The objective of this study was to determine the distribution of leakage radiation from two unshielded diagnostic-type X-ray tube housings. This information was used to determine the shielding required in the housings to bring them into compliance with the definition of a diagnostic-type protective tube housing, as set forth by the National Council on Radiation Protection and Measurements in Report No. 33.

Two special diagnostic X-ray tube units were used, one containing a rotating anode tube and the other a stationary anode tube. The only shielding supplied was that provided by the steel, oil-containing tube casing which surrounds the X-ray tube. A measurement of the distribution of leakage radiation on a sphere of one meter radius about the focal spot of the X-ray tube was made on each tube when the tube was operated at its maximum rated continuous current.
for its maximum rated operating voltage.

From the leakage radiation measured, the thickness of lead shielding required to bring the X-ray tube housing into compliance with the definition of a diagnostic-type protective tube housing was calculated.

Lead shielding was placed on each of the X-ray tube housings, and measurements were made to determine if each housing was then in compliance with the definition of a diagnostic-type protective tube housing.

As a result of this study, it was found that the distribution of leakage radiation from an unshielded diagnostic-type tube housing is non-uniform. The amount and location of shielding required in the housing is dependent upon the distribution of the leakage radiation, and is, therefore, a function of the design and rating of the X-ray tube used in the housing.
The Distribution of Leakage Radiation from an Unshielded Diagnostic-type X-ray Tube Housing

by

Royce Lynn Gragg

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Typed by Donna L. Olson for \textit{Royce Lynn Gragg}
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THE DISTRIBUTION OF LEAKAGE RADIATION FROM AN UNSHIELDED DIAGNOSTIC-TYPE X-RAY TUBE HOUSING

I. INTRODUCTION

Shortly after the discovery of X-rays in 1895, it was realized that X-radiation, in the course of dissipating its energy in biological material, could produce changes in structure and function. As biological effects began to appear, there occurred a series of accidents and experiments which demonstrated the effectiveness of X-rays in producing X-ray burns, cancers, leukemia, and anemia (Glasser et al., 1965). In contrast to these negative effects, however, X-rays were found to be of great value in medical diagnosis.

In the early period of X-ray work, there existed a dilemma; an invaluable tool to medicine had also proved to be injurious to living tissue. As diagnostic radiology became more useful in medicine, increasing numbers of people were exposed to X-rays; therefore, authoritative groups of professionally capable individuals were organized to recommend rules and establish procedures for the safe use of X-rays.

Due to the dual role of X-rays, these groups found that it was imperative to set maximum permissible exposures on the basis of a calculated risk--a balance of the probability of known good against the possibility of harm. Over the past thirty years the permissible
exposure levels have been lowered repeatedly, not because any
damage had ever been observed in individuals whose exposure had
never exceeded the earlier permissible levels, but rather in accor-
dance with the trends of scientific opinion concerning this balance
(Glasser et al., 1965).

Since maximum permissible exposure levels have been set in
order to minimize the probability of injurious effects from unwanted
X-rays, it is necessary to provide adequate protection against such
rays. To do this precautions must be taken, but the first step is to
see that the beam of X-rays leaving the tube is restricted to the area
of clinical interest. A cone or collimator is used to reduce the field
to an area less than the maximum provided by the tube casing. The
tube is then surrounded with some material which reduces the leak-
age radiation to a recommended level, leaving an opening only to
allow the passage of the useful beam of X-rays. This material sur-
rounding the major portion of the X-ray tube constitutes the protec-
tive tube housing.
II. HISTORICAL BACKGROUND

As a primary factor in X-ray protection, the diagnostic tube housing and its development have received attention throughout the history of diagnostic radiology. The improvement of the diagnostic tube housing has followed the advances in X-ray protection recommendations.

In 1895 W. C. Roentgen discovered X-rays with the use of a glass Crookes cathode-ray tube. In 1895 and 1896 in America the diagnostic X-ray system used in radiology consisted of a similarly constructed bare glass tube and the essential electrical supply components for the tube. Some of the American tube manufacturers used lead-glass in the production of X-ray tubes. However, operators favored the more economic and light-weight German tubes made of soda-lime glass with no lead protection (Kraissl, 1935). By 1897 work had been undertaken on metal X-ray tubes, although improvement of tube performance rather than radiation protection was the main objective in their construction (Clark, 1955; Kaye, 1923). By 1898 some users of medical radiographic apparatus had begun to enclose the X-ray tube as completely as possible in wooden boxes coated with lead paints (Gross, 1938). However, for the most part, there was no special shielding provided for X-ray tubes for the first few years after the discovery of X-rays.
Soon after radiography had come into use in the medical profession, reports were made concerning biological disturbances due to the use of X-radiation (For a comprehensive presentation of these reports, see Nauman, 1964). The first evidence of an attempt to recommend the use of shielded tube housings appears in an article by William Rollins in 1901. His article described a series of experiments in which he subjected guinea pigs to whole-body X-ray exposures. One of the conclusions which he reached was that one should enclose the X-ray tube in a container of "non-radiable" material (material which is opaque to X-rays).

In 1902 lead oxide impregnated rubber was in use as shielding for X-ray tubes. By 1906 it had been found that through the use of glass having a high lead content, it was possible to provide a substantial amount of X-ray protection. One of the first housings of this type was an open-topped, lead glass bowl, into which the X-ray tube was placed; with a window in the bottom, through which the useful beam could pass (Gross, 1938). Housings of this type provided then acceptable shielding for voltages up to about 140 kVp (later to 200 kVp). At higher voltages it was advisable to enclose the whole tube in a lead-lined metal container. Since this method of providing

---

1 Throughout this paper, kVp will be used to indicate the peak kilovoltage applied to the X-ray tube.
shielding resulted in heavy and expensive equipment, operators favored the use of lead-lined wooden boxes as housings (Robertson, 1948; Terrill and Ulrey, 1930). However, shields of these types adversely affected the operation, at higher voltages, of the X-ray tubes then in use, and consequently, were not consistently used.

In 1905 some further work with lead glass tubes was undertaken on a small scale (Piffard, 1905). During the early 1910's there is evidence that work was continuing on the construction and use of X-ray tubes with metal bulbs (Coolidge, 1917; Kaye, 1923), but the more promising of the work being done on tube housings continued along the lines of lead glass tubes and shields (Coolidge, 1917). In 1918 the first Coolidge hot-cathode radiator-type of tube was developed. In a tube of this type, the glass could be made thick and the bulb size small without sacrificing tube performance; therefore, the entire tube, except for the window, could be constructed from lead glass or enclosed in a lead glass housing (Coolidge, 1919).

In November 1915, the British Roentgen Society issued "Recommendations for the Protection of X-ray Operators." In the section devoted to X-ray tube shielding, the following recommendation was made (p. 341):

All X-ray tubes must be provided, when in use, with a protecting shield or cover which prevents the access of rays to the operators and which encloses the tube, leaving an adjustable opening only sufficiently large to allow the passage of a sheaf of rays the size necessary for the work in hand.
This was the first organized attempt at X-ray protection (Trout, 1960).

In April 1921, the British X-ray and Radium Protection Committee was established, and in July of the same year it issued a series of recommendations on X-ray protection. Concerning diagnostic protective tube housings, it was recommended that the X-ray bulb be enclosed as completely as possible with protective material equivalent to not less than two mm. of lead, for both radiography and fluoroscopy. If the equipment was not capable of operation above 70 kVp, the protection should not be less than 1.5 mm. lead equivalent. Revised recommendations were published in 1927, but no change was made in the recommendations concerning the protective tube housing. Both reports stressed the fact that in order to have adequate protection and necessary maneuverability, the weight of the tube enclosure must be kept to a minimum by placing the protective material as close as practical to the tube.

The first wide-scale attempt to conform to the recommendation and make the shielding an integral part of the tube came in the Philips Metalix tube in 1927 (Bouwers, 1929). There were advantages to be derived from a metal X-ray tube (Bouwers, 1929): (1) it could be so designed that the leakage radiation could be reduced to a specified level and (2) the all-glass X-ray tubes then in use could be replaced by metal tubes of higher power and more complete
In 1928 the Second International Congress of Radiology also issued recommendations concerning X-ray and radium protection. Those recommendations pertaining to the protective tube housing were: (1) the X-ray tube should be surrounded as completely as possible with protective material of adequate lead equivalent and (2) the following lead equivalents are recommended as adequate:

<table>
<thead>
<tr>
<th>Maximum kVp</th>
<th>Minimum Lead Equivalent - mm.</th>
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<tr>
<td>75</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>125</td>
<td>2.0</td>
</tr>
<tr>
<td>150</td>
<td>2.5</td>
</tr>
<tr>
<td>175</td>
<td>3.0</td>
</tr>
<tr>
<td>200</td>
<td>4.0</td>
</tr>
<tr>
<td>225</td>
<td>5.0</td>
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</table>

In 1929 the recommendations of the Second International Congress of Radiology were published in Circular No. 374 of the Bureau of Standards in the United States.

During this period the Advisory Committee on X-ray and Radium Protection was formed in the United States, and in 1931 it issued Handbook 15 through the Bureau of Standards. For X-ray protection, X-ray installations were classified as to use and
maximum kilovoltage. Of interest to this study is Class A, diagnostic X-ray installations up to 130 kVp. Three recommendations regarding tube shielding were made for this class (p. 5):

(1) A protective enclosure shall surround the X-ray tube bulb and the arms for a distance of four inches from the bulb, so that direct radiation is shielded off in all directions.

(2) Open bowls shall not be used.

(3) In the case of tubes having built-in protection, the equivalent lead thickness shall conform to Table 2 and shall shield off all direct radiation.

Table 2 contained the same lead thickness recommendations as Circular No. 374, except that it was extended to 600 kVp.

By the late 1920's the Coolidge radiator-type X-ray tube was in common use in the field of medical radiography. The heat produced in the tube was dissipated by the use of metal plates (radiators) external to the shield (Coolidge, 1919). This tube made possible the recommendation that the tube be fully enclosed in a shield (Trout, 1966).

The third recommendation of the Advisory Committee on X-ray and Radium Protection, concerning tubes with built-in protection, was necessary because of two other X-ray tube developments (Trout, 1966). In Europe a tube had been produced which had a metal center section and glass arms (Bouwer, 1929), and in America the glass radiator-type X-ray tube had been inserted into a cylinder with a
lead center section and lead-impregnated plastic arms (Coolidge and Charlton, 1945).

In 1936 the Advisory Committee on X-ray and Radium Protection issued Handbook 20 (which superseded Handbook 15) through the National Bureau of Standards. The Committee made this recommendation (p. 6):

Tubes having built-in protection, tubes placed semi-permanently in special protective containers, auto-protective or oil-immersed tubes, should be used in all new X-ray installations and should replace all obsolete installations where possible.

The lead equivalence recommendations for the tube shielding remained unchanged from Handbook 15. However, one addition in the recommendations was that the tube manufacturers place permanent markings of the lead equivalence on all material used for shielding.

In 1946 the Advisory Committee on X-ray and Radium Protection became the National Committee on Radiation Protection, and in 1949 it issued Handbook 41 (which superseded Handbook 20) through the National Bureau of Standards. Classifying X-ray installations by use and peak kilovoltage was discarded, and medical X-ray installations were placed in one of four classes--fluoroscopic, radiographic, mobile, or fluorographic--with the peak kilovoltage for each classification being 100 kVp. Rather than specifying the lead equivalence required at each maximum operating voltage a definition was given of a diagnostic-type protective tube housing (p. 3):
A diagnostic-type protective tube housing is one in which the direct radiation is reduced to at most 0.10 R per hour at a distance of one meter from the tube target when the tube is operating continuously at its maximum rated current for the maximum rated voltage.

In all probability this change in recommendations was made for two reasons: (1) the X-ray tubes in use in this country were of varied types; a recommendation to cover them all would be impractical if it were written in the same form as previous recommendations and (2) a unit for X-ray exposure, the Roentgen (R), had been defined and adopted for use throughout the X-ray field; and instrumentation for measurement of the Roentgen was commercially available.

In 1950 the National Committee on Radiation Protection clarified the definition of a diagnostic-type protective tube housing by issuing an addendum to Handbook 41 (p. 3):

A diagnostic-type protective tube housing is one in which the direct radiation is reduced to at most 0.10 R per hour at a distance of one meter from the tube target when the tube is operating at maximum continuous rated current for the maximum rated voltage.

In 1955 Handbook 60 (which superceded Handbook 41) was published through the National Bureau of Standards, but there were no changes in the recommendations concerning tube housing shielding.

In 1961 the National Committee on Radiation Protection issued NCRP Report No. 26 (NBS Handbook 76), which superceded Handbook 60, in which the shielding requirements again remained the same, but the wording and method of testing were altered (p. 2):
A diagnostic-type protective tube housing is one so constructed that the leakage radiation at a distance of one meter from the tube target cannot exceed 100 mR in one hour when the tube is operated at any of its specified ratings.

This change was brought about by a change in X-ray equipment design. Older equipment had continuously variable tube current control so that almost any current up to maximum could be attained at any rated kilovoltage. Newer equipment provided only certain pre-selected tube currents so that, in most cases, the continuous current could not be attained without modification of the equipment.

This change presented a problem in that as state regulation of X-ray installations was increasing, it was necessary for the state regulatory agency to inspect X-ray installations for non-compliance with equipment regulations. The manufacturer could test tube units for leakage radiation at the factory following the definition of a diagnostic-type protective tube housing in Handbook 60; but the newer units could not be tested in medical installations under the same definition, for they could not be operated at their continuous currents.

Thus, some provision had to be made in the recommendations so that the newer X-ray equipment could be tested for tube housing leakage at currents exceeding the maximum continuous current.

The definition stated in Handbook 76 made this provision when consideration was given to the limited duty cycle of the X-ray tube at tube currents higher than the maximum continuous current (Trout,
The National Council on Radiation Protection and Measurements (which replaced the National Committee on Radiation Protection in 1966) published Report No. 33 (which superseded Handbook 76) in 1968, in which the following definition was given (p. 37):

A diagnostic-type protective tube housing is one so constructed that the leakage radiation measured at a distance of one meter from the source does not exceed 100 mR in one hour when the tube is operated at its maximum continuous rated current for the maximum rated tube potential.

A method for testing the tube housing leakage at currents higher than the maximum continuous rated current is also outlined, and instructs one to take into account the duty cycle of the tubes.

Since the time of the Metalix tubes, the Coolidge radiator-type tube, and the oil-immersed tube, the tube housing has developed into a sturdy lead-lined metal casing which houses both the X-ray tube and necessary electrical insulation for the tube unit. In a housing of this type, the level to which the leakage radiation can be reduced is a function of the weight which the finished X-ray unit will tolerate (Trout, 1964).
III. EXPERIMENTAL PREPARATION

Installation

The X-ray tube units were installed in a room which houses a 300 kVp therapeutic X-ray unit. The shielding in this room provided adequate radiation protection for operation of the unshielded diagnostic X-ray tubes. A General Electric Model KX-10 control unit, and half-wave rectified, center-grounded, high voltage transformer capable of operation up to 140,000 volts were used to energize the X-ray tubes. Two high voltage cables, each 15 feet long and with a total effective capacitance of 1950 pF, were used to connect the high voltage transformer to the tube unit.

Two unshielded diagnostic X-ray tube units were obtained from the Dunlee Corporation for this study. One contained a type HRZ-1 rotating anode tube, and the other contained a type HSZ-1 stationary anode tube. The only shielding was that due to the steel, oil-containing tube casing which surrounds the X-ray tube.

The rotating anode X-ray tube is rated by the manufacturer for operation at a maximum voltage of 100 kVp, with an anode cooling rate of 15,000 heat units\(^2\) per minute. The maximum continuous

\(^2\)Heat unit is a measure of the amount of heat generated in an X-ray tube during an exposure. Heat unit = mA \cdot kVp \cdot exposure time in seconds.
current at 100 kVp was calculated to be $2.50 \text{ mA}^3$ from the relationship:

$$\text{mA} = \frac{1}{k\text{Vp}} \cdot \frac{1}{60 \text{ sec/min}} \cdot \frac{\text{heat units}}{\text{minute}}$$

The stationary anode X-ray tube also has a maximum rated operating voltage of 100 kVp. However, the anode cooling rate is 20,000 heat units per minute, which results in a maximum continuous current of 3.33 mA at 100 kVp. The difference in the maximum continuous currents is due to the difference in the heat storage capacity and cooling rate of the two tubes.

Upon completion of the installation of the equipment, tube current and high voltage calibrations were performed.

**Tube Current Calibration**

The first step in the calibration of the control milliammeter used to indicate X-ray tube current was to perform a milliammeter comparison test. The d.c. milliammeter (with a range of 0-12 mA) on the control unit was connected in series with a d.c. milliammeter of known calibration, a source of constant voltage, and a decade resistance box. The resistance was varied to change current, and

$^3\text{mA}$ is the abbreviation used for milliampere, a unit of electrical current.
at various values of circuit resistance, the readings of the two milliammeters were compared. From this test it was determined that the control unit milliammeter was accurate to within $+6\%$ of the true current for the two tube currents to be used. (See Appendix A, Table 1).

The next step was to determine whether the X-ray tube filament control potentiometer had the resistance range necessary to obtain the required X-ray tube currents. It was determined that the filament control potentiometer did not have the necessary resistance and that the desired tube currents could be attained for the rotating and stationary anode tubes with the addition of 130 ohms and 250 ohms, respectively, in series with the control potentiometer.

The final step in the calibration of the control milliammeter was accomplished by connecting a calibrated d.c. milliammeter, designed for high voltage operation, in the anode circuit of the X-ray tube. A specially designed porcelain insulator was used to make the connection to the X-ray tube. The control unit milliammeter was then compared to the tube circuit milliammeter over the resistance range of the filament control. For the tube currents to be used, the control unit milliammeter was determined to be accurate within $\pm 3\%$ of the true X-ray tube current. (See Appendix A, Table 2). This error is within the readability of the control unit milliammeter.
High Voltage Calibration

The control unit has an a.c. voltmeter to measure the voltage across the primary of the high voltage transformer. The kilovoltage control, which controls the voltage applied to the primary of the high voltage transformer, is an autotransformer with taps providing voltage control in three volt steps. A continuous range of primary voltages was not attainable. It was, therefore, necessary to determine the voltage to be applied to the primary of the high voltage transformer which would result in an X-ray tube voltage nearest, but not exceeding, 100 kVp.

The first step was to determine the accuracy of the control unit voltmeter. A precision a.c. voltmeter was connected in parallel with the a.c. voltmeter on the control unit. The readings of the two meters were compared over the voltage range of interest in this study, and the control unit voltmeter reading was found to be accurate to within -1.9%. This error was considered to be negligible, since the actual scale calibration was not as important as the reproducibility of that value. (See Appendix A, Table 3).

Since the control voltmeter measures the voltage across the primary of the high voltage transformer, it was necessary to relate the readings of the primary voltmeter to the corresponding voltages applied to the X-ray tube. For a given primary voltage, the
secondary voltage of the transformer depends upon the current
flowing through the X-ray tube; therefore, it was necessary to cali-
brate the voltmeter for each value of tube current to be used.

A high voltage bleeder was used for the high voltage calibra-
tion. The high voltage bleeder is a high resistance (100 megohms to
ground) voltage divider calibrated so that the output voltage is
1/1000 of the input voltage. The 15 feet long high voltage cables
were used to connect the high voltage transformer to the high voltage
bleeder. Short auxiliary high voltage cables were then used to con-
nect the X-ray tube to the high voltage bleeder. The leads from the
output of the high voltage bleeder were connected to a Tektronix type
564 oscilloscope which had been calibrated so that both the wave-
form and the magnitude of the voltage could be determined. The kVp
could be determined to within ±2 kilovolts from the waveforms. Vol-
tage measurements and waveform photographs were taken at 2.50
and 3.33 mA. (See Appendix A).

Based upon the tube voltage calibration using the high voltage
bleeder, it was determined that the stationary anode tube would be
operated at 97 kVp and 3.33 mA, and the rotating anode tube would
be operated at 98 kVp and 2.50 mA. Both these kVp values were ob-
tained with an input of 67 volts a.c. to the high voltage transformer.
The next step in primary voltage, 70 volts, yielded a tube voltage
greater than 100 kVp.
Since the maximum rated tube voltage of 100 kVp could not be attained, a determination of the variation of exposure rate with kVp was made for each X-ray tube unit. The data appear in graphical form in Appendix B. For these determinations, arbitrary tube and probe positions were chosen; and data was taken both with and without additional lead shielding. In each case the exposure rate at the lower kVp was within -8% of that at 100 kVp. It was, therefore, concluded that the exposure rates obtained at 97 kVp and 98 kVp for the stationary and rotating anode tubes, respectively, need not be corrected to values at 100 kVp, since the 8% variations are negligible when all other possible sources of error are considered and the results are presented in graphical form, as is done in this study.

Instrumentation

Exposure measurements were made using a Victoreen Instrument Company Model 555 Radocon II with Model 555 - 0.1 MA probe having a collecting volume of 97.4 cm$^3$. Measurements made with this probe are accurate to within 2% for X-ray energies from 62 to 68 keV, the approximate effective energy of the leakage radiation as

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$^4$See the Instrumentation section of Chapter III for a discussion of the measuring instrumentation used in this study.
determined from half-value layer data.

The probe was connected to a preamplifier using ten feet of radiation and R-F shielded coaxial cable. The preamplifier contained (1) circuitry necessary for amplifying the signal to be sent to the readout console and (2) the chamber voltage supply for the probe. The preamplifier was connected to the readout console using 50 feet of multi-conductor shielded cable.

The readout console was operated in the exposure mode using full scale ranges of 30, 100, and 300 mR. The scale readings obtained with the Radocon II were corrected as follows to yield mR per hour:

1. The manufacturer specified that the readout console scale readings must be corrected by a multiplier of 0.1 for the probe used in this study.

2. With an open ionization chamber, corrections for temperature and pressure variations must be made. The probe had been calibrated by the Victoreen Instrument Company to give true Roentgens at 22° C and 760 mm. Hg.; therefore the correction factor, \( k_{tp} \), was

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5Half-value layer (NCRP, 1968) is that thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the exposure rate by 1/2.
\[ k_{tp} = \frac{t + 273^\circ C}{295^\circ K} \cdot \frac{760 \text{ mm. Hg.}}{P} \]

\[ t = \text{the air temperature in } ^\circ C \]

\[ P = \text{local station barometric pressure in mm. Hg.} \]

\[ k_{tp} \text{ is a multiplicative correction factor by definition.} \]

(3) From half-value layer data it was determined that the transmitted beam had an effective energy of 62-68 keV.

From data supplied by the manufacturer, based upon the calibration of this probe against a standard air chamber, the energy dependence correction factor, \( k_E \), was 0.98.

(4) The reading in mR per minute was converted to mR per hour.

The final corrected reading was obtained as follows:

\[
\text{True mR/hour} = \text{Scale mR/minute} \times (0.1) \times (k_E) \times (k_{tp}) \times (60 \text{ min/hr}).
\]
IV. METHODOLOGY

Objective

The objective of this study is to measure the leakage radiation from two unshielded diagnostic-type X-ray tube housings and to use this information to determine the thickness of lead shielding required to bring them into compliance with the definition of a diagnostic-type protective tube housing as set forth by the National Council on Radiation Protection and Measurements in Report No. 33 (p. 37):

A diagnostic-type protective tube housing is one so designed that the leakage radiation measured at a distance of one meter from the source does not exceed 100 mR in one hour when the tube is operated at its maximum continuous rated current for the maximum rated tube potential.

Procedure

The procedure in the collection of the data was to measure the exposure rate on the surface of a sphere of one meter radius about the focal spot of each X-ray tube. To accomplish this, both tube rotation and probe rotation were required.

The probe was attached to an aluminum tube (2 cm. in diameter and 110 cm. long) which could be rotated in a complete circle and positioned such that the source-chamber distance was one meter. The arm was rotated in a horizontal plane using a television antenna rotor system. In order to minimize the contribution of radiation
scattered from the floor, the height of the probe was adjusted so that the distance from the measuring chamber to the floor was greater than one meter. A selsyn generator-motor system was installed between the control area and the rotation apparatus to indicate the position of the probe, relative to a fixed reference point. The generator was connected to the probe rotation apparatus in the X-ray room, and the motor, in the control area, positioned a circular scale, graduated in degrees.

Rotation of the X-ray tube unit was accomplished through the use of two concentric iron pipes. The outer pipe was stationary and secured to the tube unit floor-support frame. The inner pipe was secured to the right angle steel tube unit mounting plate. The 1/4 inch thick steel plate also served to block the useful X-ray beam, for the steel thickness provided ten half-value layers added shielding (NBS Handbook No. 76, 1961); and the resulting radiation transmission was less than 100 mR per hour one meter from the X-ray tube focal spot. A set screw was provided to lock the inner pipe to the outer pipe, and a circular scale, graduated in degrees, was attached to the outer pipe. The tube could then be rotated about the focal spot (by rotating the inner pipe) a known amount and locked in position while exposure rate measurements were made. The tube unit supports, both floor and tube-proper, are shown in Figures 1 and 2.

To collect the data, the exposure for a given time interval was
Figure 1. Orientation of the apparatus. Tube position: $0^\circ$. Probe position: $0^\circ$.

Figure 2. Orientation of the apparatus. Tube position: $90^\circ$. Probe position: $0^\circ$. 
determined at the reference location. The ionization chamber was rotated through an arc of ten degrees, and the exposure for a given time interval again determined. This process was repeated until a circular path had been completed around the focal spot of the X-ray tube. Data for the area between successive ten degree points were taken when the radiation intensity gradient was such that the additional data were needed.

Due to the construction of the X-ray tube unit support apparatus, the probe could only be rotated through 180 degrees for each angular tube position. Therefore, it was necessary to collect half the data (0° through 180°) and then reverse the tube on its support before the remainder of the data could be collected (180° through 360°). After the data for a given tube position had been collected, the probe was returned to its starting point, and the tube was rotated ten degrees. The procedure for data collection was then repeated. This methodology was continued until the X-ray tube had been moved through 180 degrees; at which time the tube was reversed on its support, and the remainder of the data taken. This procedure was followed for each tube.

Zero degree tube position corresponded to a vertical longitudinal tube axis with the cathode end of the tube nearest the floor (Figure 1). The tube was rotated in a clockwise direction so that the 90 degree tube position corresponded to a horizontal longitudinal tube
axis (Figure 2). When the tube was reversed on its support, it was necessary to rotate it in a counter-clockwise direction in order to maintain this orientation. The zero degree position of the probe (Figures 1 and 2) was such that when the tube was at zero degrees, the probe was directly in line with the center of the X-ray tube window. The probe was always rotated in a clockwise direction.

**Calculation of Shielding Thickness**

After the exposure rates were determined, the thickness of lead shielding required to bring the housing into compliance with the definition of a diagnostic-type protective tube housing was calculated.

The first half-value layer, at high filtration under broad beam conditions, for a peak tube potential of 100 kVp is 0.24 mm. of lead (NBS Handbook No. 76, 1961). To determine the thickness of lead required, the following calculation was made; where n equals the number of half-value layers required to reduce the exposure rate to 100 mR per hour, x is the measured exposure rate (greater than 100 mR per hour) with no added shielding, and T is the lead thickness in mm. required to reduce the exposure rate to 100 mR per hour.

\[
(1/2)^n \cdot (x) = 100 \text{ mR/hour}
\]

\[
n = (\ln x - \ln 100)/0.693
\]

\[
T = n \text{ (HVL's)} \cdot 0.24 \text{ mm. of lead/HVL}
\]
\[ T = 0.346 \ln x - 1.59 \]

**Evaluation of Calculations**

To determine where to place the lead on the housing, a flashlight was attached to the rotating arm adjacent to the probe and located such that the bright center-spot of its light beam would strike the tube housing on the area through which the leakage radiation was transmitted. Therefore, as the probe was rotated, the position of the lead could be determined using the light beam, and the lead thickness could then be placed on the housing in that area. After the addition of the lead, another exposure rate measurement was made to determine if that area of the housing was in compliance with the definition of a diagnostic-type protective tube housing.

The lead available for use in this study was 0.19 mm. thick and rectangular (five cm. by ten cm.) in shape. This size lead is larger than that needed to shield a "point" source of leakage but was used because:

1. The light beam from the flashlight was not a point spot of light but covered an area of approximately 30 cm.\(^2\) on the tube housing. The lead added to the tube housing should cover this area to insure that the lead is located between the focal spot and the measuring chamber.

2. The contribution to the measured exposure rate due to
radiation scattered from other areas of the tube unit must be considered.

(3) Due to the irregular surface configuration of the housing some surface areas could not have been adequately covered by lead smaller than that used.

The lead thickness closest to, but larger than, that calculated was selected for each area on the tube housing to be shielded.

For the determination of exposure rates with added shielding, the following lead thicknesses were used (based on the calculation described in the previous section):

<table>
<thead>
<tr>
<th>Exposure Rate Interval-mR/hr</th>
<th>Added Lead Thickness-mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 172</td>
<td>0.19</td>
</tr>
<tr>
<td>173 - 298</td>
<td>0.38</td>
</tr>
<tr>
<td>299 - 520</td>
<td>0.57</td>
</tr>
<tr>
<td>521 - 880</td>
<td>0.76</td>
</tr>
<tr>
<td>881 - 1550</td>
<td>0.95</td>
</tr>
<tr>
<td>1551 - 2650</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Since, in most cases, the thickness of lead added to the housing was greater than the calculated thickness, another calculation was made. This calculation yielded the theoretical value of the leakage radiation obtained after the addition of the shielding. This value was then compared to the experimentally determined value.
The equation used for this calculation was the following, where

\[ T \] is the thickness of lead added in mm., \( x \) is the unshielded exposure rate, and \( y \) is the expected exposure rate after \( T \) mm. of lead have been added:

\[ \ln y = \ln x - \frac{T}{0.346} \]
V. EXPERIMENTAL RESULTS

The results of this study are presented in graphical form. Two graphs are presented for each angular position of each tube. One graph shows the intensity of leakage radiation, both with and without added shielding, on a circle of one meter radius about the focal spot of the X-ray tube. The other graph shows the thickness of lead required to reduce the leakage radiation to 100 mR per hour.

Figures 5 through 40 show (1) the leakage radiation at specified locations on the surface of a sphere of one meter radius about the focal spot of the stationary anode X-ray tube and (2) the thickness of lead required to reduce this leakage radiation to 100 mR per hour. Figures 43 through 78 present the same data for the rotating anode X-ray tube.

The graphs of leakage radiation were plotted on polar coordinate paper with logarithmic longitudinal divisions in order that (1) the leakage radiation with and without added shielding could be plotted on the same co-ordinate axes and (2) the same scale could be used throughout the collection of graphs.

The widely differing exposure rates encountered would have presented awkward and difficult to read graphs if plotted on linear polar axes.

The comparison of calculated and measured exposure rates,
obtained with the added shielding, was performed as outlined at the end of Chapter IV. On the graphs of leakage radiation, the solid line with data points indicated by circles represents the measured exposure rates, and the data points indicated by triangles represent the calculated exposure rates. The difference between the measured and calculated exposure rates is due to the following:

(1) The radiation field at the measuring probe consists of both direct radiation and scattered radiation. All components that make up the tube unit are potential sources of scattered radiation, as is the tube unit support structure; the walls, floor and ceiling of the room; and the air in the room. The added shielding placed on a specific area of the tube housing will attenuate the direct radiation and radiation scattered from sources located such that the added shielding is between the source and the measuring probe, but it will not attenuate radiation scattered from other sources. As a result the relationship between the measured and calculated exposure rates through different locations of the tube housing will vary and depend upon the contribution from the various sources of scattered radiation.

(2) As noted in Chapter III, it was assumed that the leakage radiation had an effective energy such that the broad beam
half-value layer was 0.24 mm. of lead. The actual effective energy and resulting half-value layer of the radiation transmitted through a given location on the tube housing will depend upon the total equivalent filtration of the material between the source of radiation and the measuring probe. For scattered radiation, the effective energy will also depend upon scattering events that occur within the tube housing. As a result, a given thickness of added shielding can result in more or less attenuation than that calculated depending upon the actual effective energy of the X-ray beam.
Figure 3. Scale drawing of a cross-section of the stationary anode tube unit, with the useful beam directed into the paper.
Figure 4. Scale drawing of a cross-section of the stationary anode x-ray tube unit, with the useful beam directed as the arrow indicates. Planes of measurement of leakage radiation, with corresponding angular tube positions (every 30° only), are indicated by center lines.
Figure 5. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 0°.
Figure 6. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at $0^\circ$. 
Figure 7. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at $10^\circ$.
Figure 8. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 10°.
Figure 9. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 20°.
Figure 10. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 20°.
Figure 11. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 30°.
Figure 12. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 30°.
Figure 13. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 40°.
Figure 14. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 40°.
Figure 15. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 50°.
Figure 16. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 50°.
Figure 17. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 60°.
Figure 18. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 60°.
Figure 19. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 70°.
Figure 20. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 70°.
Figure 21. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 80°.
Figure 22. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 80°.
Figure 23. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 90°.
Figure 24. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 90°.
Figure 25. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 100°.
Figure 26. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 100°.
Figure 27. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 110°.
Figure 28. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode at 110°.
Figure 29. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 120°.
Figure 30. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 120°.
Figure 31. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 130°.
Figure 32. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 130°.
Figure 33. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 140°.
Figure 34. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 140°.
Figure 35. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 150°.
Figure 36. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 150°.
Figure 37. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 160°.
Figure 38. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 160°.
Figure 39. Leakage radiation (mR/hr) one meter from the focal spot of the stationary anode tube at 170°.
Figure 40. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the stationary anode tube at 170°.
Figure 41. Scale drawing of a cross-section of the rotating anode x-ray tube unit, with the useful beam directed into the paper.
Figure 42. Scale drawing of a cross-section of the rotating anode x-ray tube unit, with the useful beam directed as the arrow indicates. Planes of measurement of leakage radiation, with corresponding angular tube unit positions (every 30° only), are indicated by center lines.
Figure 43. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 0°.
Figure 44. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 0°.
Figure 45. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at $10^\circ$. 
Figure 46. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 10°.
Figure 47. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 20°.
Figure 48. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 20°.
Figure 49. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 30°.
Figure 50. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 30°.
Figure 51. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 40°.
Figure 52. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 40°.
Figure 53. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 50°.
Figure 54. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 50°.
Figure 55. Leakage radiation (mR/hr) one meter from the local spot of the rotating anode tube at 60°.
Figure 56. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 60°.
Figure 57. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 70°.
Figure 58. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 70°.
Figure 59. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 80°.
Figure 60. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 80°.
Figure 61. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 90°.
Figure 62. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 90°.
Figure 63. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 100°.
Figure 64. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 100°.
Figure 65. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 110°.
Figure 66. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 110°.
Figure 67. Leakage radiation (mR/hr) one meter from the focal spot or the rotating anode tube at $120^\circ$. 
Figure 68. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 120°.
Figure 69. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 130°.
Figure 70. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 130°.
Figure 71. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 140°.
Figure 72. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 140°.
Figure 73. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 150°.
Figure 74. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 150°.
Figure 75. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at 160°.
Figure 76. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 160°.
Figure 77. Leakage radiation (mR/hr) one meter from the focal spot of the rotating anode tube at $170^\circ$. 
Figure 78. Lead thickness (mm.) required to obtain 100 mR/hr one meter from the focal spot of the rotating anode tube at 170°.
VI. DISCUSSION OF RESULTS

As part of this study, the distribution of leakage radiation from two unshielded diagnostic-type X-ray tube housings was determined, and a non-uniform distribution was found for both tubes. By comparing the scale tube unit drawings (Figures 3, 4, 41, and 42) with the distribution of leakage radiation, the distribution for each tube can be related to structures inside the X-ray tube and housing.

The difference in the internal structure of the stationary and rotating anode tube units accounts, in part, for the difference in the distribution of leakage radiation. Another reason for this difference is the continuous current ratings of the two tubes at 100 kVp. The stationary anode tube operates at a higher maximum continuous current than does the rotating anode tube; therefore, one would expect the stationary anode tube to have leakage radiation of greater magnitude.

From the results of this study, it is evident that the thickness of protective material and its location in a tube housing will vary with the design and rating of the X-ray tube used in the housing. As a result, a savings in weight can be achieved by placing the necessary shielding properly within the housing, rather than lining the entire housing with the thickness of shielding necessary to reduce the maximum value of leakage radiation to the standard of 100 mR per hour.
BIBLIOGRAPHY


APPENDICES
APPENDIX A

Data from the Calibration of the

X-ray Generating Equipment
### Table 1. Data from the control milliammeter comparison test

<table>
<thead>
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<th>Resistance ohms</th>
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<th>Precision</th>
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<td>Milliammeter - mA</td>
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<td>3.5</td>
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### Table 2. Data from the control milliammeter X-ray calibration

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### Table 3. Data for the control voltmeter accuracy determination

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</table>
Tube voltage waveform photograph for stationary anode X-ray tube. Ninety-seven kVp, 3.33 mA, and 1950 pF total effective cable capacitance. Each minor division on the vertical axis represents four kilovolts, with zero kilovolts located at the base line in the photograph.
Tube voltage waveform photograph for rotating anode X-ray tube. Ninety-eight kVp, 2.50 mA, and 1950 pF total effective cable capacitance. Each minor division on the vertical axis represents four kilovolts, with zero kilovolts located at the base line in the photograph.
APPENDIX B

Variation of Exposure Rate with kVp
Variation of exposure rate with kVp for stationary anode x-ray tube with no added shielding.
3.33 mA
100 cm FCD
90° tube position
90° probe position

Variation of exposure rate with kVp for stationary anode x-ray tube with 0.38 mm. of lead shielding.
Variation of exposure rate with kVp for rotating anode x-ray tube with no added shielding.
Variation of exposure rate with kVp for rotating anode x-ray tube with 0.19 mm. of lead shielding.