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Title MEASUREMENT OF PEAK KILOVOLTAGE ACROSS X-RAY TUBES BY IONIZATION METHODS

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Voltage calibration methods used with X-ray tubes are either electrical procedures requiring direct electrical connection or ionization techniques which require no electrical connection to the generating system. One major restriction on the use of electrical methods for measuring the voltage applied to X-ray tubes is that special electrical adaptors are required to bring the conductors out of the grounded tube housing or high-voltage cables. X-ray installations are not normally equipped with these special adaptors and in most cases the use of the X-ray tube would be restricted by the presence of the external high-voltage adaptor.

High voltage measuring methods which do not require electrical connection to the X-ray generating system employ direct or indirect ionization techniques to measure the applied voltage. The K-edge calibration method, used in this project, is a direct ionization method based upon the detection of the K-series fluorescent radiation

from various secondary radiators. The two main advantages of this method are accuracy and the elimination of electrical connections to the X-ray generating system. Published information on this method lacked data in the region extending from 40 kV to 67 kV. The lack of calibration data in this voltage range was due to the unavailability of secondary radiator elements of suitable purity.

Certain rare earth elements were used to provide calibration measurements within this voltage range. The oxides of cerium, samarium, gadolinium, holmium and ytterbium were used and calibration data was obtained at 40.43 kV, 46.85 kV, 50.23 kV, 55.61 kV, and 61.31 kV, respectively. The K-edge calibrations for tin (29.2 kV) and tantalum (67.5 kV) were used to provide an experimental base line. These data, combined with previous reference values, permit the use of the K-edge ionization calibration method throughout the entire voltage range commonly used in diagnostic X-ray procedures.

Reproducible results can be obtained using this kilovoltage calibration method if certain variables are rigidly controlled. The geometrical arrangement of all the equipment must remain constant throughout the entire period of time during which the measurements are taken at the K-edge. Changes in geometry alter the amount of scattered radiation and the effective thickness of the secondary radiator. The oxide secondary radiator must not be subjected to mechanical shock or vibration after final positioning in the beam and its moisture content must be held constant throughout the entire measurement period. Changes in any of these parameters result in errors in the ionization chamber readings.

The accuracy and wide voltage range make the K-edge ionization method of X-ray tube kilovoltage measurement a reliable procedure for use in X-ray physics. Most other kilovoltage measuring methods encounter problems at high tube currents and short exposure times. The ionization method is restricted only by the intensity limits of the ionization chambers and if these are selected properly then this method may be used at tube currents and exposure times where most other methods fail.

MEASUREMENT OF PEAK KILOVOLTAGE ACROSS X-RAY TUBES BY IONIZATION METHODS

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

MEASUREMENT OF PEAK KILOVOLTAGE ACROSS X-RAY TUBES BY IONIZATION METHODS

INTRODUCTION

One of the parameters normally used to specify X-ray machine operation is the voltage applied to the X-ray tube. For precise control of equipment operating at high voltage it is necessary to have an accurate method of measuring the voltage. The applied voltage is usually monitored by a voltmeter in the primary circuit of the high-voltage transformer, or by some other method employing control of primary voltage to indicate secondary voltage. A variety of procedures exist which may be used to calibrate the voltage indicating device.

Calibration methods which may be used with X-ray tubes are either electrical procedures requiring direct electrical connection to the generating system or ionization techniques which require no electrical connection to the X-ray generator. Both of these calibration methods have advantages and disadvantages which limit their application. A general review of X-ray voltage calibration methods which require direct electrical connection to the generating system is presented in Appendix I.

High voltage measuring methods that require direct electrical connection to the X-ray generating system are subject to error resulting from resistance variation, stray capacitance, leakage current and onset of corona. Errors can be introduced by the frequency and waveform dependence of the instruments, influence of external electrical fields, changes in electrode geometry and variations in the dielectric strength between electrodes.

The major restriction on the use of electrical methods for measuring the voltage applied to X-ray tubes is that special adaptors are required to bring the conductors out of the grounded tube housing or high voltage cables. This limitation is encountered whenever electrical methods are used to measure the voltage applied to an X-ray tube after it is installed in its shockproof housing and connected to the generator. Most X-ray installations are not equipped with these special adaptors and in most cases the use of the X-ray tube would be restricted by the presence of the external high voltage adaptor. Therefore, a voltage measurement method that does not require electrical connection to the generating system would be desirable for use in the measurement of X-ray tube voltage in sealed shockproof systems.

High voltage measuring methods which do not require electrical connection to the X-ray generating system employ ionization techniques to measure the applied voltage. Ionization methods of kilovoltage measurement include both indirect and direct ionization procedures. Greening (15) has reported the use of certain secondary radiator materials in a direct ionization method of high voltage calibration. In this study emphasis has been placed upon the direct ionization method.

Greening (15) and others (14, 24) who have used this ionization technique were unable to obtain calibration within the voltage range from 40.4 kilovolts to 67.5 kilovolts. Since the time when these investigations were made new secondary radiator materials have become available which can be used to provide the desired calibration within this voltage range. The purpose of the thesis has been to design experiments to use these materials in X-ray tube voltage calibration. The new reference values which were obtained will provide the X-ray scientist with a rapid and accurate method for calibration of X-ray machines throughout the entire voltage range commonly used in diagnostic X-ray procedures.

HIGH VOLTAGE MEASUREMENT BY METHODS NOT REQUIRING ELECTRICAL CONNECTION TO THE X-RAY GENERATING SYSTEM

Indirect Ionization Methods

The difficulties of voltage measuring techniques that require electrical connection to the X-ray generating system suggest that other methods are needed whereby the X-ray tube kilovoltage can be determined without having to resort to electrical connection to the generator.

Penetrometer

The oldest method of measuring kilovoltage without electrical connection to the generator was introduced by L. Benoist (4) in 1902 when he designed a radiochromometer for the measurement of Roentgen rays. Benoist's radiochromometer was a penetrometer formed out of a disk of aluminum divided into twelve sections. The sections of aluminum were distributed like the hours of a clock with increasing thickness from one millimeter to twelve millimeters. The center of this circular step wedge was a disk of silver 0.11 millimeters thick.

For indirect measurement the penetrometer was placed on a radiographic film and exposed. The exposure was made at a known tube current and the resulting film density under the center silver section was compared with the densities under the circular step wedge. The step whose density matched the density under the silver reference section gave an indication of the beam "hardness".

For direct measurement the penetrometer was placed on a fluorescent screen. The penetrometer and fluorescent screen were then held in the beam during exposure and the fluorescent screen viewed directly. The intensity of the light emitted by the fluorescent screen under the circular step wedge was visually compared with the light emitted by the fluorescent screen under the silver reference section in the center of the penetrometer. The step which transmitted the same amount as the center silver section gave an indication of beam "hardness".

Thus, whether used for direct or indirect measurement, the penetrometer presented a scale of "hardness" divided into twelve arbitrary units. This method does not directly indicate tube voltage; however, the "hardness" can be related to the tube voltage. Variations of this method have been used to specify X-ray quality since 1902.

A penetrometer has been developed by Stanton, Lightfoot, and Mann (22) for use in field calibration of X-ray units operating in the low voltage diagnostic range. Their penetrometer employs a rectangular center reference block of polyethylene with identical metal step wedges on each side. The radiograph of the penetrometer is measured with a densitometer and the step wedge whose density matches the density under the polyethylene reference block gives an indication of the X-ray tube voltage. The authors report an accuracy of ± 1 kVp at low kVp values (25-45 kVp) and within ± 2% up to 110 kVp.

The penetrometer method requires an initial X-ray calibration to establish the kVp baseline, thus its accuracy is not based upon a primary calibrating device, but upon the voltage calibration of an X-ray machine.

Inferential Kilovoltmeter

A method of measuring X-ray kilovoltage by absorption in two filters was proposed by Newell and Henny in 1953 (20). Their "Inferential Kilovoltmeter" consisted of two ionization chambers, each surrounded by its own filter. The larger chamber had a sensitivity twenty times that of the smaller. The two chambers were held parallel to each other and mounted on a rectangular brass base plate. The apparatus was placed in the center of the X-ray beam and exposed. From the ratio of the readings of the two chambers, the kilovoltage was then read off of a calibration chart. Since this method is dependent upon absorption of the primary beam its accuracy is strongly influenced by changes in the voltage and current waveforms. The "Inferential Kilovoltmeter" requires an initial X-ray calibration to establish its calibration chart, thus its accuracy is not based upon a primary calibrating device, but upon the voltage calibration of an X-ray machine.

Spectrometry

One of the most accurate methods of determining X-ray tube kilovoltage is the spectrometric method (9, 14). This consists of determining the short wavelength limit of the spectrum of the beam of X rays by reflection from a crystal of known planar spacing. This wavelength (λ_0) is then used in the quantum mechanical expression

$$V = \frac{hc}{\lambda_0} = \frac{12,400}{\lambda_0}$$

where V = X-ray tube voltage in volts

$h = 6.63 \times 10^{-27}$ erg-sec

$c = 3 \times 10^{10}$ cm/sec

λ_0 = short wavelength limit in Angstroms

This method requires special equipment which limits its use in field applications (22).

The Direct Ionization Method

The direct ionization technique described by Greening (15) utilizes equipment normally found in a physics laboratory and may be used to measure X-ray tube kilovoltage from 1.5 to 115 kVp. This method makes use of the emission of characteristic radiation and the additional absorption of the primary X-ray beam on the short wavelength side of the K-edge.

Interaction of X Rays with a Secondary Radiator

Interactions between X rays and matter are of three principal kinds: the photoelectric effect, the Compton effect, and pair production. The photoelectric effect is a function of both absorber atomic number and photon energy and is the predominate interaction at low energies (up to 50 kV in aluminum and up to 500 kV in lead (24). The photoelectric effect will be the predominating interaction in the energy range involved in this study. For photon energies greater than the K-shell binding energy approximately 80% of the photoelectric interactions are with K-electrons (12, 16, 24).

When a beam of X rays is intercepted by matter, part of the radiation passes through without being altered; the rest of the radiation is transferred into heat or other forms of radiation. The interaction of a beam of X rays with an absorber is shown in Figure 1.

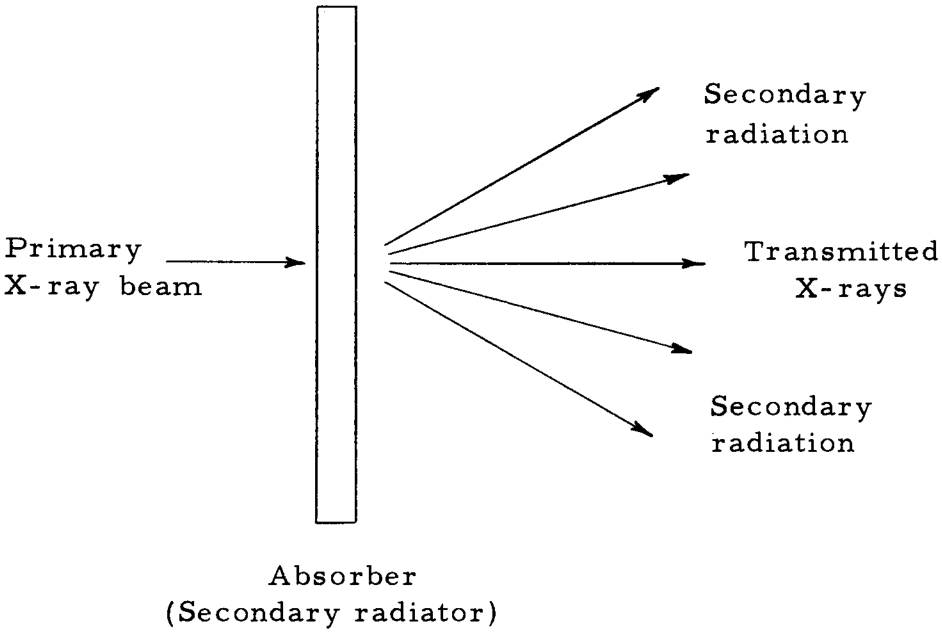

Figure 1. Interaction of X-rays with matter.

The radiation leaving the absorber consists of the transmitted primary X rays and secondary radiation (17, 18). The secondary radiation is composed of three separate types of radiation: scattered X rays, characteristic X rays, and electrons ejected from the absorber with sufficient energy to escape the surface. The scattered X rays are heterogenous and the effective energy is dependent upon the number of scattering events encountered. The characteristic X rays are homogenous and always have the same properties for a given element (9).

Emission of Characteristic Radiation

Characteristic emission lines appear in groups designated K-series, L-series, M-series, etc. Each series contains several lines of different wavelength (9).

The K-series of all elements except the very light ones are composed of four principal lines, the γ doublet, the β doublet and the doublet α_1 and α_2, in order of increasing wavelength. When a K-electron is ejected, the vacancy may be filled by an electron from one of the other energy levels.

The energy levels L, M, N, etc. are split into discrete levels as shown in Figure 2. Observation of the energy levels in Figure 2 would lead one to expect that an electron in any of the levels should be equally able to drop into a vacancy in the K-shell. However,

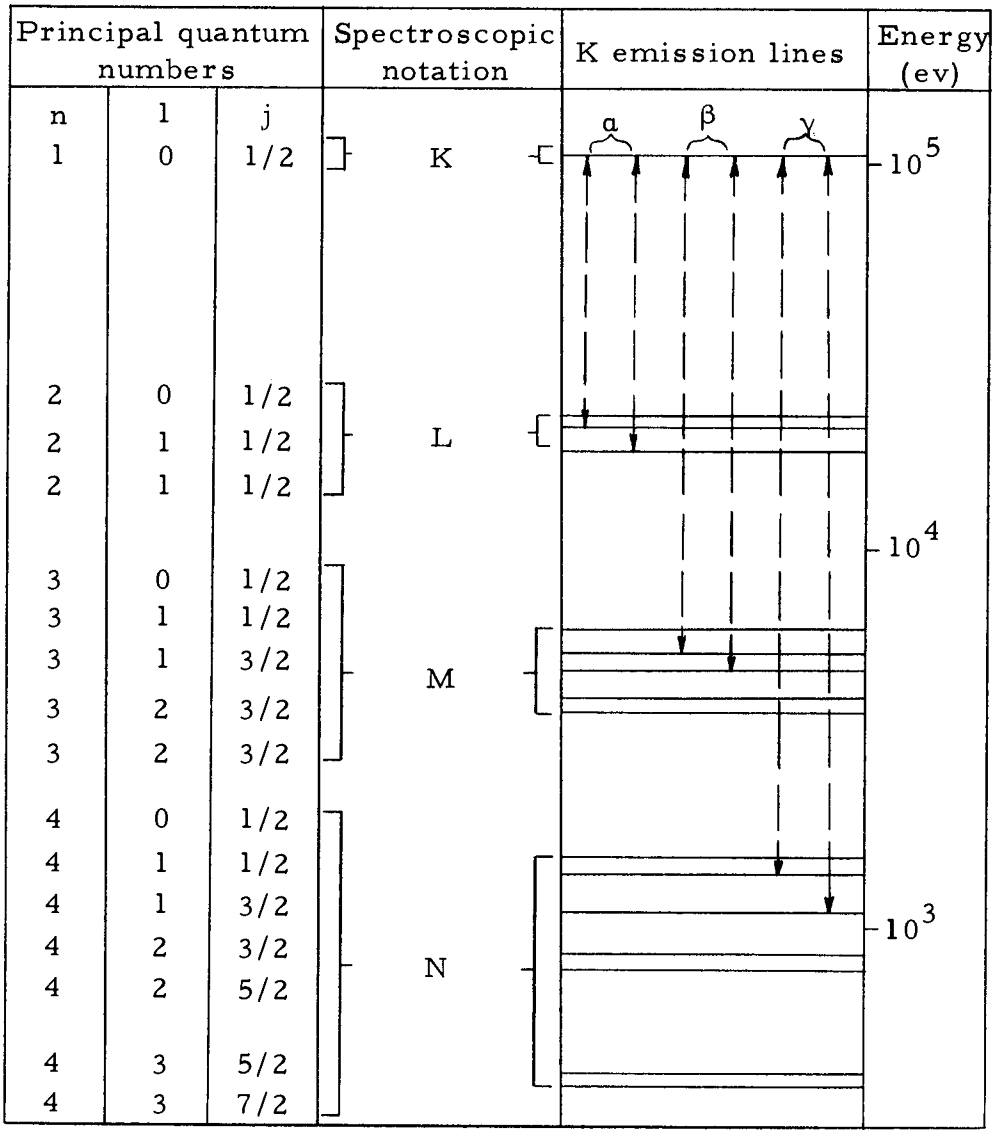

Figure 2. Diagram of the higher energy X-ray levels for uranium, showing the origin of the K-series spectral lines.

quantum mechanical consideration lead to definite selection rules governing these transitions. The selection rules on the quantum numbers allow only transitions in which:

$$\Delta n \neq 0$$

$$\Delta l = \pm 1$$

$$\Delta j = 0, \ \pm 1 \qquad (9)$$

These selection rules explain why only those transitions shown in Figure 2 are possible. The selection rules explain why the L_{II}-K transition exists and why the L_I-K transition does not. "Forbidden" lines such as N_{II}-L_{III} and N_{IV}-L_{III} have been observed but are very faint. These lines are quadrupole lines and are subject to a different set of selection rules than the common dipole lines shown in Figure 2 (9).

X-ray Absorption Spectra

When a beam of X rays passes through an absorber and the transmitted primary beam is spectroscopically analyzed, absorption discontinuities are observed in the X-ray spectrum. The wavelengths corresponding to these "absorption edges" are characteristic of the absorbing material. X rays with wavelengths shorter than the critical absorption edge wavelength will be absorbed to a greater extent than X rays with wavelengths longer than the critical wavelength. These characteristic absorption edges result when the incident energy is just sufficient to displace an atomic electron from a given energy level. The number of absorption edges is determined by the quantum numbers n, l, and j of the energy levels. Thus there is one K-absorption edge, three L-absorption edges, etc. Figure 3 illustrates the discontinuities in the photoelectric cross section at the K-absorption edge. The discontinuity results from the fact that at the absorption edge the incident photon energy has decreased to a value less than the binding energy of the electrons in the K-shell, thus the number of electrons which it is energetically able to eject is sharply decreased (24).

Relationship Between X-ray Absorption and Emission Spectra

A characteristic X-ray absorption limit is defined by the energy required to eject electrons from a given energy level out of the atom. The number of absorption edges is defined by the quantum numbers (n, l, j) of the atomic energy levels. Characteristic emission lines result from transitions between these energy levels. The wavelengths corresponding to the absorption edges are slightly shorter than the short wavelength limit of the respective emission series. For the absorption and emission wavelengths to be the same a free electron outside of the atom would have to penetrate the electron cloud and drop into the vacancy left by the electron initially ejected in the absorption process. Therefore, an

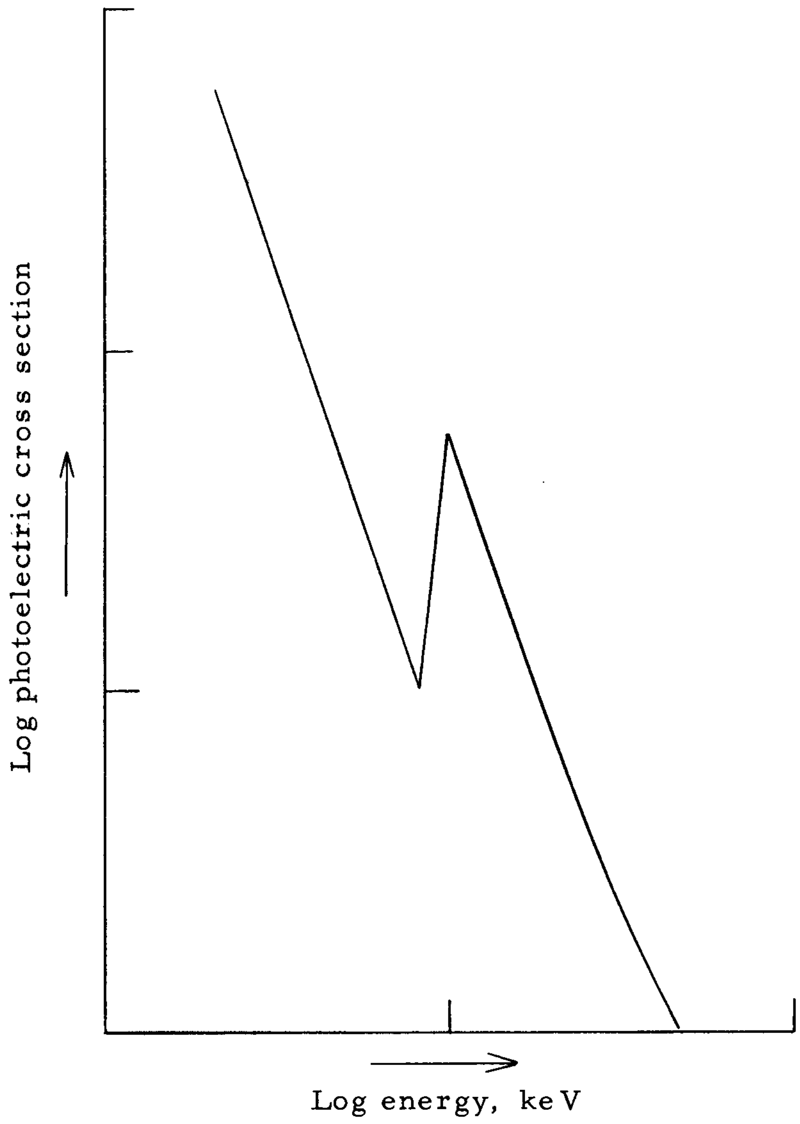

Figure 3. Variation of absorption coefficient at K-edge for typical secondary radiator.

emission series appears only at a critical voltage and any further increase in energy serves only to increase the intensity of all the lines in the series without altering their frequency or relative intensities. All lines in a particular emission series are excited simultaneously when the critical energy is reached. The emission series lines will not appear when the incident wavelength is equal to the shortest wavelength in the emission series. Only when the energy is adjusted so that

$$V = hc/\lambda_{\text{absorption edge}}$$

will the entire emission series appear. Therefore, fluorescent X rays can be emitted only when the primary X-ray beam contains X rays with wavelengths corresponding to the critical absorption edge wavelength or shorter (9, 24). Figure 4 illustrates the relationship between the wavelengths of the emission series and the wavelength of the absorption edge.

Detection of K-Series Fluorescent Radiation Threshold

Greening (15) proposed that the kilovoltage across X-ray tubes be measured without connection to the high voltage circuit. This method utilizes a voltmeter in the primary of the high voltage transformer which is calibrated to indicate X-ray beam kilovoltage from observations of the voltmeter settings at which the K-series

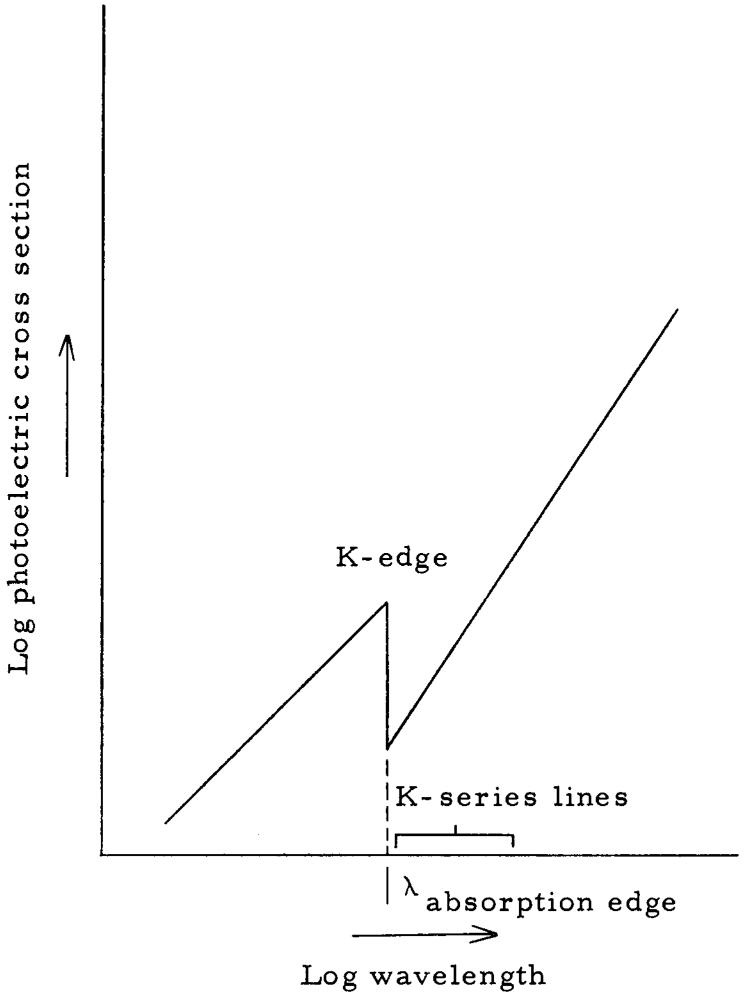

Figure 4. Relationship between characteristic absorption and emission wavelengths.

fluorescence of a number of secondary radiators in the X-ray beam are detected. The kilovoltage corresponding to the K-absorption edge for most elements has been well established for many years (7, 13).

Secondary radiation from a secondary radiator will be detected by an ionization chamber arrangement as in Figure 5. The ionization chamber is shielded to insure that the detector will be exposed to radiation coming only from the secondary radiator. The lead diaphragm confines the primary X-ray beam within the dimensions of the secondary radiator.

The secondary radiation detected by the ionization chamber will be composed of scattered X rays and fluorescent radiation characteristic of the secondary radiator (14, 15, 23). When the peak kilovoltage across the X-ray tube is less than the K-absorption edge, the secondary radiation contains no K-fluorescent radiation. As the peak kilovoltage exceeds the K-absorption edge, K-fluorescent radiation is added to the secondary radiation.

The K-radiation will be of shorter wavelength than all of the other characteristic radiation coming from the secondary radiator and will also be of shorter wavelength than most of the scattered radiation (15). If a differential filter is placed between the secondary radiator and the detector, the proportion of the total radiation reaching the detector which is K-radiation will be increased.

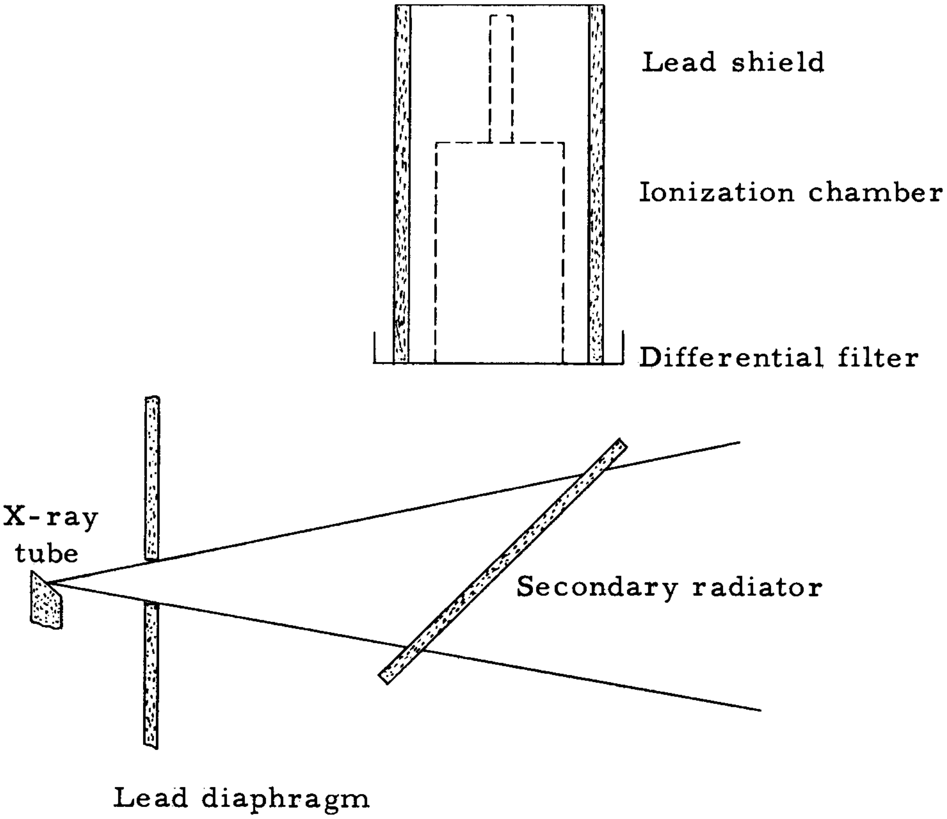

Figure 5. Determination of characteristic fluorescent radiation.

The differential filter should be of the same atomic number as the secondary radiator. This provides optimum differential filtration due to the fact that all elements have a lower absorption coefficient for their own K-radiation and a higher absorption coefficient for longer wavelength radiation. However, any element not having an absorption edge in the region of the K-edge of the secondary radiator will make a satisfactory differential filter. Figure 6 illustrates the behavior of secondary radiation as the K-edge is crossed.

An ionization chamber placed in the transmitted beam as shown in Figure 7 will detect the transmitted radiation and should indicate any variation in transmission as the K-edge of the secondary radiator is passed. Figure 8 illustrates the variation of transmitted radiation at the K-edge.

A slight change in slope should occur when the K-edge of the secondary radiator is crossed. This is due to the discontinuous nature of the absorption coefficient at the K-edge; however, this effect is masked by other radiation.

The variation of secondary radiation with primary voltage was shown in Figure 7. The exact location of the K-edge is not well defined due to the masking effect of ionization produced by radiation other than that associated with the K-edge. An even greater masking effect occurs when transmitted radiation is plotted as a function of primary voltage (Figure 9). However, if the ratio

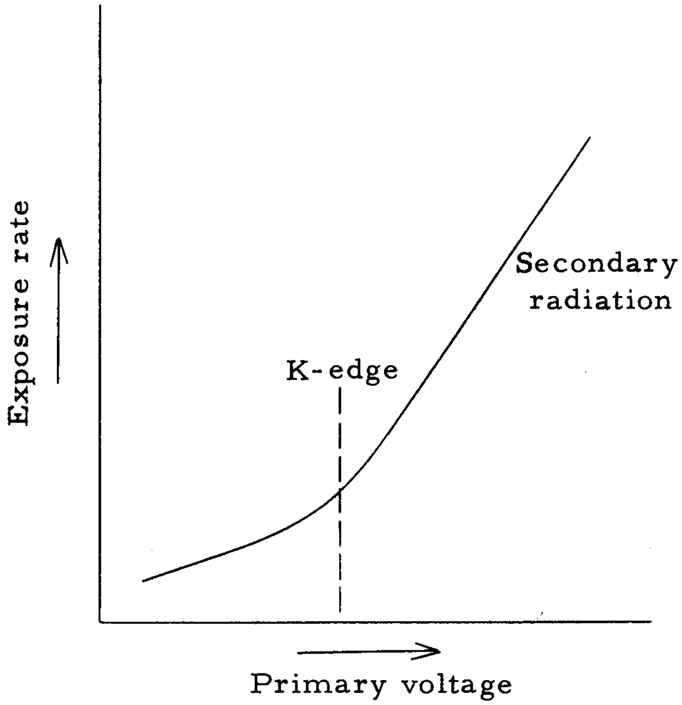

Figure 6. Variation of secondary radiation near K-edge for typical secondary radiator.

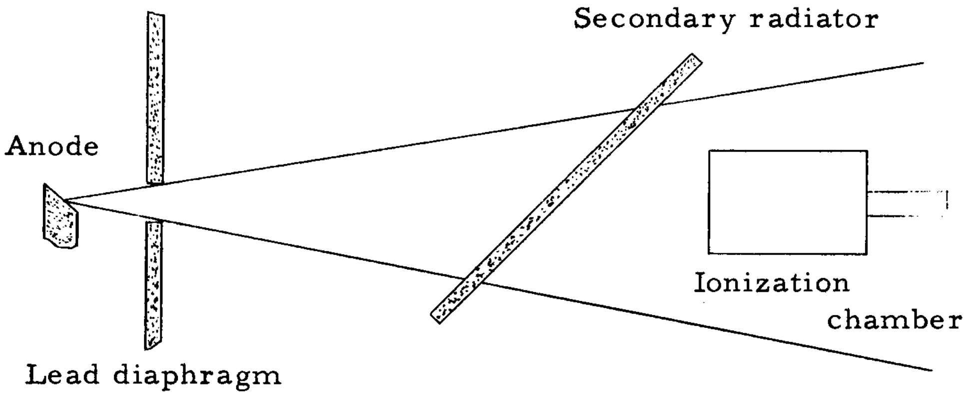

Figure 7. Detection of transmitted radiation.

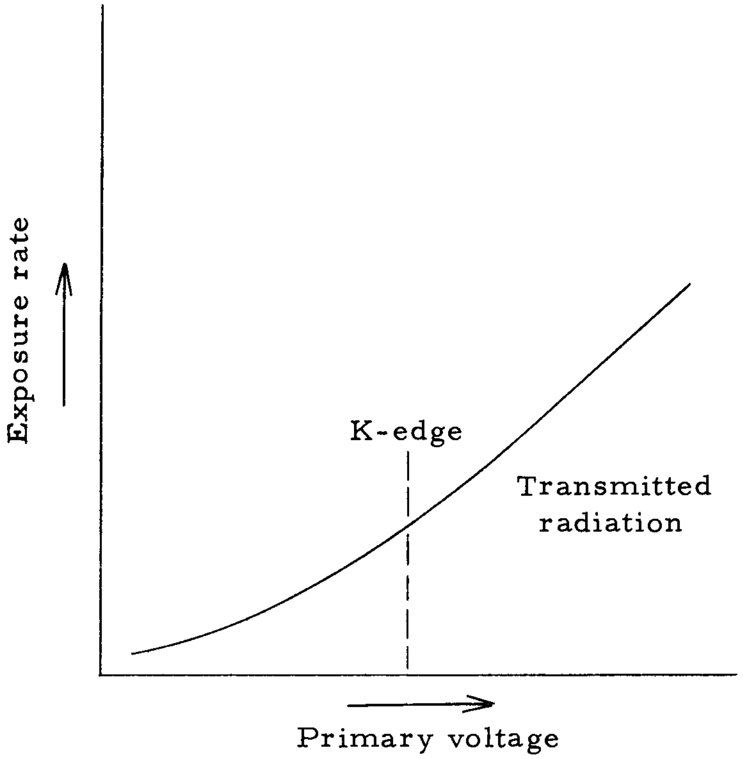

Figure 8. Transmitted radiation at K-edge for typical secondary radiator.

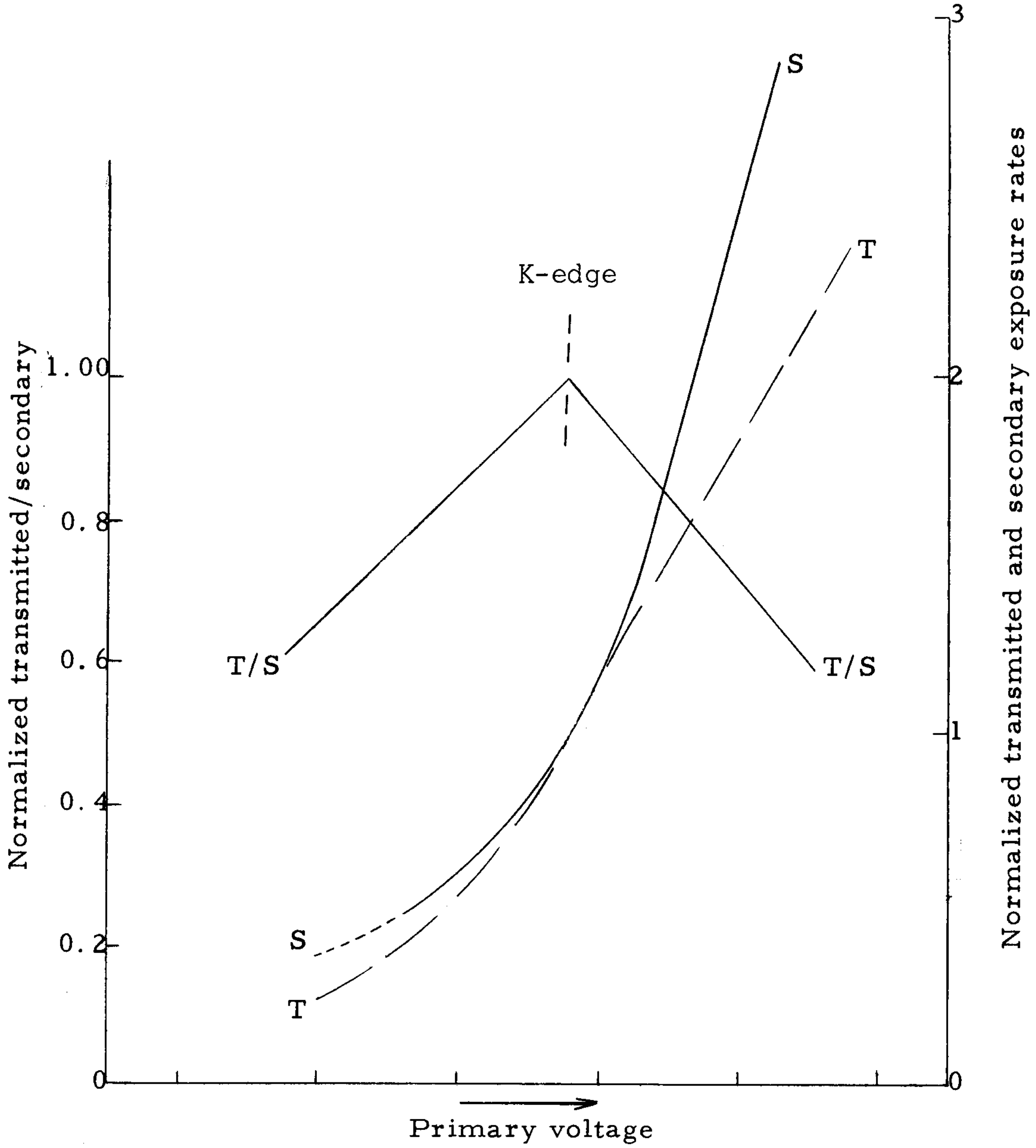

Figure 9. Ratio of transmitted/secondary radiation at K-edge of typical secondary radiator.

of transmitted to secondary radiation is computed the location of the K-edge can be determined (14, 23). Figure 9 illustrates the improved definition of the K-edge when the ratio of transmitted to secondary radiation is plotted as a function of primary voltage.

EXPERIMENTAL MEASUREMENT OF X-RAY TUBE PEAK KILOVOLTAGE BY THE DIRECT IONIZATION METHOD

Equipment

The X-ray unit used in this calibration was a Keleket type 85A mobile unit rated at a maximum voltage of 90 kVp and a maximum tube current of 30 mA. The stationary anode self-rectified X-ray tube and the high-voltage transformer were sealed in an oil-filled shockproof diagnostic tube housing. Kilovoltage control was provided by a kVp selector with fifteen positions and a high-low switch. The primary voltage of the high-voltage transformer was monitored by a voltmeter in the control panel. Tube current was continously variable from 0 to 30 milliamperes and was monitored by a milliammeter in the control panel. Victoreen Model 130, 0.25-R ionization chambers were used to measure the transmitted and secondary radiation. A Victoreen Model 570 electrometer was used to read the chambers after exposure. The X-ray machine was attached to a heavy table with the X-ray beam aligned parallel to the table center line. Alignment between the X-ray tube focal spot, the secondary radiator, and the ionization chambers was accomplished by mounting all moveable objects parallel to the X-ray beam on an optical bench which was attached to the table.

Experimental Procedure

Geometrical Layout

A diagram of the system used for the determination of peak kilovoltage is shown in Figure 10. The primary beam was limited to the area of the secondary radiator by a lead diaphragm. The diaphragm opening was 1.5 centimeters in diameter and was located 5.1 centimeters from the focal spot. The secondary radiator elements were mounted in 3.25 x 4 inch aluminum lantern slide frames. The secondary radiator was located 15.1 centimeters from the focal spot and positioned 45 degrees to the central ray of the primary beam. The 45 degree angle permitted both ionization chambers to scan equal radiator surface areas. A Victoreen Model 130, 0.25-R ionization chamber was modified to measure the secondary radiation. The modification consisted of removing the thick bakelite end cap of the chamber to increase sensitivity. The chamber was positioned perpendicular to the central ray, 5 centimeters from the intersection of the central ray and the secondary radiator. The lead shield surrounding the secondary radiation chamber was formed out of eight pound per square foot sheet lead. The shield had an internal diameter of 2.25 inches and was 6.75 inches in length. The differential filter was mounted directly on the end of the secondary radiation chamber to prevent dust from entering the chamber.

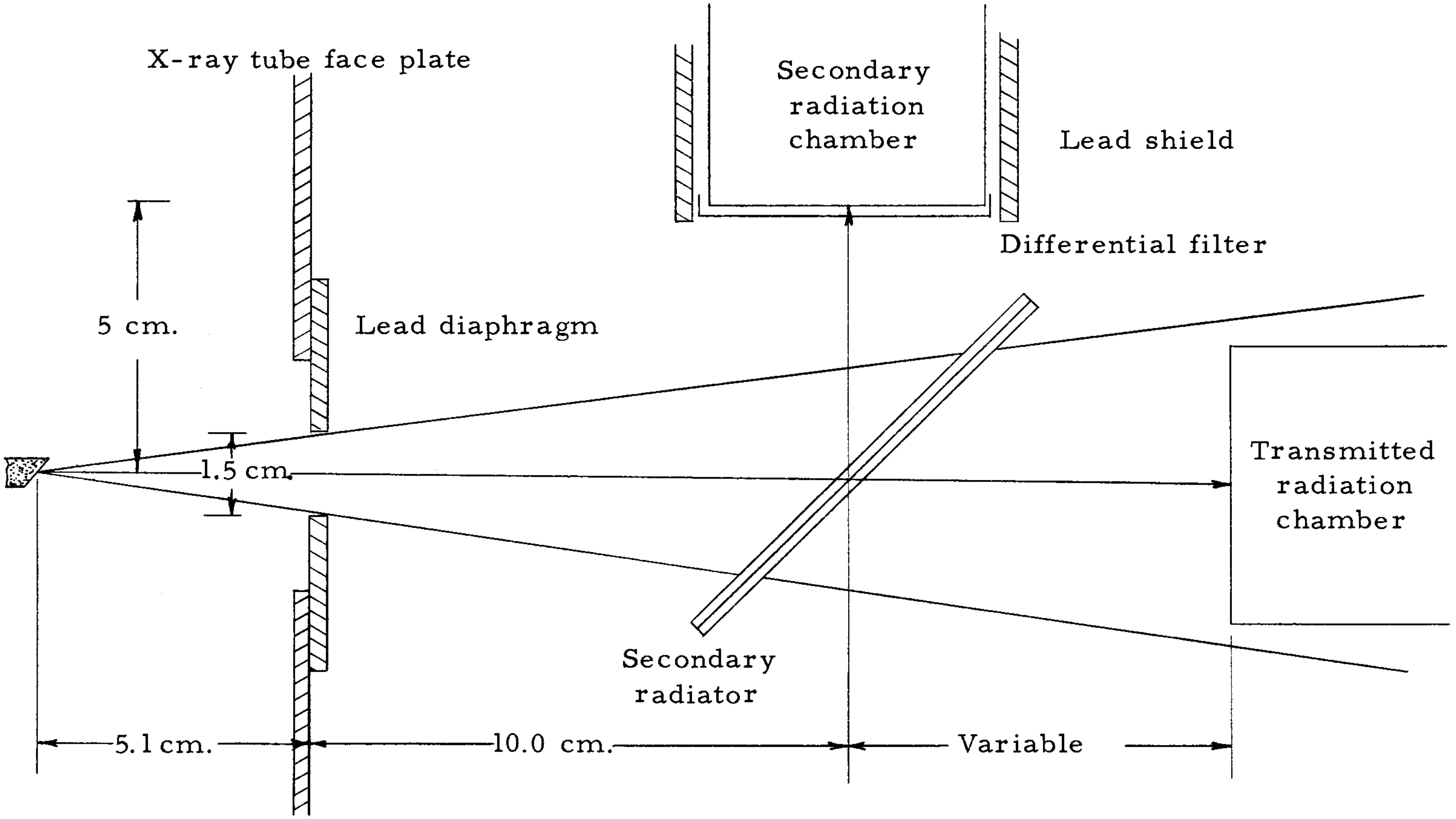

Figure 10. Experimental arrangement for determination of X-ray tube peak kilovoltage.

The differential filters used are listed in columns six and seven of Table II. Aluminum was found to provide adequate differential filtration for all of the determinations. A Victoreen Model 130, 0.25-R ionization chamber was used to measure the transmitted radiation. The X-ray machine was attached to a heavy table with the X-ray beam aligned parallel to the table center line. The focal spot was positioned twelve inches above the table top. A 115 centimeter optical bench was attached to the table parallel to its center line with one end directly under the focal spot. The secondary radiator holder was mounted on the optical bench 15.1 centimeters from the focal spot. The secondary chamber differential filter assembly and shield were mounted on a fixed stand five centimeters from the beam center line. The transmitted radiation chamber was mounted in a mobile holder directly in line with the beam center line. The distance between focal spot and transmitted radiation chamber was used as a final adjustment on the transmitted exposure rate.

Preparation and Selection of Secondary Radiators

Secondary radiator materials with well established K-edges are available from uranium (115 keV) to magnesium (1.30 keV). The usefulness of some of these elements is limited by their form and ability to be worked. Greening (15) suggested a list of 18 elements but used only three. Trout *et al*. (23) used nine elements in their investigation. Both of these investigators found elements 59 to 71 (the rare earths) difficult to obtain in an uncontaminated form. This left a gap of 30 keV in available calibration points. In recent years the rare earths have been made available in purities satisfactory for use in kVp measurements (1, 2). Table I contains a list of some of the materials available for calibration points. Table II lists the secondary radiators used in this investigation. Elements with K-edges above 90 keV were not considered because the maximum-rated voltage of the unit was 90 kVp. The secondary radiator elements that were obtained in foil form were easily mounted in the aluminum frames. The oxides were suspended in distilled water, painted onto plastic lantern slide covers, then covered with an additional plastic lantern slide cover. When the water evaporated a thin, evenly distributed, oxide layer was deposited between the plastic sheets. The oxide-coated plastic sheets were then mounted in the aluminum frames. Care had to be taken that the dry oxide secondary radiators were not subject to mechanical shock after final positioning in the beam as this would result in the oxide breaking loose from the plastic and would change the geometry of the secondary radiator thus altering the ratio of the transmitted to secondary radiation (T/S). The moisture content of the oxide was held constant for all T/S determinations at any one K-edge by monitoring atmospheric humidity and taking measurements only

Table I. Secondary radiator materials.

Z	Element	K-edge, kV (7)
13	Aluminum	1.559
22	Titanium	4.966
29	Copper	8.982
37	Rubidium	15.197
42	Molybdenum	20.003
47	Silver	25.535
50	Tin	29.182
55	Cesium	35.974
58	Cerium	40.43
62	Samarium	46.85
64	Gadolinium	50.23
67	Holmium	55.61
70	Ytterbium	61.31
73	Tantalum	67.46
74	Tungsten	69.51
77	Iridium	76.11
79	Gold	80.67
81	Thallium	85.52
82	Lead	87.95
90	Thorium	109.8
92	Uranium	115.0

Table II. kVp calibration information.

Secondary Radiator					Differential Filter		Distance from focal spot to transmitted Radiation Chamber (cm)
Z	Element	Form	Thickness mg/cm^2	K-edge kev(kVp)	Thickness mm	Element	
1	2	3	4	5	6	7	8
47	Ag	Foil	52.5	25.535	.02	Al	70
50	Sn	Foil	555	29.182	.02	Al	70
58	Ce	Oxide	154	40.43	.02	Al	60*
62	Sm	Oxide	154	46.85	.10	Al	60
64	Gd	Oxide	154	50.23	.10	Al	60
67	Ho	Oxide	154	55.61	1.25	Al	60
70	Yb	Oxide	154	61.31	1.25	Al	60
73	Ta	Foil	83	67.46	1.25	Al	70
79	Au	Powder	3.7	80.67	.06	Al	70
82	Pb	Foil	565	87.95	.10	Pb	30

* 70 cm used at 20 mA.

when the humidity remained constant throughout the entire series of measurements necessary to locate the K-edge. This was necessary because any change in moisture content would alter the value of the transmitted radiation.

Selection of Differential Filters

Differential filter elements were selected on the basis of availability, malleability, and location of filter K-edge in relation to K-edge of secondary radiator. Aluminum has been found to have the required properties for the range of energies investigated (15, 23). Differential filters of sufficient thicknesses to give a sharp peak in the transmitted/secondary ratio were formed from aluminum foil and special aluminum filter stock (Table II).

Preliminary System Evaluation

Several possible sources of error were investigated prior to determination of the calibration points. Effects evaluated included leakage radiation from the tube housing, scattered radiation from the secondary radiator holder, and scattered radiation from the wooden support of the secondary radiation chamber.

Tube Housing Leakage Radiation. A series of exposures were made at maximum kVp and 5 mA to evaluate the effect of leakage radiation on ionization chamber readings. The tube housing port was blocked with 8 pound per square foot sheet lead, the secondary radiator holder removed from the optical bench, the transmitted radiation chamber positioned 70 centimeters from the focal spot, and a 0.2 millimeter aluminum differential filter mounted in front of the secondary radiation chamber. The transmitted radiation chamber detected no measurable radiation under these conditions and the secondary radiation chamber detected less than one milliroentgen during a sixty second exposure, thus indicating tube housing leakage would not affect the ionization chamber readings.

Scattered Radiation. The lead diaphragm was installed and another series of maximum kVp exposures were made to evaluate scatter from the secondary radiator holder. An empty secondary radiator frame was installed in the holder and exposures were made with the holder in place and with the holder removed. The transmitted radiation chamber was positioned 70 centimeters from the focal spot and a 0.2 millimeter aluminum differential filter was used with the secondary radiation chamber. Comparison of transmitted and secondary radiation chamber readings, with and without the secondary radiator holder assembly in place, indicated that there was no significant scatter from the holder assembly.

Wood blocks were used to support the lead shield for the secondary radiation chamber. Scatter from this low atomic number material into the secondary radiation chamber was evaluated by making a series of exposures with the wood blocks shielded by eight pound per square foot sheet lead and comparing the secondary radiation chamber readings under this condition with readings obtained with the wood blocks unshielded. Results indicated that scatter from the wood shield support into the secondary radiation chamber was insignificant.

Beam Alignment. A final check on beam alignment was made before the calibration data were taken. An X-ray film in a 5 x 7 inch film holder was mounted in the secondary radiator holder and placed perpendicular to the X-ray beam. The developed film indicated that the beam was symmetrical with a diameter of 4.2 centimeters and had good definition. Another film was mounted in the secondary radiator holder and positioned 45 degrees to the X-ray beam. The resulting elliptical image on the developed film had maximum dimensions of 2-7/16 inch by 1-11/16 inch and was centered well within the boundary of the secondary radiator frame.

Results

Focal spot to transmitted radiation chamber distance was varied for each secondary radiator to allow adjustment of the exposure rate at the transmitted radiation chamber to produce half-scale discharges in both chambers following simultaneous exposure. The thickness of the differential filters used with each of the secondary radiators was adjusted to give the best possible definition of the K-edge. Table II lists the secondary radiators and differential filters used to produce each of seven calibration points. Calibration peaks for each of the seven secondary radiator elements are presented in Appendix II, Figures 15-21. Figure 11 summarizes the 5 mA calibration data, and these results are presented in a normalized form in Figure 12. Table III summarizes the kVp calibration data obtained from Figures 15-21.

The peak in the transmitted to secondary radiation ratio (Figures 15-21) can be determined to within ± 0.5 primary exposure volts corresponding to ± .05 secondary kilovolts. The sharpness of the transition as the K-edge is passed gives an indication of the voltage and current waveform. Most of the curves in Figures 15-21 show a sharp peak indicating voltage and current waveforms were shaped such that the radiation produced at the peak voltage was a large proportion of the total radiation output. For gadolinium (50.23 kV) at 20 mA, Figure 18 shows a smooth, flat-topped curve with no peak in the T/S ratio. This type of result is what one would expect if the voltage waveform were peaked and the current waveform flat so that the radiation produced at the peak voltage is a small proportion of the whole.

The sharpness of the transition as the K-edge is passed, depends on the spectral distribution of the output radiation. An X-ray

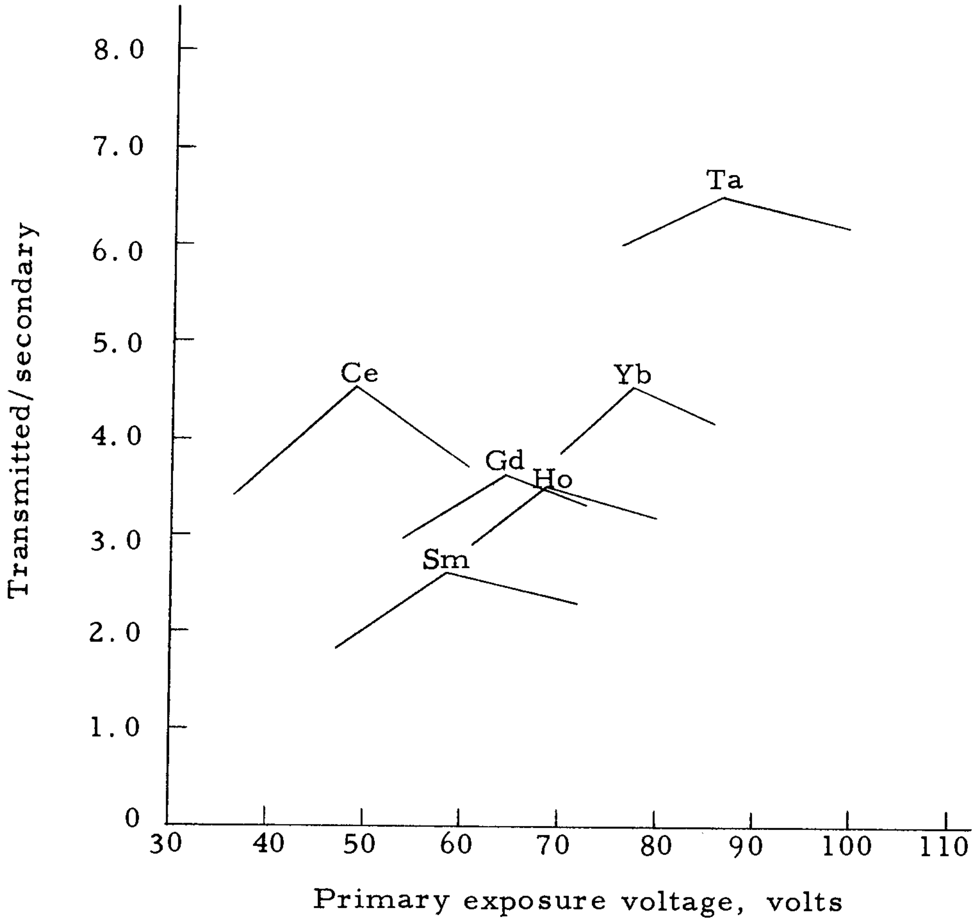

Figure 11. 5 mA calibration data.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5 mA for six selected secondary radiator elements.

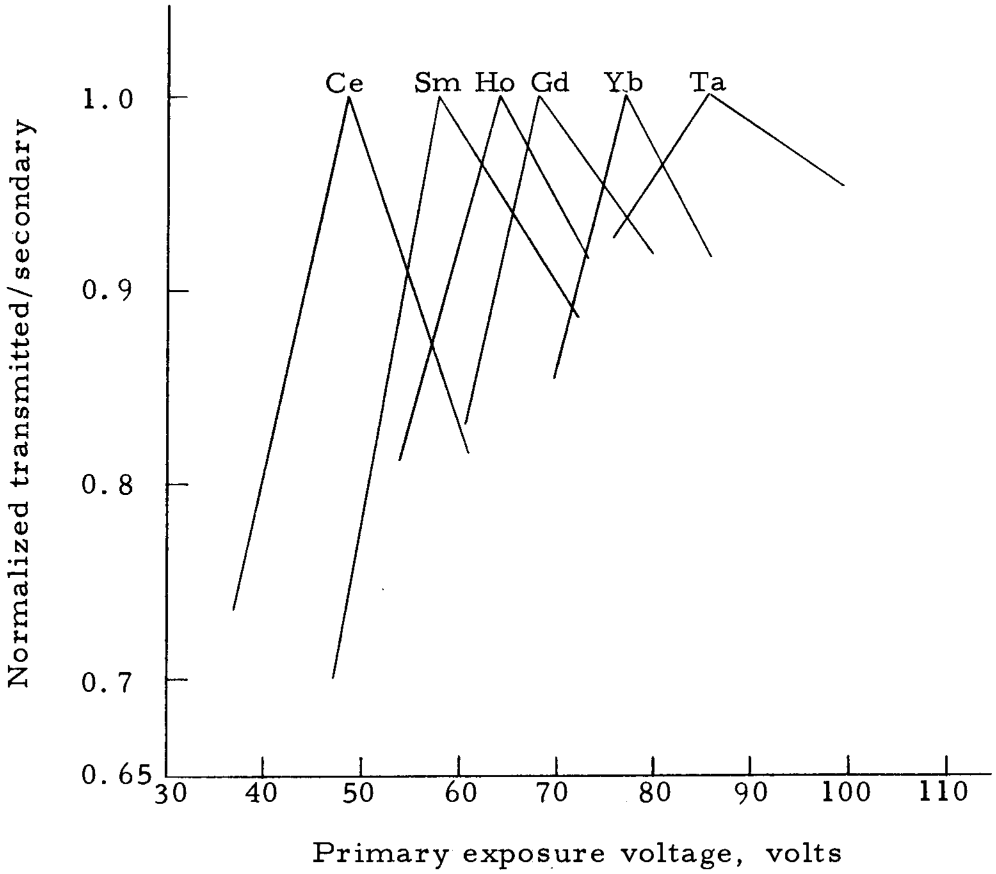

Figure 12. Normalized 5 mA calibration data.

Normalized ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5 mA for six selected secondary radiator elements.

Table III. Kilovoltage calibration data.

Secondary Radiator		K-edge	Primary Exposure Voltage at K-edge, Volts			
Z	Element	kVp	5 mA	10 mA	15 mA	20 mA
47	Ag	25.535	**	*	*	*
50	Sn	29.182	**	**	43.4	45.1
58	Ce	40.43	48.7	55.0	58.5	61.6
62	Sm	46.85	58.2	61.0	*	*
64	Gd	50.23	64.3	*	*	73.7
67	Ho	55.61	69.0	74.4	77.6	*
70	Yb	61.31	77.4	81.2	*	88.8
73	Ta	67.46	86.0	89.0	93.0	97.0
79	Au	80.67	***	*	*	*
82	Pb	87.95	***	*	*	*

* No data taken.

** Minumum primary exposure voltage too high to allow k-edge to be detected.

*** Maximum primary exposure voltage too low to allow k-edge to be detected.

beam with a steep rise at the short wavelength limit (peak voltage) of its spectral distribution will give a sharper transition than one having a slow rise at the short wavelength limit. The sharpness of the transition is a function of the spectral distribution of the output radiation since it is the radiation corresponding to the short wavelength limit that produces characteristic radiation as the K-edge is crossed. If a large proportion of the total radiation output is produced near the short wavelength limit, the transition will be sharp. If a small proportion of the total radiation is produced near the short wavelength limit, the transition will be less sharp. The X-ray unit used in this investigation was not provided with voltage or current stabilizers. It may, therefore, be concluded that those T/S curves which show no clear peak in the T/S ratio as the K-edge is crossed resulted from variations in the input current and/or voltage waveforms.

The final kilovoltage calibration curve derived from the data for the 90 kVp X-ray unit used in the experimental procedure is presented in Figure 13. The calibration curve indicates that the output voltage of the high-voltage transformer is linear over its full range of operation. Analysis of the data reveals a shift in the calibration curve with increasing X-ray tube current. This effect is due to increased current loading in the high voltage transformer secondary as the tube current increases. Table IV lists the primary

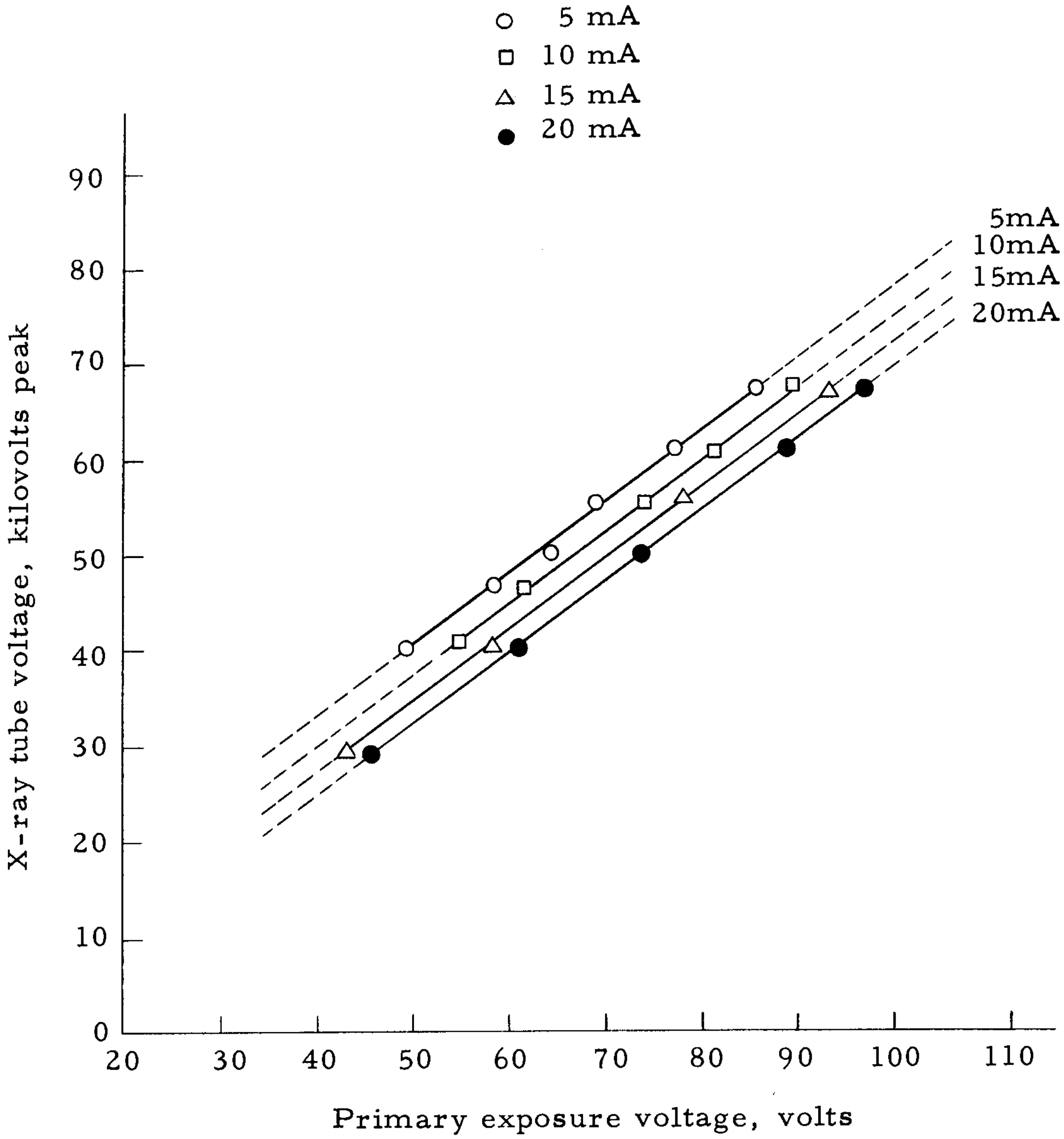

Figure 13. Calibration of peak voltage across X-ray tube.

X-ray tube peak kilovoltage as a function of high voltage transformer primary exposure voltage at 5, 10, 15, and 20 mA.

voltage range and shows how the effects of increased secondary loading result in a decrease in the primary voltage during exposures at high tube currents.

Table IV. Primary voltage range.

kVp Selecter setting	Primary Voltage Pre-Exposure	Exposure			
	0-30 mA	5 mA	10 mA	15 mA	20 mA
Low - 1	40	40	40	40	38
High - 15	110	108	104	104	102

The X-ray unit used in this investigation was not provided with circuitry to compensate for increased voltage drop at various tube currents. As a result, at a constant primary exposure voltage, there was a 2.75 kVp decrease in kilovoltage with every 5 mA increase in tube current over the current range 5 mA to 20 mA. The lack of compensation necessitates a primary exposure voltage increase of 3.75 volts with each 5 mA increase in tube current to maintain a constant output kilovoltage. The calibration curves at all tube currents should be identical for an X-ray unit provided with compensating circuitry and operating under conditions of constant current and voltage waveforms.

SUMMARY AND CONCLUSIONS

The K-edge ionization method for measuring kilovoltage across X-ray tubes has been used in this investigation to calibrate a 90 kVp X-ray machine. The method of kilovoltage calibration was developed by Greening in 1955 (15) and is held by certain investigators (14, 23) to be one of the most accurate calibration methods because it provides a direct measurement of the kilovoltage at the desired tube current. The measurement of the ionization is accomplished by using two ion chambers, one detecting the transmitted radiation and the other the secondary radiation. Since it is the ratio of the ionization in two chambers that is of concern and not the absolute value of the individual chamber ionization readings, it is not necessary to insure a high accuracy of control of the exposures. This method requires only a few exposures to determine the K-edge, and the results are obtained immediately. The two main advantages of this procedure are accuracy and the elimination of electrical connections to the X-ray generating system.

Greening (15) used three elements in his study which demonstrated the validity of the K-edge ionization calibration method and suggested a series of elements to expand the calibration from 20 kV to 115 kV. The list of elements lacked specific points in the region extending from 40 kV to 67 kV. This gap in the calibration data was due to the unavailability of purified secondary radiator material, such as the rare earth elements whose K-edges occur in the range of 40 kV to 67 kV. Trout et al. (23) used nine elements to obtain calibration points over the range 9 kV to 115 kV but also lacked calibration data in the range between 40 kV and 67 kV. Thus, as late as 1960, investigators had been unable to supply calibration data in this interval due to the unavailability of elements of suitable purity.

The X-ray unit calibrated in this study was designed to operate from 30 kVp to 85 kVp. A major portion of the kVp output of this machine is in the range of 40 kV to 70 kV. Thus, the lack of calibration data from 40 kV to 67 kV for the K-edge ionization method of kilovoltage calibration was in the area of major use of this unit and other similar diagnostic X-ray machines.

Individual rare elements of suitable purity for use as secondary radiators are now available (1, 2). Due to the high costs of rare earths rolled in foil form, it was necessary to use the oxides coated on plastic film. A possible source of error, variation in secondary radiator thickness, would affect the magnitude of the ionization response but would not influence the location of the ionization ratio peak when the ratio is plotted against primary voltage. Uniform procedures used in the experimental protocol reduced this possibility of error to a minimum.

The oxides of cerium, samarium, gadolinium, holmium, and ytterbium were used to obtain calibration points of 40.43 kV, 46.85 kV, 50.23 kV, 55.61 kV, and 61.31 kV, respectively. The K-edge calibration data for tin (29.2 kV) and tantalum (67.5 kV) previously reported by others (15, 23) was confirmed in this study and used as an experimental base line. These two reference points combined with the data obtained in this study now provide calibration points from 29 kV to 67 kV at 5 kV intervals. This is the kilovoltage range of major use for the X-ray unit used in this study. The data, combined with the additional reference values previously reported (15, 23), permit the use of the K-edge ionization calibration method throughout the entire voltage range commonly used in diagnostic X-ray techniques.

The use of an external kilovoltage calibration method introduces certain variables which must be rigidly controlled if one is to obtain reproducible results. For example, the oxide secondary radiators must not be subjected to mechanical shock or vibration after final positioning in the beam, as this may loosen the oxide layer and thereby change its thickness and geometry. The moisture content of the oxide must be held constant throughout the entire period of time during which ionization measurements are taken at any one K-edge for changes in the moisture content of the oxide will alter the value of the transmitted radiation. However, a more important requirement in the use of this method is that the geometrical arrangement of all the quipment must remain constant throughout the entire period of time during which the measurements are taken at the K-edge. Changes in geometry alter the amount of scattered radiation and the effective thickness of the secondary radiator. Changes in any of these parameters result in errors in the ionization chamber readings. In calibrating X-ray machines, such as the one used in this study, which do not have adequate compensating circuitry, it is necessary to calibrate the unit at the various tube currents of interest.

The accuracy and availability of calibration points make the K-edge ionization method of X-ray tube kilovoltage measurement a reliable procedure for use in X-ray physics. Most other kilovoltage measuring methods encounter problems at high tube currents and short exposure times. However, the ionization method is restricted only by the intensity limits of the ionization chambers. If ionization chambers with the proper intensity limits are selected, then this method may be used at tube currents and exposure times where most other methods fail.

BIBLIOGRAPHY

1. American Potash and Chemical Corporation, Rare Earth (Lindsay) Division. Rare earth and yttrium metals. Chicago, Illinois, 1964. 24 p.

2. American Potash and Chemical Corporation, Rare Earth (Lindsay) Division. Thorium, rare earth, and yttrium chemicals. Chicago, Illinois. 1964. Various paging.

3. Anthony, W. A. and A. Ball. Theory of electrical measurements. New York, John Wiley & Sons, 1913. 122 p.

4. Benoist, L. Radiochromometer for roentgen rays. Comptes rendux hebdomadaires des Seances de l'Academie des Sciences 134:225-227. 1902.

5. Bowdler, G. W. Measurement of alternating and direct voltages with special reference to absolute methods. In: Precision Electrical Measurements: Symposium held at the National Physical Laboratory, London, 1954. London, Her Majesty's Stationery Office, 1955. p. 17P1-17P7.

6. Block, P. and J. Hale. Determination of maximum energy X-rays from a constant potential X-ray machine. (Abstract) Physics in Medicine and Biology 11:141. 1966.

7. Chemical Rubber Company. Handbook of chemistry and physics. 46th ed. Cleveland, Ohio, 1965. Various paging.

8. Chubb, L. W. and C. Fortescue. Calibration of the sphere gap voltmeter. Transactions of the American Institute of Electrical Engineers 32:739-748. 1913.

9. Clark, G. L. Applied X rays. 4th ed. New York, McGraw Hill, 1955. 843 p.

10. Craggs, J. D. and J. M. Meek. High voltage laboratory technique. London, Butterworths, 1954. 404 p.

11. Edwards, F. S. High voltage measurement by sphere gaps. In: Precision Electrical Measurements: Symposium held at the National Physical Laboratory, London, 1954. London, Her Majesty's Stationery Office, 1955. p. 20P1-20P2.

12. Evans, R. D. The atomic nucleus. New York, McGraw Hill, 1955. 972 p.

13. Fine, S. and C. F. Hendee. X ray critical absorption and emission energies. Nucleonics 13:36-37. 1955.

14. Glasser, O. et al. Physical foundations of radiology. 3d ed. New York, Paul B. Hoeber, 1965. 503 p.

15. Greening, J. R. The measurement by ionization methods of the peak kilovoltage across X-ray tubes. British Journal of Applied Physics 6:73-78. 1955.

16. Hine, G. J. and G. L. Brownell. Radiation dosimetry. New York, Academic Press, 1956. 932 p.

17. Johns, H. E. The physics of radiology. 2d ed. Springfield, Illinois, Thomas, 1964. 767 p.

18. Kaplan, I. Nuclear physics. 2d ed. Reading, Massachusetts, Addison Wesley, 1964. 770 p.

19. Laws, F. A. Electrical measurements. 2d ed. New York, McGraw Hill, 1938. 738 p.

20. Newell, R. R. and G. C. Henny. Inferential kilovoltmeter. Radiology 64:88-93. 1955.

21. Peek, F. W. Jr. Dielectric pehnomena in high voltage engineering. 3d ed. New York, McGraw Hill, 1929. 410 p.

22. Stanton, L., D. A. Lightfoot and S. Mann. A penetrometer method for field kV calibration of diagnostic X-ray machines. Radiology. (In press).

23. Trout, E. D., J. P. Kelley and A. C. Lucas. Influence of cable length on dose rate and half-value layer in diagnostic X-ray procedures. Radiology 74:255-264. 1960.

24. Whyte, G. N. Principles of radiation dosimetry. New York, John Wiley & Sons, 1958. 124 p.

APPENDIX

HIGH VOLTAGE MEASUREMENT BY ELECTRICAL CONNECTION TO THE X-RAY GENERATING SYSTEM

Two classes of procedures have been found most satisfactory for measuring peak and effective values of alternating and direct voltage in the kilovoltage range. The first class are those methods in which a low voltage measuring instrument is used in conjunction with a voltage divider or other circuit component capable of withstanding the total voltage to be measured. The second class are procedures where the full voltage is applied to the measuring instrument. It is possible to design and construct an instrument of the second class which allows the calculation of the voltage from the measurement of the electrostatic force developed by the voltage applied to electrodes of known geometry. This type of voltage measuring instrument is called an absolute instrument. Most of the instruments included in these two broad classifications have been used to determine the peak or effective voltage applied to X-ray tubes (9).

Methods Using Low Voltage Instruments

Methods of measurement using low voltage instruments can be classified into two groups. The first group includes those in which a voltage measuring instrument of negligible current consumption is used with a voltage divider network. The second group includes those procedures in which a current measuring device is used in series with a high impedance.

Instruments Employing Voltage Dividers

In this group of voltage measuring instruments the total voltage to be measured is applied to two impedances connected in series and the voltage appearing across the low impedance element is measured (Figure 14). Electrostatic voltmeters which operate in the 100 volt range are available with an accuracy ± .01% (5). Their negligible current consumption makes them well suited for use in conjunction with voltage dividers.

Resistance Voltage Dividers. A voltage divider network using resistors can be used with either alternating or direct voltages. The voltage ratio is easily computed from the resistance of its components. As the applied voltage increases, the ratio may vary due to self-heating of the resistors, onset of corona, or leakage over the insulating supports. With alternating voltages the phase shift, due to stray capacitance, may introduce errors. Special wire wound resistors and "high stability" resistors are now available that introduce negligible self-heating error and by careful screening of components the phase errors can be held to a minimum (5). Although their current requirements are low, the major disadvantage in the use of resistance voltage dividers is

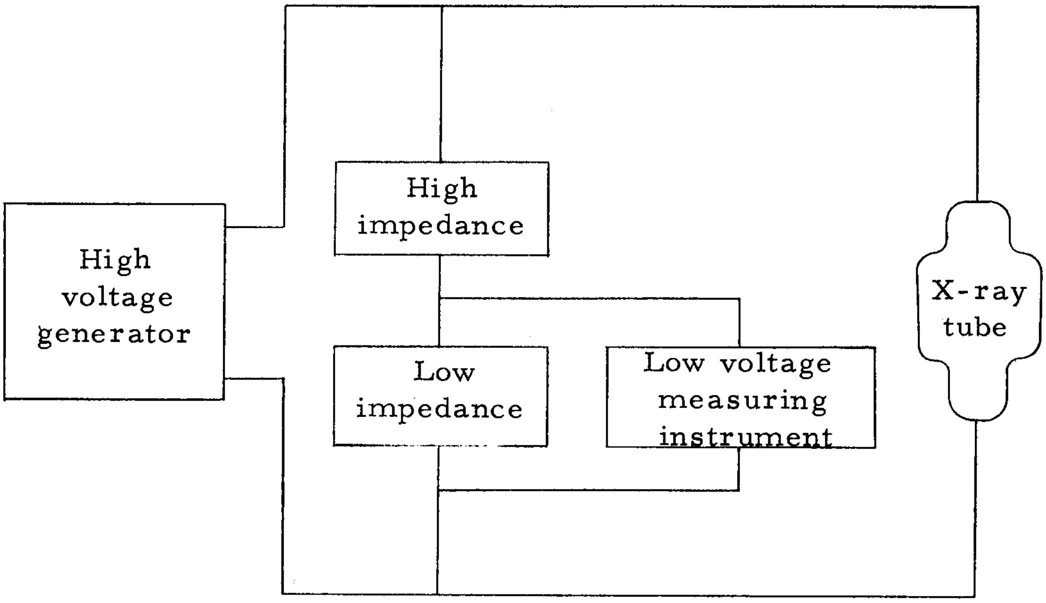

Figure 14. Voltage divider used to measure high voltage.

that an additional load is incurred in the high voltage transformer secondary which alters the original circuit conditions.

Capacitance Voltage Dividers. Capacitor voltage dividers consisting of two capacitors in series cannot be used for measurement of direct voltage, but for measurement of alternating voltages they have the advantage that they consume no power and can be used at higher voltages and frequencies than any other form of divider (5). With a suitably designed high voltage capacitor, the voltage ratio will be constant from low voltages up to the maximum that the components can withstand. The phase error will be negligible if a suitable capacitor is used for the low-voltage leg of the divider. However, this method is limited to measurement of alternating voltage and cannot be used for measurement of direct voltage.

Inductive Voltage Dividers. Voltage transformers can be used as a form of voltage divider to allow low-voltage instruments to be used in high voltage measurements. A common method used in X-ray tube voltage measurement is to place a voltmeter in the primary circuit of the high voltage transformer. Since it is possible to construct voltage transformers that will have a constant ratio of transformation and negligible phase shift over a large voltage range, this method is quite satisfactory in some cases (10). Another procedure utilizing a transformer as a voltage divider involves tapping the secondary circuit of the high-voltage transformer near ground. The total secondary voltage is then related to the applied voltage by the ratio of turns tapped to total turns in the secondary (8). Secondary loading problems similar to those incurred in voltage divider methods are also encountered.

Current Measuring Instruments in Series with a High Impedance

Two of the more important high-voltage measuring instruments use a moving coil instrument in series with a high-voltage capacitor. These are the Chubb (8) voltmeter and the generating voltmeter (5).

The Chubb Voltmeter. The Chubb peak voltmeter utilizes a capacitor of constant capacitance in series with a moving coil ammeter and has rectifiers arranged so that the current is sent through the ammeter when the voltage is at maximum or minimum value (8). The instrument measures the peak to peak value of an alternating voltage.

The Generating Voltmeter. A generating voltmeter uses a moving coil instrument in conjunction with a rectifier, in series with a high-voltage capacitor (5, 10, 19). The high-voltage capacitor has a movable low-voltage electrode which rotates at a constant speed so that the capacitance with respect to the high-voltage electrode varies cyclically in time from zero to a maximum value. The current from the low-voltage electrode to ground is directed through the moving coil instrument at the instant when the capacitance is at its maximum and minimum values. When measuring alternating voltage, the frequency of rotation of the low-voltage electrode is synchronized with the frequency of the applied voltage.

Methods Using High-Voltage Instruments

Instruments to which the total voltage is applied are of two types; those which rely on measurement of the elctrostatic force acting on an electrode and those which make use of the breakdown of air between specified electrodes.

Electrostatic Instruments

Electrostatic voltmeters rely for their operation on the force experienced by conductors charged to a difference of potential. The magnitude of the force depends on the geometry of the electrode system, the relative potentials of its parts, and the dielectric strength of the medium separating the electrodes. The force between the electrodes is proportional to the square of the potential difference between the electrodes, thus making these instruments particularly applicable to the measurement of alternating voltages (3, 5, 10, 19).

Electrostatic instruments are classed as absolute instruments if the voltage can be computed from the electrode geometry and the forces observed. Electrostatic instruments in which it is not possible to directly calculate the voltage from the measured values of the forces and the geometry are called empirical instruments.

Absolute and Empirical Instruments. Most high-voltage electrostatic instruments are based on the attracted disk electrometer developed by Lord Kelvin (19). The electrodes in these instruments are a pair of parallel plates of the same diameter. One of the plate electrodes has a small movable disk at its center. Instruments of this type are extremely sensitive to conductors which bear corona and to changes in electrode geometry (5, 10).

In an empirical voltmeter the disk is balanced by a spring or other mechanical device, the strain of which causes a pointer to be deflected along a scale. The movable electrode is connected to a calibrated spring balance in an absolute voltmeter. The potential difference between the electrodes is then directly computed from the value of the attractive force (5, 10, 19).

Spark-Gap Instruments

Spark-gap voltmeters depend on the dielectric strength of air for their operation. At power frequencies a spark gap breaks down at the crest of the voltage wave irrespective of the wave form; thus spark-gap instruments indicate only peak voltages (11).

The sphere-gap voltmeter, due to its basic simplicity, is the most commonly used method of measuring X-ray tube voltage (11).

The open circuit transformer secondary voltage or the voltage across the X-ray tube at low tube current may be measured by the sphere-gap technique. The voltage drop at higher tube currents is taken into account by theoretical computation or by means of a radiographic calibration utilizing a penetrometer. The voltage at all tube currents may be measured by a sphere-gap but the short exposure times required at higher currents increase the possibility that surge voltages will be measured rather than true peak voltage. A procedure where several X-ray tubes are connected in parallel across the high voltage transformer secondary may be used to allow sufficient exposure time to permit sphere-gap adjustment during exposure and thus reduce the possibility of measuring surge voltages at high tube currents (15). However, in this procedure the voltage is not measured with the X-ray tube which is to be used. Other limitations on the use of sphere-gap voltmeters arise from the fact that they disturb the circuit when the spark-over occurs and they cannot give a continuous measurement of peak voltage (5, 6, 11, 22).

Limitations of Methods That Require Direct Electrical Connection to the X-ray Generating System

High voltage measuring methods which use low voltage instruments in conjunction with voltage dividers are subject to error resulting from resistance variation, onset of corona, leakage currents, and stray capacitance. If a current measuring instrument is used in series with a high impedance, some of these problems are eliminated and others are created. The Chubb (8) voltmeter and the generating voltmeter eliminate most of the problems discussed, but both have certain restrictions on their use due to their dependency on the frequency and waveform of the applied voltage.

High voltage measurement with instruments to which the total voltage is applied is subject to error from changes in electrode geometry, influence of external electrical fields, onset of corona, and variation in the dielectric strength between electrodes.

There is one major restriction on the use of all of these methods of high voltage measurement. This restriction results from the fact that special electrical adaptors will be required to bring the conductors out of the grounded tube housing or high voltage cables. This is the major limitation encountered whenever these methods of high voltage measurement are to be used to measure the voltage applied to an X-ray tube after it is installed in its shockproof housing and connected to the generator (5, 23). Most X-ray installations are not equipped with these special adaptors and in most cases the use of the X-ray tube would be restricted by the presence of the external high voltage adaptor. Therefore, a voltage measurement method that does not require electrical connection to the generating system would be desirable for use in the measurement of X-ray tube voltage in sealed shockproof systems.

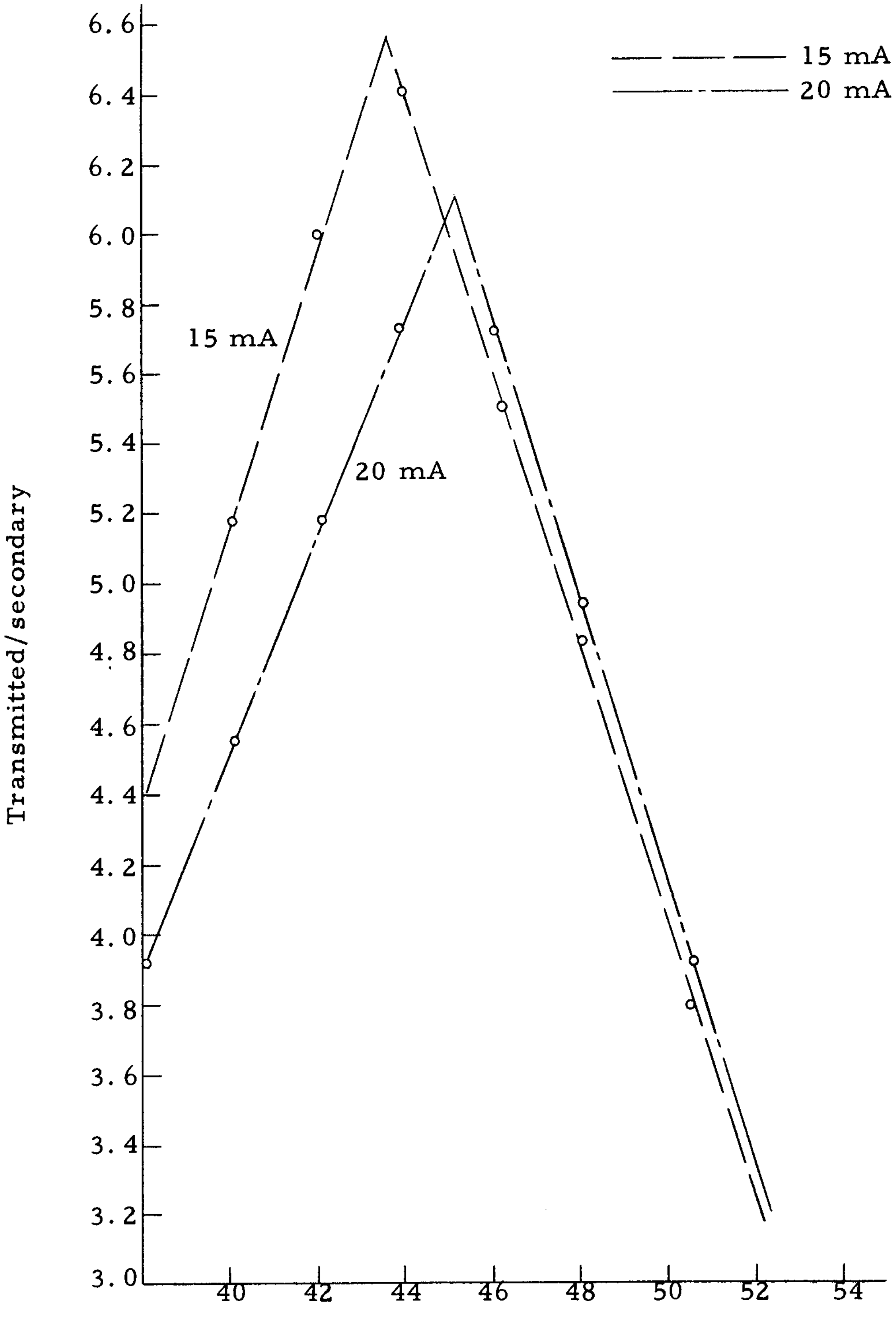

Figure 15. Determination of K-edge of tin.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 15 and 20 mA.

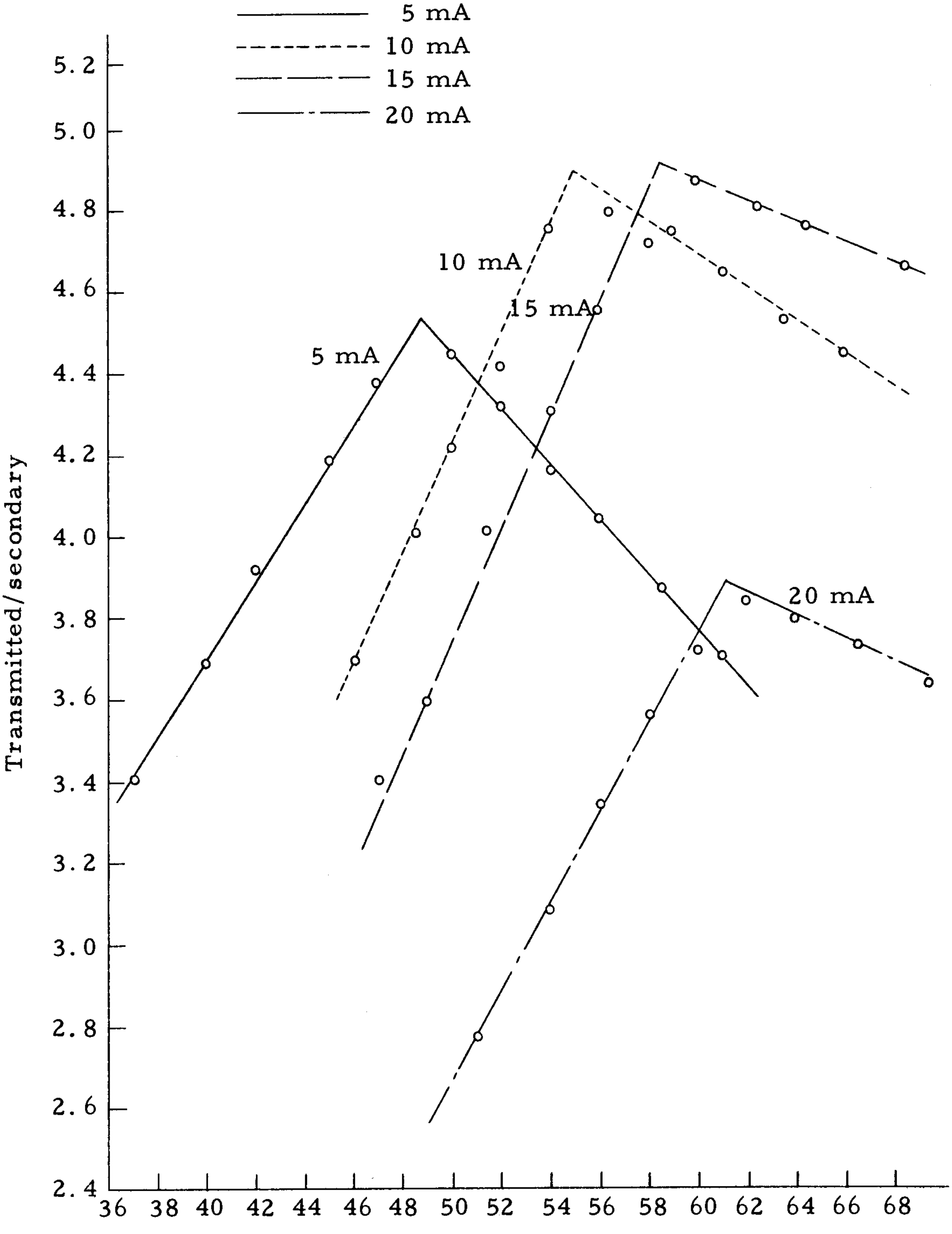

Figure 16. Determination of K-edge of cerium.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5, 10, 15, and 20 mA.

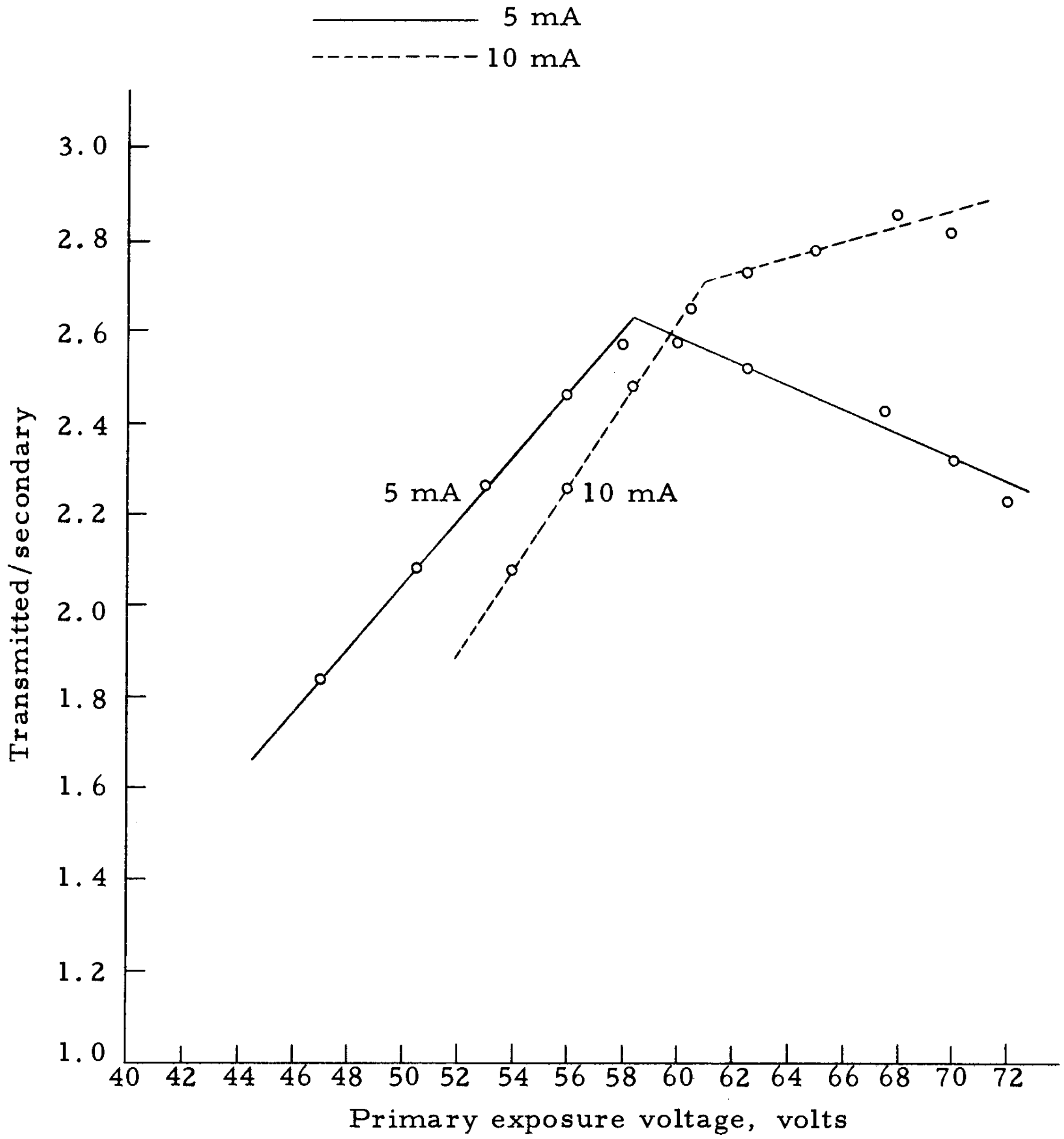

Figure 17. Determination of K-edge of samarium.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5 and 10 mA.

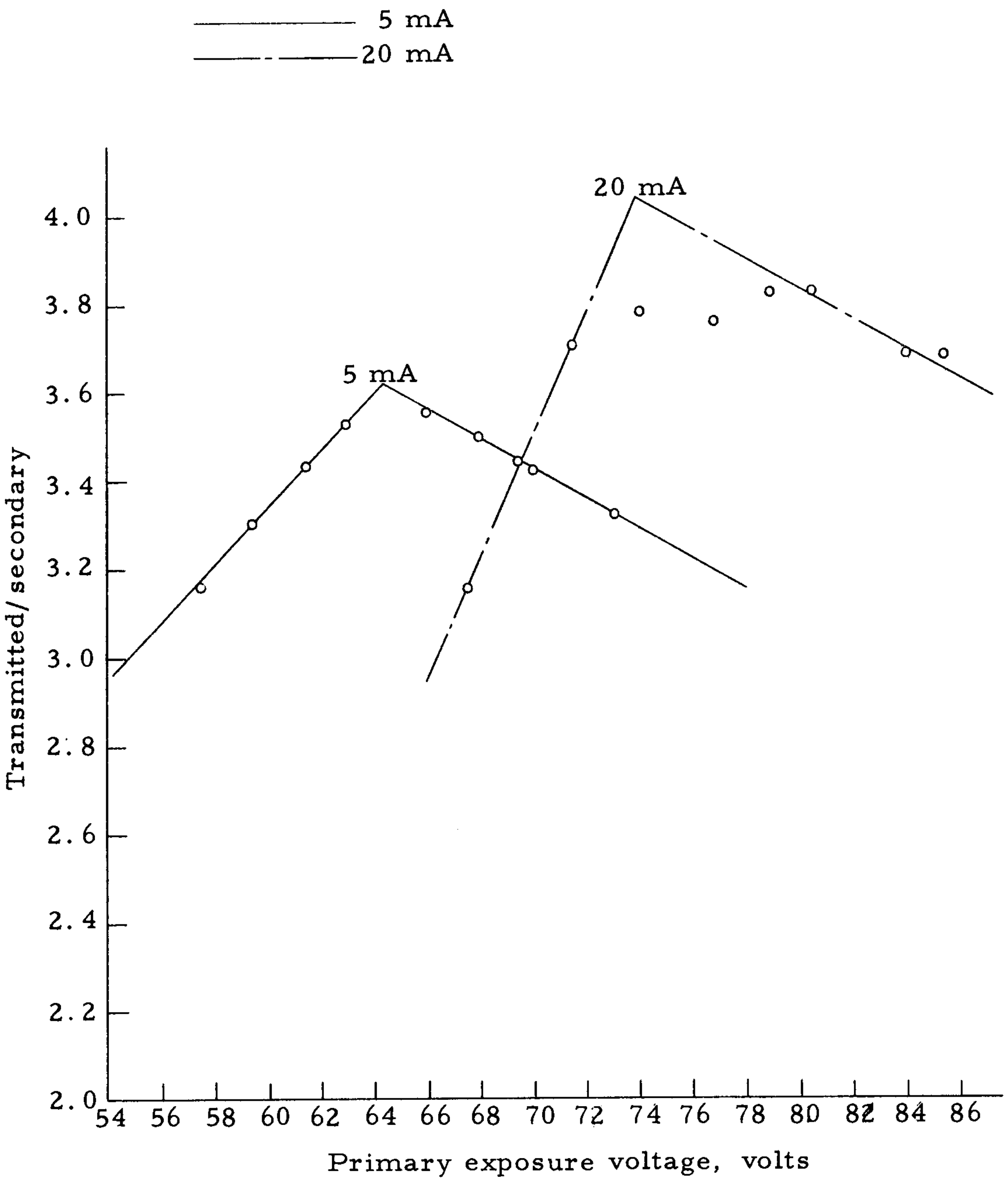

Figure 18. Determination of K-edge of gadolinium.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5 and 20 mA.

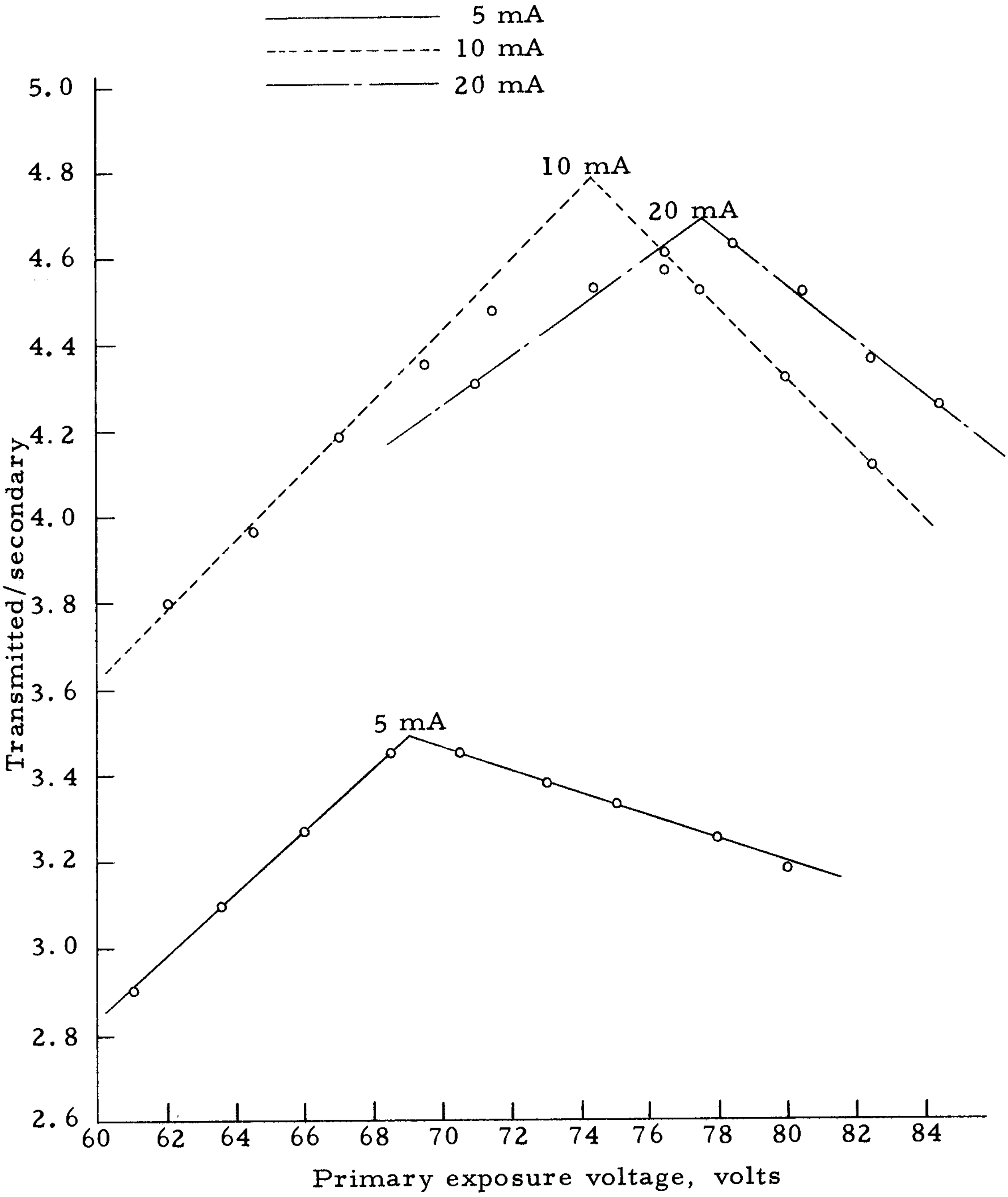

Figure 19. Determination of K-edge of holmium.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5, 10, and 15 mA.

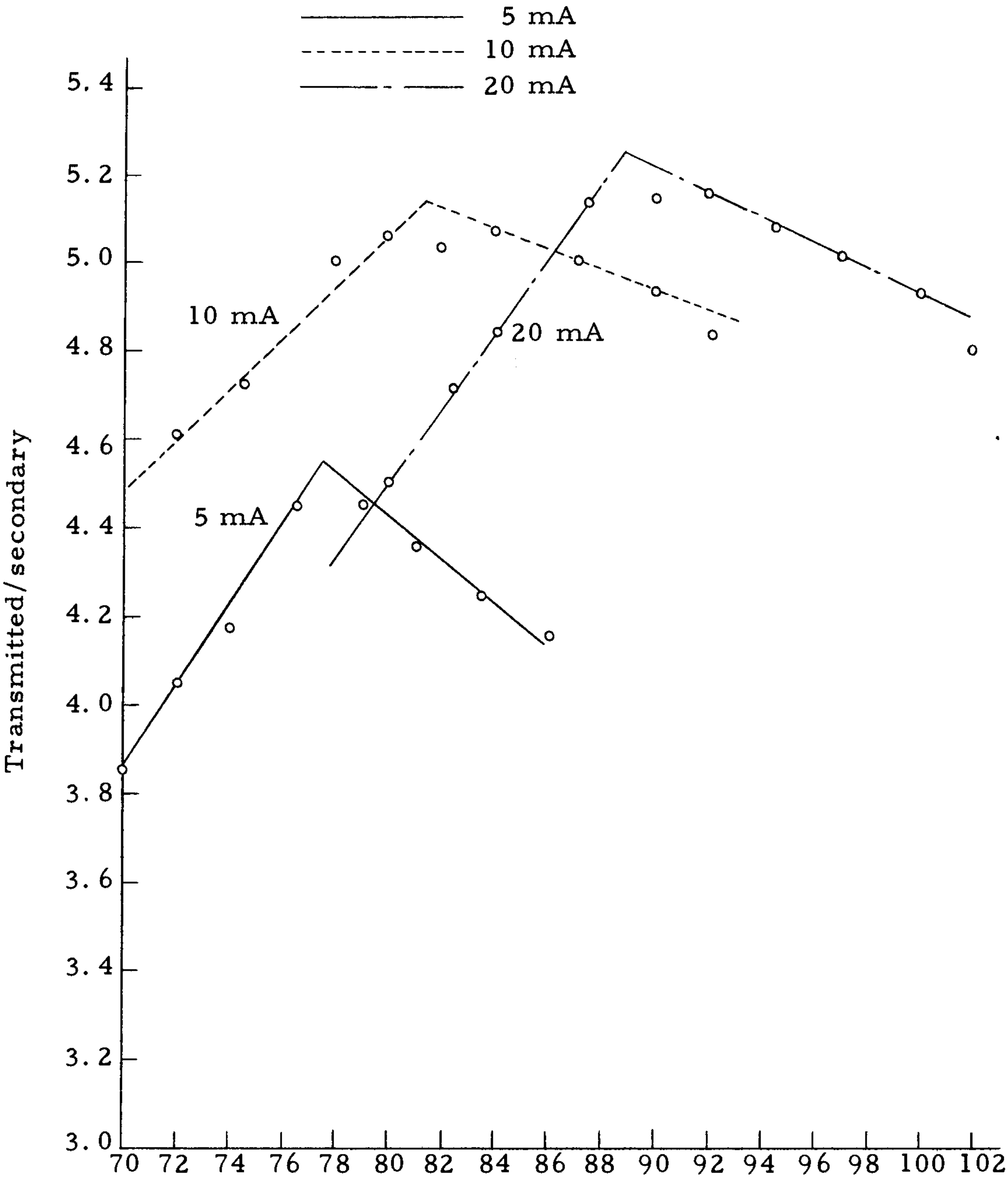

Figure 20. Determination of K-edge of ytterbium.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5, 10, and 20 mA.

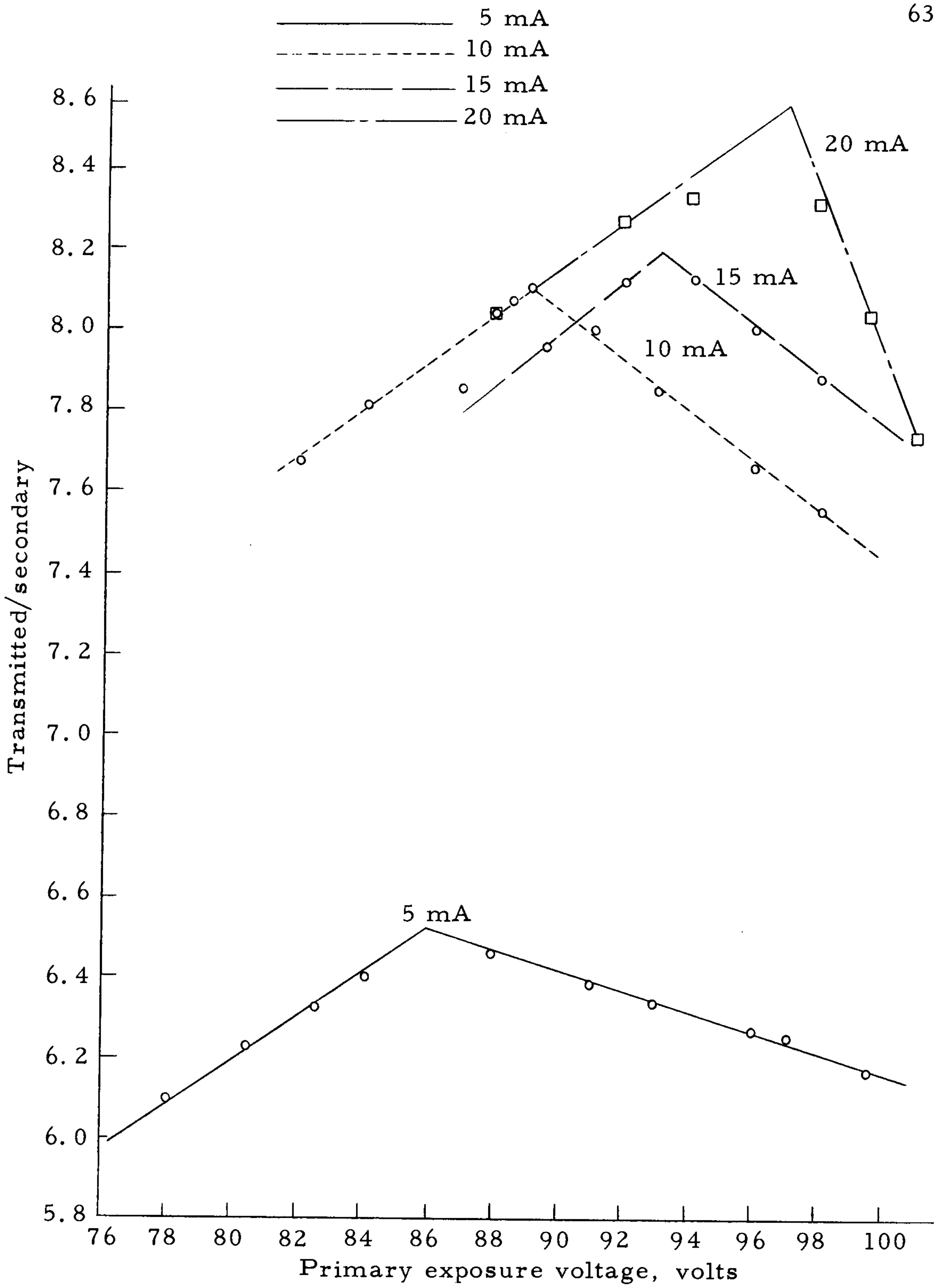

Figure 21. Determination of K-edge of tantalum.

Ratio of transmitted to secondary radiation as a function of high voltage transformer primary exposure voltage at 5, 10, 15, and 20 mA.