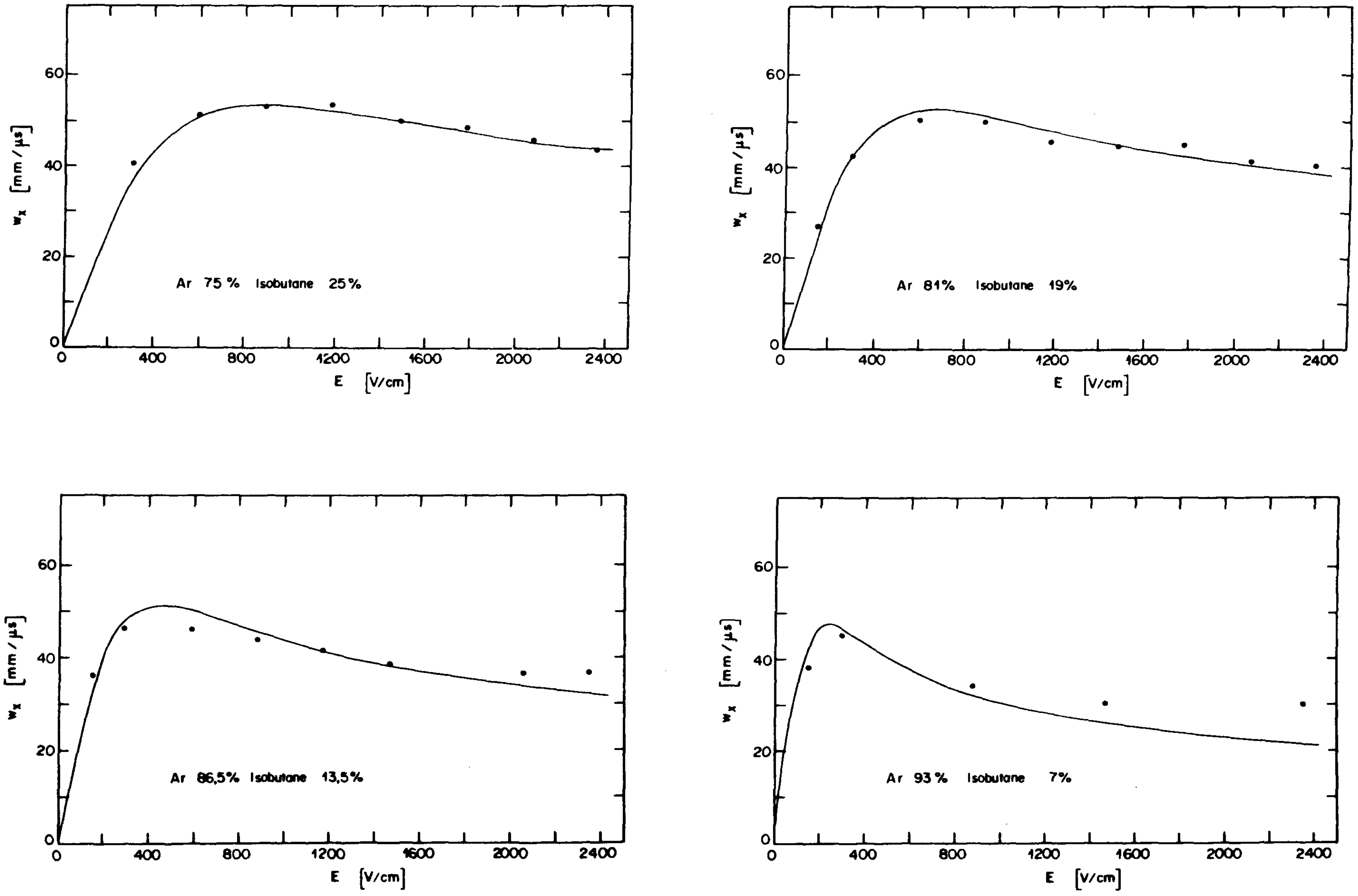
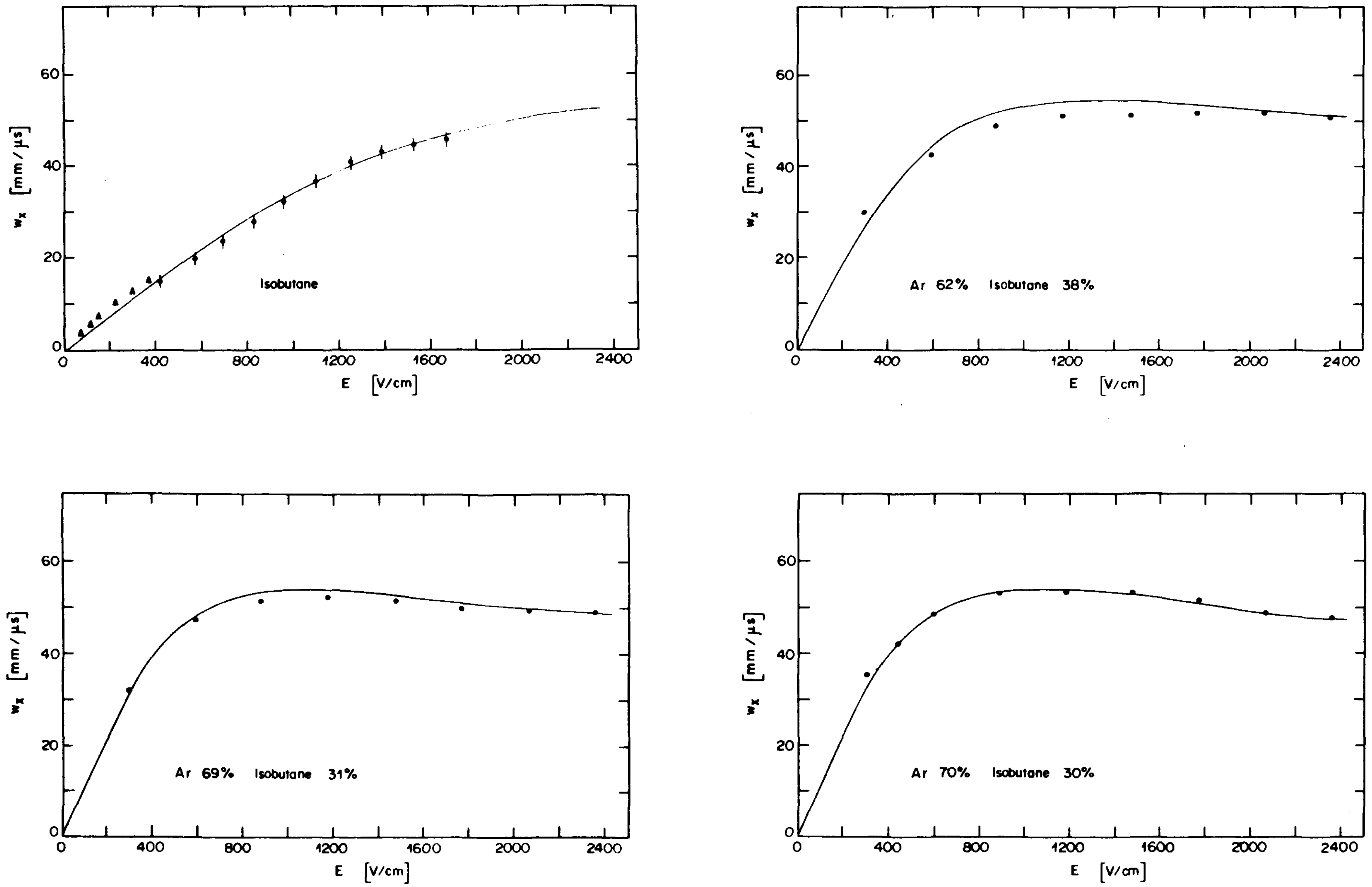


Fig. 116 Schultz (1976)



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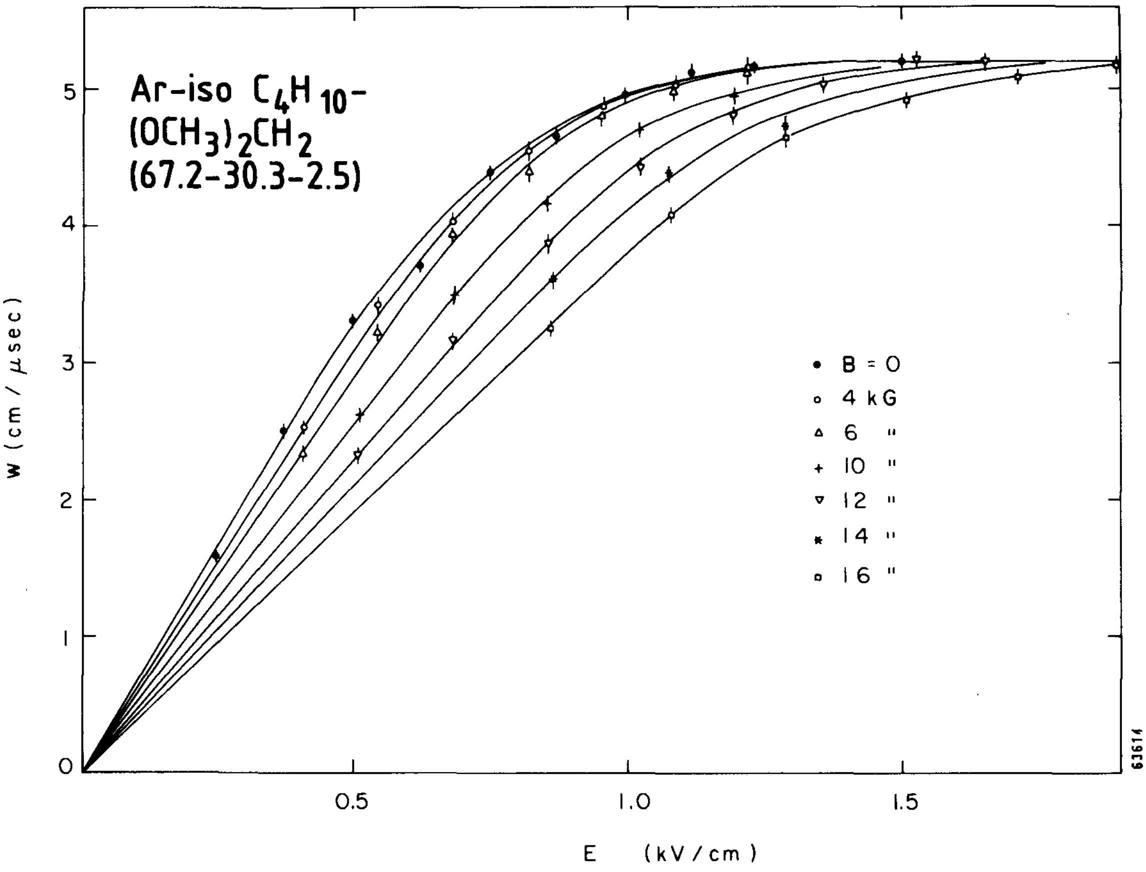
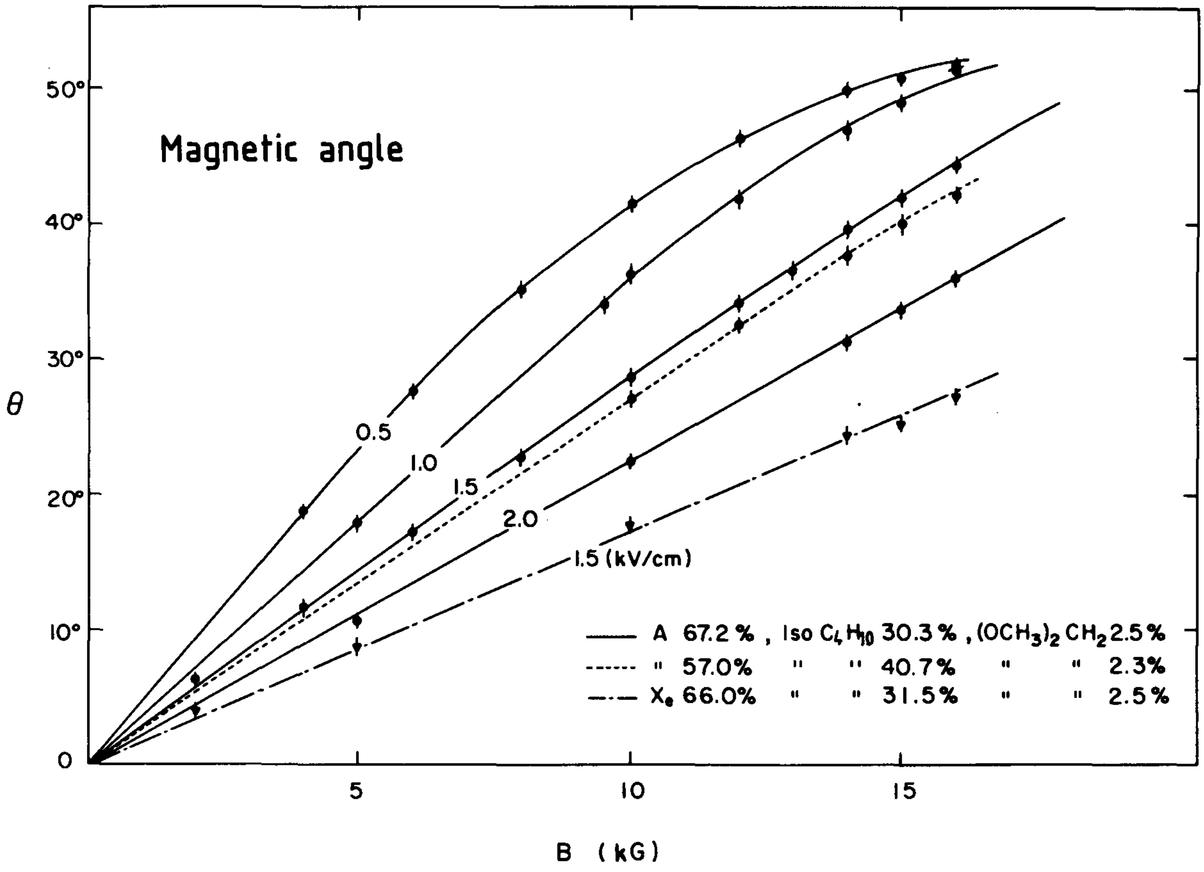


Fig. 118 Breskin et al. (1975)



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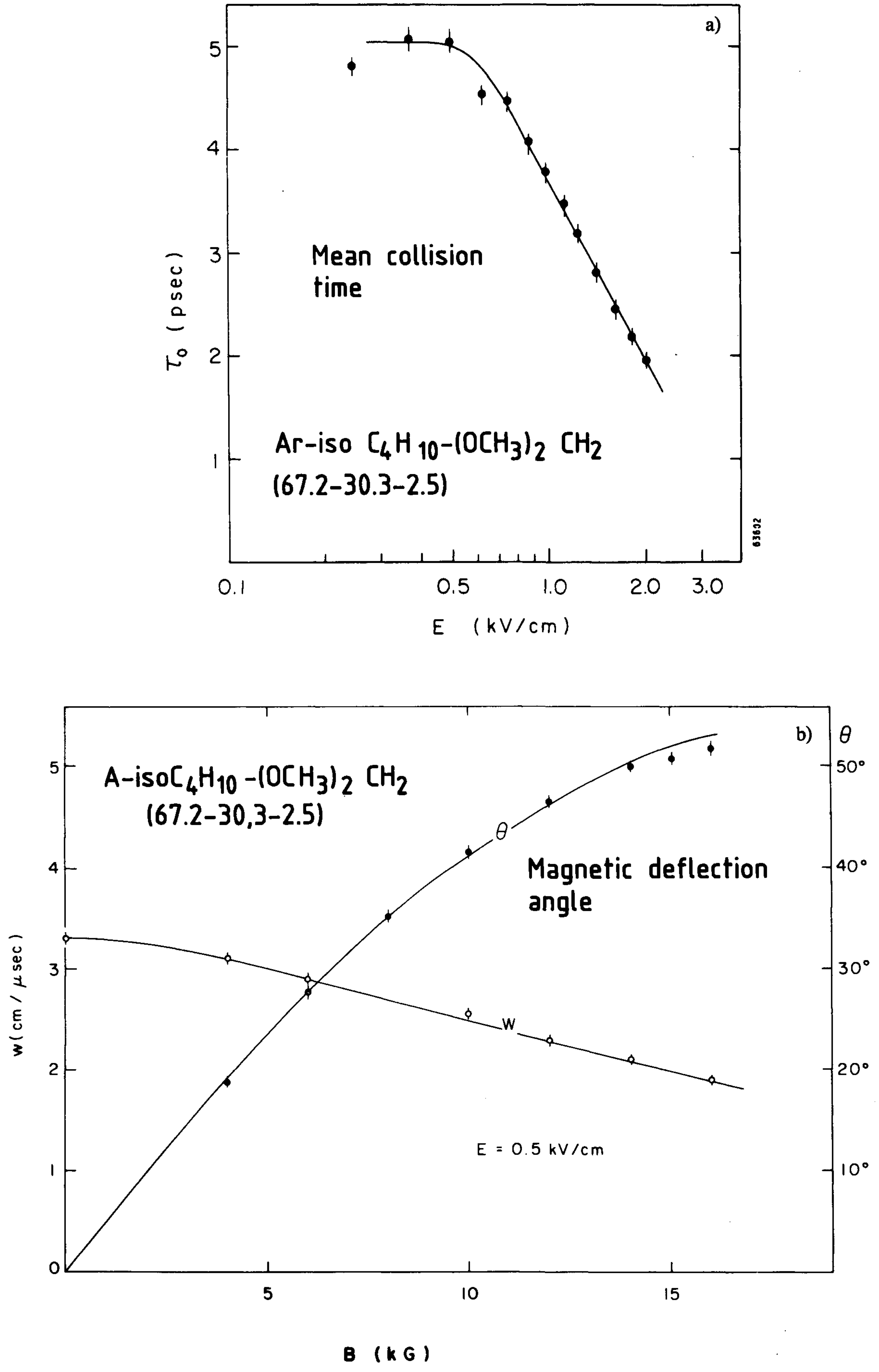

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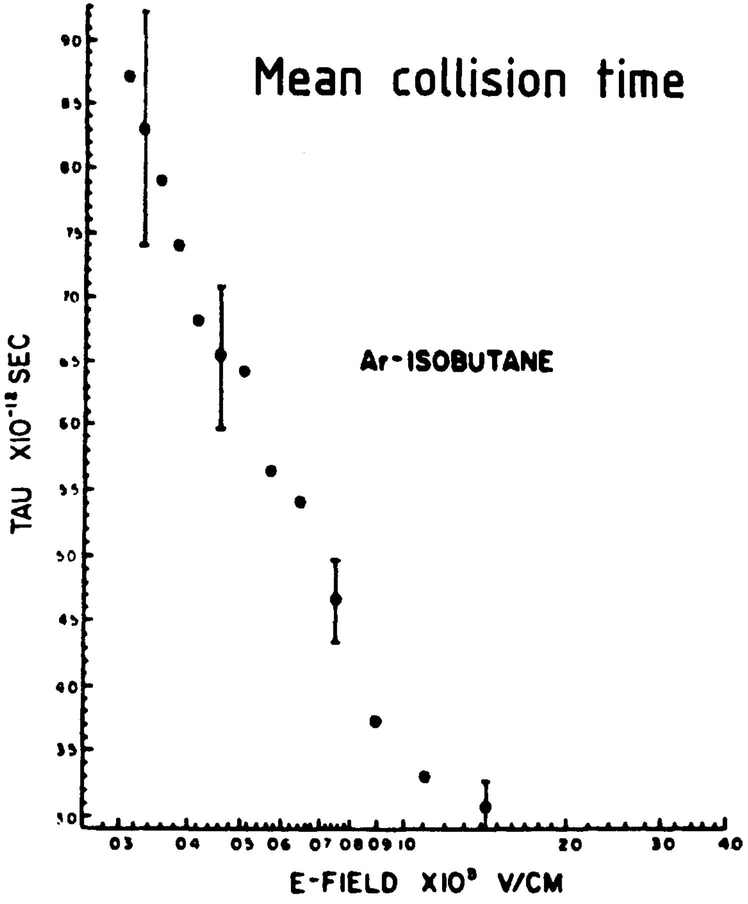
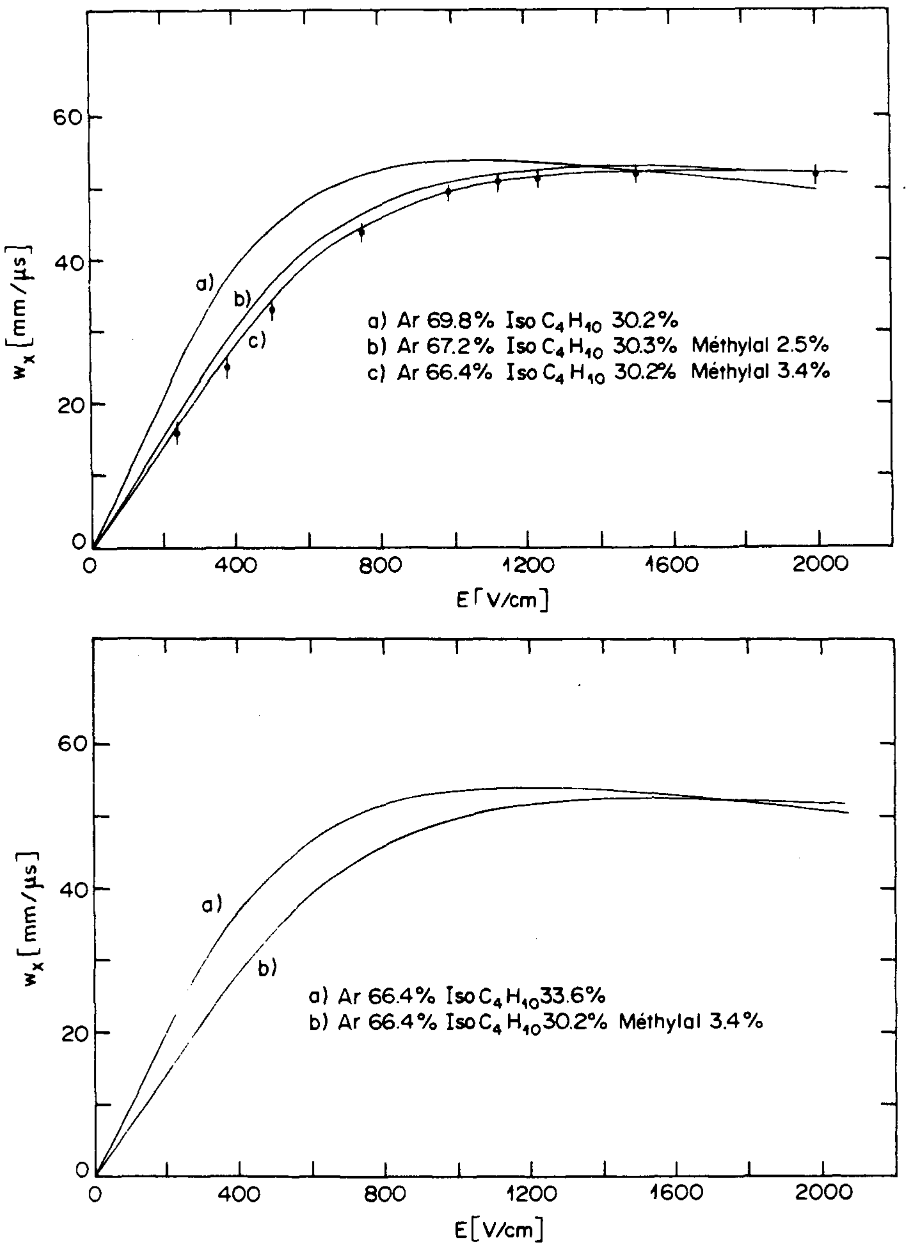


Fig. 121 Baranko et al. (1980)



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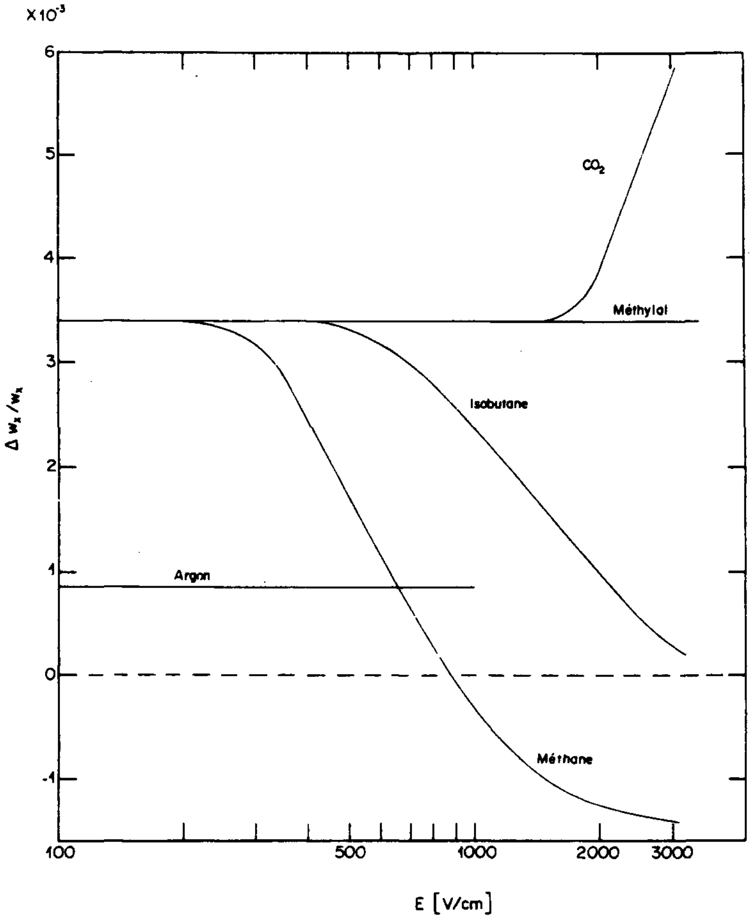

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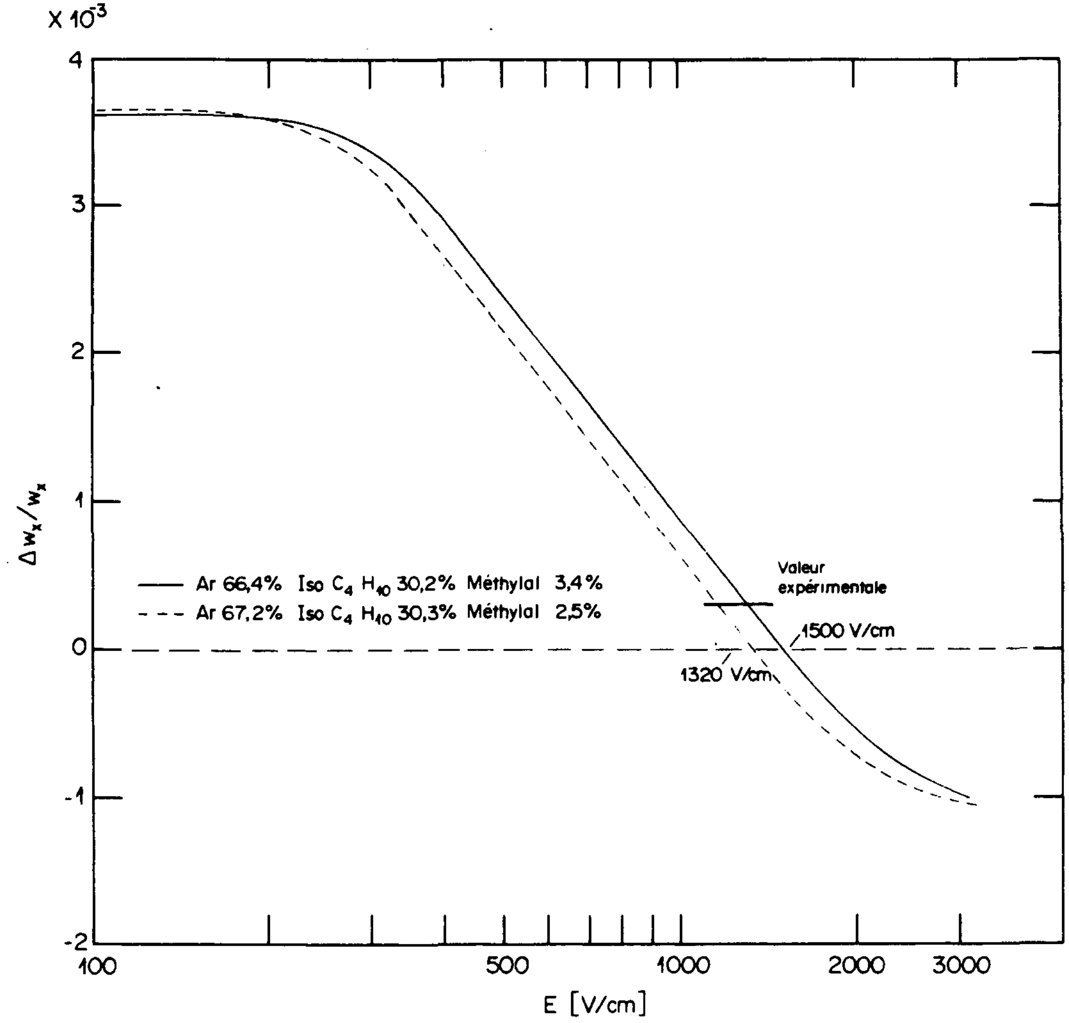

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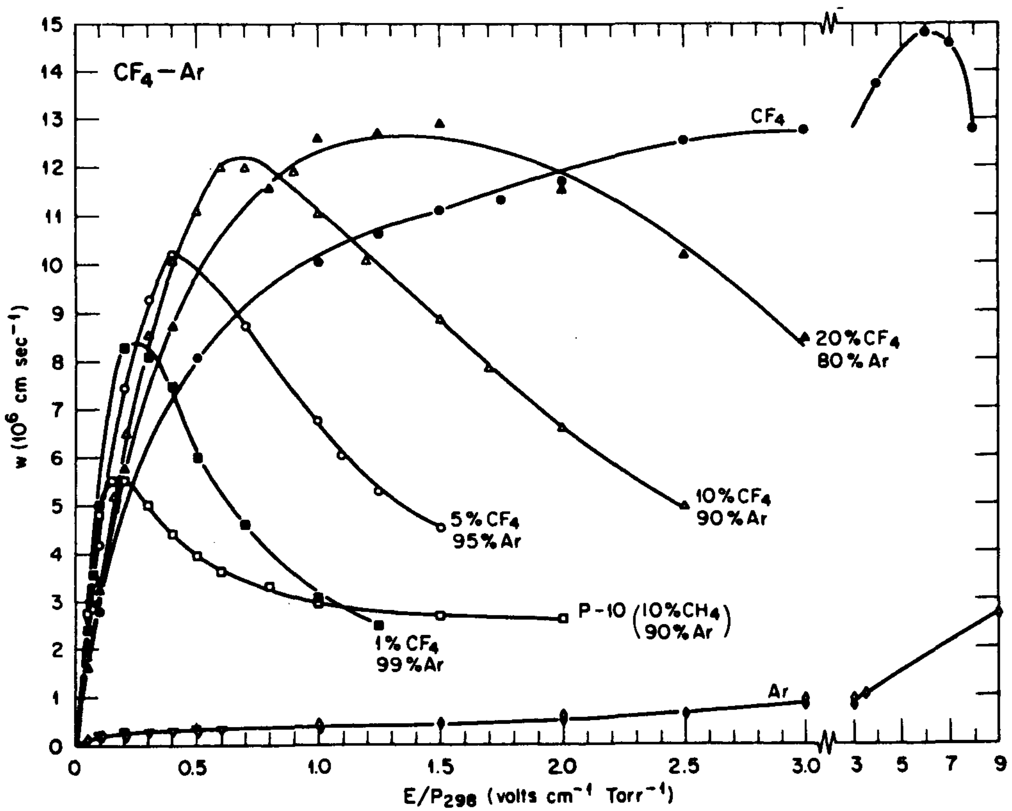
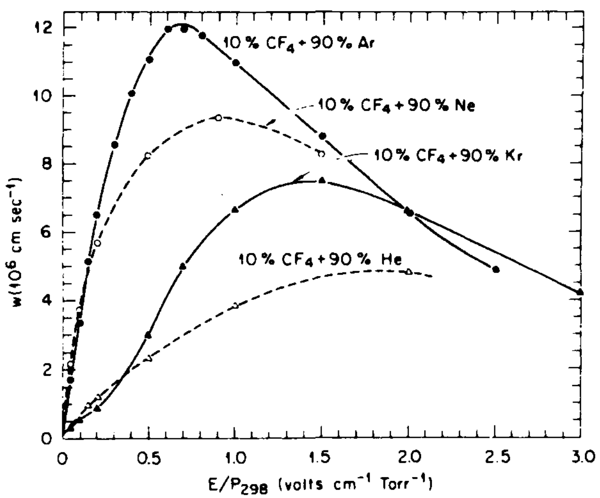


Fig. 125 Christophorou et al. (1979)



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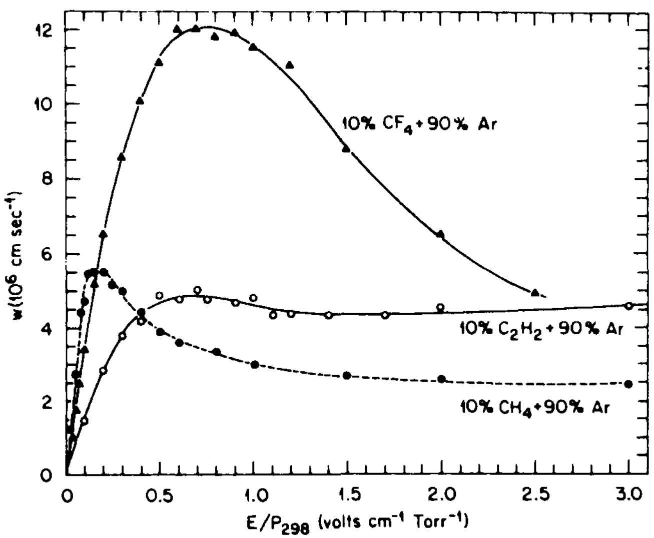

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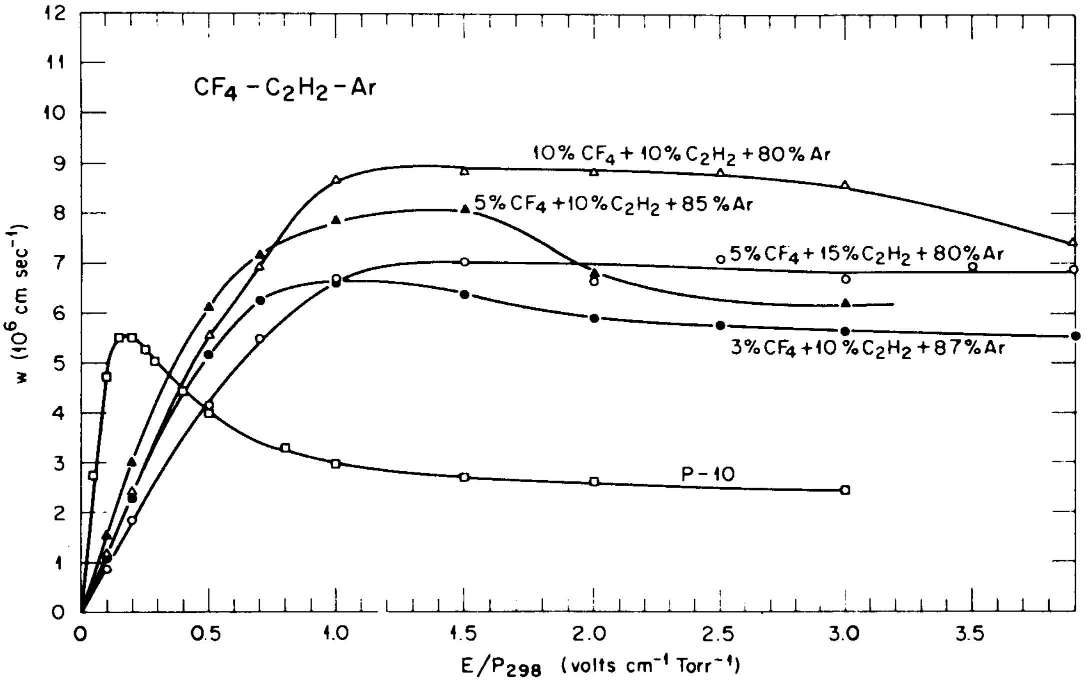

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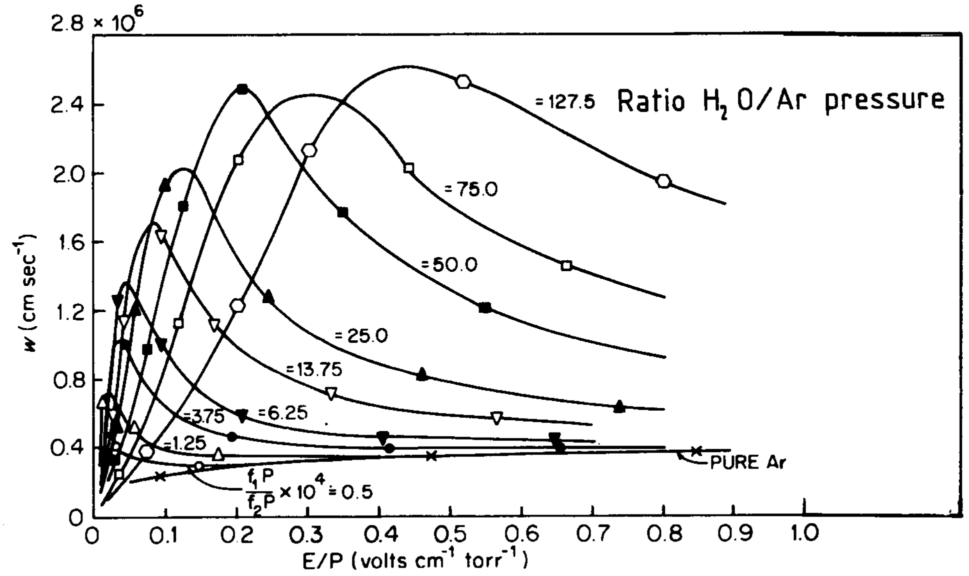


Fig. 129 Christophorou (1971)

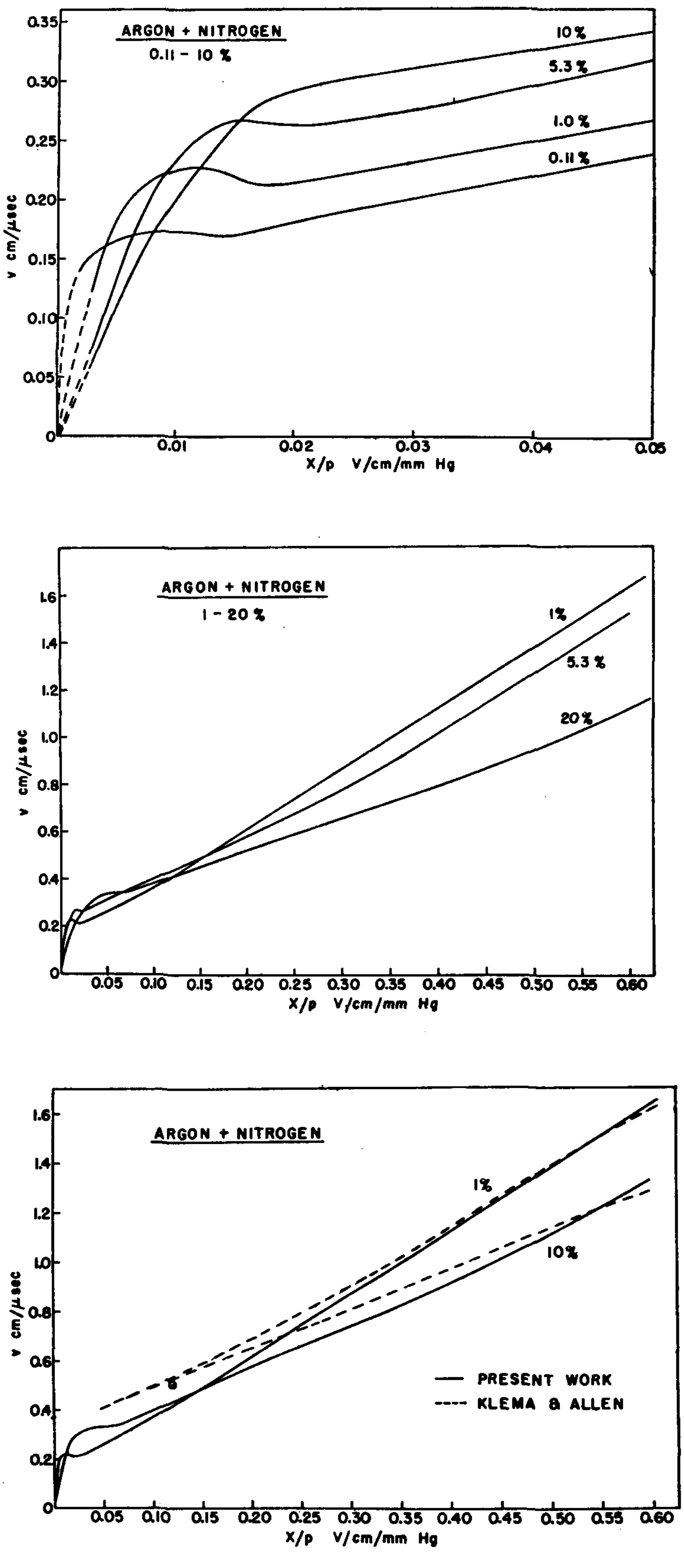


Fig. 130 English and Hanna (1953)

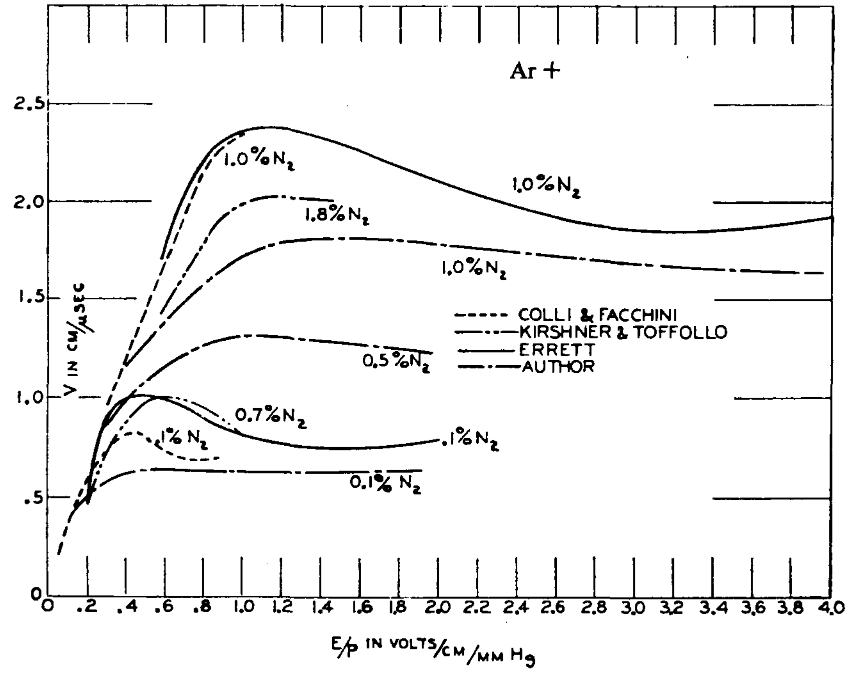


Fig. 131 Uman and Warfield (1960)

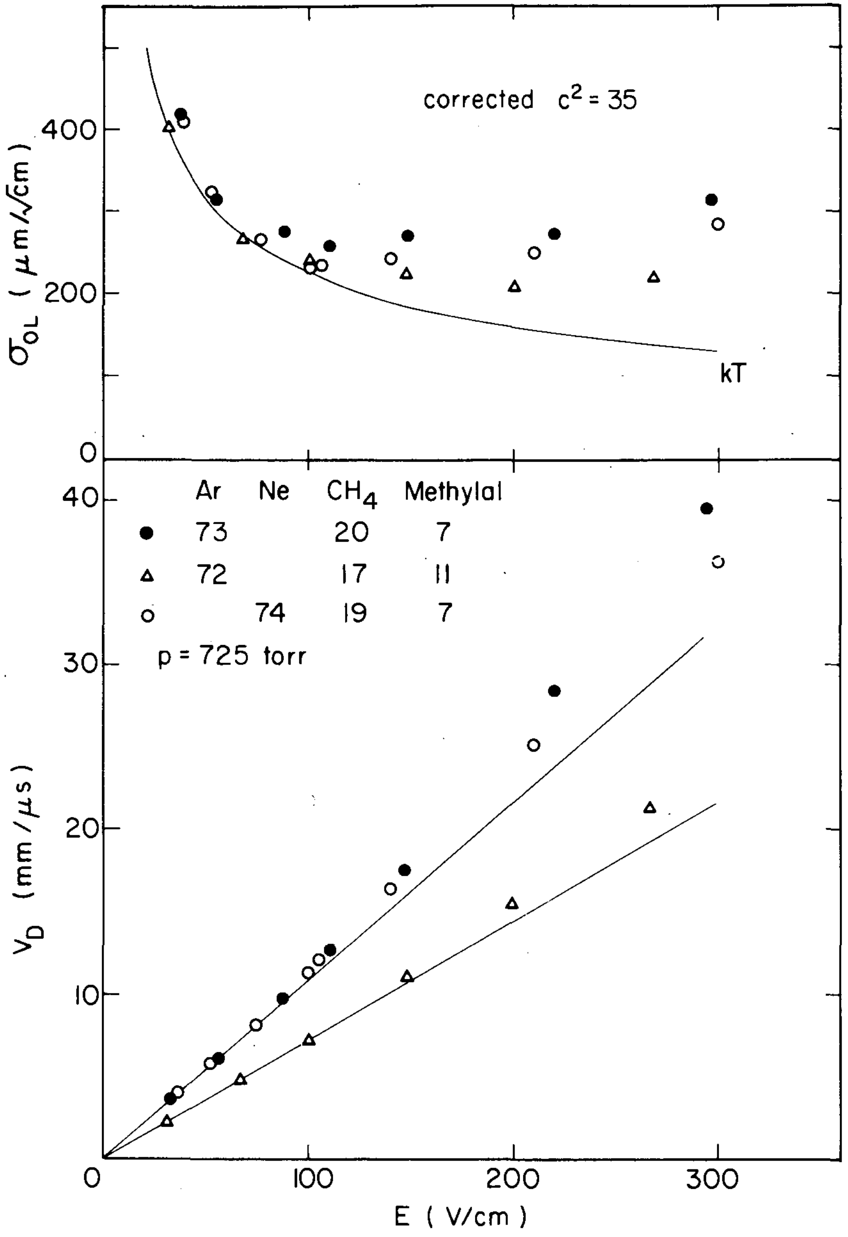


Fig. 132 Piuz (1983)

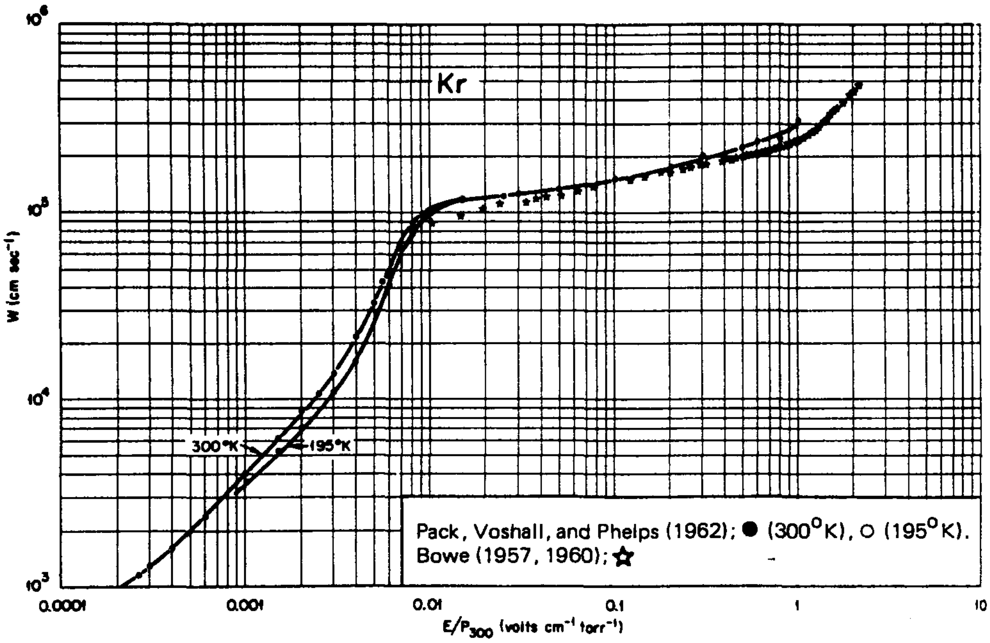


Fig. 133 Christophorou (1971)

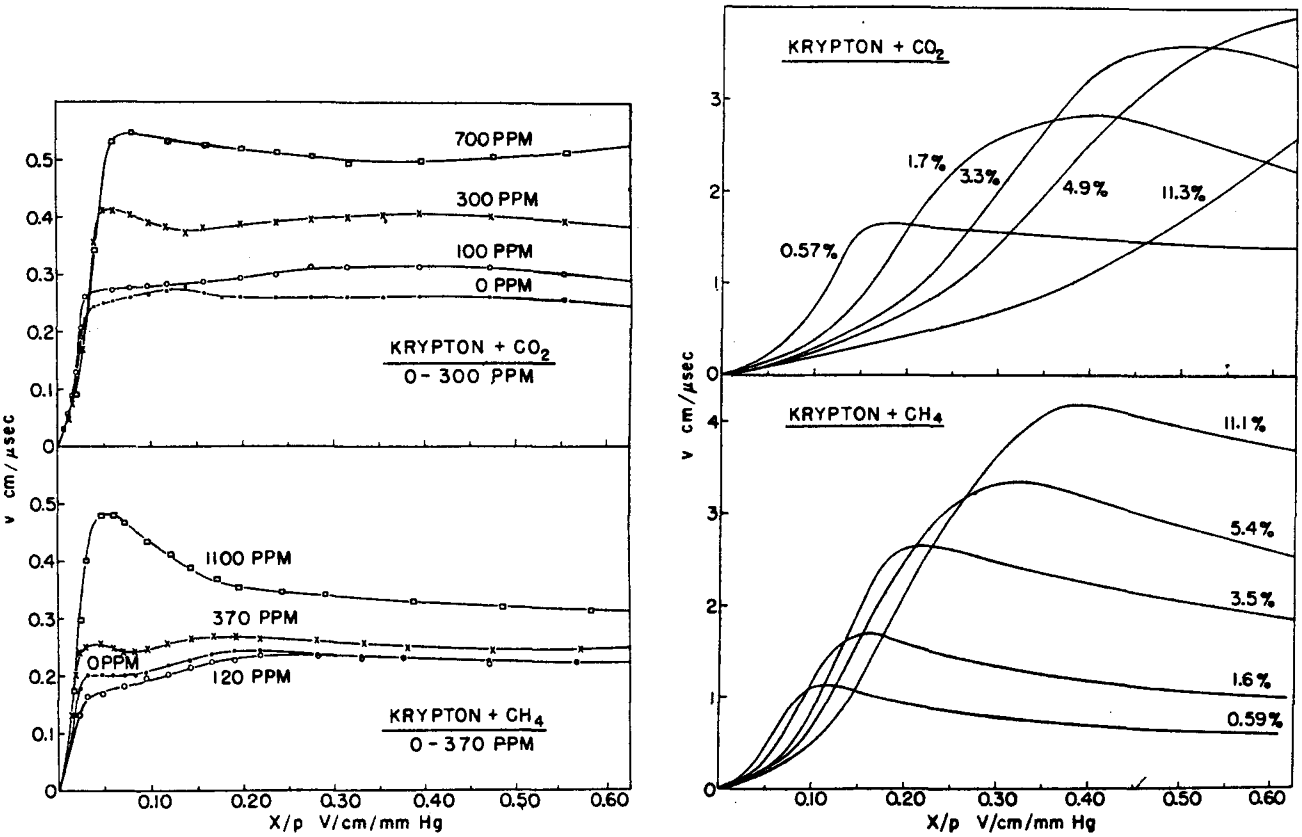


Fig. 134 English and Hanna (1953)

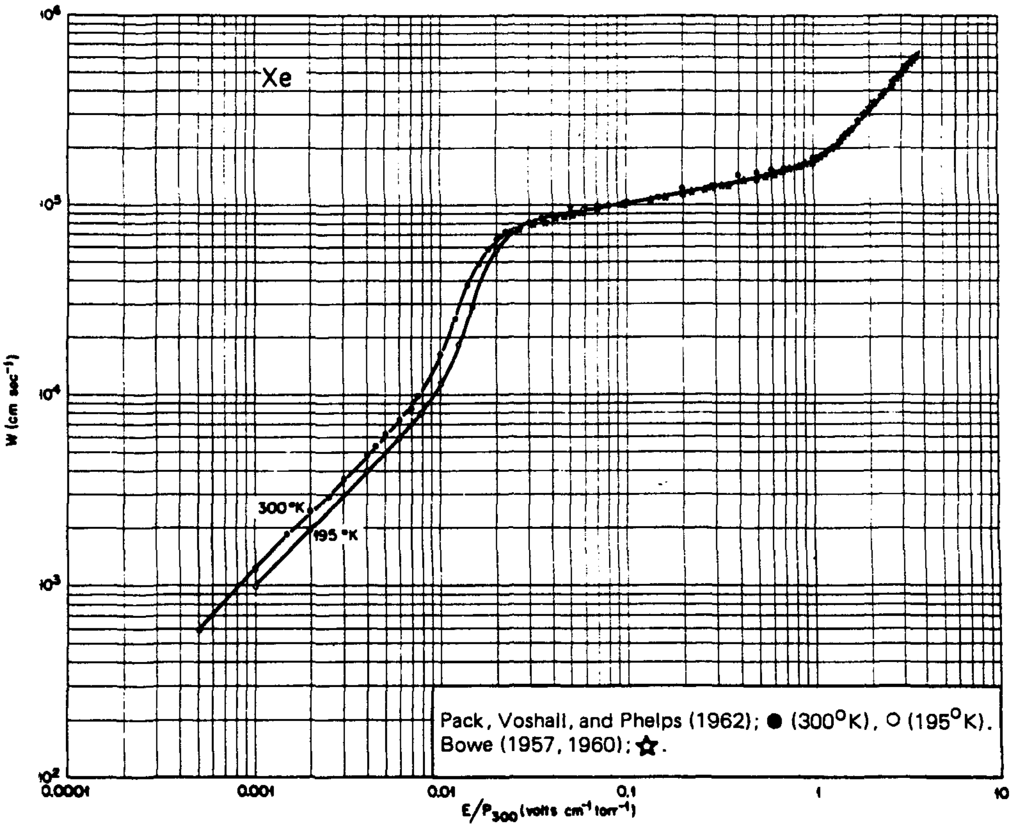


Fig. 135 Christophorou (1971)

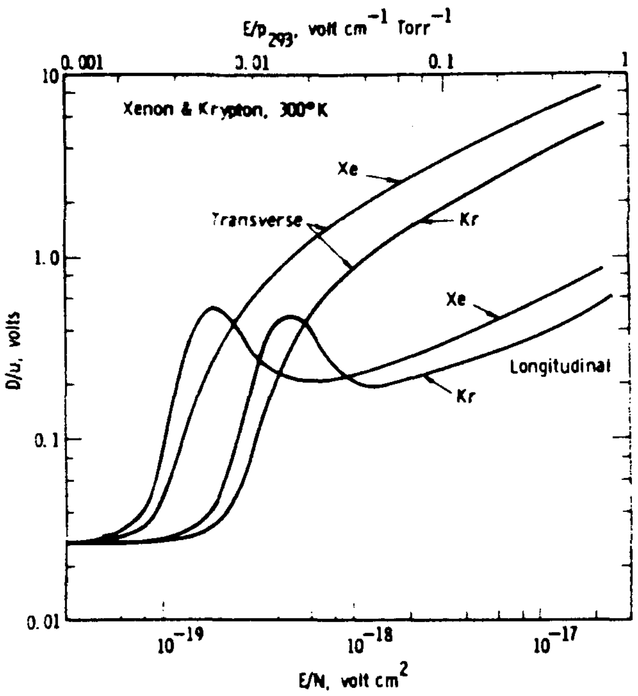


Fig. 136 Lowke and Parker (1969)

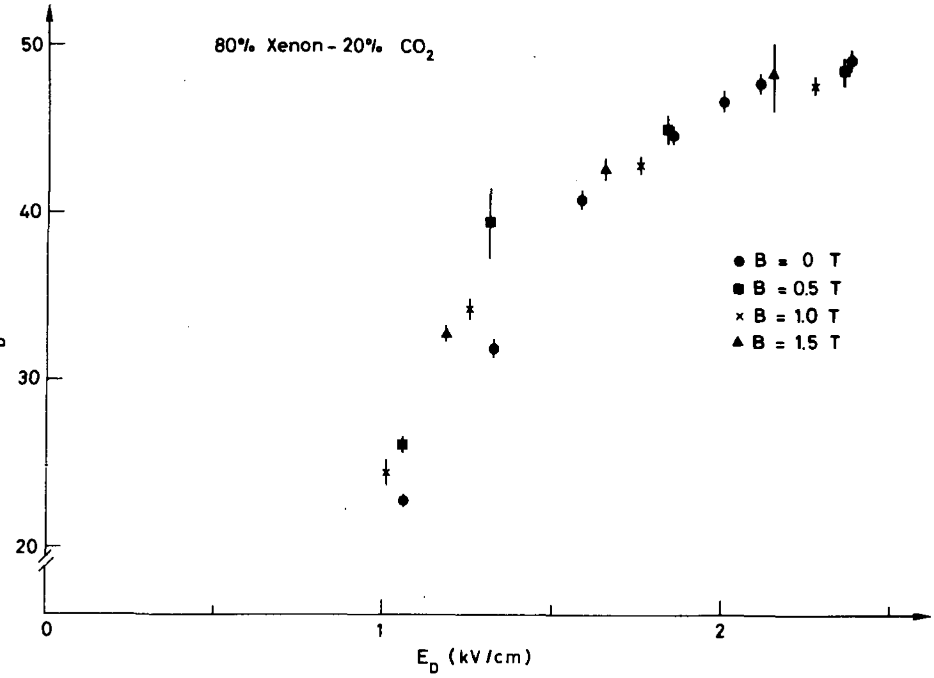


Fig. 137 Daum et al. (1978)

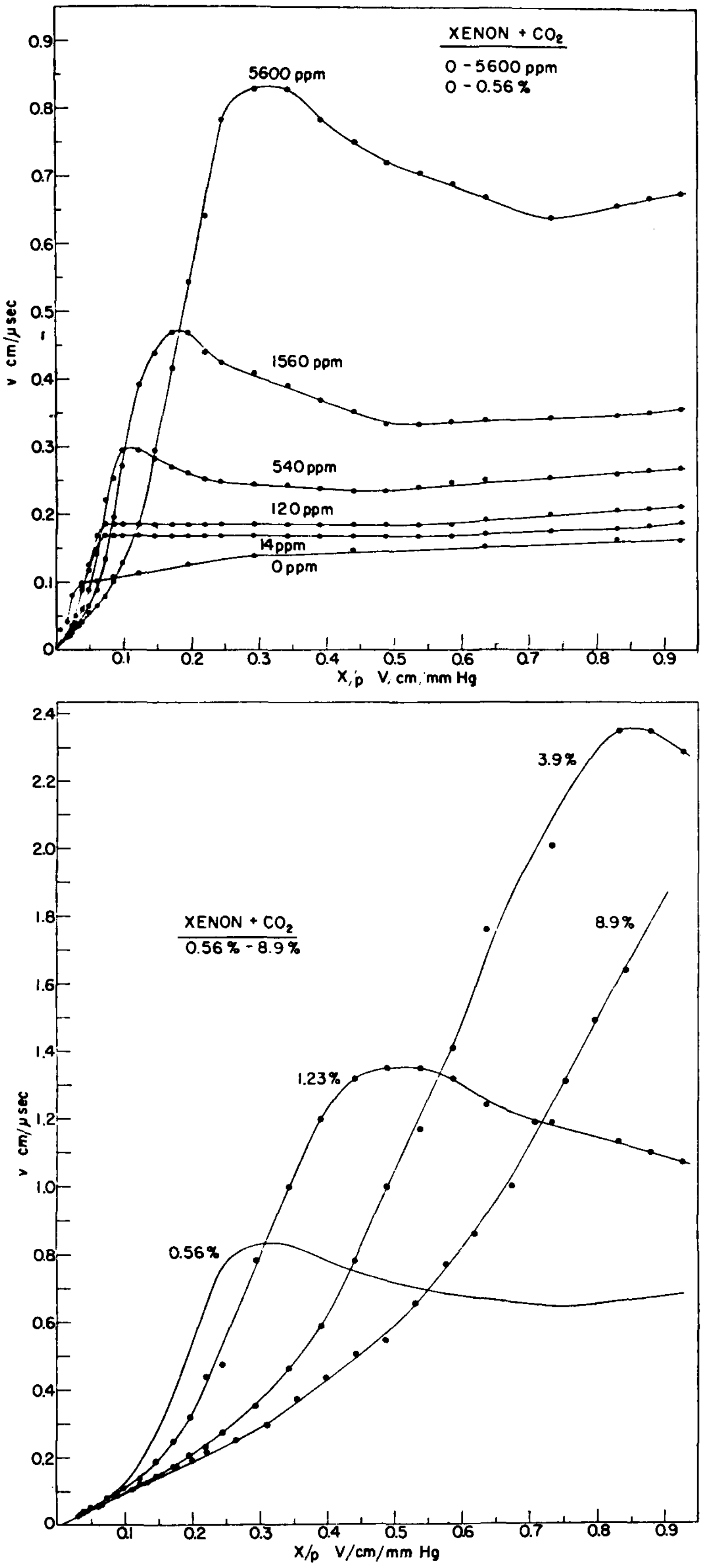


Fig. 138 English and Hanna (1953)

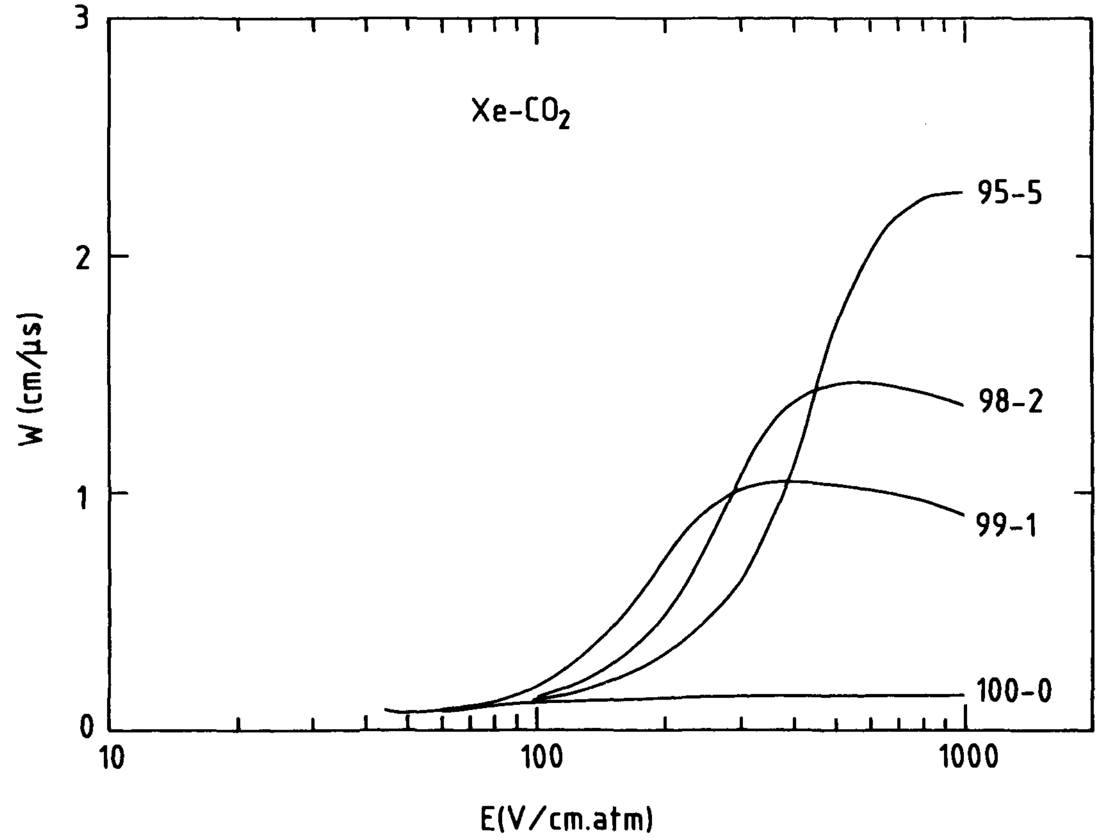


Fig. 139 Peisert and Sauli (1984)

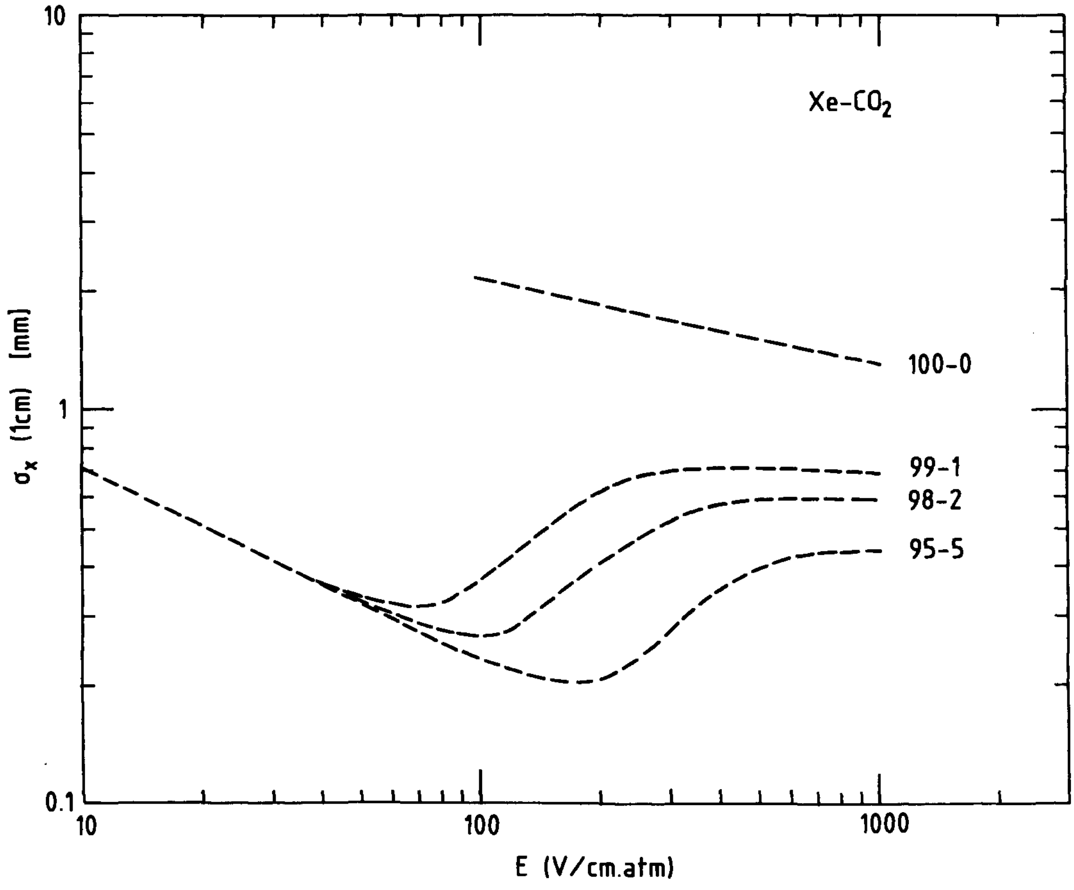
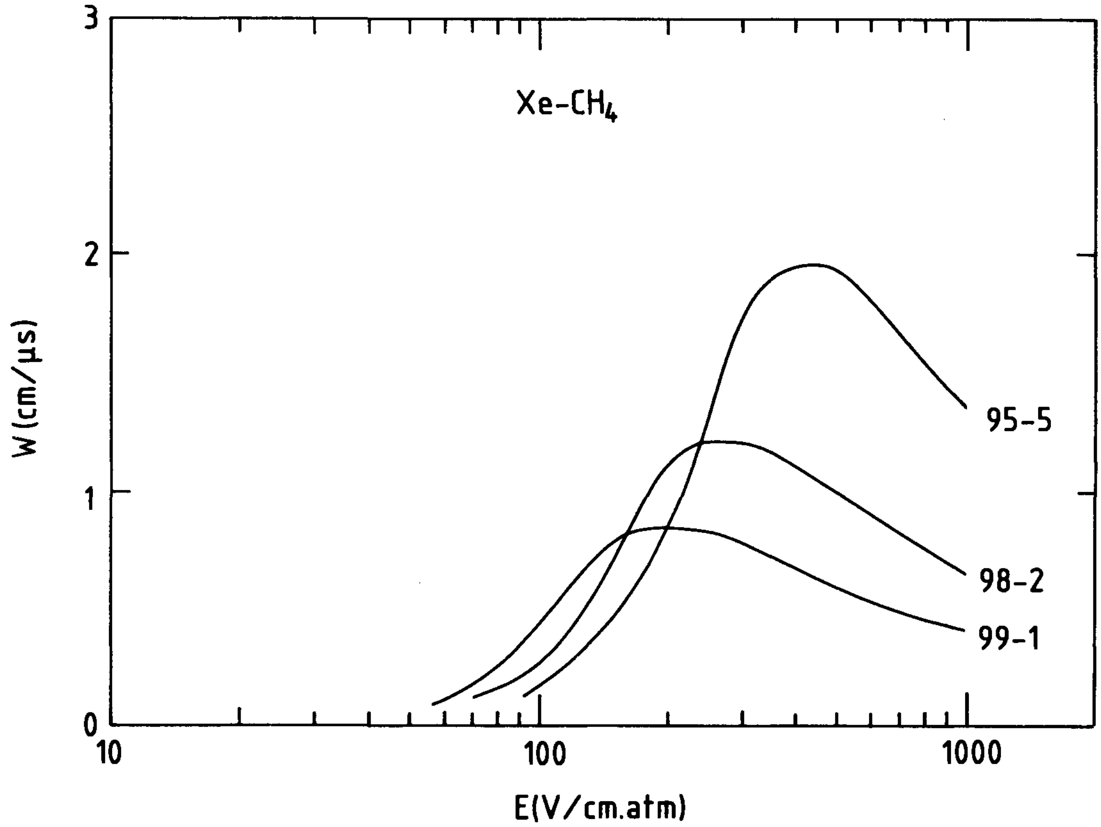


Fig. 140 Peisert and Sauli (1984)



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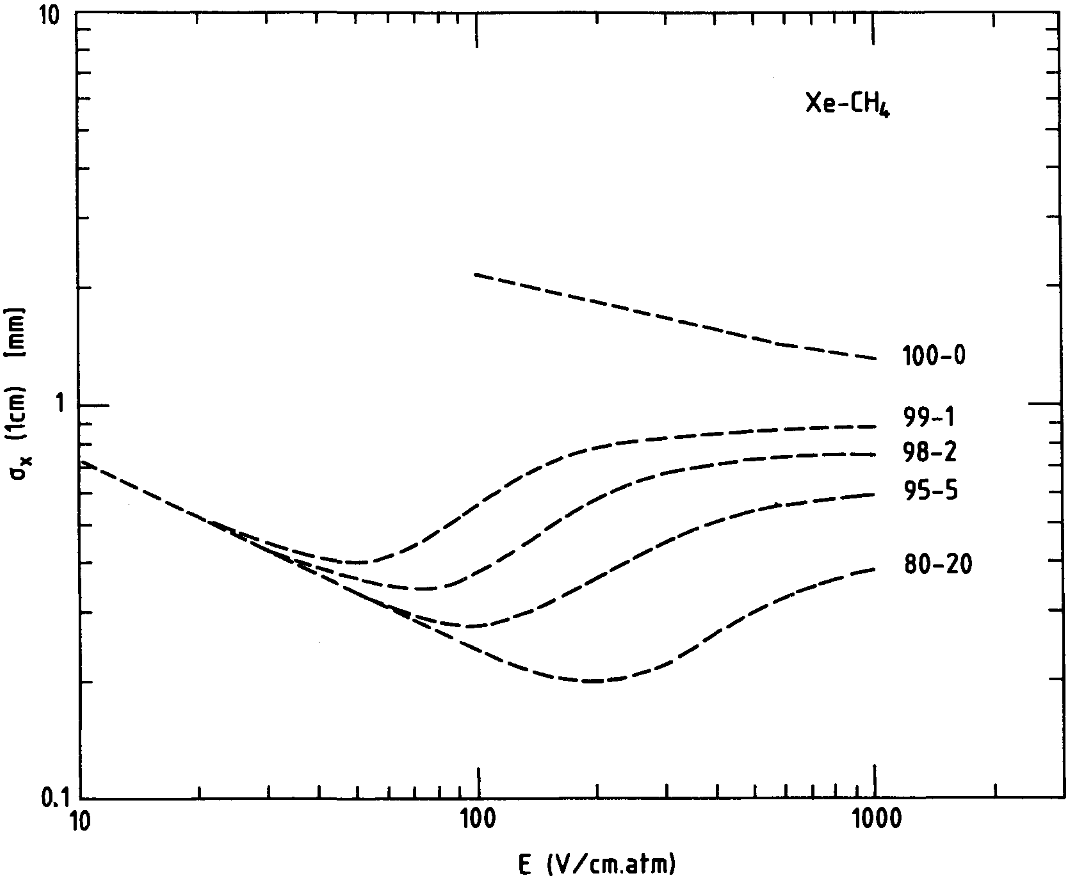


Fig. 142 Peisert and Sauli (1984)

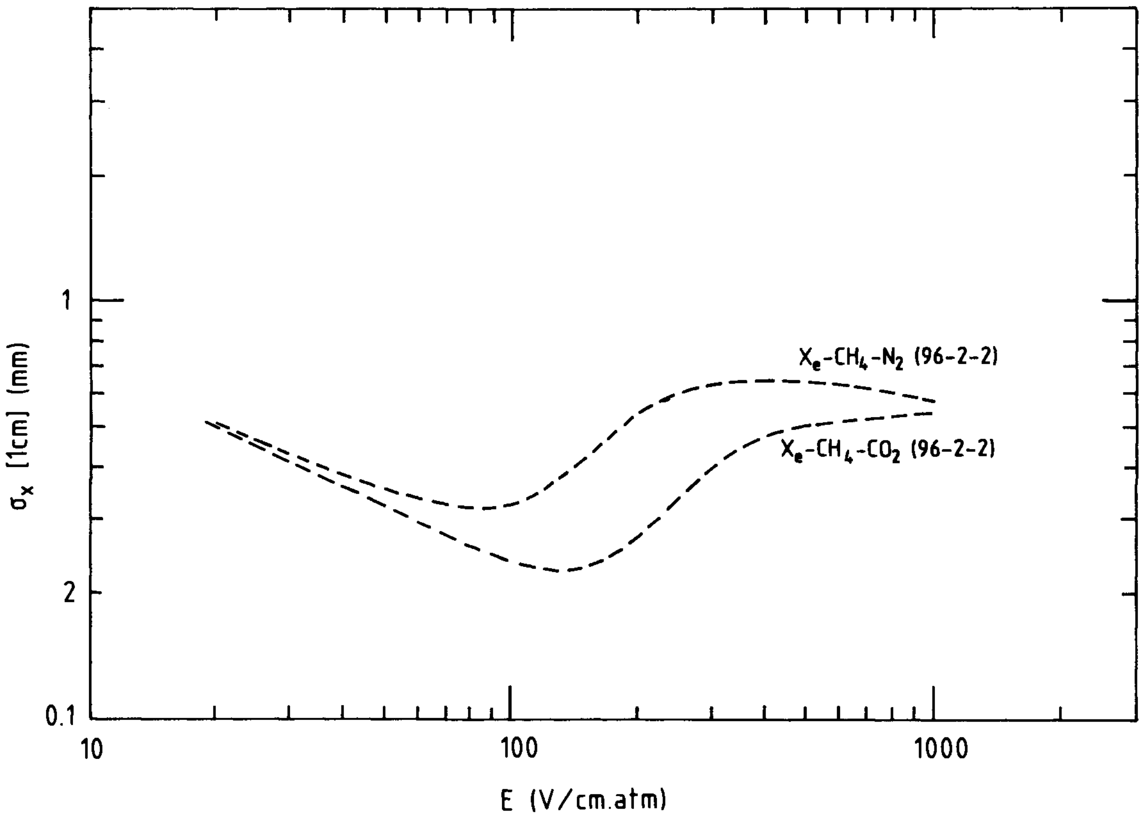


Fig. 143 Peisert and Sauli (1984)

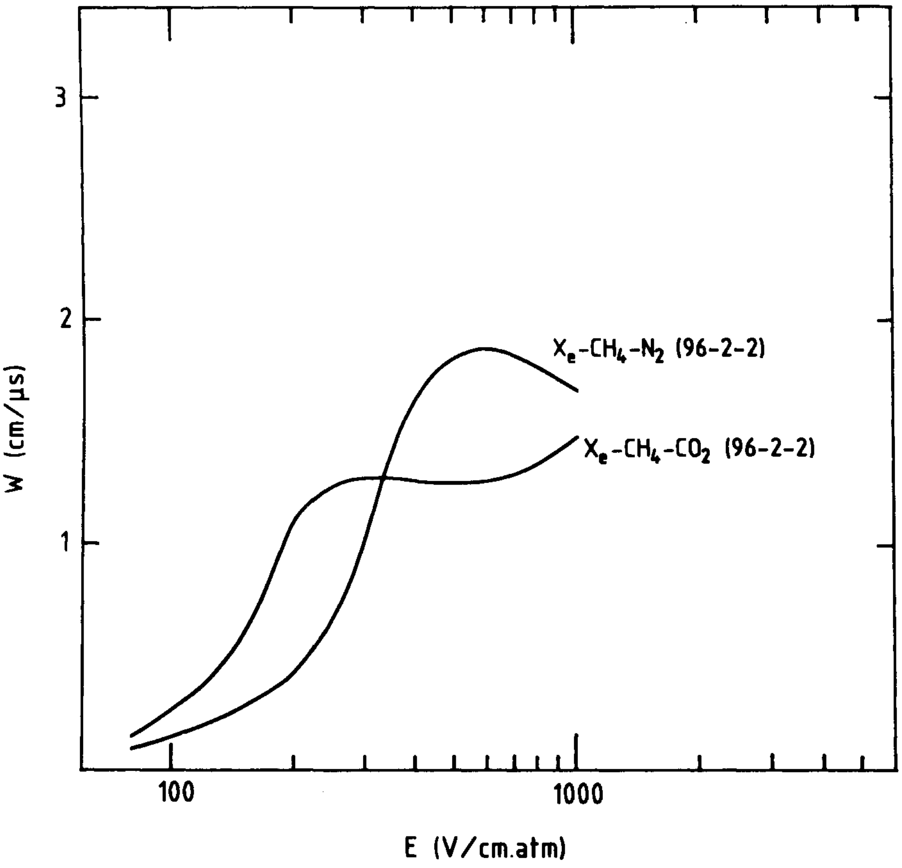


Fig. 144 Peisert and Sauli (1984)

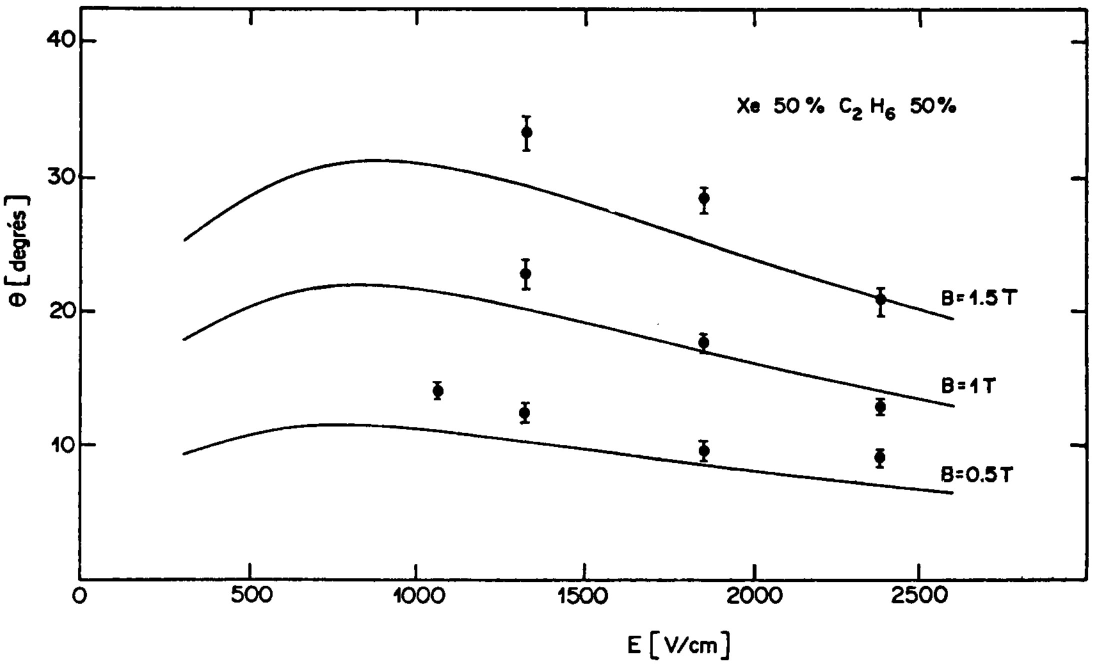


Fig. 145 Ramanantsizehena (1979)

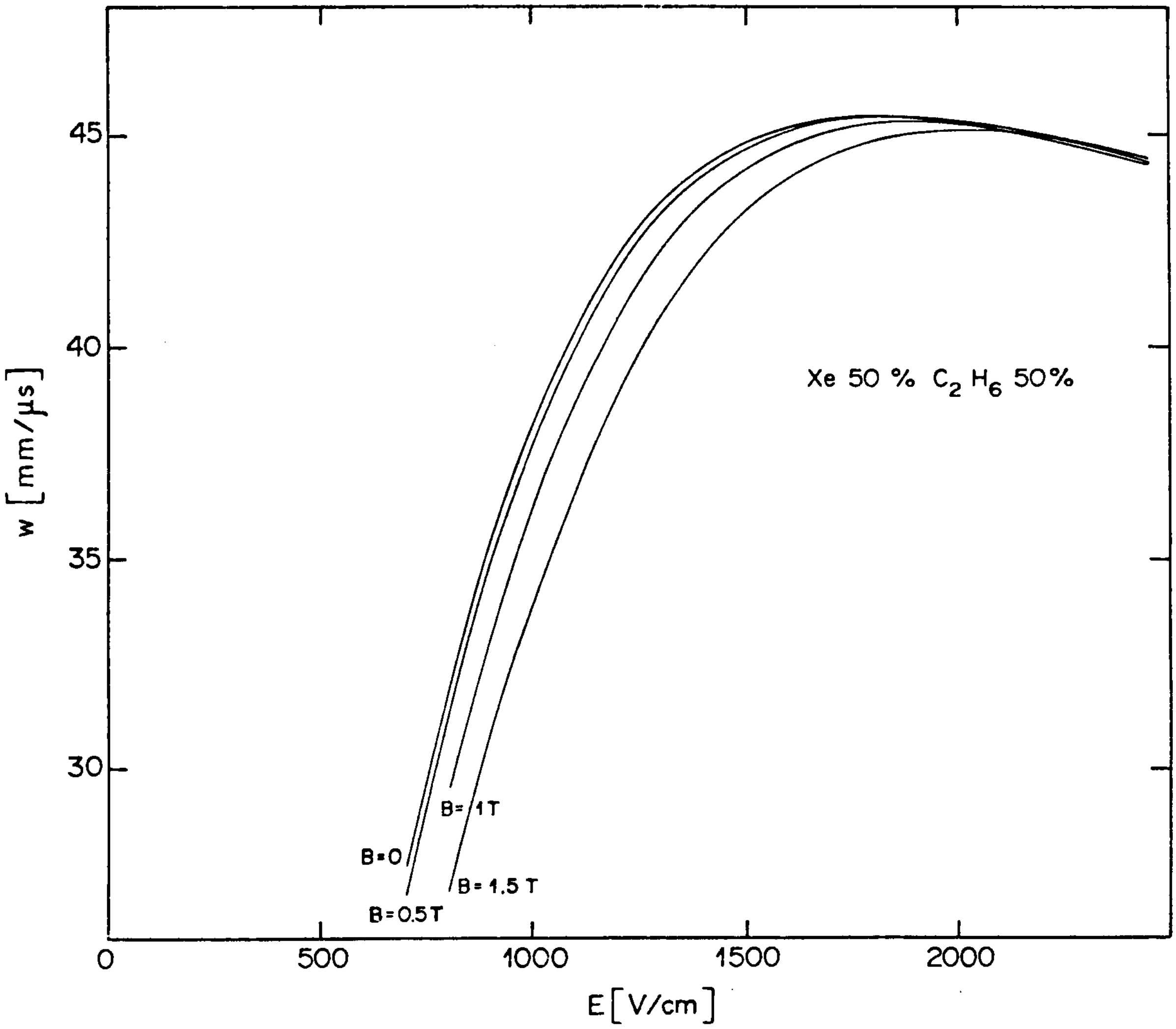


Fig. 146 Ramanantsizehena (1979)

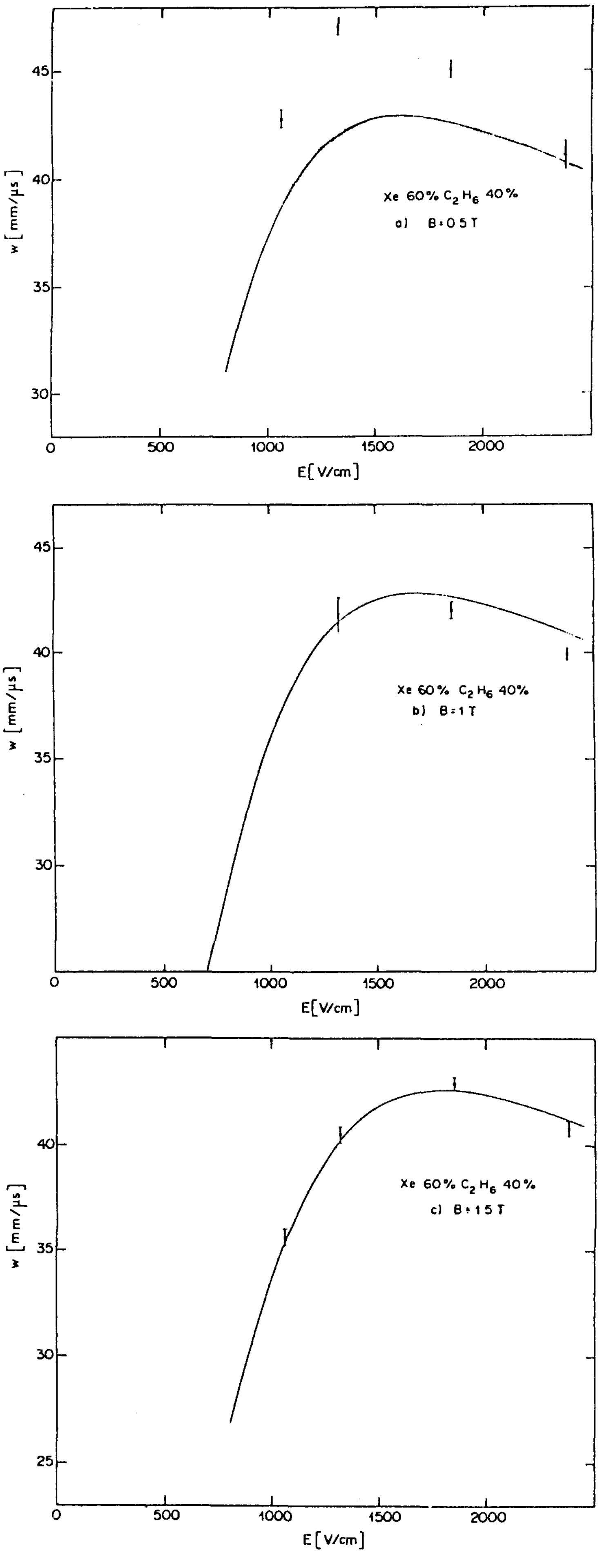


Fig. 147 Ramanantsizehena (1979)

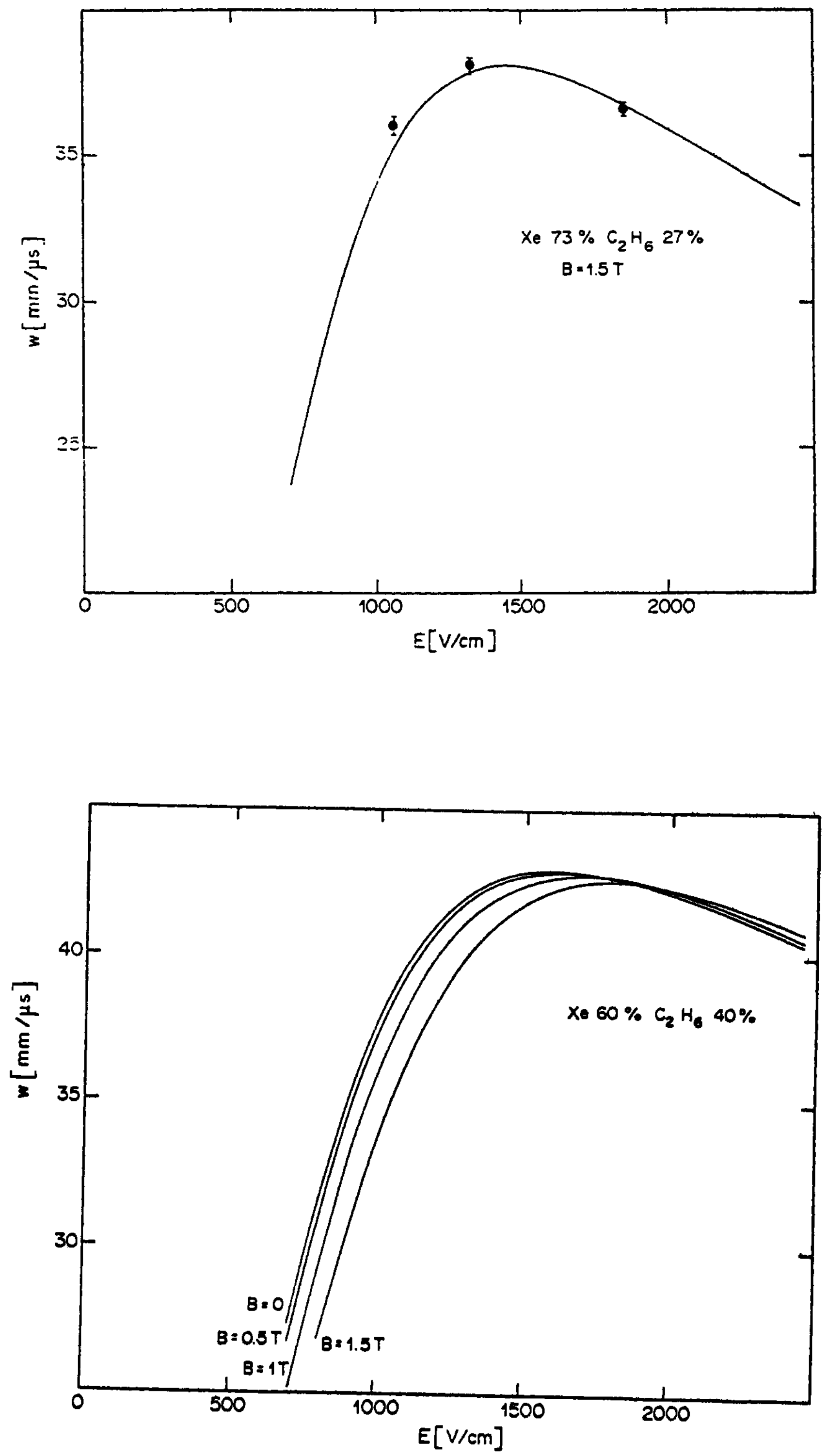


Fig. 148 Ramanantsizehena (1979)

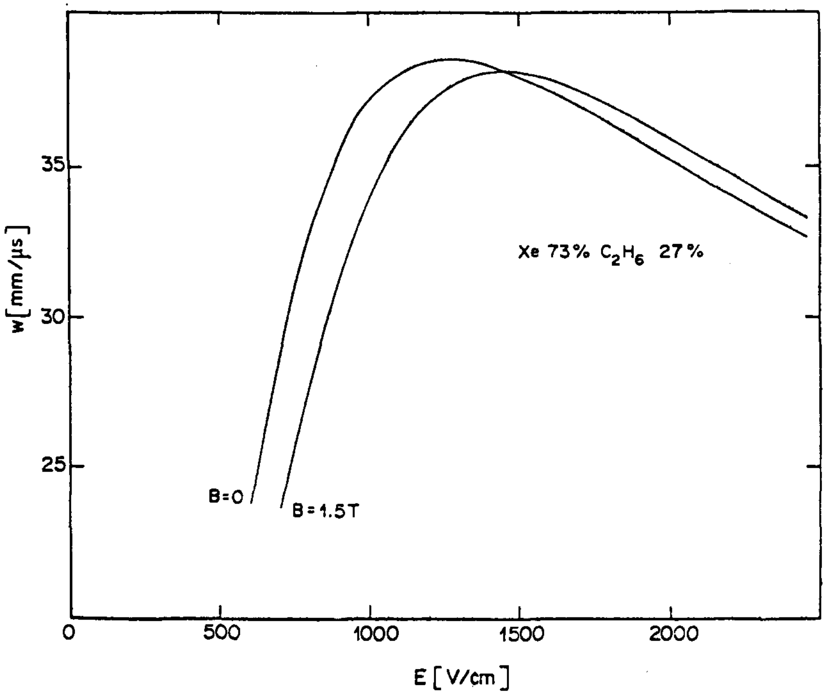


Fig. 149 Ramanantsizehena (1979)

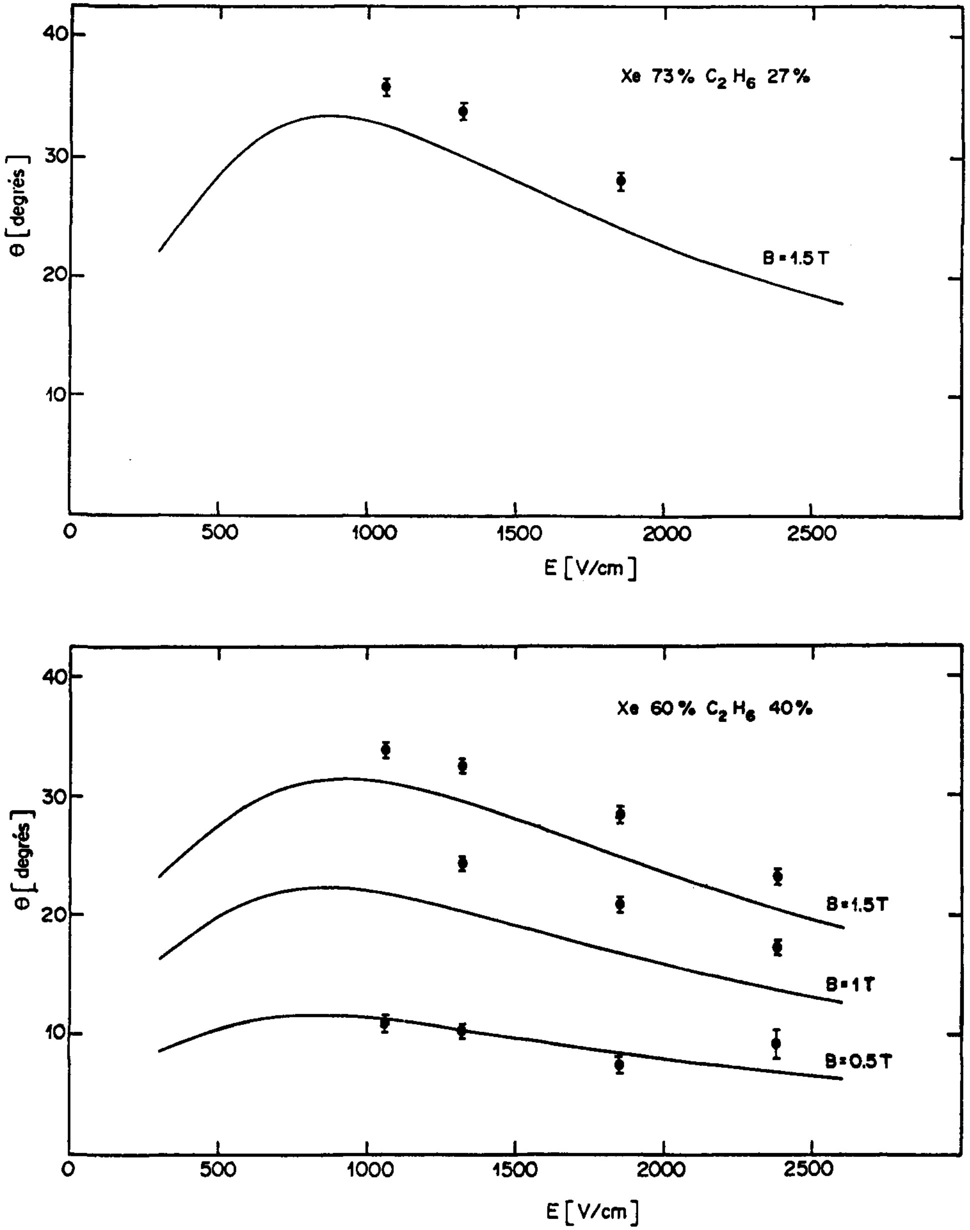


Fig. 150 Ramanantsizehena (1979)

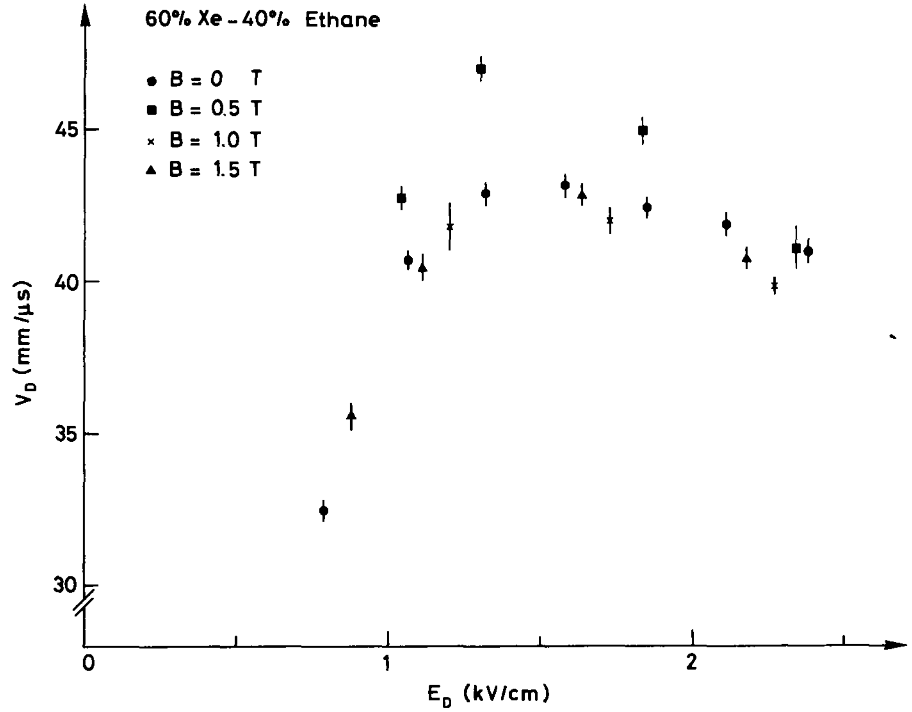
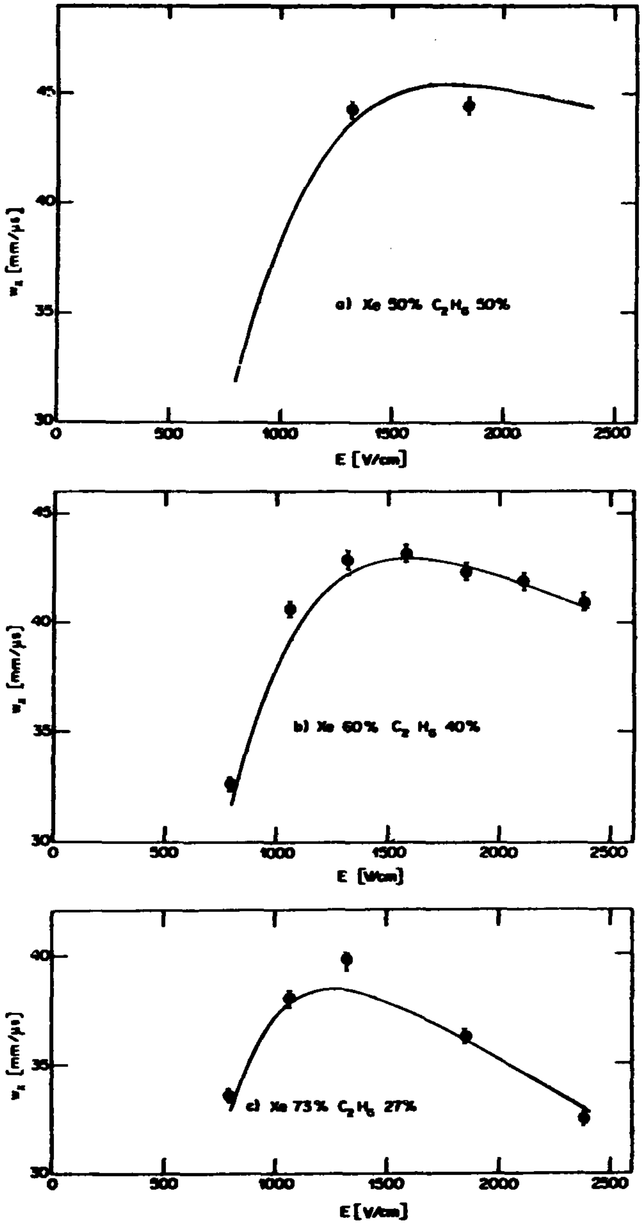


Fig. 151 Daum et al. (1978)



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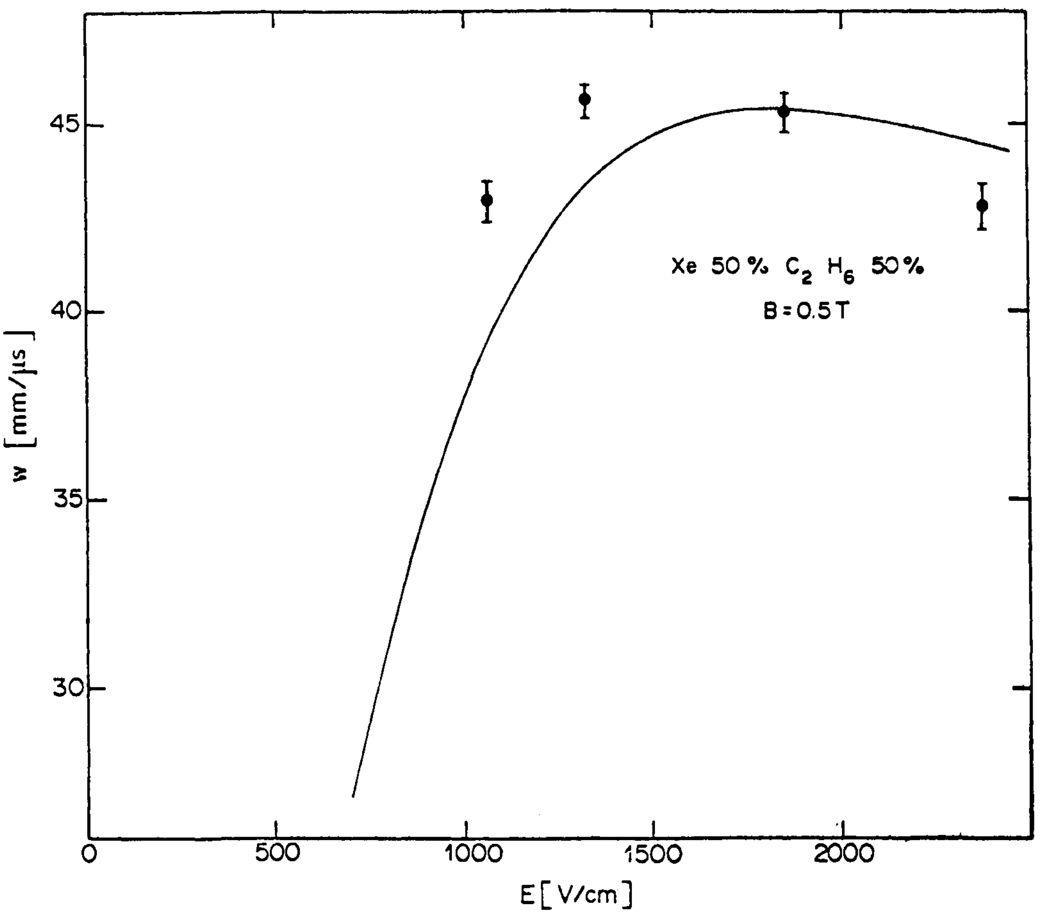

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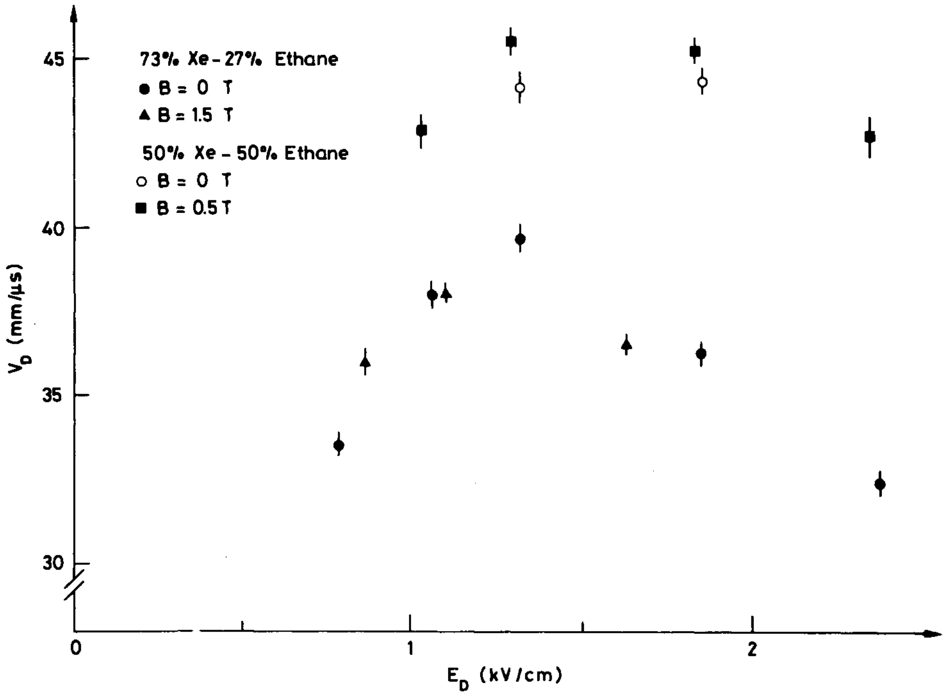

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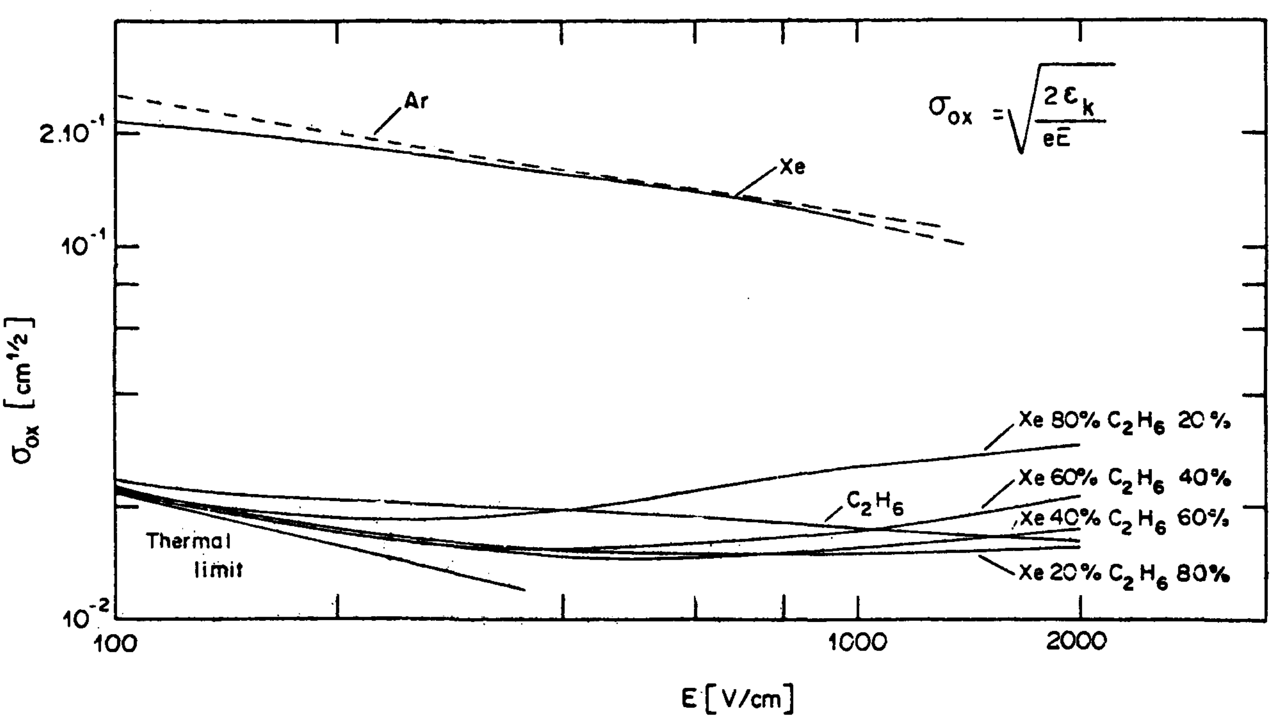


Fig. 155 Ramanantsizehena (1979)

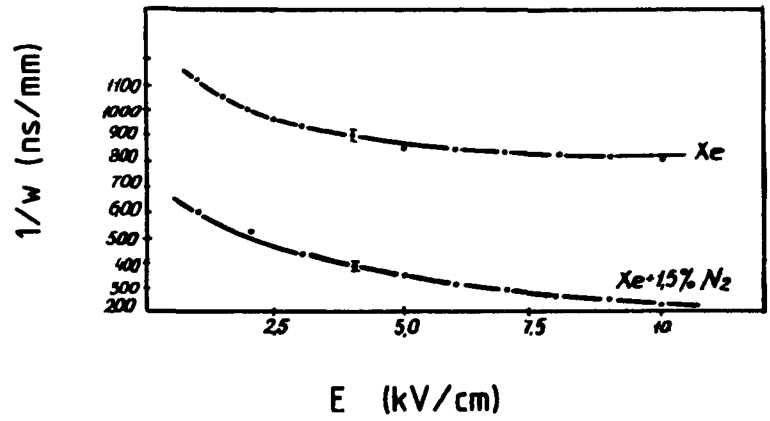


Fig. 156 Alichanian et al. (1979)

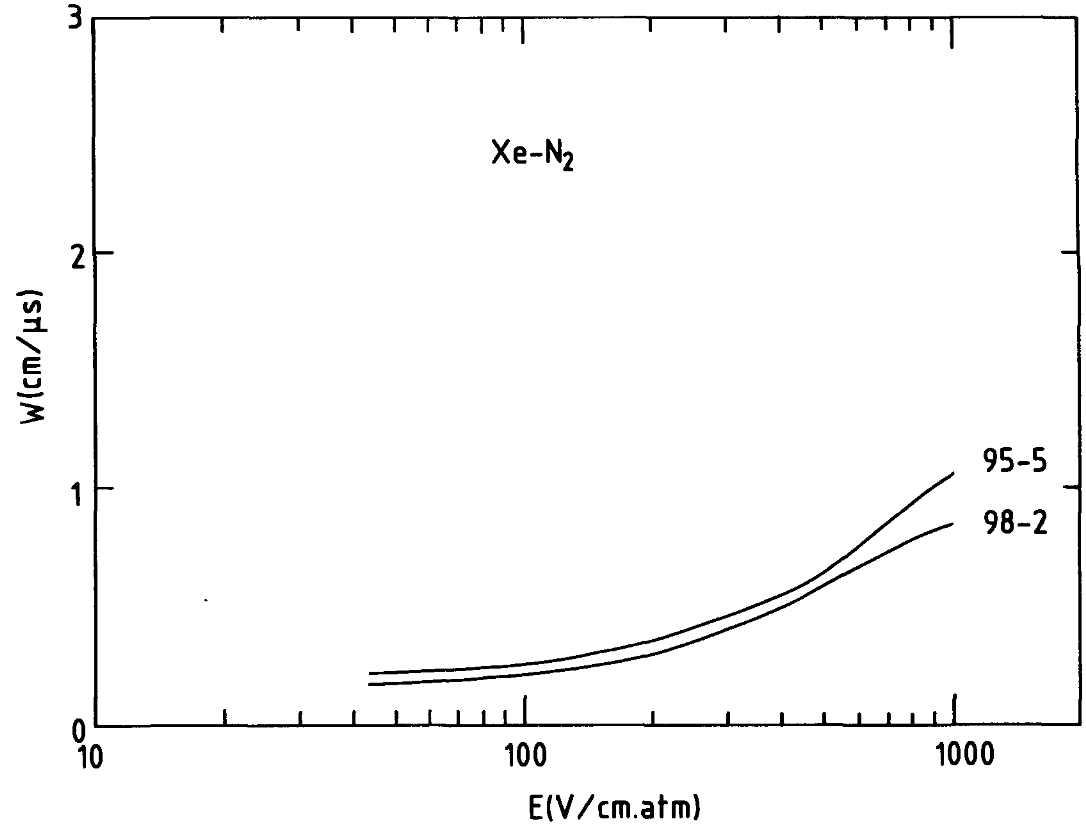


Fig. 157 Peisert and Sauli (1984)

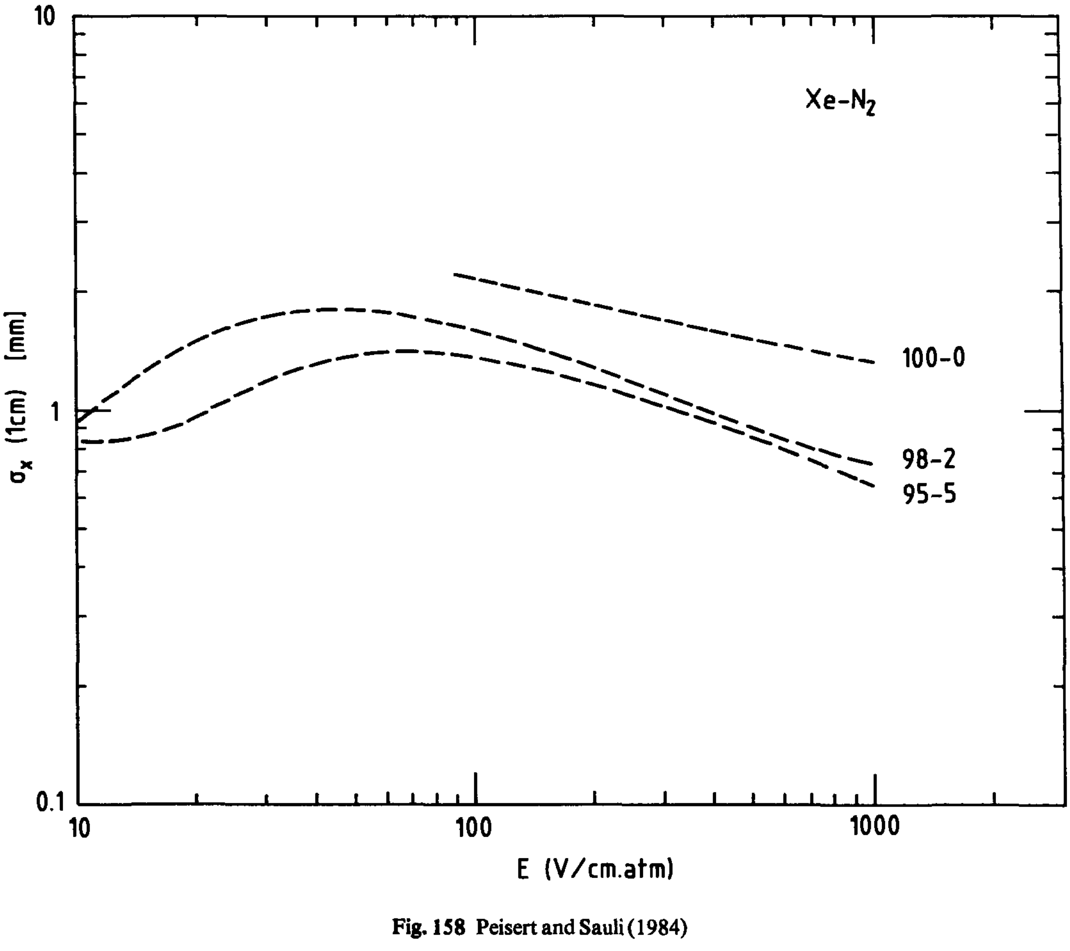


Fig. 158 Peisert and Sauli (1984)

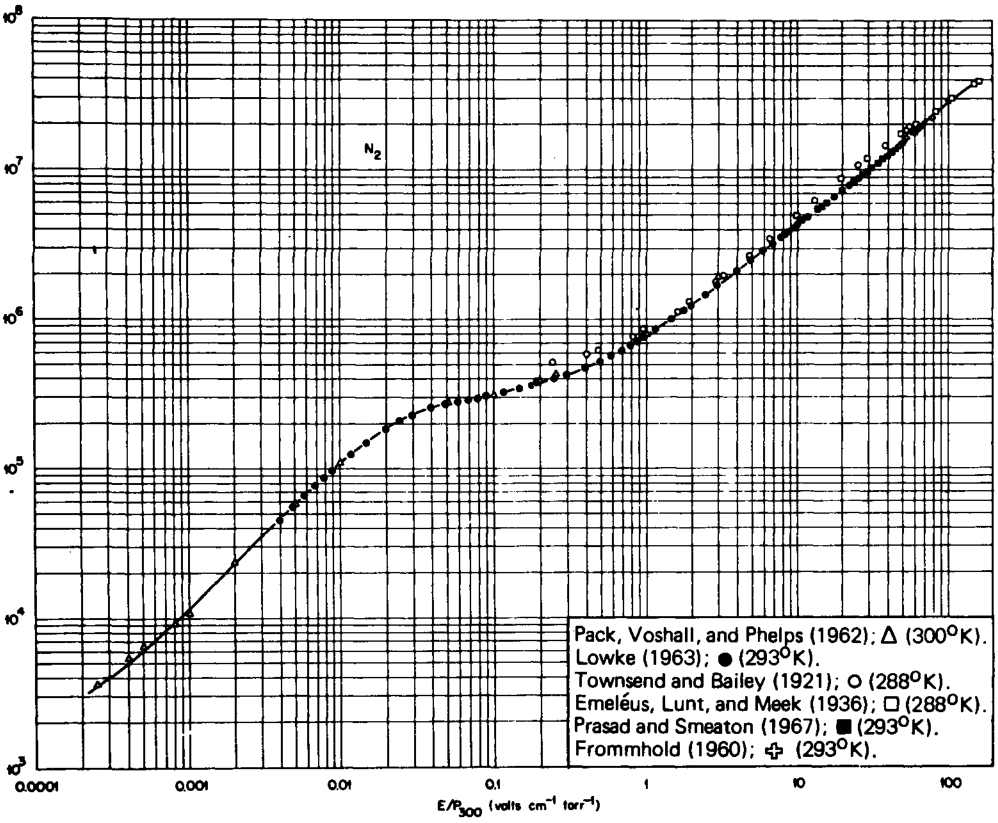


Fig. 159 Christophorou (1971)

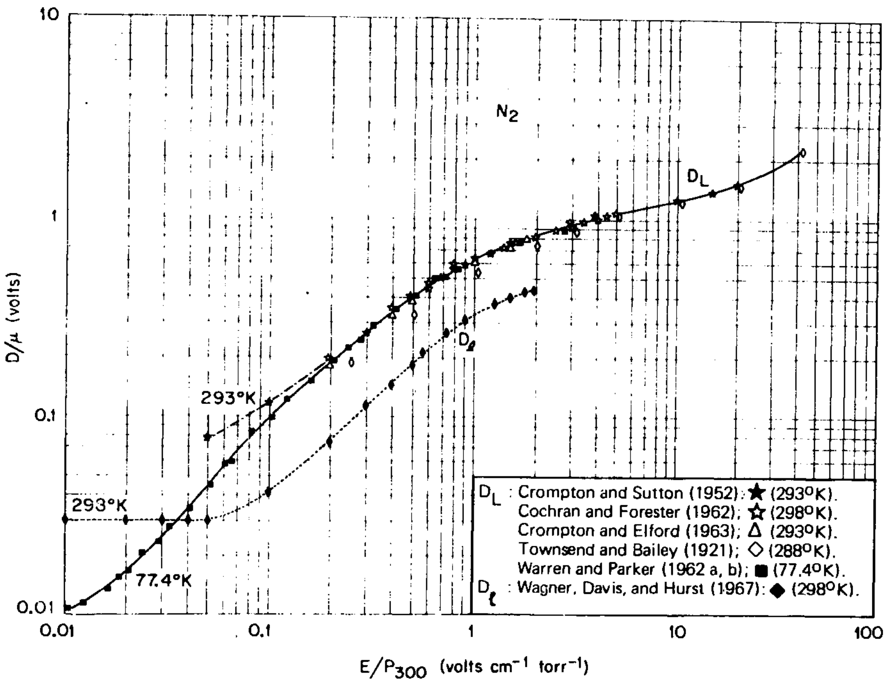


Fig. 160 Christophorou (1971)

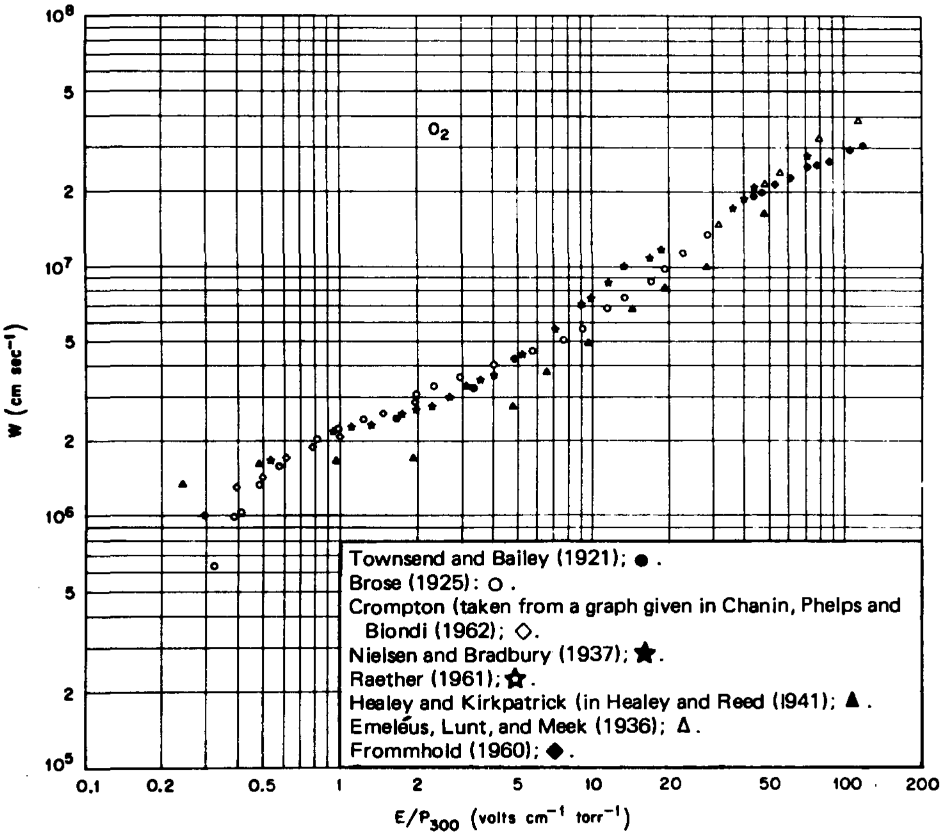


Fig. 161 Christophorou (1971)

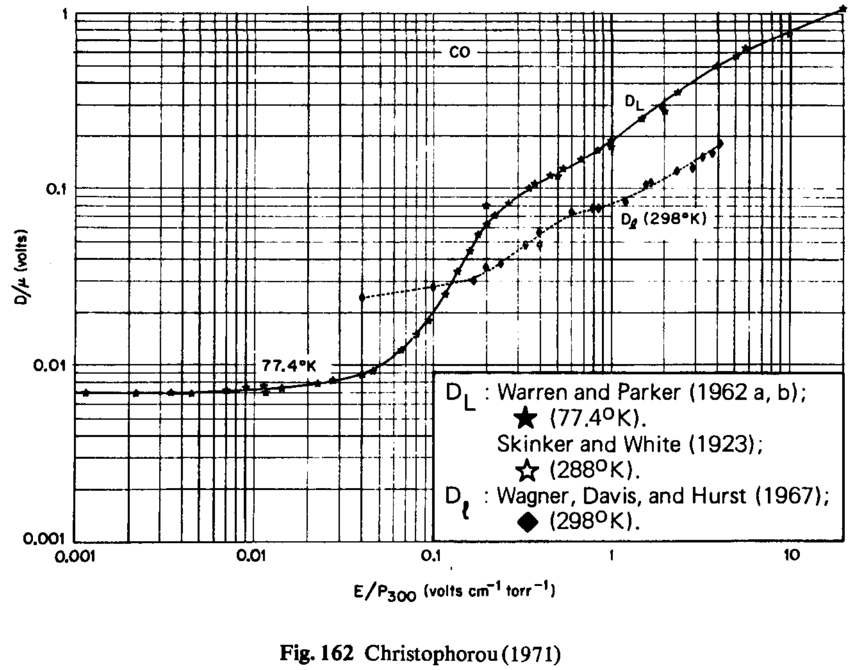


Fig. 162 Christophorou (1971)

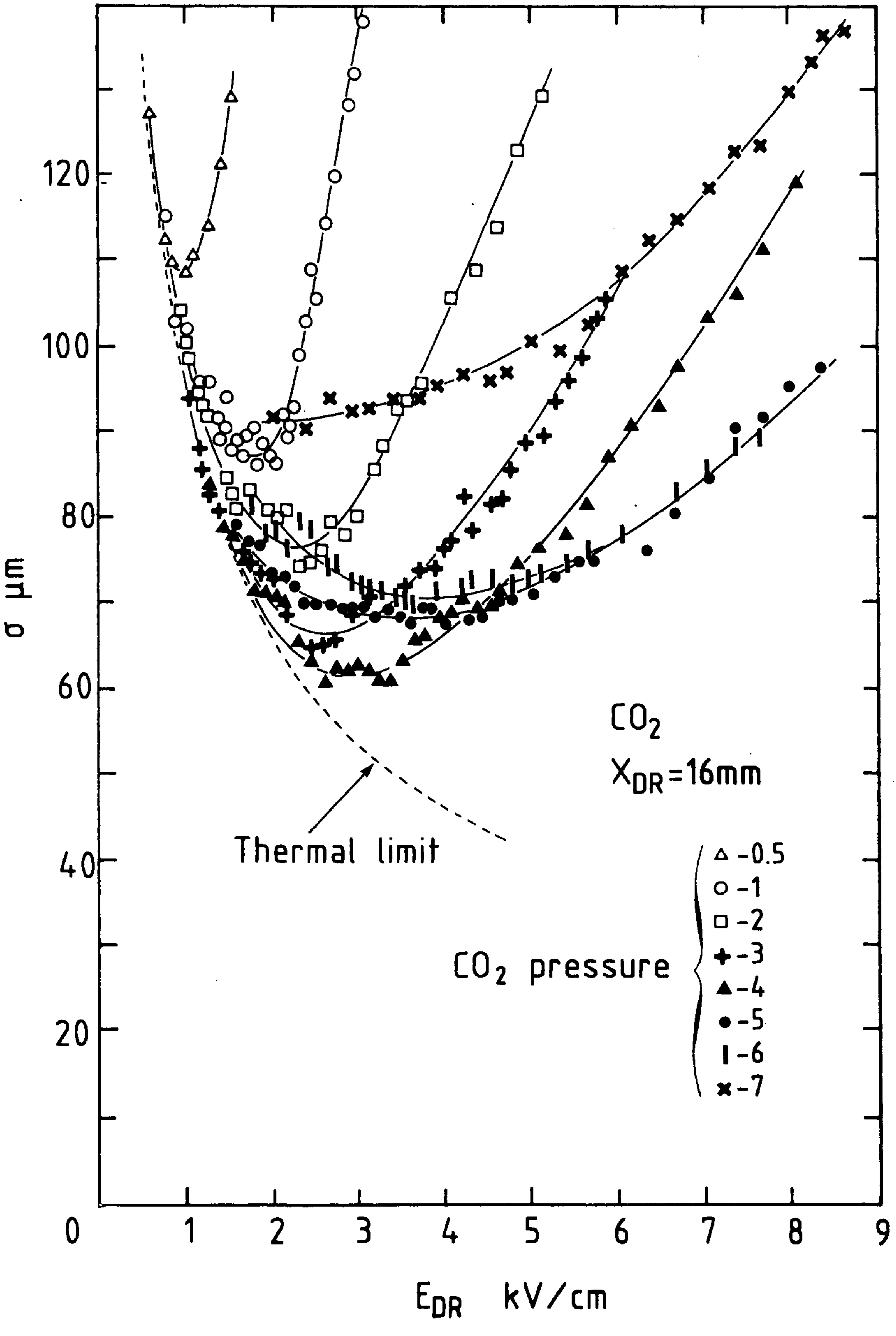


Fig. 163 Bobkov et al. (1983)

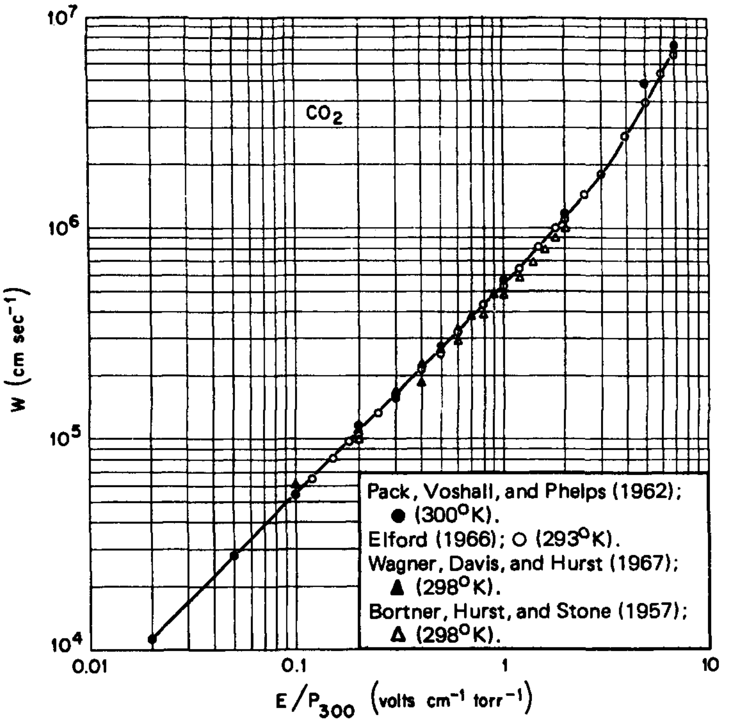


Fig. 164 Christophorou (1971)

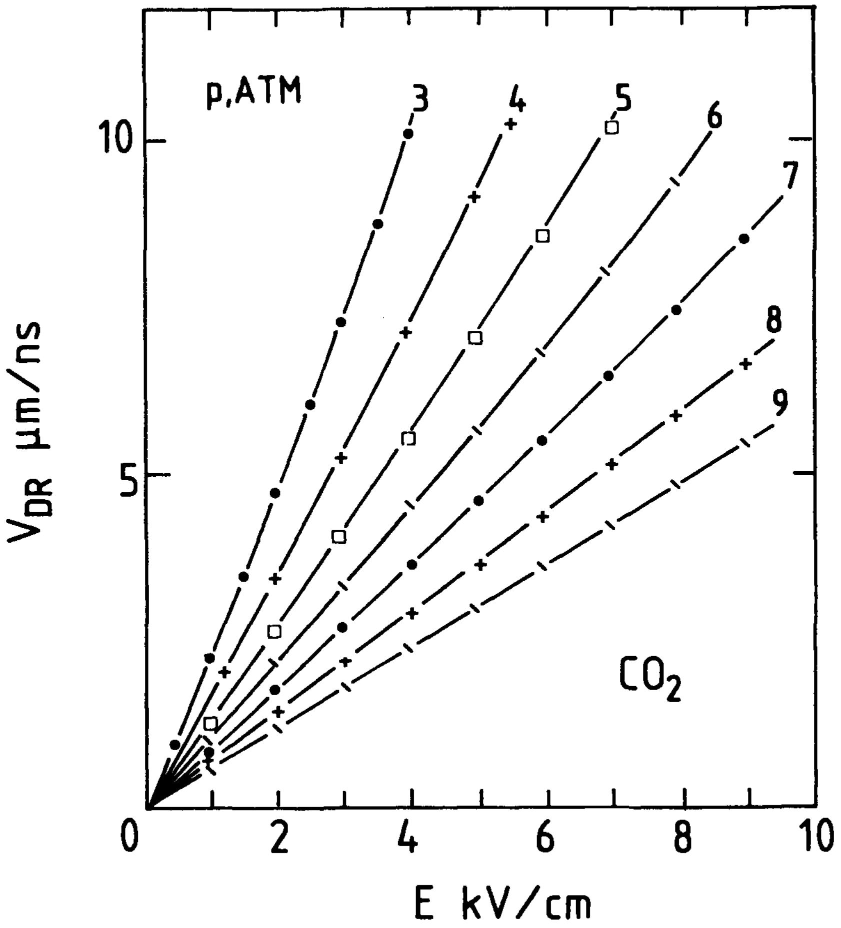


Fig. 165 Bobkov et al. (1983)

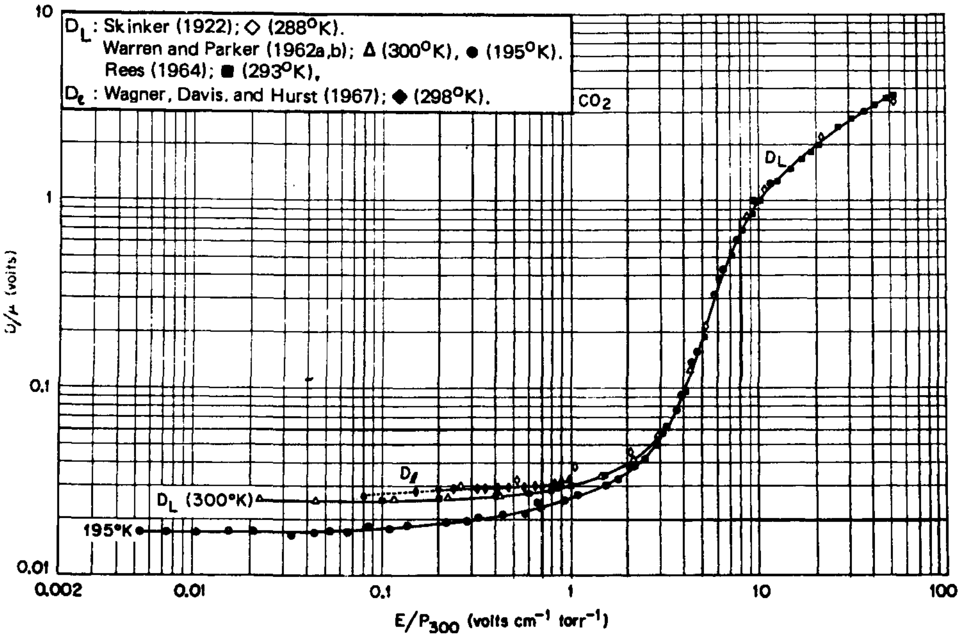


Fig. 166 Christophorou (1971)

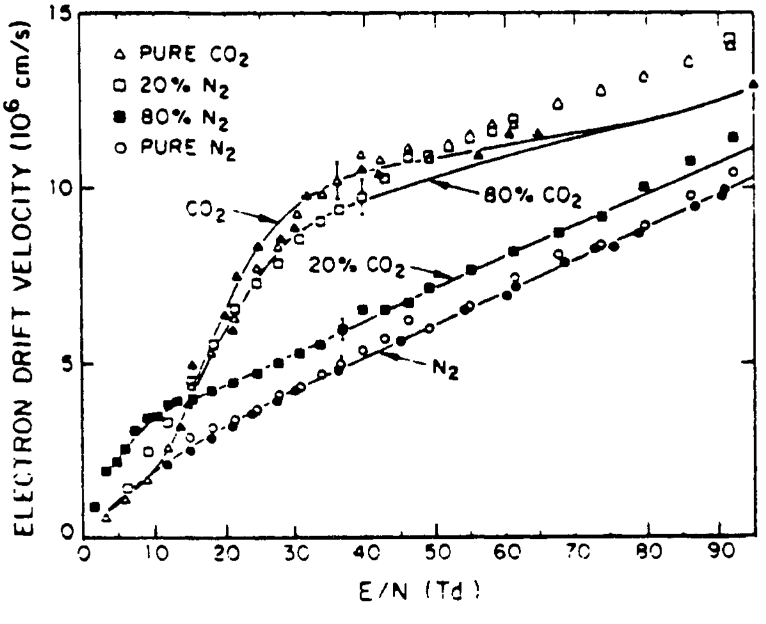


Fig. 167 Fletcher (1981)

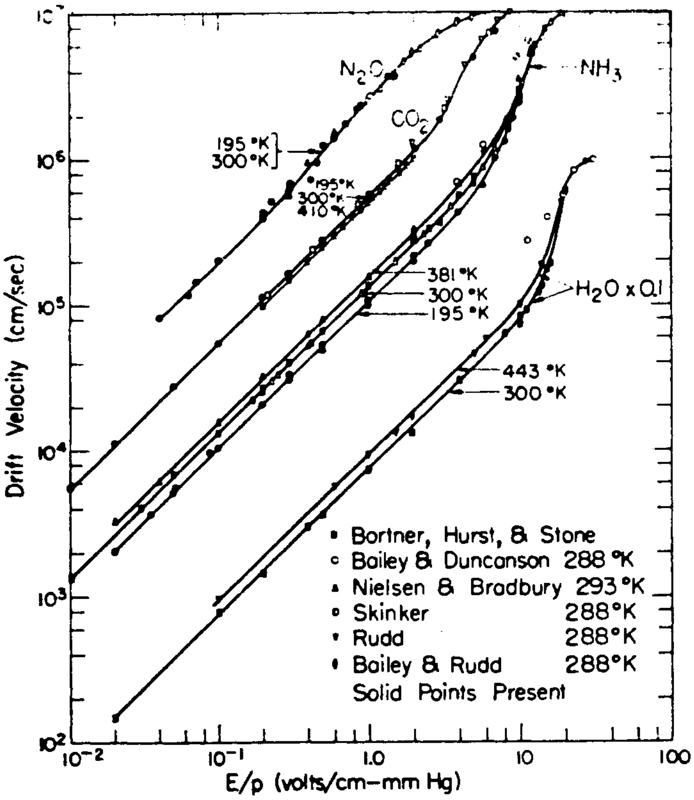


Fig. 168 Pack et al. (1962)

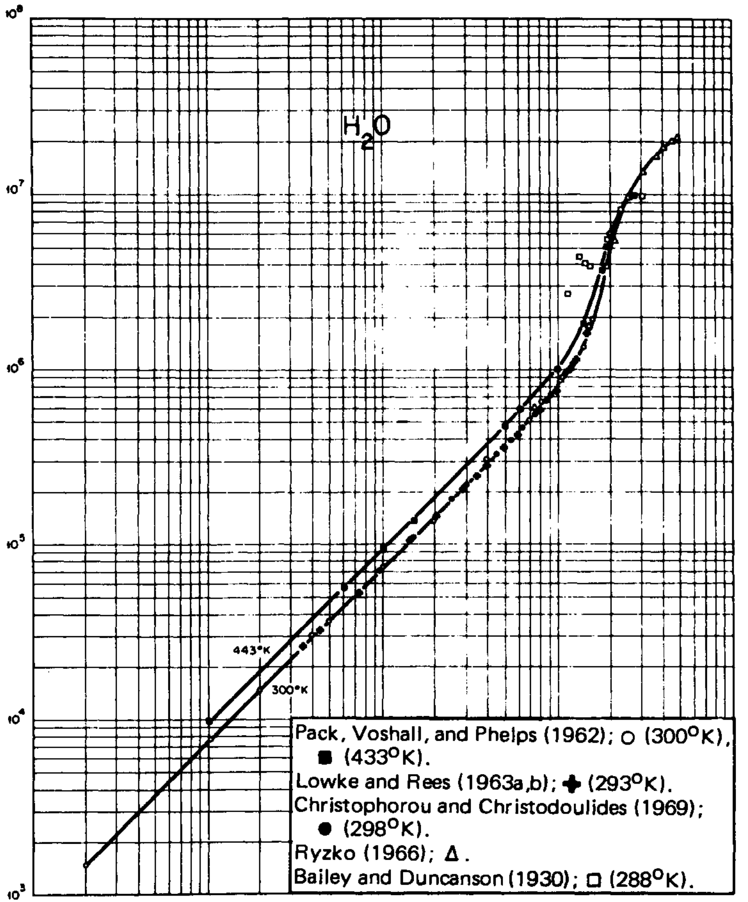


Fig. 169 Christophorou (1971)

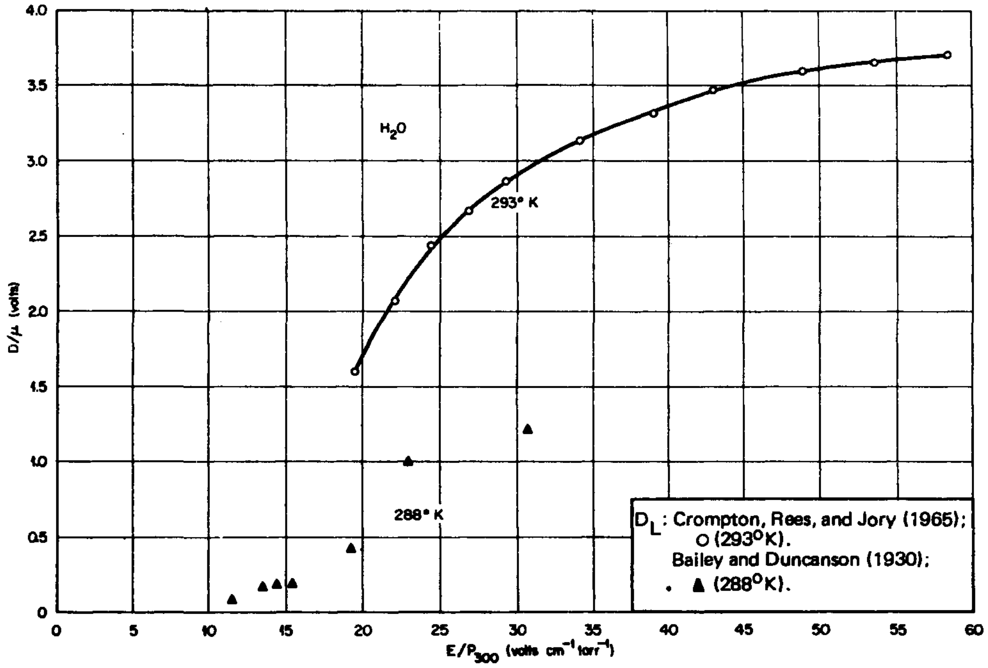


Fig. 170 Christophorou (1971)

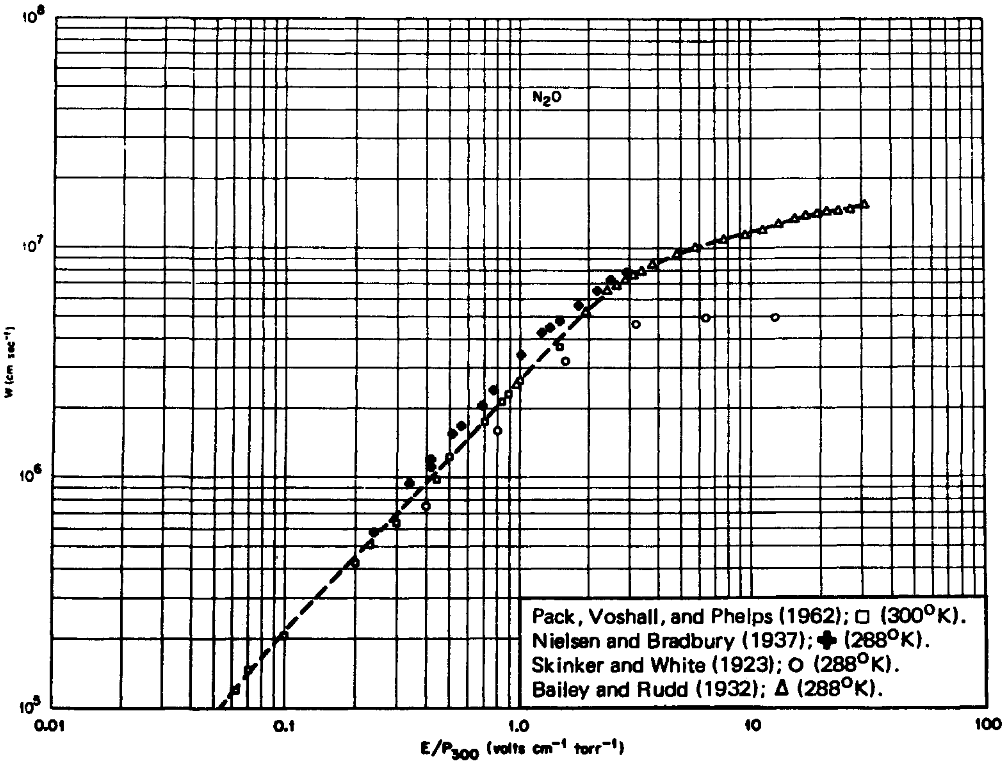


Fig. 171 Christophorou (1971)

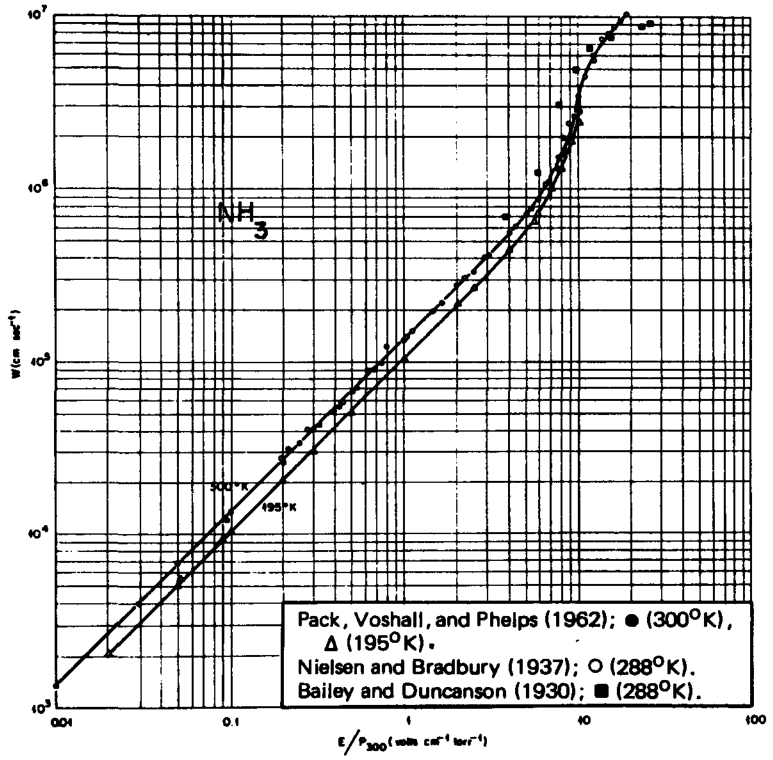


Fig. 172 Christophorou (1971)

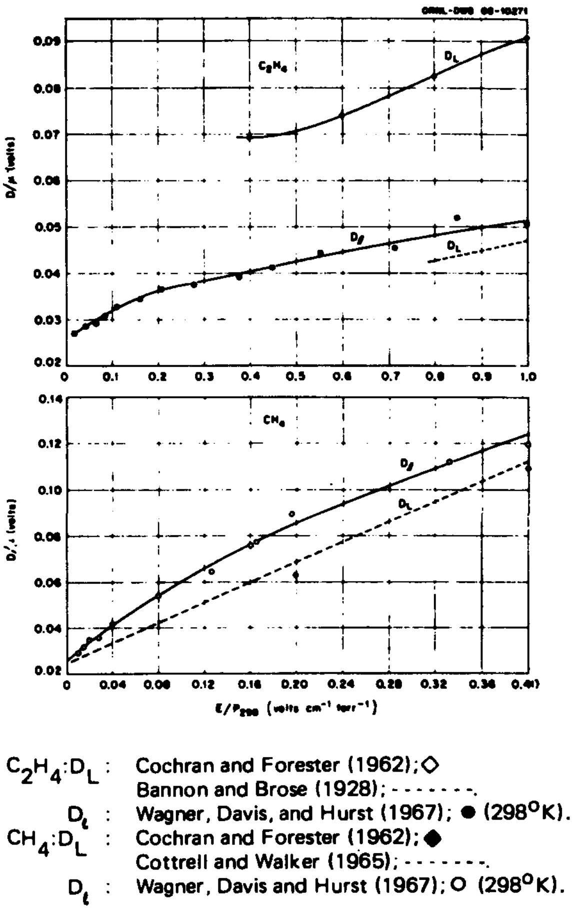
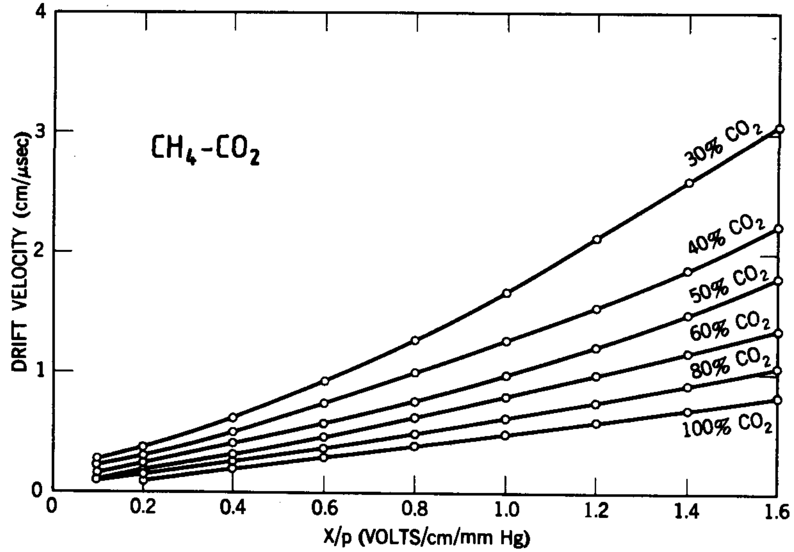


Fig. 173 Christophorou (1971)



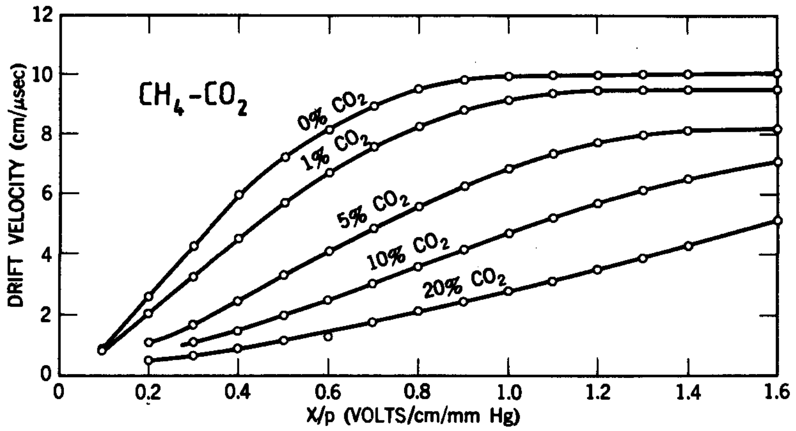


Fig. 174 Franzen and Cochran (1956)

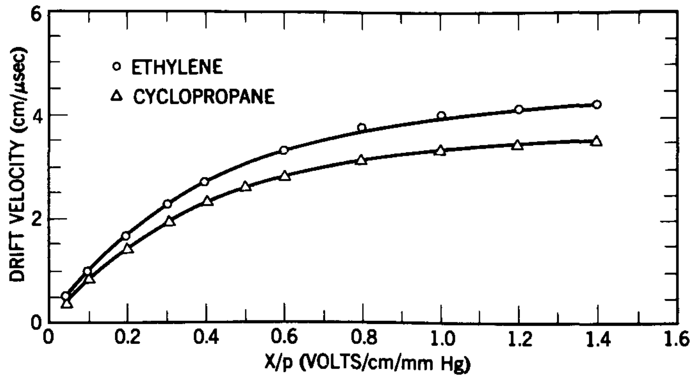


Fig. 175 Franzen and Cochran (1956)

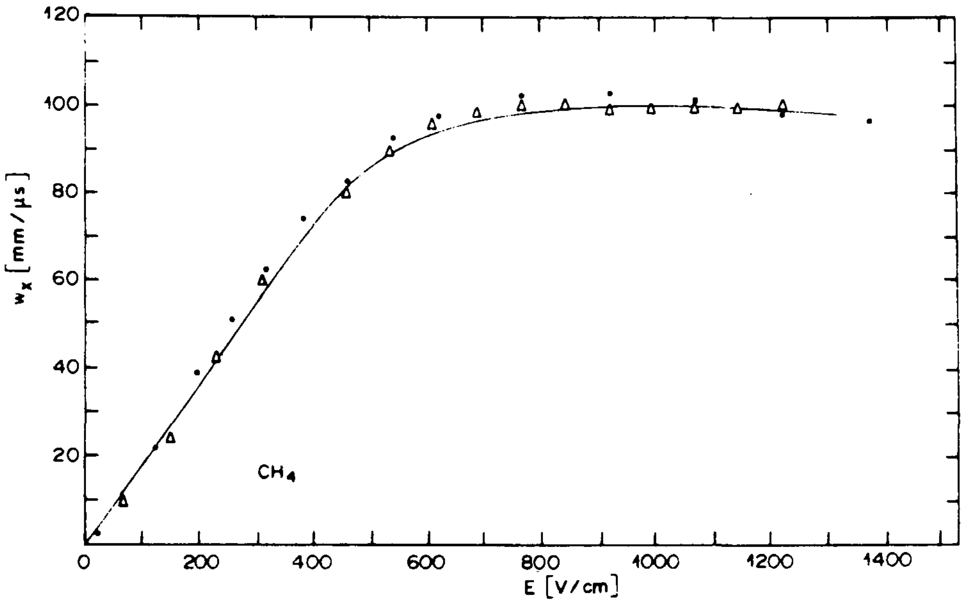


Fig. 176 Schultz (1976)

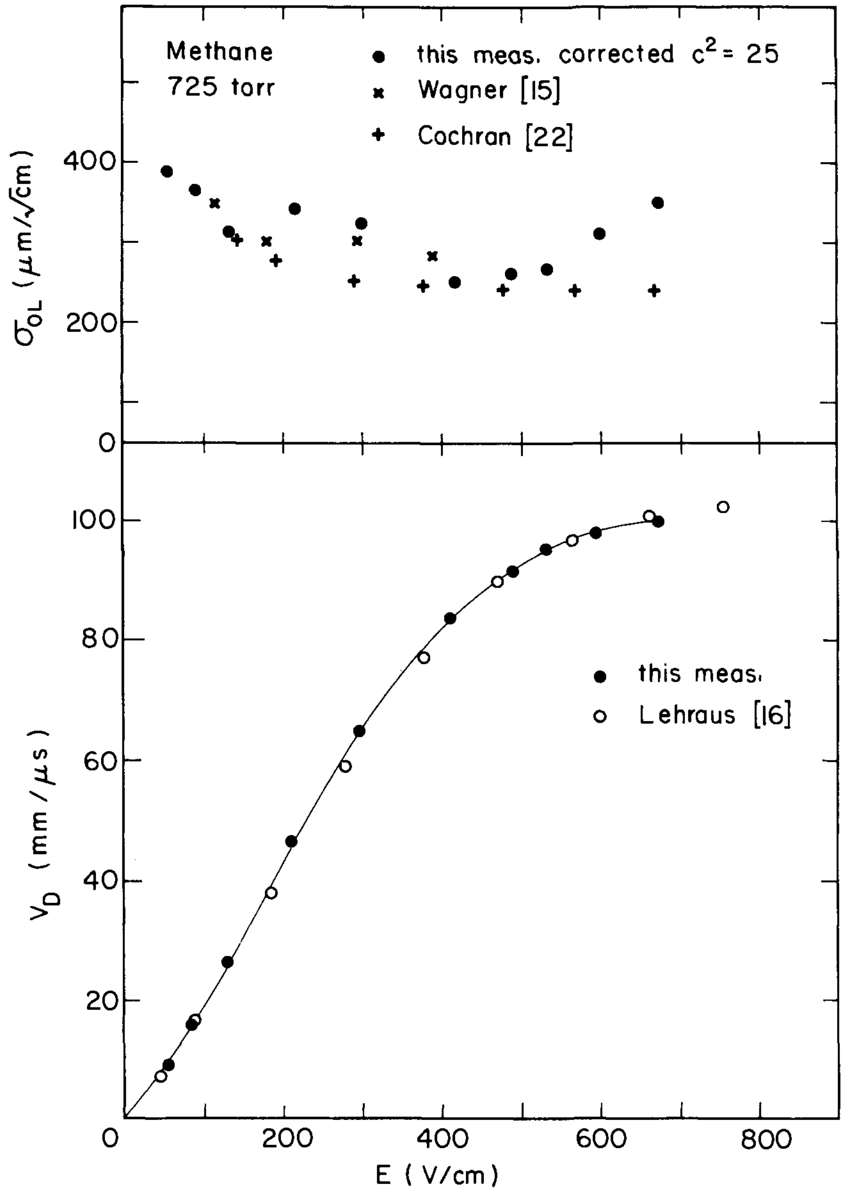


Fig. 177 Piuz (1983)

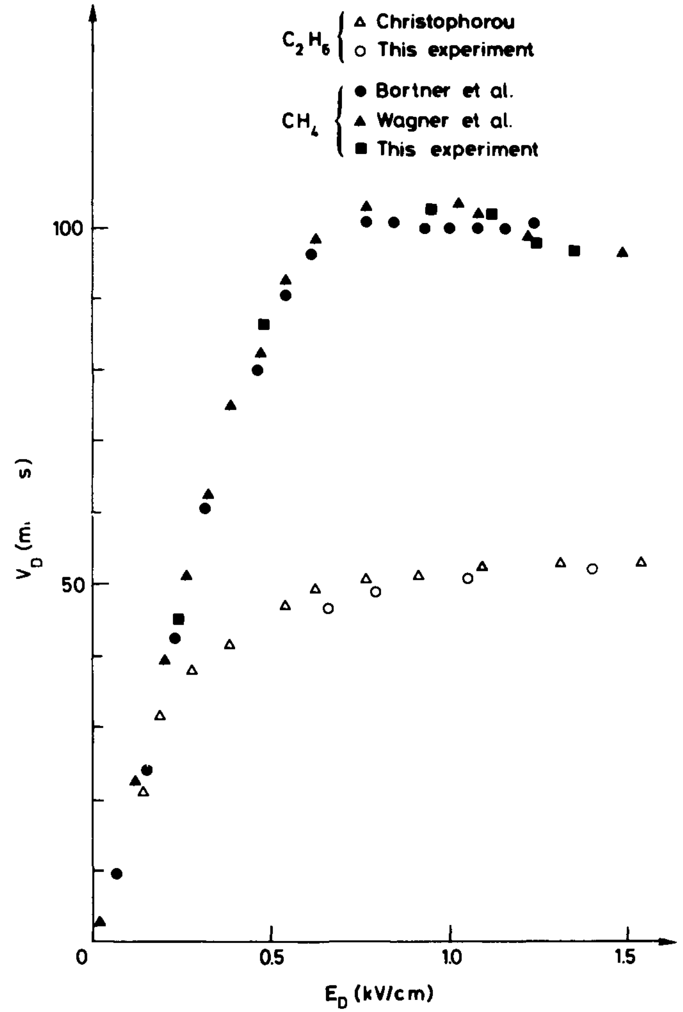


Fig. 178 Daum et al. (1978)

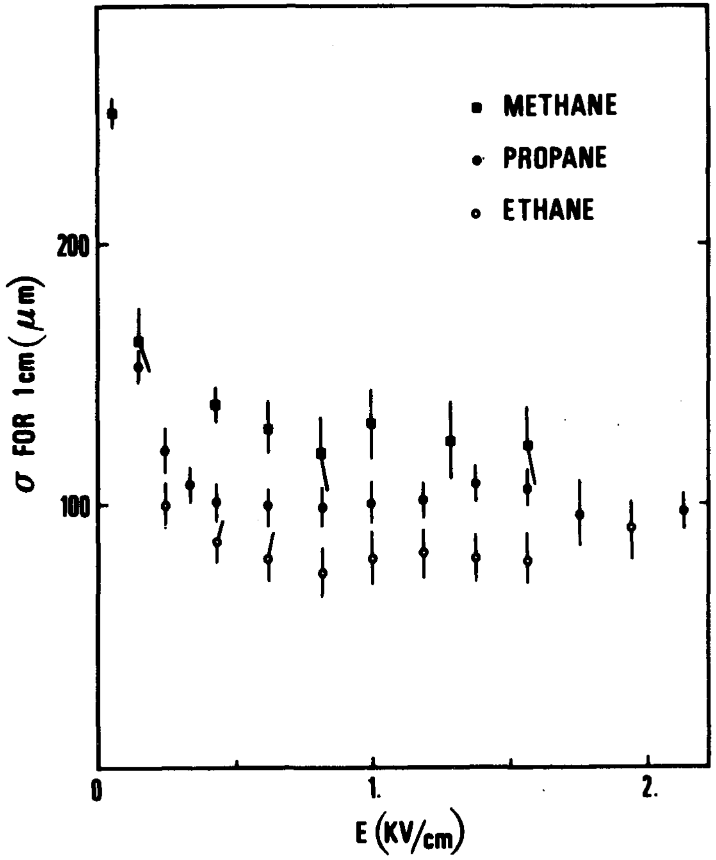


Fig. 179 Jean-Marie et al. (1979)

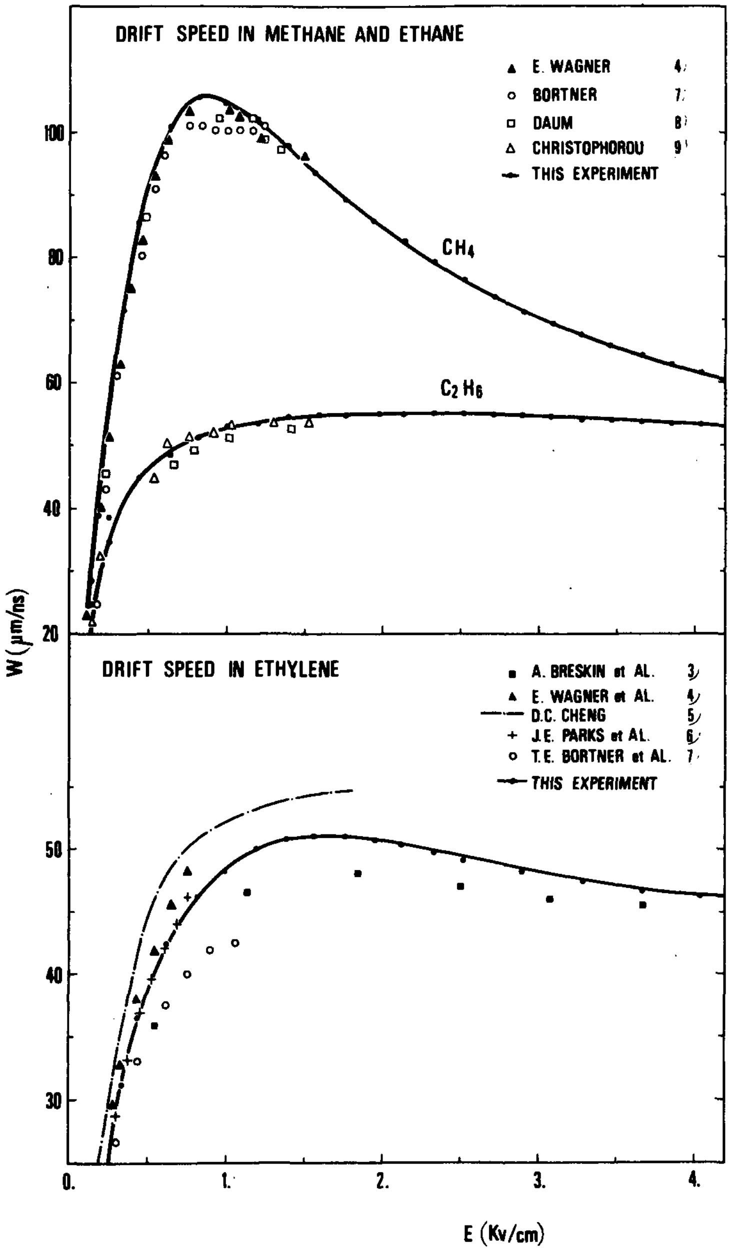


Fig. 180 Jean-Marie et al. (1979)

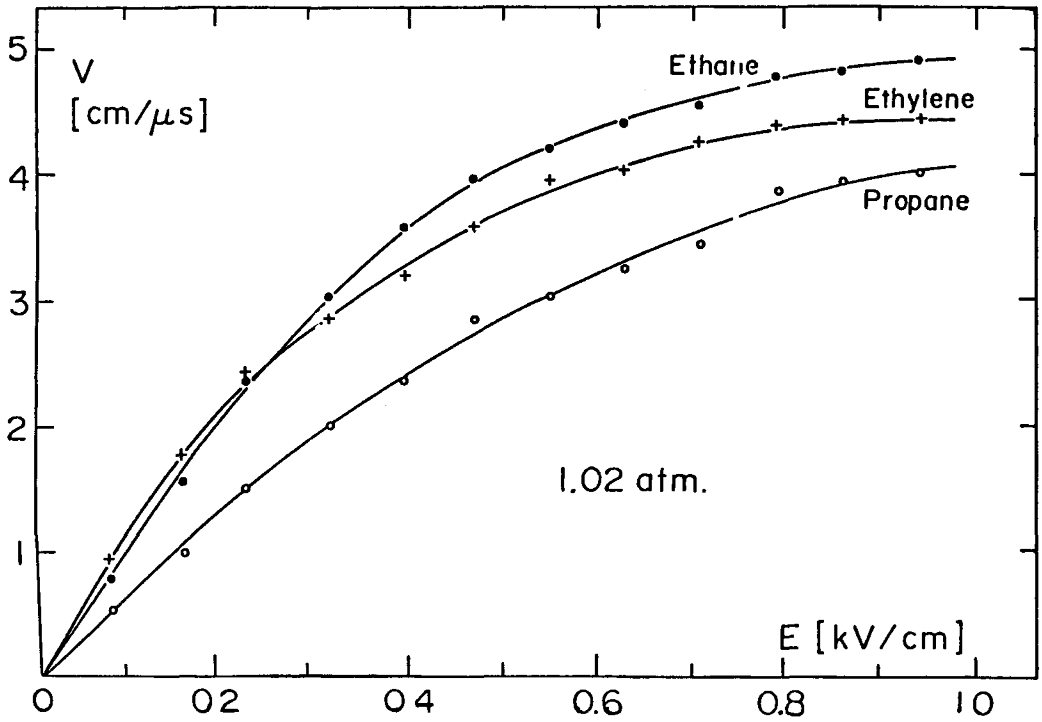


Fig. 181 Fehlmann and Viertel (1983)

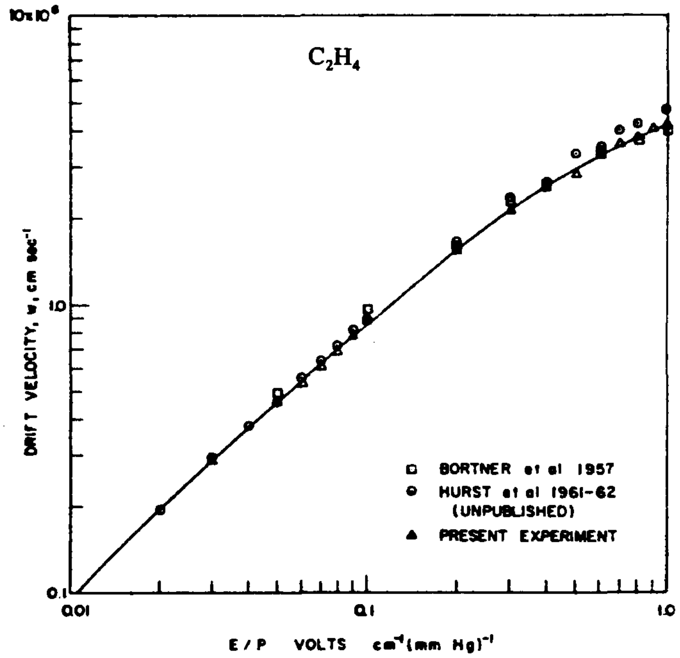


Fig. 182 Hurst et al. (1963)

$C_2 H_6$

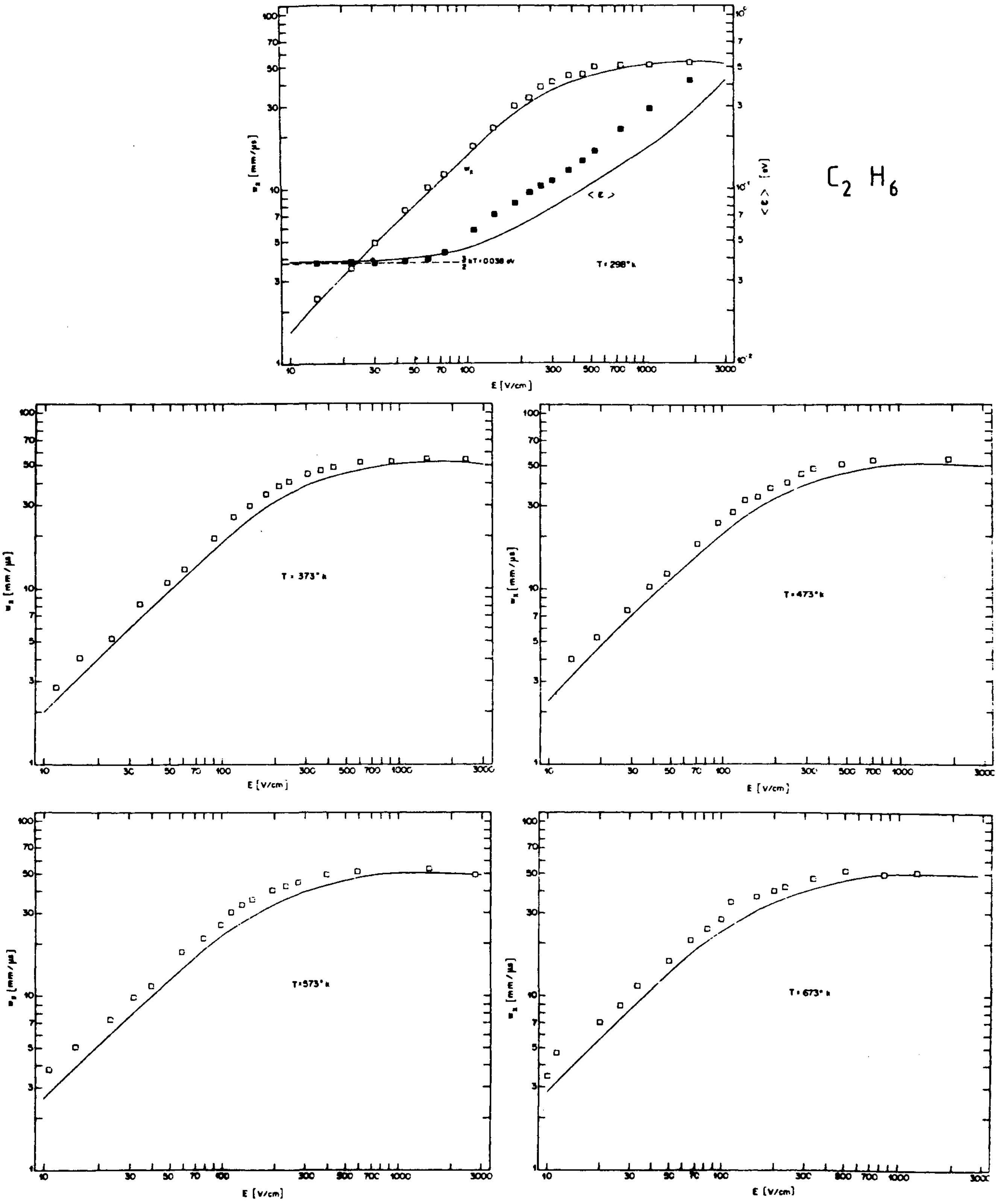


Fig. 183 Ramanantsizehena (1979)

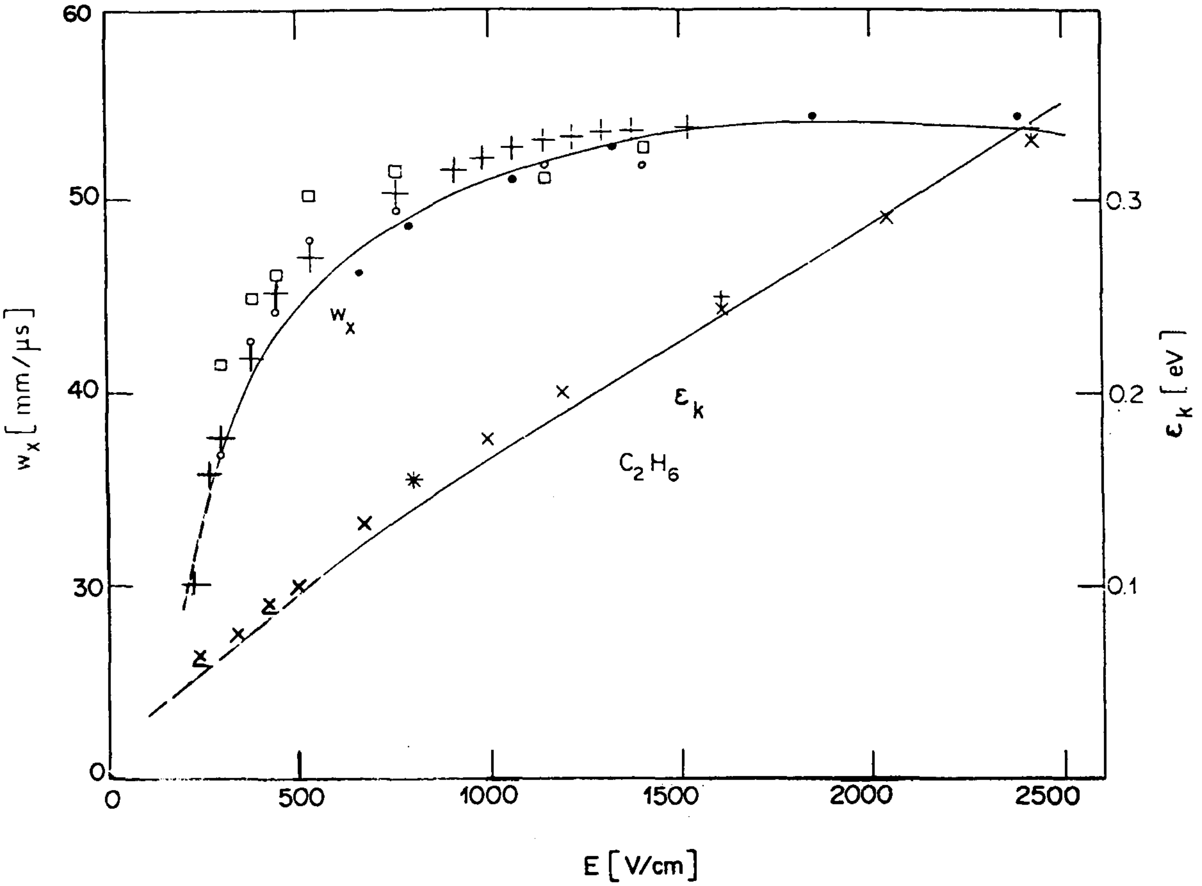


Fig. 184 Ramanantsizehena (1979)

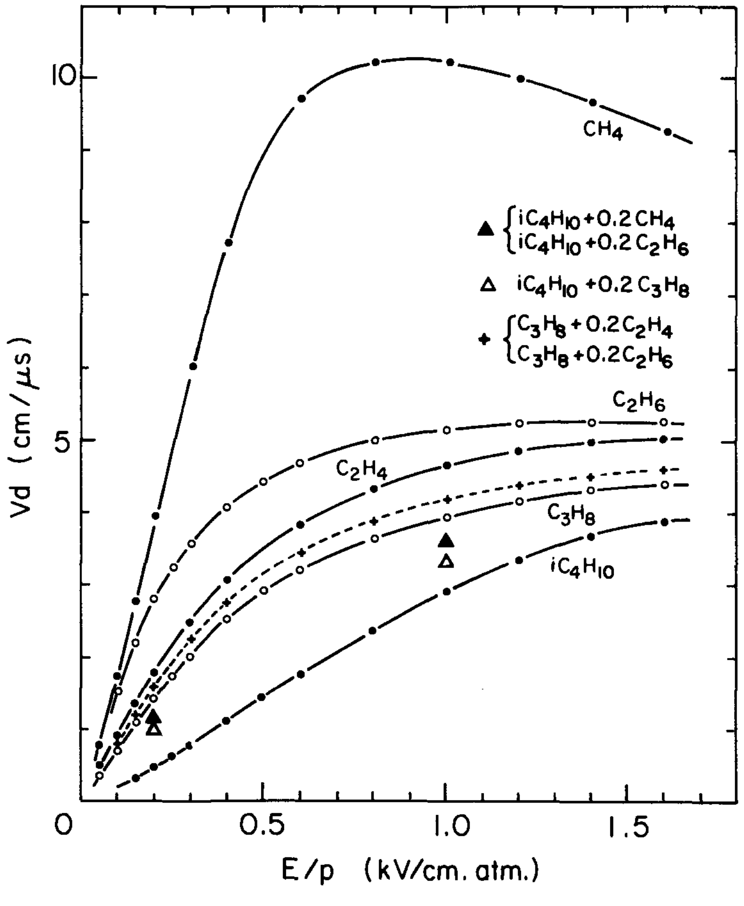
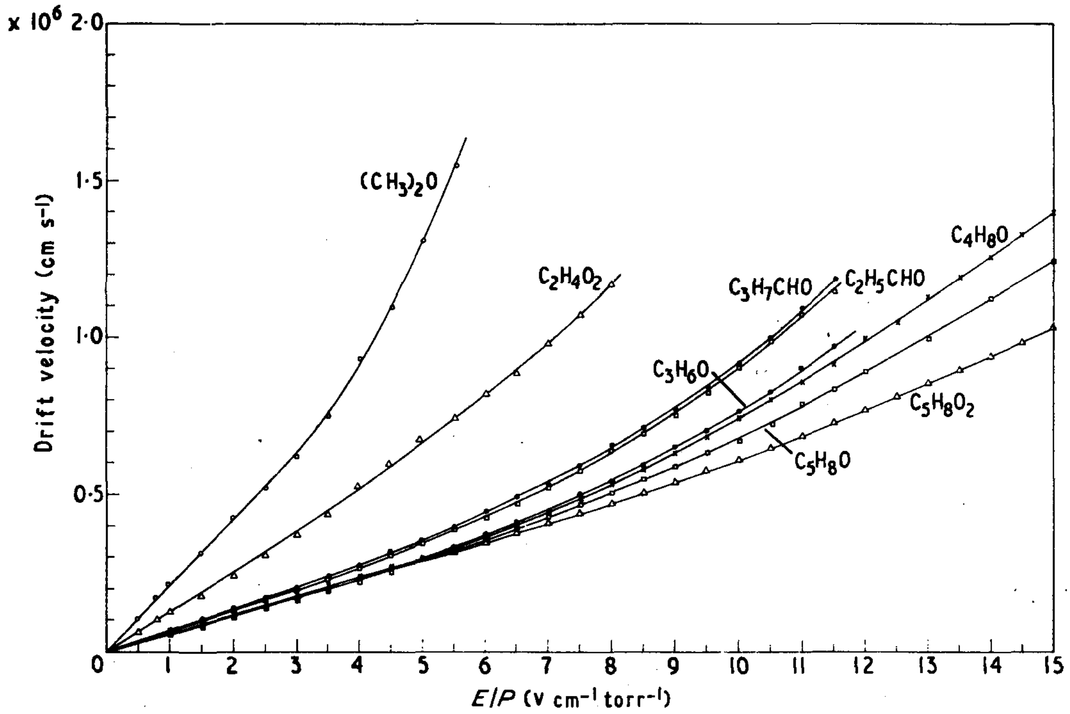
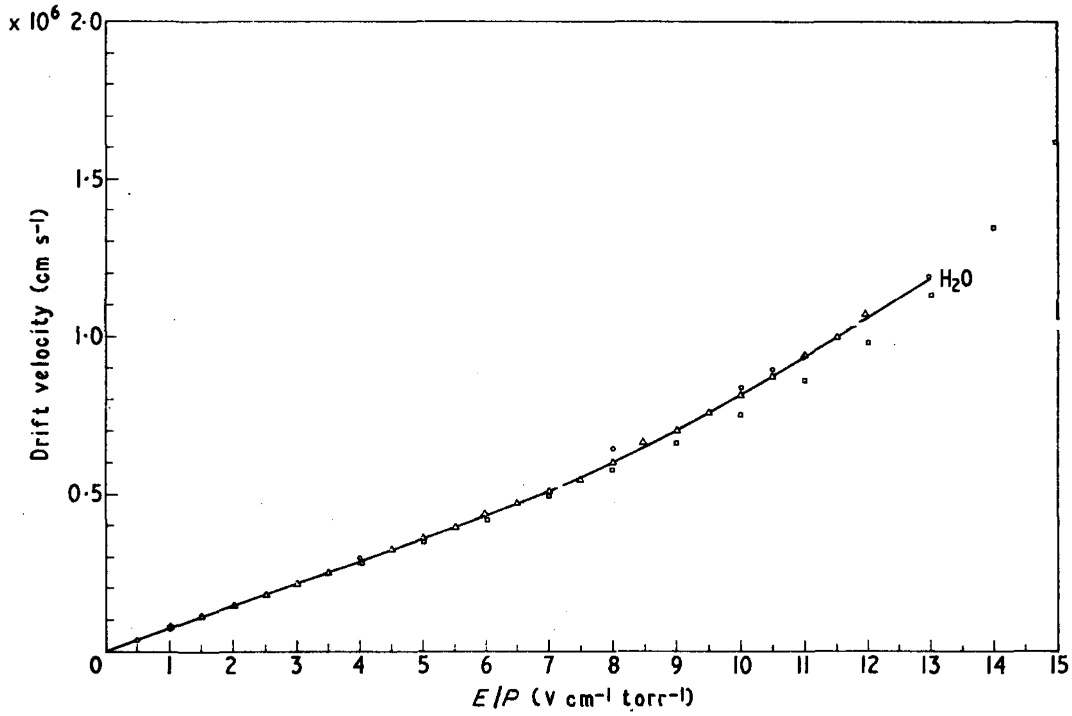


Fig. 185 Lehraus et al. (1982)

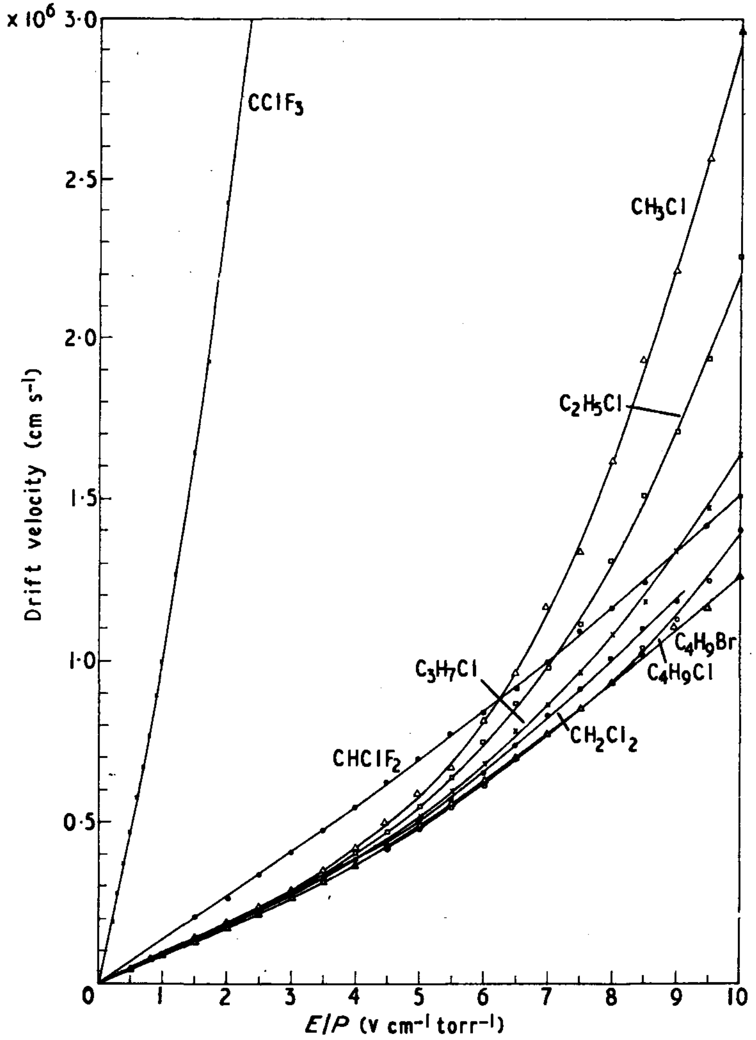


Electron swarm drift velocities in methyl ether ($(CH_3)_2O$), methyl formate ($C_2H_4O_2$), butyraldehyde (C_3H_7CHO), propionaldehyde (C_2H_5CHO), acetone (C_3H_6O), 2-butane (C_4H_8O), cyclopentanone (C_5H_8O) and acetylacetone ($C_5H_8O_2$).



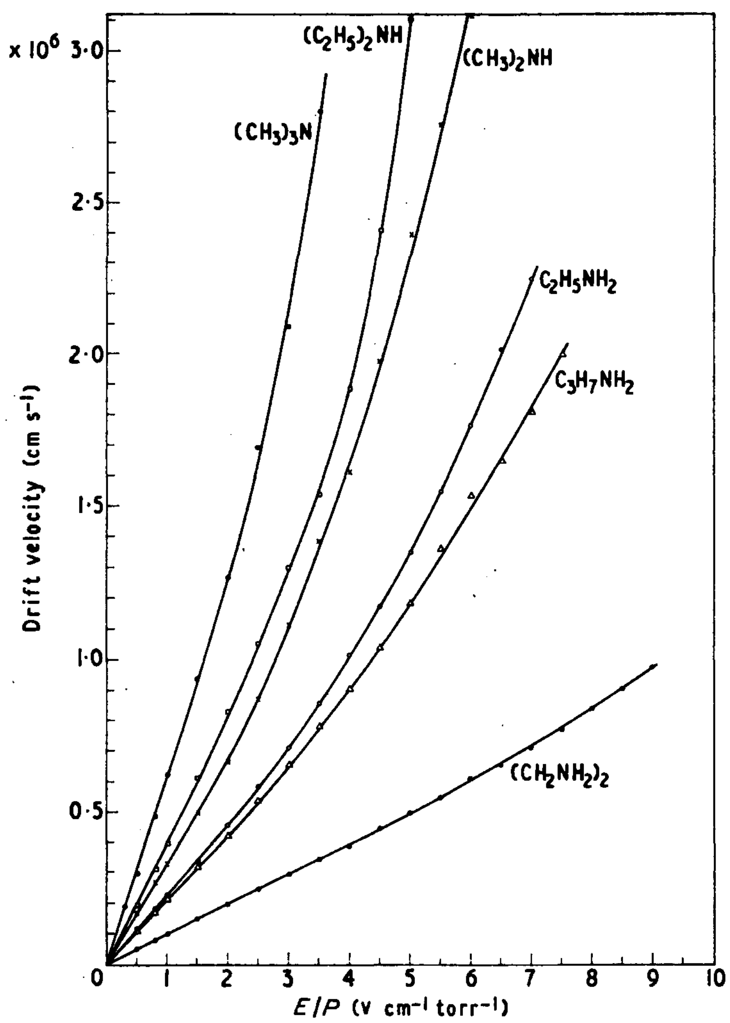
Electron swarm drift velocities in water: △, present work; ○, Pack *et al.* 1962; □, Lowke and Rees 1963.

Fig. 186 Christophorou and Christodoulides (1969)



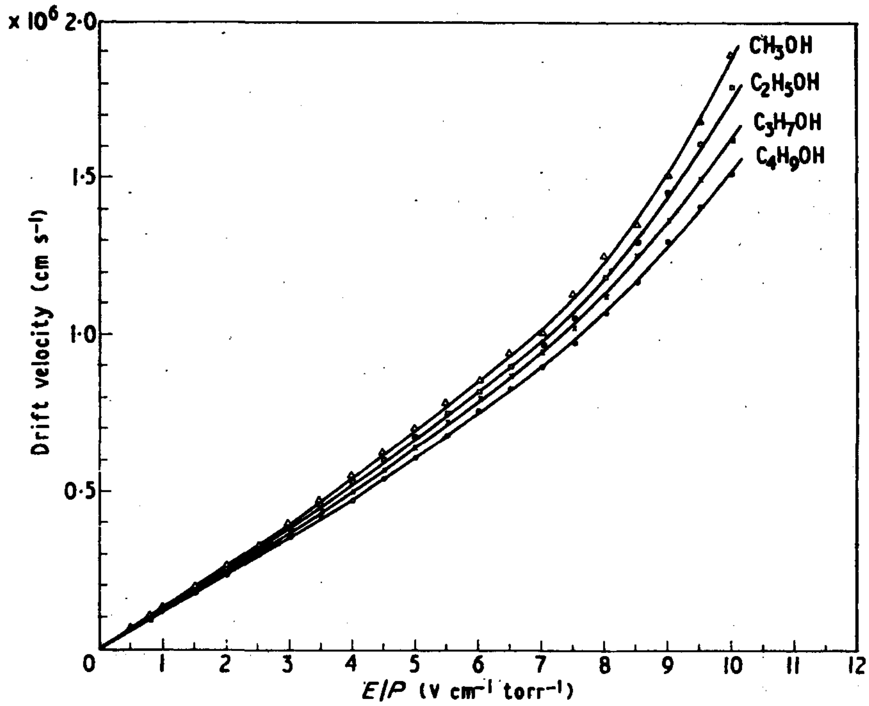
Electron swarm drift velocities in chlorotrifluoromethane ($CClF_3$), chloromethane (CH_3Cl), chloroethane (C_2H_5Cl), 1-choropropane (C_3H_7Cl), chlorodifluoromethane ($CHClF_2$), dichloromethane (CH_2Cl_2), 1-chlorobutane (C_4H_9Cl) and 1-bromobutane (C_4H_9Br).

Fig. 187 Christophorou and Christodoulides (1969)

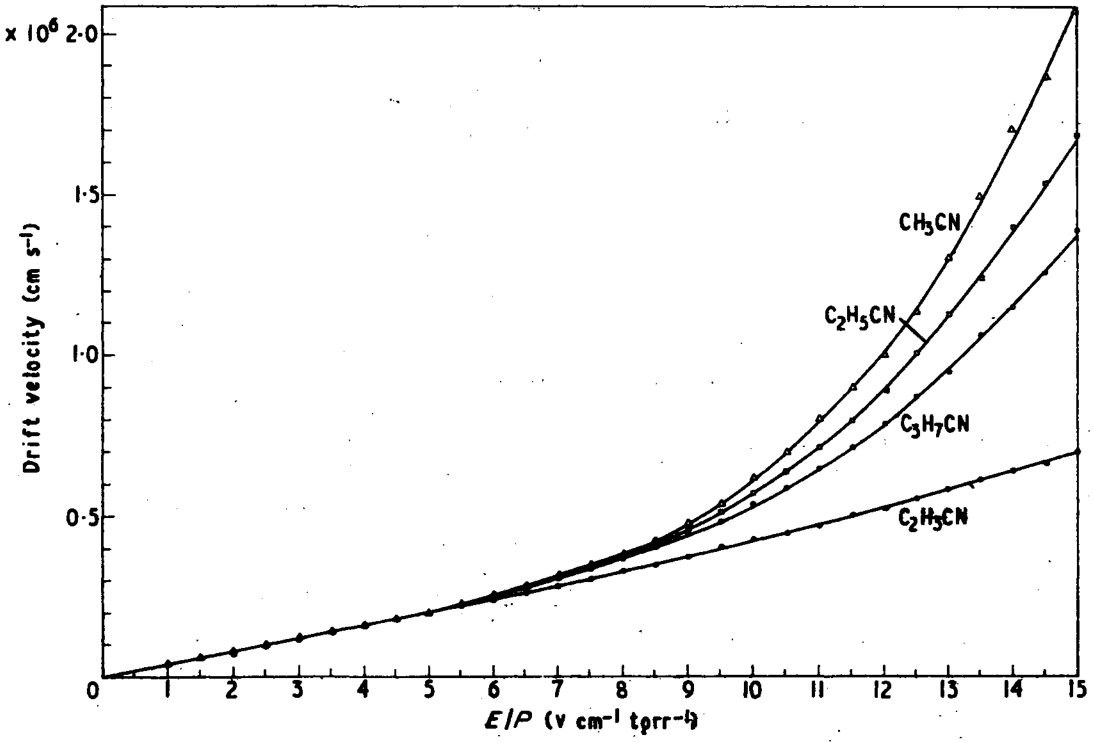


Electron swarm drift velocities in trimethylamine ($(CH_3)_3N$), diethylamine ($(C_2H_5)_2NH$), dimethylamine ($(CH_3)_2NH$), ethylamine ($C_2H_5NH_2$), n-propylamine ($C_3H_7NH_2$) and ethylenediamine ($(CH_2NH_2)_2$.

Fig. 188 Christophorou and Christodoulides (1969)



Electron swarm drift velocities in methanol (CH$_3$OH), ethanol (C$_2$H$_5$OH), 1-propanol (C$_3$H$_7$OH) and 1-butanol (C$_4$H$_9$OH).



Electron swarm drift velocities in acetonitrile (CH$_3$CN), propionitrile (C$_2$H$_5$CN), butyronitrile (C$_3$H$_7$CN) and acrylonitrile (C$_2$H$_3$CN).

Fig. 189 Christophorou and Christodoulides (1969)

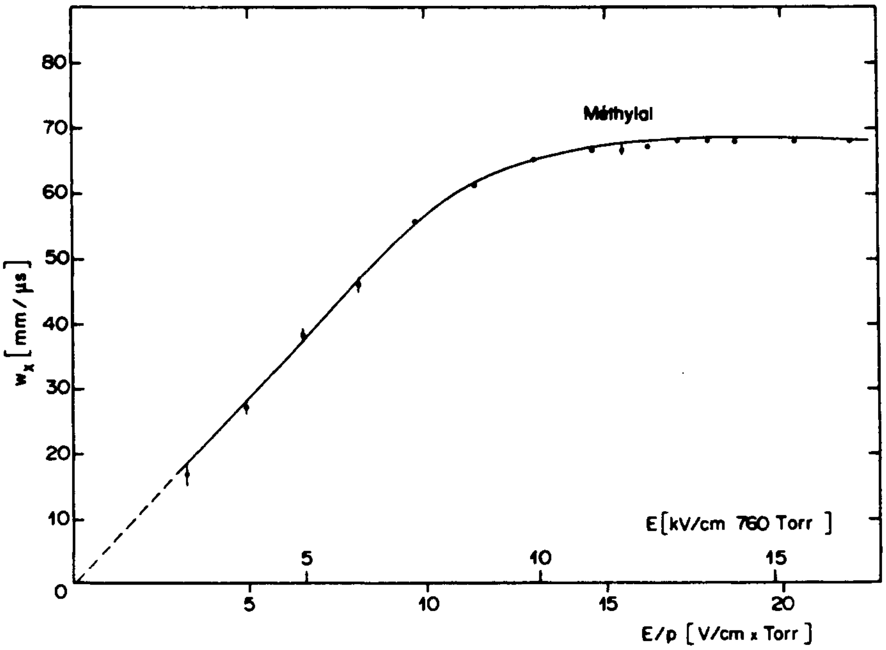


Fig. 190 Schultz (1976)

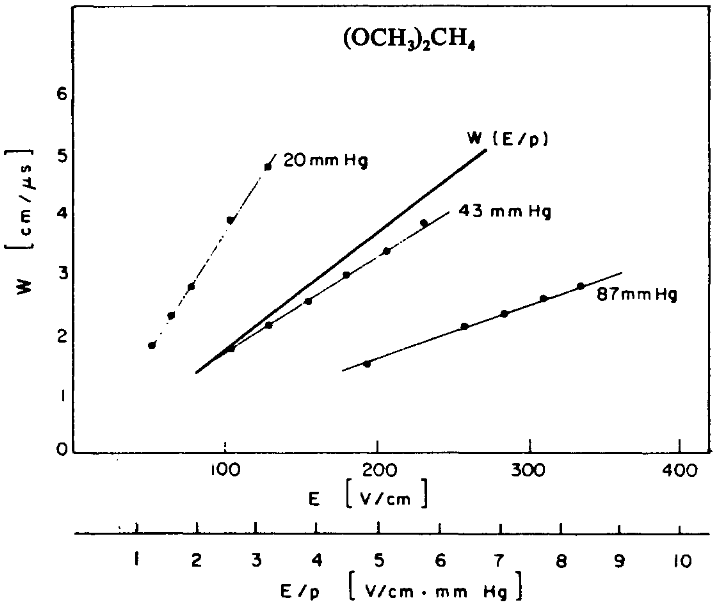
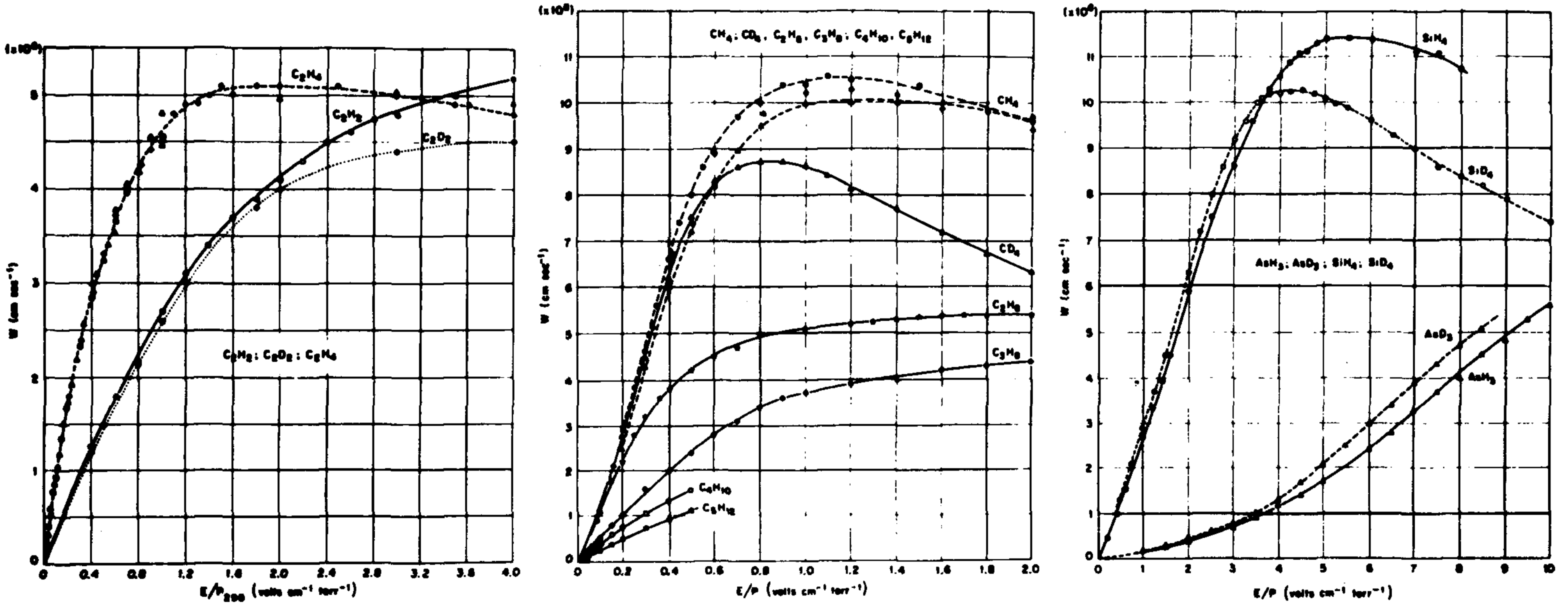


Fig. 191 Breskin (1974)



C_2H_2;C_2D_2: Cottrell and Walker (1965).
C_2H_4: Hurst and Parks (1966) ● (298°K);
Wagner, Davis, and Hurst (1967) ▲ (298° K);
Bowman and Gordon (1967) Δ ;
Cottrell and Walker (1965) ◊.

CH_4: Cottrell and Walker (1965) ● ;
Bortner, Hurst, and Stone (1957) Δ ;
Wagner, Davis and Hurst (1967) ◊ .
CD_4, C_2H_6, C_3H_8: Cottrell and Walker (1965).
C_4H_{10}, C_5H_{12}: Christophorou, Hurst, and Hadjiantoniou (1966).

AsH_3, AsD_3, SiH_4, SiD_4: Cottrell and Walker (1965).

Fig. 192 Christophorou (1971)

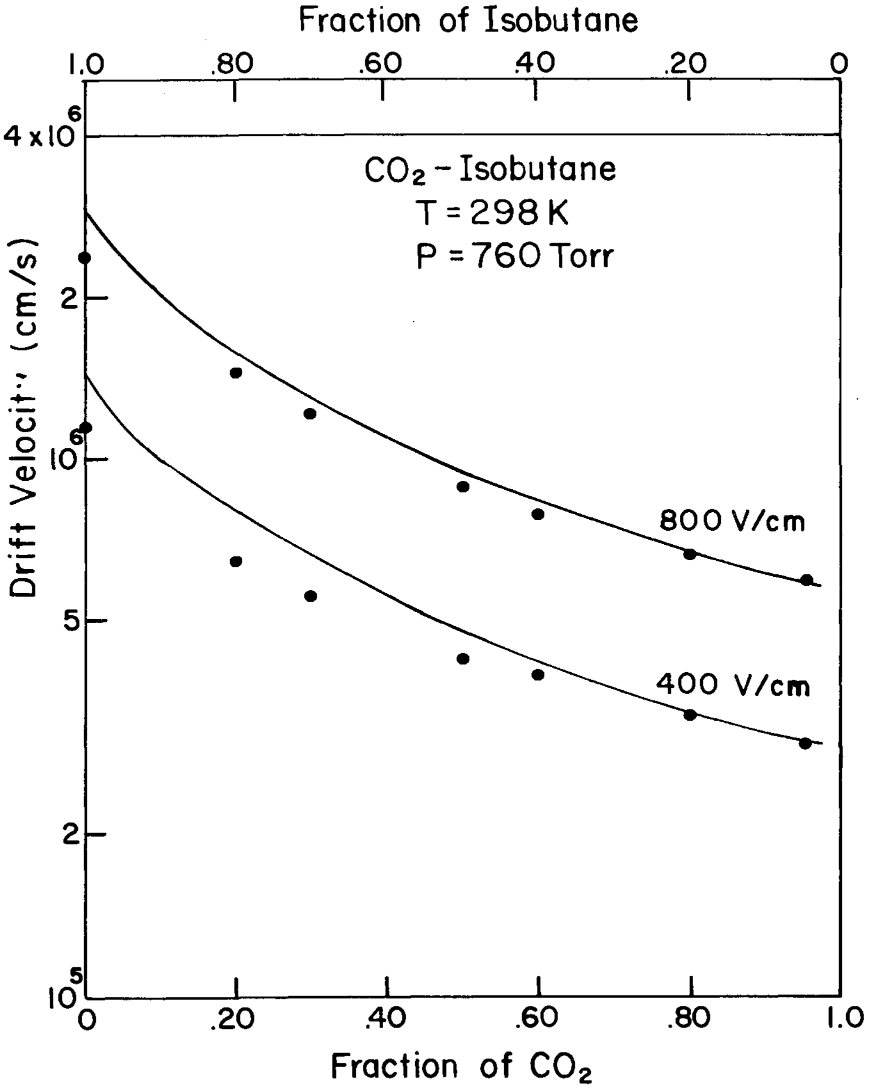


Fig. 193 Becker et al. (1983 b)

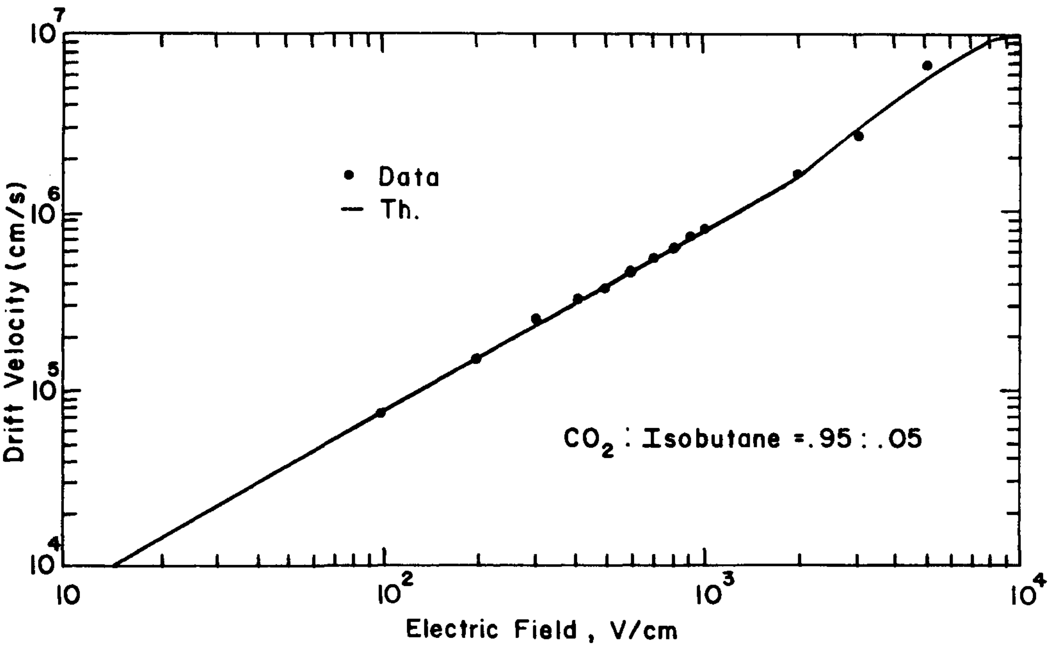


Fig. 194 Becker et al. (1983 b)

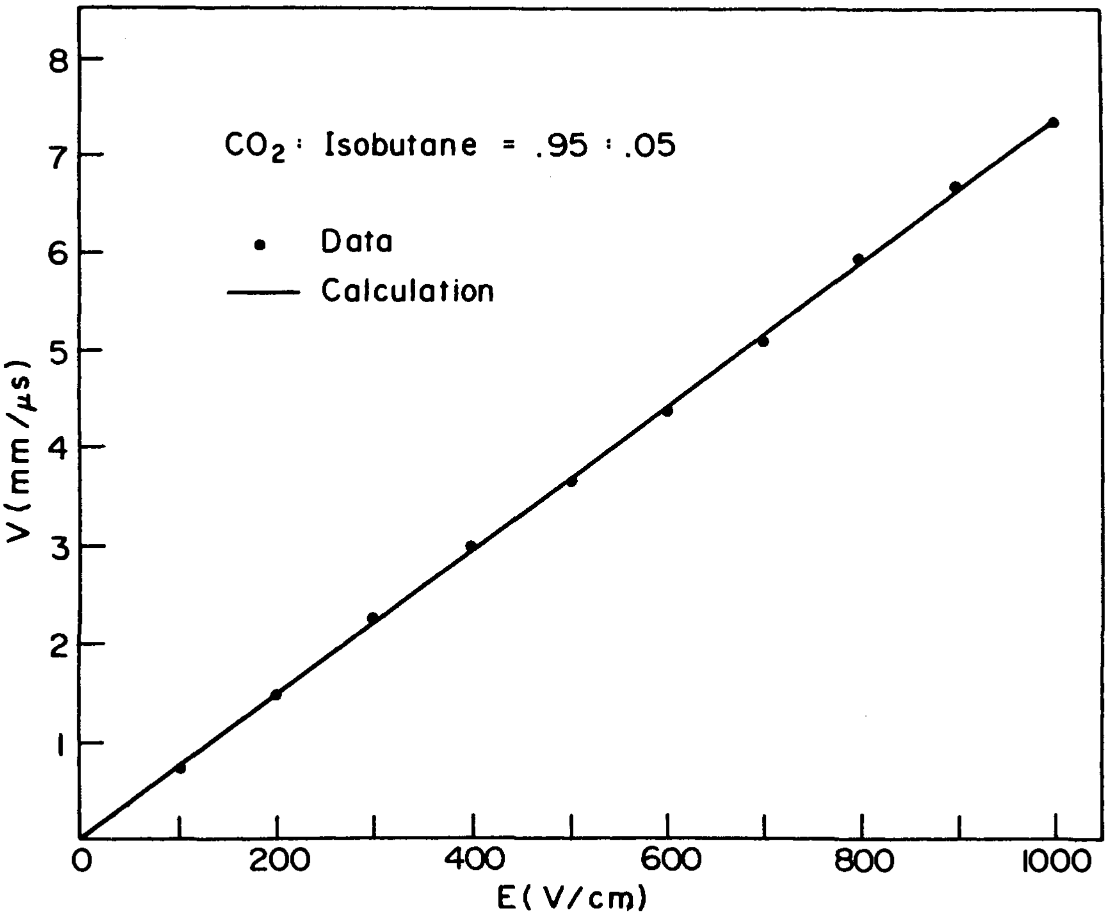


Fig. 195 Becker et al. (1983 b)

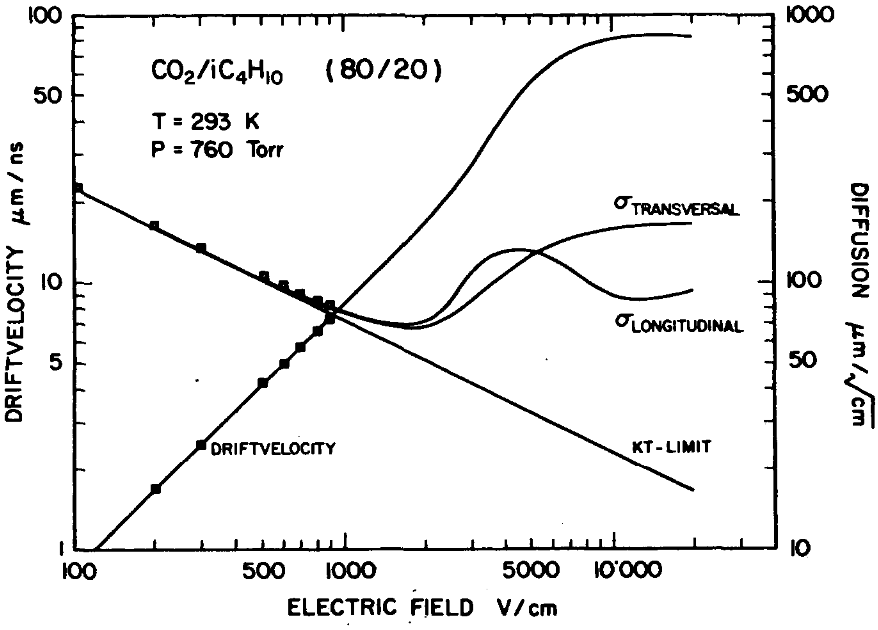


Fig. 196 Fehlmann et al. (1983)

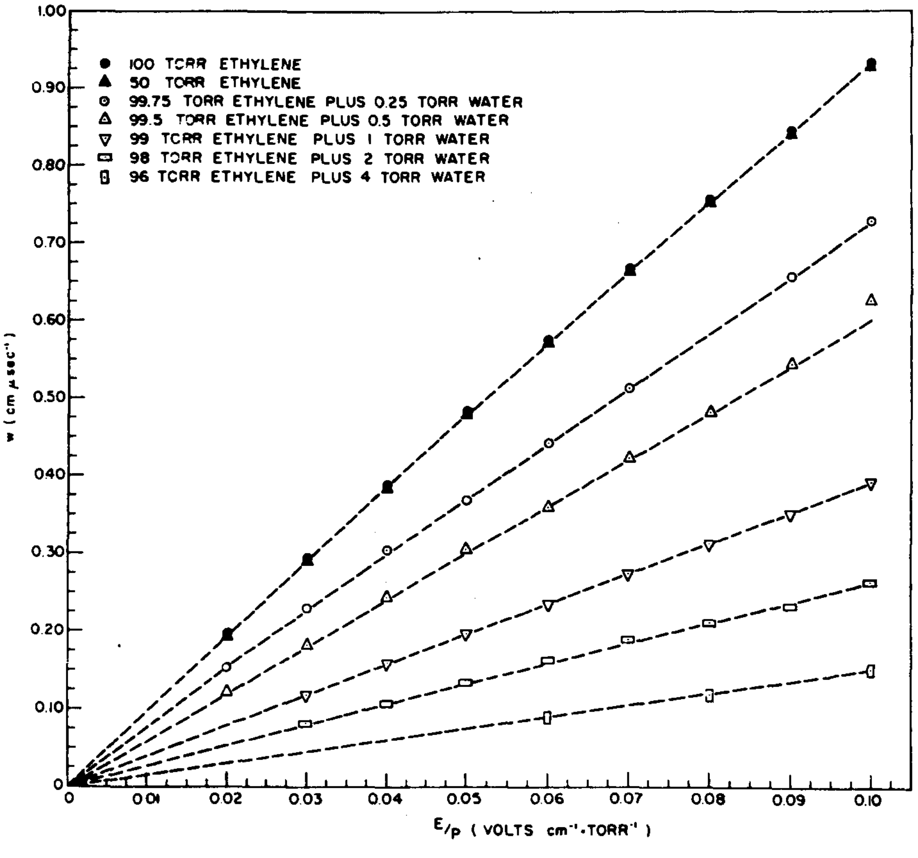


Fig. 197 Hurst et al. (1966)

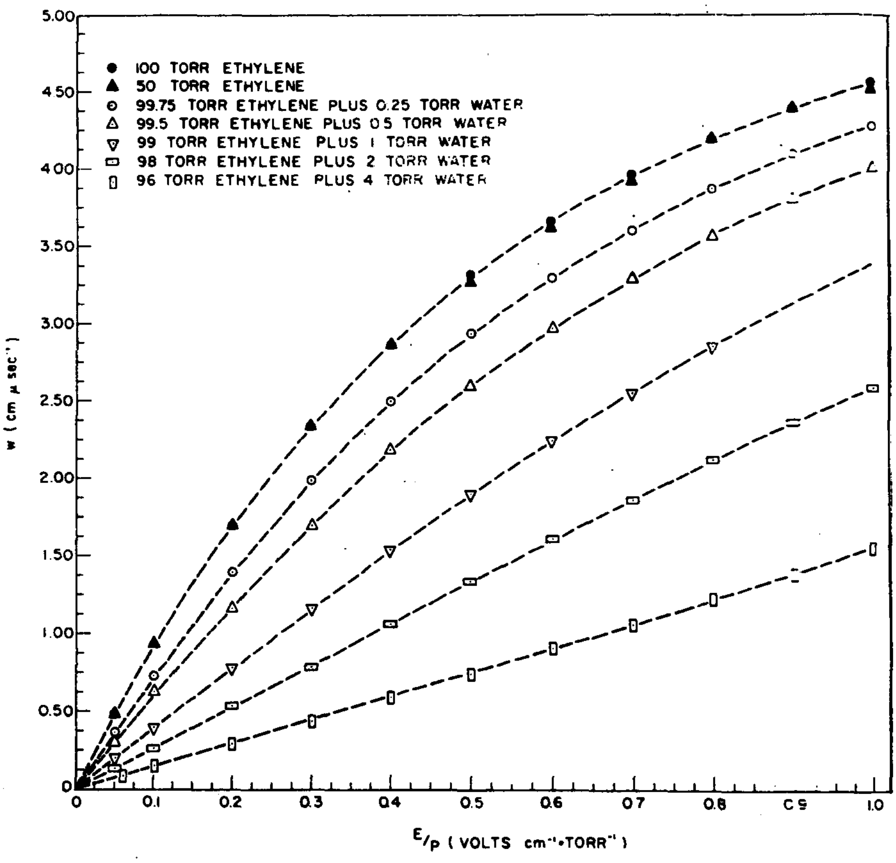


Fig. 198 Hurst et al. (1966)

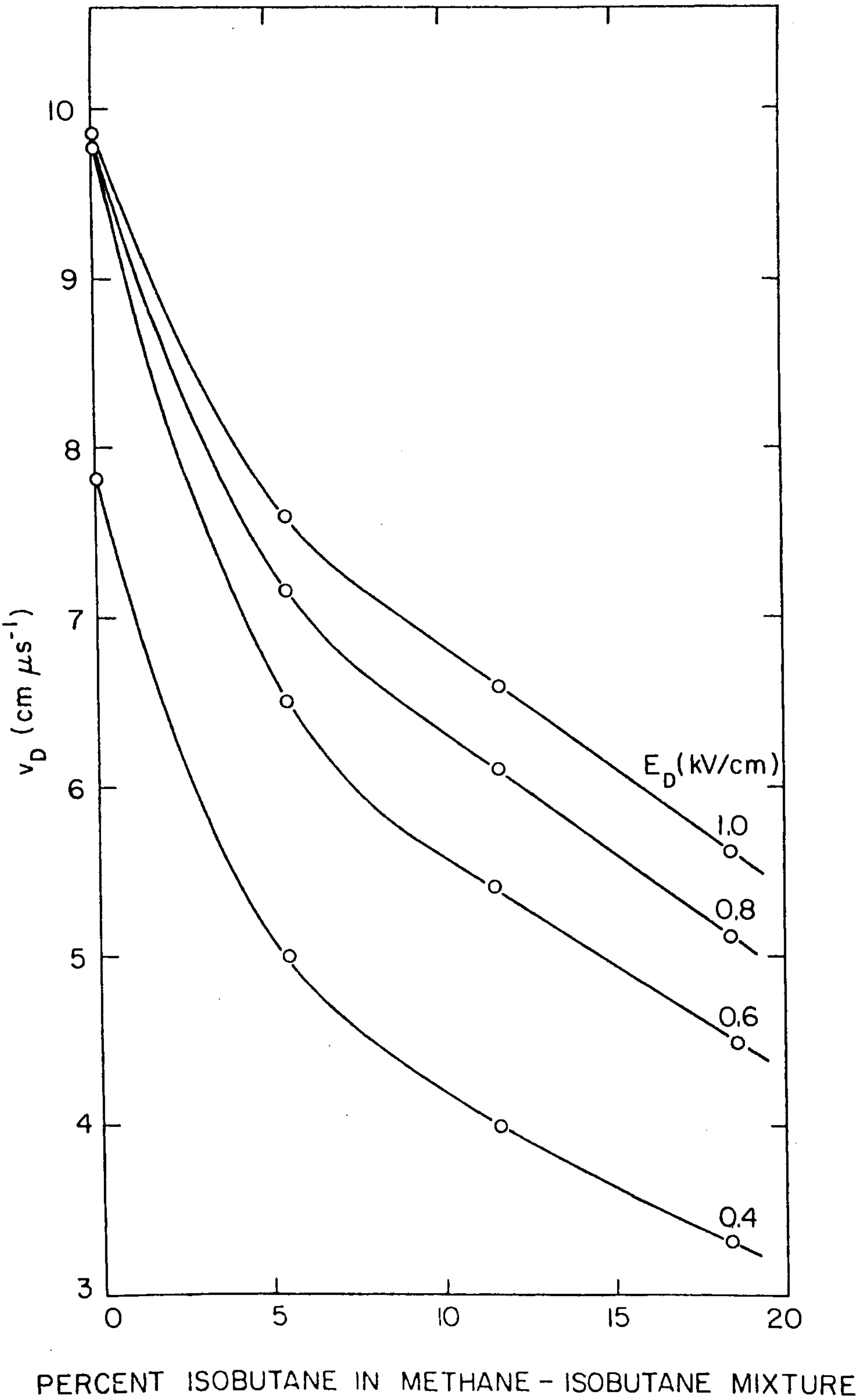


Fig. 199 Barrelet et al. (1982)

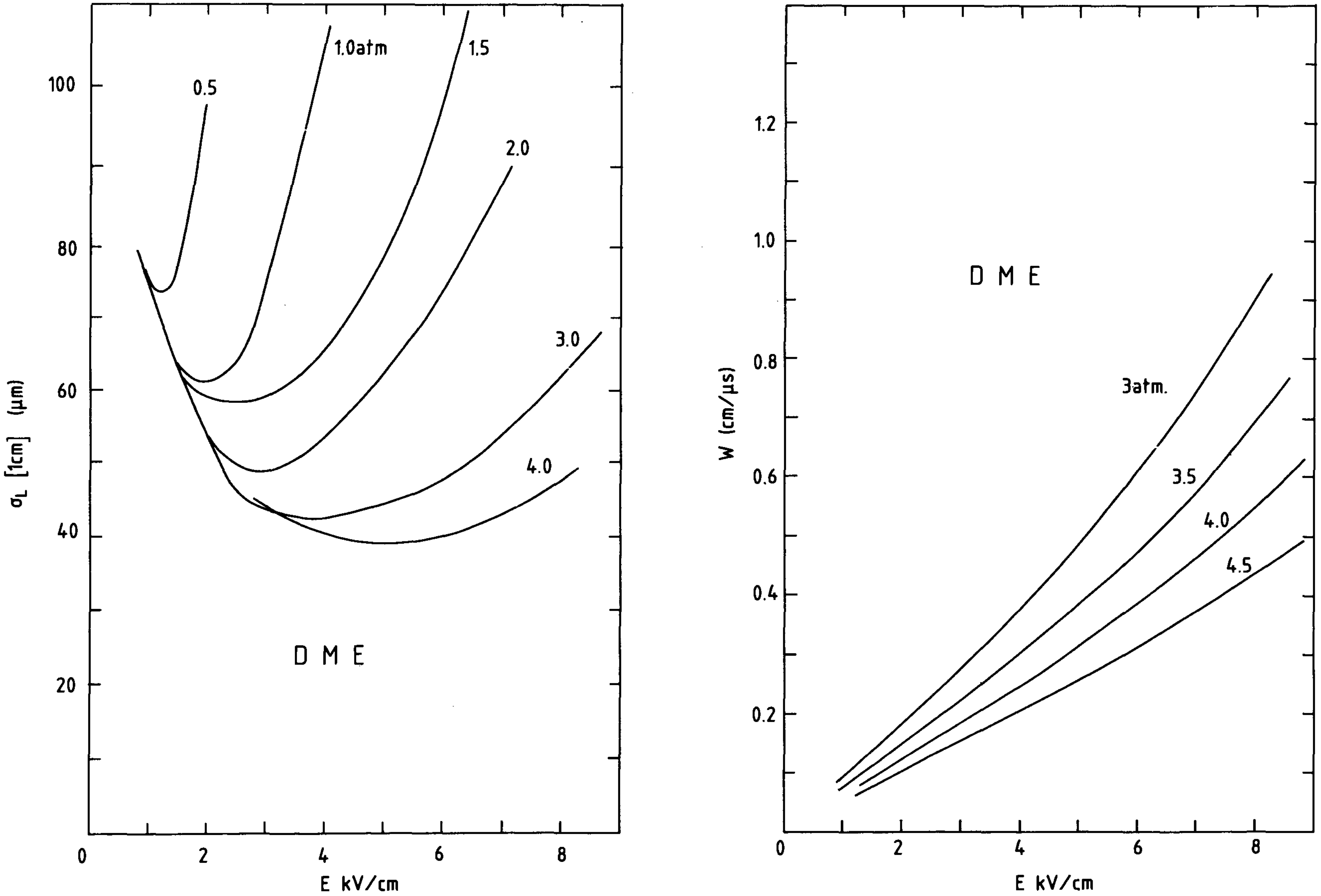


Fig. 200 Dolgoshein (1984)

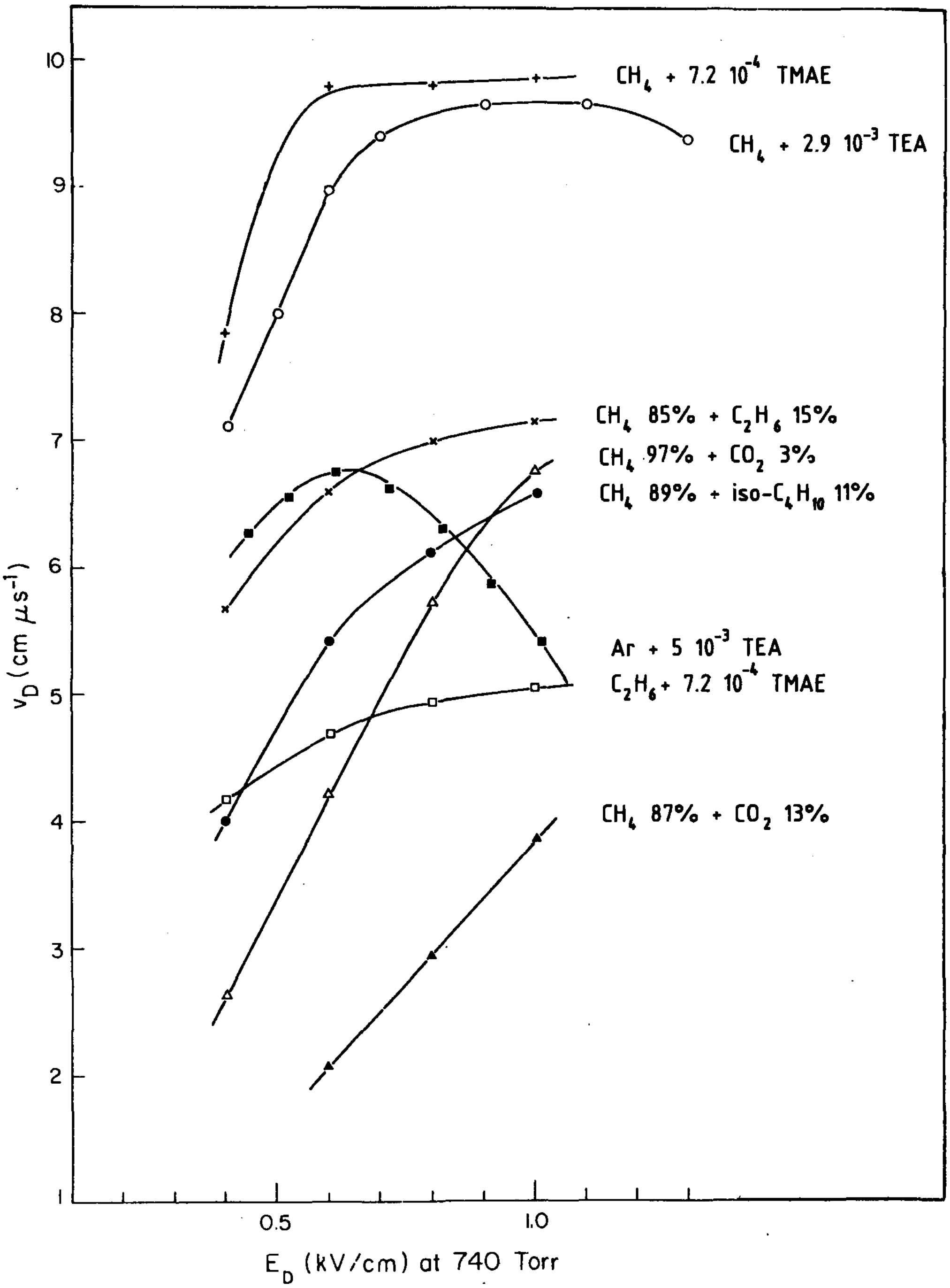


Fig. 201 Barrelet et al. (1982)

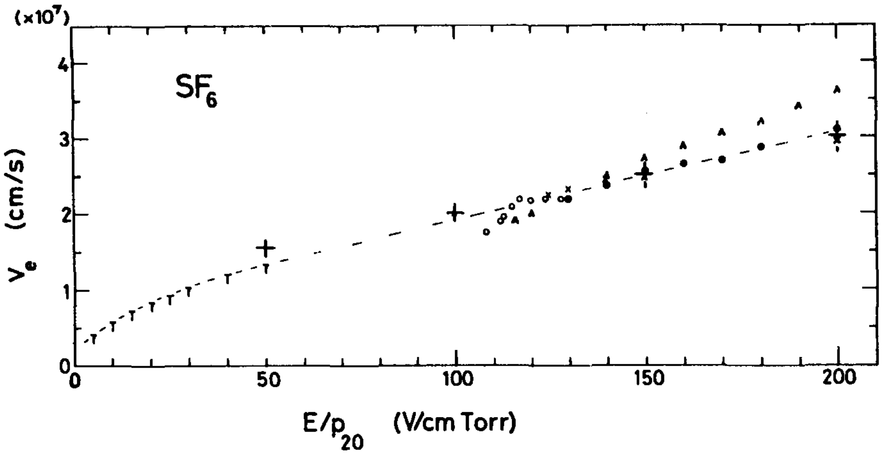


Fig. 202 Teich (1981)

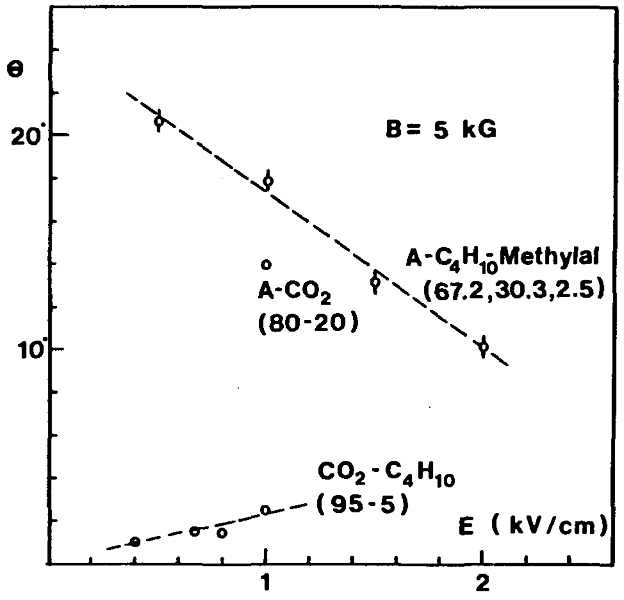


Fig. 203 Sauli (1984); Becker et al. (1983 a)

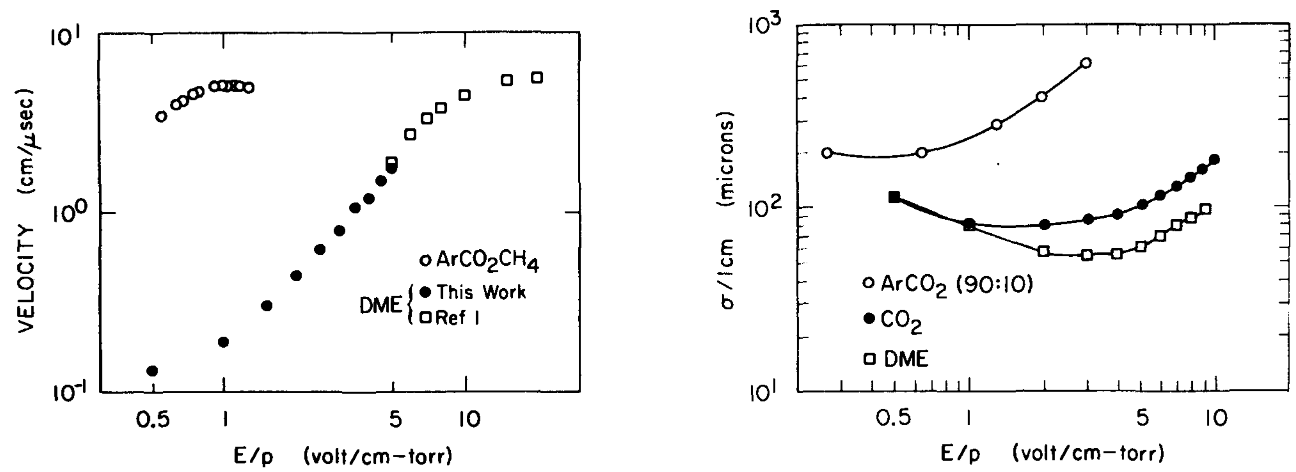


Fig. 204 Villa (1983)