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AVERAGE ENERGY LOSS PER ION PAIR PRODUCED BY ALPHA PARTICLES IN BINARY GAS MIXTURES

T. D. Strickler

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HEALTH PHYSICS DIVISION

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I. INTRODUCTION

If an alpha particle of kinetic energy E_o is completely stopped in a gas, and in becoming stopped produces N_i ion pairs, then the mean energy lost per ion pair E_o/N_i is commonly called the W of the gas for alpha particles. The W of most gases lies in the range 20 to 46 ev per ion pair and in many cases is found to be practically independent of the energy of the initial ionizing particle.

The practical importance of W (in the measurement of radiation dose, in the calculation of energies of particles in nuclear reactions and in the interpretation of radiation-induced chemical reactions) and its theoretical significance have been pointed out in many recent publications on the subject.[1-3]

In the case of binary mixtures of gases, two general effects have been distinguished. One concerns the marked increase in ionization, and consequent decrease in W when small amounts of some gases are mixed with the noble gases. This has been studied by Jesse and Sadauskis[4-6] using helium and neon, and by Melton, Hurst, and Bortner[7]

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[1] S. C. Curran and J. M. Valentine, Rep. Prog. Phys. 21, 1 (1958).

[2] W. Binks, Acta Radiol., Suppl. 117, 85 (1954).

[3] R. L. Platzman, NAS-Nat'l. Res. Council Publication 752, 109 (1960).

[4] W. P. Jesse and J. Sadauskis, Phys. Rev. 88, 417 (1952).

[5] Ibid., 90, 1120 (1953).

[6] Ibid., 100, 1755 (1955).

[7] C. E. Melton, G. S. Hurst, and T. E. Bortner, Phys. Rev. 96, 643 (1954)

using argon. The effect is attributed, in part, to the excitation of the metastable level in the noble gases and the subsequent ionization of the impurity (by interaction with the excited atom) provided the ionization potential of the impurity is lower than that of the metastable state. This has been referred to as the "Jesse effect".[8] The fact that increased ionization occurs in argon, even when the impurity has an ionization potential greater than that of the metastable level, has been demonstrated by Melton, Hurst, and Bortner,[7] but the explanation of the effect is not entirely clear.

The second effect, prominent in most gases, shows the W of the mixture to lie between the extreme values for the pure gases and to change smoothly from one limit to the other as the composition of the mixture is changed. This has been studied by Huber et. at.[9-10] in Switzerland, and by Hurst's group[11-13] at the Oak Ridge National

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[8] R. L. Platzman, "The Physical and Chemical Basis of Mechanisms in Radiation Biology", pp. 15-72 in Radiation Biology and Medicine, ed. by W. D. Claus, Addison-Wesley Publishing Co., Inc., Reading, Mass., 1958.

[9] P. Huber, E. Baldinger, and W. Haeberli, Helv. Phys. Acta. 23, Suppl. 111 (1949).

[10] W. Haeberli, P. Huber, and E. Baldinger, Helv. Phys. Acta. 26, 145 (1953).

[11] T. E. Bortner and G. S. Hurst, Phys. Rev. 93, 1236 (1954).

[12] H. J. Moe, T. E. Bortner, and G. S. Hurst, J. Phys. Chem. 61, 422 (1957).

[13] G. S. Hurst and T. D. Strickler, Nat'l Acad. Sci.-Nat'l Res. Counc. Publication 752, 134 (1960).

Laboratory. It has been shown that the W of any mixture of two of these gases can be expressed in terms of the W's of the pure gases, the partial pressures, and an empirical constant characteristic of the two gases.

This report consists mainly of an extension of the work on binary gas mixtures in an attempt to determine more of these empirical constants and to study possible relationships between them.

II. EXPERIMENTAL TECHNIQUE AND RESULTS WITH SINGLE GASES

Much of the work described here was carried out in the Physics Department at Berea College in Berea, Kentucky, using the same ionization chamber and associated equipment described and used by Bortner and Hurst.[11] This consisted of a large parallel-plate ionization chamber enclosed in a vacuum tank capable of holding gas at pressures up to two atmospheres. Alpha particles from the uncollimated source of Pu^{239}, located at the center of the bottom plate, were completely stopped in the chamber and the total ionization was measured by the time required to charge a capacitor to a fixed potential. Electric fields as high as 10^3 volts/cm could be applied to the chamber with the limit usually being set by sparking in the gas.

Since the W, in most cases, changes very little with energy of the incident alpha particle, a rather strong Pu^{239} source (approximately 3×10^6 cpm) was used in the chamber even though the thickness of this source prohibited the possibility of obtaining purely monoenergetic alpha particles. A spectral analysis of this source showed that over 90% of the ionization was from alpha particles of energy above 3.0 Mev. The use of such a source resulted in better statistical accuracy than could have been obtained with a very thin, monoenergetic source and, therefore, a better demonstration of the particular effects under study was obtained.

No purification techniques were employed and commercially available gases were used throughout. These were reported, by the manufacturers, to have purities of 99% or more in all cases except

acetylene.* Since small impurities have no great effect on the majority of measurements, it was assumed that the impurities remaining in these tanks would not markedly affect the results described.

Absolute measurements of W were not possible with this arrangement, principally because of the unknown amount of self-absorption in the source. Relative measurements were made by comparing the rate of charge collection in the mixture with that in pure nitrogen. Nitrogen** was assumed to have a W of 36.3 ev/ion pair and all measurements reported are subject to this assumption. At each mixture, the rate of charge collection was made several times with different voltages on the chamber in an attempt to insure saturation (complete collection of ions with no recombination). However, complete saturation was never achieved even at the highest field strengths obtainable. Consequently, the collection time was plotted against the reciprocal of the voltage, the best straight line drawn through these points, and the line extrapolated to zero (infinite voltage). In the case of any particular gas (or mixture) measured at several total pressures, the resulting lines would extrapolate to about the same point even though the slopes were different. An example of this is shown in Fig. 17.

The gases used in this study, with the exception of the noble gases, are listed in Table I along with the measured W values. These

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*Mass spectrographic analysis of a typical tank of acetylene showed: C_2H_2 (97.8), N_2 + CO (1.4), Acetone (0.5), H_2O (0.3), where numbers in parantheses are per cent abundance.

**Mass spectrographic analysis of actual tank of N_2 showed N_2 (99.997), H_2O (0.0008), and Ar (0.002).

results are comparable to those measured at other laboratories with the possible exception of hydrogen for which the value quoted in Table I appears to be somewhat low. This is an indication of the purity found in most of the gases, and is an indication of the presence of some impurities in the hydrogen.* The ionization potential has also been included in the table[14] as well as the ratio of W to the ionization potential since the constancy of this ratio is of some theoretical interest.

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*Mass spectrographic analysis of the tank of H_2 showed H_2(99.3), H_2O (0.30), N_2 + CO (0.26), with traces of CH_4, O_2, HC, Ar, and CO_2.

[14] F. J. Field and J. L. Franklin, Electron Impact Phenomena, pp. 105-127, Academic Press, New York, 1957.

Table I. Values of W and f for Various Molecular Gases

Formula	Gas	W (ev/ion pair)	Ionization Potential (volts)	$\frac{W}{\text{Ionization Potential}}$	f
N_2	Nitrogen	36.3*	15.6	2.32	1.0**
CO_2	Carbon Dioxide	34.1	13.85	2.46	1.8
H_2	Hydrogen	35.8	15.43	2.32	0.5
O_2	Oxygen	32.1	12.1	2.65	1.3
CH_4	Methane	28.9	13.12	2.20	1.8
C_2H_2	Acetylene	27.4	11.42	2.40	3.3
C_2H_4	Ethylene	27.85	10.56	2.64	3.4
C_2H_6	Ethane	26.4	11.65	2.27	3.5
C_3H_6	Cyclopropane	25.8	10.23	2.52	4.5
C_3H_6	Propylene	27.0	9.80	2.76	---
C_3H_8	Propane	26.1	11.21	2.33	4.5
C_4H_8	Isobutylene	26.6	9.35	2.85	---
C_4H_8	1-Butene	26.5	9.72	2.73	6.3
C_4H_8	2-Butene	26.1	9.3	2.81	6.3
C_7H_8	Toluene	28***	8.7	3.22	15

* Assumed value. ** By definition.
*** Value extrapolated from N_2-C_7H_8 Mixture

III. SUMMARY OF RESULTS USING MIXTURES OF "REGULAR GASES" ---- THE f-RATIO

This report is concerned mainly with the determination of the W of mixtures of two gases. It has been shown[11] that the W for a mixture of two "regular gases" (in which the Jesse effect is not pronounced) can be given by

$$\frac{1}{W_{ij}} = \left(\frac{1}{W_i} - \frac{1}{W_j} \right) Z_{ij} + \frac{1}{W_j} \tag{1}$$

where

$$Z_{ij} = \frac{P_i}{P_i + a_{ij} P_j} .$$

Here W_{ij} refers to the W of the mixture, W_i and W_j to that of the pure gases, each of which is present with fractional pressures P_i and P_j, and a_{ij} is a constant determined empirically for any particular pair of gases.

In many respects it is convenient to replace a_{ij} in Eq. (1) by $W_j f_j / W_i f_i$ in which case Eq. (1) can be written in simpler form,

$$W_{ij} = (W_i - W_j) Z''_{ij} + W_j$$

where

$$Z''_{ij} = \frac{f_i P_i}{f_i P_i + f_j P_j} = \frac{P_i}{P_i + (f_j/f_i) P_j} = \frac{P_i}{P_i + f_{ij} P_j} \tag{2}$$

This can be plotted as a linear relationship between W_{ij} and Z''_{ij} provided the proper value of the empirical constant f_{ij} is used for any pair of gases. This has been done for many pairs of gases listed in

Table 1. The results are shown in Figures 1 through 5 and the empirical constant f_{ij} associated with each pair of gases can be found in column 3 of Table II. These constants have each been assigned a probable error which was obtained by consideration of the accuracy of the W measurements. For any particular gas, the measurements were found to be reproducible to about 0.2%. The probable errors were then determined by finding that variation in f_{ij} which would move the W value at the midpoint of the curve ($Z''_{ij} = 0.5$) off the line by as much as 0.2%. This variation is therefore seen to be large in the case of mixtures whose two component gases have W's which are close together. In these cases, large changes in f_{ij} have little effect in shifting the curve from a straight line.

Correlation Between f-Ratios

Closer observation of the constants listed in this column shows that, with a few exceptions, they very nearly satisfy the relationship,

$$f_{ij} = f_j/f_i = \frac{f_j/f_k}{f_i/f_k} = f_{kj}/f_{ki} \qquad (3)$$

where i, j, and k refer to any three gases in the table. In fact, if the constants are replaced by the values shown in column 4 of this table, the relationship given by Eq. (3) is made to hold exactly. Many of these constants are within the probable error of those listed in column 3 and most of the others are close approximations. Moreover, if these constants are used in Eq. (2), the curves obtained are very nearly

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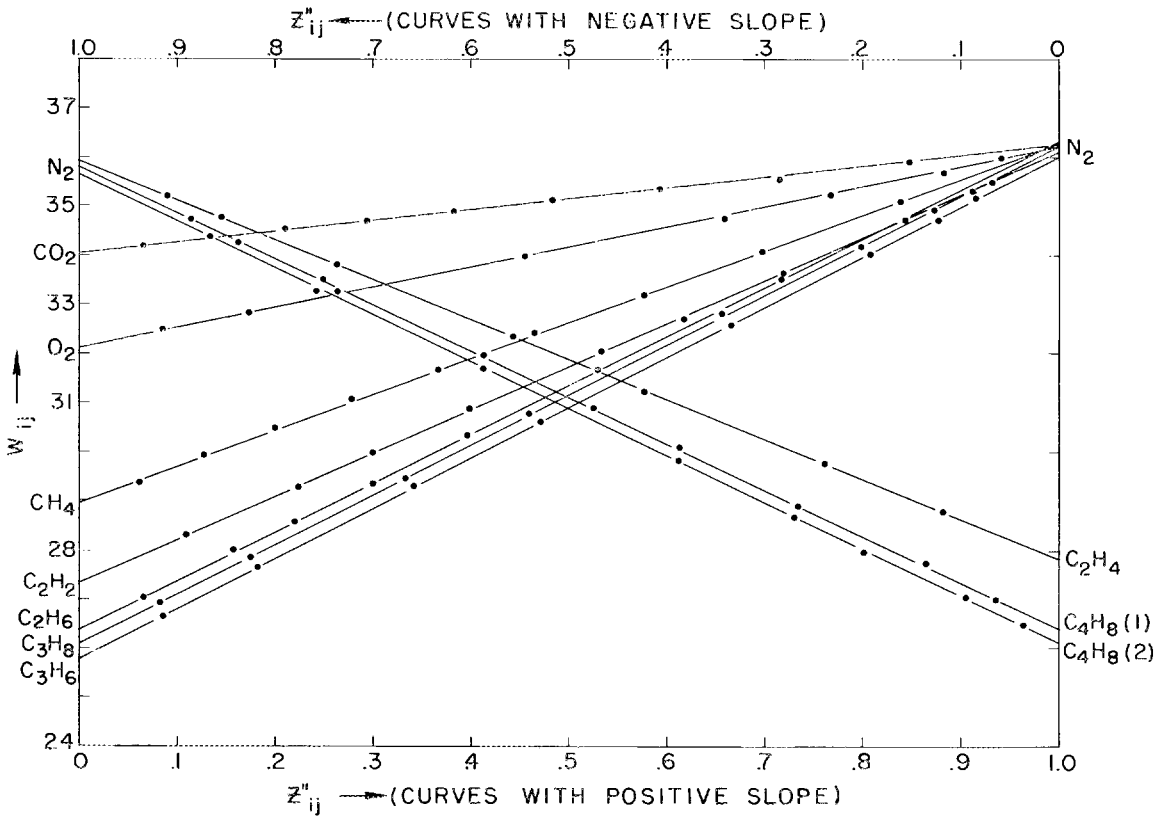

Fig. 1. Plot of W_{ij} vs Z''_{ij} for mixtures of N_2 with CO_2, O_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8, C_4H_8 (1-butene), and C_4H_8 (2-butene) using Z''_{ij} calculated from measured constants shown in column 3 of Table II.

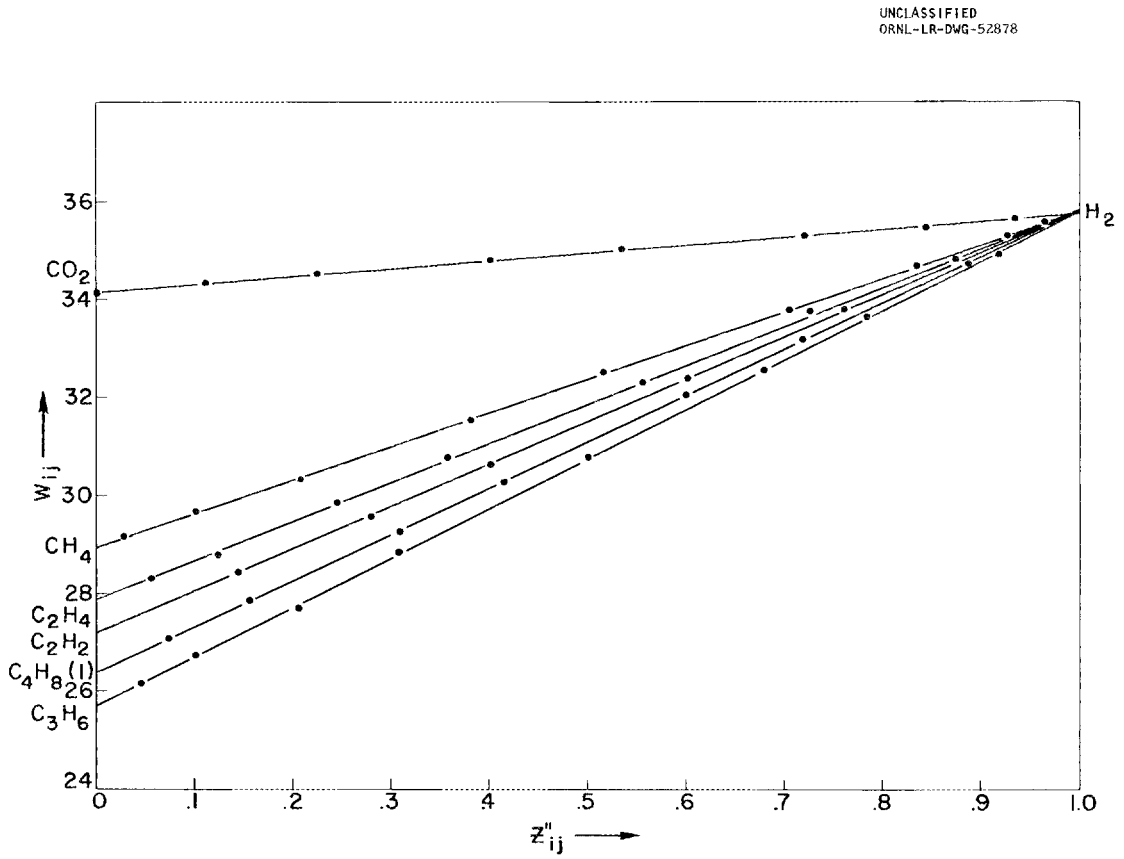

Fig. 2. Plot of W_{ij} vs Z''_{ij} for mixtures of H_2 with CO_2, CH_4, C_2H_2, C_2H_4, C_3H_6 (cyclopropane), and C_4H_8 (1-butene) using Z''_{ij} calculated from measured constants shown in column 3 of Table II.

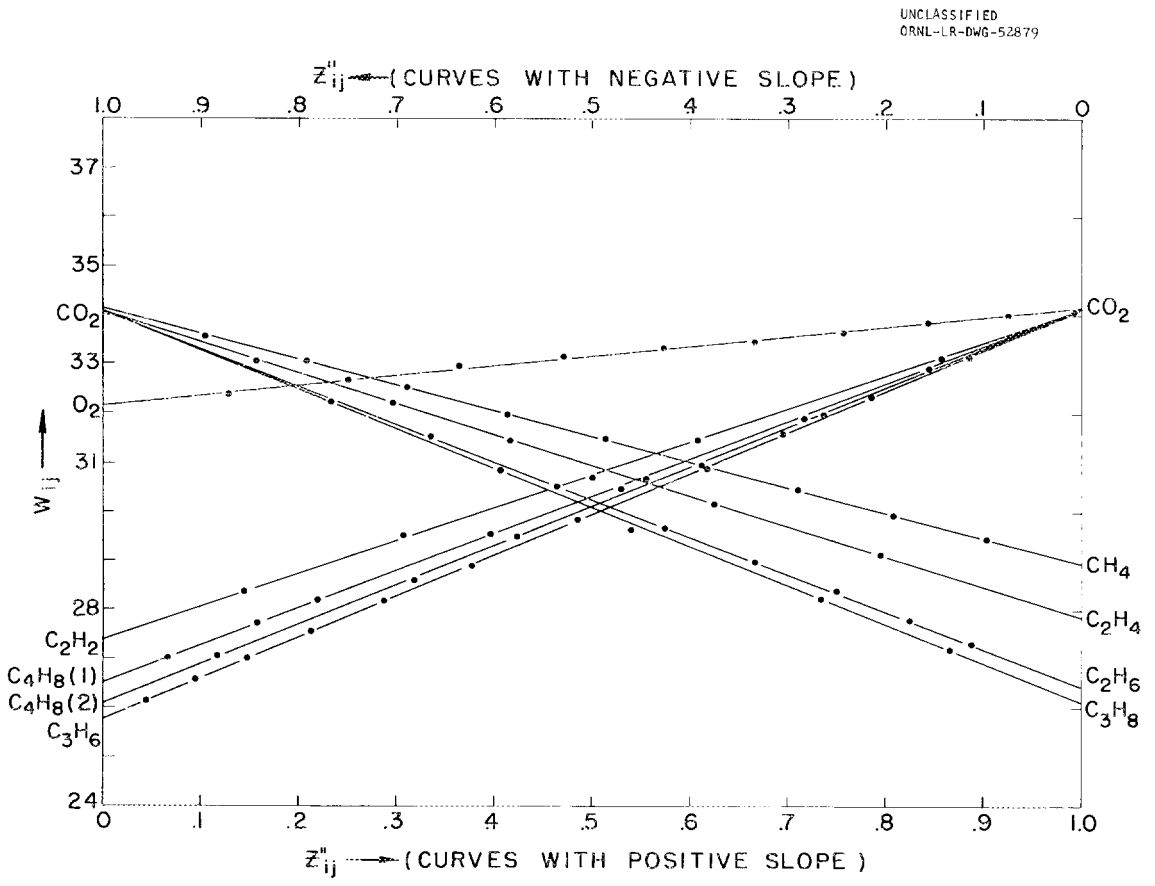

Fig. 3. Plot of W_{ij} vs Z''_{ij} for mixtures of CO_2 with O_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8, C_4H_8 (1-butene), and C_4H_8 (2-butene), using Z''_{ij} calculated from measured constants shown in column 3 of Table II.

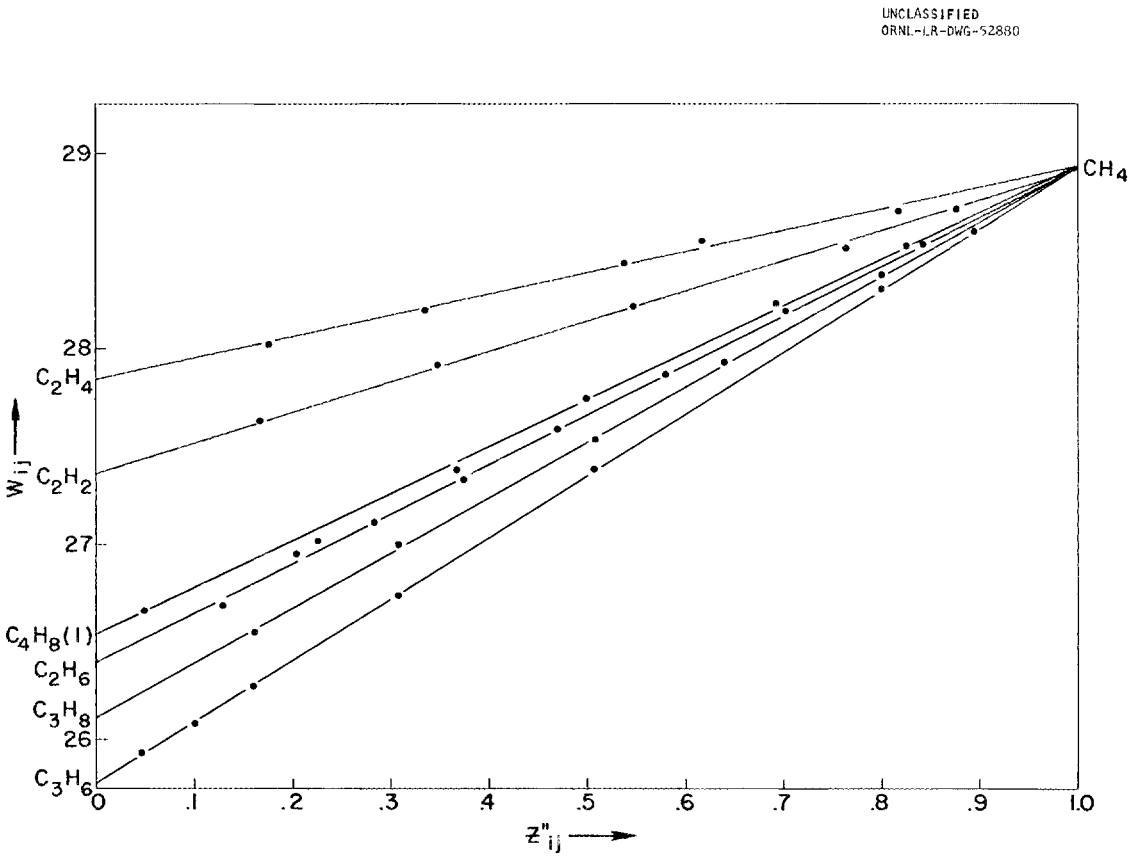

Fig. 4. Plot of W_{ij} vs Z''_{ij} for mixtures of CH_4 with C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8 and C_4H_8 (1-butene), using Z''_{ij} calculated from measured constants shown in column 3 of Table II.

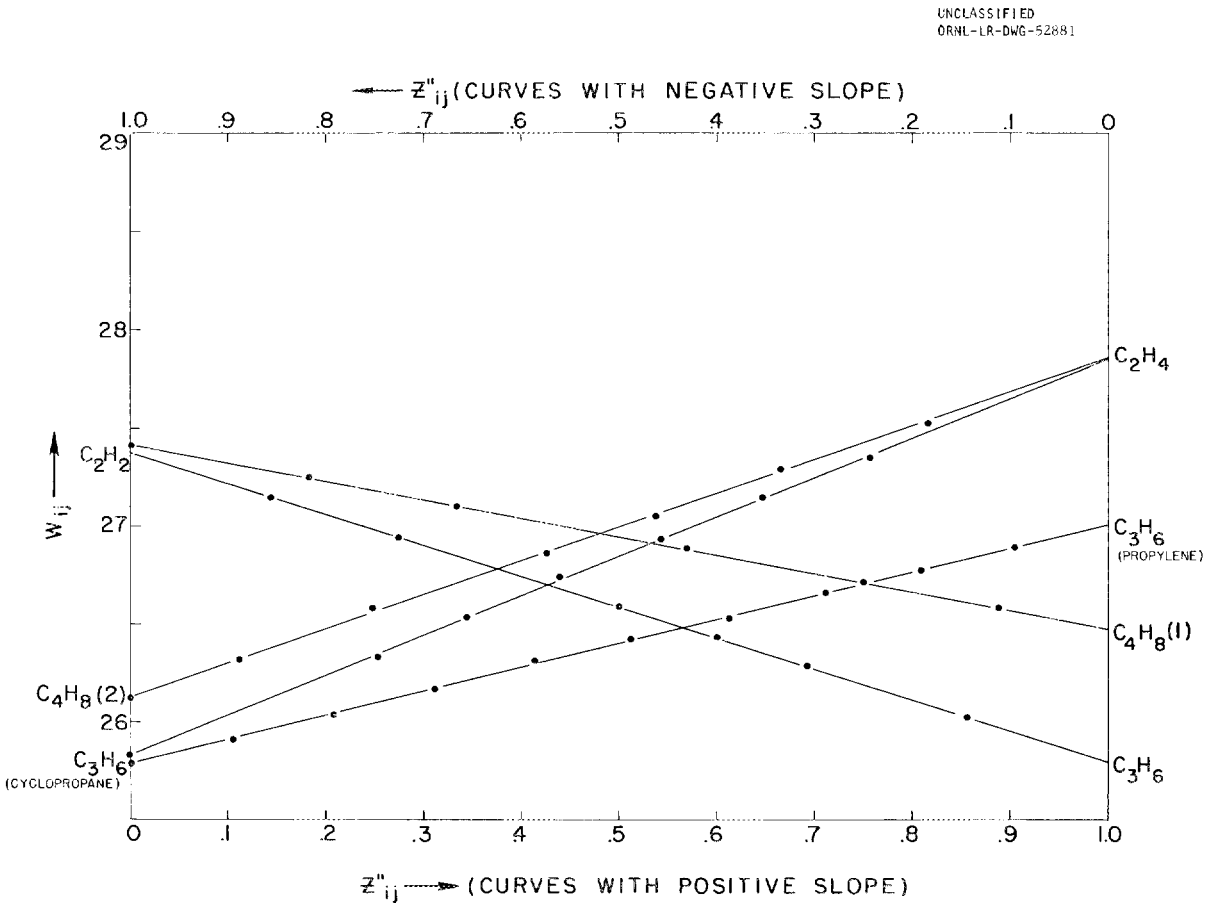

Fig. 5. Plot of W_{ij} vs Z''_{ij} for mixtures of C_2H_2 with C_3H_6 (cyclopropane) and C_4H_8 (1-butene); for mixtures of C_2H_4 with C_3H_6 (cyclopropane) and C_4H_8 (2-butene); and for the C_3H_6 (propylene) - C_3H_6 (cyclopropane) mixture; all using Z''_{ij} calculated from measured constants shown in column 3 of Table II.

Table II. Measured and Calculated Ratios f_j/f_i for Various Combinations of Molecular Gases

GAS i	GAS j	f_j/f_i (MEASURED)	f_j/f_i (CALCULATED)
N_2	CO_2	1.6 ± 0.2	1.8
N_2	O_2	1.2 ± 0.1	1.3
N_2	CH_4	1.7 ± 0.05	1.8
N_2	C_2H_2	3.5 ± 0.1	3.3
N_2	C_2H_4	3.2 ± 0.1	3.4
N_2	C_2H_6	3.5 ± 0.1	3.5
N_2	CYCLOPROPANE	4.5 ± 0.1	4.5
N_2	C_3H_8	4.7 ± 0.1	4.5
N_2	1-BUTENE	6.3 ± 0.2	6.3
N_2	2-BUTENE	6.3 ± 0.2	6.3
H_2	CO_2	3.5 ± 0.6	3.6
H_2	CH_4	3.8 ± 0.15	3.6
H_2	C_2H_2	6.0 ± 0.2	6.6
H_2	C_2H_4	7.2 ± 0.2	6.8
H_2	CYCLOPROPANE	9.0 ± 0.25	9.0
H_2	1-BUTENE	12.7 ± 0.3	12.6
CO_2	O_2	0.75 ± 0.1	0.72
CO_2	CH_4	1.05 ± 0.05	1.0
CO_2	C_2H_2	1.5 ± 0.05	1.83
CO_2	C_2H_4	1.7 ± 0.06	1.89
CO_2	C_2H_6	2.0 ± 0.06	1.95
CO_2	CYCLOPROPANE	2.5 ± 0.1	2.5
CO_2	C_3H_8	2.7 ± 0.1	2.5
CO_2	1-BUTENE	3.55 ± 0.1	3.5
CO_2	2-BUTENE	3.2 ± 0.1	3.5
CH_4	C_2H_2	1.25 ± 0.2	1.83
CH_4	C_2H_4	2.0 ± 0.4	1.89
CH_4	C_2H_6	1.7 ± 0.15	1.95
CH_4	CYCLOPROPANE	2.3 ± 0.2	2.5
CH_4	C_3H_8	2.25 ± 0.2	2.5
CH_4	1-BUTENE	4.0 ± 0.4	3.5
C_2H_2	CYCLOPROPANE	1.5 ± 0.2	1.36
C_2H_2	1-BUTENE	2.0 ± 0.4	1.91
C_2H_4	CYCLOPROPANE	1.3 ± 0.1	1.32
C_2H_4	2-BUTENE	2.0 ± 0.2	1.85
PROPYLENE	CYCLOPROPANE	0.95 ± 0.15	

straight lines as seen from Figures 6 through 10 where they have been shown on the same scale as Figures 1 through 5. The shaded areas shown in some of these curves are used to indicate the variation from a straight line, and acetylene appears to be the only gas in the group whose mixtures show W's off the line by as much as 1%. Thus, if each gas is assigned an f value such as that shown in column 6 of Table 1 (where nitrogen was arbitrarily assigned the value 1), then the constant $f_{ij} = f_j/f_i$ determined from any two of these can be used in Eq. (2) to give the W of any mixture of the gases within the accuracy described above.

Analysis of Mixtures Containing Helium, Neon, and Argon

Neglecting the effects (such as the Jesse effect) of the addition of small portions of impurities in the gases helium, neon, and argon, it has been shown[11] that further addition of the second gas leads to more regular changes in W similar to that observed in the molecular gases. These latter changes can be represented by Eq. (1) and therefore also by Eq. (2) by proper choice of constants. In these cases, the straight lines obtained do not necessarily pass through the W of the pure noble gas but through some point characteristic of the "contaminated" gas.

In Figure 11 the W's have been plotted for mixtures of helium with nitrogen, acetylene, and cyclopropane. With the addition of a small fraction of 1% of the second gas, the W drops from about 46 to about 30 ev/ion pair, but from there on the changes are more gradual. Fig. 12

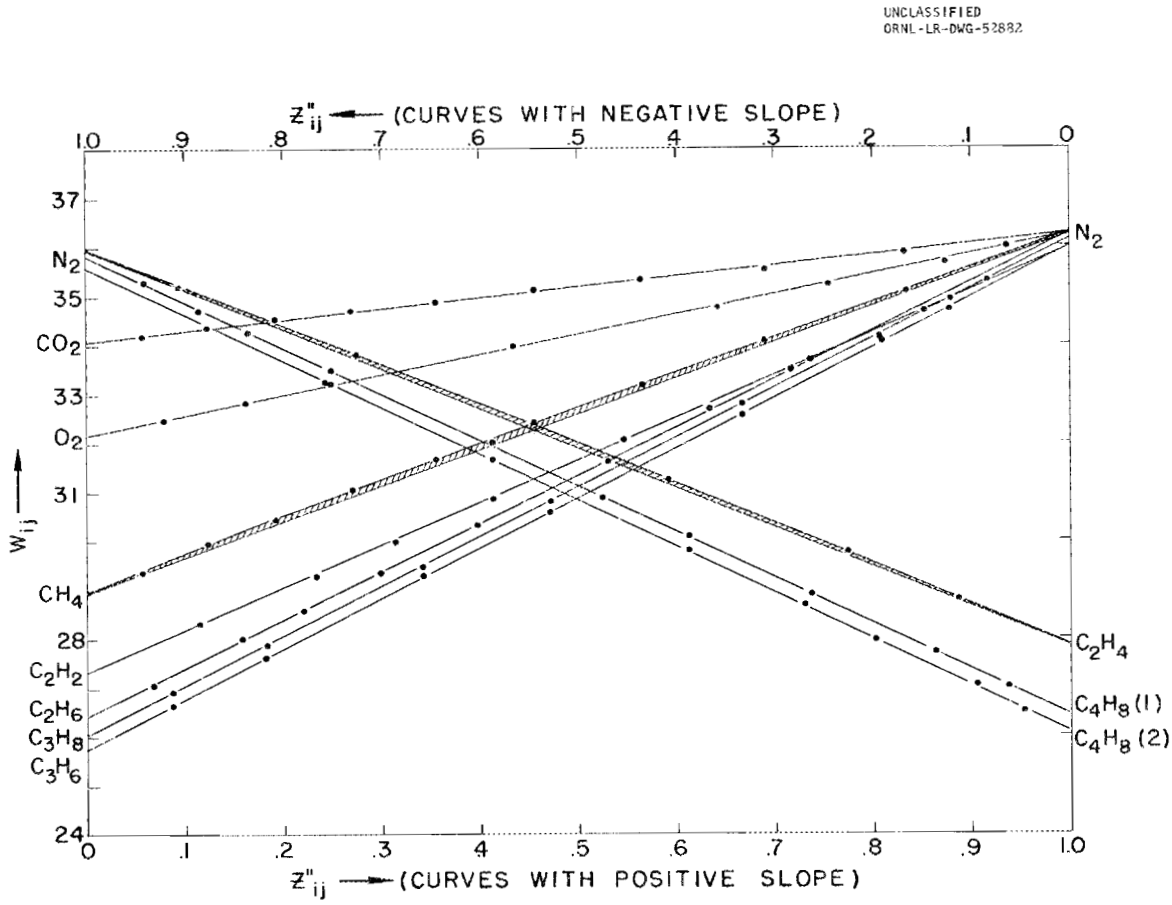

Fig. 6. Plot of W_{ij} vs Z''_{ij} for mixtures of N_2 with CO_2, O_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8, C_4H_8 (1-butene), and C_4H_8 (2-butene) using Z''_{ij} calculated from measured constants shown in column 4 of Table II.

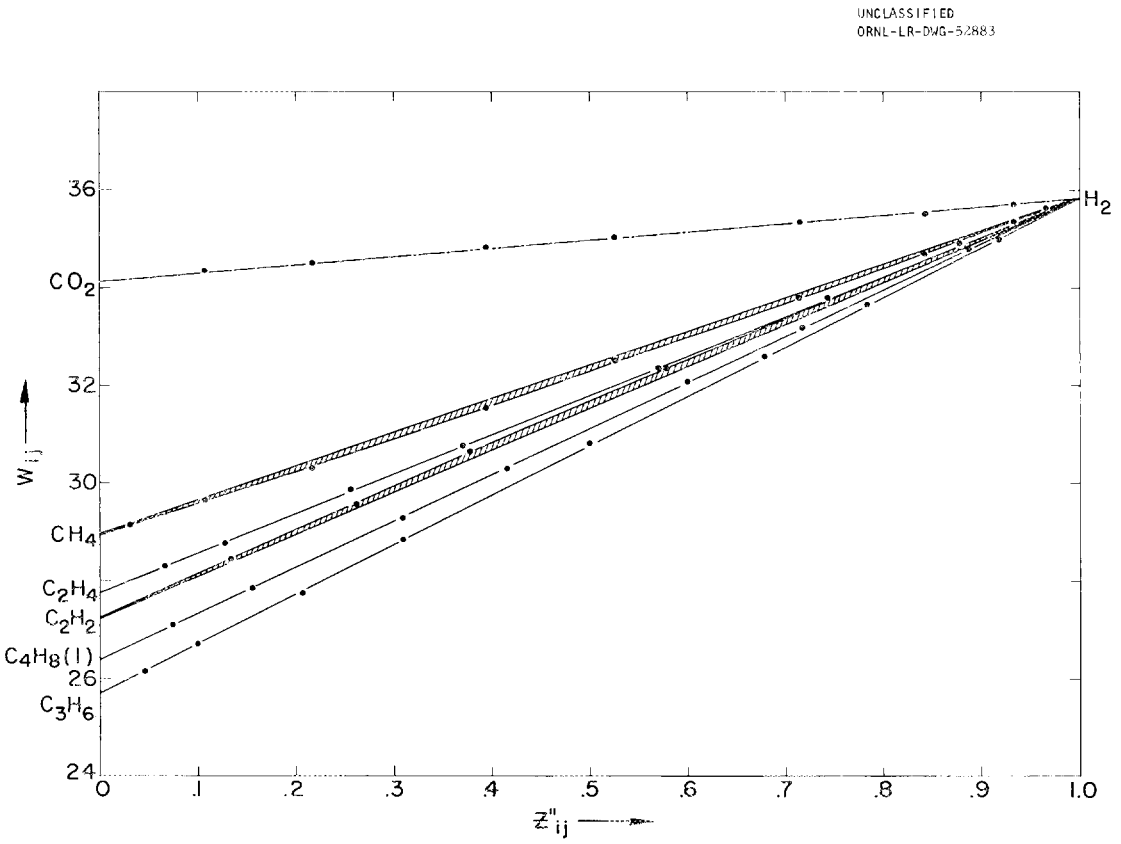

Fig. 7. Plot of W_{ij} vs Z''_{ij} for mixtures of H_2 with CO_2, CH_4, C_2H_2, C_2H_4, C_3H_6 (cyclopropane), and C_4H_8 (1-butene) using Z''_{ij} calculated from measured constants shown in column 4 of Table II.

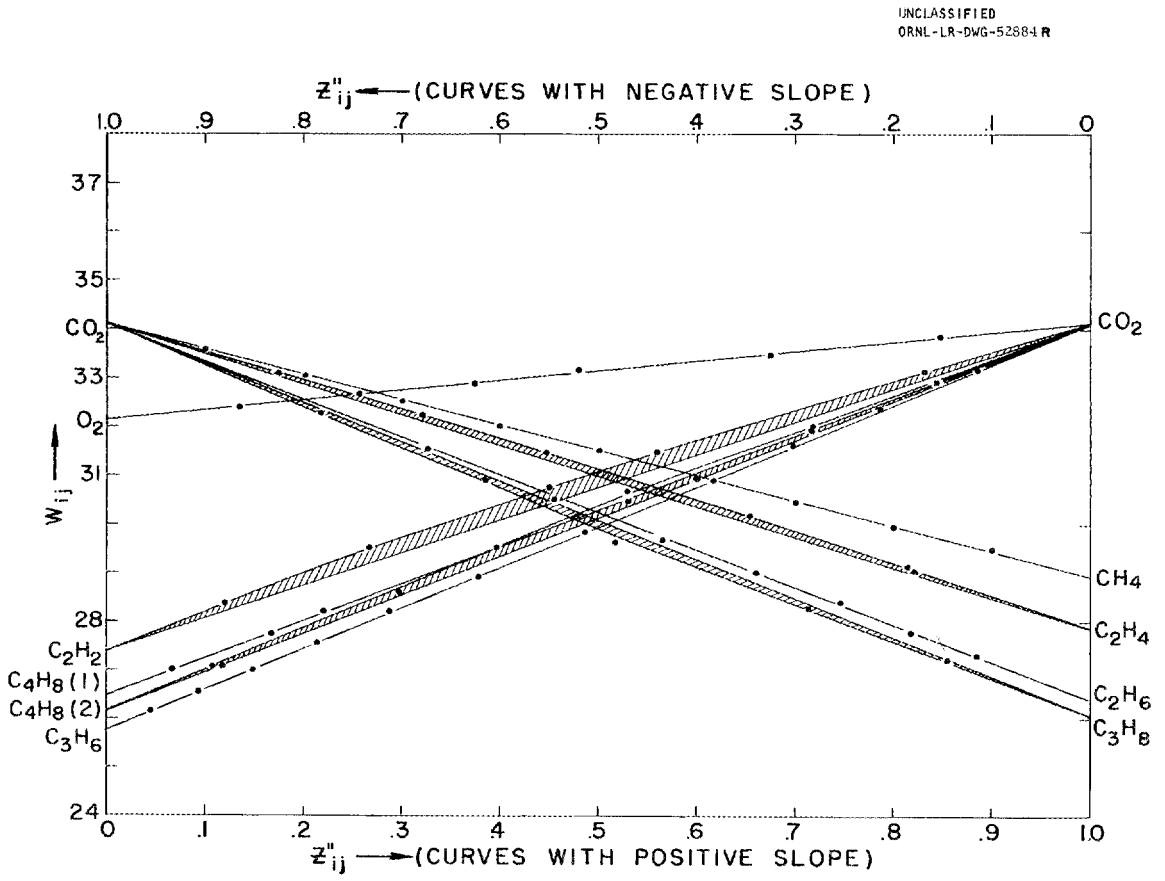

Fig. 8. Plot of W_{ij} vs Z''_{ij} for mixtures of CO_2 with O_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8, C_4H_8 (1-butene), and C_4H_8 (2-butene), using Z''_{ij} calculated from measured constants shown in column 4 of Table II.

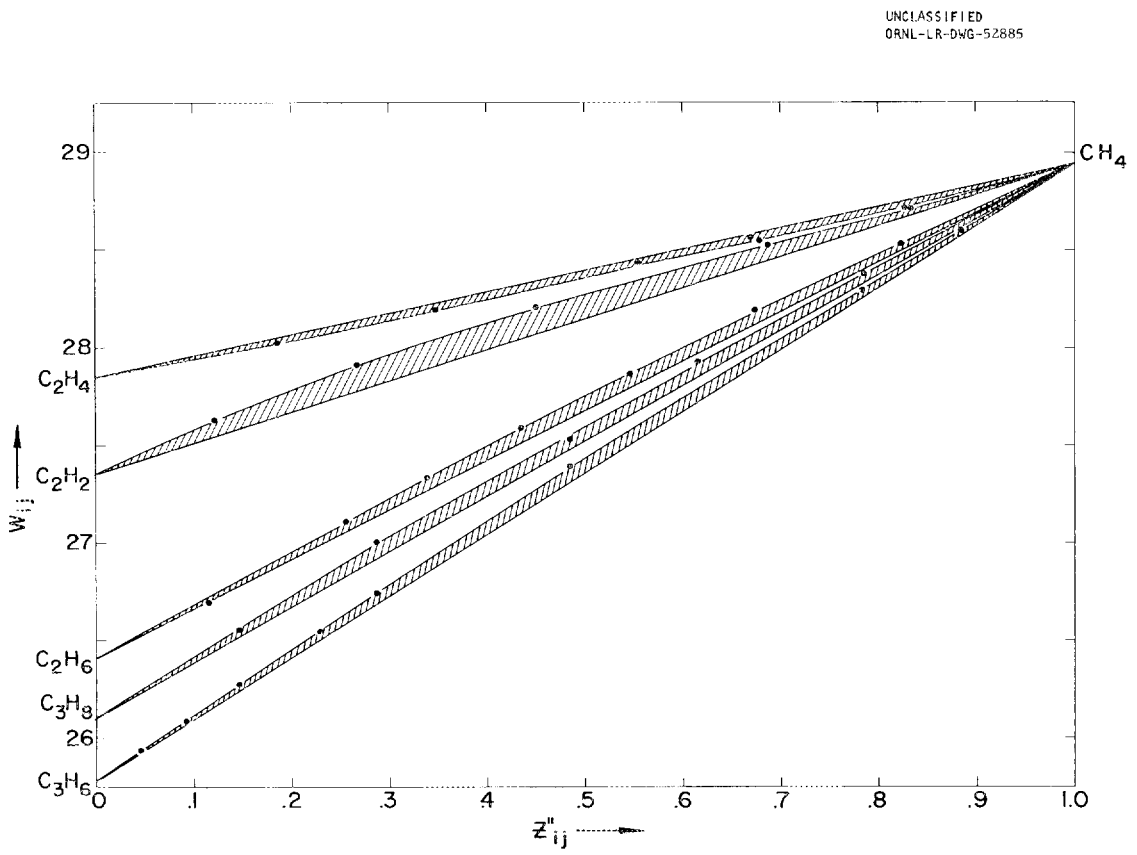

Fig. 9. Plot of W_{ij} vs Z''_{ij} for mixtures of CH_4 with C_2H_2, C_2H_4, C_2H_6, C_3H_6 (cyclopropane), C_3H_8 and C_4H_8 (1-butene), using Z''_{ij} claculated from measured constants shown in column 4 of Table II.

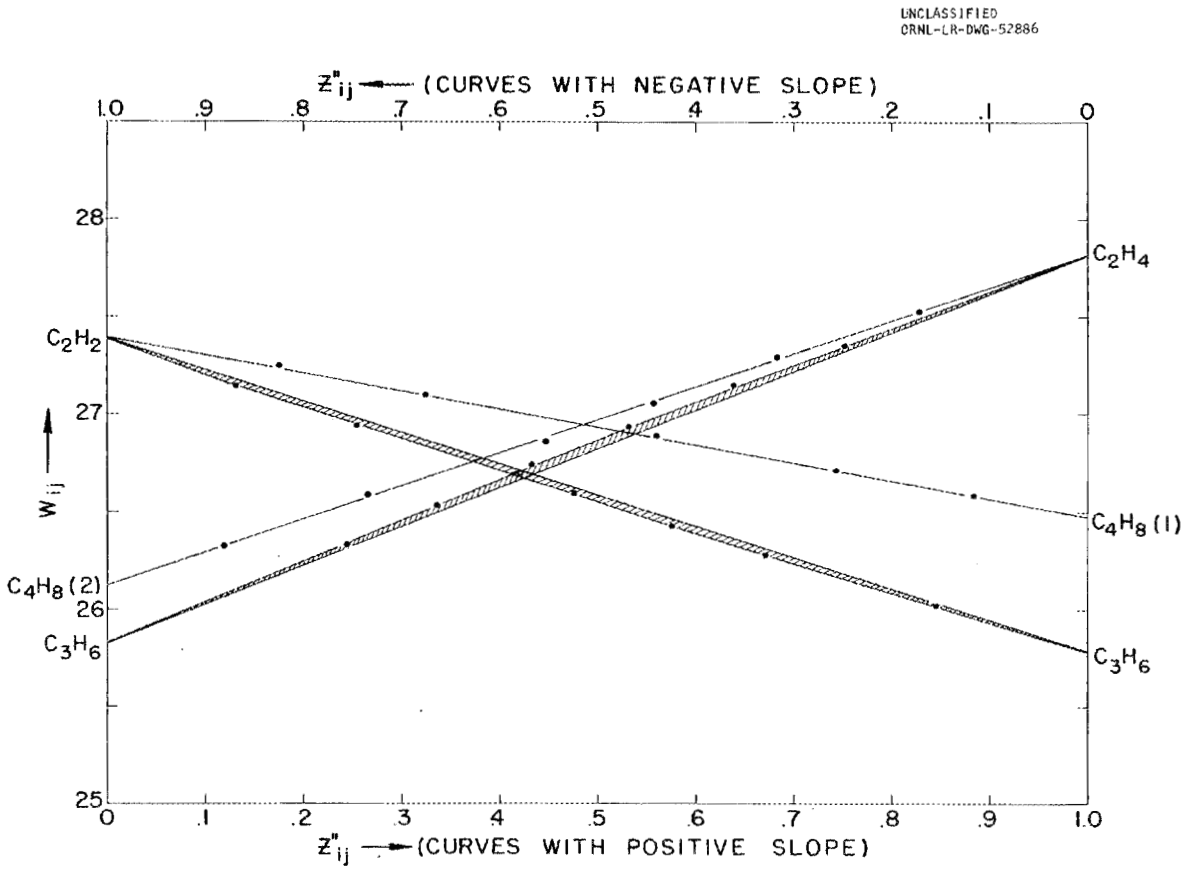

Fig. 10. Plot of W_{ij} vs Z''_{ij} for mixtures of C_2H_2 with C_3H_6 (cyclopropane) and C_4H_8 (1-butene) and for mixtures of C_2H_4 with C_3H_6 (cyclopropane) and C_4H_8 (2-butene), using Z''_{ij} calculated from constants shown in column 4 of Table II.

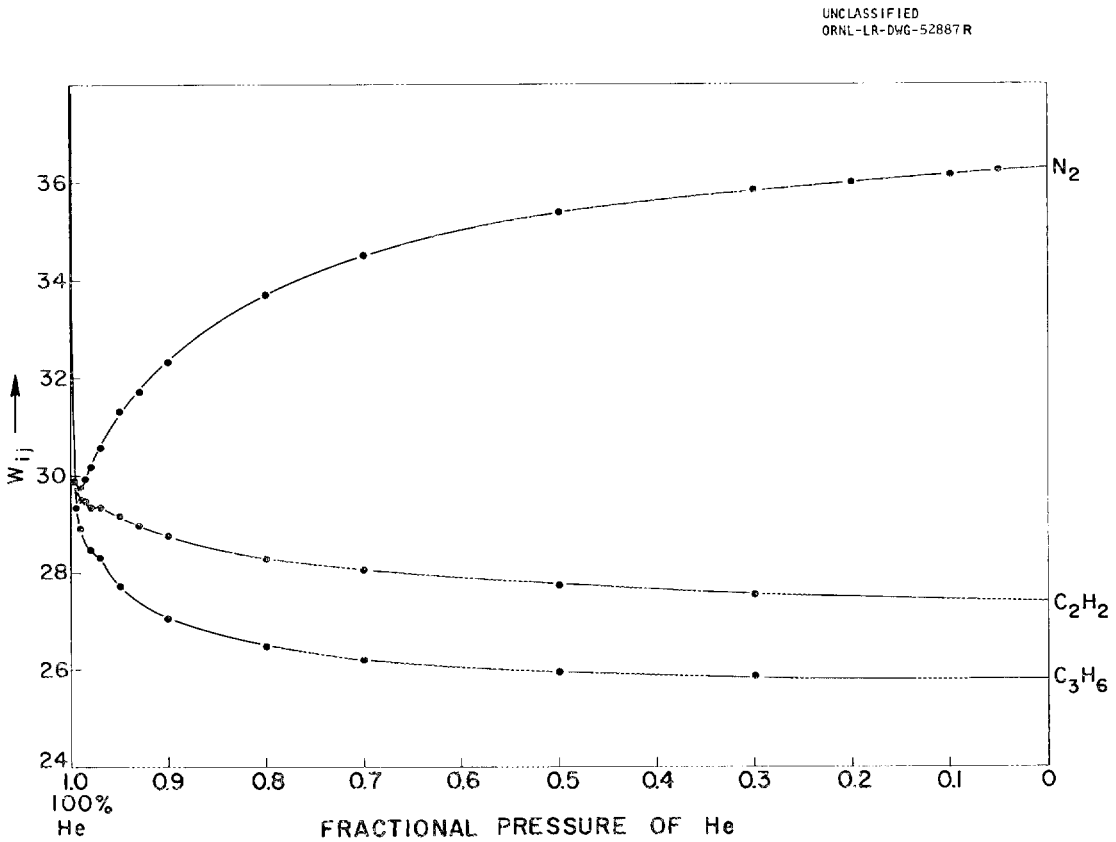

Fig. 11. Plot of W_{ij} for mixtures of He with N_2, C_2H_2, and C_3H_6, as a function of the fractional pressure of He in the mixture.

shows the same data plotted from Eq. (2) using constants f_{ij} given in Table III. The data points are seen to follow the predicted straight line down to a value of Z''_{ij} equal to 0.2 or 0.3 where the curve drops slightly below the line and then rises sharply to the W of pure helium. In these measurements, the best grade of helium available had a measured W of 38 ev/ion pair which can be compared with the value 46 ev/ion pair measured by Bortner and Hurst.[15] This is an indication of impurities being present in the tank. These impurities should have little effect on the portions of the curves shown in Figures 11 and 12.

A more complicated situation is found in the case of neon when mixed with nitrogen, acetylene, and cyclopropane. Figure 13 shows the variation in W with increasing concentrations of these gases. The acetylene mixture has previously been measured by Moe.[12] In the mixture neon-cyclopropane, the right hand portion of the curve (above 3% C_3H_6) can be plotted on a straight line with Eq. (2) if f_{ij} is set equal to about 0.2. In this plot, shown in Figure 14, below $Z''_{ij} = 0.2$, the curve again dips below the line, but much more sharply than in the case of helium, before rising to the W of pure neon. The data on neon-nitrogen and neon-acetylene mixtures were not sufficiently detailed to warrant an analysis of this type.

In a test of the pressure dependence of this dip in the W curve, it was found that at one particular concentration (0.6% C_3H_6), the W steadily increased from 26.65 ev/ion pair at 60 cm Hg total pressure to 26.80 ev/ion pair at 150 cm total pressure. This change was barely perceptible but indicated that perhaps the effects which give rise to

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[15] T. E. Bortner and G. S. Hurst, Phys. Rev. 90, 160 (1953).

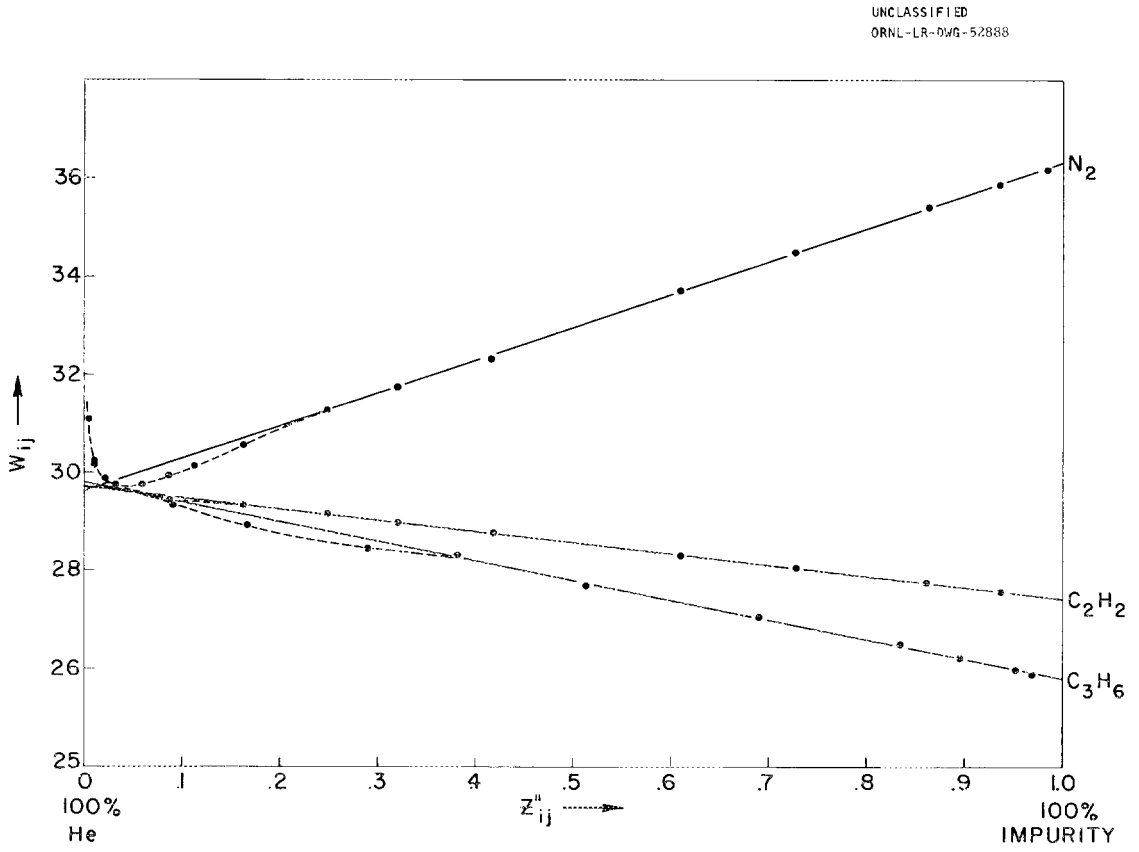

Fig. 12. Plot of W_{ij} vs Z''_{ij} for mixtures of He with N_2, C_2H_2, and C_3H_6 (cyclopropane) using constants shown in Table III.

Table III. Ratios f_j/f_i for Some Molecular Gases Mixed with the Inert Gases

Gas i	Gas j	f_j/f_i
N_2	He	0.16
C_2H_2	He	0.16
Cyclopropane	He	0.05
Cyclopropane	Ne	0.2
N_2	Ar	1.0
1-Butene	Ar	0.23
Cyclopropane	Ar	0.25

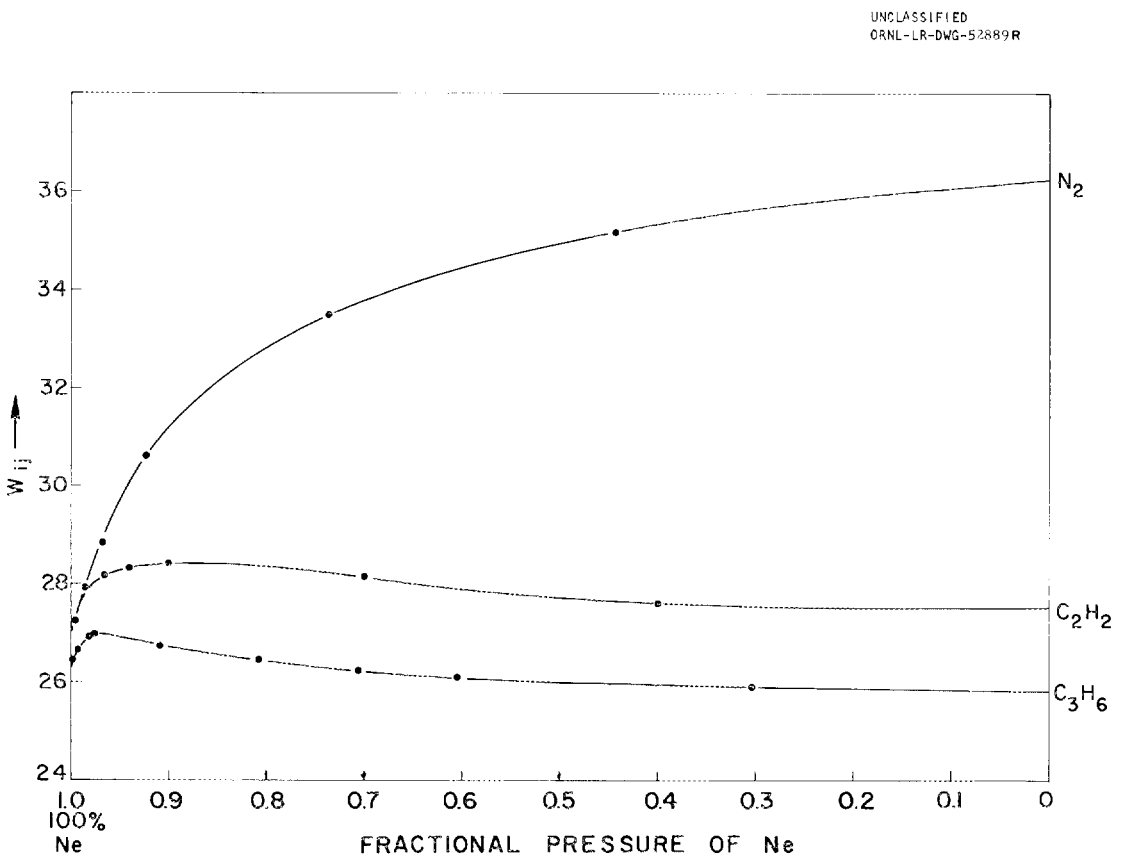

Fig. 13. Plot of W_{ij}, for mixtures of Ne with N_2, C_2H_2, and C_3H_6, as a function of the fractional pressure of Ne in the mixture.

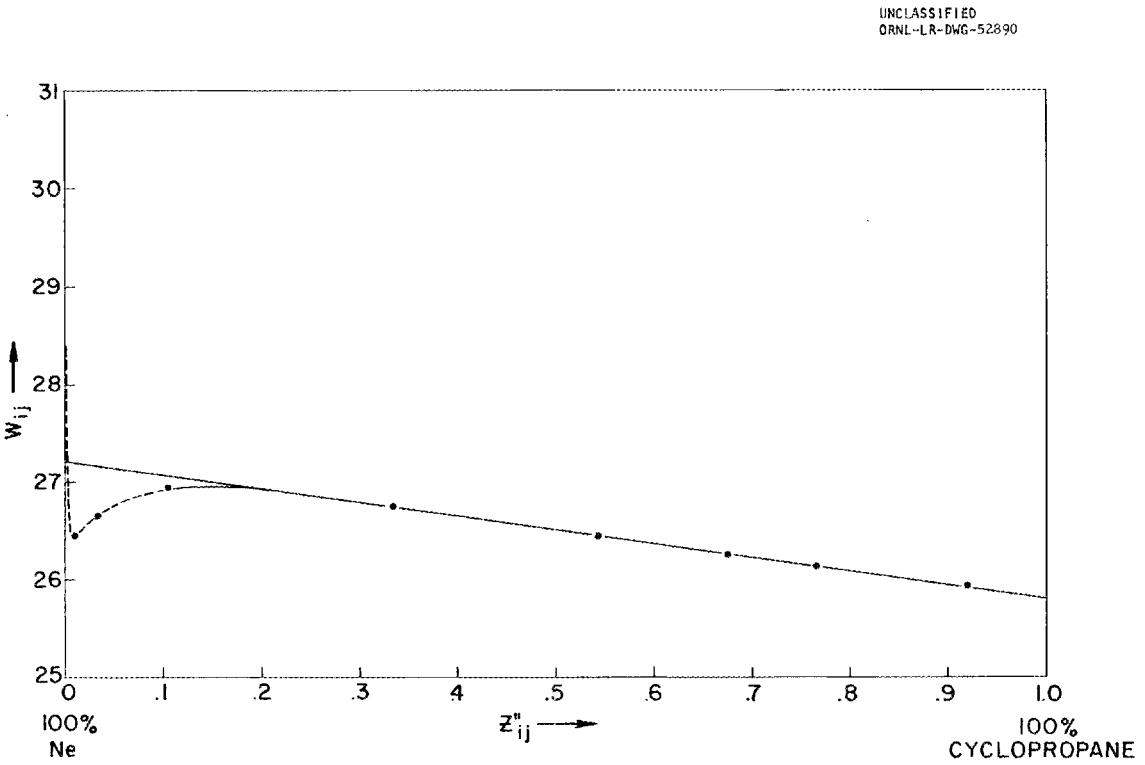

Fig. 14. Plot of W_{ij} vs Z''_{ij} for mixtures of neon and cyclopropane using $f_{ij} = 0.2$.

this dip do depend on the total pressure of the mixture. This type of pressure dependence is not found in most other portions of the curves. Several argon mixtures were included in this study. Figure 15 shows the W for mixtures of argon-nitrogen, argon-1 butene, argon-cyclopropane, and argon-krypton. With more than 5% of the second gas present in the mixture, the changes are again "regular" and can be represented as straight lines as shown in Figure 16. Here again the constants shown in Table III have been used with Eq. (2). In the case of nitrogen, which has an ionization potential well above the metastable level in argon, the line approaches the W of pure argon, while in the other cases they approach values considerably lower. No indication was observed of any dip below this line as seen in the neon mixtures (and very slightly in the helium cases).

The krypton mixture represents a case where there is a considerable lowering of the W of argon by a gas with an ionization potential well above the metastable level in argon. The curve has been noted in Ref. 7 and the experiment was repeated here for an examination of the pressure dependence. The total pressure of the mixture was changed from 150 cm to 40 cm Hg, while the charge collection time was measured at three different field strengths. Figure 17 shows the results at four different pressures, of a plot of collection time against the reciprocal of the voltage on the chamber. The mixture in this case was 82% argon-18% krypton and at each pressure the curve extrapolates roughly to the same point within 0.2%. Similar attempts to detect changes in W with changes in total pressure, were made with other

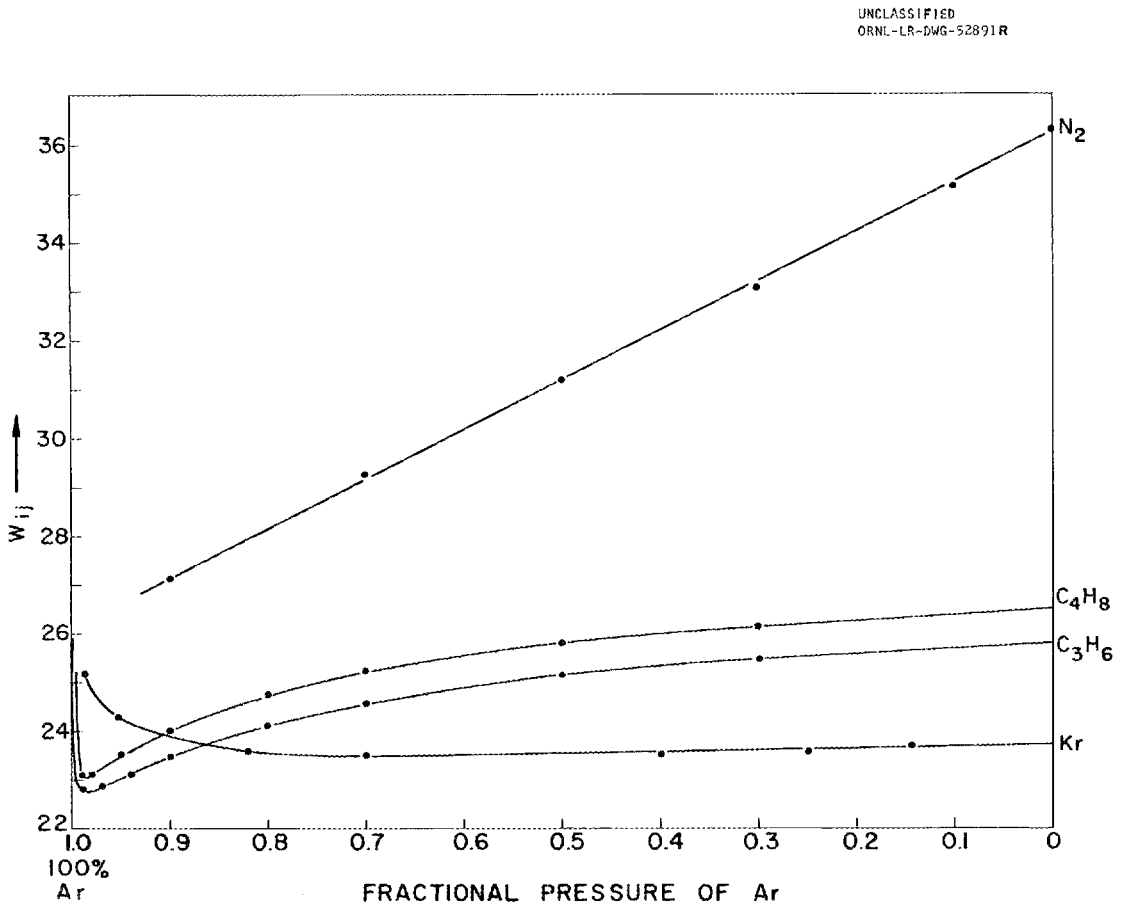

Fig. 15. Plot of W_{ij} for mixtures of Ar with N_2, Kr, C_3H_6 (cyclopropane), and C_4H_8 (1-butene), as a function of the fractional pressure of Ar in the mixture.

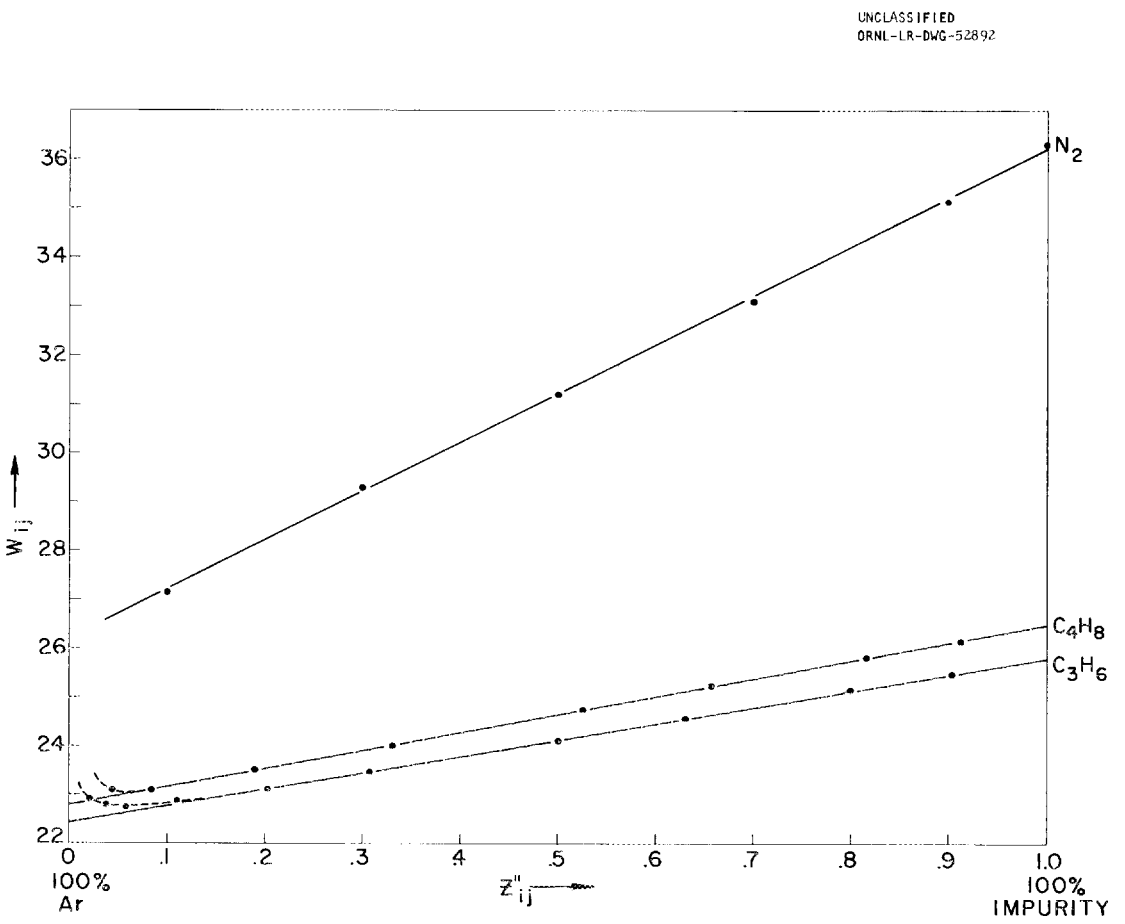

Fig. 16. Plot of W_{ij} vs Z''_{ij} for mixtures of Ar with N_2, C_3H_6 (cyclopropane) and C_4H_8 (1-butene) using constants shown in Table III.

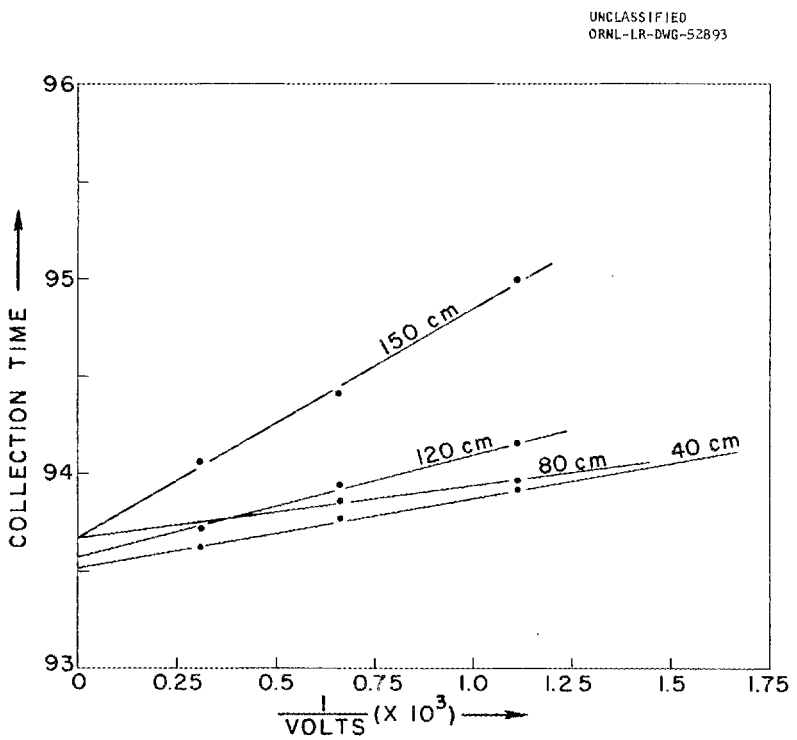

Fig. 17. Plot of collection time vs $(\text{voltage})^{-1}$, at four different pressures, for a mixture of 82% Ar - 18% Kr.

mixtures. These included 95.2% Ar - 4.8% Kr; 98.7% Ar - 1.3% Kr; 98% Ar - 2% C_3H_6; 99% Ar - 1% 1-butene; 97% Ar - 3% C_2H_6; and 95% Ar-5% O_2. Between the same pressure limits mentioned above, no consistent changes in W were detected greater than 0.2%. Most of these (with the exception of the krypton mixtures) represented mixtures near the minimum point of the W curve.

Possibility of a Jesse Effect in Nitrogen

Closer examination of Figure 1 shows an effect in nitrogen similar to the Jesse effect. This was first noticed in the case of mixtures of nitrogen and acetylene where the best straight line using Eq. (2) was obtained with $f_{ij} = 3.5$. This line, however, approached a W of 36.1 ev/ion pair instead of 36.3 ev/ion pair (the W of pure nitrogen). An illustration of this is given in Figure 18 where the nitrogen-acetylene data are drawn using several values of the constant f_{ij}.

Subsequent mixtures of nitrogen with ethylene, cyclopropane, 1-butene, and 2-butene showed the same rapid decrease in W as the first 1% to 3% of the second gas was added to the nitrogen and the more "regular" decrease from there on. Figure 19 shows an expanded view of the upper portion of these curves from $Z''_{ij} = 0.5$ to $Z''_{ij} = 1.0$ in the region near that of pure nitrogen. In the case of CO_2, the line approaches 36.3 ev/ion pair but in the case of C_2H_2, C_3H_6, and C_4H_8, the straight lines approach points considerably below the W of nitrogen. Furthermore, in the cases shown, the lower the ionization potential of the second gas, the greater is the depression of the line. In fact,

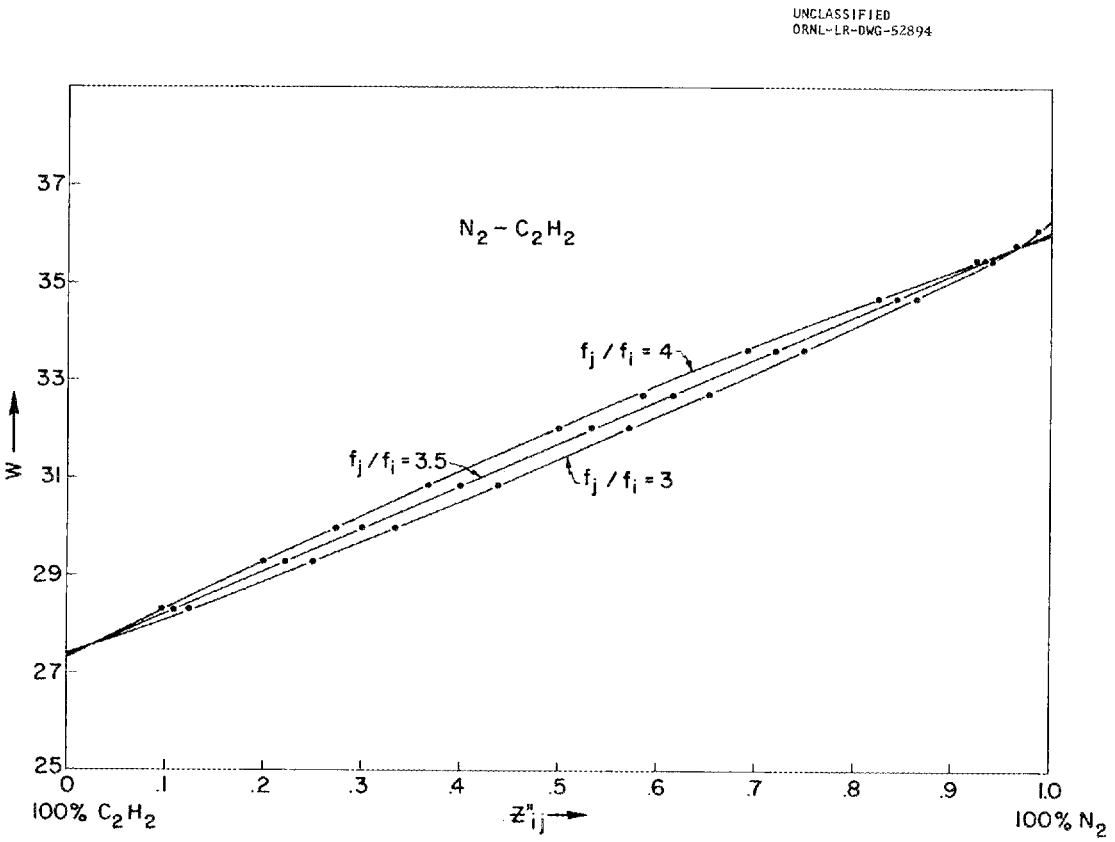

Fig. 18. Plot of W_{ij} vs Z''_{ij} for mixtures of N_2 - C_2H_2 using three different values of f_{ij}.

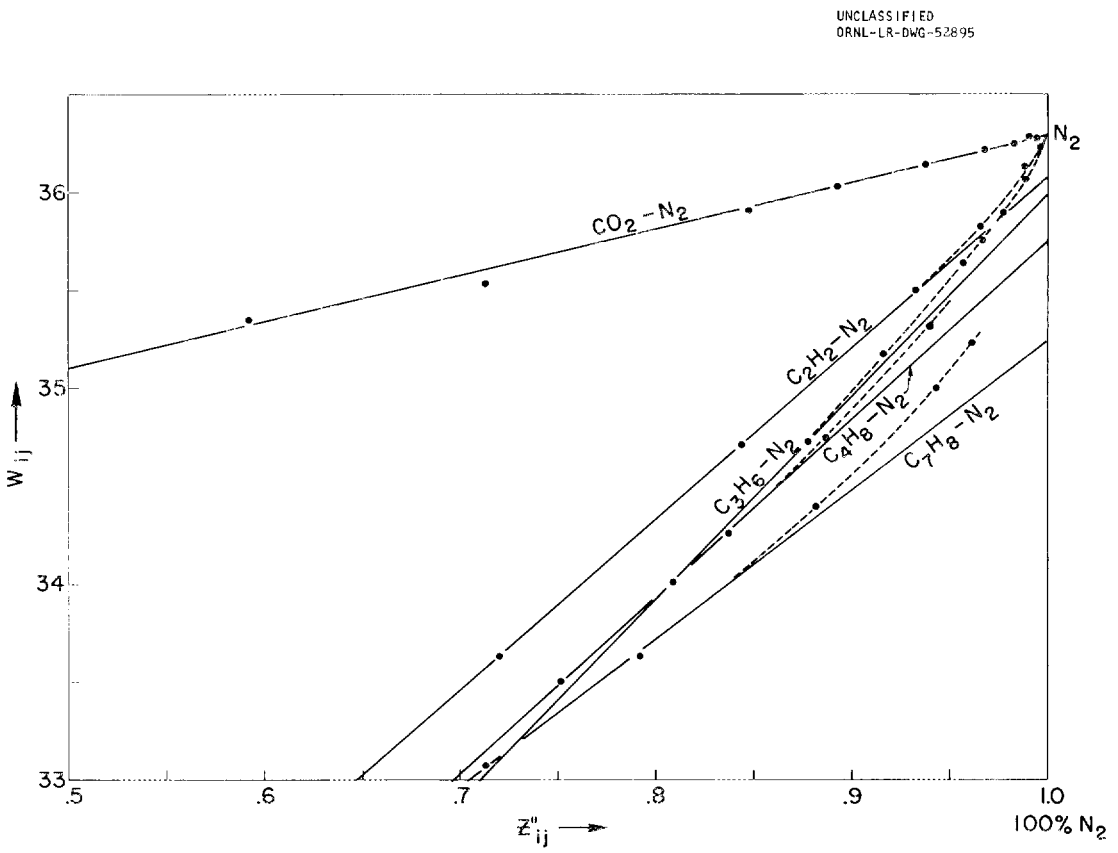

Fig. 19. Expanded scale plot of W_{ij} vs Z''_{ij} for mixtures of N_2 with CO_2, C_2H_2, C_3H_6 (cyclopropane), C_4H_8 and C_7H_8 (toluene).

in the case of cyclopropane and 1-butene, the butene has a lower ionization potential than the cyclopropane but a higher W. The initial drop in W from 36.3 ev/ion pair is therefore greater for butene and the two lines subsequently cross at about $Z''_{ij} = 0.8$.

W of Toluene Vapor

A further check on this effect was made by mixing small amounts of toluene vapor with nitrogen, since toluene has a rather low ionization potential. At room temperature, as much as 3 cm Hg of this vapor could be admitted to the chamber with nitrogen, resulting in a mixture up to 12% toluene - 88% nitrogen. Above 1% toluene, the W's of the mixtures fall on a fairly straight line, using Eq. (2), provided f_{ij} is set equal to about 15. Figure 20 shows this line as well as the curvature which results when the constant f_{ij} is made as low as 10 or as high as 20. The line approaches 35.3 ev/ion pair on the nitrogen side, indicating a large initial drop from the value of pure nitrogen (the upper portion of this curve is also reproduced in Figure 19), and approaches the value 28 ev/ion pair on the toluene side. This extrapolated estimate for the W of pure toluene may be in error by as much as 5%, but the value has been included in Table I for comparison. It points out the possibility of using this method of mixtures to obtain the W of other vapors, particularly heavy vapors, when the vapor pressure of the pure substance, at room temperature, is not alone sufficient to completely stop the alpha particles in the chamber. To substantiate further this W measurement of toluene, mixtures were also run of toluene and cyclopropane. Assuming

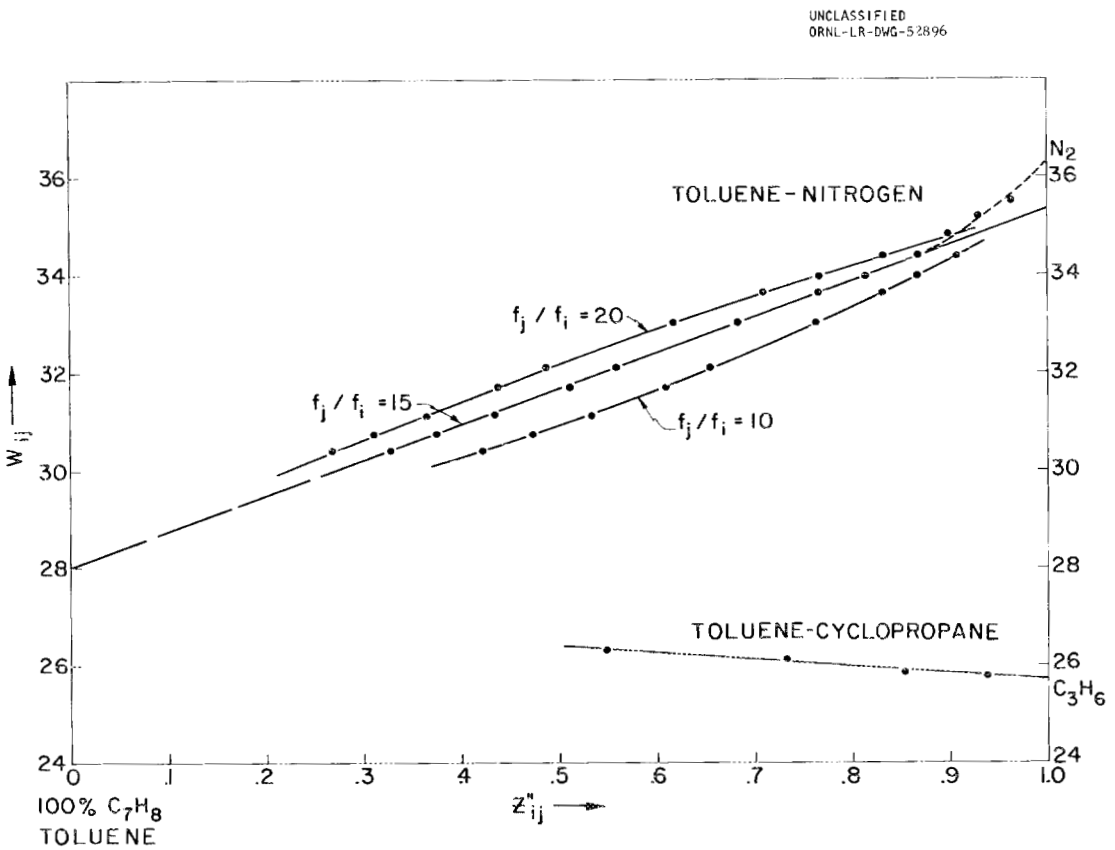

Fig. 20. Plot of W_{ij} vs Z''_{ij} for mixtures of N_2 - C_7H_8 using three different values of f_{ij}.

the validity of Eq. (3) in this case, the constant $f_{ij} = 15/4.5 = 3.3$ (using Table II) and the resulting line for this mixture is shown at the bottom of Figure 20. The W of this mixture increases with increasing amounts of toluene and extrapolates very roughly to about 27 ev/ion pair.

IV. CONCLUSIONS

The results described in this report represent an attempt to show the wide applicability of Eq. (2) [or equally well, Eq. (1)] in presenting data on W's of binary gas mixtures, even to some extent when one of the constituents is a noble gas. By use of these equations, it is possible to pick out those regions where other effects, such as the Jesse effect, are predominant, whereas these other effects might not otherwise be distinguished. Such is the case in nitrogen, where the effects of small impurities of gases with low ionization potential become noticeable only when the data are plotted in this way. It is also possible to extrapolate the straight line obtained with these equations to predict the W of pure vapors even when the vapor is part of a mixture and can only be obtained in concentrations up to 10% (by volume).

The relationship between the f constants given by Eq. (3) is somewhat surprising, and is of considerable practical interest in that it allows one to predict unknown W's of mixtures of gases such as might be found in nuclear counters. The extensive application of this relationship to other gases has not been tested, but it might be found to apply to many other molecular gas mixtures.

The accuracy of any particular combination may be limited by gas purity since no attempt was made to purify the gases used. It is worth repeating that the W's were measured relative to nitrogen which was assumed to have a W of 36.3 ev/ion pair. Furthermore, the results do not necessarily apply to monoenergetic alpha particles of 5 Mev since the energy spectrum was considerably broadened by the thickness of the Pu^{239} alpha source.

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