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EXPERIMENTAL DETERMINATION OF GAMMA EXPOSURE RATE IN PLUM BROOK HB-6 FACILITY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The gamma ray exposure rates in the HB-6 beam hole facility of the NASA Plum Brook Reactor were measured with lithium fluoride thermoluminescent dosimeters and argon-filled ion chambers. The exposure rates varied as a function of position in the test cavity and the time of measurement. To define and predict variations of the gamma exposure rate, an empirical relation between a standardized exposure rate and various reactor parameters was formulated. The standardized exposure rate, defined at 60 megawatts of reactor power, median values of reactor parameters, and the center of the radiation beam, was measured to be 7.6×10^4 roentgens per hour (19.6 (C/kg)/hr).

INTRODUCTION

Semiconductor device for nuclear space power systems will be required to operate in a nuclear environment. The HB-6 facility at the Plum Brook Reactor (ref. 1) was designed and constructed primarily to test the performance of various types of semiconductor devices under simulated nuclear space power system environments.

The nuclear environment in the HB-6 facility is expected to vary considerably with both reactor parameters and the test configuration, namely, reactor power, shim-control-rod positions, perturbations by other experiments, vertical and horizontal position in the HB-6 facility, and the condition of the water-filled attenuation tanks. Thus, proper assessment of the radiation damage to semiconductor devices necessitates an ability to predict the nuclear environment to which the test semiconductor devices are exposed. This report will enable the experimenter to predict the gamma exposure rate as conditions change in the HB-6 beam hole.

Lithium fluoride (LiF) thermoluminescent dosimeters (ref. 2) were chosen as a means of determining the gamma exposure rate. They are small and are easily calibra-

ted as absolute detectors. Argon-filled ion chambers were used to monitor the time-dependent variations of the gamma exposure rate continously.

This report discusses (1) the setup of the experiment to measure variations in the exposure rate as a function of geometric changes in the reactor core and the HB-6 facility; (2) the data obtained that yielded an empirical prediction equation; and (3) the calibration of the thermoluminescent dosimeters and ion chambers.

EXPERIMENT DESIGN AND PROCEDURE

To determine and predict the changes in the gamma exposure rate in the HB-6 facility, extensive data from thermoluminescent dosimeters and argon-filled ion chambers were gathered. The calibration of each of these devices is discussed in appendixes A and B. The calibrated thermoluminescent dosimeters (TLD's) were polytetrafluoroethylene vials, 3/4 inch (1.9 cm) high with a 3/16-inch (0.475-cm) outside diameter. These were filled with treated LiF powder, taped to the foil plate (fig. 1), and exposed from 15 to 60 minutes in the HB-6 facility radiation environment. The dosimeters determined the spatial dependence of the gamma exposure rate. The time dependence of the gamma exposure rate was measured with two stainless steel argon-filled ion chambers, which were $2\frac{1}{2}$ inches (6.35 cm) long with a $\frac{1}{4}$-inch (0.635-cm) outside diameter. In the HB-6 facility these chambers were stationary devices mounted on a separate plate (fig. 2) which was located near the foil plate.

The assumption was made that the various parameters that influence the gamma exposure rate act independently of one another. Therefore, an empirical equation that predicts the exposure rate could be formulated. This equation is expressed as a standardized exposure rate modified by correction factors, which represent fractional changes in the standardized exposure rate due to changes in various parameters. Thus,

$$X = X_0 \cdot M_1 \cdot M_2 \cdot M_3 \cdot M_4 \cdot M_5 \cdot M_6 \qquad (1)$$

where

X exposure rate to be determined, R/hr

X_0 standardized exposure rate (R/hr) at median values of reactor and experimental parameters (23-in. (58.5 cm) shim control rods, 60 MW reactor power, no water in attenuation tanks, center of foil plate, no perturbations in reactor core)

M_1 zone correction factor representing fractional changes in exposure rate (due to radial position changes) on face of foil plate.

M_2 fractional changes in exposure rate due to shim-control-rod position

M_3 fractional changes in exposure rate as function of distance behind foil plate

M_4 fractional changes in exposure rate due to changes in amount of water in attenuation tanks

M_5 fractional changes in exposure rate due to changes in reactor power level

M_6 fractional changes due to perturbations in reactor core by other experiments in reactor

ANALYSIS OF DATA

Correction Factors

Zones (M_1). - In an effort to determine the spatial variations of the gamma exposure rates on the face of the foil plate, a large number of TLD's were exposed on the foil plate. From each exposure on the plate, equal exposure rate zones were drawn as shown in figure 3. The data from each zone were normalized to the data in zone 2. This normalization yielded the zone correction factors presented in table I.

TABLE I. - ZONE CORRECTION FACTORS

Zone	Correction factor
1	1.12
2	1.00
3	.88

Shim-control-rod position (M_2). - In an effort to determine the effect of the reactor's shim-control-rods argon-filled ion chamber currents were recorded during a period of 1 year. These currents were plotted as a function of shim-control-rod position. Normalizing a number of ion chamber currents to the value of the current when the shim-control-rods were at 23 inches (58.5 cm) yielded the shim-control-rod position correction factors presented in figure 4. This figure shows the fractional increase in the gamma exposure rate as a function of shim-control-rod position. A sampling of data that indicates the spread of data is also shown.

Horizontal position (M_3). - No data were available for the determination of the horizontal position correction factor. An inverse square law from the foil plate to the beam catchers, and a distance of 5 feet, was assumed. In figure 5 is shown the fractional change in the gamma exposure rate as a function of distance from the foil plate. In the

region from 10 to 26 inches (25.4 to 66.0 cm) beyond the foil plate, the correction factor is taken to be 0.75±0.10.

Attenuation tanks (M_4). - The effects of the attenuation tanks were determined by recording ion chamber currents as the attenuation tanks (shown in fig. 1) were filled with different thicknesses of water. Ion chamber currents at various thicknesses of water were then normalized to the ion chamber currents with no water in the tanks. The normalized data points thus obtained constitute the attenuation tank correction factor and are plotted in figure 6.

Reactor power (M_5). - During a reactor run there are a number of reactor power changes. The argon-filled ion chamber currents were recorded as a function of these power changes. The currents at a specific reactor power were normalized to ion chamber currents at a power of 60 megawatts, which occurred just prior to the power change. This normalization resulted in a fractional decrease in the gamma exposure rate that is presented as a function of the reactor power in figure 7.

Other experiments (M_6). - During a period of 1 year, no changes in ion chamber currents could be related directly to perturbations caused by other experiments in the reactor core. It is therefore assumed that the correction factor M_6 will be 1. An obvious exception would occur when the horizontal through hole 1 (HT-1) duct is completely voided. It is estimated that voiding HT-1 would increase the gamma exposure rate by about 25 percent.

Standardized Gamma Exposure Rate

With the use of the appropriate correction factors, shown in figures 3 to 7, the standardized gamma exposure rate can be calculated. TLD data from the foil plate insertions were normalized to a shim-control-rod position of 23 inches, to a reactor power level of 60 megawatts, to zone 2, and to no water in the attenuation tanks. The standardized gamma exposure rate X_0 calculated was 7.6×10^4 roentgens per hour (19.6 (C/kg)/hr).

Error

The errors associated with the use of the correction factors in equation (1) are listed in table II. The error given for the standardized exposure rate X_0 is the absolute error in gamma measurement.

Inquiries into the gamma exposure rate in the HB-6 facility will necessitate the use of all or just some of the correction factors, in either case the gamma exposure rate

TABLE II. - ERRORS IN CORRECTION FACTORS

	Percentage error in -						
	Standardized exposure rate, X_0	Shim-rod position, M_1	Reactor power, M_2	Attenuation tanks, M_3	Horizontal position, M_4	Zone, M_5	Other experiments, M_6
Standard deviation	8	3.8	4.6	4	12	10	--

is calculated from equation (1). With the use of all the correction factors the absolute accuracy is ±20 percent within 1 standard deviation.

Verification by Independent Measurements

The independence of the various correction factors used in equation (1) was verified. Equation (1) was used to predict the gamma exposure rate for a relatively wide range of operating parameters, including four different reactor operating cycles. These predicted values were compared with the exposure rates actually measured by the argon-filled ion chambers and LiF thermoluminescent gamma dosimeters. Table III presents the predicted exposure rate and also presents the gamma exposure rate actually measured by TLD's and the argon-filled ion chambers. The measured and predicted values are in good agreement well within the expected error.

The TLD exposure rate was determined by the use of the calibration curve shown in figure 8, and the ion chamber exposure rate was determined by use of the calibration curve shown in figure 9.

TABLE III. - VERIFICATION BY INDEPENDENT MEASUREMENTS

[Foil plate in horizontal position.]

Zone	Shim rod length		Attenuation tank water		Reactor power, MW	Date	Predicted exposure rate		Measured exposure rate		Ratio of predicted to measured exposure rate
	in.	cm	in.	cm			R/hr	(C/kg)hr	R/hr	(C/kg)hr	
1	24.50	62.3	22.5	57.3	60	Feb. 1965	1.3×10^4	3.4	1.5×10^4	3.9	0.87
2	18.07	45.9	0	0	40	June 1965	3.8	9.8	3.7	9.6	1.03
2	27.25	69.3	10.5	26.7	60	Dec. 1965	3.2	8.3	3.2	8.3	1.00
2	28.15	71.5	0	0	60	Feb. 1965	8.7	22.4	8.4	21.7	1.04

SUMMARY OF RESULTS

The HB-6 facility in the Plum Brook Reactor provides a nuclear environment testing facility for semiconductor devices used in space. This report defines the gamma exposure rate in this facility.

An empirical prediction equation, comprised of a standardized gamma exposure rate modified by six factors that influence the gamma exposure rate, was postulated. The six factors that influence the gamma exposure rate take into consideration shim-control-rod position, reactor power, amount of water in the attenuation tanks, horizontal and vertical position in the HB-6 facility, and perturbations in the reactor core that were caused by other experiments. The standardized gamma exposure rate at the fiducial test conditions of (1) reactor power at 60 megawatts, (2) shim-control-rods at 23 inches (58.5 cm), (3) no water in the attenuation tanks, (4) no other experiments in the reactor, and (5) vertical center point of the foil plate, was experimentally determined to be (by use of lithium fluoride thermoluminescent dosimeters) 7.6×10^4 roentgens per hour (19.6 (C/kg)/hr) ±20 percent within 1 standard deviation.

The empirical equation successfully predicts the gamma exposure rate within the experimental errors.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 7, 1967,
120-27-04-35-22.

APPENDIX A

CALIBRATION OF LITHIUM FLUORIDE THERMOLUMINESCENT DOSIMETERS

The theory of LiF thermoluminescent dosimeters is explained elsewhere (ref. 2), but a brief description is given here. Exposing LiF powder to ionizing radiation causes the electrons in the powder to be raised to a metastable energy state. Controlled heating of this powder allows the electrons to return to their stable states. Upon this deexcitation, energy is released in the form of light. By determining the amount of light given off per unit mass of LiF powder, the dose to which the LiF powder was exposed can be determined.

Prior to inserting the LiF TLD's into the HB-6 facility, the LiF powder had to be calibrated. Previous calibrations (ref. 2) showed that the LiF powder is purely dose dependent and to a large extent independent of the type and the energy of ionizing radiation. The LiF powder was calibrated with three gamma sources: a 7-curie (2.6×10^{11}-dis/sec) cobalt 60 source, a 500-curie (1.85×10^{13}-dis/sec) cobalt 60 source, and the Plum Brook Reactor. With the 7-curie (2.6×10^{11}-dis/sec) cobalt 60 source, the standard measuring device was a small air-equivalent, nylon, ion chamber system that was calibrated to ±5 percent by a standard source before delivery. With the 500-curie (1.85×10^{13}-dis/sec) cobalt 60 source and the Plum Brook Reactor, the standards were Fricke (ferric sulfate) dosimeters (ref. 3).

Figure 10 shows the experimental setup by which the TLD powder was calibrated with a 7-curie (2.6×10^{11}-dis/sec) cobalt 60 source. Prior to irradiation of the TLD LiF powder by this small source, the experiment (shown in fig. 10) was calibrated with the use of the nylon ion chamber just mentioned. The graph of total exposure dose to which the TLD's were subjected as a function of the distance from the cobalt 60 source is shown in figure 11. The data fit well to an inverse square decrease as shown. After exposure of the LiF TLD's in this facility for periods up to 3 days, the relative light output per unit mass from the powder was measured. The 500-curie (1.85×10^{13}-dis/sec) cobalt 60-source irradiation experiment is shown schematically in figure 12. The thermoluminescent LiF powder vials were taped to the Fricke dosimeters that were inserted into a cavity 2 inches (5.1 cm) in diameter which was surrounded by cobalt 60 pencils. Additional data were obtained by exposing TLD's to both a reactor core and depleted fuel elements from the Plum Brook Reactor. The effect of neutrons, fast and thermal, on TLD readings was calculated to be less than 1 percent.

Data obtained from the aforementioned methods are shown in figure 8. These data (in the form of relative TLD readings per milligram of LiF powder as a function of the total exposure dose) were then fitted to a curve by the least squares method assuming a power fit, $Y = AX^B$, where Y is the total dose, X is the relative reading per milligram of TLD powder, and A and B are constants. The solid line in figure 8 is the result of this fit and constitutes the calibration curve for LiF thermoluminescent dosimeters. The error in this calibration curve is ±8 percent.

APPENDIX B

CALIBRATION OF ARGON-FILLED ION CHAMBERS

The LiF TLD's were used to calibrate the two argon-filled ion chamber systems shown in figure 2. The TLD's were exposed on the foil plate in the same vertical position as that occupied by the two ion chambers which were placed on another plate (figs. 1 and 2). Two exposures of TLD's taped to the foil plate were made at different shim-control-rod positions. Ion chamber currents were recorded as a function of the TLD exposure rates. The currents from both ion chambers at the two shim-control-rod positions with their respective exposure rates are shown in figure 9. Both currents and exposure rates were then normalized to a shim-control-rod position of 23 inches (58.5 cm). The resultant data points yielded the curve shown in figure 9, which constitutes the calibration curve for the two ion chambers for exposure rates in zone 2 of the foil plate. The extrapolation beyond the indicated data points was performed by use of the attenuation tank correction factors shown in figure 6.

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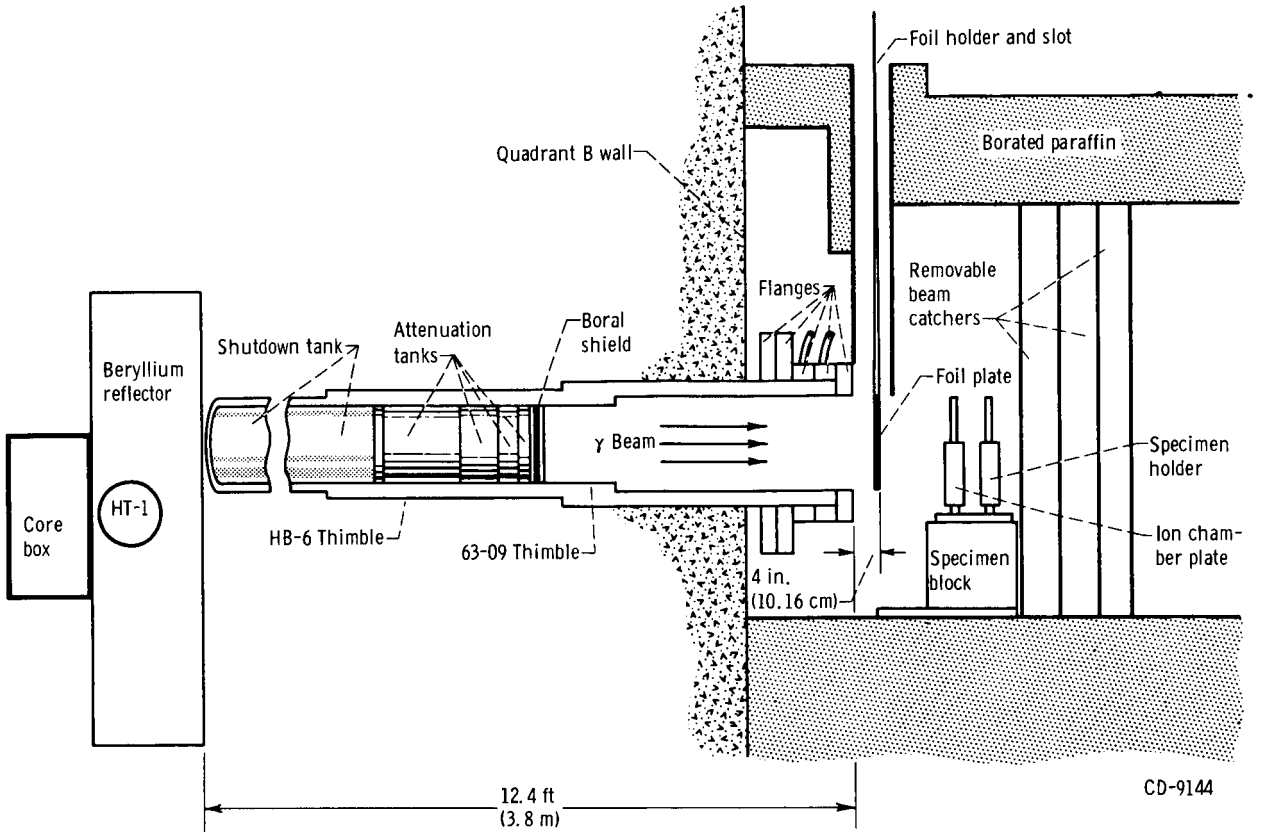

Figure 1. - HB-6 Facility.

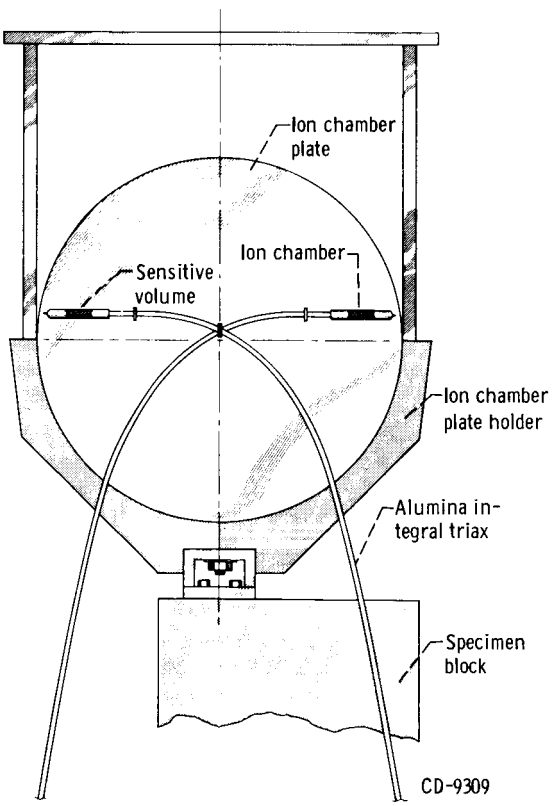

Figure 2. - Ion chamber plate.

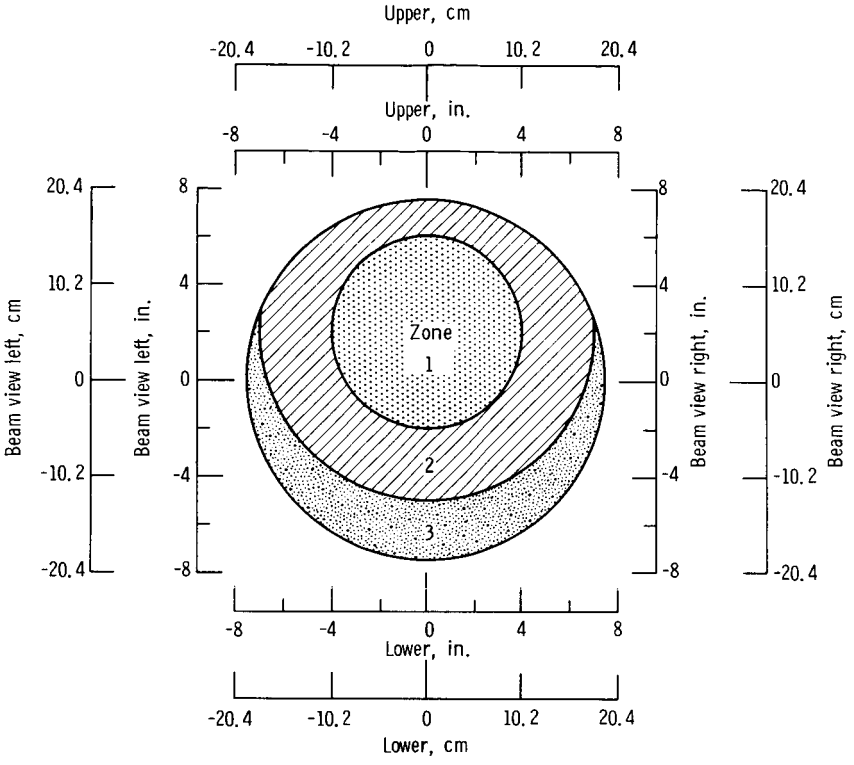

Figure 3. - Zone correction factors in HB-6 facility as viewed from beryllium reflector.

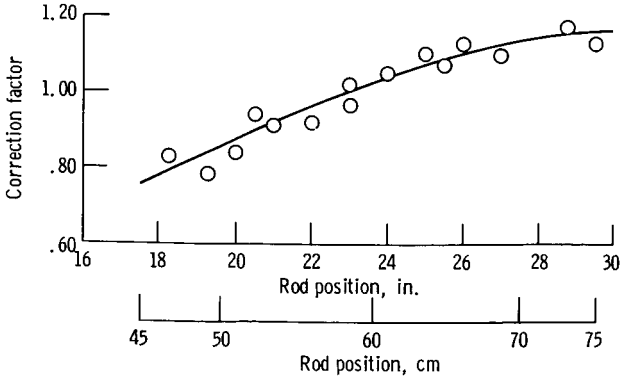

Figure 4. - Shim-control-rod position correction factor.

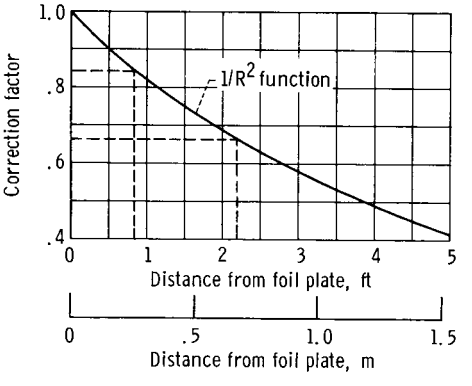

Figure 5. - Horizontal distance correction factor for gamma exposure rates.

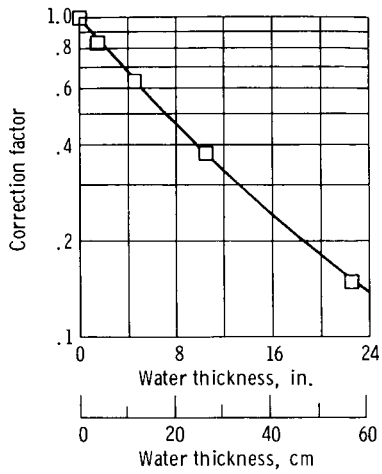

Figure 6. - Attenuation tank correction factor as function of water thickness.

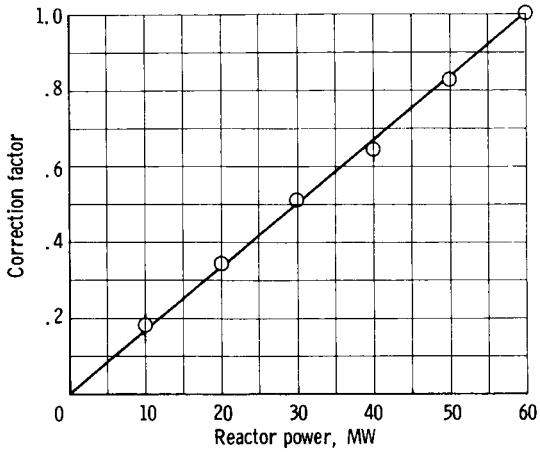

Figure 7. - Correction factor as function of reactor power level.

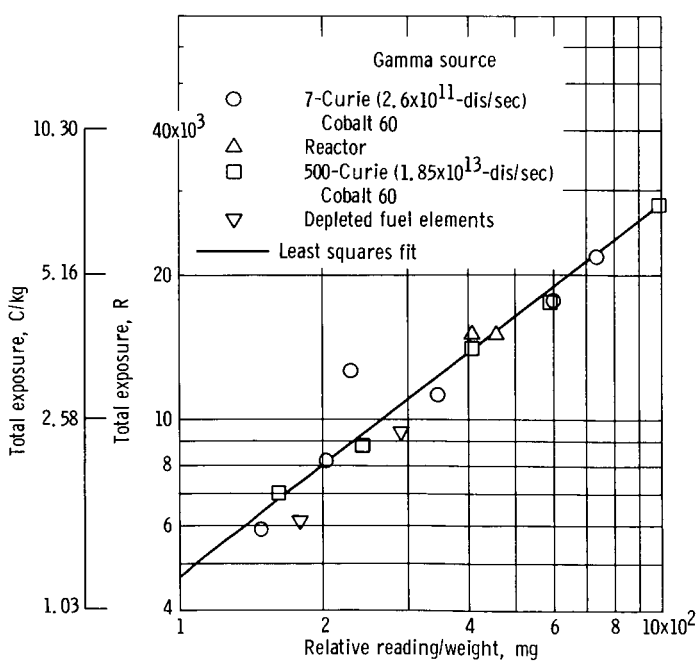

Figure 8. - Thermoluminescent dosimeter calibration curve.

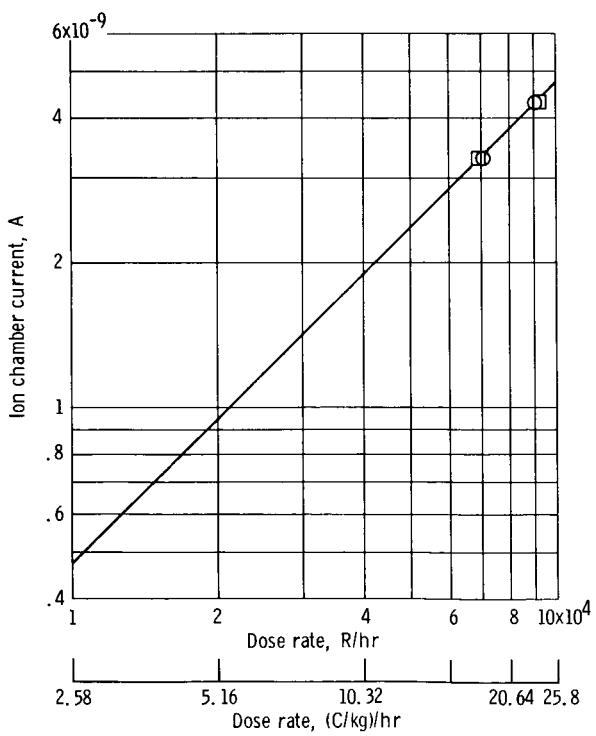

Figure 9. - Ion chamber calibration curve.

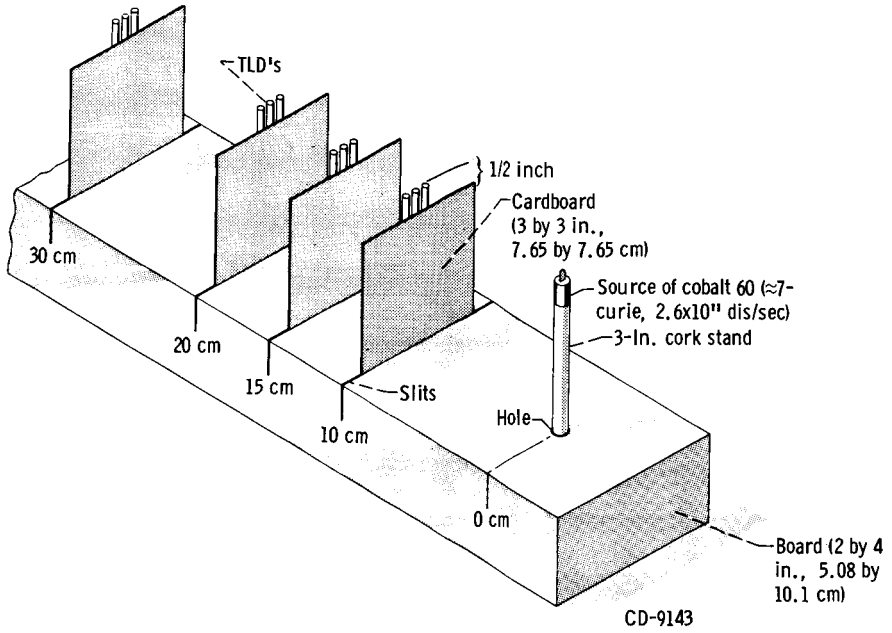

Figure 10. - Thermoluminescent dosimeter calibration facility with 7-curie (2.6x10"-dis/sec) cobalt 60 source.

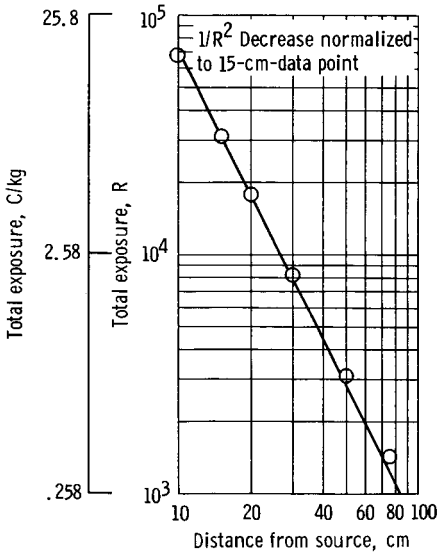

Figure 11. - Calibration of 7-Curie ($2.6x10^{11}$-dis/sec) cobalt 60 source.

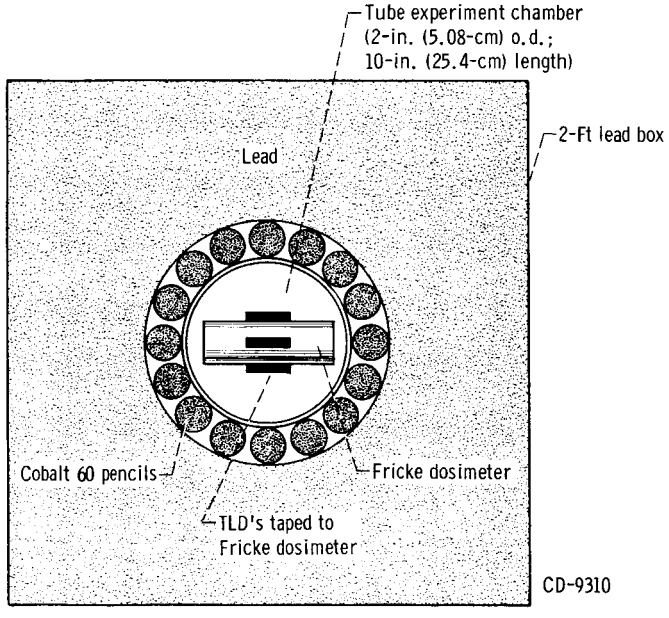

Figure 12. - 500-Curie ($1.85x10^{13}$ dis/sec) cobalt 60 source in facility.