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CHARGE COLLECTION CHARACTERISTICS OF AN AIR ION CHAMBER FOR 0.2 -μsec PULSES OF 25 MeV ELECTRONS

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ABSTRACT

The charge collection characteristics of a parallel-plate transmission air ion chamber have been measured for 0.2-μsec pulses of 25 MeV electrons over a range of initial charge densities from 0.6 to 430 esu/cm^3. Plate spacings of 0.07, 0.40 and 0.73 cm were used with E/p values of 1 and 6; 1, 3 and 6; and 1 and 3 V/cm·mm Hg, respectively. Electron beam monitoring was done with a graphite Faraday cup. The results of the experiment were compared with calculated values of charge collection efficiency from a model that accounts for negative ion collection by means of Boag's theory and electronic charge collection by an empirical model. The relative proportion of negative ions to electron charge carriers was calculated from a theory due to Thomson and to Boag and Wilson. Charge collection efficiency as calculated from the model was in good agreement with experimental values.

I. INTRODUCTION

To monitor the electron beam of the electron linear accelerator (LINAC) at the Armed Forces Radiobiology Research Institute (AFRRI) during narrow beam operations, a parallel-plate transmission air ion chamber has been designed and fabricated. The chamber is intended to operate at dosc rates from about 3×10^5 up to 3×10^8 rads/sec. To achieve a reasonable charge collection efficiency at the higher dose rates it is necessary to operate the chamber with a plate spacing < 1 mm and at several hundred volts plate bias. Under these conditions previous measurements of chargc collection efficiency have yielded poor agreement with the prevailing Boag theory,[2-4,6,7] which is based on the assumption of total electron attachment and charge collection by positive and negative ions. There is evidence that under the conditions described above an appreciable fraction of the collected charge is carricd by unattachcd clectrons.[5,11] Ellis and Read attempted to account for this by empirically altering Boag's thcory but with little success. Thus it was decided to measure the chamber charge collection efficiency at three plate spacings and at several values of E/p and to fit the data with a model that treats ionic recombination according to Boag's theory and electronic charge collection separately by means of an empirical model.

II. CALCULATIONAL MODEL

In this section the model used to calculate chargc collection efficiency will be described. Assumptions that are made will be stated here with justifications and detailed discussion deferred to Section IV. In the model adoptcd it is assumcd that total charge collection cfficiency f_T, which is the ratio of chargc collected tc charge produced, may be written as the sum of two parts $f_T = F_i f_i + F_e f_e$ where f_i and f_e are the collection

efficiencies for negative ions and clcctrons, respectively, and are dependent on initial charge density or dose rate; F_i and F_e are the fractions of negative charge carried by negative ions and elcctrons. (Obviously, $F_i + F_e = 1.$) It is furthcr assumed that F_e depends only on E/p and plate spacing and remains constant during the charge collection process.

Calculation of electronic charge carrier fraction F_c. Consider a parallel-plate ion chamber with plates at X = 0 and X = d. Thomson[11] has shown that a free electron created at a point, X, between the plates, has a probability of reaching d, unattached, given by $P(X) = e^{-\psi(d-X)}$, where $\psi = hu/\lambda w$, and h = attachment probability per collision, u = electron mean random velocity, λ = electron mean free path, and w = electron mean drift velocity. Thus, as shown by Boag and Wilson,[5] for uniform electron production between the plates, the fraction of electrons that remain unattached is given by $F_e = \frac{1}{d}\int_o^d e^{-\psi(d-X)}dX = (1-e^{-\psi d})/\psi d$. This expression, with values of h, u, λ and w as compiled by Loeb,[8] was used to calculate F_e. Figure 1 shows F_e as a function of E/p for d = 0.07, 0.40 and 0.73 cm.

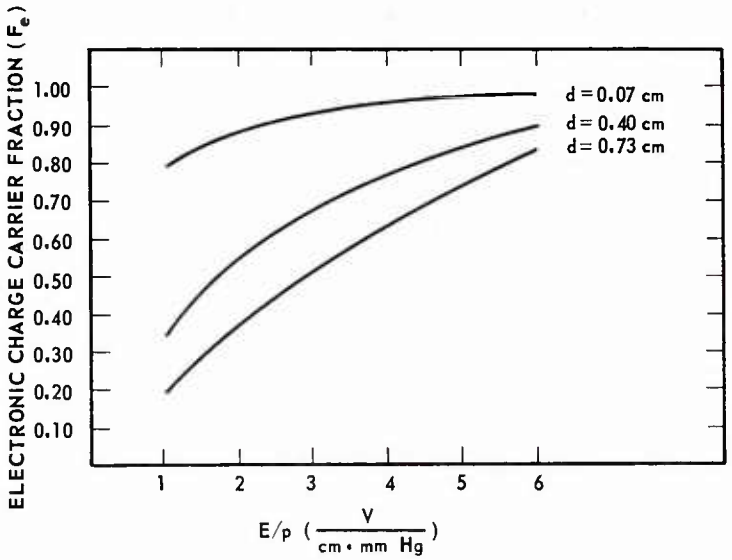

Figure 1.
Fraction of negative charge carried by electrons as a function of E/p for the indicated plate spacings

The number of electrons actually collected will depend on f_e, the chamber electron collection efficiency, which is discussed below. The model assumes that F_e and f_e are independent.

Empirical determination of electron collection efficiency f_e. Boag and Wilson[5] and Boag[4] have shown that for electronic charge collection, efficiency is limited by space charge effects, i.e., by the positive ions remaining after the electrons are collected, and that for an initial charge density $r \leq r_o = V/600\pi d^2$ esu/cm^3 for a parallel-plate chamber, collection is approximately 100 percent. V is plate bias in volts per centimeter, and d is plate spacing in centimeters. No theory exists for $r > r_o$. Thus, electron collection efficiency f_e for the present model was determined empirically. This was accomplished using experimental data calculated to have an electron fraction $F_e = 0.98$. These data, obtained at a plate spacing of 0.07 cm and with $E/p = 6$ V/cm·mm Hg, are shown in Figure 2 along with that for $E/p = 1$. Values of r_o are

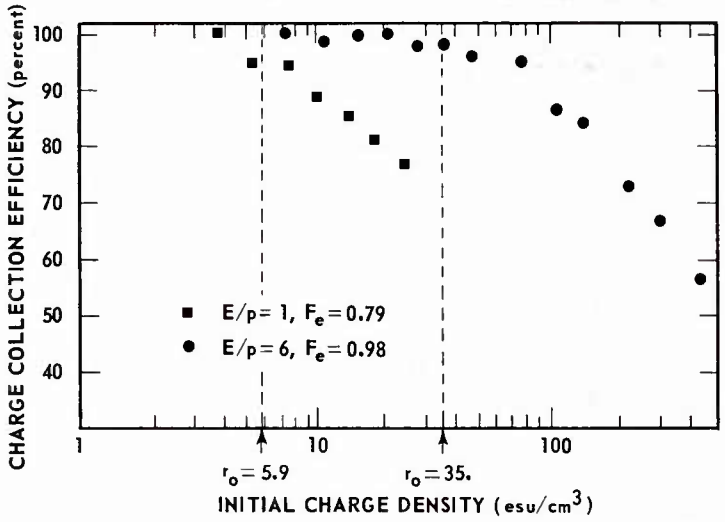

Figure 2. Measured total charge collection efficiency as a function of initial charge density for a plate spacing of 0.07 cm and the indicated values of E/p. For $r < r_o = V/600\pi d^2$, electronic charge collection is ~100 percent efficient.

indicated. The curve for $E/p = 6$ is in excellent agreement with the assumption that $f_T \approx 100$ percent for $r \leq r_o$ and less than 100 percent for $r > r_o$. The data taken at the same plate spacing with $E/p = 1$ do not fit that criterion.

To obtain a curve of $f_e(r)$ useful for calculational purposes, the $E/p = 6$ data ($F_e = 0.98$) were plotted with initial charge density normalized to 1 at $r = r_o$ as shown in Figure 3. It was then assumed that for other experimental conditions, with initial charge density in units of r_o, electron collection efficiency f_e could be read from this curve. The solid curve is the best visual fit to the $E/p = 6$ data. Also shown in Figure 3 are values of $f_e(r)$ obtained from the experimental data with $d = 0.07$ cm and $E/p = 1$. Under these conditions $F_e = 0.79$ and f_e is not the same as the measured f_T and must be calculated from the model, i.e., $f_e = (f_T - F_i f_i)/F_e$. (The f_i was calculated from Boag's theory as described below. Actually, for the sake of

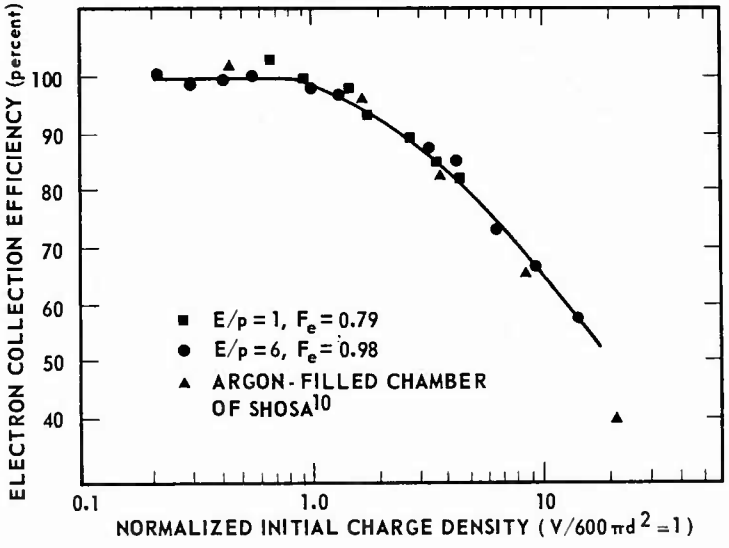

Figure 3. Electron collection efficiency as a function of normalized initial charge density ($r_o = V/600\pi d^2 = 1$) for the data indicated. The solid curve was used to determine f_e in the model.

consistency, the E/p = 6 data were calculated in the same way, though clearly for $F_e = 0.98$, $f_e \approx f_T$.) The two sets of data are in good agreement.

The triangular data points in Figure 3 are from the work of Shosa[10] of this laboratory. He has measured the charge collection efficiency of a miniature 0.5 cm^3 argon-filled ion chamber for short LINAC pulses and some of his data, with r normalized to 1 at r_o, are shown. Argon does not normally form negative ions so charge collection is entirely electronic. At moderate dose rates, up to about 3 r_o, where collection efficiency is still close to 90 percent, the agreement between Shosa's data and the E/p = 6 data may be interpreted as verification that at d = 0.07 cm and E/p = 6 V/cm·mm Hg, charge collection in the parallel-plate chamber is largely electronic. At higher dose rates, because charge loss mechanisms in the two chambers may be quite different, the meaning of the agreement is not so clear.

Boag's treatment of negative ion collection efficiency. Boag's theory of charge collection is well known and will not be discussed in detail.[2-4] Briefly, the theory assumes that charge collection is by positive and negative ions and is limited by ionic recombination. The collection efficiency is given by $f_i = [\ell n(1+u)]/u$, where $u = \mu r d^2/V$ with r = initial charge density in esu/cm^3, d = plate spacing, V = plate bias voltage, and $\mu = \alpha/(k_- + k_+)e$ where α = ionic recombination coefficient, $k_\pm$ = ion mobilities and e = electronic charge in esu. As suggested by Boag, μ is usually taken as an adjustable parameter to be determined by fitting the data. In this way local experimental conditions are accounted for. In using Boag's theory to calculate f_i for this model McGowan's[9] value of $\mu = 750$ V·cm/esu for laboratory air was used. As a check, data from the present experiment, with the minimum electronic charge carrier fraction

$F_e = 0.21$, were used to obtain $f_i = (f_T - F_e f_e)/F_i$. (Throughout this work f_T will be used for total charge collection efficiency whether experimental or calculated. As used in context no confusion is anticipated.) The best Boag theory fit to these data was obtained for $\mu = 792\,V \cdot cm/esu$, in good agreement with McGowan.

In summary, the charge collection model for this investigation assumed that collection efficiency could be written as $f_T = F_e f_e + F_i f_i$. The fraction of electrons that remain unattached F_e was calculated from a theory due to Thomson[11] and to Boag and Wilson,[5] with parameters as compiled by Loeb.[8] Negative ion collection efficiency f_i was calculated from Boag's[2] theory with $\mu = 750\ V \cdot cm/esu$. Electron collection efficiency f_e was determined using the empirical model described above.

III. EXPERIMENTAL CONSIDERATIONS

The ion chamber. Figure 4 is a drawing of the ion chamber without the plates in position; a plate is shown alongside. The chamber is composed of two pieces of Lucite with a 2" diameter circular cutout in each and a pair of arc-shaped 0.029" thick pieces of aluminum sandwiched between. The aluminum serves as shoulders on which the plates rest, spacers to separate them and electrical conductors for plate bias and charge collection. The plates are 2" diameter x 1/32" thick polystyrene with 0.001" thick aluminum foil as the conducting surface. A portion of each plate is left bare of foil, as shown in Figure 4, so that each plate can rest on both aluminum shoulders while in electrical contact with one. Variation in plate separation is achieved by using additional spacers between the shoulders and plates.

Charge collection and measurement was by means of a Keithley electrometer system and a Hewlett-Packard precision digital voltmeter.

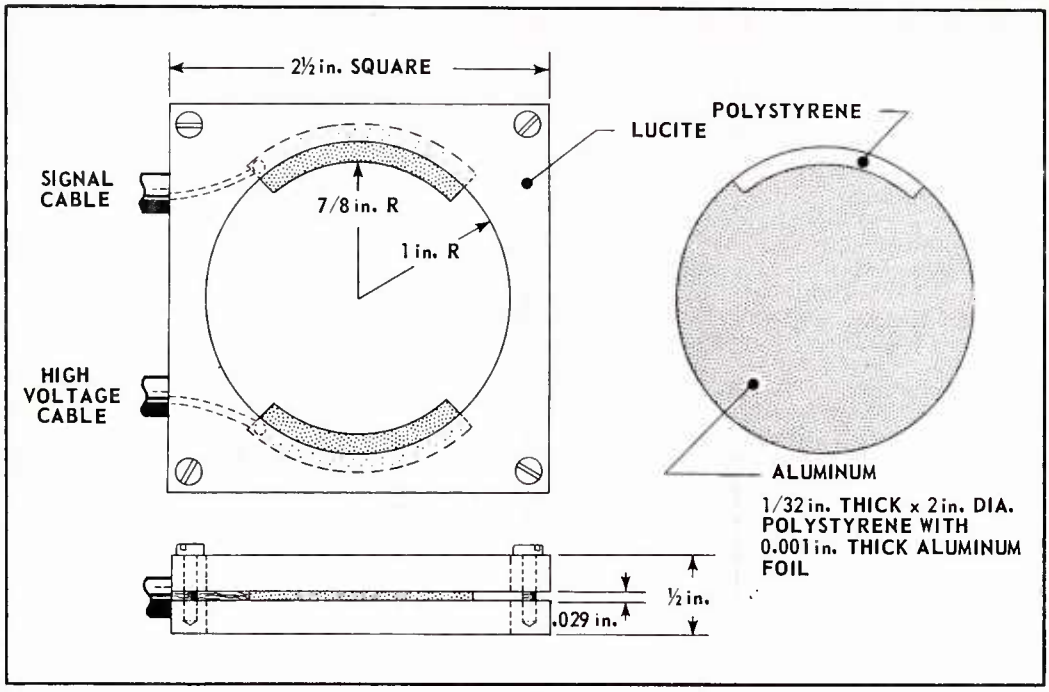

Figure 4. Transmission ion chamber without the plates in place. The plates rest on each side of the aluminum spacers, the metal conductor being removed at one edge of each plate.

Apparatus arrangement. Figure 5 is a schematic diagram of the experimental arrangement. Electron collimation was achieved by means of a 6" o.d. x 1" i.d. x 10" long Lucite collimator. The 2' square x 6" thick outer shield was of high density Masonite. The 2" thick lead collimator was to attenuate bremsstrahlung radiation produced in the Lucite. The ion chamber was directly behind the lead collimator and ~ 1" behind that was a 2-3/4" diameter x 4-1/2" long graphite Faraday cup in an evacuated brass chamber. Beam access to the Faraday cup was through 0.003" of brass. Charge was collected and measured as with the ion chamber. The entire experiment was mounted on a movable table so that radiation dose, i.e., initial charge density, could be varied by changing the distance to the LINAC beam exit window.

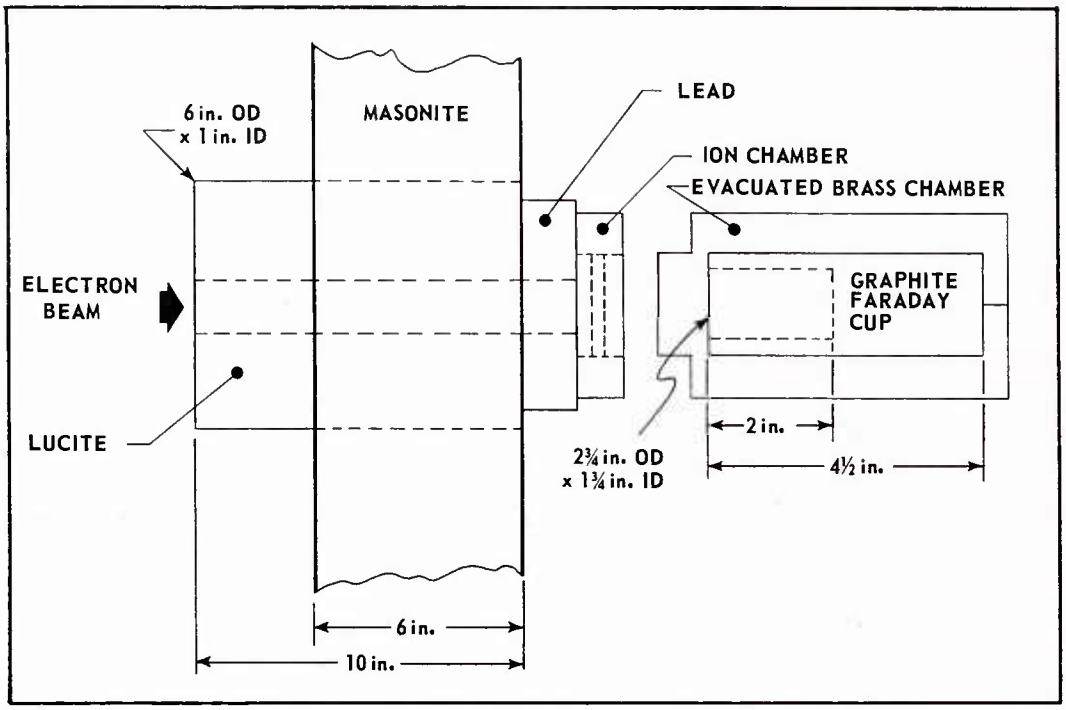

Figure 5. Schematic diagram of the experimental arrangement. The electron beam is collimated to 1" in diameter before passing through the ion chamber and into the Faraday cup.

Dose could also be varied remotely by inserting various thicknesses of polystyrene scatterer in the beam at the exit window. Experimental data were obtained by simultaneously measuring ion chamber and Faraday cup outputs for each point.

Correlation of radiation dose and beam current. Values of initial charge density, in esu/cm^3 per unit beam current, were calculated using 33.7 eV per ion pair and Berger and Seltzer's[1] air stopping powers, yielding 45.6 esu/cm^3.n coulomb of beam for $\rho_{air} = 1.19 \times 10^{-3}$ g/cm^3. This number was then compared with the results of a previous experiment in which 1-cm thick containers of ferrous sulfate solution were exposed while monitoring with the Faraday cup; the ferrous containers replaced the ion chamber in the present experiment. With a g value of $g(Fe^{3+}) = 15.6$ ions

per 100 eV and maintaining a dose rate less than 50 rads per 1-μsec pulse, this experiment yielded a value of 38.8 $\pm$2 percent water-rads/n coulomb of beam, which converts to 43.0 esu/cm^3·n coulomb, 5.7 percent less than the calculated value. The average of the two values, 44.3 esu/cm^3·n coulomb, was used.

IV. RESULTS AND DISCUSSION

Figure 6 shows the data obtained at plate spacings of 0.40 and 0.73 cm for the indicated values of E/p. The solid curves were calculated from the model; the points are experimental. As is apparent, agreement is excellent.

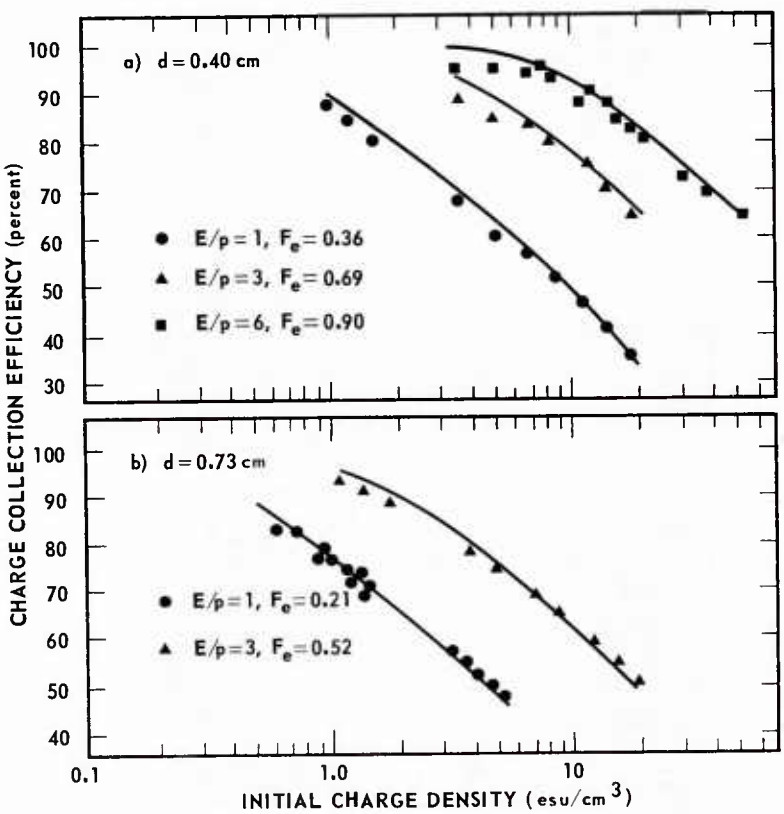

Figure 6. Charge collection efficiency as a function of initial charge density for plate spacings of 0.40 and 0.73 cm. The solid curves are calculated and the points experimental.

Figure 7 shows six sets of experimental data with total collection efficiency plotted against rd^2/V. The solid curves are best visual fits to the experimental points for $F_e = 0.98$, 0.52, and 0.21 and are included merely to clarify the trend of the data. It is evident that the data points are grouped according to the fraction of negative charge carried by electrons, as calculated from the model, with the minimum F_e points grouped about the lower curve, the maximum F_e points about the upper curve, and the remainder of the data appearing, in order, in between. It is also of interest that the best Boag theory fit to the $F_e = 0.98$ data is obtained for $\mu \approx 230$ V·cm/esu and to the $F_e = 0.21$ data with $\mu \approx 610$ V·cm/esu. A linear extrapolation to $F_e = 0$ gives $\mu \approx 715$ V·cm/esu in good agreement with McGowan's value. While it is not meant to be implied that such a linear extrapolation is valid in an absolute way, clearly the trend is correct.

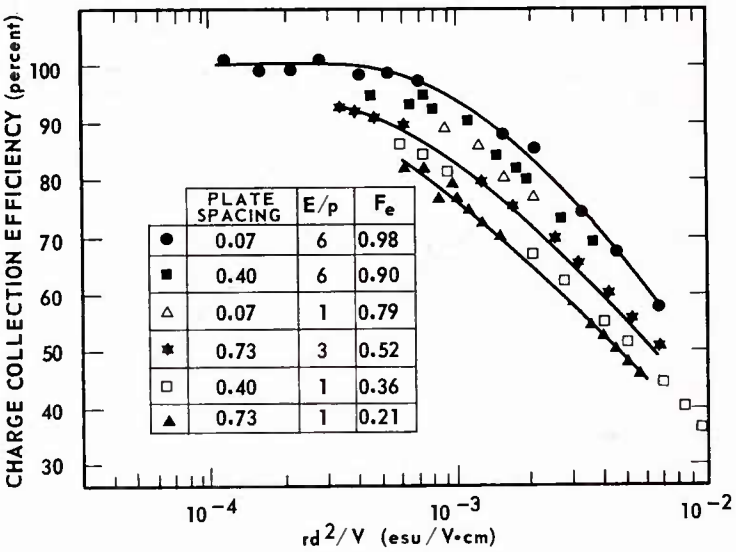

Figure 7. Charge collection efficiency as a function of rd^2/V. The solid curves are best visual fits to the data for $F_e = 0.98$, 0.52 and 0.21.

Experimental reproducibility was excellent. The data were accumulated over a period of several days and results could be reproduced to better than ± 2 percent. The only exception to this was the one case where plate voltage was 1800 V and leakage current was somewhat high. There reproducibility was about ± 3 percent.

The primary purpose of this experiment was to generate a set of experimental charge collection data, obtained over a reasonably wide range of conditions, and to fit the data with the simplest model possible that treated ionic and electronic charge collection as separate phenomena. That the best fit was obtained with a model initially intended as a first approximation was somewhat surprising and is probably due to the cancellation of several compensating effects.

As a first approximation, and at moderate dose rates, the model is reasonable. Electrons are about 10^3 times more mobile than ions, and those that remain unattached, i.e., do not form negative ions, are collected within a few tens of nanoseconds of the end of a radiation pulse. The positive and negative ions remaining are then collected on a microsecond time scale, negative charge density being reduced by the amount collected as electrons. Any particular negative ion will have about the same probability of undergoing a collision with a positive ion as when all electrons are attached. Thus, one would expect that the collection efficiency calculated from Boag's theory, multiplied by an appropriate weighing factor, would yield the contribution of negative ions to the total charge collection. This argument does not include the effects of space charge which become significant at higher dose rates.

Electronic charge collection is limited by space charge effects. It has been shown that at some initial charge density r_o and below, where the collecting field just

goes to zero at the positive plate, collection efficiency is approximately 100 percent. This situation is schematically diagramed in Figure 8a. For $r > r_o$ the field will approximate zero at some distance S in front of the plate, and a static field free region will be created in the chamber, as illustrated in Figure 8b. Electrons trapped in this region will be collected with some efficiency between 0 and 100 percent. As shown by Boag and Wilson,[5] if one assumes that all electrons trapped are lost, then $f_e = 1 - S/d$, which was shown to underestimate collection efficiency. Obviously not all are collected. Since no generally accepted theory has been proposed to calculate this fraction, for the model of this experiment electron collection efficiency was determined empirically.

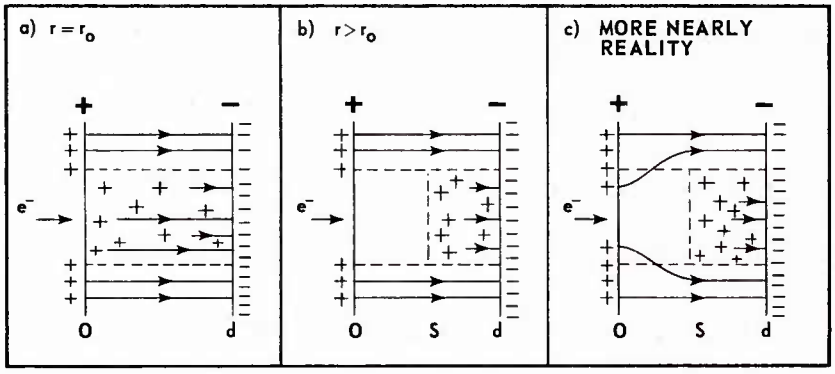

Figure 8. Schematic diagram of the charge collection in a transmission parallel-plate ion chamber for a) $r = r_o$ so that the field just goes to zero at plate O; b) $r > r_o$ where the field goes to zero at a distance, S, in front of plate O; and c) more nearly the true situation for $r > r_o$.

The two charge collection mechanisms, ionic and electronic, are not independent as assumed in the model. Space charge created by rapid collection of electrons will reduce the collecting field and thus the collection efficiency of negative ions. The relatively immobile negative ions created by electron attachment will reduce the density of the positive space charge and increase electron collection efficiency. These effects

are in opposite directions and are small, except at high dose rates. They apparently cancel each other to a remarkable degree for this particular chamber and set of experimental conditions.

The method of determining F_e, as described in Section II, is sound theoretically and the values calculated are uncertain only to the extent that the parameters h, u, λ, and w are uncertain. These are experimental, as compiled by Loeb,[8] and uncertainties are difficult to ascertain. However, one reasonable interpretation of the data presented in Figure 7 is that the F_e's are fairly accurate. The assumption that F_e remains constant during the entire charge collection process is reasonable at moderate dose rates. F_e is not a particularly strong function of E/p, and the collecting field changes significantly only at high dose rates where space charge effects are large.

V. SUMMARY AND CONCLUSIONS

An experiment has been designed and carried out to measure the charge collection efficiency of a parallel-plate air ion chamber for 0.2-μsec pulses of 25 MeV electrons. The data were obtained at plate spacings of 0.07, 0.40 and 0.73 cm with values of E/p of 1 and 6; 1, 3, and 6; and 1 and 3 V/cm·mm Hg, respectively. Calculated values of charge collection efficiency were obtained from a model that treated ionic and electronic charge collection as independent phenomena. A phenomenological argument was presented to show that, while the model is partially empirical, it has some physical merit at moderate dose rates. When space charge effects are large, the model is primarily empirical and its general applicability to other ion chambers and other experimental conditions is open to question, though agreement with Shosa's[10] data (Figure 3) was good at 20 r_o.

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