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# Intense and Short Pulse Electric Field (DC and Microwave) Air Breakdown Parameters

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Experimental data for the drift velocity and Townsend ionization coefficient in $N_2$ and $O_2$ are utilized to obtain the ionization rates in $N_2$, $O_2$ and air. These rates are given over a wide range of E/p and differ from those of Felsenthal and Proud at high E/p because of the draft velocity dependence on E/p. Felsenthal and Proud assume a linear dependence on E/p while experimentally, especially at high E/p, this dependence varies as $\sqrt{E/p}$. The developed rates agree well with recent experimental short pulse air breakdown data and are recommended for use in high power microwave (short pulse) air breakdown and propagation calculations.

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# INTENSE AND SHORT PULSE ELECTRIC FIELD (DC AND MICROWAVE) AIR BREAKDOWN PARAMETERS

## 1. Introduction:

Breakdown data in gases under intense electric fields, whether static or oscillating (e.g. microwaves), are essential in understanding the basic physics and for scaling purposes in high voltage applications. Additionally, short pulse breakdown regimes (≤ 10 nsec) are of considerable interest for intense microwave and electron beam propagations, high voltage pulsed power switching and accelerator design.

This paper, therefore, deals with developing the appropriate paramenters for short pulse and intense field air breakdown conditions where data is sparse as to be non-existent.

Air breakdown studies by microwave radiation are numerous[1,2,3-9] and are well understood. The majority of these studies, however, have been performed under the continuous wave (cw) conditions and have concentrated on obtaining the breakdown threshold power, its dependence on gas pressure, and microwave frequency. Most of the pulsed microwave breakdown studies, on the other hand, have been made with pulse durations of μ sec or longer. There are only a few air breakdown studies[6,9] with microwave pulses as short as 0.1 μ sec. Microwave air breakdown data with pulses shorter than 0.1 μ sec, at this point in time, do not exist. There exist, however, nanosecond-pulse breakdown studies in air and other gaseous elements using the DC pulse method[10]. Such DC breakdown data can be utilized for microwave breakdown[11], using the

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effective field concept. Three other observations, on the microwave air breakdown data, are in order. First, the lowest gas pressures where experiments were conducted are 0.1 Torr for pulsed breakdown and 0.01 Torr for cw breakdown. Second, almost all the breakdown experiments were performed in resonance cavities and not in open air. Third, in terms of breakdown studies at very high power radiation, with short pulse duration, the data is non-existent. Therefore, it is of interest to see if one could correlate and extend the current data to regions of interest.

## 2.0 The Ionization Frequency

The static electric field or microwave breakdown of air proceeds through the avalanche ionization[1,2]. Where a free electron gains sufficient energy from the field to generate another, culminating in the avalanche ionization and hence breakdown.

To describe the ionization process one needs to know the ionization frequency $\nu_i$ which can be obtained in two ways. One approach is to use the measured cross sections for the electron impact ionization of $N_2$ and $O_2$ with the appropriate electron velocity distribution. The proper averaging of the electron velocity times the cross section over the electron velocity distribution yields the ionization rate coefficient $\nu_i/N$ where N is the density of the molecular species. The measured cross sections[12] for the ionization of $N_2$ and $O_2$ are very reliable and hence the ionization rate coefficient obtained in this manner will be reliable provided one knows or calculates the electron velocity distribution accurately. Fig (1) shows the ionization rate coefficient for $N_2$, $O_2$ and air as a function of the electron temperature, obtained[13] for a Maxwellian electron velocity distribution, using the cross sections of Ref (12). However, in the absence of knowledge of the electron velocity distribution a second approach for obtaining $\nu_i$ can be utilized. In this case one can use the experimentally obtained data of the Townsend ionization coefficient $\alpha/p$ and the electron drift velocity $V_d$. The ionization frequency then is obtained according to Eq. (1)

$$\nu_i = \alpha V_d \tag{1}$$

## 2.1 The Ionization Coefficient

The Townsend onization coefficient $\alpha$ has been measured by many investigators for a wide range of E/P (Volt $cm^{-1}$ $Torr^{-1}$) where E is the electric field and P is the pressure. Most of these data are compiled in Refs. 14 and 15. It suffices to state, however, that the recent measurements [16-18] are in good agreement with each other and also with the older measurements[14] especially in the region of high E/P. The older measurements, however, are not reliable for low E/P because the air was contaminated with mercury, which has a lower ionization energy in comparison with the air molecules. A best fit to the ionization coefficient data which is given in Table I, can be expressed by Eqs. (2) and (3) for E/P between 54 and 1000.

$$\alpha/P = 8.34 \,\mathrm{Exp}\,(-273.8\ P/E) \qquad 120 \geq E/P \geq 54 \tag{2}$$

$$\alpha/P = 16.0 \,\mathrm{Exp}\,(-359\ P/E) \qquad 1000 \geq E/P \geq 120 \tag{3}$$

## Table I

## Air Ionization Coefficient (α /P) as a Function of (E/P)

| E/P | α /P | E/P | α /P |
|---|---|---|---|
| 54 | 5.24 (-2) | 330 | 4.95 |
| 60 | 8.70 (-2) | 360 | 5.47 |
| 66 | 1.32 (-1) | 390 | 5.96 |
| 72 | 1.86 (-1) | 420 | 6.41 |
| 80 | 2.72 (-1) | 450 | 6.82 |
| 90 | 3.98 (-1) | 480 | 7.21 |
| 100 | 5.40 (-1) | 520 | 7.68 |
| 120 | 8.52 (-1) | 540 | 7.90 |
| 130 | 9.93 (-1) | 580 | 8.69 |
| 140 | 1.17 | 620 | 9.11 |
| 150 | 1.36 | 660 | 9.49 |
| 160 | 1.55 | 700 | 9.83 |
| 170 | 1.73 | 740 | 10.15 |
| 180 | 1.92 | 780 | 10.45 |
| 196 | 2.20 | 820 | 10.73 |
| 210 | 2.49 | 860 | 10.98 |
| 230 | 2.94 | 900 | 11.22 |
| 250 | 3.37 | 940 | 11.44 |
| 270 | 3.79 | 980 | 11.65 |
| 300 | 4.39 | | |

As for the ionization coefficient below E/P = 54, it is instructive to confer Fig. 2. In this figure we show the measured ionization coefficients for $O_2$ and $N_2$ in the region of E/P < 50. The data for $O_2$ is by Price, et al[19] and those for $N_2$ are by Daniel and Morris[20] whose measurements are in good accord with those of Cookson, et al[16]. From these data we derive the ionization coefficient in air shown in Fig (2) as a dashed line. However, we also present in the same figure the ionization coefficient in air as measured by Moruzzi and Price[22] down to E/P = 37.5 and by Dutton, et al[23] for E/P down to 34. The values of $\alpha$ /P derived form the data of $N_2$ and $O_2$ is higher by no more than 40% compared to the measurements of Moruzzi and Price[22] . The fit to this data, which merges smoothly into the data above E/P = 35, is expressed by

$$\alpha/P = 2.44 \text{ Exp } (-208 \text{ P/E}) \qquad 54 \geq E/P \geq 30 \qquad (4)$$

This expression [23] may be uncertain by ~ 50% in the lowest end, i.e. for E/P ~ 30.

## 2.2 The Drift Velocity

The electron drift velocity in air has been measured for E/P up to 104, the agreement between the measurements are quite good[14,15]. The data in this region can be expressed by the following relation.

$$V_d = 6.0 \times 10^6 + 2.3 \times 10^5 \text{ (E/P)} \qquad 54 \leq E/P \leq 120 \qquad (5)$$

which reproduces the measured drift velocity with an uncertainty of 10%. For the data below $E/P = 54$, the following fit expresses the data rather well (again to better than 10% uncertainty)

$$V_d = 5.4 \times 10^6 + 2.2 \times 10^5 (E/P) \qquad 54 \geq E/P \geq 30 \qquad (6a)$$

and

$$V_d = 7.43 \times 10^5 + 4.36 \times 10^5 (E/P) \qquad 30 \geq E/P \geq 1 \qquad (6b)$$

However, there exists no measurements for the drift velocity in air for $E/P > 100$. To obtain $V_d$ for higher E/P we utilize the existing measurements[24] of the drift velocity in $N_2$ and $O_2$.

For $N_2$ the measured velocity is expressed with good accuracy by

$$V_d = 3.3 \times 10^6 (E/P)^{1/2} \qquad 120 \leq E/P \leq 3000 \qquad (7)$$

For $O_2$, on the other hand, the drift velocity has been measured for E/P from 100 to 8000 and the data can be expressed by

$$V_d = 3.75 \times 10^6 (E/P)^{1/2} \qquad 120 \leq E/P \leq 8000 \qquad (8)$$

The drift velocity in air can be obtained by using the mobility relation[25] for gaseous mixtures, that is

$$\mu = \left(\frac{f_1}{\mu_1} + \frac{f_2}{\mu_2}\right)^{-1} \qquad (9)$$

where $f_1$ and $f_2$ are the fractions of $N_2$ and $O_2$ in air and $\mu_1$ and $\mu_2$ are the electron mobilty in $N_2$ and $O_2$, respectively. From the last three equations (Eqs. 7-9) we obtain the following expression for the drift velocity in air

$$V_d = 3.38 \times 10^6 \, (E/P)^{1/2} \qquad 120 \le E/P \le 3000 \qquad (10)$$

## 2.3 The Ionization Frequency and Comparison with Other Data

We can now give expressions for the ionization frequency in air based on the relations developed in Sections 2.1 and 2.2. Even though our interest is in the high E/P regimes, nonetheless we give expressions for the low regions of E/P for the sake of completeness. Our expressions for $\nu_i/P$ are:

$$\nu_i/P = [1.32 + 0.054(E/P)] \times 10^7 \; \mathrm{Exp}\,(-208\, P/E) \qquad 54 \ge E/P \ge 30 \qquad (11)$$

$$\nu_i/P = [5.0 + 0.19(E/P)] 10^7 \; \mathrm{Exp}\,(-273.8\, P/E) \qquad 120 \ge E/P > 54 \qquad (12)$$

and

$$\nu_i/P = 54.08 \times 10^6 \, (E/P)^{1/2} \; \mathrm{Exp}\,(-359\, P/E) \qquad 3000 \ge E/P \ge 120 \qquad (13)$$

The reduced ionization frequency $\nu_i/P$ based on the above expressions is shown in Fig (3) .

To compare our results with the previous data, especially those by Felsenthal and Proud[10], we utilize their expression for the drift velocity given by Eq. (14)

$$V_d = 7.0 \times 10^6 + 2.0 \times 10^5 (E/p) \qquad (14)$$

It should be noted, however, that this expression was based on measurements of the drift velocity for E/P from 0.2 to 20 volt $cm^{-1} Torr^{-1}$. Its extension to high E/P, as proposed by Felsenthal and Proud[10], in 1965, is not warranted. This is because the drift velocity depends linearly on E/P only for low values of E/P ($E/P < 100$) At higher values of E/P the drift velocity varies as $(E/P)^{1/2}$ as shown experimentally by Schlumbohm[24]. The extension of Eq. 14 to higher E/P will clearly over estimate the ionization frequency. For example, Eq. (14) yields a value of $2.0 \times 10^8$ cm/sec at $E/p = 1000$ compared to $1.0 \times 10^8$ cm/sec obtained from our expression for $V_d$ (See Eq 10). If, however, we utilize our expressions for the ionization coefficient (see Eqs. 2-4), which should not differ widely from $\alpha/P$ used by Felsenthal and Proud[10] with Eq. 14 for $V_d$ in Eq. (1) we obtain $\nu_i/P$ according to Falsenthal and Pround. The result is shown in Fig (3) for comparison with our proposed data. A comparison shows that the ionization rate, if one follows Felsenthal and Proud, is higher at high E/P compared to ours. The implications are obvious in terms of breakdown time in air at high E/P. Our expression predicts longer times for breakdown at high regions of E/P.

## 3.0 The Ionization Frequency for Microwave Air Breakdown

We have provided expressions for the ionization frequency based on DC field data. However, one can use these expressions for microwave air breakdown provided that the electric field in our expressions is replaced by the effective field. The effective electric field $E_e$ is related to the rms field, $E_{rms}$, by Eq (15)

$$E_e = E_{rms} \left( \frac{\nu_m^2}{\nu_m^2 + \omega^2} \right)^{1/2} \qquad (15)$$

Here $\nu_m$ is the electron collision frequency for momentum transfer and $\omega$ is the natural frequency of the microwave radiation. This approach is valid for pulsed breakdown where the pulse duration is $\geq 0.1\ \mu$ sec, based on the voluminous works of MacDonald[2] and others. However, we propose to extend this approach to short pulse breakdown ($\tau \leq 0.1 \mu$ sec) as was done by Felsenthal[11]. Accordingly we construct the E/P vs $P\tau$ diagram, using our expressions developed earlier and compare the results with those of Felsenthal, various other microwave breakdown data, and the most recent[9] high power microwave breakdown data of LLNL which were conducted under short pulse irradiations (see Fig 4). In the diagram shown in Fig (4) $\tau$ denotes the formative time defined [11] as the time when the electron density reaches a value of $10^8$ cm$^{-3}$. Accordingly, and using the avalanche ionization concept we obtain:

$$\nu_i \tau = 18.4 \qquad (16)$$

which can be rewritten as

$$\nu_i/P = 18.4/P\tau \qquad (17)$$

From this and Eqs. (11-13) one can construct the E/P vs $P\tau$ diagram which is shown in Fig. 4. This figure shows that our calculations are in better agreement with the most recent results[9] for short pulse breakdown in air.

## 4.0 The Collision Frequency for Momentum Transfer

To obtain the effective electric field (see Eq 15) one needs to know the collision frequency for momentum transfer, $\nu_m$ . This quantity is also needed in calcualting the attenuation coefficient of microwave radiation propagating through the ionized air.

The collision frequency for momentum transfer is due to electron neutral and electron ion collisions., However, for our purposes, where the degree of ionization is very small, we can neglect the electron-ion collisions. Therefore, the discussion will center on the electron-molecule collisions.

The collision frequency is obtained, in general, when the electron velocity distribution and the momentum transfer cross section are known. For air, however, one relies on the momentum transfer cross sections of $N_2$ and $O_2$, where data, experimental and calculated exists[26] for electron energies from 0.01 to 1000 eV. For example, the most recent measured[27] cross section in $N_2$ for electron energies from 1.5 to 400 eV is in good agreement with the most recent theoretical calculation of Jain et al [28], and they are in good agreement with the other measurements[29-32] (for details see Ref. 26 and Figure 5). For $O_2$, on the other hand, the momentum transfer cross section data are shown in Fig 6 based on the data of Hake and Phelps[33], Shyn and Sharp[34], Wedde and Strand[35] and Martin and Von Engel[36] (See Ref. 26 for details).

From the cross sections of $N_2$ and $O_2$ one can obtain the collision frequency for momentum transfer in air. However, it is of interest to illustrate the definition of $\nu_m$ . In general the concept of the electron momentum transfer collision frequency, $\nu_m$, is defined by [37,38] Eq. (18).

$$< \frac{1}{\nu_m} > = \frac{A}{N} \int \frac{4\pi v^3 dv}{3\sigma_m(v)} \frac{\partial f}{\partial v} \tag{18}$$

where the electric field disturbs the velocity distribution. In Eq. (18) A is the normalization constant, N the density of the molecules and $\sigma_m(v)$ the momentum transfer cross section. However, other definitions of $\nu_m$ are also available, e.g.[39]

$$< \nu_{eff} > = AN \int 4\pi \, v^3 \, dv \, \sigma_m(v) \frac{\partial f}{\partial v} \tag{19}$$

and in the absence of the electric field by [13]

$$< \nu_a > = A \int f(v) \, v^3 \, \sigma_m(v) \, dv \tag{20}$$

Using these definitions we calcualte [40] the momentum transfer collision frequency in $N_2$ for a Maxwellian electron velocity distribution. These results are shown in Figures 7a and 7b. It is interesting to observe that $\nu_m$ , which is more appropriate for the propagation calculation, agrees very well with $\nu_a$ for up to Te =20 eV and the deviation is 20% for Te > 20 eV in the range shown in Figs. (7) . Of interest, however, is the collision frequency for momentum transfer in air. Thus using Eq. (18) with a Maxwellian velocity distribution and $\sigma_m(\text{air}) = 0.8 \ (N_2) + 0.2 \ \sigma_m(O_2)$, we calculate

$\nu_m/N$, where the result is shown in Figures 8a and 8b. Also shown in Figs. 8a and 8b, for comparison, is the momentum transfer collision frequency obtained from combinig the data of Phelps and his colleagues[41] for $N_2$ and $O_2$, based on the swarm experiments.

However $\nu_m$ can also be expressed as a function of E/P based on the relation between $\nu_m$ and the electron drift velocity where one can define [41,42] an effective collision frequency by

$$\nu_m = \frac{e}{m}\frac{E}{V_d} \qquad (21)$$

Using Eqs. 6a, 6b and 10 for $V_d$ we obtain the following expressions for $\nu_m$ over a wide range of E/P (1-500)

$$\frac{\nu_m}{P} = \frac{2.35 \times 10^9 (E/P)}{1 + 0.58\,(E/P)} \qquad 1 \le E/P \le 30 \qquad (22)$$

$$\frac{\nu_m}{P} = \frac{3.24 \times 10^8 (E/P)}{1 + 0.04\,(E/P)} \qquad 30 \le E/P \le 54 \qquad (23)$$

$$\frac{\nu_m}{P} = \frac{2.93 \times 10^8 (E/P)}{1 + 0.041\,(E/P)} \qquad 54 \le E/P \le 120 \qquad (24)$$

$$\frac{\nu_m}{P} = 5.2 \times 10^8 (E/P)^{1/2} \qquad 120 \le E/P \le 3000 \qquad (25)$$

where P is the pressure in Torrs. These expressions are used to calculate the coefficient for the momentum transfer collision frequency, shown as a function of the electron temperature in Figures 8a and 8b. The dependence of the electron temperature on E/P is discussed in the next section. In Figure 8b we give $\nu_m$ as a function of the electron energy where $\nu_m$ (see Eq. 18) and $\nu_a$ (see Eq. 20) are shown for a Maxwellian distribution. Results obtained using relations 22-25 are shown for up to $E = 10$ eV along with those of Phelps.[41] Also shown is the result obtained via $\sigma v$ with no averaging, applicable to a single electron model. Obviously, the agreement is reasonable for $E < 10$ eV. However, for higher energy electrons a difference of a factor of 2 or more is evident, suggesting that a Boltzmann model is necessary to obtain the actual collision frequency.

## 5.0 The Electron Temperature

The electron temperature or the average energy are necessary for the calculations of the two imporatant paramenters, i.e., $\nu_i$ and $\nu_m$. In general, however, if the appropriate cross sections and the electron velocity distribution are known, various transport coefficients can be calcualted. On the other hand, one may obtain the characteristic energy[43] or the electron temperature as a function of E/P from swarm experiments. Figure 9 shows the electron temperature in dry air over a wide range of E/P based on experimental data[17,44,45]. These data can be expressed with an accuracy of 5% by

$$T_e = 0.31\ (E/P)^{0.75} \qquad 1 \leq E/P \leq 5 \qquad (25)$$

$$T_e = 0.82 + 0.035\ (E/P) \qquad 5 \leq E/P \leq 30 \qquad (26)$$

$$T_e = 0.12\ (E/P)^{0.8} \qquad 30 \leq E/P \leq 54 \qquad (27)$$

$T_e = 2.17\ (E/P)^{0.15}$ $\qquad 54 \le E/P \le 150$ $\qquad (28)$

$T_e = 0.18\ (E/P)^{0.65}$ $\qquad 150 \le E/P \le 500$ $\qquad (29)$

## 6. Summary

Data based on dc field and obtained under steady state conditions were utilized to develop appropriate parameters for high E/p breakdown in air. The extension of these parameters for high power microwave air breakdown, under short pulse conditions was proposed. Using these parameters an E/p vs $P\tau$ diagram ws constructed over a wide range of E/p and compared with current and old data. The agreement is quite good warranting the use of these parameters for HPM short pulsed breakdown analysis.

One of the parameters of interest, $\nu_m$ , was presented for a Maxwellian electron velocity distribution and from emperical data. These were compared with data obtained using an average electron velocity approach. All these data show that a reasonable value for $\nu_m$ can be used for calculating the effective electric field as well as for microwave attenuation through a plasma over the E/p or Te ranges given in Figures 7 and 8.

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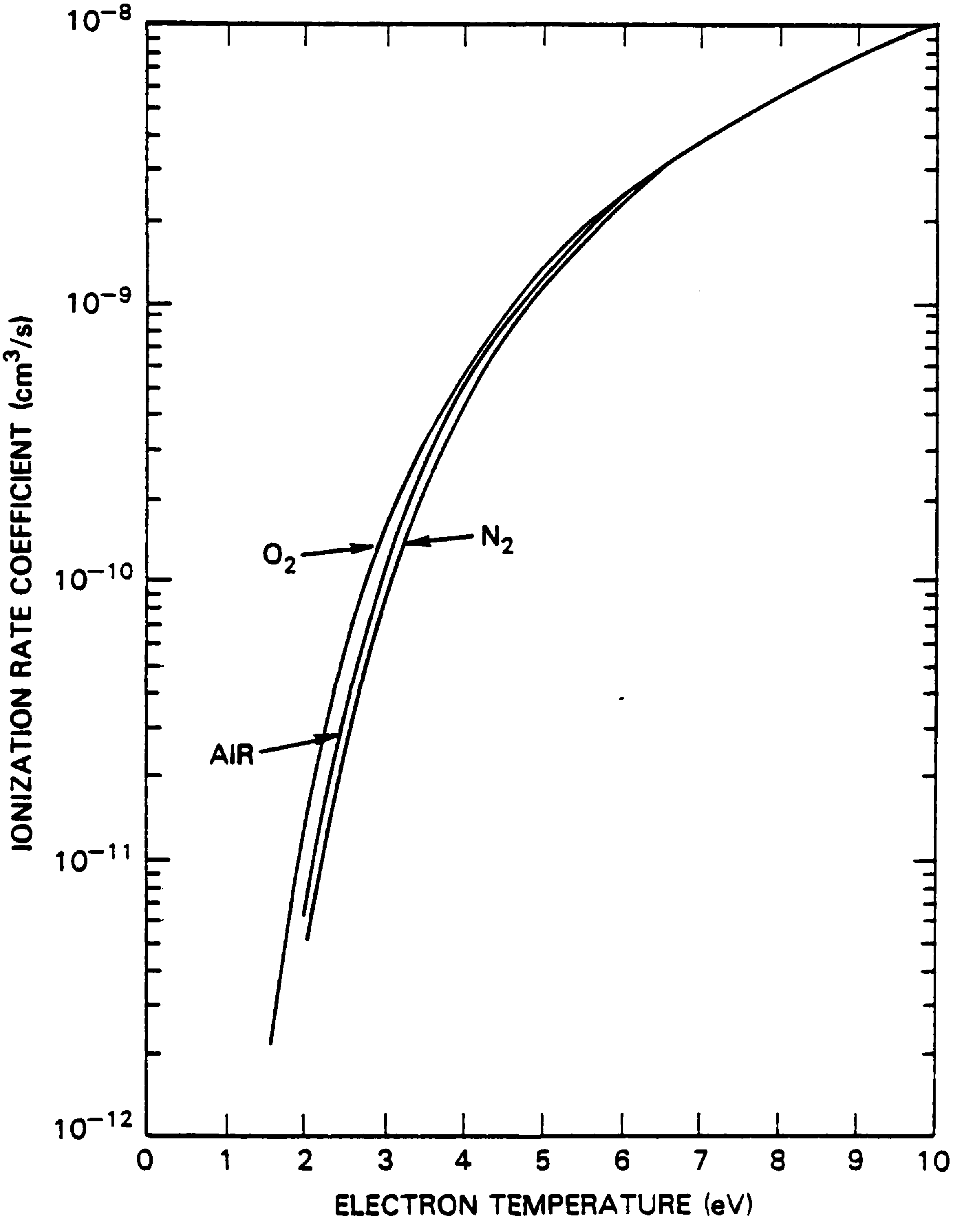

Figure 1. The Ionization Rate Coefficients for $N_2$, $O_2$ and Air as a Function of the Electron Temperature.

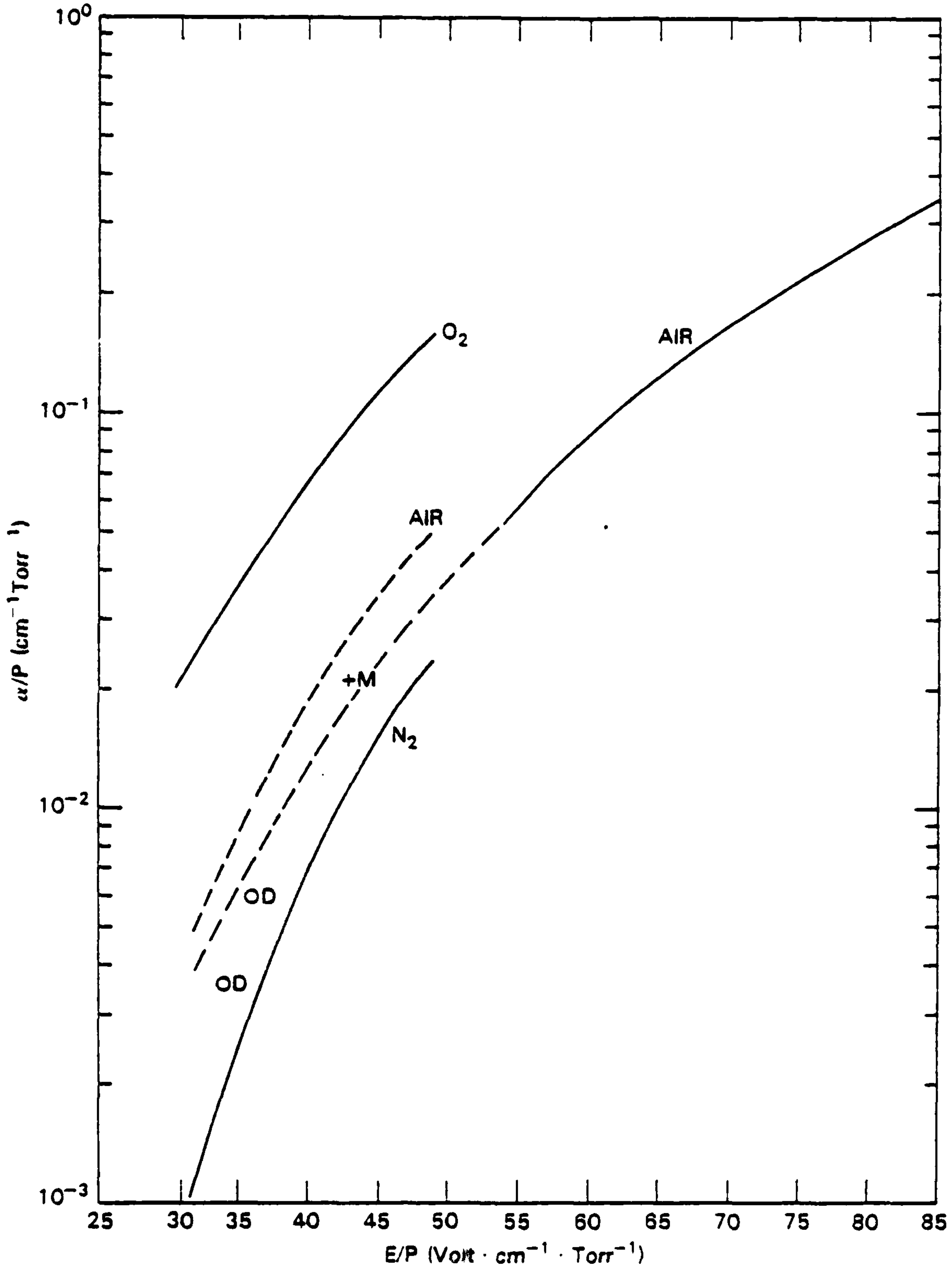

Figure 2. Townsend Ionization Coefficients for $N_2$, $O_2$ and Air as a Function of E/P.

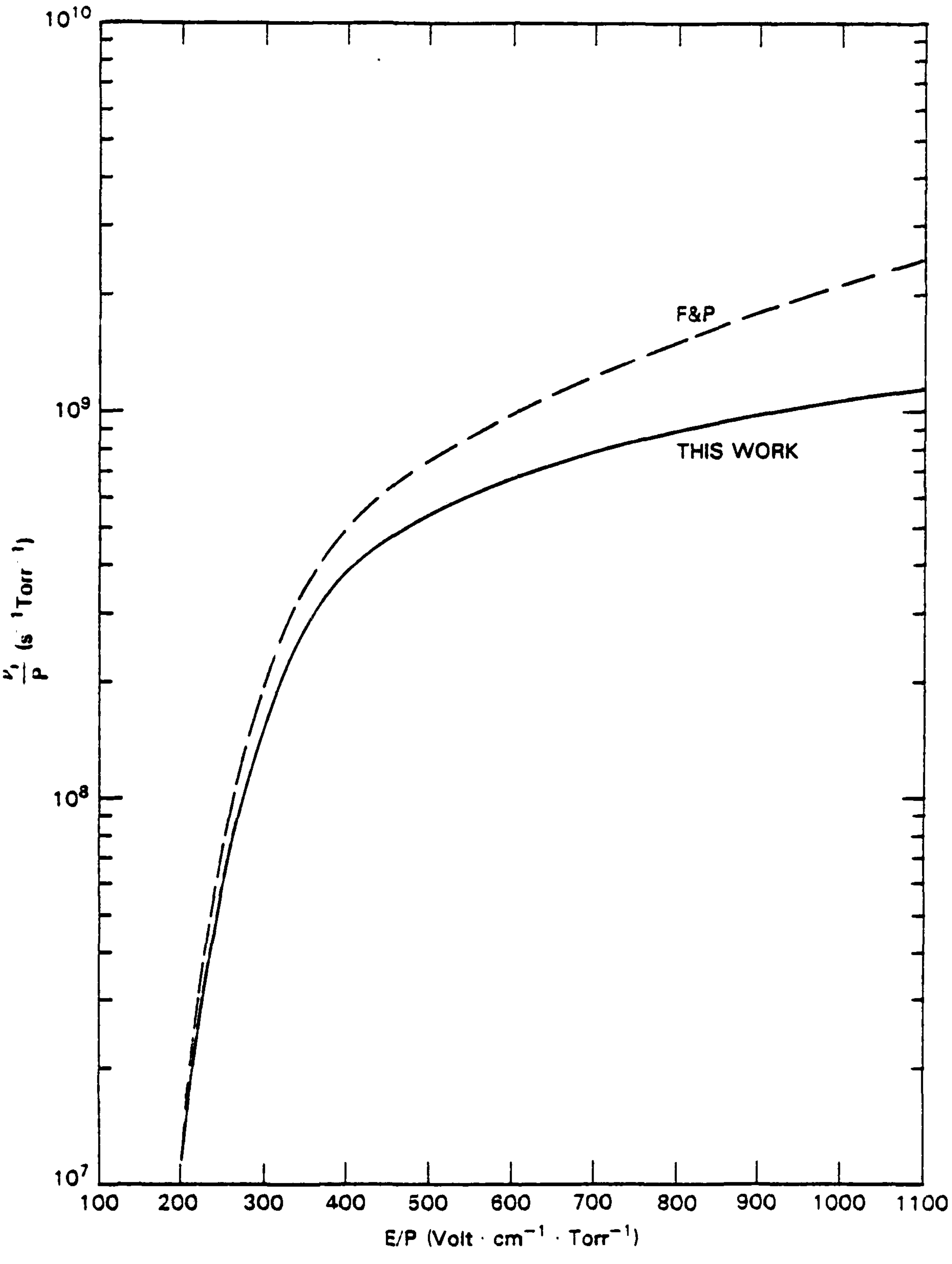

Figure 3. The Reduced Ionization Frequency ($\nu_i$/P) for Air as a Function of E/P.

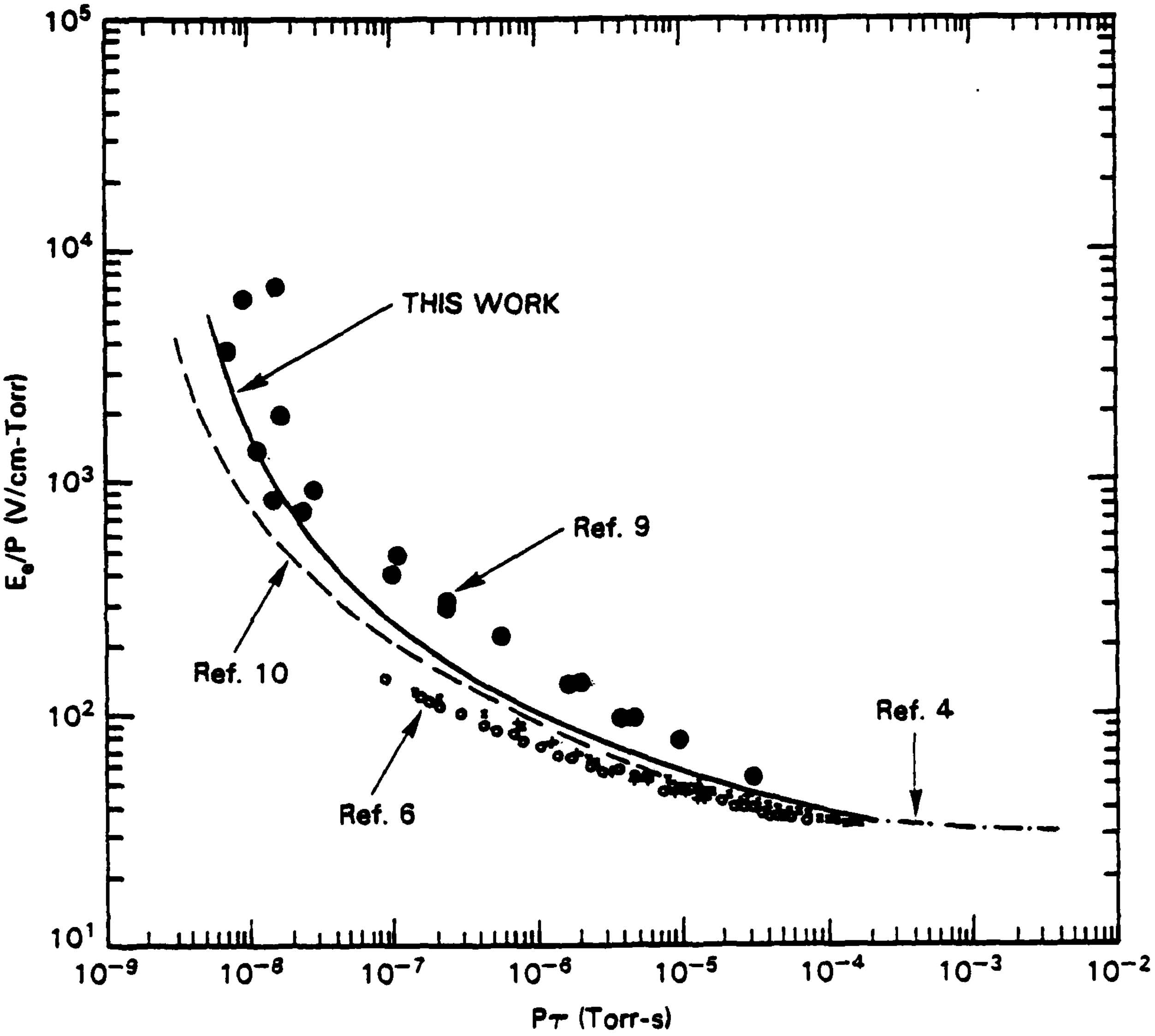

Figure 4. The Pτ vs E/P Diagram for a Wide Range of E/P

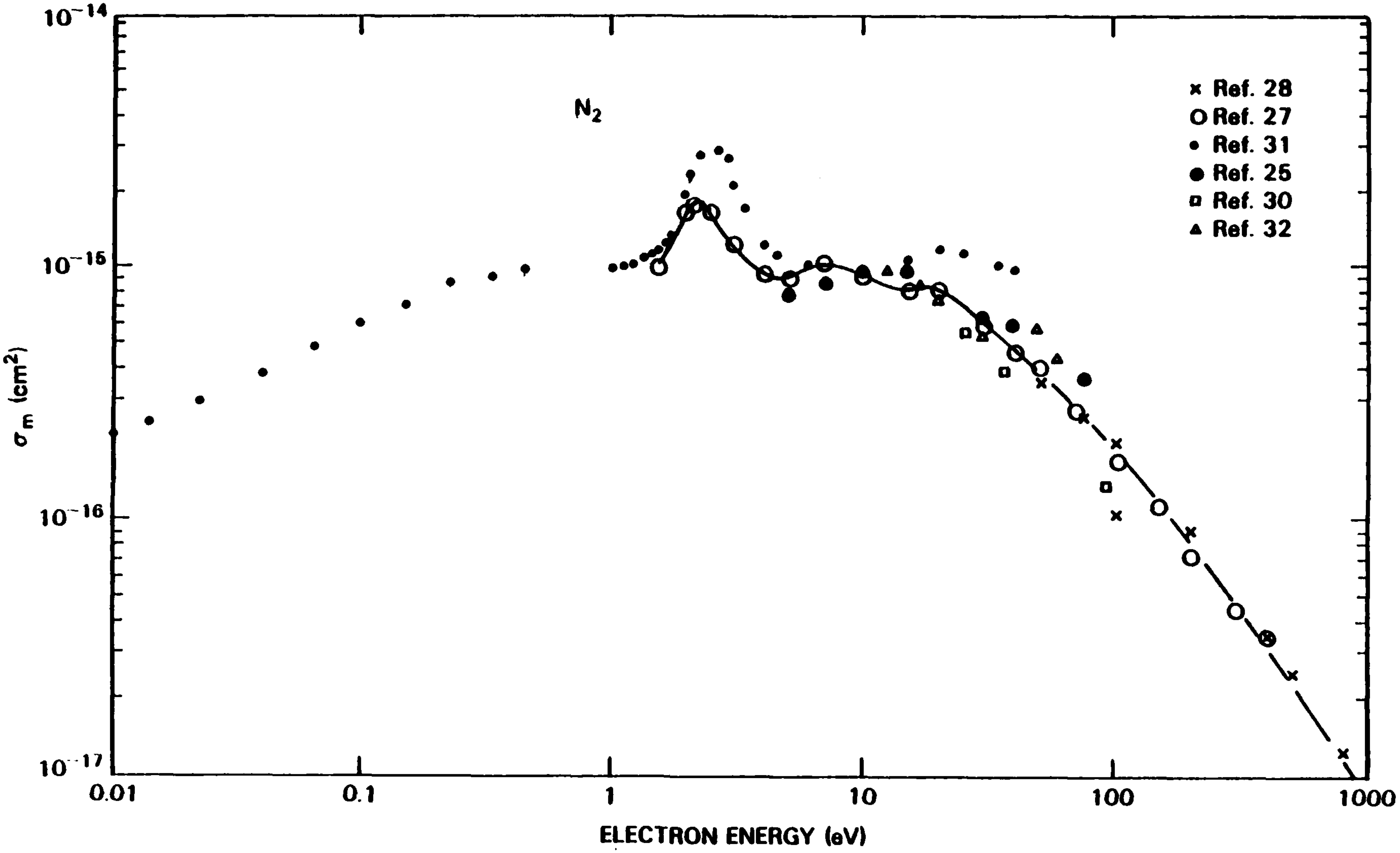

Figure 5. The Electron Momentum Transfer Cross Section in $N_2$.

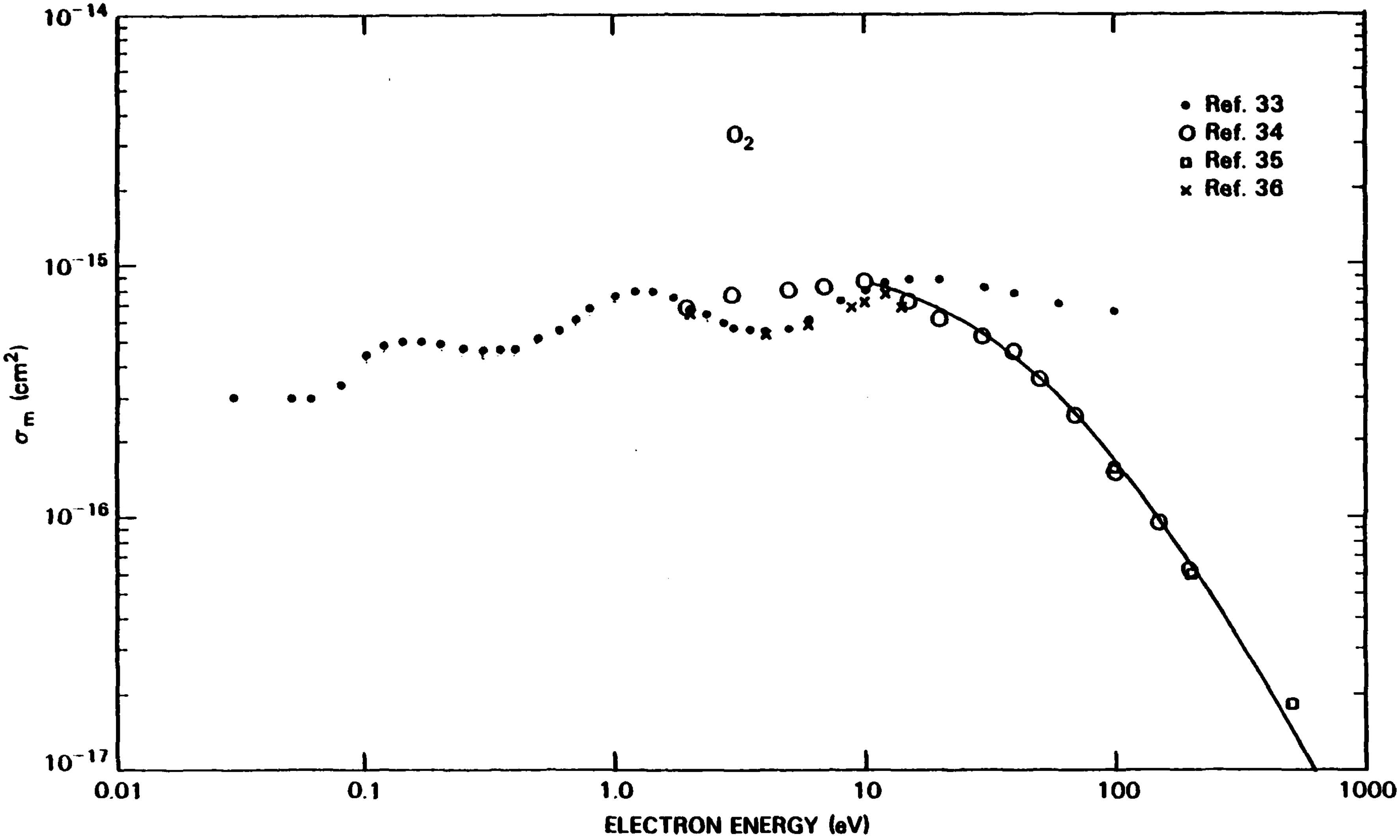

Figure 6. The Electron Momentum Transfer Cross Section in O$_2$.

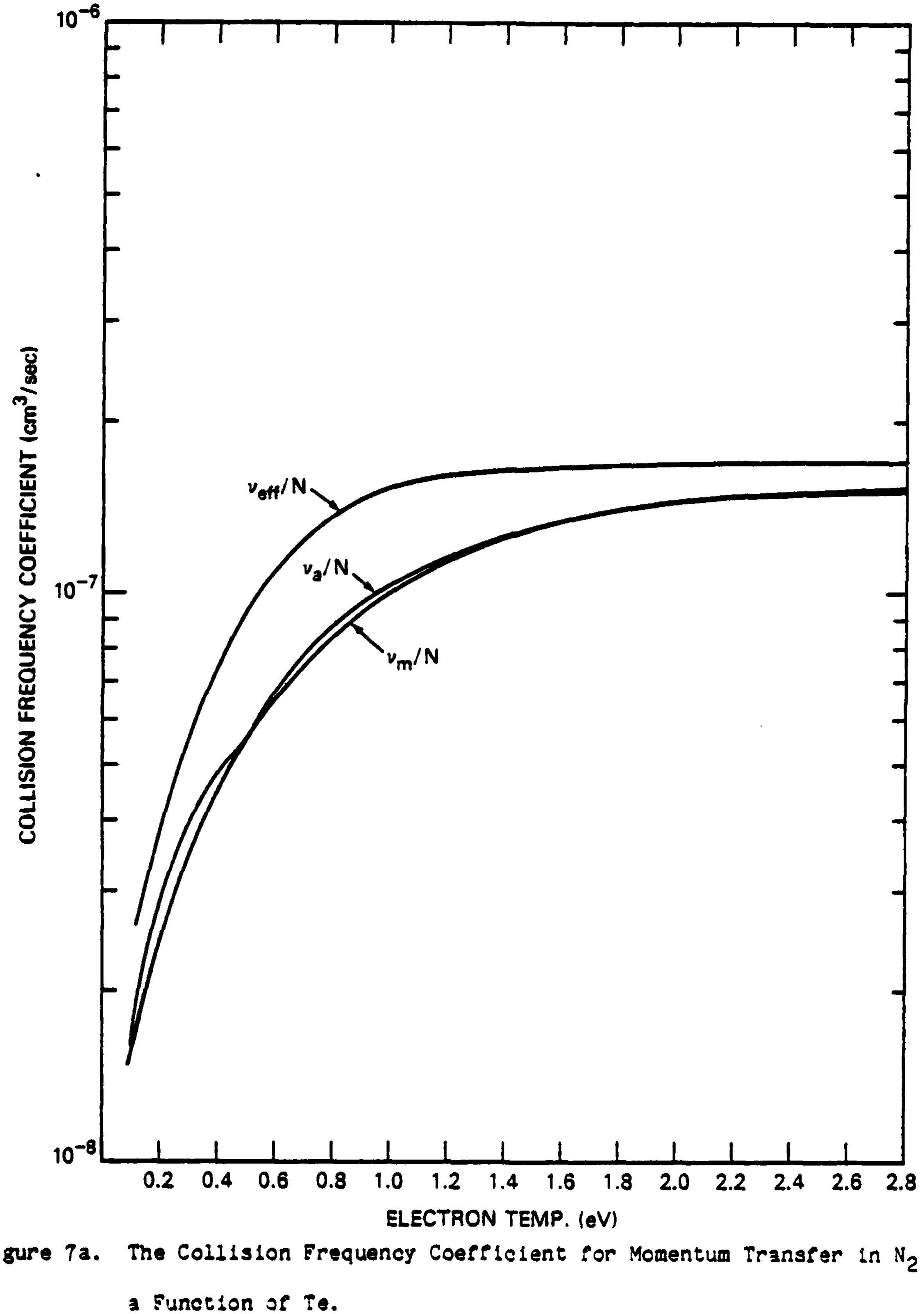

Figure 7a. The Collision Frequency Coefficient for Momentum Transfer in $N_2$ As a Function of Te.

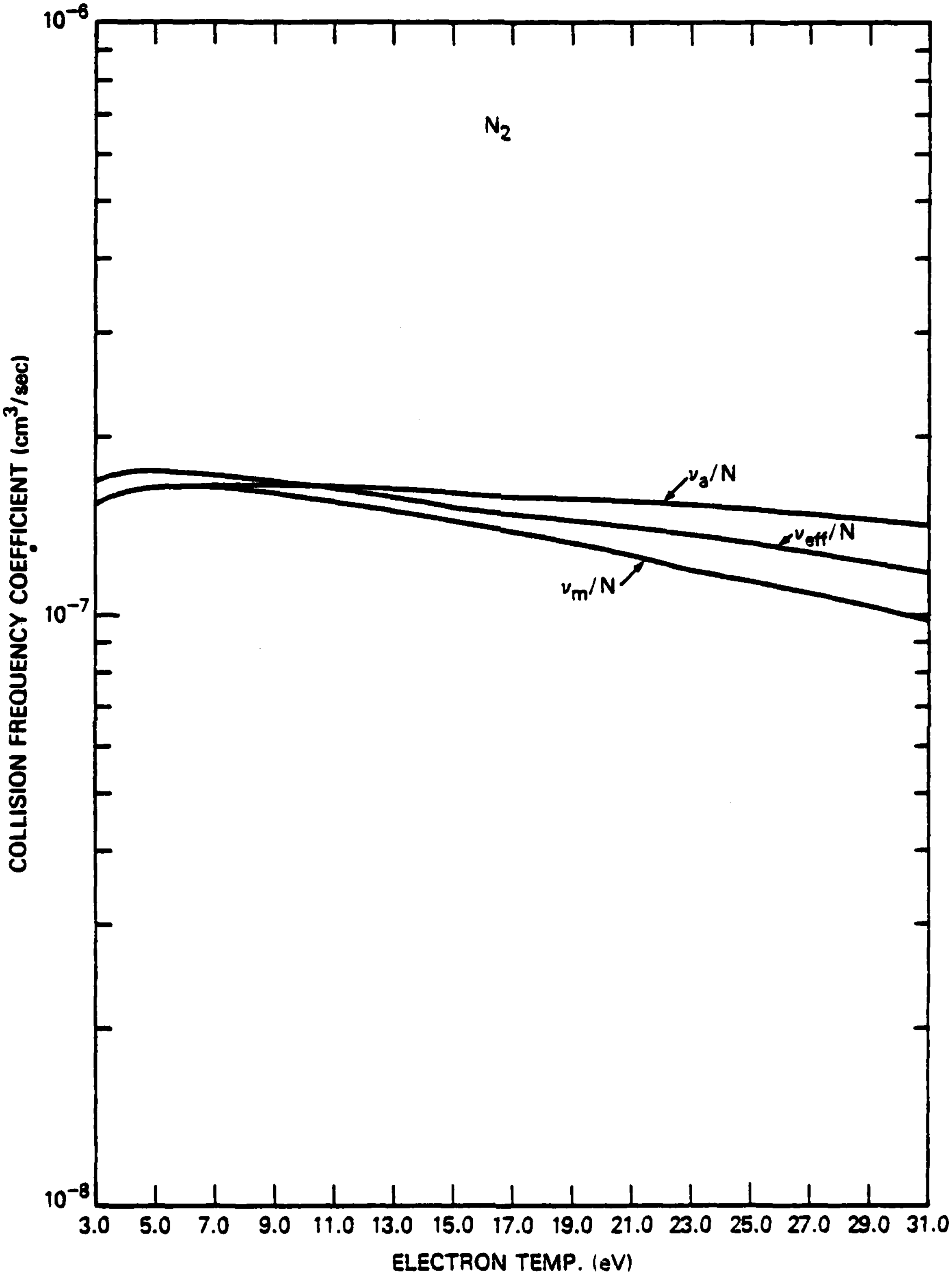

Figure 7b. The Collision Frequency Coefficient for Momentum Transfer in $N_2$ as a Function of Te.

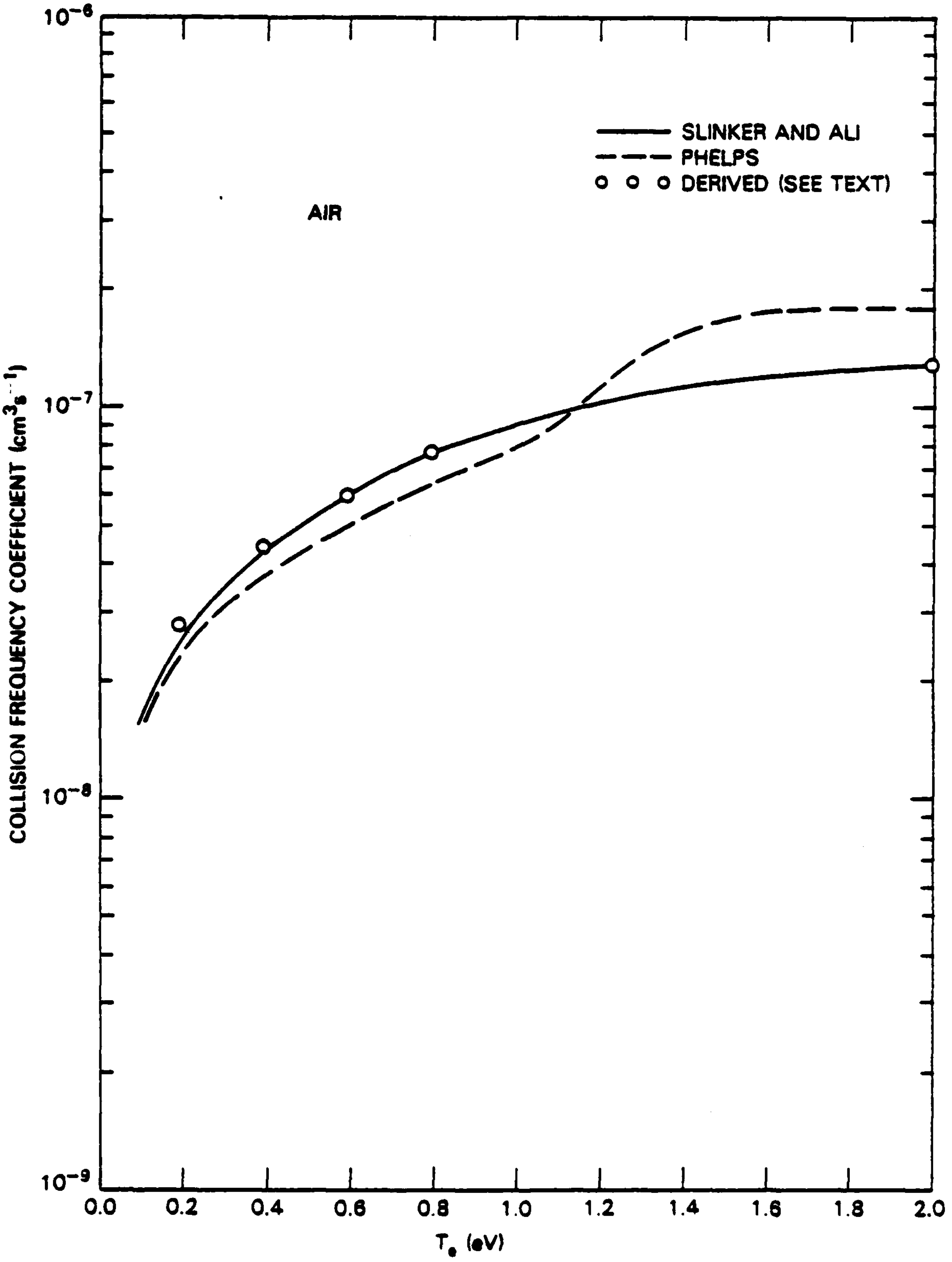

Figure 8a. The Collision Frequency Coefficient for Momentum Transfer in Air as a Function of Te.

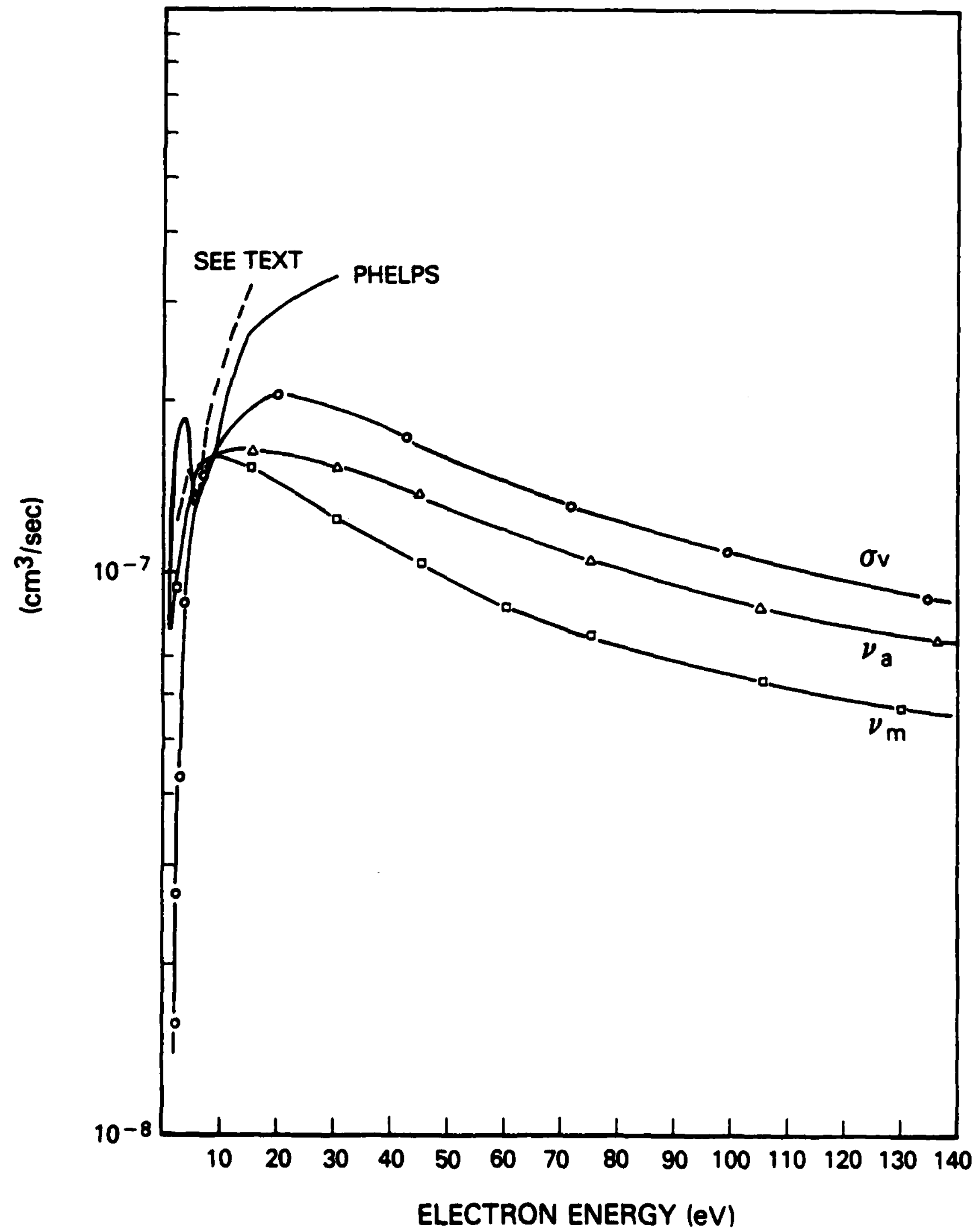

Figure 8b. The Collision Frequency Coefficient for Momentum Transfer in Air as a Function of the electron energy.

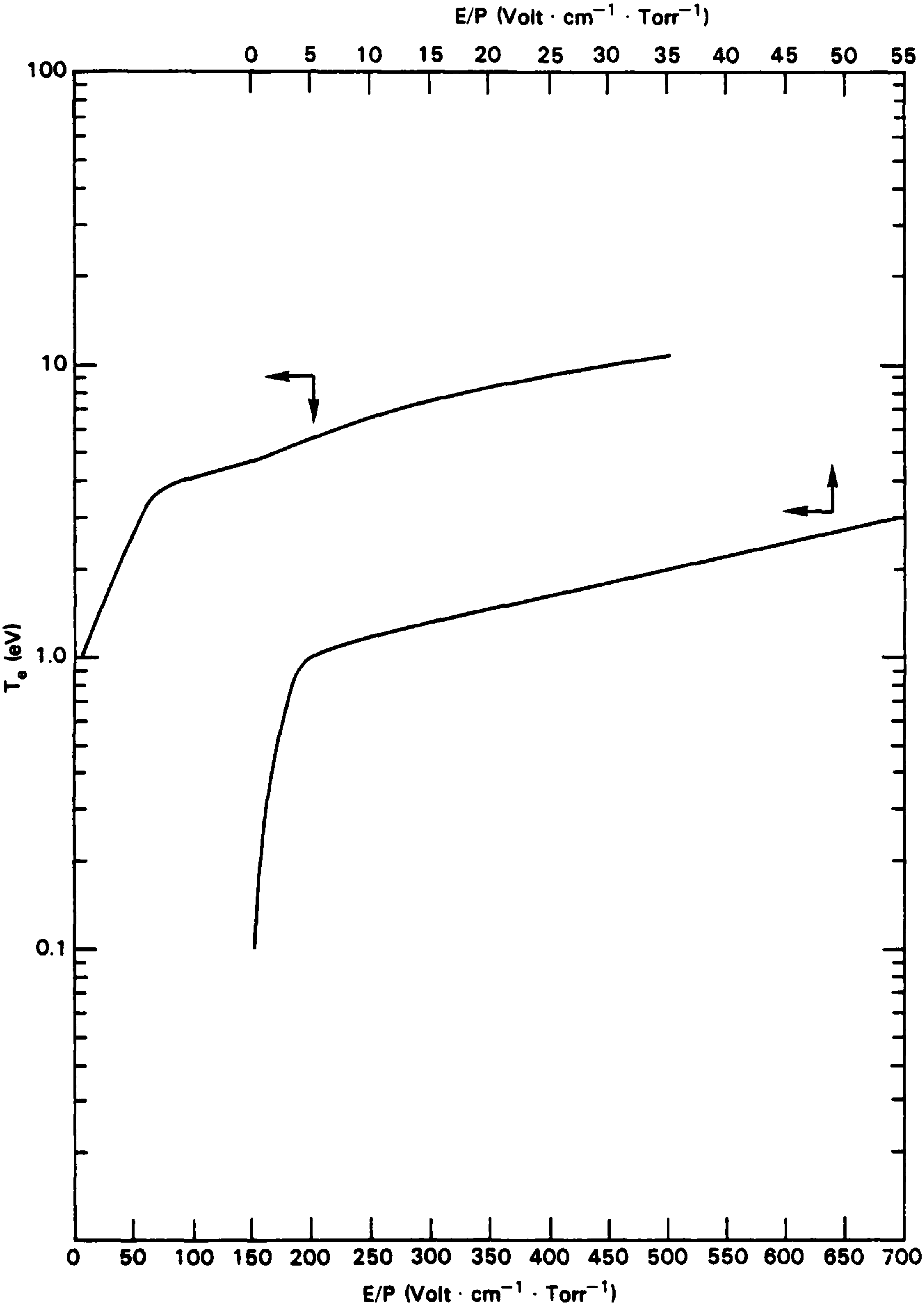

Figure 9. The Electron Temperature as a Function of E/P.