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X-ray Calibration of Radiation Survey Meters, Pocket Chambers, and Dosimeters

By Frank H. Day

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Contents

X-ray Calibration of Radiation Survey Meters, Pocket Chambers, and Dosimeters

Frank H. Day

The responses of instruments of ionization-chamber and Geiger-Müller counter types to measured exposures or intensities have been studied for radiations generated by applied X-ray tube potentials ranging from 30 to 1,200 kilovolts. The results of these studies indicate that instruments of a given type constructed by different manufacturers behave similarly in the 250 to 1,200-kilovolt range. However, marked discrepancies occur among instruments of the same type constructed by different manufacturers for radiations generated by potentials lower than 250 kilovolts. These discrepancies are related to the atomic numbers of the wall materials that envelop the sensitive volumes of the instruments.

I. Introduction

With the tremendously increased demands for nucleonic instruments of the monitoring and survey types, greater attention is now being directed to their performance and to the standardization of their component parts. Of special interest is a more detailed knowledge of the response of a particular instrument to radiations covering a wide energy band. It is furthermore becoming more necessary to standardize the design factors to a maximum degree in order that the number of models of instruments for a specific purpose may be minimized. It is probably desirable also to approach instrument standardization to the point where there is a greater interchangeability of essential parts. The movement in standardization is being sponsored by the Atomic Energy Commission, the National Military Establishment, and the Radio-Television Manufacturers Association, the latter organization being concerned with standardization for users other than government agencies.

As a part of the general program of standardization, the National Bureau of Standards has contracted with the Atomic Energy Commission and the National Military Establishment for the calibration of instruments of the health-physics type. One phase of the work for the Atomic Energy Commission has been completed, and is summarized in this report. The primary objective has been to determine correction factors[1] of detectors for various qualities of radiation. This was accomplished by observing their readings in beams for which exposure rates were established by standard chambers for various applied X-ray tube potentials and beam filtrations. Of secondary concern has been the observation of details relating to the durability of the instruments and the reproducibility of results. Each of these has been noted under conditions of their normal usage.

Instruments submitted by the Atomic Energy Commission fall into two classes. The first consists of condenser ionization chambers with a 200-mr full-scale range, otherwise known as "pocket chambers"[2] and "pocket dosimeters".[3] The other consists of survey meters of Geiger-Müller counter and ionization-chamber types. A list of the various units studied is given in table 1.

TABLE 1. *Description and number of instruments of each type.*

Number of units	Instruments	Model No. or trade name	Manufacturer
50	Pocket chambers	Minometer	The Victoreen Instrument Co.
50	do	Idl	Instrument Development Laboratory.
50	do	K-700	The Kelley-Koett Manufacturing Co.
3	Charge-readers	Minometer	The Victoreen Instrument Co.
2	do	K-425	The Kelley-Koett Manufacturing Co.
50	Pocket dosimeters	BM-17400	Cambridge Instrument Co., Inc.
50	do	Ring-type	Arnold O. Beckman, Inc.
50	do	K-109	The Kelley-Koett Manufacturing Co.
2	Charging units	K-135	Do
7	Geiger-Muller counter survey meters	2610	Nuclear Instrument & Chemica Corp.
4	do	263A	The Victoreen Instrument Co.
1	do	263B	Do
3	do	SM-3	El-Tronics, Inc.
3	do	101	Precision Radiation Instruments, Inc.
3	Ionization-chamber survey meters	247A	The Victoreen Instrument Co.
3	do	RD-316	Sylvania Electric Products, Inc.
3	do	MX-6	National Technical Laboratories.

[1] The term "correction factor", as here used, is a number by which readings of radiation detectors must be multiplied to obtain true readings in roentgens, or roentgens per unit time.

[2] "Pocket chamber" is a term used to designate a condenser ionization chamber of fountain-pen size that is used in conjunction with an auxiliary electrometer and charging device known as a "charge-reader".

[3] "Pocket dosimeter" is a term used to designate a condenser ionization chamber of fountain-pen size which has an integral reading mechanism and which is charged with a device known as a "charging unit".

II. Calibration of Pocket Chambers and Pocket Dosimeters

1. Method and Precautions

Three sets of 50 pocket chambers and 3 sets of 50 pocket dosimeters were calibrated for radiations generated by applied X-ray tube potentials of 50, 100, 250, and 1,200 kv, and 5 chambers[4] were then selected from each set, the correction factors of which correspond most closely to the average correction factor of each set. Additional correction factors were obtained for the selected chambers for radiations generated by applied tube potentials of 30, 40, 75, 150, 200, 500, 800, and 1,000 kv. Two readings were observed for each chamber at each radiation quality.

In view of the large number of readings involved, it was desirable to expose several chambers simultaneously. To do this the chambers were supported by placing their ends in holes bored 4 cm apart in wooden supports of dimensions 2 by 2 by 95 cm. Scattering by the supports and mutual scattering among chambers contributed little to the chamber readings. This was evident by observing that the readings were not noticeably different as the chambers were held, first, by a wooden support and, second, by strings, provided that the chambers were separated by at least 4 cm. Corrections for various chamber positions in the wooden supports were necessary because the standard chamber measurements were made only in the center of the beam, and radiations which diverged sufficiently from the center to cover chambers in off-center positions were somewhat less intense than those of the center of the beam. These corrections were determined by measurements made with a given set of chambers moved successively from one position to another until each chamber had occupied each of the positions on the support. The sum of the readings of the chambers in the center position divided by the sum of the readings of the chambers in a given off-center position gave a factor by which the subsequent chamber readings in this off-center position were multiplied. These factors varied from 1.00 in the center of the beam to maxima of 1.06 to 1.10, depending upon the applied tube potentials, beam filtrations and target-to-chamber distances. Position corrections were determined for radiations generated by tube potentials of 50, 100, 250, and 1,200 kv, inasmuch as 50 chambers of each set were calibrated for each of these radiation qualities. They were not determined for exposures at the intermediate tube potentials because only the selected chambers were exposed to these radiations, and of these only five were exposed simultaneously. Position corrections required for five chambers only were 0.5 per cent or less for the four radiation qualities for which these were determined. They were, therefore, assumed to be negligible for radiations of the intermediate qualities.

[4] For brevity the term "chamber" is hereinafter used for either "pocket chamber" or "pocket dosimeter", unless one of the latter is explicitly designated.

Readings of ionization chambers that are not hermetically sealed vary with atmospheric temperature and pressure. Inasmuch as readings were taken over a period of several days, they were reduced to the common base of 22° C and 760 mm mercury pressure. The atmospheric correction is then

$$2.576\left(\frac{273 + t}{p}\right),$$

where t is the temperature in degrees centigrade, and p is the pressure in millimeters of mercury at the time observations were made.

Pocket chamber clips, when placed in the direction of an incident beam, caused a noticeable reduction in readings for all radiations produced by a potential of 100 kv or less. Therefore, the clips were placed at 90 degrees to the direction of the incident beam for all the measurements.

The chambers were exposed at sufficiently low intensities to insure that practically all of the ions produced within the chamber cavities would be collected. In other words, the chambers were calibrated under assured saturation conditions. Intensities at which the chambers were exposed ranged from 20 to 30 mr/min. Intensities of approximately 10,000 times these are permissible as far as the saturation limitation is concerned. However, saturation is not attained if full-scale readings are observed in less than about 1/25 second.

It is necessary to take the precaution of observing the fiber position of a pocket dosimeter because the fiber weight is not negligible and, therefore, its position depends upon the orientation of the instrument in the earth's gravitational field. The dependence of position upon orientation is referred to as a "geotropic effect", and its magnitude may be expressed as a percentage of full-scale deflection which is observed by holding a dosimeter horizontally and rotating it through 180 degrees. The average magnitude of the effect is 5 percent for Kelley-Koett dosimeters, 6 percent for Cambridge dosimeters, and 11.5 percent for Beckman dosimeters. To reduce readings to a common base, the dosimeters were directed horizontally and rotated until their fibers became vertical.

The fiber of a charge-reader usually undergoes a change of position upon removal of a pocket chamber from its barrel. An equal and opposite change of position is observed upon reinsertion of the chamber into the barrel. Some of the change of position of the charger fiber may result from contact potentials, particularly if electrodes of pocket chambers and charge readers are constructed of dissimilar materials. A portion of the fiber shift may also be ascribed to the change of voltage on a pocket-chamber-charge-reader combination that is caused by the change of capacitance resulting from insertion or removal of a chamber. To compensate for deflections that result from removal and insertion, it has been the practice to observe the position of the fiber upon removal of a chamber from a charge-reader and to reset it at the same position just prior to reinsertion of the chamber. For a large number of chambers it is, therefore, desirable that the deflections of the various chambers be uniform so that it is not necessary to earmark individual chambers for their deflections. These deflections were not uniform for Victoreen pocket chambers and Minometers because of bronze fingers that were attached to the central electrodes of the Minometer barrels to make sliding contact with the central electrodes of the pocket chambers. Deflections of plus to minus 1 division from the zero position resulted while the fingers were in place to slide over the central electrodes of aluminum. The fingers were therefore removed, and the deflection for these chambers then became uniformly 0.3 division. It should be noted that removal of the fingers changed the capacitance of the pocket-chamber Minometer combinations, and, hence, the correction factors for them. Thus, for million-volt radiation the average correction factor of Victoreen chambers changed from 1.06 with the fingers in place to 1.00 with the fingers removed. All data observed with Victoreen Minometers were obtained with the fingers removed.

Idl pocket chambers were used in conjunction with Victoreen Minometers. The fingers were removed from Minometers for Idl-chamber readings so that the required pressure could be applied to make contact. These chambers have diaphragms designed to make them watertight, and in order to make contact with the central electrodes, it was necessary to apply a force of about 6 pounds. If this is not done, readings will be approximately one-tenth the proper value. Capacitative deflection of Minometer fibers was approximately 0.7 division for Minometer-Idl-chamber combinations.

Kelley-Koett pocket chambers were used in conjunction with Kelley-Koett charge-readers, and the capacitative deflection for this combination was uniformly 0.7 division. It was not feasible to use a Kelley-Koett chamber with a Victoreen Minometer because the capacitative deflection threw the fiber off scale.

2. Standardization Equipment

Two sets of standardization equipment were used, on a Westinghouse constant-potential X-ray generator, together with a free-air standard chamber, and the other a 10-section rectifier-type generator constructed by the General Electric Co., together with a cavity chamber having a ⅛-inch Bakelite wall.

The Westinghouse machine was used for the range 30 to 250 kv of applied X-ray tube potentials and the General Electric machine for the range 500 to 1,200 kv. The inherent filtration of the Westinghouse machine is equivalent to approximately 3 mm of aluminum. For the General Electric machine it is 2.8 mm of tungsten, plus 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water.

The free-air chamber had an effective volume of 5,498 cm^3 for a parallel beam of X-rays. On the other hand, the total volume between the collector electrode and the high-voltage plate was 170,000 cm^3, all of which was ionized by cosmic rays and natural radioactivity. The exposure rate of X-rays alone was determined by subtracting the ionization current caused by cosmic rays and natural radioactivity from the ionization current observed as X-rays irradiated the 5,498-cm^3 volume.

The cavity chamber used as a standard has an air volume of 2,320 cm^3. As a check on its reliability for measurement in roentgens, it was exposed to a standard radium sample. A factor of 1.04 was applied in the calculation inasmuch as bakelite, according to Laurence[5] is not air-equivalent[6]. One percent agreement was obtained between the amount of ionization collected in the 2,320-cm^3 air volume and the amount which should be collected, assuming the usually accepted emission constant of radium.

While this method of high-energy X-ray measurement is probably satisfactory within a few percent, it should be pointed out that the absolute measurement of million-volt radiation is not settled. This problem is being studied with the Bureau's standard pressure chamber.

To insure that the radiation measured by the chamber under study be nearly all primary radiation, lead-brick walls were constructed close to the tubes in addition to the lead shielding already incorporated in their housings, thus to reduce the intensity of background[7] radiation to 0.05 mr/hr. or less at the positions of measurement. The measured radiations were thus almost entirely those that proceed directly from the targets to the detectors. While some scattered radiation from the filters interposed in the path of the beam reached the detectors, it was minimized by the use of narrow beams and by using filters of high-atomic-number materials placed as close as practical to the tube targets. Lead was selected as the filter except at 30 and 40 kv, where aluminum and copper were used because sufficient intensity was not attained for practical measurements through lead filters. The measurements were taken as close to the targets as practicable in order to have sufficient intensities for the use of large amounts of filter, with consequent less heterochromatic beams. Correction factors for given applied tube potentials were determined with different filtrations. No noticeable change of correction factors was observed for given applied tube potentials for filtrations somewhat greater or less than those used for the calibrations. The target-to-chamber distance was 2.3 m for the Westinghouse machine and 4.0 m for the General Electric machine.

[5] G. C. Laurence, Can. J. Research, **15,** 67–78 (1937).

[6] An air-equivalent wall material of a cavity ionization chamber is one which causes the same ionization rate per cubic centimeter of air to be developed within its cavity as is developed within a free-air chamber exposed in a beam of the same quality and intensity.

[7] The term "background", as here used, refers to the reading of a Geiger-Muller counter placed at the positions where calibrations were made when the tube portal was covered by a barrier that was many half-value layers thicker than the lead shielding. It thus includes scattered radiation that is transmitted through the shielding, as well as cosmic rays and natural radioactivity.

Ionization currents were measured to accuracies of about 1 percent with FP–54 electrometers used as null-detectors. These were employed in circuits in which the potential drops produced by the ionization-chamber currents across calibrated Victoreen "hi-meg" resistors were measured with a portable potentiometer.

The beam from the Westinghouse machine was directed horizontally at a height of 104 cm from the floor and exposure rates were established in the plane of the limiting diaphragm of the free-air chamber. The chamber, operating on tracks 11 meters long, was driven away from the tube 3 m or more, and the detectors were then exposed under the conditions for which the exposure rates had been established. The beam was diaphragmed near the X-ray tube to be as narrow as practicable, thus minimizing scattering from the floor and objects in the room. In most cases the divergence of the primary beam was insufficient to allow it to strike the floor ahead of the positions of the radiation detectors.

The beam of the General Electric machine was directed vertically into a pit at the top of which exposures were made. The pit is 1.8 m square by 3 m deep. The divergence of the beam was such that it first struck the sidewalls about halfway down. The contribution to the measured intensities from sidewall scattering was less than 1 percent, as determined by the differences between measured intensities and those expected according to inverse-square-law calculation for various positions within the pit.[8]

3. Discussion of Pocket Chamber or Dosimeter Correction Factors

Theoretical and experimental evidence, summarized by Gray[9], shows that if a homogeneous medium is uniformly irradiated, the energy absorbed may be represented by ionization of air in a tiny cavity within the medium. The standard homogeneous medium is the air of a free-air chamber. Furthermore, electronic emission and stopping power of media of various atomic numbers depends upon the energy of the radiation. Therefore, wall materials of pocket chambers or dosimeters must have the same effective atomic number as air for their readings to agree with those of a standard chamber over a wide range of wavelengths.

It is apparent from table 2 that manufacturers have attempted to attain air-equivalent construction by the use of low-atomic-number wall materials, for example, polystyrene, methyl methacrylate, or cellulose acetate butyrate; also, by the use of materials like graphite and Formvar (polyvinal formaldehyde) for conducting coatings. However, the effective atomic number of the chambers is still too high, for, as seen in figure 1, correction factors for all pocket chambers and dosimeters are less than 1.00 for radiations generated by applied tube potentials in the range 40 to 250 kv. This indicates the presence of too much ionization, the maximum of which occurs for a tube potential of about 100 kv. At this potential Victoreen, Idl, and Kelley-Koett pocket chambers have readings that are about 1½ times too high. Cambridge and Kelley-Koett pocket dosimeters have readings that are about twice the proper value, and Beckman pocket dosimeters about four times. It is the practice to use phosphor bronze central electrodes for pocket dosimeters, while aluminum is used for pocket chambers. The high photoelectric emission of the phosphor bronze explains, at least in part, why correction factors are farther from 1.00 for pocket dosimeters than for pocket chambers. The readings of the Beckman dosimeter are even further from correct values in the region of predominant photoelectric emission than are those of other chambers because, in addition to the use of a phosphor bronze central electrode, it has an aluminum wall which is not coated with sufficient thickness of Formvar to establish electronic equilibrium in the Formvar for 100-kv radiation. The excessive photoelectric emission of high-atomic-number materials may be eliminated by coatings of air-equivalent materials, provided that they are sufficiently thick to cover the range of predominant photoelectric emission, that is, for radiations ranging in energy up to about 350 kev. A coating of an air-equivalent material that is sufficiently thick to establish electronic equilibrium therein for radiations up to this energy requires a thickness of about 0.1 g/cm^2.

Kelley-Koett and Victoreen pocket chambers have bare aluminum in contact with their sensitive volumes in the caps and cap ends of the chambers. The presence of the bare aluminum accounts for the fact that these chambers have correction factors of about 0.7 for 100-kv radiation. This has been demonstrated by blocking radiation from striking the bare aluminum, and then observing that the chamber readings are independent of radiation quality in the range, 100 to 250 kv of applied tube potentials. Fifteen percent less ionization was observed for a tube potential of 50 kv than was observed for 250 kv. The lesser ionization for the 50-kv potential is explained by absorption in the chamber wall. The cardboard insert of the Victoreen chamber and the phenolic carbon of the Kelley-Koett chamber have effective atomic numbers less than that of air. Under these circumstances electronic emission would be insufficient were it not for photonic scattering in the walls, and for the transmission of some photoelectrons from the aluminum central electrodes through the thin coatings of graphite.

It has been demonstrated with the Victoreen and Kelley-Koett pocket chambers that it is not difficult to design chambers that have no quality dependence for radiations generated by applied tube potentials of 100 to 250 kv. For these chambers in particular, the substitution for the bare aluminum of materials having the same effective atomic number as the main bodies of the chambers would satisfy the

[8] Wyckoff, Kennedy, and Bradford, Nucleonics **3,** No. 5, 62–70 (1948).
[9] L. H. Gray, Proc. Roy. Soc. (London) (A), **156,** 578–596 (September 1936).

TABLE 2. *Description of materials that determine the number of electrons which traverse the sensitive volumes of various radiation detectors.*

Detector	Wall materials and their thicknesses	Central electrode materials and their thicknesses	Gas filling of cavity
Victoreen Minometer pocket chamber.	0.0875-in. outer casing of Tenite II (cellulose acetate butyrate), 0.017-in. cardboard insert coated with approximately 0.0005 in. of graphite. Note. Bare aluminum is in contact with the sensitive volume in the cap and on the cap-end of the chamber.	0.062-in.-diameter aluminum wire, coated with approximately 0.0005 in. of graphite.	Air at atmospheric pressure.
Kelley-Koett pocket chamber.	0.083-in. phenolic carbon. Note. Bare aluminum is in contact with the sensitive volume in the cap and on the cap-end of the chamber.	0.060-in.-diameter aluminum wire, coated with approximately 0.0003 in. of graphite.	Air at atmospheric pressure.
Idl pocket chamber	0.092-in. Tenite II (cellulose acetate butyrate) coated with 0.002 in. of rubalt (carbon).	0.045-in.-diameter 2S aluminum wire coated with 0.001 in. of rubalt (carbon).	Air at approximately atmospheric pressure. Note: Chamber is sealed with airtight diaphragm having uncoated stainless steel contact point.
Cambridge dosimeter, model BM 17400.	0.016-in. outer casing of aluminum; 0.022-in. polystyrene-graphite insert.	0.025-in.-diameter phosphor bronze wire coated with graphite, together with quartz fiber sputtered with platinum.	Air at atmospheric pressure.
Beckman dosimeter, ring type.	0.035-in. outer casing of aluminum, 0.026-in. aluminum insert coated with Formvar (polyvinal formaldehyde), varying in thickness from 0.0005 to 0.002 in.	0.020-in.-diameter phosphor bronze wire partially coated with Formvar.	Do
Kelley-Koett dosimeter, model K–109.	0.0135-in. outer casing of aluminum, .047-in. Lucite (methyl methacrylate) graphite insert.	0.025-in.-diameter phosphor bronze wire, coated with approximately 0.0003 in. of graphite.	Do
Victoreen gamma survey meter, model 247A.	Outer casing of ⅛-in. aluminum. Cavity wall of 3/32-in. polythelene with 0.02-in. cardboard insert coated with approximately 0.0005 in. of graphite.	0.093-in.-diameter aluminum wire, coated with approximately 0.00005-in. of graphite.	Dry air at approximately atmospheric pressure. Note: Chamber is sealed, together with activated silica gel, in an aluminum case with a rubber gasket.
Beckman gamma survey meter, model MX-6.	Outer casing of 0.040-in. steel, 0.031-in. fiber spacer and 0.016-in. dairy tin. Cavity wall of 0.064-in. aluminum, 52S half hard, coated with approximately 0.001-in. Aquadag. (Colloidal carbon which contains traces of high atomic number elements.)	0.020-in. sheet steel coated with approximately 0.001 in. of Aquadag.	Three-pounds gauge pressure of monochlorodifluoromethane.
Sylvania beta-gamma survey meter, model RD-316.	⅛ to 3/16-in. cotton-base laminate coated with approx. 0.0005-in. Aquadag. The beta-ray window is constructed of rubber hydrochloride 0.0002-in. thick, and it also is coated with approximately 0.0005-in. of Aquadag.	5/16-in.-diameter cotton base laminate coated with approx. 0.0005-in. of Aquadag.	Air at atmospheric pressure.
Idl G-M Counter, model No. 2610.	0.005 to 0.006-in. Pyrex glass coated with 5 to 8 mg/cm^2 of silver.	0.004-in. diameter tungsten wire	Neon and ethyl ether.
El-Tronic G-M counter, model SM3.	0.005-in. Pyrex glass coated with 3 to 5 mg/cm^2 of silver.	0.003-in.-diameter tungsten wire	Do
Precision G-M counter, model 101.	0.005-in. Pyrex glass coated, with 3 to 5 mg/cm^2 of silver.	0.003-in.-diameter tungsten wire	Do
Victoreen G-M counter, model No. 263A.	0.005-in. Pyrex glass coated with silver of unspecified thickness.	0.004-in.-diameter tungsten wire	Argon and ethyl ether.
Victoreen G-M counter, model 263B.	30 mg/cm^2 of aluminum coated with approximately 0.0005 in. of graphite.	0.002-in.-diameter tungsten wire	Do

requirement. However, it is more difficult to design a chamber to have no quality dependence for 5 to 100-kv radiations because of the relatively greater part played by the photoelectric effect in this range, and also because wall absorption becomes pronounced for the softer radiations. For 5 to 100-kv radiations a thickness of 0.001 inch of an air-equivalent material might be practical, provided that the walls were shielded by an air-equivalent grid having a large area of mesh openings in comparison with the area subtended by the grid structure.

For million-volt radiations correction factors of pocket chambers and dosimeters are generally within 5 percent of the desired correction factor, 1.00. This is shown in figure 1 to be the case for all of the chambers and charge-readers, except for Kelley-Koett pocket chambers used in conjunction with charge-reader 105. This error should be discounted because this was one of the first Kelley-Koett charge-readers produced and also because Kelley-Koett charge-reader 182, which later became available, required an average correction factor of 0.96 for million-volt radiation when used with the same chambers.

The reproducibility of the readings of individual pocket chambers and dosimeters for identical exposures in a given X-ray beam is of the order of 1 percent, provided that the instruments are not overexposed just prior to calibration. However, if the chambers are previously exposed to about 25 r over a short period, their insulators become conducting to the extent that their correction factors are altered from 2 to 3 percent, as determined in short exposure periods immediately after overexposure. Correction factors of overexposed chambers may then be restored to their normal values if the chambers are kept charged and are not exposed for a period of an hour or more. It is believed that the correction factors as given in figure 1 may be considered accurate within 4 percent inasmuch as the chambers were not overexposed just prior to calibration.

To determine the quality control of manufacturing processes, the dispersion of the readings of various chamber types is plotted in figure 2. Uniformity of readings depends, among other factors, upon care exercised in the choice and application of materials used to approximate air-equivalent construction. Therefore, the readings for the dispersion study were obtained at 100 kv applied tube potential inasmuc as their wavelength dependence is more pronounce at this potential than at any other applied tub potential.

Instruments of the pocket-chamber type ar more durable than those of the dosimeter type This is apparent, inasmuch as all the pocket chamber were satisfactorily usable throughout the course o the measurements, while 17 Beckman, 11 Cam bridge, and 8 Kelley-Koett pocket dosimeter required repairs before the studies were completed

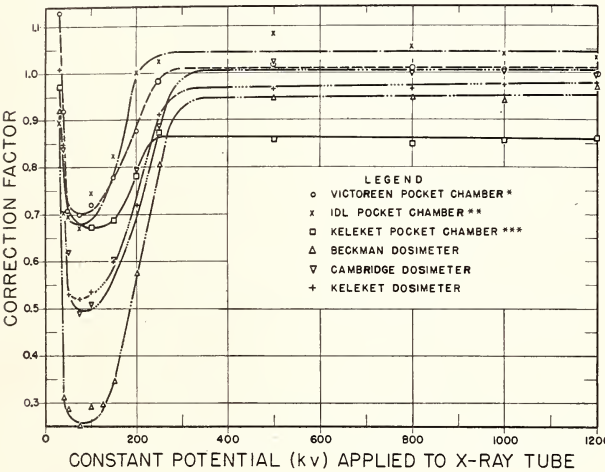

Figure 1—*Comparison of pocket-chamber and pocket-dosimeter readings against those of standard chambers for X-radiation of various qualities.*

* The correction factors indicated for Victoreen chambers are those obtained in conjunction with Minometer 1668. Factors with Minometer 1668 are the same as those with No. 1734, while those with No. 1684 are 2 percent lower.

** Idl pocket chambers were used in conjunction with Victoreen Minometer 1668.

*** The correction factors indicated in the graph for Kelley-Koett pocket chambers were obtained in conjunction with Kelley-Koett charge-reader 105. This was the only charge-reader available when the general calibrations were undertaken. Later, Kelley-Koett charge-reader 182 also became available. Correction factors obtained with it were 0.96 for million-volt radiations, rather than the value 0.86 obtained with charge-reader 105.

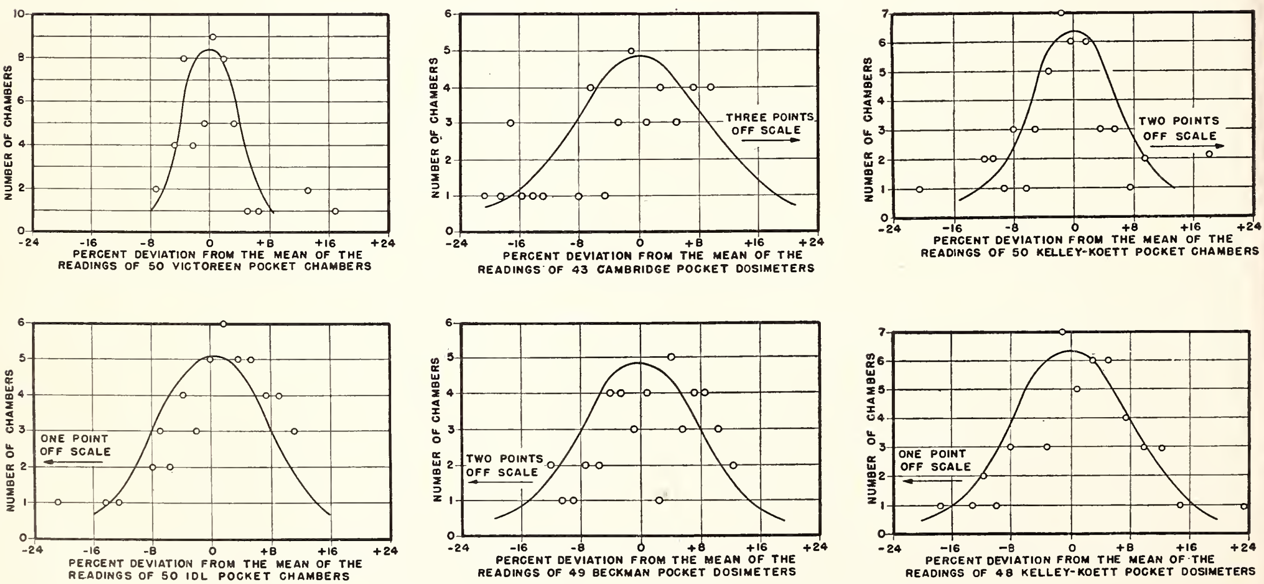

Figure 2—*Dispersion of readings of various types of pocket chambers and dosimeters.*

III. Calibration of Survey Meters

1. Experimental Procedure

The same standardization equipment was used for survey-meter as for pocket-chamber calibrations. However, various beam filtrations were used to attain the required range of intensities. This changed the "effective potentials" for given applied X-ray tube potentials as shown, for example, in table 3. The effective potentials were estimated as follows: Absorption coefficients of filtered radiations were determined in the same materials and for the same thicknesses thereof that served as filters. The effective potentials were then regarded as the voltages corresponding to monochromatic radiations that would exhibit the same absorption coefficients[10] as the filtered radiations.

The survey meters were supported on the edge of a small wooden stand rising 1 m from the bottom of the pit. The meters were turned on at least 1 min prior to exposure in order that the components would attain sufficient temperature equilibrium to make drift negligible.

Zero adjustments of ionization-chamber-type meters were conducted prior to their exposures, and note was made whether or not zero returns were satisfactory upon removal of the meters from the radiation fields. If the returns were not satisfactory, new adjustments were made and the exposures repeated. This did not apply to the Geiger-Müller counters inasmuch as they required no zero adjustments except for their microammeters, and these only while switches of the counters remained in their "off" positions.

TABLE 3. *Conditions of filtration and potential applied to X-ray tubes, together with effective potentials, as calculated.*

Potentials applied to X-ray tubes	For pocket chamber and dosimeter calibrations		For Geiger-Müller counter calibrations	
	Added beam filtration	Effective potential	Added beam filtration	Effective potential
kv	mm	kv	mm	kv
30	3.16 Al	22	----	----
50	0.66 Cu	36	0.44 Pb	32
75	.48 Pb	62	.91 Pb	66
100	.96 Pb	77	1.55 Pb	78
150	1.44 Pb	123	2.66 Pb	143
200	1.92 Pb	165	3.55 Pb	170
250	3.36 Pb	230	6.14 Pb	240
500	3.18 Pb	330	14.0 Pb	365
800	9.5 Pb	493	44.0 Pb	585
1,000	19.0 Pb	593	----	----
1,200	30.0 Pb	732	85.0 Pb	980

To avoid any possible directional effects, care was taken for exposures of survey meters to insure that radiations were incident normal to the sides of the instruments that are nearest their sensitive volumes and, for Geiger-Müller counters in particular, to insure that they were incident normal to the directions of the Geiger-Müller counter tube axes. This meant that the instruments could be supported in their normal carrying positions for the horizontally directed radiations and that for the vertically directed radiations it was necessary to support the counter tubes horizontally and to lay the Beckman MX-6 and the Victoreen 247A meters sideways.

Saturation of the Geiger-Müller counters was studied by calibrating in fields of various intensities. Within experimental error the same correction factors were observed for exposure rates of 0.05 to 15 mr/hr. Therefore, the dead time is unimportant at intensities for which the counters were designed to operate.

Saturation of the ionization-chamber survey meters was studied by adding plate voltage to their normal plate supplies. The Victoreen 247A and the Sylvania meters were each 95 percent saturated, and the Beckman MX–6 was 60 percent saturated at 2,400 mr/hr. However, saturation was practically complete on the lower ranges of each of these instruments. Only the normal plate voltage was used while observations were made to determine wavelength dependence.

For protection of personnel a telescope and mirror were used to observe meter readings for all exposure rates exceeding 15 mr/hr.

2. Discussion of Correction Factors of Survey Meters of Ionization-Chamber Type

In general, what has been said regarding the quality dependence of pocket chambers or dosimeters is also applicable to survey meters of the ionization-chamber type. However, it is more difficult to attain practical air-equivalence for these chambers than for ionization-chamber-type survey meters because the ratio of air volume to wall area is greater for the survey meters.

Representative correction factors for survey meters of the ionization-chamber-type are given in figures 3, 4, and 5 for Victoreen, Sylvania, and Beckman meters, respectively. Data plotted in these figures are typical of those obtained for two other meters of each type. It is worthy of note that the correction factors of the Victoreen and Sylvania meters are practically independent of quality of radiations generated by potentials in the range 75 to 1,200 kv, while correction factors around the figure 0.4 for the Beckman meters indicate the presence of more than twice the correct amount of ionization for 100-kv radiation. These differences of response should be noted in connection with the constructional details of the ionization chambers as listed in table 2. Wall materials that are nearly air-equivalent are attained by the use of polyethylene and a cotton-base laminate in the Victoreen and Sylvania instruments; aluminum, which is used for the Beckman chamber walls, is too high in atomic number, even though coated with Aquadag. The coating of Aquadag is apparently not sufficiently thick to eliminate all photoelectronic emission from the

[10] J. A. Victoreen, J. Applied Phys. **20**, 1141 (December 1949).

aluminum. Furthermore, air, which is used in the cavities of the Victoreen and Sylvania instrument, is better than the monochlorodifluoromethane used in the Beckman meter.

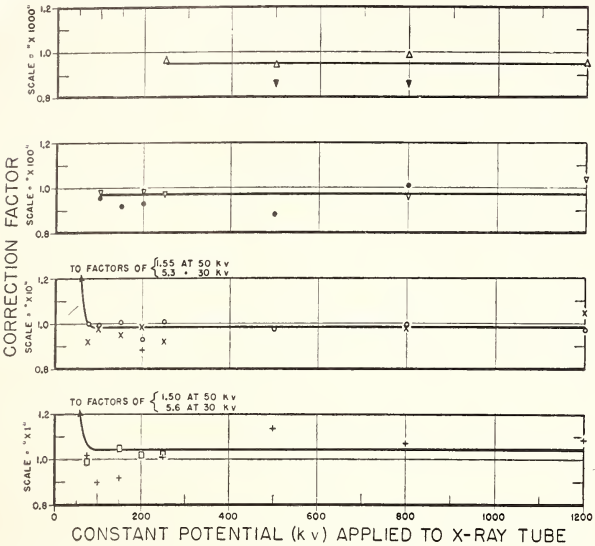

FIGURE 3—*Correction factors for Victoreen gamma survey meter—1966, model 247A.*

△=900, ▲=450, ▽=90, ●=45, ○=15, X=5, +=1.8, □=0.5 mr/hr.

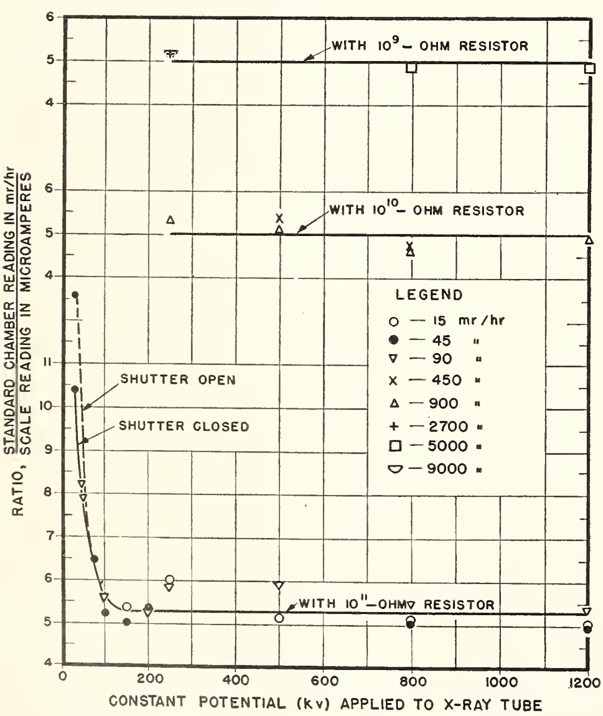

FIGURE 4—*Correction factors for Sylvania beta-gamma survey meter 117.*

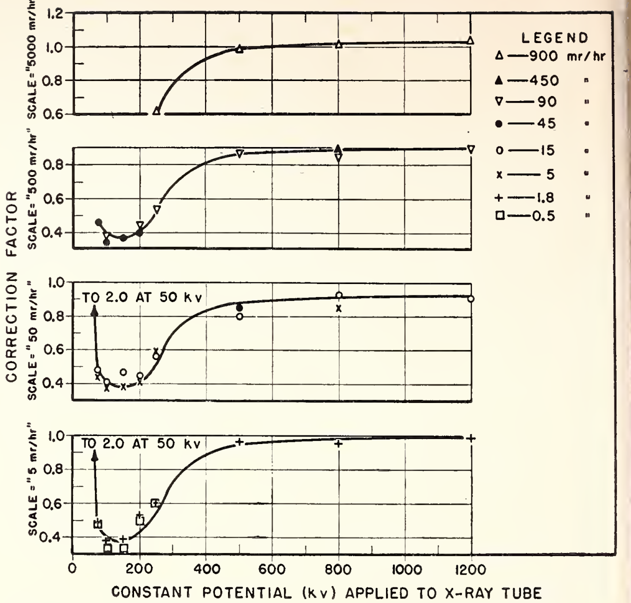

FIGURE 5—*Correction factors for Beckman gamma survey meter 1004, model MX-6.*

3. Discussion of Correction Factors of Survey Meters of Geiger-Müller Counter Type

A plot of correction factor versus photon energy for a Geiger-Müller counter exhibits the following general trend: For million-volt radiation the correction factor is equal to or near 1.0; in other words, for photons of this energy, counter tube discharges are produced primarily by recoil electrons ejected from the tube walls under conditions resembling those existing as the counter was originally calibrated against a source of radium gamma rays. For less energetic radiations the plot exhibits maximum and minimum values of correction factors. The high-energy side of the maximum is determined primarily by Compton recoil electron emission, and the low-energy side of the maximum by photoelectron emission. Furthermore, the high-energy side of the minimum is determined primarily by the release of photoelectrons, and the low-energy side of the minimum by absorption of photons.

As the energy of radiation is reduced below 1,200 kv, the correction factor rises to a maximum value in the region of 250 to 300 kv. Upon further decreases in energy the correction factor drops rapidly and passes through a minimum around 100 kv, after which it again rises sharply. The reason for the rise to the maximum as the energy is reduced below 1,200 kv may be understood by comparing the absorption mechanism of a standard chamber with that of a Geiger-Müller counter.

The response of a standard chamber depends primarily upon the number of electrons released in the vicinity of its sensitive volume, and upon the energy of these electrons. On the other hand, the response of a Geiger-Müller counter depends primarily upon the number of electrons that traverse its sensitive volume. This number is proportional to the number of electrons released in the vicinity of the sensitive volume and to the range of these electrons. Therefore, other conditions being equal, the correction factor of a Geiger-Müller counter varies primarily in proportion to the ratio energy/range of electrons generated in the vicinity of the instruments. The range of an electron increases faster than its energy increases at moderately high energies and in direct proportion to its energy in the multimillion-volt region. Therefore, for energies of the present experiments, that is, up to 1,200 kv, the energy-to-range ratio must increase as the X-ray energy decreases.

The preceding argument, qualified by the statement, "other conditions being equal," implies that the ratio between the numbers of electrons released in the vicinity of a standard chamber and of a Geiger-Müller counter is independent of the X-ray energy. This assumption is approximately valid in the high-energy region, where most of the electrons arise from the Compton effect, because this effect is almost independent of the mode of binding of the electrons within matter. Consequently, electrons are released by high-energy X-rays equally well in the free-air of a standard chamber as in the materials surrounding the sensitive volume of a counter.

However, lower energy X-rays release electrons primarily because of the photoelectric effect. This effect is the more intense (in the X-ray region) the more tightly bound are the electrons within matter, that is, the higher is the atomic number of the material. Therefore, the presence of high-atomic-number materials in the proximity of the sensitive volume of a Geiger-Müller counter increases its response to low-energy X-rays sharply. Accordingly, the "correction factor" must be expected to drop, as one proceeds from high to low energies, as soon as the photoelectric effect becomes important.

Figure 11 shows a plot of the rate of release of electrons per unit mass of various materials by X-ray photons of different energies. The sharp knees in the curves mark the onset of the photoelectric effect. Notice the correspondence between the position of the knee in the silver curve and the position of the dip of the correction factors for the silver-lined Geiger-Müller counters shown in figures 6, 7, 9, and 10 of Idl, Victoreen, Precision, and El-Tronics manufacture, respectively. The correction factors shown in figure 6 are similar to those of three other Idl counters; those in figure 7 to three other Victoreen counters; those in figure 9 to two other Precision counters; and those in figure 10 to two other El-Tronics counters. Figure 8 shows correction factors of a counter which has an aluminum-wall tube internally coated with approximately 0.0005 inch of graphite. Because of the lesser photoelectric emission from this tube, correction factors in the photoelectric region do not dip below the value 1.0; whereas for the silver-lined tubes they dip to values around 0.2. Inasmuch as marked photoelectric absorption in carbon and aluminum occurs for much less energetic photons than in silver (see fig. 11), it might be expected that the position of the correction-factor dip would be shifted further to the softer X-ray region than is indicated in figure 8. This would, in fact, be the case if the wall of the aluminum tube had approximately the same thickness in milligrams per square centimeter as that used for the silver-lined tubes. Note in table 2 that the silver linings of these tubes fall in the thickness range 3 to 8 mg/cm^2, while the thickness of the aluminum tube is 30 mg/cm^2.

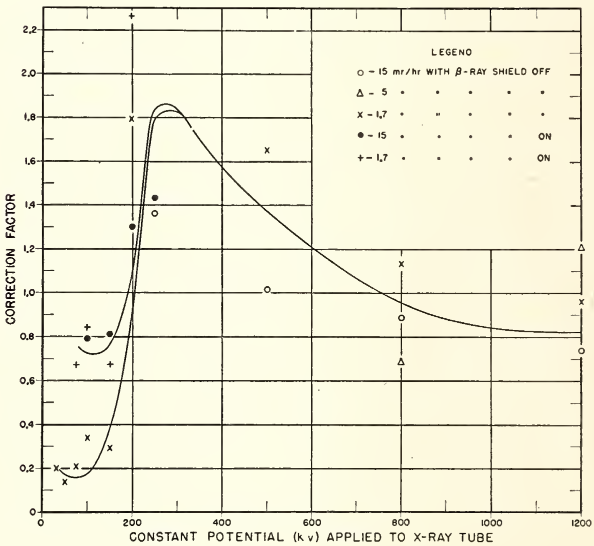

FIGURE 6—*Correction factors for Idl Geiger-Müller counter 560, model 2610.*

A silver lining of 3 to 8 mg/cm^2 is not sufficiently thick for the attainment of electronic equilibrium therein for 200- to 400-kv radiations. Therefore, the quality-dependence of these Geiger-Müller tubes could be improved by increasing the thickness of the silver linings. It is apparent from figure 11 that greater response could thus be obtained for the 200- to 400-kv range, and compensation for deficiencies in readings of thinly lined tubes would be achieved for these radiations. At the same time, response to radiations in the 40- to 100-kv range would be desirably reduced by increased photonic absorption.

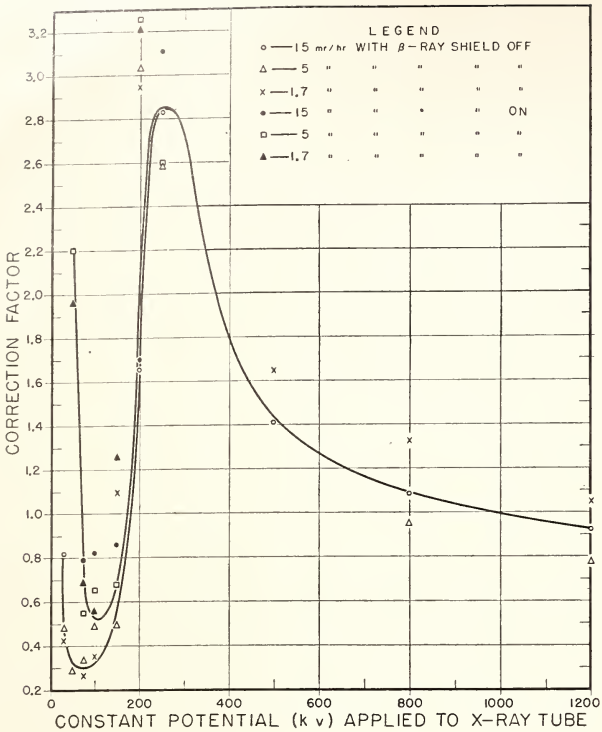

FIGURE 7—*Correction factors for Victoreen Geiger-Müller counter 509, model 263A.*

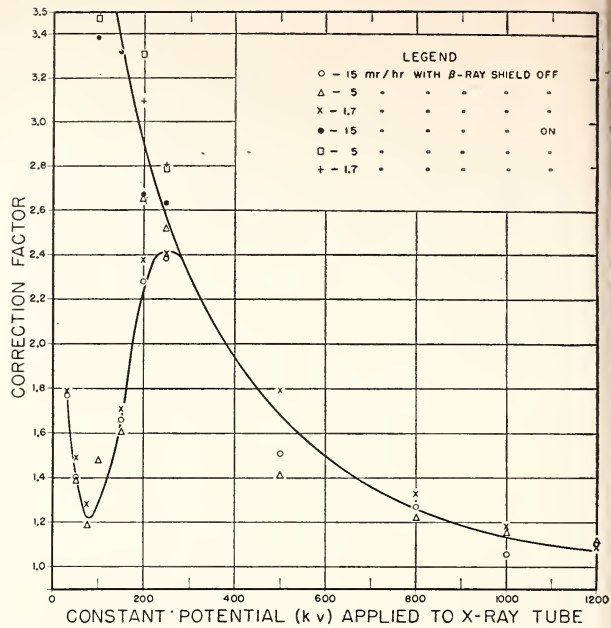

FIGURE 8—*Correction factors for Victoreen Geiger-Müller counter 1939, model 263B.*

As distinguished from all other counters calibrated, the Victoreen model 263B has an aluminum-wall counter tube internally coated with graphite. The tube of this counter is otherwise known as the 1B85 Thyrode.

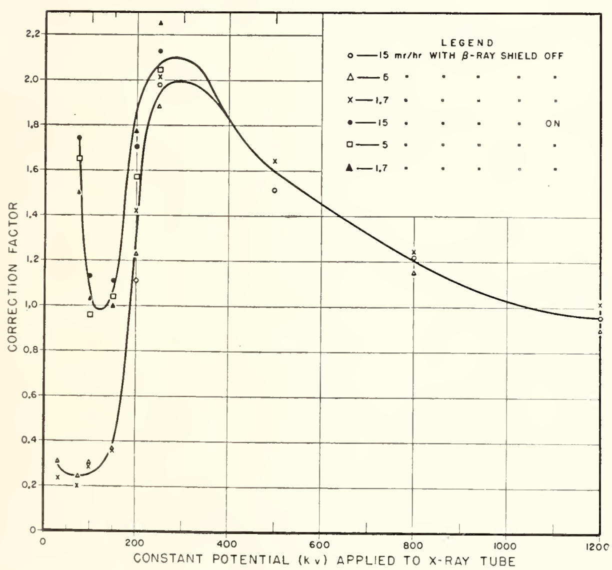

FIGURE 9—*Correction factors for Precision Geiger-Müller counter 120, model 101.*

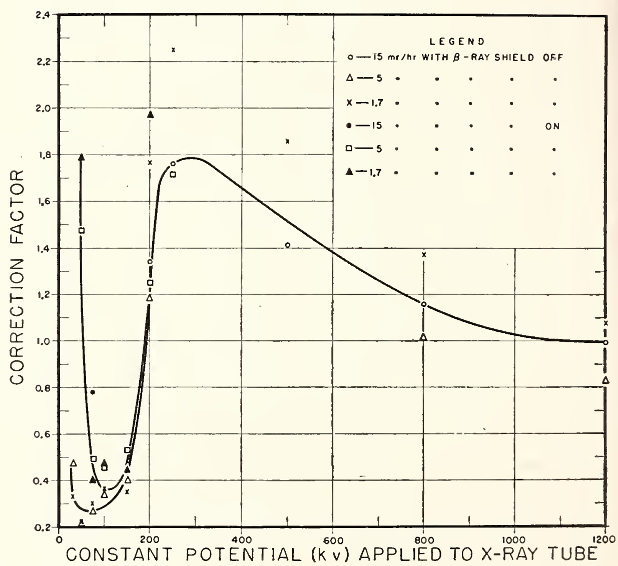

FIGURE 10—*Correction factors for El-Tronics Geiger-Müller counter 115, model SGM 18A.*

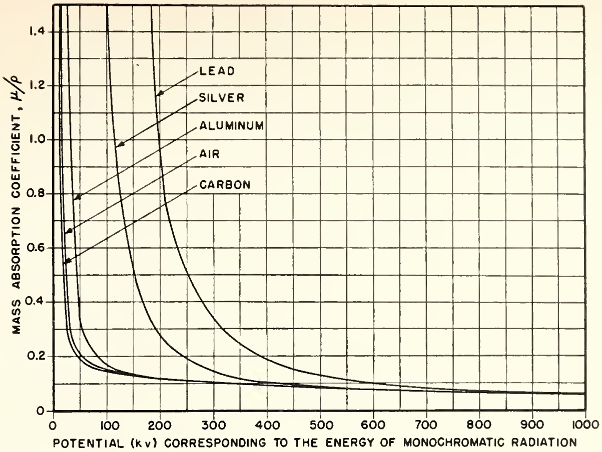

FIGURE 11—*Rate of release of electrons per unit mass of various materials by X-ray photons of different energies.*

IV. Conclusions

Among the instruments calibrated for the purpose of this report, the Victoreen 247A and Sylvania survey meters have the least quality dependence. In contrast, all of the pocket chambers and dosimeters, as well as the Geiger-Müller counters calibrated, have wide variations in quality dependence. Therefore, except for million-volt radiations, the readings of the latter are in general erroneous.

While this report indicates the status of instrument development at the time these instruments were received at the National Bureau of Standards (December 1948), considerable improvement in the quality-dependence of detectors of various types has been achieved since then. However, there are many instruments of the older types still in use, regarding which the correction factors of this Circular are applicable. Of the improved instruments, some have the same appearance as the older types, the improvements being made in the internal coatings. Therefore, caution should be exercised in applying these correction factors to new instruments. If the response of new instruments is to be estimated from the graphs of this Circular, then the manufacturer's dated literature should be consulted, or he should be consulted directly, regarding the wall materials and internal coatings of the instrument, and this information compared with the listings in table 2.

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