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To the Graduate Council:

I am submitting herewith a thesis written by Youssef H. Hilal entitled "Energy to Produce an Electron-Ion Pair in SF_6 and SF_6 Mixtures." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

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ENERGY TO PRODUCE AN ELECTRON-ION PAIR
IN SF₆ AND SF₆ MIXTURES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Youssef H. Hilal

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ABSTRACT

The resurgence of interest in the dielectric properties of SF_6 and mixtures containing SF_6 has resulted in increasing research activity related to the problems associated with the practical uses of SF_6 . One problem relating to such use is the role of the initiatory electron (i.e., electron that initiates voltage breakdown in SF_6) which can be produced within the gas by cosmic and natural radiation, or by the collisional detachment processes from negative ions (i.e., SF_6^-). The proper assessment of the effect of cosmic radiation and gamma or x-radiography measurements for the detection of unwanted particles or broken insulators that might lead to a breakdown, required by a fast charged particle to create an electron-ion pair in a given gas medium, i.e., $W = E_0/N_i$ where E_0 is the initial energy of the charged particle, and N_i is the total number of electron-ion pairs produced by the complete absorption of E_0 in the gas. This last question is addressed hereby measuring the ionization produced in SF_6 and mixtures containing SF_6 , when an alpha particle of energy E_0 produces N_i electron-ion pairs in becoming completely stopped in the gas or its gas mixtures.

The objectives of this work are:

1. To measure the W values of SF_6 and SF_6 mixtures as a function of the applied voltage and pressure.

2. To determine the possibility of the existence of metastable states in SF_6 under electrically stressed conditions.

The W value of SF_6 was found to be 35.45 electron volt/ion pair (eV/ip); this rather high value is attributed to the large cross section for electron impact dissociation of SF_6 into neutral fragments. The W values of the gases N_2 , C_2F_6 , C_2H_2 and 2- C_4H_8 , normally mixed with SF_6 for various insulating needs, have also been measured and are reported. Quantitative measurements of the W values for the binary gas mixtures $\text{SF}_6/\text{C}_2\text{H}_2$, $\text{SF}_6/2\text{-C}_4\text{H}_8$ and $\text{SF}_6/\text{C}_2\text{F}_6$ have also been studied.

No Penning ionization was observed for the binary gas mixtures; however, $\text{SF}_6/2\text{-C}_4\text{H}_8$ showed an increase of ionization due to the ionization of 2- C_4H_8 by metastable SF_6^* molecules. This result, then, establishes the existence of SF_6^* metastables and indicates that further studies are needed to explain the role of SF_6^* metastables in ionization of the gas and electron ejection upon their collision with the electrode surface.

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CHAPTER I

INTRODUCTION

One of the major advances in modern high voltage technology resulted from the deployment of compressed dielectric gases, especially sulfur hexafluoride (SF_6) as a primary insulating medium. SF_6 is a very important gas which, under "ideal" conditions of nearly uniform fields and smooth electrodes, has a breakdown strength about 2.5 times that of air.¹ SF_6 has been used extensively as an electrical insulator in a variety of high voltage apparatus, such as research equipment (high voltage power supplies), circuit breakers, compressed gas-insulated substations and compressed gas-insulated cables. This extensive use of SF_6 is mainly due to its distinct advantages (e.g., low weight, excellent dielectric strength, excellent dielectric and thermal recovery properties, low dielectric losses, good thermal conductivity, compactness of equipment, environmental advantages, etc.).²

The resurgence of using SF_6 in high voltage equipment led to extensive studies of the problems associated with such usage. Of primary concern are the processes in the high voltage breakdown of electrically stressed SF_6 under impulse conditions. Impulse breakdown mechanism in SF_6 can be explained by the streamer theory.^{3,4,5} When an impulse voltage of magnitude greater than the dc breakdown voltage is applied to a gas-insulated gap, breakdown will occur after a finite time $t = t_s + t_f$. The t_s is known as the statistical time lag and is

the time elapsed between the application of the impulse voltage and the appearance of a free electron in the gap to initiate a discharge. The t_f is called the formative time lag and is the time required for the spark discharge which, once initiated, to develop across the gap. The statistical time lag t_s varies from nanoseconds to milliseconds² depending on the time it takes for the initiatory electron to become available as the magnitude of the impulse voltage becomes greater or equal to the dc breakdown voltage. The statistical time lag in SF_6 is of practical importance for the insulation coordination and over-voltage protection of SF_6 insulated equipment.

The initiatory electron can be emitted from the cathode of the electrode system, or from within the gaseous medium. Electrons emitted from the cathode will quickly attach to SF_6 to form SF_6^- (i.e., negative ions). Then, there are two other possible sources of free electrons:⁶

1. Free electrons can be produced in SF_6 by cosmic radiation and natural radiation.
2. They can also be produced by collisional detachment processes from negative ions (i.e., SF_6^-).

In SF_6 insulated equipment, the temporal and spatial distribution of breakdown is determined by the statistical time lag when SF_6 is electrically stressed by the applied impulse voltage.⁷ In calculating the statistical time lag, it is necessary to know the actual ion density profile in the electrode system (Kindersberger et al.⁸). The basic data for the calculation of the ion density profile are the

rate of electron-ion pair generation, the ion mobility and the ion-ion recombination. The rate of ion pair generation by cosmic and natural radiation can be determined from W (i.e., the average energy required to produce an electron-ion pair in a gas). In high voltage SF_6 insulated transmission lines, gamma- and X-radiography have been used to detect unwanted particles or broken insulators that might lead to a breakdown in the system.⁹ Knowledge of W was again needed to determine the number of electron-ion pairs produced by the photon flux absorbed in SF_6 .

The objectives of this work are:

1. To measure the ionization produced in SF_6 and SF_6 gas mixtures, when an alpha particle of kinetic energy E_0 produces N_i electron-pairs in becoming completely stopped in the gas or gas mixture. The mean energy lost per electron-ion pair produced E_0/N_i is called the W of the gas for the alpha particles.¹⁰
2. To determine the possibilities of the existence of metastable states in SF_6 under electrically stressed conditions.

The W value has been found to be largely independent of the mass of highly energetic particles. However, there is a slight dependence on the type and energy of the ionizing particle.¹⁰ The W value has been found to be greater than the lowest ionization potential of a given gas for which it is being measured. The W values include not only the ionization energy, but also the kinetic energy given by the particle to the gas atom or molecule in exciting it above its ground state, and

the kinetic energy given to the electrons removed by the ionization process. For most gases, W is found to lie in the range 20 to 40 electron volts per ion pair (eV/i.p.).

An approximate value of W for different molecules irradiated by alpha particles can be found from:¹⁰

$$W_{\alpha}(\text{molecule}) = 9.8 + 1.67 I \quad (1.1)$$

where I is the ionization potential in (eV) of the molecule. The magnitude of W is important in a practical number of areas such as nuclear radiation detection, radiation dose measurements, dose partition, radiation-induced chemical reactions and gas discharges.

The W value for the unary gases SF_6 , N_2 , C_2H_2 , C_2F_6 , cis 2- C_4H_8 , and that for binary gas mixtures SF_6/N_2 , $\text{SF}_6/\text{C}_2\text{H}_2$, $\text{SF}_6/\text{C}_2\text{F}_6$, and $\text{SF}_6/\text{cis 2-C}_4\text{H}_8$ were obtained by comparison with that of a standard gas such as argon (26.4 eV/i.p.)¹⁰ (Table I). In the case of binary gas mixtures, there have been three distinguished effects: One concerns the increase of ionization, and consequent decreases in W as the component ratios of the gas mixture ($\text{SF}_6/\text{cis 2-C}_4\text{H}_8$) are varied from 0-100%. This effect is attributed in part to excitation of metastable SF_6 molecules and the subsequent ionization of the additive gas (by interaction with these metastable SF_6 molecules) provided that the ionization potential of the additive gas is lower than the energy of the SF_6 metastable states. The second effect concerns the decrease in ionization (i.e., increase in W) as the gas mixture ($\text{SF}_6/\text{C}_2\text{F}_6$) component ratios are varied from 0-100%. However, this effect is not pronounced, and further investigation is needed

TABLE I
MEASUREMENT OF ΔT AS A FUNCTION OF THE APPLIED
VOLTAGES FOR ARGON AT 101 kPa

Applied Voltage (kV)	Δt_{AR}^* (sec)
0.75	45.58
1.0	45.54
2.0	45.39
3.0	45.36
4.0	45.30
∞	45.19**

* Δt is defined on p. 15 as the time required to charge the capacitor to a fixed value (1.824 volts).

**Extrapolated value as $1/V \rightarrow 0$ (i.e., $v \rightarrow \infty$).

$$W_{AR} = 26.4 \text{ eV/i.p.}$$

with another gas molecule whose ionization potentials are about equal to that of SF_6 , and which has large cross section for dissociation into neutral fragments. The third effect, prominent in most gases, shows the W value of the gas mixture to lie between the extreme values of the individual gases and to change smoothly from one extreme to the other as the gas mixture component ratios are changed. The W of gas mixtures can be expressed in terms of the W 's of the pure gases, the partial pressure and an empirical constant characteristic of the two gases.¹⁰

CHAPTER II

APPARATUS SYSTEM

I. IONIZATION CHAMBER AND GAS SYSTEM

Figure 1 shows the mechanical system arrangement which consists of the ionization chamber system and the gas purification system. The ionization chamber was constructed earlier for electron swarm studies, but several changes were incorporated with the help of J. G. Carter as follows: Figure 2 illustrates a cross sectional view of the ionization chamber. The chamber is constructed from non-magnetic stainless steel. The top flange is sealed with a copper gasket to the chamber by means of twenty-four bolts and nuts. A high voltage ceramic bushing is mounted on the side flange which is sealed with a copper gasket to the chamber by means of six bolts. A thin rod, connected to the high voltage electrode plate and enclosed in a quartz tube, is passed through the vacuum tight bushing end to the negative polarity high voltage power supply. Two copper parallel plate electrodes of 0.3175 cm thickness are set at 5 cm separation. The electrode edges are rounded to eliminate corona discharges that will disturb the measurement. The guard ring surrounds the collector plate with a gap of 0.1 cm and is supported by three steel rods welded to the top flange. The collector plate is 11.1 cm in diameter and is attached to the guard ring by three equally spaced ceramic insulators. A thin wire is attached to the collector plate at one end, and on the other

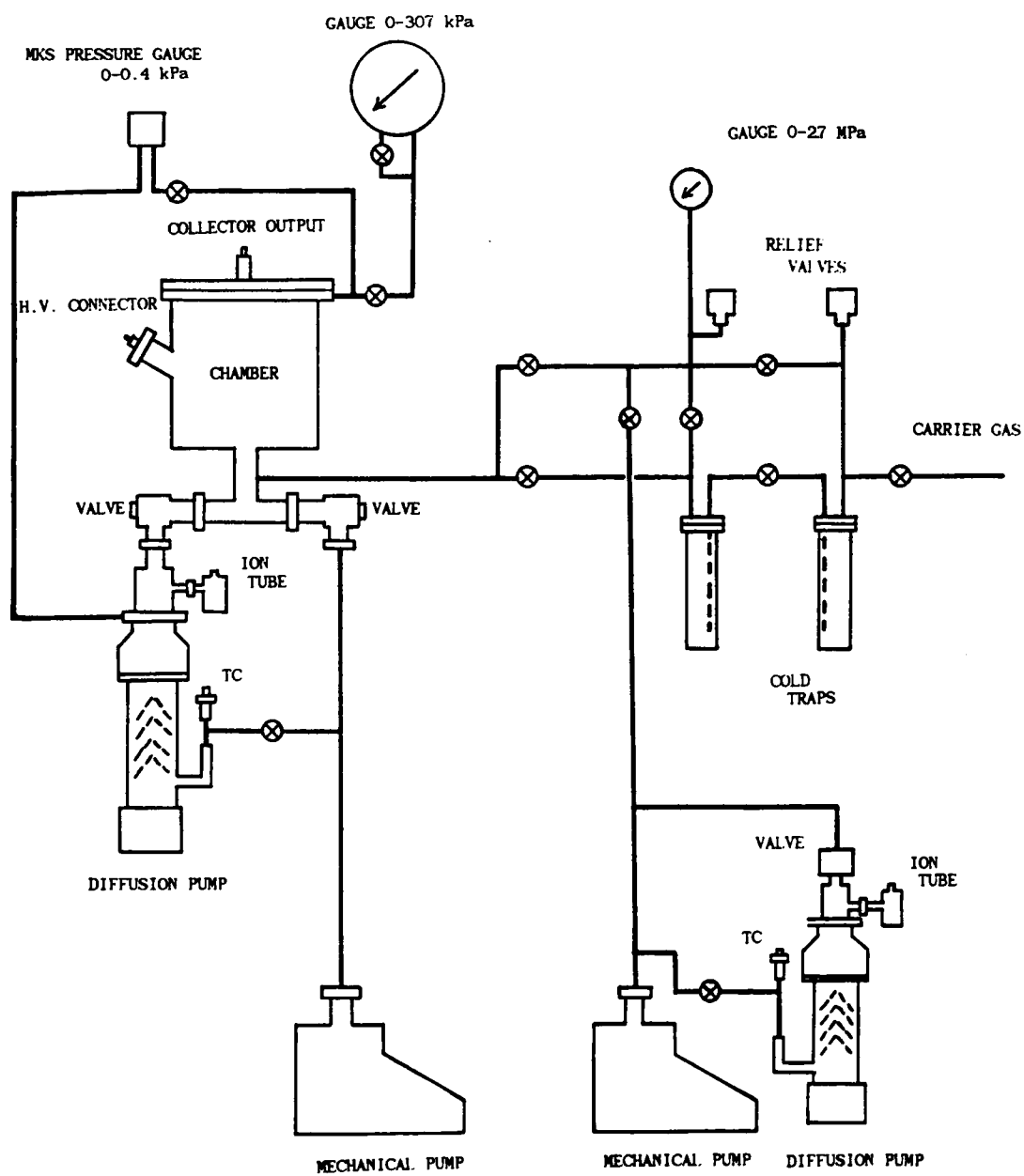


Figure 1. A schematic diagram of the mechanical system.

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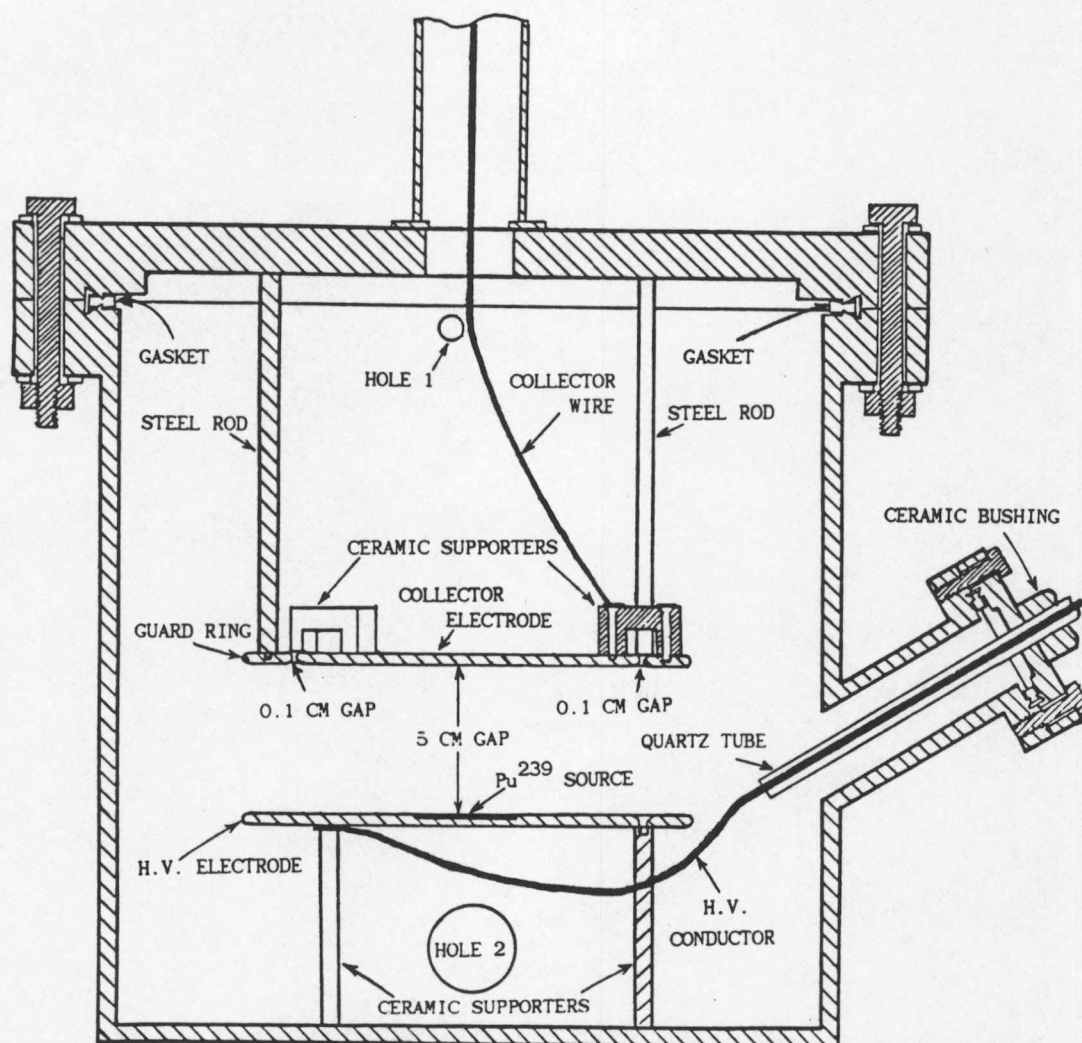


Figure 2. A cross-sectional view of the ionization chamber.

end to the rod extended from a vacuum tight connector which, in turn, is welded to a hole drilled through the top flange. The high voltage plate electrode is supported by three equally spaced ceramic insulator rods mounted on the bottom of the chamber.

As a source of ionization, an uncollimated Pu^{239} alpha particle source deposited on a platinum plate of 0.16 cm in thickness and 2.5 cm in diameter is flush mounted in the center of the high voltage plate electrode, itself 15.4 cm in diameter. The ionization source produces $\sim 6 \times 10^4$ alpha particles per second with each alpha particle having an initial energy of 5.1 MeV.¹¹ Also shown in Figure 2 are holes 1 and 2. Hole 1 was drilled through the top flange and was connected to a steel tube of 0.635 cm in diameter which leads to the baratron pressure meter. Hole 2 in the chamber side is welded to a steel tube of 2.54 cm in diameter which serves as the gas inlet and outlet.

Two liquid nitrogen traps were used for gas purification in order to eliminate impurities, especially air and water vapor. Cajon connectors and a steel tubing with a diameter of 0.635 cm were used to connect the components of the gas system.

II. OTHER COMPONENTS

The voltage across the parallel plate electrodes was supplied by a Bertan high voltage power supply, Model 205A-20N (0-20 kV) with uncertainty better than 2%. The accuracy of the voltage measurement is not crucial in determining the W values.

Measurement of gas pressures is made with a Wallace and Tiernan pressure gauge Model FA145 (0-307 kPa with increment of 0.266 kPa). However, for very low gas mixture concentration ($\leq 1\%$), the partial pressure of the low-concentration component is read with a MKS Baratron gauge which is connected to a MKS head (0-1.329 kPa) gauge Model 94H-10.

For the pumping down process, a water cooled diffusion pump is used besides the mechanical forepump to attain a vacuum pressure of less than 0.13×10^{-7} kPa. An ion gauge tube is used in conjunction with an ionization gas control unit with a range of 0.13×10^{-4} kPa to 0.13×10^{-9} kPa to read pressure of less than 0.13×10^{-4} kPa.

III. MEASURING CIRCUIT

A block diagram of the experimental apparatus employed for measuring the W values of the gases under investigation is shown in Figure 3. The principle of the measurement circuit has been outlined by Bortner et al.¹² However, an automatic feedback control system was incorporated into the measurement circuit by Nakanishi et al.¹¹ to improve the accuracy of the measurement.

Ionization produced by the energy decay of alpha particles in the gas enclosed by the collecting electrodes induces a current in the collector circuit. When the switch is closed to position 2 (see Figure 3), the induced current of electrons and ions in the collector circuit will flow into a high quality (low loss) capacitor.

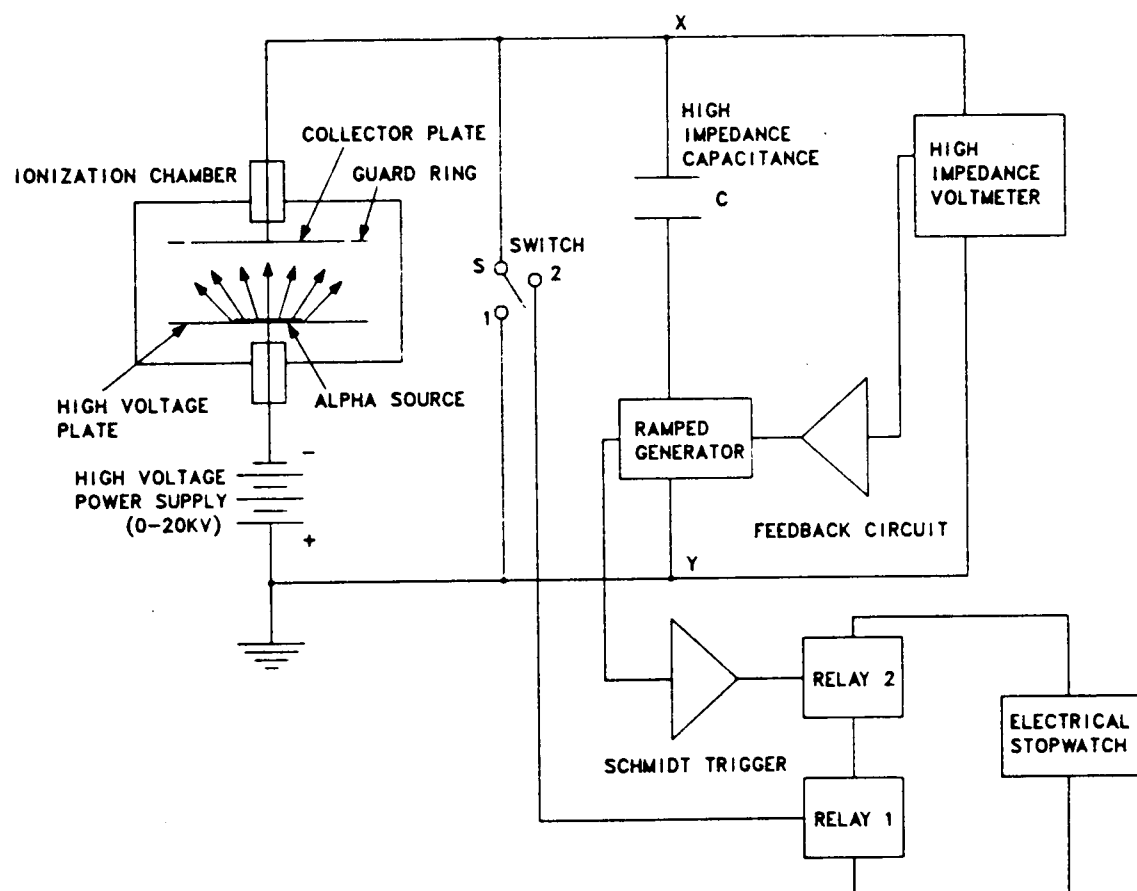


Figure 3. A schematic diagram of the apparatus for measurement of the W values.

Simultaneously an electrical stopwatch starts counting time by closing relay 1. The voltage rise across the capacitor is compensated by applying an equal voltage to the other side of the capacitor. This is done by using a ramped generator as a source for bucking the voltage to the capacitor. A very high impedance voltmeter (Keithley 614 electrometer) with a drain current negligible compared to the current in the collector circuit is used to monitor the potential between X and Y in Figure 3. The output of the voltmeter is fed through a feedback circuit to control the voltage of the ramped generator. When the voltage of the ramped generator reaches an arbitrary fixed value¹¹ (1.824 volts, calculated from the circuit design), which is the threshold of the Schmidt trigger circuit, the electrical stopwatch is stopped by the signal from the Schmidt trigger circuit (i.e., relay 2 is opened). To perform subsequent measurements, the switch is thrown to position 1 (see Figure 3) to discharge the capacitor, and then to position 2 to start a new measurement.

CHAPTER III

EXPERIMENTAL PROCEDURE

I. DETERMINATION OF W

The energy required to produce an electron-ion pair, W , is derived as follows (see Ref. 11). The charge collected at the capacitor is expressed as the product of the capacitance C and the voltage across the capacitor V .

$$Q = C V . \quad (3.1)$$

The capacitor charge rate of change is

$$\frac{dQ}{dt} = C \frac{dV}{dt} \quad (3.2)$$

where $\frac{dV}{dt}$ is the voltage rate of change across the capacitor. The number n of electron-ion pairs produced per second is given by

$$n = \frac{1}{e} \cdot \frac{dQ}{dt}$$

$$n = \frac{C}{e} \cdot \frac{dV}{dt} \quad (3.3)$$

where e is the electron charge. The total energy deposited in the gas per second by the alpha particles is given by

$$E_0 = \epsilon_0 N_0 \quad (3.4)$$

where ϵ_0 is the energy of each alpha particle (5.1 MeV), and N_0 is the number of alpha particles (6×10^4 particles $\cdot \text{sec}^{-1}$)¹¹ which are completely stopped in the gas per second. The average energy required to produce an electron-ion pair W , is equal to

$$W = \frac{E_0}{n} = \frac{\epsilon_0 N_0}{n}$$

$$W = e \frac{\epsilon_0 N_0}{C} \cdot \frac{\Delta t}{\Delta V} \quad (3.5)$$

where C , ϵ_0 , e and N_0 are constant during the experiment, and Δt is the time required to charge the capacitor to a fixed voltage value ΔV (1.824 volts), which was defined at the end of Chapter II as the threshold of the Schmidt trigger circuit.

Absolute W measurement using Eq. (3.5) is a complicated process due to the lack of knowledge of the exact number N_0 (i.e., number of α -particles completely stopped in the gas enclosed by the collecting electrodes). In practice, W of argon is well established.¹⁰ Argon is used as the standard reference gas in our experiment, then the unknown W value for gas or gas mixtures under investigation can be determined by measuring Δt for argon and that of the gas under investigation. Thus the unknown W value for gas or gas mixture is found from

$$\frac{W_{\text{unknown}}}{W_{\text{AR}}} = \frac{\Delta t_{\text{unknown}}}{\Delta t_{\text{AR}}} \quad (3.6)$$

The accuracy of the technique is checked by measuring Δt for both argon and nitrogen. The ratio $\frac{\Delta t_{AR}}{\Delta t_{N_2}}$ is found to be 0.723, which compares well with the value 0.725 of the ratio $\frac{W_{AR}}{W_{N_2}}$ obtained from the literature.¹⁰ In the process of measuring W it is necessary that the alpha particles are completely stopped by the various gases within the drift gap (i.e., the gap between the electrodes). Since each gas has different stopping power, measurement of W values are made at a pressure high enough to cause the alpha particles to expend their energies within the drift gap.

II. MEASUREMENT PROCEDURE

Measurement of W values were made at a pressure (≥ 67.33 kPa) which is sufficient to stop completely the alpha particles within the drift gap. If the alpha particles were to travel beyond the electric field, some of the electron-ion pairs produced would not be collected, and this would tend to increase Δt for the gas under investigation. The "critical" pressure needed to completely stop the alpha particles within the interelectrode distance was found as follows: The chamber was filled with the gas to be investigated to a pressure of about 67.33 kPa. A constant voltage (5 kV) was applied to the chamber, Δt was measured as a function of the pressure, which was slowly decreased until there was an increase in Δt . The pressure at which Δt started to increase was defined as the critical pressure.

The W value for each gas or gas mixture studied was measured at ambient temperature ($\sim 300^\circ\text{K}$). The W value of gases or gas mixtures

was determined by measuring Δt as a function of the total pressure P (ranged from 34 to 303 KPa) and applied voltage (ranged from 1 to 20 kV). A minimum of eight measurements were taken to determine Δt (by averaging the eight readings) for each pressure and applied voltage.

In order to eliminate impurities, especially water vapor and air, all gases were passed through a liquid nitrogen trap. The gases were introduced into the liquid nitrogen trap and pumped with the forepump or the diffusion pump depending on the physical constants of gases (i.e., the gas vapor pressure at liquid nitrogen temperature) under consideration to a pressure of less than 0.93×10^{-7} kPa. Prior to introducing the gas into the ionization chamber, the chamber and the gas handling system were pumped down to a pressure of less than 0.13×10^{-7} kPa.

Two gas mixing procedures were employed in this experiment to insure accurate concentration. When making mixtures between 10% and 80%, the low concentration gas component was first introduced to the chamber followed by the other gas component. The gas mixture was allowed to mix for several minutes before any measurement was taken. For concentrations less than 10% in SF_6 the following procedure was used: The pressure of the original mixture was reduced by a factor of (new percentage/old percentage) by allowing the forepump to slowly remove the necessary volume of gas. Then pure SF_6 is added to bring the total pressure of the gas mixture back to the original value. For example, suppose that a 10% original mixture

existed in the chamber, then a new concentration of 5% could be achieved by reducing the pressure of the original mixture by a factor of 5/10. Since the concentration error tends to increase due to the accumulative human error as the number of successive mixtures is increased, this process was not repeated more than five times before the gas was completely discarded and a new mixture made. At lower concentrations the necessary time for the gas mixture to reach equilibrium was increased to more than 30 minutes.

III. SELECTION OF GASES

Two major factors were considered in selecting additive gases to be used in SF_6 . One was the requirement for all gases to be in the gas phase at standard temperature and pressure. The other was their ionization potential. The ionization potentials of the gases were to be within certain ranges determined by the energy of the known excited states of SF_6 . The quoted purity and manufacturer of the gases are: Ar—99.999% (Matheson); C_2F_6 —99.6% (Matheson); C_2H_2 —99.6% (Matheson); cis 2- C_4H_8 —95% (Matheson); N_2 —99.999% (Matheson); SF_6 —99.8% (Air Product). All gases were passed through a liquid nitrogen trap for further purification.

CHAPTER IV

EXPERIMENTAL RESULTS

The W values for pure gases and gas mixtures studied were measured as a function of the total pressure and the applied voltage. These measurements were made several times with different collector voltages in an attempt to insure saturation (complete collection of ions and electrons by the collector electrode with no recombination). However, complete saturation was never achieved, since the voltages that could be applied to the chamber could not be high enough to collect all the electron-ion pairs produced in the chamber by the energy decay of alpha particles in the gas. Consequently, to determine a W value which is independent of the applied voltage and pressure, the inverse of the measured W values (W^{-1}) was plotted as a function of the inverse of the collector voltage ($1/V$). The W values for unary gases and binary gas mixtures were determined by using a nonlinear least-squares fitting routine¹³ to extrapolate W^{-1} versus V^{-1} as $V^{-1} \rightarrow 0$ (i.e., $E/N \rightarrow \infty$), where E is the applied electric field and N is the density of the gas (molecules/cm³).

The Appendix lists the measured W values as a function of the total pressure, and the applied voltages for all the gases studied in this experiment. Since the W value of pure argon is well known,¹⁰ the unknown W values for pure gases and gas mixtures were found at each total pressure and applied voltage. From (see p. 15)

$$W_{\text{unknown}} = \frac{\Delta t_{\text{unknown}}}{\Delta t_{\text{Argon}}} \cdot W_{\text{Ar}}$$

where $\Delta t_{\text{unknown}}$ is the measured time for the capacitor to reach the fixed value of 1.824V and Δt_{Argon} is the calculated value found by using a nonlinear least-squares fitting routine¹³ to extrapolate the value of Δt_{Ar} as $V^{-1} \rightarrow 0$. See Figure 4. Table I (p. 5) lists the values of Δt_{AR} as a function of the applied voltage for a pressure of 101 kPa. Also presented in Table I is the extrapolated value of Δt_{Argon} as $V^{-1} \rightarrow 0$.

I. UNARY GASES

The W values for pure gases studied in this experiment are presented in this section. Table II lists the ionization potentials, the measured W values and the W values as given by other sources. As can be seen from Table II, the measured W values for the unary gases studied compare well with those of other sources.¹⁰ Figures 5, 6 and 7 illustrate the plotting and extrapolating of W^{-1} versus V^{-1} as $V^{-1} \rightarrow 0$ of C_2F_6 , C_2H_2 and cis-2- C_4H_8 , respectively, for a total pressure of 101 kPa.

The W value for nitrogen was measured in the pressure range $101 < P_T < 303$ kPa for applied voltages up to 6 kV. These data have been plotted as W^{-1} vs. V^{-1} in Figure 8. Similar measurements were carried out for pure SF_6 in the pressure range $34 \leq P_T \leq 303$ kPa for applied voltages up to 20 kV. Figure 9 presents the plotting of W^{-1} vs. V^{-1} for pure SF_6 as $V^{-1} \rightarrow 0$, where the total gas pressure

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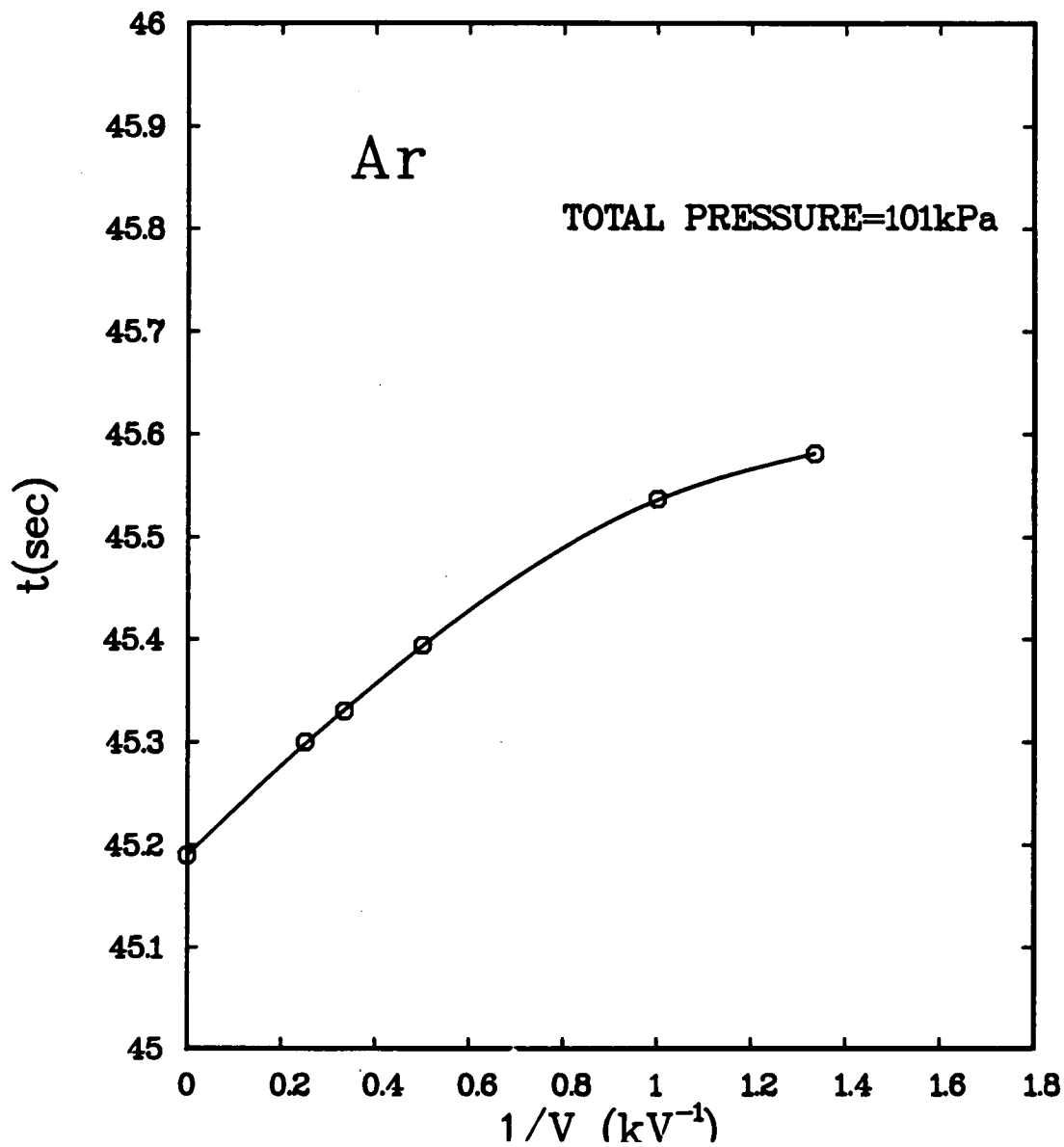


Figure 4. Plot of t (Δt_{AR}) for pure argon as a function of $1/V$ for a total gas pressure of 101 kPa.

TABLE II
W VALUES AND IONIZATION POTENTIALS FOR ALL GASES USED

Gas	Ionization Potential (in eV)	W Value (in eV/ip)	
		Present	Other
Sulfur Hexafluoride	15.7 ^a	35.45	34.0 ± 0.4 ^b *
Nitrogen	15.59 ^c	36.50	36.39 ^c
Acetylene	11.40 ^c	27.62	27.5 ^c
Cis-butene II	9.24 ^c	26.13	26.29 ^c
C ₂ F ₆	14.6 ^a	34.40	34.5 ^d ; 34.7 ^e

^aR. D. Levin and S. G. Lias, "Ionization Potential and Appearance Potential Measurements, 1971-1981" (U.S. Department of Commerce, NBS, 1982), NSRDS-NBS-71.

^bI. Lopes, H. Hilmert, and W. F. Schmidt, J. Phys. D: Appl. Phys. 19, 107 (1986).

^cL. G. Christophorou, Atomic and Molecular Radiation Physics (Wiley-Interscience, New York, 1971), Chap. 2.

^dG. F. Reinking, L. G. Christophorou, and S. R. Hunter, J. Appl. Phys. 60, No. 2 (1986).

^eK. Nakanishi and L. G. Christophorou, J. Appl. Phys. 58, No. 2, 633 (1985).

*The value (34.0 ± 0.4) reported by I. Lopes, H. Hilmert, and W. F. Schmidt is the measured W value using γ rays as a source of ionization. W_{α}/W_{γ} varies between 1.00 to 1.15 for a wide range of molecules (see Ref. c above).

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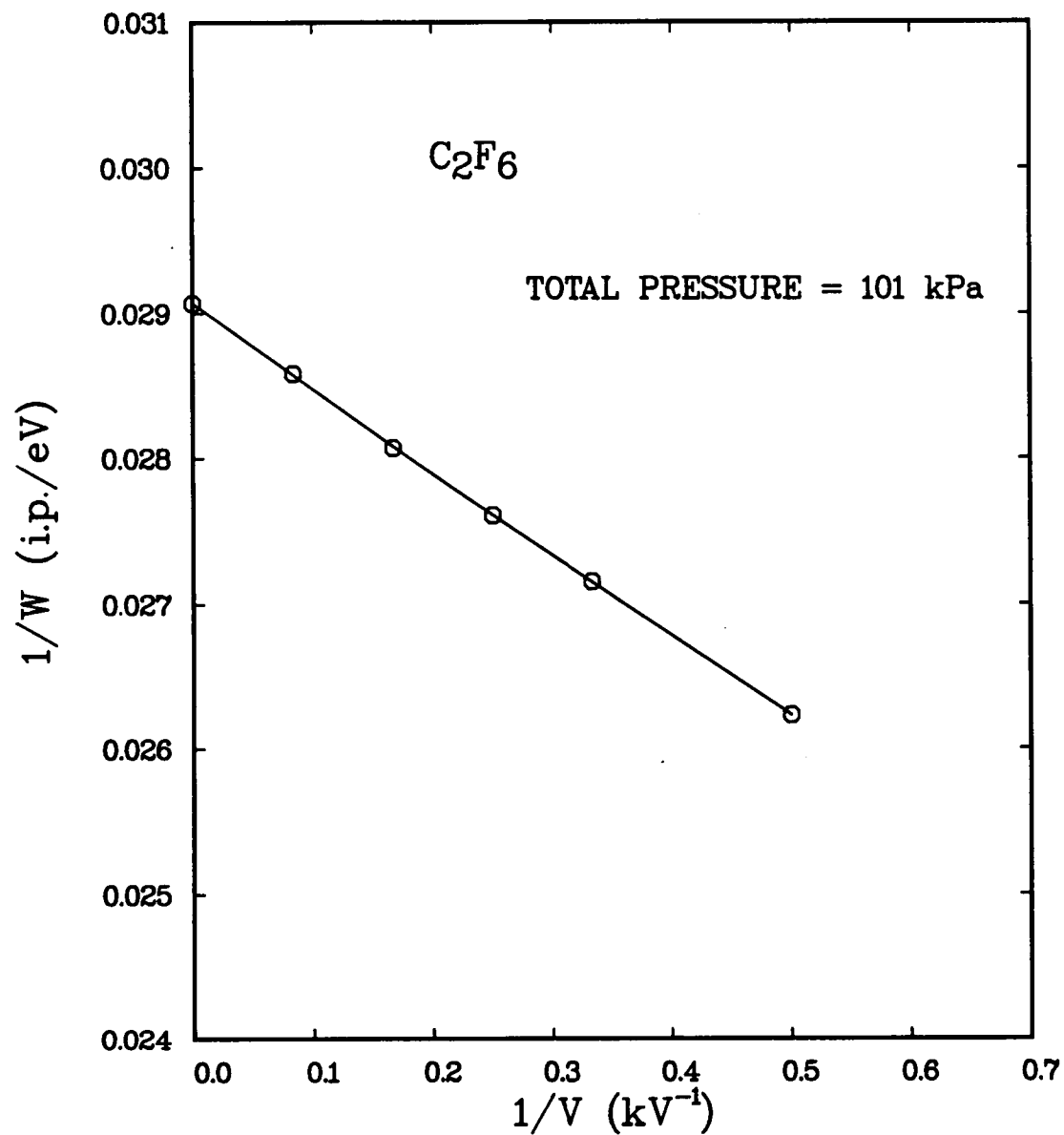


Figure 5. Plot of $1/W$ for pure C_2F_6 as a function of $1/V$ for a total gas pressure of 101 kPa.

ORNL-DWG. 87-6927

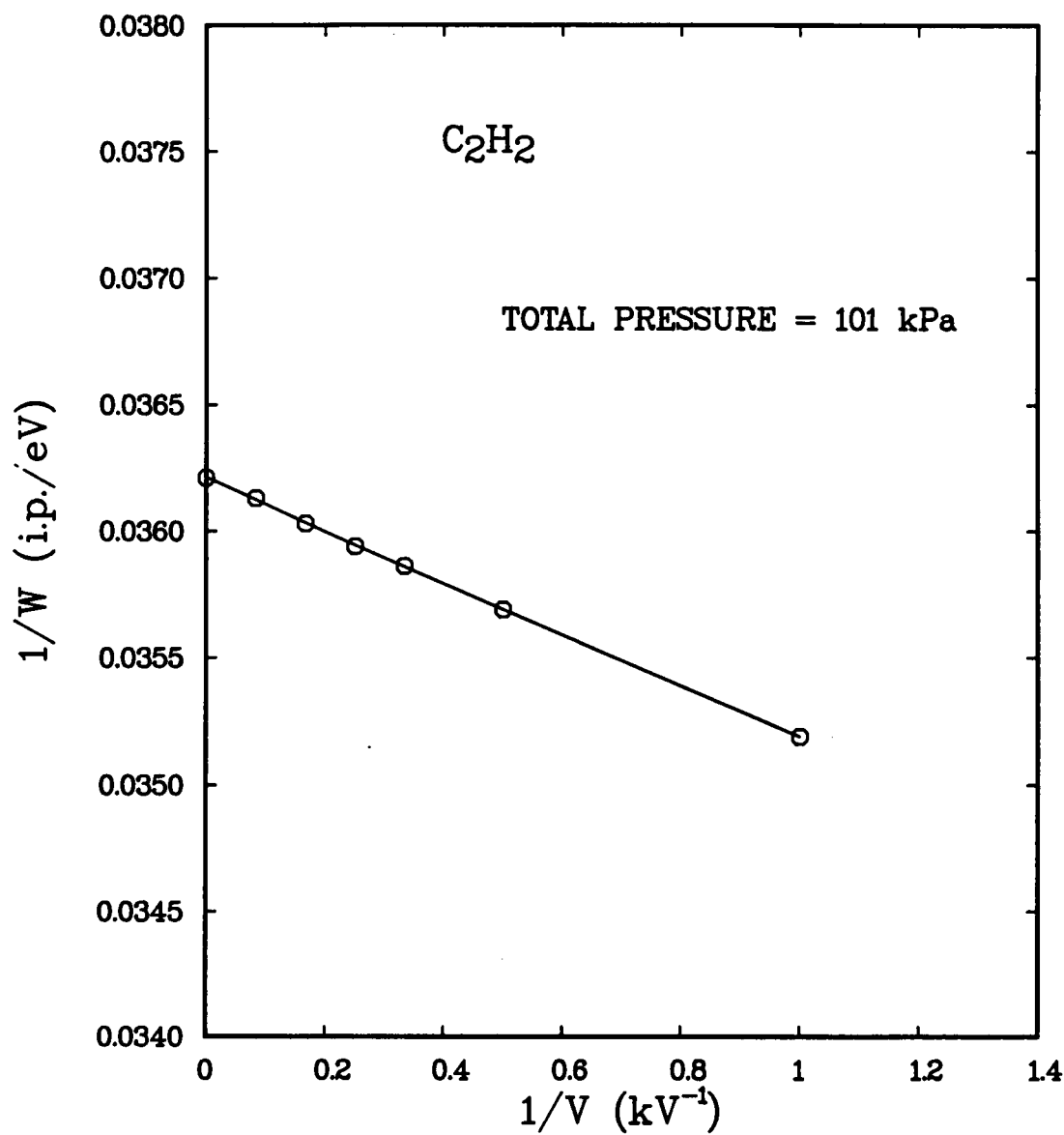


Figure 6. Plot of $1/W$ for pure C_2H_2 as a function of $1/V$ for a total gas pressure of 101 kPa.

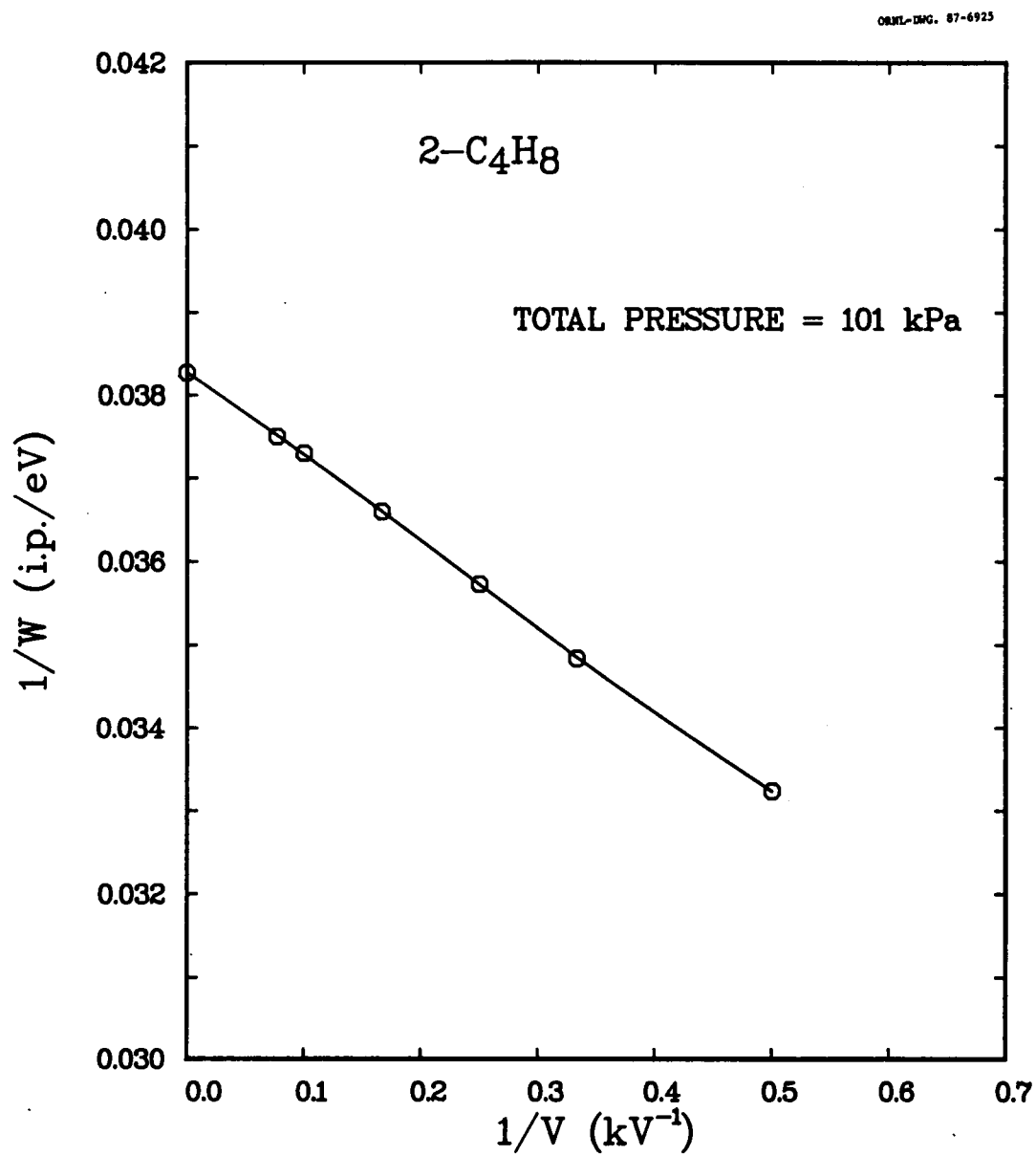


Figure 7. Plot of $1/W$ for pure $2\text{-C}_4\text{H}_8$ as a function of $1/V$ for a total gas pressure of 101 kPa.

ORNL-DWG. 87-6926

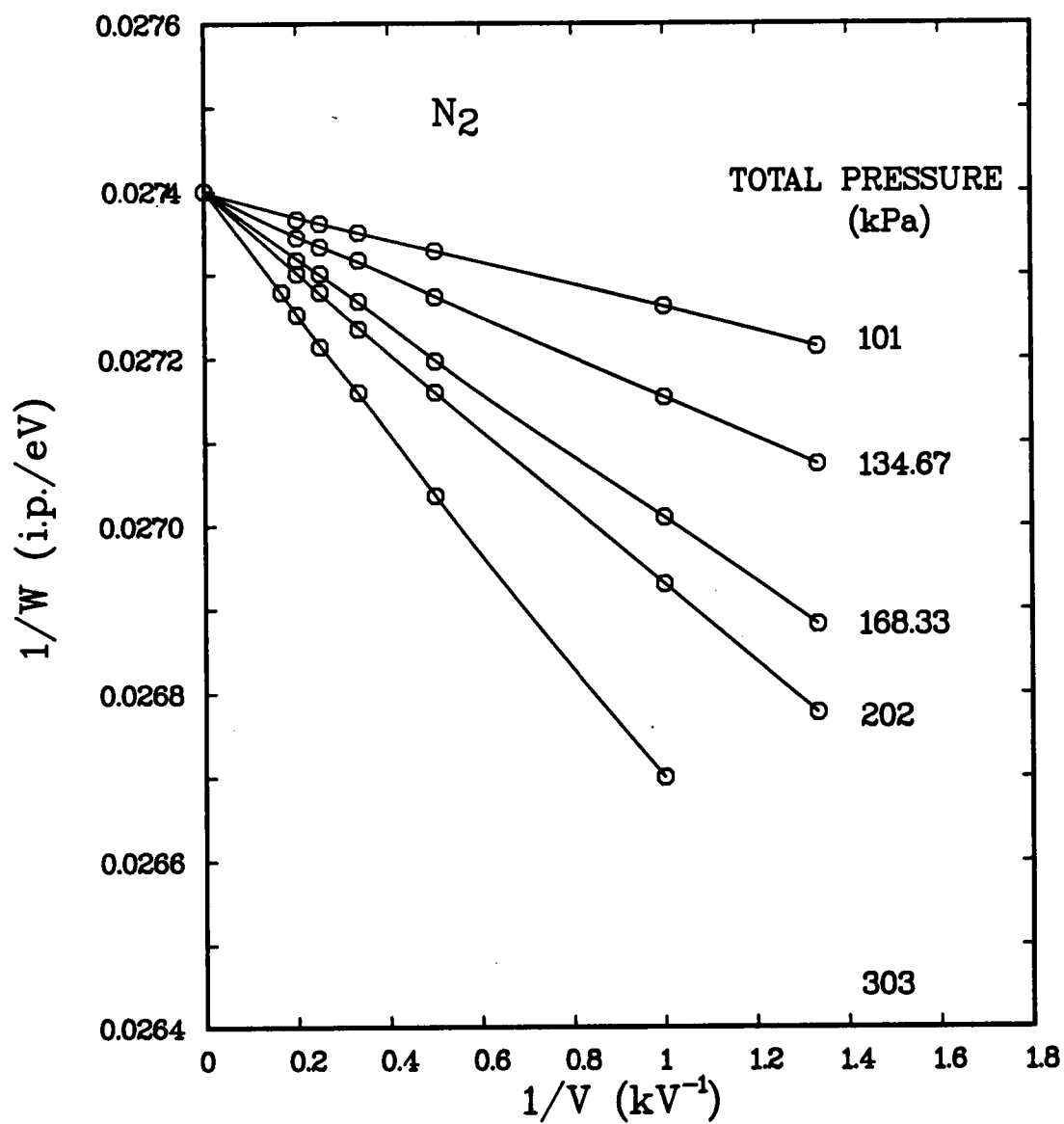


Figure 8. Plot of $1/W$ for pure N_2 as a function of $1/V$ for a number of gas pressures.

ORNL-DWG. 87-6919

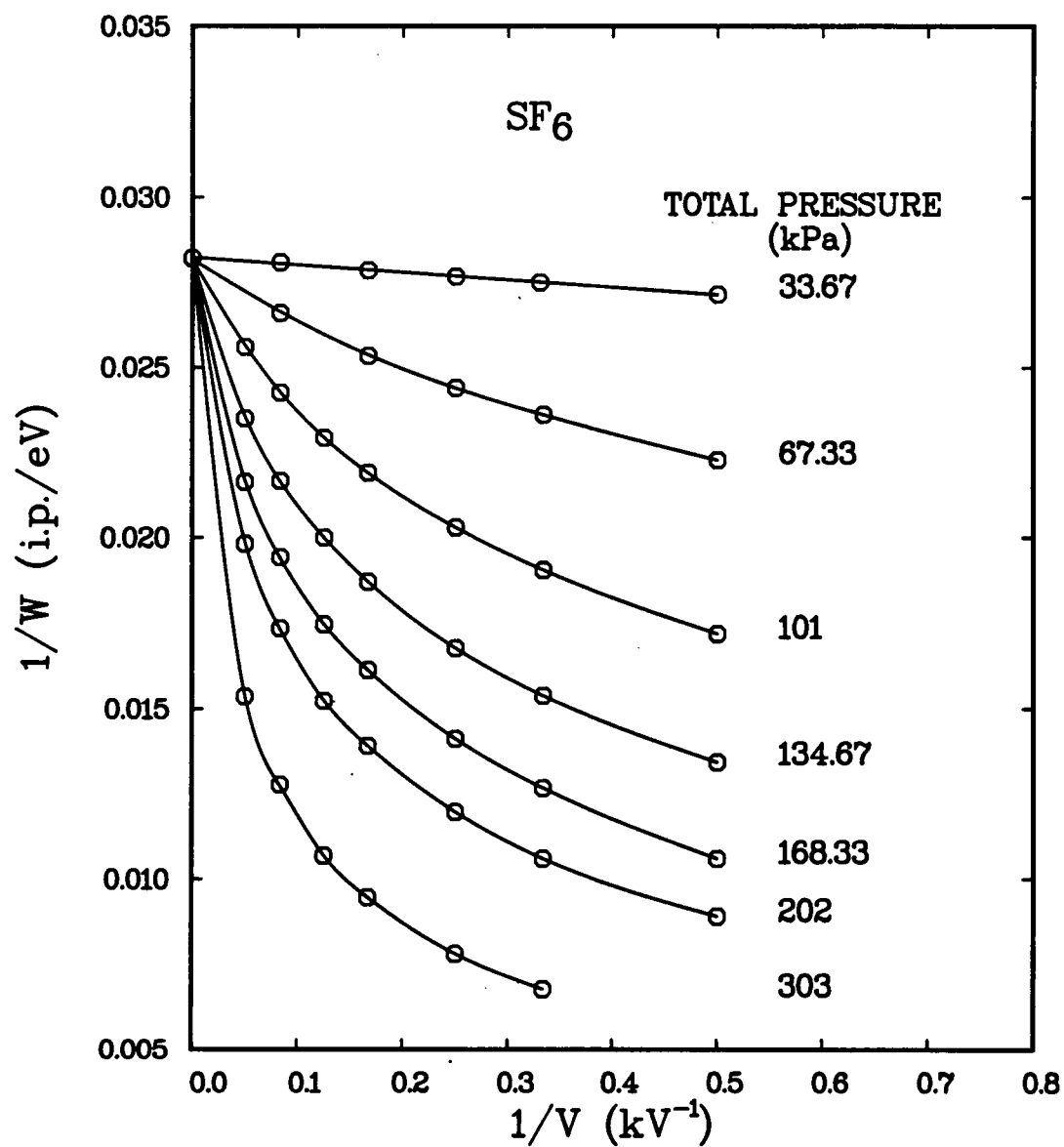


Figure 9. Plot of $1/W$ for pure SF_6 as a function of $1/V$ for a number of gas pressures.

ranged from 34 to 303 kPa. Also shown in Figure 10 is the plotting of W vs. P for a set of six constant applied voltages. Figure 11 illustrates the plotting of the W values as a function of the density reduced electric field (i.e., E/N). As can be seen from Figures 9, 10 and 11, complete saturation (i.e., complete collection of electron-ion pairs produced in the chamber by the decay of alpha particles with no recombination) was never achieved, even at the highest field strength obtainable. This phenomenon is attributed to the large cross section for electron attachment to SF_6 producing negative ions (i.e., SF_6^-). The resultant negative ions have large negative ion-positive ion recombination coefficients (much larger than the electron-positive ion recombination coefficient at a given E/N value), and thus large fields are required to reduce the recombination coefficient to insignificant levels.¹¹ Also, as can be seen from Figure 9, the W^{-1} values will extrapolate nicely to a single value, when $V^{-1} \rightarrow 0$. This is evident in Figure 10 where the W values are plotted as a function of the pressure. The rate at which the W values increase is considerably lower as the applied voltage increases.

II. BINARY GAS MIXTURES

The W values for binary gas mixtures were again determined from W^{-1} vs. V^{-1} plots as in the case of the unary gases for a total gas pressure of 101 kPa. Tables III, IV and V list the calculated W values of the binary gas mixtures SF_6/C_2F_6 , SF_6/C_2H_2 and $SF_6/cis\ 2-C_4H_8$, respectively, as the additive concentrations of C_2F_6 , C_2H_2 and

ORNL-DWG. 87-6921

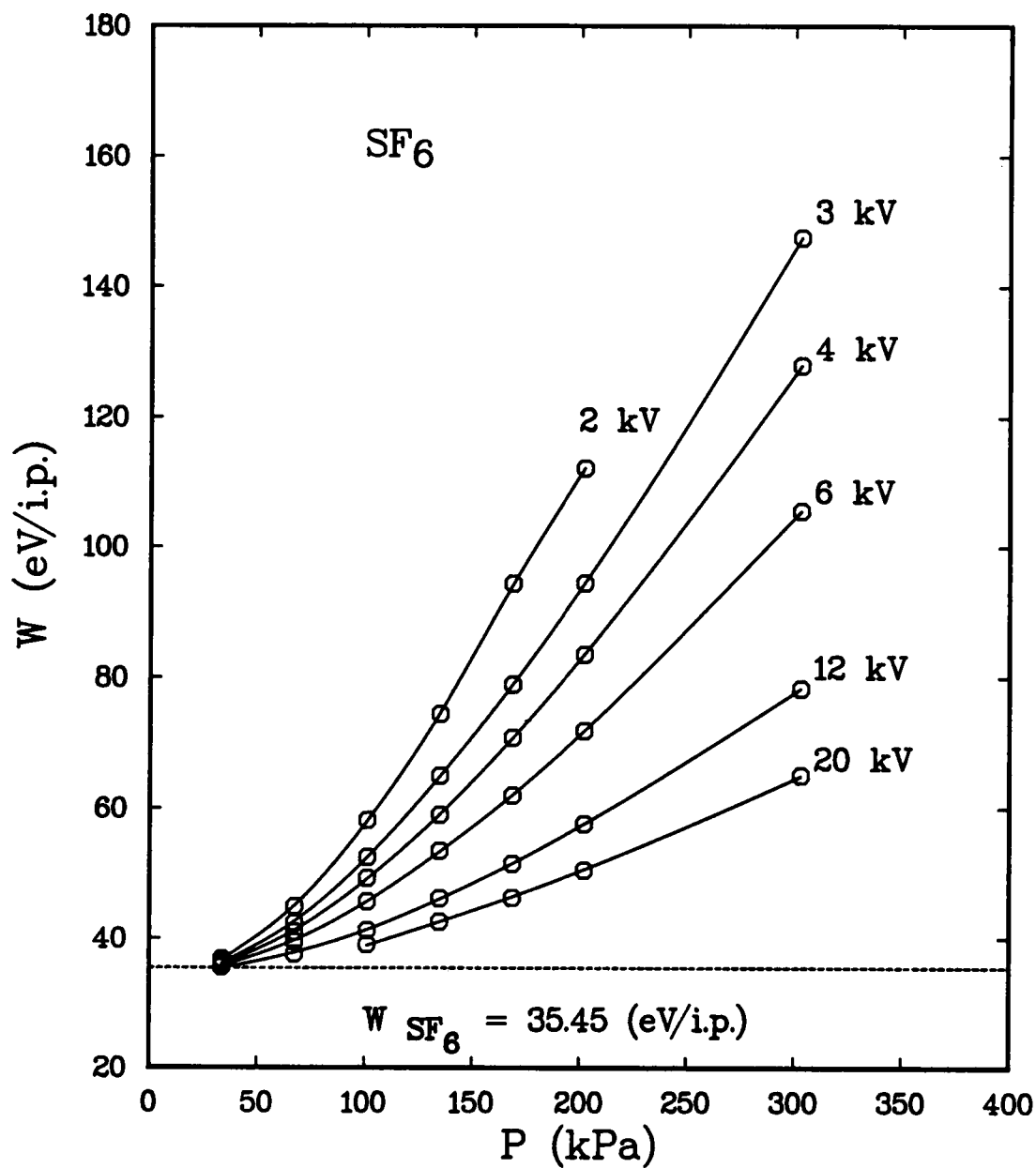


Figure 10. Plot of W for pure SF_6 as a function of the pressure for a set of six constant applied voltages.

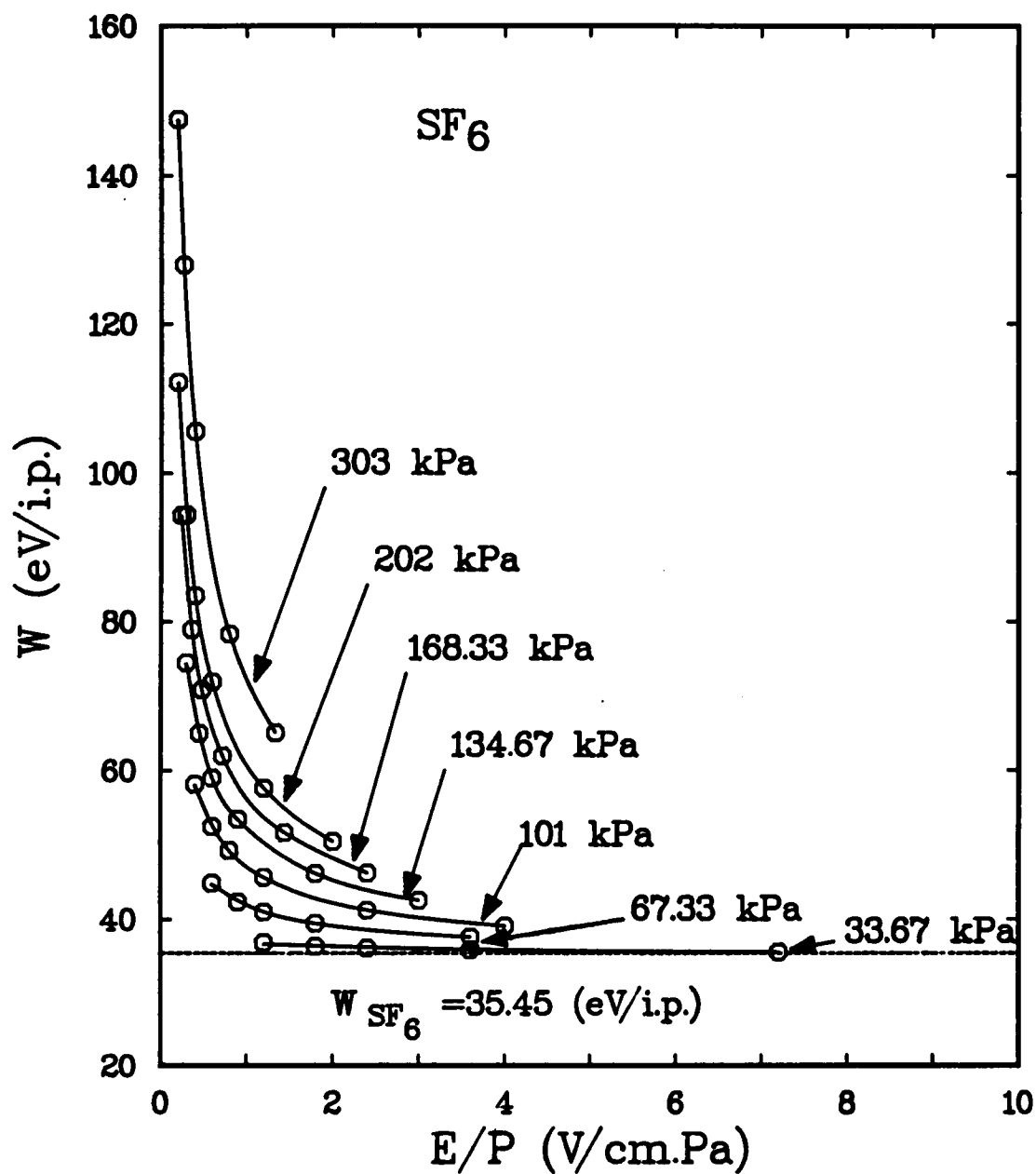


Figure 11. Plot of W for pure SF_6 as a function of the density-reduced electric field (E/N) for a number of gas pressures.

TABLE III
VALUES OF W_m FOR MIXTURES OF SF_6/C_2F_6

Percent of C_2F_6	W_m (eV/ip)
100.00	34.40
80.00	34.96
60.00	35.19
40.00	35.36
20.00	35.53
10.00	35.52
5.00	35.65
2.00	35.42
1.00	35.42
0.75	35.48
0.50	35.42
0.25	35.48
0.00	35.45

TABLE IV
VALUES OF W_m FOR MIXTURES OF SF_6/C_2H_2

Percent of C_2H_2	W_m (eV/ip)
100.00	27.62
80.00	29.26
60.00	30.70
40.00	32.10
20.00	33.55
10.00	34.38
5.00	34.90
2.00	35.22
1.00	35.38
0.75	35.43
0.50	35.47
0.25	35.47
0.00	35.45

TABLE V
VALUES OF W_m FOR MIXTURES OF SF_6 /cis 2- C_4H_8

Percent of cis 2- C_4H_8	W_m (eV/ip)
100.00	26.13
80.00	28.04
60.00	29.40
40.00	30.70
20.00	32.29
10.00	33.25
5.00	34.16
2.00	34.85
1.00	35.11
0.75	35.19
0.50	35.35
0.25	35.27
0.00	35.45

cis 2-C H were varied from 0% to 100% of the total gas pressure. Figures 12, 13 and 14 represent the calculated W values of the binary gas mixtures $\text{SF}_6/\text{C}_2\text{F}_6$, $\text{SF}_6/\text{C}_2\text{H}_2$ and $\text{SF}_6/\text{cis 2-C}_4\text{H}_8$, respectively, as their component ratios were varied from 0% to 100%. Figure 15 represents the plotting of W^{-1} as a function of V^{-1} for the binary gas mixture SF_6/N_2 as the total gas pressure was varied from 67.33 kPa to 303 kPa.

None of the binary gas mixtures showed a "Jesse effect"¹⁰ (i.e., an abrupt decrease in the W value of the gas mixture as a small amount of C_2H_2 and cis 2- C_4H_8 were added, respectively, to SF_6). However, there was an increase in ionization (i.e., decrease in W) in the gas mixtures $\text{SF}_6/\text{C}_2\text{H}_2$ and $\text{SF}_6/\text{cis 2-C}_4\text{H}_8$ as their component ratios were varied from 0% to 100%. This phenomenon is illustrated in Figures 13 and 14. The increase in ionization due to the collision of excited SF_6 molecules with C_2H_2 and cis 2- C_4H_8 is more pronounced as the ionization potential of the additive gas (Table II, p. 22) decreases. As illustrated in Figure 12, the observed decreases in ionization in the gas mixture as the ratio of $\text{C}_2\text{F}_6/\text{SF}_6$ increases are considered to be due to the quenching of the excited SF_6 molecules by C_2F_6 leading to the dissociation of the latter into neutral fragments.

ORNL-DMG. 87-6922

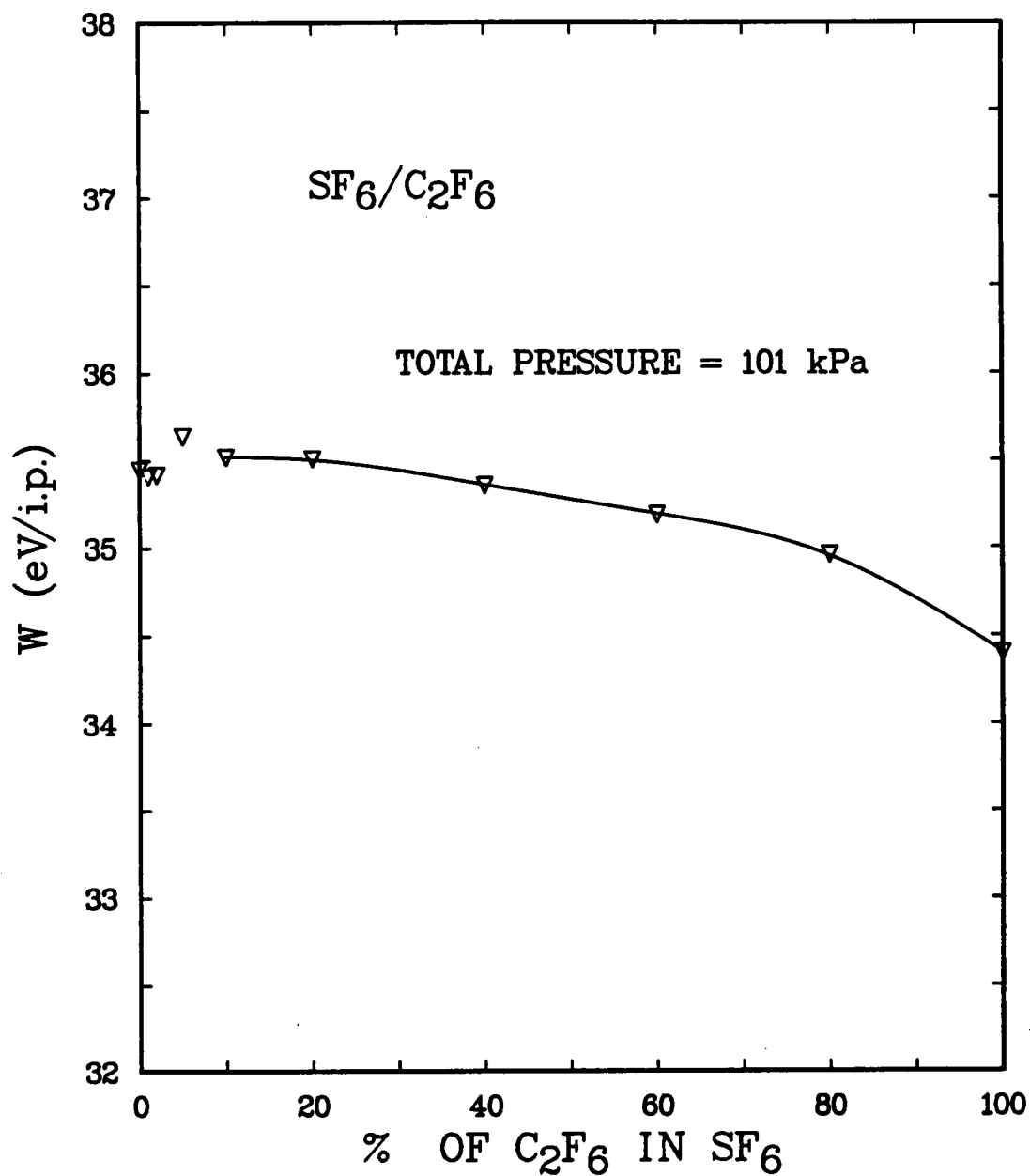


Figure 12. Experimental W values of $\text{SF}_6/\text{C}_2\text{F}_6$ gas mixtures as a function of the percentage of C_2F_6 in SF_6 .

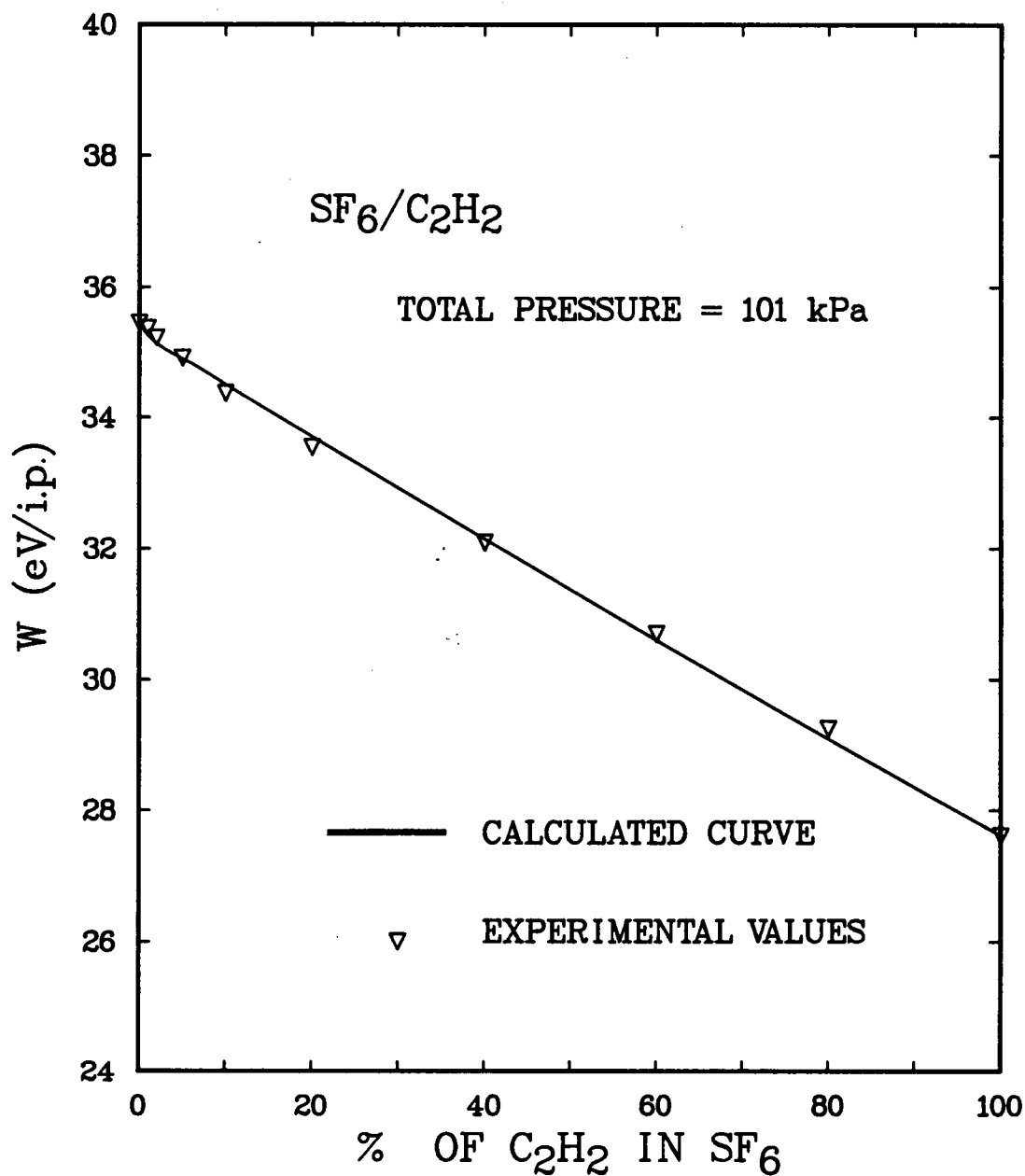


Figure 13. Experimental W values of SF_6/C_2H_2 gas mixtures as a function of the percentage of C_2H_2 in SF_6 . The symbols are the experimental values; the line is the calculated results using Eq. (5.11).

ORNL-DWG. 87-6924

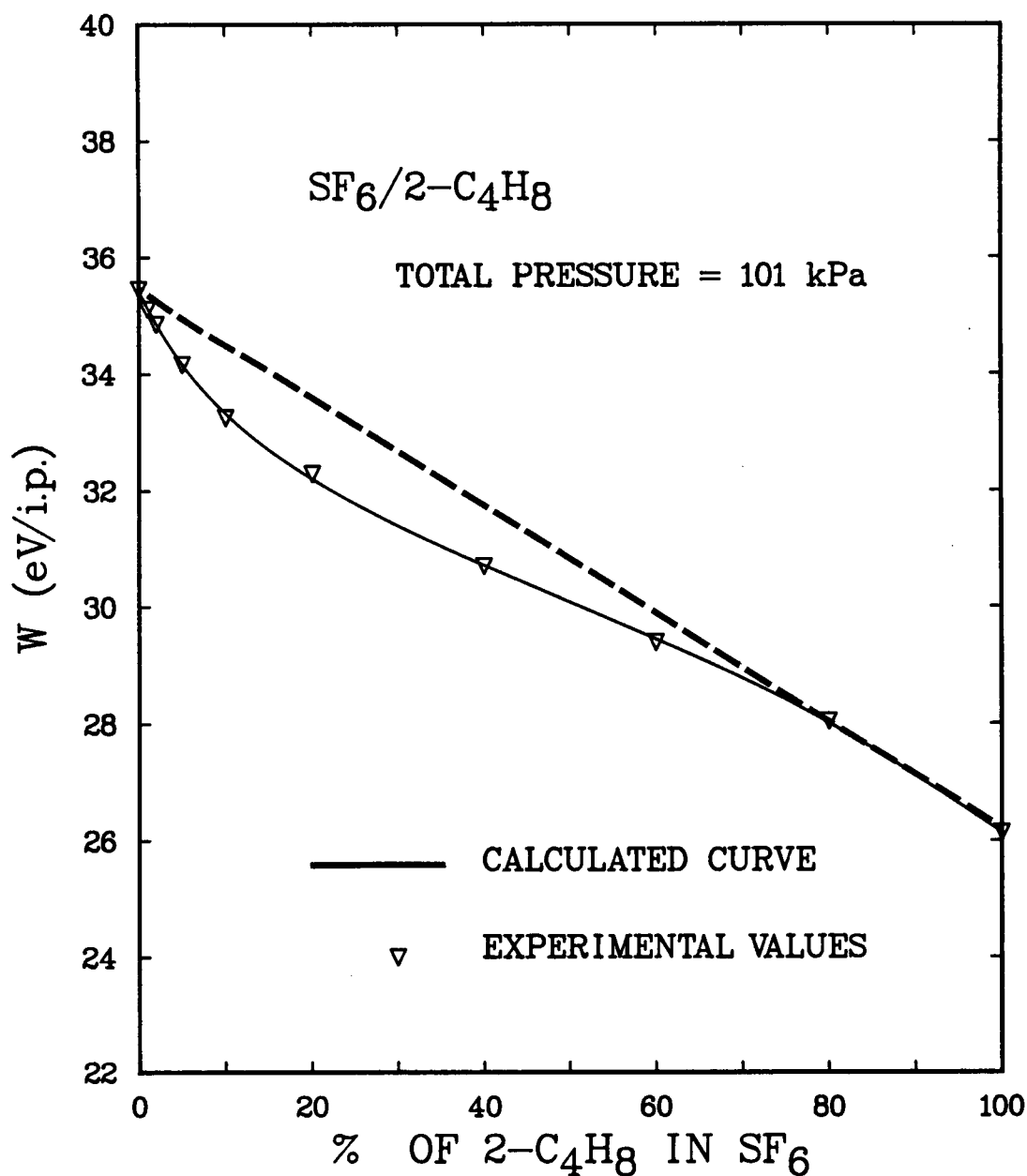


Figure 14. Experimental W values of SF₆/2-C₄H₈ gas mixtures as a function of the percentage of 2-C₄H₈ in SF₆. The symbols are the experimental values; the solid line is the calculated results using Eq. (5.20). The dashed line represents the W values calculated using the partial pressure weighted average values of SF and 2-C₄H₈ (i.e., the calculated W values using Eq. (5.11) when $a = 1$).

ORNL-DWG. 87-6920

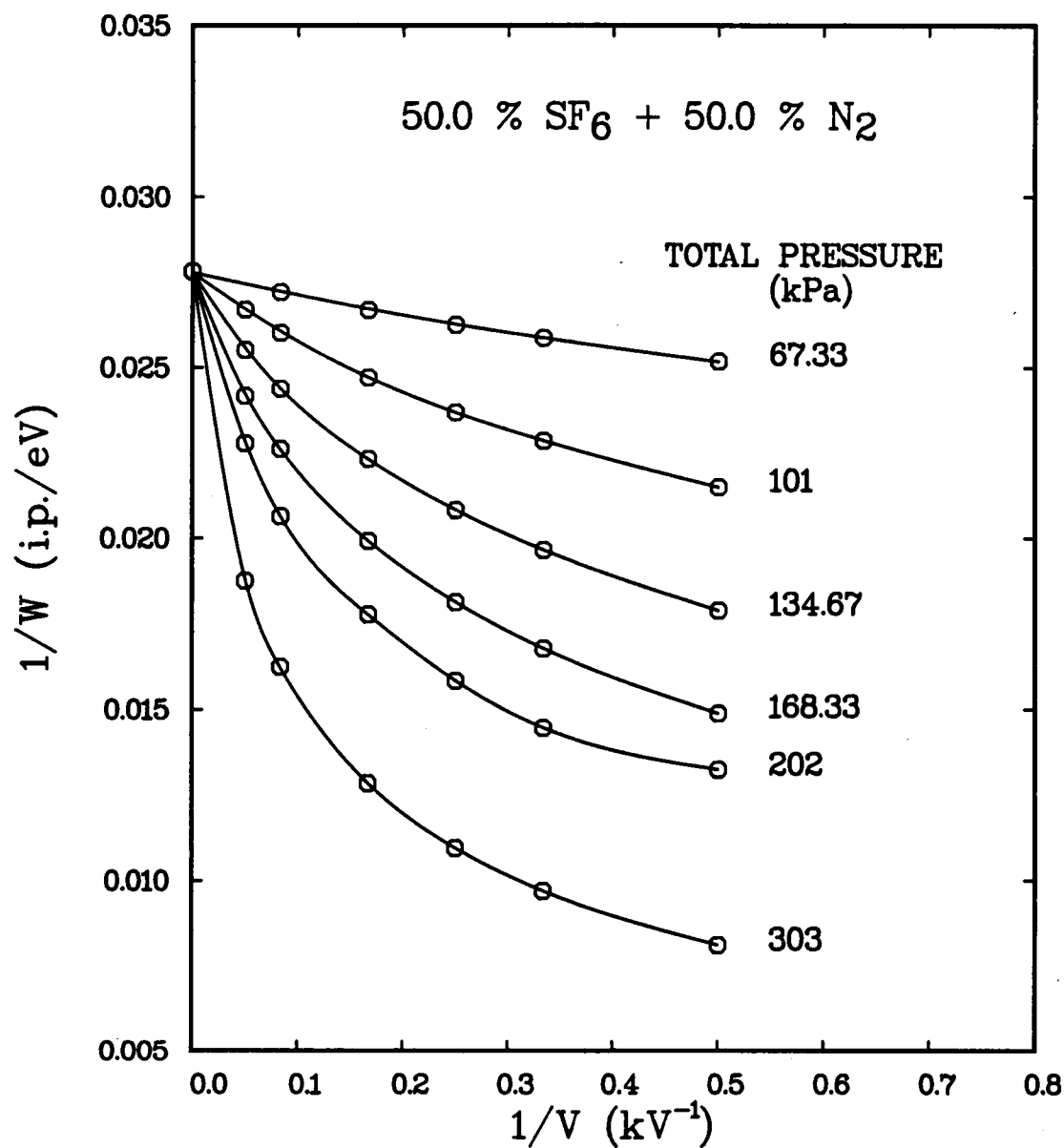


Figure 15. Plot of $1/W$ for 50% SF_6 + 50% N_2 as a function of $1/V$ for a number of gas pressures.

CHAPTER V

ANALYSIS OF BINARY GAS MIXTURES

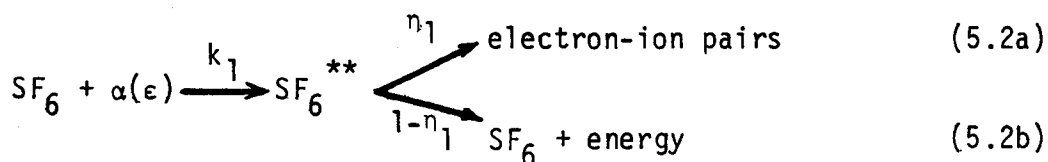
The W_m (W value for gas mixture) for which the "Jesse effect" is not appreciable lies between the extreme W values of the individual gases and varies smoothly from one extreme to the other as the binary gas component ratios are changed. For a large number of binary gas mixtures it has been found for alpha particles¹⁴ that W_m can be expressed as

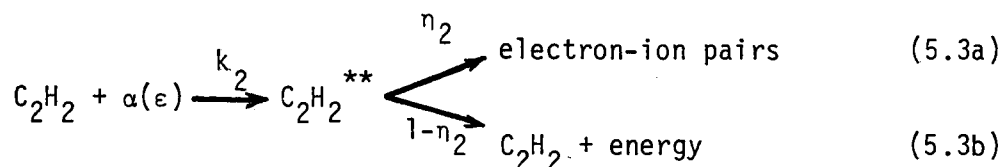
$$\frac{1}{W_m} = \left(\frac{1}{W_i} + \frac{1}{W_j} \right) \frac{P_i}{P_i + a_{ij} P_j} + \frac{1}{W_j} \quad (5.1)$$

where W_i and W_j , P_i and P_j are, respectively, the W values and the partial pressure of the i th and j th components, and a_{ij} is an empirical constant for a particular mixture.

I. SF_6/C_2H_2

This mixture shows practically no evidence of increased ionization due to a Penning ionization process. As in Ref. 11, then, we assume that the following reactions take place in the SF_6/C_2H_2 mixture.





(5.3b)

where $k_1 P_s$ and $k_2 P_c$ are the rates of energy transfer from the alpha particle $\alpha(\epsilon)$ of energy ϵ to SF_6 and C_2H_2 , P_s and P_c are the partial pressures of SF_6 and C_2H_2 , and η_1 and η_2 are the ionization probabilities of the superexcited SF_6^{**} and $\text{C}_2\text{H}_2^{**}$ molecules. The total energy deposited in the gas mixture per second, between the collecting electrodes by the alpha particles, is $\epsilon_0 N_0$, where ϵ_0 is the initial energy of each alpha particle, and N_0 is the initial number of alpha particles per second. Thus, from (5.2a) and (5.3a) the number n_{is} of SF_6 electron-ion pairs and n_{ic} of C_2H_2 electron-ion pairs produced per second is given by

$$n_{is} = \frac{k_1 P_s}{k_1 P_s + k_2 P_c} \eta_1 \frac{\epsilon_0 N_0}{I_s} \quad (5.4)$$

$$n_{ic} = \frac{k_2 P_c}{k_1 P_s + k_2 P_c} \eta_2 \frac{\epsilon_0 N_0}{I_c} \quad (5.5)$$

where I_s and I_c are the ionization potential energy of SF_6 and C_2H_2 . Since W is defined as $\frac{\epsilon_0 N_0}{n_i}$, then

$$W_{\text{SF}_6} = \epsilon_0 N_0 / \eta_1 \left(\frac{\epsilon_0 N_0}{I_s} \right) = \frac{I_s}{\eta_1} \quad (5.6)$$

and

$$W_{C_2H_2} = \frac{I_c}{n_2} \quad (5.7)$$

Substituting $\frac{1}{W_{SF_6}}$ and $\frac{1}{W_{C_2H_2}}$ for $\frac{n_1}{I_s}$ and $\frac{n_2}{I_c}$ in Eqs. (5.4) and (5.5), then

$$n_{is} = \frac{1}{W_{SF_6}} \frac{k_1 P_s \epsilon_0 N_0}{k_1 P_s + k_2 P_c} \quad (5.8)$$

$$n_{ic} = \frac{1}{W_{C_2H_2}} \frac{k_2 P_c \epsilon_0 N_0}{k_1 P_s + k_2 P_c} \quad (5.9)$$

The total number of electron-ion pairs produced per second in the gas mixture by the deposition of $\epsilon_0 N_0$ eV/s is $n_{is} + n_{ic}$, and thus the W_m for the gas mixture is

$$\frac{1}{W_m} = \frac{n_{is} + n_{ic}}{\epsilon_0 N_0} = \frac{1}{W_{SF_6}} \frac{k_1 P_s}{k_1 P_s + k_2 P_c} + \frac{1}{W_{C_2H_2}} \frac{k_2 P_c}{k_1 P_s + k_2 P_c} \quad (5.10)$$

or

$$\frac{1}{W_m} = \left(\frac{1}{W_{SF_6}} - \frac{1}{W_{C_2H_2}} \right) \frac{P_s}{P_s + a P_c} + \frac{1}{W_{C_2H_2}} \quad (5.11)$$

where $a = k_2/k_1$. Equation (5.11) has the same form as that of Eq. (5.1).¹⁴ In deriving Eq. (5.11), it was assumed that no excess energy was absorbed by C_2H_2 producing either electronically or vibrationally excited ions and neutral radicals.

A nonlinear least-squares fitting routine¹³ has been used to calculate the ratio k_2/k_1 for $\text{SF}_6/\text{C}_2\text{H}_2$ mixture using the experimental measurements given in Table VI. Also calculated was the standard deviation of the ratio and the coefficient of determination D^{13} defined as

$$D^2 = 1 - \frac{\sum_{i=1}^m R_i^2}{\sum_{i=1}^m (y_i - \bar{y})^2}$$

where R_i is the difference between the calculated and observed value y_i at the i th observation, and $\bar{y}$ is the mean of the observed values (i.e., $\bar{y} = \frac{1}{m} \sum_{i=1}^m y_i$). The coefficient of determination will always have a value between zero and one; the closer the value to one, the better the fit.

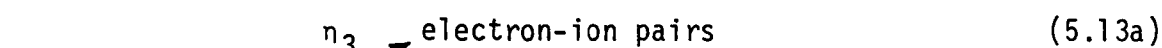
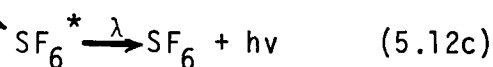
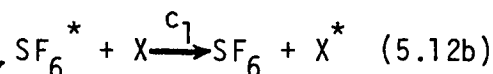
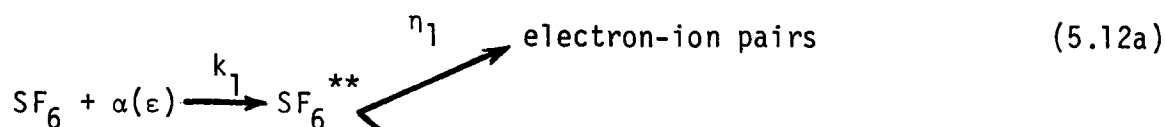
The calculated ratio k_2/k_1 is used in Eq. (5.11) to plot W_m as the component ratios of $\text{SF}_6/\text{C}_2\text{H}_2$ vary from 100% to 0.0%. This plotted curve is shown in Figure 13 (p. 36) along with the experimental values.

II. SF_6/X (= cis 2- C_4H_8)

This mixture shows no evidence of a Penning effect; however, there was an increase in the total ionization for the mixtures compared to the partial pressure weighted average values of the separate component. We then assume the following processes take place to account for the extra source of ionization.

TABLE VI
THE PARAMETERS CALCULATED IN A NONLINEAR LEAST SQUARES FIT
TO THE EXPERIMENTAL DATA IN THE BINARY GAS MIXTURE

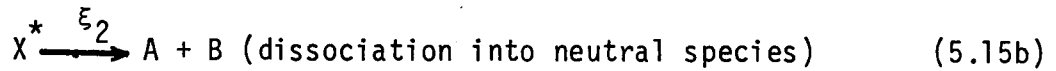
C_2H_2/SF_6	
k_2/k_1	0.82 ± 0.038
Coefficient of determination	0.9973
$2-C_4H_8/SF_6$	
k_3/k_1	0.4 ± 0.047
λ/c_1	0.17 ± 0.036
α	0.0035 ± 0.000384
Coefficient of determination	0.9996



where c_1 is the rate constant for the reaction (5.12b), η_1 and η_3 are the ionization probabilities of SF_6 and X , and λ is the apparent rate for the radiative decay of SF_6 . The number of excited SF_6 molecules is

$$n_{es} = \frac{k_1 P_s}{k_1 P_s + k_3 P_x} (1 - \eta_1) \frac{\epsilon_0 N_0}{\epsilon_s} \quad (5.14)$$

where $k_1 P_s$ and $k_3 P_x$ are the rate at which the energy is transferred from the alpha particle of energy ϵ to SF_6 and X , respectively, and ϵ_s is the average excitation energy of SF_6 . The increase in ionization is accounted for by the excited impurity (X^*) in process (5.12b) which decays as follows:



where ξ_1 , ξ_2 and ξ_3 are the probabilities for the processes (5.15a), (5.15b) and (5.15c), respectively. The number, n'_{ix} , of ion pairs produced by processes (5.12b) and (5.15a) can be expressed as

$$n'_{ix} = \xi_1 \frac{k_1^P s}{k_1^P s + k_3^P x} (1 - \eta_1) \frac{\epsilon_0 N_0}{\epsilon_s} \frac{c_1^P x}{c_1^P x + \lambda} \quad (5.16)$$

Then, the total number of ion pairs produced per second as a result of the energy deposition of $\epsilon_0 N_0$ by the alpha particles in SF_6/X gas mixture per second is

$$n_i = n_{is} + n_{ix} + n'_{ix} \quad (5.17)$$

$$n_i = \frac{1}{W_{SF_6}} \frac{k_1^P s}{k_1^P s + k_3^P x} \epsilon_0 N_0 + \frac{1}{W_x} \frac{k_3^P x}{k_1^P s + k_3^P x} \epsilon_0 N_0 + \frac{\xi_1 (1 - \eta_1) \epsilon_0 N_0}{\epsilon_s} \frac{k_1^P s}{k_1^P s + k_3^P x} \frac{c_1^P x}{c_1^P x + \lambda} \quad (5.18)$$

Thus the W_m for the SF_6/X gas mixture is

$$\frac{1}{W_m} = \frac{n_{is} + n_{ix} + n'_{ix}}{\epsilon_0 N_0} \quad (5.19)$$

$$\frac{1}{W_m} = \left(\frac{1}{W_{SF_6}} - \frac{1}{W_x} \right) \frac{P_s}{P_s + (k_3/k_1) P_x} + \frac{1}{W_x} \quad (5.20)$$

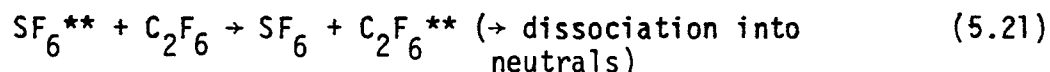
$$+ \alpha \frac{P_s}{[P_s + (k_3/k_1) P_x]} \frac{P_x}{[P_x + \lambda/c_1]} \quad (5.20)$$

where $\alpha = \xi_1(1 - \eta_1)/\epsilon_s \text{ (eV)}^{-1}$.

The ratios of k_3/k_1 , λ/c_1 and the parameter α were calculated through the nonlinear least-squares fitting routine¹³ using the experimental measurements given in Table V (p. 33). These results are listed in Table VI along with the standard deviation of the ratio and the coefficient of determination D.

III. SF_6/C_2F_6

This mixture shows a moderate increase in the W values and consequently a decrease in ionization (i.e., the experimental values for W_m are slightly higher than the values predicted by Eq. 5.1). The decrease in ionization for the gas mixture compared to that for the individual gas components is still not understood. One interpretation is that long-lived superexcited states of SF_6 (i.e., SF_6^{**}) exist, which instead of decaying by autoionization producing electron-ion pairs, collide with C_2F_6 to which they transfer their energy. The so formed superexcited states of C_2F_6 (i.e., $C_2F_6^{**}$) dissociate into neutral fragments, as indicated by Eq. 5.21:



CHAPTER VI

DISCUSSION

The measured W values for the binary gas mixture $\text{SF}_6/\text{C}_2\text{H}_2$, which show no evidence of increased ionization due to the Penning effect have been understood by considering the constant (a) in Eq. 5.11 as the effective ratio of the probabilities of energy transfer from the alpha particles to the two gas constituents. The constant a (i.e., k_2/k_1) has been calculated through the nonlinear least squares fitting routine and found to be 0.82. This indicates that the rate of energy transfer to SF_6 is about 1.22 that to C_2H_2 . The increase in the total ionization for the gas mixture $\text{SF}_6/\text{cis } 2\text{-C}_4\text{H}_8$, which shows no evidence of Penning effect, has been understood similarly, but by incorporating the mechanism for the ionization of $\text{cis } 2\text{-C}_4\text{H}_8$ by the excited SF_6 molecules to account for the extra source of ionization. The calculated value of k_3/k_1 , α and λ/c_1 have been found to be 0.4, 0.0035, and 0.17, respectively. The rate of energy transfer from the alpha particles to SF_6 is about 2.5 that of $\text{cis-C}_4\text{H}_8$, and the collisional de-excitation of SF_6 by $\text{cis } 2\text{-C}_4\text{H}_8$ is about 5.8 times the de-excitation by radiative decay.

The decrease in the total ionization for the gas mixture $\text{SF}_6/\text{C}_2\text{F}_6$ is not well understood. One possible explanation is the quenching of the superexcited state SF_6^{**} by C_2F_6 molecules, which subsequently decay to neutral fragments. Despite our rather simplified

analysis, we obtained good agreement between the experimental and the calculated W values for the gas mixtures studied.

The plotting of W as a function of the density reduced electric field (i.e., E/N) for SF_6 is shown in Figure 11 (p. 30). This figure indicates that for highly attaching gases, or gas mixtures, measurements of W should be made at a pressure slightly higher than the critical pressure which is defined at the beginning of Section II, Chapter III. At this pressure W values vary slightly as a function of the applied field; therefore, linear regression or lower order polynomials can be used to extrapolate the W value of gases or gas mixtures under investigation as $(\frac{1}{V}) \rightarrow 0$. The calculated W values for SF_6/C_2F_6 show some discrepancy for concentrations between 0 and 20% of C_2F_6 . At those concentrations, the amount of change in Δt (i.e., the time required to charge the capacitor to 1.824 volts) for two consecutive concentrations measurement is in the order of $\pm 0.1\%$. This change attributes to the inconsistency in the extrapolated W values, since third or fourth order polynomials are needed to extrapolate W 's at 101 kPa. However, this discrepancy can be negated by using lower order polynomials to extrapolate W at a pressure slightly higher than the critical pressure.

CHAPTER VII

SUMMARY AND CONCLUSIONS

In this experiment the average energy required to produce an electron-ion pair, W , has been measured. For SF_6 , N_2 , SF_6/N_2 and SF_6 mixtures such as $\text{SF}_6/\text{C}_2\text{H}_2$, $\text{SF}_6/\text{C}_2\text{F}_6$ and $\text{SF}_6/\text{cis-2 C}_4\text{H}_8$ as their component ratios were varied from 0% to 100%.

The W value for SF_6 has been measured and found to be 35.45 eV/ip. This rather high value is attributed to the large cross section for electron impact dissociation of SF_6 into neutral fragments.

The measured W values for N_2 , C_2F_6 , C_2H_2 and cis-2 C_4H_8 are listed in Table II (p. 22) and are in good agreement with those given by other sources.¹⁰ For the binary gas mixture $\text{SF}_6/\text{C}_2\text{H}_2$, the alpha particle's energy is partitioned between SF_6 and C_2H_2 approximately in the ratio 1.22:1. Similarly, for the binary gas mixture $\text{SF}_6/2\text{-C}_4\text{H}_8$, the partitioning of the alpha particle's energy between the two gas constituents is in the ratio 2.5:1.

The increase in ionization for the gas mixture $\text{SF}_6/2\text{-C}_4\text{H}_8$ is attributed to the ionization energy of 2- C_4H_8 which is considerably lower than the excitation energy of the SF_6^* molecules. This result, then, establishes the existence of SF_6^* metastables and indicates that further studies are needed to explain the role of SF_6^* metastables in ionization of the gas and electron ejection upon their collision with the electrode surface.

The experimental results have been modeled, and good agreement has been obtained between the experimental and the calculated values.

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APPENDIX

TABLE A-I

VALUES OF W AS A FUNCTION OF THE TOTAL PRESSURE AND THE APPLIED VOLTAGE FOR SF₆

Applied Voltage (kV)	W (eV/ip)						
	33.67 kPa	67.33 kPa	101 kPa	134.67 kPa	168.33 kPa	202 kPa	303 kPa
2.0	36.84	44.89	58.16	74.45	94.35	112.17	
3.0	36.37	42.36	52.48	64.99	78.94	94.41	147.53
4.0	36.14	41.00	49.26	59.60	70.83	83.54	127.93
6.0	35.91	39.46	45.66	53.45	61.96	71.89	105.56
12.0	35.61	37.60	41.22	46.16	51.46	57.60	78.34
20.0			39.07	42.55	46.24	50.46	65.05

TABLE A-II
VALUES OF W AS A FUNCTION OF THE TOTAL PRESSURE
AND THE APPLIED VOLTAGE FOR N₂

Applied Voltages (kV)	W (eV/ip)				
	101 kPa	134.67 kPa	168.33 kPa	202 kPa	303 kPa
0.75	36.75	36.94	37.20	37.35	
1.0	36.68	36.83	37.02	37.13	37.45
2.0	36.59	36.67	36.77	36.82	36.99
3.0	36.56	36.61	36.67	36.72	36.82
4.0	36.55	36.59	36.63	36.66	36.75
5.0	36.54	36.57	36.61	36.63	36.70
6.0					36.66

TABLE A-III

VALUES OF W AS A FUNCTION OF THE TOTAL PRESSURE AND THE
APPLIED VOLTAGE FOR A 50% MIXTURE OF SF₆ AND N₂

Applied Voltage (kV)	W (eV/ip)					
	67.33 kPa	101 kPa	134.67 kPa	168.33 kPa	202 kPa	303 kPa
2.0	39.70	46.52	55.87	67.17	79.54	123.06
3.0	38.65	43.76	50.87	59.55	69.15	103.02
4.0	38.10	42.23	48.03	55.14	63.12	91.33
6.0	37.48	40.48	44.82	50.21	56.25	77.93
12.0	36.75	38.44	41.03	44.25	48.47	61.53
20.0		37.46	39.20	41.39	43.92	53.32

TABLE A-IV
VALUES OF W FOR SF₆/C₂F₆ GAS MIXTURES AS A FUNCTION OF THE APPLIED VOLTAGE
AND THE PERCENTAGE OF C₂F₆ IN SF₆ AT 101 kPa

Applied Voltage (kV)	W (eV/ip)												
	100.00%	80.00%	60.00%	40.00%	20.00%	10.00%	5.00%	2.00%	1.00%	0.75%	0.50%	0.25%	0.00%
2	38.12	57.40	58.71	59.01	58.92	58.57	58.20	58.30	58.30	58.34	58.35	58.35	58.16
3	36.83	51.36	52.52	52.88	52.98	52.73	52.52	52.59	52.56	52.63	52.63	52.60	52.48
4	36.22	47.98	48.98	49.42	49.59	49.46	49.28	49.34	49.36	49.38	49.38	49.37	49.25
6	35.63	44.20	45.06	45.49	45.73	45.73	45.68	45.74	45.71	45.72	45.72	45.74	45.66
10								42.32	42.29	42.33	42.21	42.34	42.28
12	34.99	39.77	40.44	40.87	41.18	41.25	41.30						41.22
13								40.96	40.95	40.98	40.98	41.01	

VALUES OF W FOR SF_6/C_2H_2 GAS MIXTURES AS A FUNCTION OF THE APPLIED VOLTAGE AND THE PERCENTAGE OF C_2H_2 IN SF_6 AT 101 kPa

Applied Voltage (kV)	W (eV/ip)												
	100.00%	80.00%	60.00%	40.00%	20.00%	10.00%	5.00%	2.00%	1.00%	0.75%	0.50%	0.25%	0.00%
2	28.02	37.98	43.57	49.16	54.26	56.60	57.56	57.82	57.94	58.03	56.99	58.16	58.16
3	27.88	35.64	40.29	44.85	49.04	50.98	51.87	52.12	52.28	52.35	51.83	52.48	52.48
4	27.83	34.41	38.45	42.38	46.02	47.79	48.63	48.91	49.10	49.13	48.79	49.25	49.25
6	27.78	32.94	36.35	39.56	42.66	44.22	44.96	45.32	45.49	45.53	45.37	45.63	45.66
10		31.68	34.40	36.96	39.55	40.89	41.59	41.93	42.12	42.18	42.11	42.26	42.28
12	27.71												41.22
15		30.93	33.28	35.52	37.76	38.98	39.63	40.01	40.19	40.23	40.21	40.32	40.96

VALUES OF W FOR SF₆/cis 2-C₄H₈ GAS MIXTURES AS A FUNCTION OF THE APPLIED VOLTAGE AND THE PERCENTAGE OF cis 2-C₄H₈ IN SF₆ at 101 kPa

TABLE A-VI

Applied Voltage (kV)	W (ev/ip)												
	100.00%	80.00%	60.00%	40.00%	20.00%	10.00%	5.00%	2.00%	1.00%	0.75%	0.50%	0.25%	0.00%
2	30.09	47.03	50.96	53.78	56.21	57.37	58.08	58.40	58.31	58.28	58.37	58.49	58.16
3	28.70	41.99	45.37	47.86	50.15	51.27	52.05	52.52	52.48	52.50	52.59	52.66	52.48
4	27.95	39.13	42.11	44.45	46.65	47.80	48.61	49.13	49.17	49.24	49.28	49.36	49.25
6	27.23	35.92	38.49	40.59	42.67	43.88	44.72	45.34	45.48	45.57	45.58	45.69	45.63
10	26.80	32.98	35.16	37.06	39.06	40.23	41.14	41.81	42.05	42.10	42.19	42.24	42.28
13	26.72	31.85	33.84	35.64	37.60	38.78	39.72	40.43	40.67	40.77	40.83	40.85	

VITA

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