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BETA DOSE RATE EVALUATIONS WITH A GEIGER-MUELLER PANCAKE DETECTOR

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Robert L. Coleman

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ABSTRACT

Methods for estimating dose rates to the 70 μm layer of the human dermis from external beta (β) emitters with a Geiger-Mueller (GM) pancake detector have been investigated through experimental evaluation. First, dose rates were measured for two separate groups of sources by use of an extrapolation chamber on the first group and by use of the computer code VARSKIN on the second group. Second, the response of a GM pancake probe with a 16 mesh stainless steel screen was measured on each of these sources in a configuration which is typically used during field survey activities. The results were compiled in the form of a response curve showing the dose rate response of the GM pancake as a function of average beta energy. This curve provides useful data pertaining to the energy dependency of a standard GM pancake probe when converting beta measurements to dose rates. Third, a special system for measuring β dose rates was developed by making measurements with a series of three sequential thicknesses of plastic placed over the probe on each of the sources. These measurements were made with the intent to derive a calculational technique by which dose rates could be accurately assessed with a pancake detector with no prior knowledge of the beta spectra being measured. Measurements were made with plastic filter thicknesses of 6.5, 13.5, and 44.3 mg cm^{-2} thereby breaking the source beta spectra into three consecutive energy bands. A multivariate regression was performed on the resulting count rate bands and a mathematical relationship between the known β dose rates and the filtered count rate measurements was formulated.

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I. INTRODUCTION

Many types of radiation fields are encountered during radiation surveys by health physics personnel. A health physicist is often required to characterize such radiation fields for reporting and personnel protection purposes. The method of characterization varies, but the final reported quantity is usually expressed as a unit which can be easily related to by any other health physics practitioner with little knowledge of the actual measurement technique. Examples of such dimensions are roentgen (R), rad (rad), rem (rem), and nuclide disintegration rate in units of disintegrations per minute (dpm).

Beta radiation is often the primary quantity detected during surveys. If the beta emissions can be attributed to surface contamination, then the surface areal activity is commonly estimated by use of a Geiger-Mueller or gas proportional detector with a calibration correction factor. Beta emissions do not exclusively originate from surface contamination, but instead may result from nuclides mixed within porous material such as soil, plants, and wood. Samples can be collected from such contaminated materials and quantified in an analysis laboratory. The results of these analyses are usually reported in activity concentration units such as pCi/g. These methods are valid and serve their purpose well, but the applied health physicist is often required to quantify radiation fields directly in an effort to estimate the magnitude of direct exposure. The energy deposition rate from the β emitters is the

common unit of measurement and data are usually reported in units of Gy/h (rad/h) to tissue.

Methods for evaluating exposures from gamma radiation and energetic x-rays have been well developed over the years, but methods for measuring doses from beta and very low energy x-ray emitters have not been as well established. Recent governmental emphasis on environmental cleanup efforts introduces even more difficulties for measuring β dose rates due to the very low levels that must be measured.

Geiger Mueller pancake detection systems are commonly used by health physicists when performing all types of radiation surveys. The instrument is well suited for measuring low levels of β emitters due to its unique design characteristics and detection properties. As with all health physics instrumentation, the output of pancake detectors must be converted to some unit that can be compared to a unit of significance. Detection efficiencies for surface contamination are routinely determined during pancake calibrations by most organizations and the results are usually reported in units of percent efficiency (cpm per dpm). This type of calibration is easily performed and the results are well understood.

The standard calibration values are of no use when trying to estimate β fluence from objects such as contaminated trees, soil, or other porous material. The radionuclides in these instances and others are not distributed on the surface and therefore cannot be characterized in simple terms of surface contamination (dpm). The only meaningful radiological quantities that can be obtained when characterizing

such hazards are the radionuclide concentration (pCi/g) or the direct β dose rate. Valid methods exist for sampling and analyzing such materials, but dose rate measurements with GM pancakes usually must be estimated based on ad-hoc conversion factors which are usually not very well documented and the error associated with the measurements are usually not known at all.

The intent of this research was two fold. The first goal was to characterize the response output of a pancake detector ($\text{cpm} \cdot \text{mGy}^{-1} \cdot \text{h}^{-1}$) with a 16 mesh stainless steel protective screen placed over the entrance window. This is a standard configuration used by health physics survey personnel at Oak Ridge National Laboratory (ORNL) and it was expected that the results from the research could be used for converting field measurements to dose rate estimates with known levels of confidence.

The second goal was to develop a measurement system using three sequential thicknesses of plastic absorber on the probe and to analyze the resulting data to find a relationship between the count rates and the β dose rate. The goal was to develop a method which could be used by health physicists to more accurately estimate low β dose rates to skin with no prior knowledge of the isotope or β spectra being measured.

II. BACKGROUND

Many parameters must be reviewed when attempting to develop a method for measuring or estimating dose rates with portable instrumentation. Biological tissue detriment associated with β irradiation, electron transport mechanisms, and the detection properties of the equipment used must all be considered. Existing technologies and previous studies must also be reviewed in order to minimize duplication of efforts.

EXTERNAL BETA DOSIMETRY

Evaluation of electron transport and energy deposition in external tissues have been studied by both in-vitro techniques and by Monte Carlo transport modeling. Studies performed primarily from the 1950's through the late 1970's evaluated the biological detriment associated with energy deposition within the exterior tissues of the human body. These studies focused on the effects of external irradiation to the skin but also included the effects of external irradiation to the human eye and to the male testicle. These studies formed the basis for subsequent recommendations by national advisory committees on both dose limitations to these organs and on where they should be measured.

Advanced Monte Carlo calculational codes have been used to provide valuable insight into the transport mechanisms associated with electrons. These calculations have allowed transport paths and energy deposition parameters to be evaluated for

electrons traveling through tissue. This information has been used by researchers to better understand how electrons distribute their energy within the human dermis.

Measurement Point

Personnel dosimetry has traditionally been divided into internal, deep, and shallow dose evaluations. Shallow dose evaluations are reserved for radiations that deposit most of their energy within approximately the first centimeter of tissue which includes all particulates with ranges greater than roughly 20 μm . Deep dose evaluations are performed for radiations that deposit most of their energy at depths greater than 1 cm in tissue.

Due to biological damage that occurs to the basal cells of the skin, the ICRP recommended that all shallow dose evaluations of the human dermis be performed at a depth of 7 mg cm^{-2} (70 μm) below the surface (ICRP, 1990). Current field measurement techniques for estimating β dose rates do so at the 70 μm skin layer.

Beta Spectra

Beta emissions from radioactive nuclides produce a continuous spectrum of particle energies due to energy sharing with the antineutrino and the nucleus. Composite beta spectra are shown in Figure 1 illustrating the emissions from five sources designed for minimum self absorption. These measured spectra correspond very well with theoretical emissions calculated for the nuclides. Spectra for beta emitters found during routine health physics surveys rarely resemble the emissions

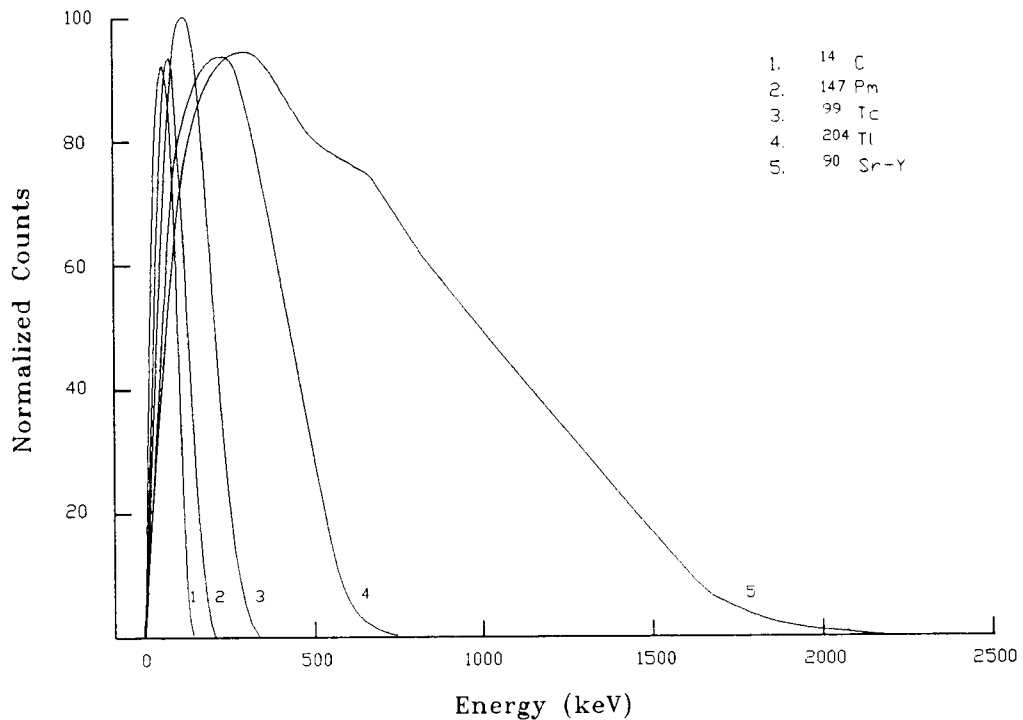


Figure 1 Composite beta spectra of five calibrated beta plaque sources (Martz, 1986).

sources such as these. Interactions within the nuclide binding medium tends to shift the upper end of the spectrum down and filter out the very low energy particles thereby degrading the spectrum. Figure 2 shows several beta spectra obtained in the field by use of a tissue equivalent beta spectrometer (Martz et al 1986) . The gamma contributions have been removed to reveal the pure beta spectra.

Electron Transport

Electrons passing through matter follow very tortuous paths. Although the ranges of electrons with given energies have been determined both experimentally and theoretically, the actual penetration abilities have not and cannot be. Given the

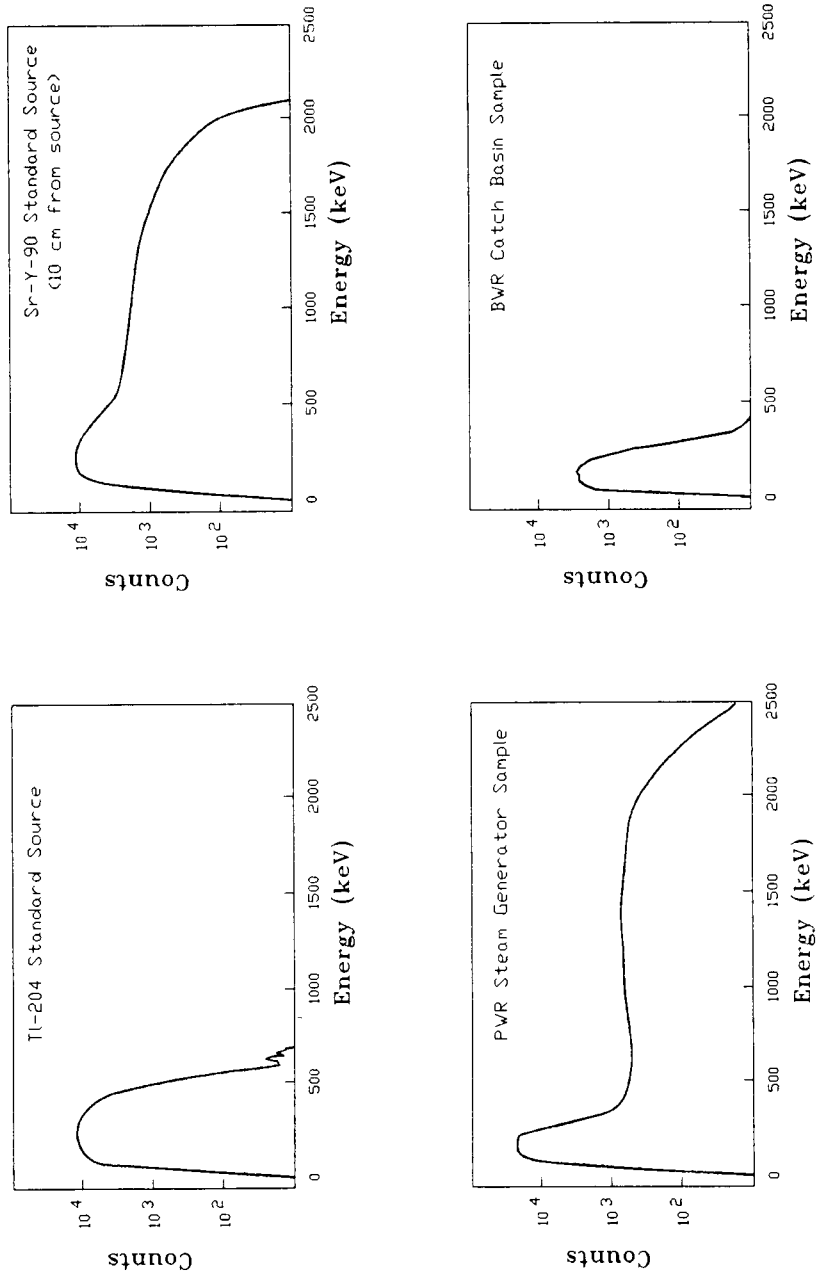


Figure 2 Examples of actual beta spectra taken with a tissue equivalent beta spectrometer (Martz, 1986).

energy of an electron impinging on the surface of a material, one cannot explicitly calculate how deep the electron will penetrate. Electrons with identical velocities at the surface will penetrate to different depths, depending on the path that they follow. The amount of energy deposited at a particular depth by a given electron in the material therefore cannot be explicitly determined. Only when the path histories of many electrons with identical properties are compiled can meaningful statistics about the electrons be estimated. Monte Carlo techniques have been used to analyze the statistics of range and energy deposition for monoenergetic electrons passing through matter. Figure 3 shows the results for one set of such Monte Carlo calculations indicating the total range, average penetration depth, and the depth of maximum dose for electrons incident on the surface of water (Turner et al. 1988).

Of particular importance to this study is the energy deposited at 70 μm by electrons impinging on the surface of the human epidermis. Figure 4 shows the energy deposited at 70 μm by electrons with initial energies from 0 to 2.5 MeV. This curve was developed using Monte Carlo techniques and shows very good agreement with semi-empirical laboratory measurements (Martz et al. 1987). Electrons with energies below about 60 keV cannot penetrate through any more than 60 μm of tissue and therefore cannot contribute any dose to the 70 μm dermal layer.

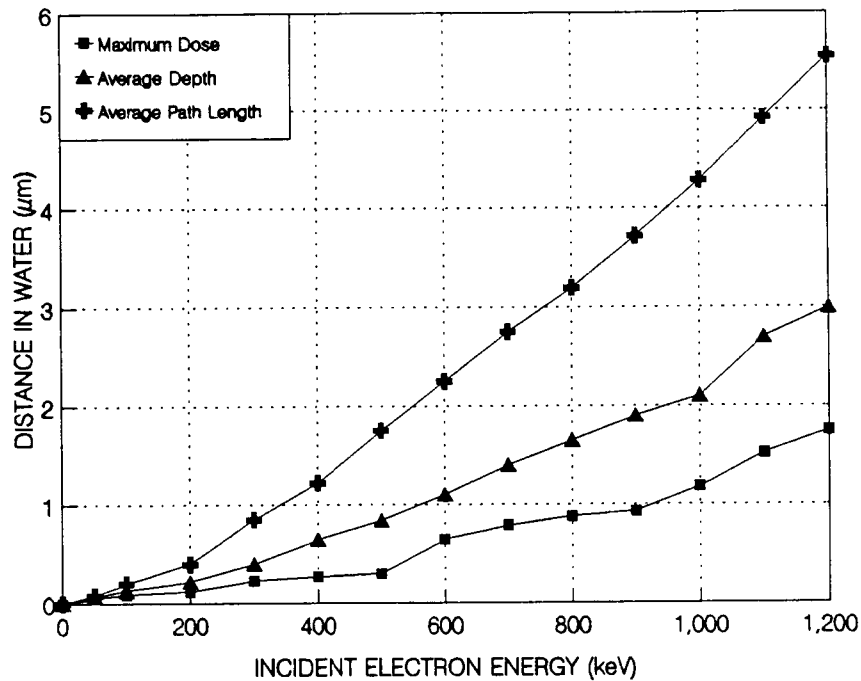


Figure 3 Average path length, average maximum penetration depth, and depth of maximum dose as functions of energy for electrons normally incident on water (Turner et al. 1988).

PREVIOUS INSTRUMENTATION STUDIES

Many facilities such as nuclear power stations routinely report skin dose rates from beta emitting nuclides and have chosen the 70 μm skin layer as the measurement point. The most widely accepted method for performing these measurements makes use of detectors commonly known as ionization chambers. Different models are in use, but they all have the same basic characteristics and operational properties. These instruments are primarily designed for measuring photon exposure rates to air but have been generally accepted as an adequate instrument for performing beta dose rate estimations.

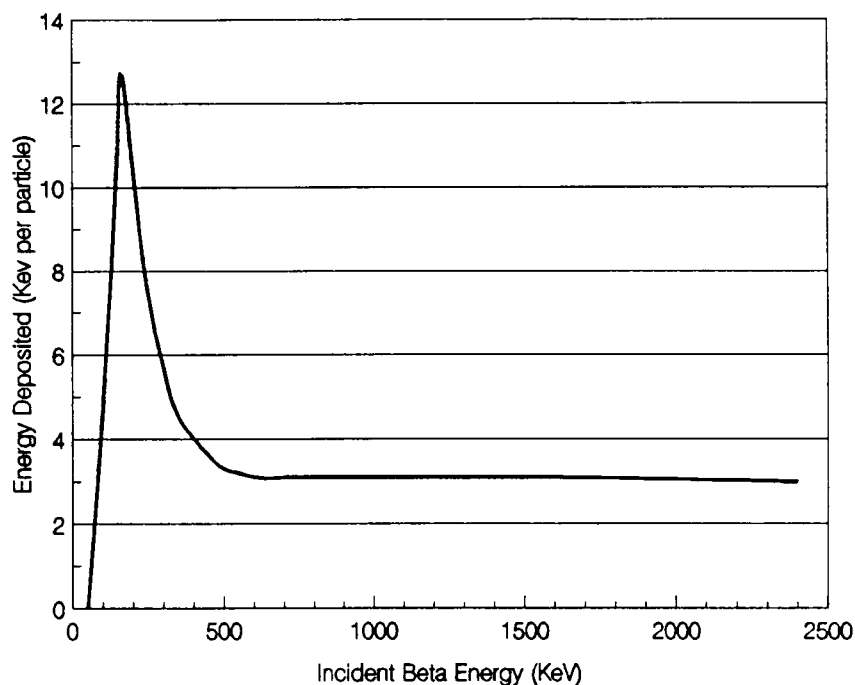


Figure 4 Energy deposited at 70 μm by electrons incident on the surface of the human dermis (Martz et al 1987).

Ion chambers have been widely accepted as dose rate meters because their fundamental detection mechanism gives a response that is directly proportional to the amount of energy deposited within them. Unfortunately, the response does not directly indicate the amount of energy that would be deposited at 70 μm in tissue. Measurements of this important quantity with this type of instrument can yield results with errors up to 100% depending upon calibration parameters and the type of β field being measured (Herbaut et al. 1986). At some sites the beta fields are found to be similar for many contamination areas allowing a constant correction factor to be applied to all ion chamber measurements to correct for inaccuracies. This is not always the case and no single correction factor can be used without biasing the

results. Unfortunately, these types of instruments are very sensitive to humidity, temperature and atmospheric pressure variations which has limited their use for low level measurements during outdoors environmental characterizations.

Some detectors have been developed for the special purpose of making shallow dose rate measurements. One such detector developed at the Jülich Nuclear Research Center in Germany made use of a small ionization detector which had a much more shallow chamber depth than typical (Heinzelmann et al. 1986). The detector had a 7 mg cm^{-2} entrance window and was reported to respond to within 20% of actual dose rates across a wide β energy range. The principal limitation of the detector was its minimum detection level of 1 mGy h^{-1} (100 mRad h^{-1}) which was too high to be of use for most environmental surveillance work.

A second detector, developed at Idaho National Engineering Laboratory (Martz et al. 1986), made use of a thin tissue equivalent plastic scintillator. The 0.05 mm thick scintillator was placed directly underneath a $50 \text{ }\mu\text{m}$ layer of tissue equivalent plastic such that incident radiation would deposit energy within a layer of scintillant located at the same depth as the critical layer of the skin. The output of the scintillant was directly proportional to the energy deposited within it and therefore gave a direct indication of the dermal dose rate. Published test data for the system showed accuracy within 20% although the minimum detection level was never reported. The electronics required to drive the system were fairly complicated and as a result the technology was never marketed.

GEIGER-MUELLER PANCAKE DETECTOR

Figure 5 illustrates a cross sectional view of a typical GM tube used in pancake probes. The pancake detector is a gas filled, thin window detector which operates in a Geiger-Mueller avalanche mode and has the following design characteristics:

- ▶ Mica window, 1.4 to 2.0 mg cm^{-2} (TGM[†])
- ▶ Dead time = $50 - 100 \text{ } \mu\text{s}$ (typical)
- ▶ Operating voltage: 900 Volts (typical)
- ▶ Can detect electrons with energies $\approx \geq 30 \text{ keV}$

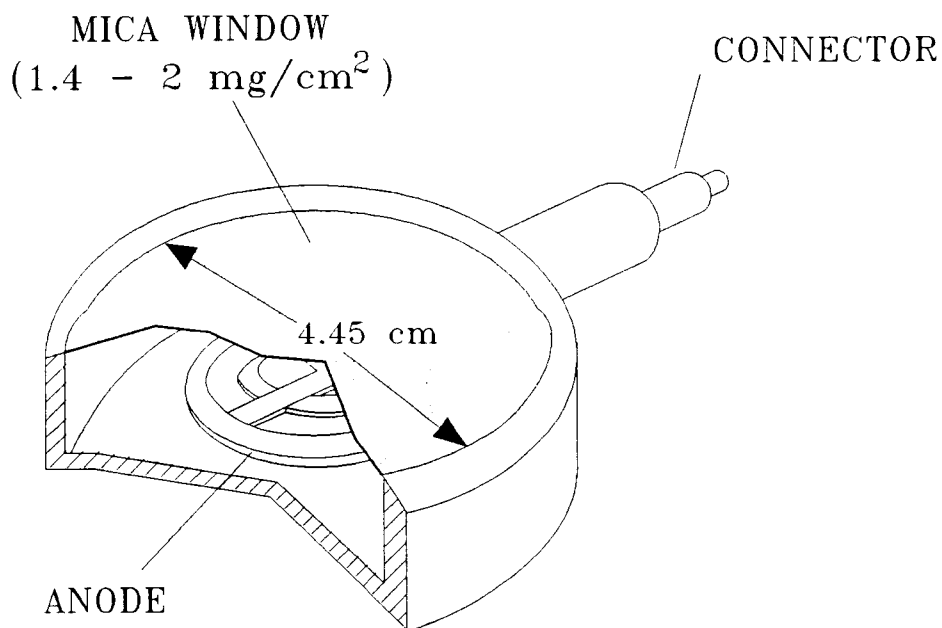


Figure 5 Cross sectional diagram of a GM pancake tube.

[†] TGM Detectors, Inc. is a major manufacturer of GM pancake probes.

Ionizing interactions within the probe produce large voltage drops which can be measured with a pulse type meter. Regardless of the magnitude of the ionizing event, the amplitude and shape of the voltage drop will be the same. The only response possible with a pancake detector system is a count or count rate indicating the number of radiation interactions that have occurred within the probe.

The reasons for choosing a GM pancake probe for this study were:

1. The design characteristics of the probe allow for detection of electrons across the entire energy spectrum of interest for skin dosimetry.
2. The pancake is currently widely used by most organizations for general contamination surveys and is relatively inexpensive and durable.
3. Very low levels of contamination can be detected.
4. The response of the detector is not affected by common adverse environmental conditions such as humidity and temperature due to its gas tight design.
5. The complete detection system is small and easily portable.

III. METHODS and DATA

Different isotopes with varying β spectra were used so that the dose response characteristics of the pancake GM tube could be analyzed as a function of average beta energy. Skin dose rates were measured for one group of sources with an extrapolation chamber and were calculated on a second group of sources by using the computer code VARSKIN (Traub et al. 1987).

Once the dose rates had been determined, pancake measurements were made on each source under two different irradiation conditions. The first set of measurements were performed with a 16 mesh etched stainless steel screen placed over the detector entrance window. This type of screen is a standard protective screen on all currently employed pancake models at ORNL. The purpose of these measurements was to characterize the dose rate response characteristics of the pancake tube as a function of average beta energy. The second set of measurements were made with a set of three plastic filters of different thicknesses placed in sequence over the detector entrance window. These measurements were made with the intent to derive a calculational technique by which dose rates could be accurately assessed with a pancake detector with no prior knowledge of the beta spectra being measured.

EXTRAPOLATION CHAMBER MEASUREMENTS

All extrapolation chamber measurements were taken at the Radiation Standard and Calibration Laboratory (RASCAL) at ORNL.

Equipment

<u>Description</u>	<u>Serial #</u>	<u>Make / model</u>
Extrapolation chamber	24715	PTW B23392
Electrometer	40758	Keithley 35617EBS
Thermometer/Hygrometer	89-092144	
Barometer	0229	

A thin window, parallel plate, extrapolation ionization chamber was used for all direct beta dose measurements. The extrapolation chamber was designed by the Physikalisch-Technische Bundesanstalt (PTB) in Germany and built by Pychlau Technical Works (PTW) and was used in conjunction with a beta particle calibration system designed and manufactured by Amersham-Buchler. A detailed description and design schematic of the measurement chamber and associated equipment can be found in the National Bureau of Standards (NBS) special publication 250-21 (NBS 1988).

Sources

The irradiation sources used were primary beta standards calibrated by the PTB in Germany. The calibration documentation provided for each source lists the irradiation distance, absorbed dose rate in air, absorbed dose rate in tissue, tissue depth-dose transmission factors, and the date of the calibration measurements. PTB source set number 64 was used and included the sources listed in Table 1. The tissue dose rates listed for each source were directly measured by the PTB with an extrapolation chamber at 0.0 mg cm^{-2} . Depth dose transmission factors published in the PTB calibration documentation were used to extrapolate the calibration values to 7 mg cm^{-2} ($70 \text{ }\mu\text{m}$) tissue dose rates. The extrapolation chamber and associated equipment used to determine these dose rates at the PTB were identical to the equipment used during this study.

Table 1 PTB sources used for the study. The dose rates were directly measured by the PTB with an extrapolation chamber.

Isotope	Activity (Bq)	Half Life (yr)	Date	Calibration Distance (cm)	0 mg/cm ² Tissue Dose Rate (mGy h ⁻¹)	Depth Dose Transmission Factor (7 mg cm ⁻²)	7 mg/cm ² Tissue Dose Rate (mGy h ⁻¹)
⁹⁰ Sr	1.85x10 ⁹	27.5	Nov-14-1985	30	246.6	1.06	261.4
				50	87.2	1.05	91.6
⁹⁰ Sr	7.40x10 ⁷	27.5	Sep-30-1985	30	7.2	1.04	7.5
²⁰⁴ Tl	1.85x10 ⁷	3.8	Oct-01-1985	30	1.0	0.99	0.99
¹⁴⁷ Pm	5.18x10 ⁸	2.6	Sep-30-1985	20	1.6	.18	0.29

Measurements

A readable description of the design and use considerations for extrapolation chambers has been published by Loevinger (Loevinger, 1953). All extrapolation chamber measurements for this study were performed in accordance with methods outlined in NBS publication 250-21 (NBS 1988).

Three of the dose rate calibration points listed for the sources in Table 1 were directly usable for this study without modification. To obtain an additional data point, two extrapolation measurements were made. The first measurement was made under irradiation conditions that matched that of the PTB calibration procedure for the 1.85 GBq ^{90}Sr source at a source to detector distance of 30 cm. The purpose of this measurement was to test the response of the extrapolation chamber system and to validate calculational techniques. A second measurement was then made on the 74 MBq ^{90}Sr at an irradiation distance of 50 cm to provide a fourth data point for the study.

Measurement technique

The Amersham-Buchler beta particle calibration system was designed such that special β beam-flattening filters could be placed at a set distance between the source facing and the extrapolation chamber. These filters were designed for each individual source to achieve beam cross sections of relatively constant absorbed dose rates over the entrance window of the chamber at close irradiation distances. The filter designed for the 1.85 GBq ^{90}Sr source at an irradiation distance of 30 cm was

used as designed, but no filter was used on the 74 MBq ^{90}Sr source since an irradiation distance of 50 cm allowed for inherent irradiation uniformity across the detector entrance window.

Prior to making any extrapolation chamber measurements, the atmospheric pressure, temperature, and the relative humidity were measured and recorded. Equipment setup consisted of connecting the extrapolation chamber to a combination electrometer and voltage bias supply and connecting the source holder assembly to a remote switch unit (Figure 6). The PTB used a circular, plastic beam flattening filter when measuring the dose rate from the 1.85 GBq ^{90}Sr source, therefore this filter was placed appropriately while measuring this source. The chamber was placed at the desired irradiation distance with a collection plate separation distance of 2.5 mm and a voltage bias of +25V was applied to the chamber. The system was allowed to set untouched in this configuration until transient noise current had settled out. The amount of time required for the noise current to subside was approximately 2 hours for the 1.85 GBq source measurement and 24 hours for the 74 MBq source measurement.

After the system had stabilized, the desired source was placed into the source holder assembly, the voltage bias was set to +5 volts, and the chamber collection plates were adjusted to a separation distance of 0.5 mm. This setting gave an electric field strength of 10 V/mm between the collection electrodes. The source holder shutter was opened to irradiate the chamber and the electrometer was reset to zero and switched to integral charge collection mode. The charge collection rate was

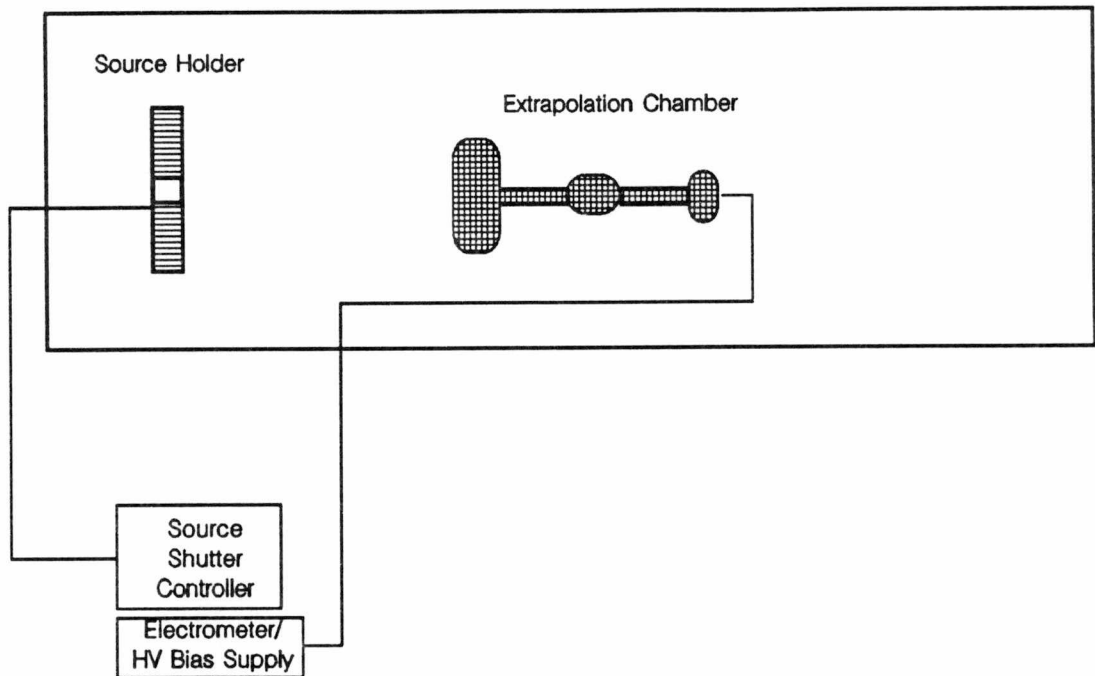


Figure 6 Equipment setup for extrapolation chamber system.

monitored so that a sampling time could be determined. Once the charge collection sampling time, t_1 , had been determined, the electrometer was reset to zero and the measurement process was started.

The total charge collected from the chamber was read from the electrometer every period of t_1 until it was decided that enough data had been collected for the +5 volt setting. The polarity of the voltage bias supply was then adjusted to -5 volts and the charge collection process was repeated. These measurements were repeated in increments of 5 volts bias and 0.5 mm plate separations up to 25 volts and 2.5 mm respectively keeping a constant collection field strength of 10 V/mm.

Data

The first measurement was made on the 1.85 GBq ^{90}Sr source at a source to detector distance of 30 cm. The data from this measurement is presented in Table 2.

The second measurement was made on the 74 MBq ^{90}Sr source at a source to detector distance of 50 cm. The data from this measurement is presented in Table 3.

Calculations

Ionization currents were calculated from the charge collection measurements by use of Equation 1 for the data presented in Table 2 and Table 3. The resulting currents for both the positive and negative bias settings were then averaged together to give an average current for each plate separation distance. The results for the two data sets are presented in Table 4.

$$I = \frac{\frac{\sum (Q_i - Q_{i-1})}{n}}{dT} \quad \text{Equation 1}$$

Where:

- I = Ionization current (Amperes)
- Q_i = Charge collected during time interval dT (Coulombs)
- n = Number of charge collection measurements
- dT = Charge collection time interval (sec)

Table 2 Data for extrapolation chamber measurements on the 1.85 GBq ^{90}Sr source.

Date collected: Feb-05-1992

Time interval 10 seconds

Temperature 22.5 °C

Barometric pressure . 736 mm Hg

Relative humidity . . . 20.7%

Source 1.85 GBq ^{90}Sr

Irradiation distance . 30 cm

Other PTB beam flattening filter in place

Charge Collected (coulomb x 10^{-12})

0.5 mm		1.0 mm		1.5 mm		2.0 mm		2.5 mm	
+5 V	-5 V	+10 V	-10 V	+15 V	-15 V	+20 V	-20 V	+25 V	-25 V
0.0045	0.0033	0.0050	0.0036	0.0046	0.0038	0.0045	0.0038	0.0046	0.0054
0.0096	0.0125	0.0169	0.0193	0.0232	0.0260	0.0299	0.0325	0.0364	0.0405
0.0143	0.0218	0.0288	0.0350	0.0416	0.0482	0.0554	0.0612	0.0683	0.0758
0.0197	0.0309	0.0408	0.0507	0.0602	0.0705	0.0809	0.0899	0.1002	0.1109
0.0248	0.0402	0.0527	0.0664	0.0787	0.0927	0.1063	0.1185	0.1320	0.1461
0.0299	0.0494	0.0646	0.0820	0.0973	0.1149	0.1316	0.1472	0.1639	0.1813
0.0351	0.0586	0.0766	0.0977	0.1158	0.1370	0.1570	0.1758	0.1959	0.2139
0.0400	0.0679	0.0885	0.1134	0.1344	0.1592	0.1824	0.2044	0.2278	0.2517
0.0454	0.0770	0.1004	0.1290	0.1530	0.1814	0.2079	0.2330	0.2596	0.2868
0.0506	0.0861	0.1123	0.1447	0.1716	0.2036	0.2333	0.2616	0.2916	0.3220
0.0558	0.0951	0.1242	0.1604	0.1901	0.2258	0.2587	0.2902	0.3235	0.3572
0.0611	0.1043	0.1361	0.1761	0.2087	0.2480	0.2841	0.3188	0.3554	0.3922
0.0663	0.1129	0.1481	0.1917	0.2272	0.2702	0.3095	0.3474	0.3873	0.4274

Table 3 Data for extrapolation chamber measurements on the 74 MBq ^{90}Sr source.

Date collected: Feb-06-1992
 Time interval 180 seconds
 Temperature 25.3 °C
 Barometric pressure . 730 mm Hg
 Relative humidity . . . 16.5%

Source 74 MBq ^{90}Sr
 Irradiation distance . 50 cm

Charge Collected (coulomb x 10^{-12})

0.5 mm		1.0 mm		1.5 mm		2.0 mm		2.5 mm	
+5 V	-5 V	+10 V	-10 V	+15 V	-15 V	+20 V	-20 V	+25 V	-25 V
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002
0.0007	0.0027	0.0026	0.0055	0.0038	0.0074	0.0082	0.0095	0.0089	0.0121
0.0021	0.0051	0.0049	0.0107	0.0083	0.0150	0.0157	0.0191	0.0166	0.0239
0.0046	0.0075	0.0075	0.0151	0.0134	0.0227	0.0221	0.0282	0.0245	0.0340
0.0070	0.0099	0.0102	0.0196	0.0193	0.0299	0.0279	0.0366	0.0332	0.0431
0.0093	0.0124	0.0125	0.0242	0.0251	0.0371	0.0339	0.0455	0.0421	0.0502
0.0111	0.0153	0.0156	0.0287	0.0307	0.0436	0.0407	0.0544	0.0518	0.0576
0.0129	0.0178	0.0194	0.0330	0.0363	0.0493	0.0484	0.0634	0.0614	0.0660

The average ionization currents presented in Table 4 had to be corrected to account for chamber, source and environmental irradiation conditions. Equation 2 shows the parameters that were considered when normalizing the measured currents.

$$I_c = I_o \sum c_i \sum k_i \quad \text{Equation 2}$$

Where

I_c = Corrected ionization current

I_o = Ionization current calculated by use of

and, c_i and k_i factors were as taken from NBS publication 250-21, except where noted, as follows:

Table 4 Average currents calculated by use of Equation 1 for data listed in Table 2 and Table 3.

Average Current (pA)									
0.5 mm		1.0 mm		1.5 mm		2.0 mm		2.5 mm	
+5 V	-5 V	+10 V	-10 V	+15 V	-15 V	+20 V	-20 V	+25 V	-25 V
1.85 GBq ⁹⁰ Sr, 30 cm									
0.515	0.913	1.19	1.57	1.86	2.22	2.54	2.86	3.19	3.52
Avg = 0.714		Avg = 1.38		Avg = 2.04		Avg = 2.70		Avg = 3.36	
74 MBq ⁹⁰ Sr, 50 cm									
1.2E-2	1.4E-2	1.5E-2	2.6E-2	2.9E-2	3.9E-2	3.8E-2	5.0E-2	4.9E-2	5.2E-2
Avg = 1.3E-2		Avg = 2.1E-2		Avg = 3.4E-2		Avg = 4.4E-2		Avg = 5.1E-2	

- c_{foil} = Correction for entrance window thickness from the chamber window of 2.6 mg cm^{-2} to 7 mg cm^{-2} skin thickness. A value of 1.02 was used for ^{90}Sr (Reaves, 1992).
- c_{div} = Correction for beam divergence within the chamber. A value of $1+.0033d$ was used, where d is the plate separation distance (mm).
- $c_{\text{t,p}}$ = Correction for air density changes within the chamber due to pressure and temperature variations. This correction factor was calculated by $760*(t + 273.2) / (295.2*p)$, where p was the atmospheric pressure in mm Hg, and t was the temperature in degrees Celsius.
- c_{back} = Correction for difference between β backscatter from water compared to that of PMMA, the chamber electrode material. A value of 1.006 was used.
- c_{side} = Correction for side scatter from chamber. A value of $1-.0032d$ was used, where d was the plate separation distance (mm).
- c_{recom} = Correction for ion recombination and diffusion in the air inside the chamber. A value of $(R_v R_i R_{\text{df}})^{-1}$ was used where $R_v = 1-[5.05 \text{E} 13 * I d^3 / (A V^2)]$, $R_i = 1-[4.4 \text{ d} / V]$, $R_{\text{df}} = 1-[(17.24 \text{E} -5)(t+273.2)/V]$, I = current (A), d = plate separation (m), A = area of collection electrodes (m^2), V = bias voltage (V), and t = temperature (degrees C).

k_{mass} = Correction for the total mass of air between the source and the chamber. A value of $(1-0.085h-0.027h^2)^{-1}$ was used, where $h = 1-(c_{\text{tp}})^{-1}$.

k_{hum} = Correction for air density variations caused by water vapor in the air. A value of $e^{4.4\text{E-}4 H}/1.02$ was used, where H = relative humidity (%).

The results from these corrections are presented in Table 5.

Once the collection currents had been measured and corrected, the absorbed dose rates to skin were calculated for each source configuration. The absorbed dose rate to tissue was calculated by use of Equation 3.

$$\dot{D} = 3600 W_e S_{t,a} \frac{\Delta I_c}{\Delta d} \frac{1}{\rho_o A} \quad \text{Equation 3}$$

Where:

$\dot{D}$ = Dose rate to tissue (mGy h^{-1})

3600 = Conversion factor from Gy s^{-1} to Gy h^{-1} .

W_e = Energy required to produce an ion pair in air. A value of 33.7 J/C was used.

$S_{w,a}$ = Ratio of average electron mass stopping power of tissue to that of dry air. A value of 1.11 was used as reported by the PTB in calibration documentation that came with each source.

ρ_o = Density of dry air at STP. A value of 1.3 kg m^{-3} was used.

Table 5 Corrections for ionization currents listed in Table 4 by use of Equation 3.

Plate Spacing (mm)	Bias Voltage (V)	Measured Current (A)	$\Sigma c_i \Sigma k_i$	Corrected Current (A)
(A) 1.85 GBq ^{90}Sr at 30 cm				
0.5	5	7.14 E-13	1.079	7.70 E-13
1.0	10	1.38 E-12	1.075	1.48 E-12
1.5	15	2.04 E-12	1.075	2.19 E-12
2.0	20	2.70 E-12	1.088	2.94 E-12
2.5	25	3.36 E-12	1.089	3.66 E-12
(B) 74 MBq ^{90}Sr at 50 cm				
0.5	5	1.3 E-14	1.100	1.4 E-14
1.0	10	2.1 E-14	1.096	2.3 E-14
1.5	15	3.4 E-14	1.096	3.7 E-14
2.0	20	4.4 E-14	1.097	4.9 E-14
2.5	25	5.1 E-14	1.097	5.5 E-14

A = Area of collecting electrodes. The area of a single electrode in the PTB extrapolation chamber is $7.08 \times 10^{-4} \text{ m}^2$.

$\Delta I_c / \Delta d$ = Slope of collected ionization current versus plate separation (A m^{-1})

The slopes of collected ionization current versus plate separation, $\Delta I_c / \Delta d$, was calculated for each source by linear regression. A slope of $1.44 \times 10^{-9} \text{ A/m}$ was calculated for the 1.85 GBq ^{90}Sr source and a slope of $2.34 \times 10^{-11} \text{ A/m}$ was calculated for the 74 MBq ^{90}Sr source. A regression plot is shown in Figure 7 and Figure 8 for each source. It should be noted that the 2.5 mm measurement on the 74 MBq ^{90}Sr source was discarded when calculating the slope for this source because the raw data showed a severe non-linearity of collected charge per measurement period (Table 3).

Results

The dose rate for the 1.85 GBq ^{90}Sr source was calculated to be 232 mGy h^{-1} . This result was compared to the dose rate measured under the same irradiation conditions for this source by the PTB. The PTB reported the dose rate to be 261 mGy h^{-1} on November 14, 1985. Correcting for the decay of ^{90}Sr with a half life of 27.5 years, the PTB dose rate on February 5, 1992 was calculated to be 223 mGy h^{-1} . The measured dose rate was 4% higher than the dose rate reported by the PTB.

The dose rate for the 74 MBq ^{90}Sr source was calculated to be 3.8 mGy h^{-1} .

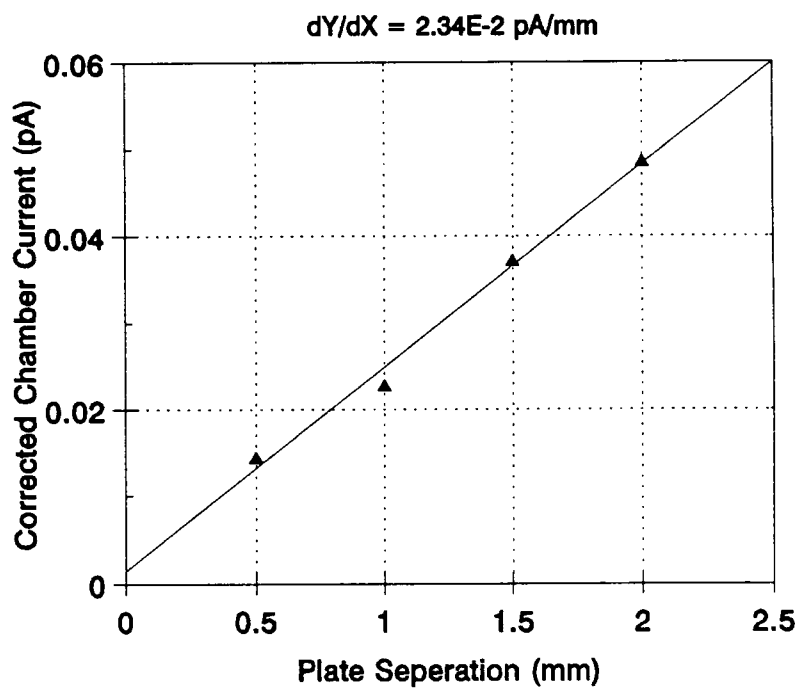


Figure 7 Regression of current versus plate separation for 74 MBq ^{90}Sr source.

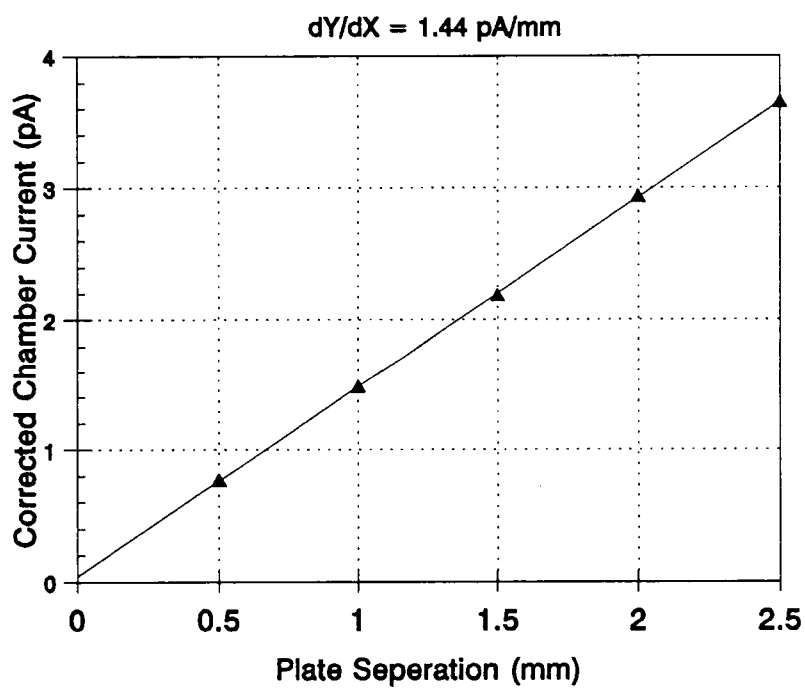


Figure 8 Regression of current versus plate separation for 1.85 GBq ^{90}Sr source.

VARSKIN CALCULATIONS

The computer code VARSKIN (Traub et al. 1987) was used to calculate the skin dose rates from a second set of sources. The dose rates from these sources were too low to be measured directly with an extrapolation chamber.

Sources

Table 6 gives a listing of the β emitting radionuclides used for the VARSKIN calculations. Each source consisted of a specific radionuclide encased in a disc structure as shown in Figure 9. All the sources except ^{210}Pb had a 0.9 mg cm^{-2} aluminized Mylar^{TM†} protective film covering the isotope active area. The ^{210}Pb source was covered with a 7 mg cm^{-2} aluminum film. The sources were manufactured by Isotope Product Laboratories by means of depositing the dissolved nuclides onto the disc surfaces and evaporating the solvent.

Calculations

In order to calculate the skin dose rates from the sources, the irradiation parameters were defined as follows:

- The dose rates were calculated at contact with the surface of the source.
- The active areas of the sources were assumed to have a diameter of 1.27 cm and all the activity was assumed to be distributed evenly within this area.

[†] Mylar is a trademark of E.I. Du Pont de Nemours & Co., Inc., 1007 N. Market St., Wilmington, DE 19801.

Table 6 Sources used for VARSKIN calculations.

Serial #	Isotope	Activity (Ci)	Date	Half Life (y)
371-67-8	^{14}C	1.04×10^{-6}	Feb-01-1992	5.73×10^3
396-75-2	^{147}Pm	9.47×10^{-9}	Feb-01-1992	2.62
371-68-8	^{99}Tc	1.00×10^{-8}	Feb-01-1992	2.13×10^5
396-75-1	^{36}Cl	9.87×10^{-9}	Feb-01-1992	3.01×10^5
371-70-8	^{210}Pb	9.16×10^{-9}	Feb-01-1992	2.23×10^1
371-72-8	^{90}Sr	9.65×10^{-9}	Feb-01-1992	2.75×10^1

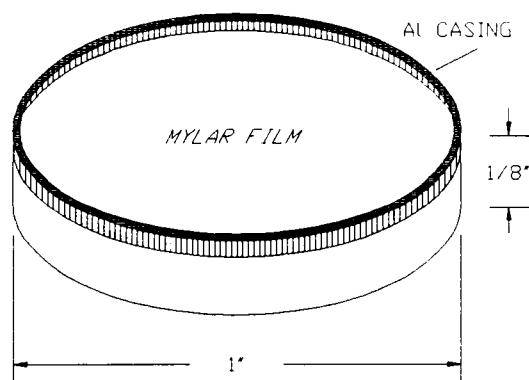


Figure 9 Enclosure casing for sources listed in Table 6 and used for VARSKIN calculations.

- The dose rates were evaluated at a depth of $(7+x)$ mg cm⁻², where x was the thickness of the mylar protective film on the source (mg cm⁻²).
- An irradiation time of 3600 seconds was used.
- The activity for each source was corrected by decay to March 31, 1992.

The input parameters and the resulting VARSKIN output data are presented in Table 7 for each source. The VARSKIN algorithm calculated the dose received to the prescribed tissue depth as a function of radial distance from the center of the source. The resulting dose rates were then averaged with a weighting scheme as shown in Equation 4. This algorithm weights each dose data point by the area receiving that dose. The resulting averaged dose rates are presented in Table 8. Since the irradiation time was set to 3600 seconds the resulting average dose rates in mGy h⁻¹ were equal to the average doses.

$$D_A = \sum_{i=1}^n \left[\frac{(r_i^2 - r_{i-1}^2)}{A} D_i \right] \quad \text{Equation 4}$$

Where:

- D_A = Average dose received by tissue within the active area of the source (Gy).
- r_i = Radius from center of the source at which the dose D_i was calculated (cm).
- D_i = Dose to tissue at a distance of r_i from the source center (Gy).
- A = Area of total irradiated area for 1.27 cm diameter circle (1.27 cm²).
- n = Number of radial dose data points.

Table 7 Output values for VARSKIN calculations.

Date: March 31, 1992

Distance (cm)	Dose (mGy)	Distance (cm)	Dose (mGy)	Distance (cm)	Dose (mGy)
¹⁴ C, 7.9 mg cm ⁻²		¹⁴⁷ Pm, 7.9 mg cm ⁻²		⁹⁹ Tc, 7.9 mg cm ⁻²	
0	0.064	0	0.013	0	0.024
0.6196	0.065	0.6064	0.013	0.5887	0.024
0.6221	0.064	0.6109	0.013	0.5961	0.024
0.6243	0.064	0.6151	0.013	0.6028	0.024
0.6264	0.062	0.6189	0.012	0.6090	0.024
0.6282	0.059	0.6223	0.012	0.6144	0.023
0.6298	0.055	0.6253	0.012	0.6192	0.022
0.6312	0.051	0.6278	0.011	0.6234	0.021
0.6323	0.046	0.6300	0.01	0.6270	0.02
0.6333	0.041	0.6318	0.009	0.6299	0.018
0.6340	0.037	0.6332	0.008	0.6321	0.015
0.6346	0.034	0.6342	0.007	0.6337	0.013
0.6349	0.033	0.6348	0.007	0.6347	0.012
0.6350	0.032	0.6350	0.006	0.6350	0.012
³⁶ Cl, 7.9 mg cm ⁻²		²¹⁰ Pb, 14 mg cm ⁻²		⁹⁰ Sr + ⁹⁰ Y, 7.9 mg cm ⁻²	
0	0.055	0	0.044	0	0.116
0.4408	0.053	0.2663	0.042	0.0507	0.116
0.4718	0.054	0.3252	0.042	0.1014	0.116
0.5001	0.054	0.3789	0.044	0.194	0.114
0.5257	0.054	0.4276	0.042	0.2778	0.113
0.5487	0.054	0.4711	0.043	0.3528	0.113
0.5689	0.053	0.5095	0.04	0.4189	0.111
0.5864	0.052	0.5428	0.041	0.4762	0.109
0.6013	0.049	0.5710	0.039	0.5248	0.108
0.6134	0.046	0.5940	0.036	0.5644	0.104
0.6229	0.041	0.6120	0.032	0.5953	0.097
0.6296	0.035	0.6248	0.027	0.6174	0.086
0.6337	0.029	0.6324	0.023	0.6306	0.065
0.6350	0.027	0.6350	0.021	0.6350	0.055

Table 8 Weighted average dose rates for VARSKIN output shown in Table 7.

Isotope	Average Dose Rate (mGy h ⁻¹)
¹⁴ C	0.64
¹⁴⁷ Pm	0.12
⁹⁹ Tc	0.23
³⁶ Cl	0.51
²¹⁰ Pb	0.39
⁹⁰ SrY	1.04

URANIUM SLAB SOURCE

A plate of depleted ²³⁸U, approximately 10 cm by 10 cm by 0.5 cm thick was used at RASCAL as part of the study. The β dose rate at the surface of the slab was taken from literature reference since the same value was expected for all depleted uranium slabs with thicknesses greater than ~0.25 cm. The β dose rate at the surface of the uranium slab was assumed to be 2.3 mGy h⁻¹ (Health Physics Handbook, 1969).

PANCAKE MEASUREMENTS

Two sets of pancake measurements were made on the PTB sources, on the Isotope Products sources that were characterized with VARSKIN, and on the ²³⁸U slab source. The first set of measurements were made with an Eberline 16 mesh etched stainless steel screen placed over the entrance window of the probe. The

second set of measurements were made with a set of plastic and Mylar filters placed in sequence over the entrance window.

Equipment

<u>Description</u>	<u>Serial #</u>	<u>Make / model</u>
Scaler	3490-04R	Ludlum 2221
Pancake probe	none	Eberline HP-260

Equipment setup

Prior to making any measurements, the pancake detection system was calibrated in accordance with a calibration procedure used by the Measurement Applications and Development (MAD) Group at ORNL. The calibration procedure is included in Appendix I. The calibration results are included in Appendix II.

All pancake measurements had to be corrected for dead time losses inherent to the detection system. In order to determine this parameter, a ^{90}Sr split source system was used and Equation 5 was used to calculate the dead time (Knoll, 1979).

$$\tau = \frac{m_1 m_2 - \sqrt{m_1 m_2 (m_{12} - m_1)(m_{12} - m_2)}}{m_1 m_2 m_{12}} \quad \text{Equation 5}$$

Where:

τ = System dead time constant (min)

m_1 = Count rate for source #1 (cpm)

m_2 = Count rate for source #2 (cpm)

m_{12} = Count rate for source #1 and source #2 together

The count rates were measured to be 47236 cpm for source #1, 47483 cpm for source #2, and 86266 cpm for the combination of the two sources at the same time. The system dead time was then calculated to be 2.07×10^{-6} minutes (124 μ s). All count rate measurements were corrected for dead time losses by use of Equation 6 (Knoll, 1979).

$$C = \frac{C_o}{1 - C_o \tau} \quad \text{Equation 6}$$

Where:

C = Corrected count rate (cpm)

C_o = Measured count rate (cpm)

τ = Dead time constant (2.07×10^{-6} min)

Screen measurements

The first set of pancake measurements were made with an Eberline 16 mesh etched stainless steel screen placed over the probe. This type of probe screen is the typical type used by health physics survey personnel at ORNL. The purpose of these measurements was to characterize the dose rate response of the pancake probes that are currently employed during survey activities as a function of β energy.

Screen measurements on PTB sources

The pancake probe was completely saturated by the PTB sources when irradiated uniformly across the entire probe face. A copper plate was constructed with a 1.27 cm (0.5 in) diameter circular aperture in the center as shown in Figure 10. The plate had a thickness of 800 mg cm⁻² and no β particles with energies below ~2 MeV could enter the probe window except through the aperture. This design allowed count rates to be measured that were ~8.2% of what would have been expected had the entire entrance window been irradiated.

The pancake probe was placed at the calibration point for each source with the source shutter assembly closed and a one minute integrated background count was taken. The source shutter assembly was then opened and a one minute

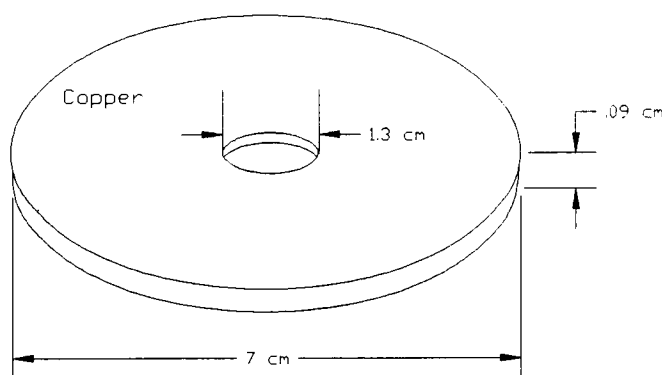


Figure 10 Diagram of copper plate used as aperture assembly for high count rate measurements on PTB sources and on the ²³⁸U slab.

integrated count was taken with the probe being irradiated by the source. Each count was corrected for dead time and the background was subtracted giving a net corrected count rate for each source. The results for these measurements are presented in Table 9. The dose rate for each source was corrected for decay to April 1, 1992 on which date the pancake measurements were made.

Screen measurements on VARSKIN sources

A background was taken with a one minute integrated count. Each source was then placed at contact with the face of the probe screen and a one minute integrated count was taken for each. The resulting counts were corrected for dead time and the background count was subtracted giving a net corrected count rate for each source. The results for these measurements are presented in Table 10. All the activity for these sources was assumed to be evenly distributed within a 1.27 cm diameter circular area and therefore only 1.27 cm² of the total probe area of 15.5 cm² was assumed to be irradiated.

Screen measurements on ²³⁸U slab source

The copper plate shown in Figure 10 had to be used to reduce the irradiation area for the uranium slab measurements to prevent saturation of the system. A 1000 mg cm⁻² plate of lucite was placed over the uranium slab, the pancake probe was placed on top of the lucite, and a one minute integrated background count was taken. The lucite plate was removed, the pancake probe was placed at contact with the

Table 9 Pancake data for PTB source measurements with a 16 mesh stainless steel screen.

Measurement date: April 1, 1992

Source	7 mg cm ⁻² Dose Rate (mGy h ⁻¹)	Source/Detector Distance (cm)	Background Count Rate (cpm)	Source Count Rate (cpm)	Net Corrected Count Rate (cpm)
⁹⁰ Sr, 74 MBq	6.41	30	555	187044	304353
	3.84	50	265	134832	186652
²⁰⁴ Tl, 18.5 MBq	.30	30	152	5984	5907
¹⁴⁷ Pm, 518 MBq	.05	20	139	1216	1080

surface of the uranium slab, and a one minute scaled count was taken. The resulting data and count rate corrections are presented in Table 10.

Filtered measurements

The second set of pancake measurements were made with a series of plastic and Mylar filters placed over the probe with no protective screen. The purpose of these measurements was to characterize the β spectra as a function of energy with the intent of formulating a dose rate measurement system that could be used with no prior knowledge of the beta spectra being measured.

Based on the energy deposition curve shown in Figure 4 it was decided that the most important energy region for which spectral information was needed for skin dose calculations was between approximately 60 and 400 keV. The absorbed dose is strongly dependant on the spectrum shape in this region. All electrons with

Table 10 Pancake data for VARSKIN source measurements with a 16 mesh stainless steel screen.

Date: March 31, 1992

Background: 40 cpm for all except ^{238}U slab. The background for the ^{238}U slab was 5700 cpm.

Source	7 mg cm ⁻² Dose Rate (mGy h ⁻¹)	Source Count Rate (cpm)	Net Corrected Count Rate (cpm)
^{14}C	.64	15007	15488
^{147}Pm	.12	2416	2428
^{99}Tc	.23	3996	3989
^{36}Cl	.51	8107	8205
^{210}Pb	.39	7685	7769
^{90}Sr	1.04	18774	19492
^{238}U slab	2.3	55717	57200

impinging energies greater than ~400 keV deposit a similar amount of energy at the 70 μm tissue layer. The skin dose due to the energetic electrons above ~400 keV would therefore only be a function of the total number of particles and would have little dependance on their relative energy distribution.

It was decided to break the spectra into the following bands:

- 1) 60 → 150 keV
- 2) 150 → 300 keV
- 3) 300 → maximum β energy

It was not possible to determine exactly what absorber thicknesses would be required due to the probabilistic nature of electron transport. Electron ranges in water have been calculated by Monte Carlo (Turner, 1986) and were used as a basis for determining what thickness the filters should be. Since the average linear penetration depth of electrons is usually slightly less than half of their full range (Turner et al. 1988), approximately one half of the published range values were used as the filter thicknesses required. The linear ranges and the average penetration depths are listed in Table 11 for the bracketed cut-off energies.

The plastic used was made from polyethylene which has a density range of 0.910 to 0.965 g cm⁻³ (CRC, 1972). Plastic bags with manufactured thicknesses of 1.5 mil, 4 mil, and 8 mil were used and assuming a density of 0.93 g cm⁻³ this equates to density thicknesses of 3.5, 9.5, and 18.9 mg cm⁻² respectively. The Mylar used was aluminized and had a density thickness of 0.5 mg cm⁻². The thickness of the mica

Table 11 Electron ranges and average penetration depths in water.

Electron Energy (keV)	Total Linear Range in Water (mg cm ⁻²)	Average Penetration Depth (mg cm ⁻²)
60	6	3
150	29	14
300	87	43

entrance window on the pancake probe was assumed to be 1.5 mg cm^{-2} . The mass stopping powers of polyethylene plastic and Mylar for electrons are similar to that of water and tissue, therefore the ranges of electrons in these materials are very close to what they are in water when the distances are expressed as density thicknesses.

Only β particles that could deposit energy in the $65 \text{ }\mu\text{m}$ to $75 \text{ }\mu\text{m}$ layer of tissue were of interest, so β particles which could not penetrate the dead layer of the skin (7 mg cm^{-2}) were filtered out completely. The thickness of the entrance window of the probe was increased to $\sim 6.5 \text{ mg cm}^{-2}$ by the addition of a base filter consisting of one 3.5 mg cm^{-2} polyethylene layer and three 0.5 mg cm^{-2} Mylar layers.

Filter #2 was made from two 3.5 mg cm^{-2} polyethylene layers. When placed in combination over the first filter, the total thickness was 13.5 mg cm^{-2} .

Filter #3 was made from two 18.9 mg cm^{-2} plus one 3.5 mg cm^{-2} polyethylene layers. When placed in combination over the first filter, the total thickness was 44.3 mg cm^{-2} .

Filtered measurements on PTB sources

The copper plate shown in Figure 10 had to be used to reduce the irradiation area of the probe to prevent system saturation. The base filter was positioned across the aperture window for all measurements.

The pancake probe was placed at the calibration point for each source with a 1 cm thick lucite plate covering the entrance window and a one minute integrated background count was taken. The lucite plate was removed, the source shutter

assembly was then opened and a one minute integrated count was taken with the probe being irradiated by the source. Filter #2 was then placed over the base filter and another one minute integrated count was taken. Filter #2 was removed and Filter #3 was placed over the base filter. A final one minute integrated count was taken. All counts were corrected for dead time and the background counts were subtracted to give net corrected count rates for each filter configuration. The results for these measurements are presented in Table 12.

Filtered measurements on VARSKIN sources

A background was taken with a one minute integrated count. The base filter was placed over the probe, each source was placed at contact with the filter, and a one minute integrated count was taken. Filter #2 was placed over the base filter and a second one minute integrated count was taken with each source at contact with the filters. Filter #2 was removed, filter #3 was placed over the base filter, and a third count was taken with each source at contact with the filters. The resulting counts were corrected for dead time and the background count was subtracted giving a net corrected count rate for each source. The results for these measurements are presented in Table 12. All the activity for these sources was assumed to be evenly distributed within a 1.27 cm diameter circular area so it was therefore assumed that only 1.27 cm² of the total probe area of 15.5 cm² was irradiated.

Table 12 Filtered pancake measurements for: (A) PTB sources, (B) VARSKIN sources and ^{238}U slab source.

A. PTB sources

Date: February 28, 1992

Source	Source/ Detector Distance (cm)	Measured Count Rates (cpm)				Net Corrected Count Rates (cpm)		
		Background (cpm)	6.5 mg cm^{-2}	13.5 mg cm^{-2}	44.3 mg cm^{-2}	6.5 mg cm^{-2}	13.5 mg cm^{-2}	44.3 mg cm^{-2}
^{90}Sr , 74 MBq	30	1081	143204	142696	142467	202318	201295	200835
	50	524	104484	104284	102506	132735	132409	129534
^{204}Tl , 18.5 MBq	30	178	6771	5848	3458	6689	5741	3305
^{147}Pm , 518 MBq	20	171	550	283	200	380	112	29

B. VARSKIN sources and ^{238}U slab

Date: March 31, 1992

Source	Source/ Detector Distance (cm)	Measured Count Rates (cpm)				Net Corrected Count Rates (cpm)		
		Background (cpm)	6.5 mg cm^{-2}	13.5 mg cm^{-2}	44.3 mg cm^{-2}	6.5 mg cm^{-2}	13.5 mg cm^{-2}	44.3 mg cm^{-2}
^{14}C , 371-67-8	0	40	2202	209	39	2172	169	0
^{147}Pm , 396-75-2	0	40	864	268	36	826	228	0
^{99}Tc , 371-68-8	0	40	2238	1166	92	2208	1129	52
^{36}Cl , 396-75-1	0	40	7054	5779	3557	7118	5809	3543
^{210}Pb , 371-70-8	0	40	6861	5762	3893	6920	5791	3885
^{90}Sr , 371-72-8	0	40	14384	12310	9301	14785	12591	9443
^{238}U slab	0	5772	55195	54082	49302	56460	55046	49054

Filtered measurements on ^{238}U slab

The copper plate shown in Figure 10 had to be used to reduce the irradiation area of the probe to prevent system saturation. A 1000 mg cm^{-2} plate of lucite was placed over the uranium slab, the pancake probe was placed on top of the lucite, and a one minute background count was taken. The base filter was placed over the probe, the probe was placed at contact with the slab, and a one minute integrated count was taken. Filter #2 was placed over the base filter and a second one minute integrated count was taken with each source at contact with the slab. Filter #2 was removed, filter #3 was placed over the base filter, and a third count was taken at contact with the slab. The resulting counts were corrected for dead time and the background count was subtracted giving a net corrected count rate. The results for these measurements are presented in Table 12.

SOURCE SPECTRA

The average β energy was determined for each source. Literature data was referenced for the VARSKIN sources and calculations were performed on published spectral data for both the PTB sources and the ^{238}U slab.

VARSKIN sources

Published data was referenced for the sources used during the VARSKIN calculations (Kocher, 1981). The average β energy for each source is listed in Table 13.

Table 13 Average β energies of the sources used for VARSKIN calculations (Kocher 1981).

Source	Average β Energy (keV)
^{14}C	50
^{147}Pm	62
^{99}Tc	85
^{36}Cl	251
^{210}Bi	389
$^{90}\text{Sr} + ^{90}\text{Y}$	565

PTB sources and ^{238}U slab

Spectral data for the PTB sources were taken from literature reference (NBS 1988) as was the spectra for the ^{238}U slab source (Martz et al. 1986). To determine the average β energy for each source, the spectra were divided into discrete energy bands and evaluated by use of Equation 7. The results for the computations are listed in Table 14.

Figure 11, Figure 12, and Figure 13 show the spectra for each source. The vertical lines indicate the integral boundaries for the successive energy bands used for calculating the average β energies.

$$E_{avg} = \sum_{i=1}^m \left[\frac{E_i + E_{i+1}}{2} \right] \left[\frac{(E_{i+1} - E_i) \left(\frac{C_i + C_{i+1}}{2} \right)}{\sum_{n=1}^m (E_{n+1} - E_n) \left(\frac{C_n + C_{n+1}}{2} \right)} \right] \quad \text{Equation 7}$$

Where:

E_{avg} = Average energy of β spectrum.

E_i = Boundary for energy band.

C_i = Number of counts at the energy band boundary E_i .

m = Total number of energy bands.

Table 14 Average β energies for spectra shown in Figure 11, Figure 12, and Figure 13 calculated by the use of Equation 7.

Source	Average β Energy (keV)
^{147}Pm , 20 cm	60
^{204}Tl , 30 cm	240
^{90}Sr , 30 cm	700
^{90}Sr , 50 cm	665
^{238}U Slab	600

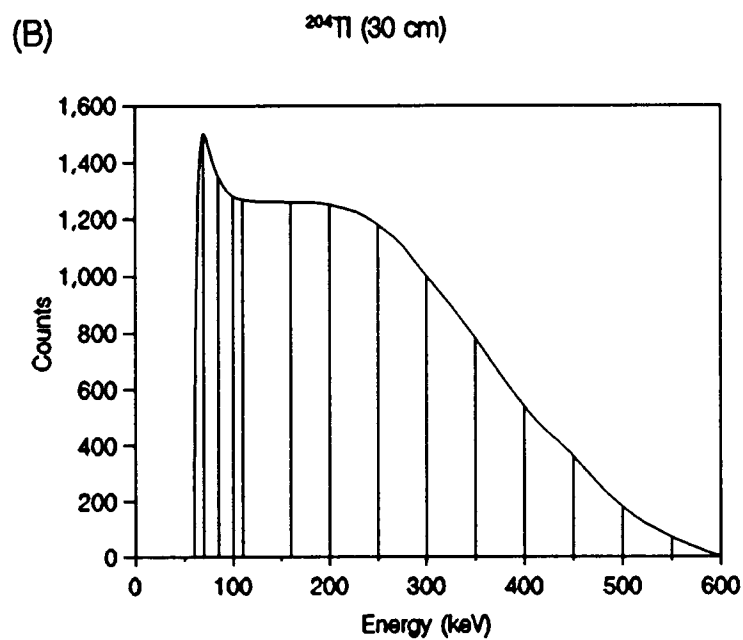
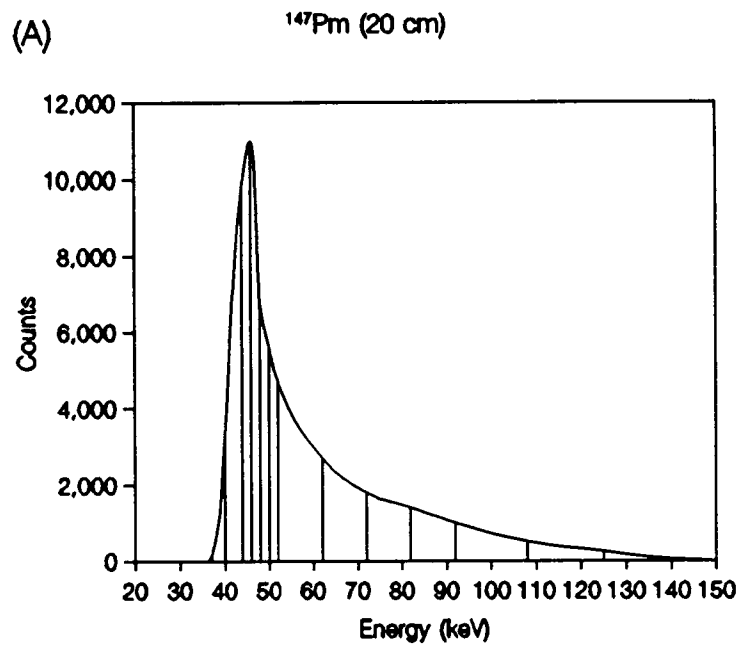


Figure 11 PTB source spectra: (A) ^{147}Pm at 20 cm (B) ^{204}Tl at 30 cm (NBS 1988).

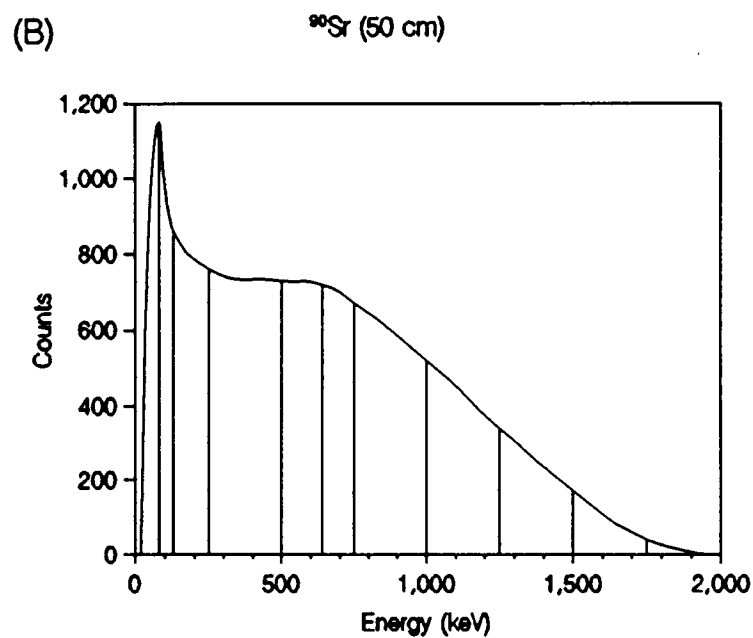
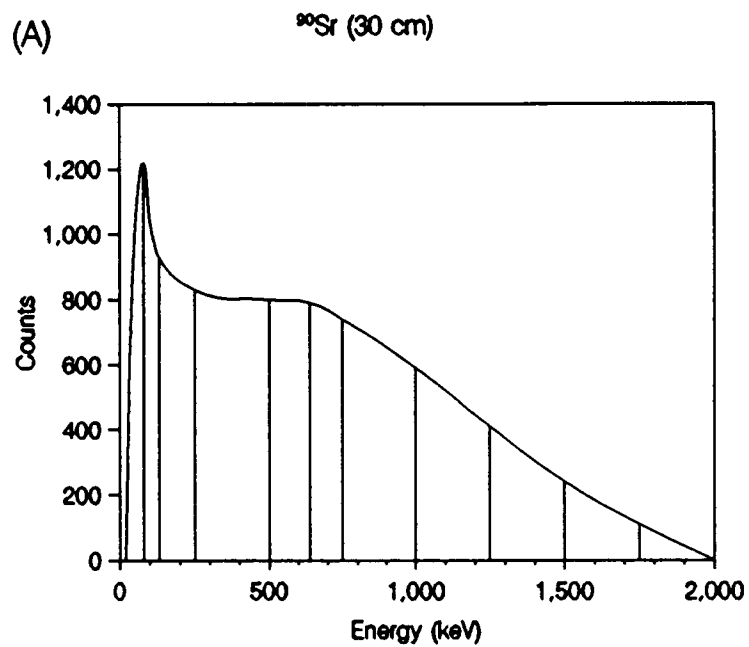


Figure 12 PTB source spectra: (A) ^{90}Sr at 30 cm (B) ^{90}Sr at 50 cm (NBS 1988).

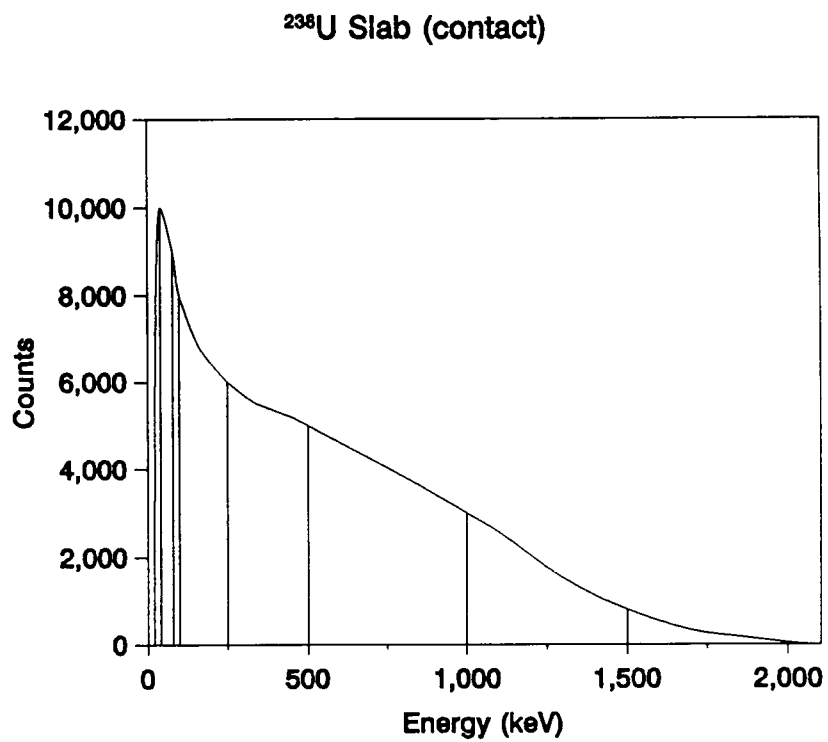


Figure 13 Beta spectra for a ^{238}U slab source (Martz et al 1986).

IV. ANALYSIS and RESULTS

SCREEN MEASUREMENTS

The dose rate response of the pancake probe was analyzed as a function of average β energy with the 16 mesh stainless steel screen over the probe entrance window. The initial evaluation was performed by calculating the count rate per unit dose rate with a 1.27 cm diameter section of the probe being irradiated. Table 15 gives a summary of the data used along with the calculated dose rate response values (cpm mGy⁻¹ h⁻¹) for each source. Figure 14 shows the dose rate response plotted as a function of average β energy.

The response data points were then multiplied by the ratio of the actual entrance window area of the probe (15.5 cm²) to that of the 1.27 cm² irradiation area as shown in Equation 8. This transformation was performed to approximate the pancake dose response function during irradiation of the full entrance window of the probe.

$$R = R_o \left(\frac{15.5 \text{ cm}^2}{1.27 \text{ cm}^2} \right) \quad \text{Equation 8}$$

Where:

R = Expected response of the pancake probe (cpm mGy⁻¹ h⁻¹) if it were irradiated uniformly across the entire entrance window with a β fluence equal to that which generated the response R_o .

R_o = Response of the pancake probe (cpm mGy⁻¹ h⁻¹) when irradiated through a 1.27 cm diameter aperture.

The results from these transformations are listed in Table 15. Figure 15 shows the transformed response data plotted as a function of average β energy.

FILTERED MEASUREMENTS

The count rate data taken with plastic filters over the probe entrance window was analyzed by multivariate regression analysis. The purpose of this analysis was to derive a mathematical relationship between the count rates in each of the bracketed energy bands to the skin dose rate.

The filtered, net count rate data was first broken into three adjacent bands as follows:

$$\text{Band 1} = \text{cpm}_{6.5} - \text{cpm}_{13.5}$$

$$\text{Band 2} = \text{cpm}_{13.5} - \text{cpm}_{44.3}$$

$$\text{Band 3} = \text{cpm}_{44.3}$$

Where:

$$\text{cpm}_{6.5} = \text{Count rate measured with the } 6.5 \text{ mg cm}^{-2} \text{ filter.}$$

$$\text{cpm}_{13.5} = \text{Count rate measured with the } 13.5 \text{ mg cm}^{-2} \text{ filter.}$$

$$\text{cpm}_{44.3} = \text{Count rate measured with the } 44.3 \text{ mg cm}^{-2} \text{ filter.}$$

The results from these calculations are presented in Table 16. The count rate in band 1 was expected to be due to β particles with incident energies between 60 and

Table 15 Summary of data used for evaluating the dose response function of the pancake probe with a 16 mesh stainless steel screen.

Source	Dose Rate (mGy h ⁻¹)	Average β Energy (keV)	Net Count Rate* (cpm)	$\frac{\text{cpm}}{\text{mGy h}^{-1}}$ (1.27 cm ²)	$\frac{\text{cpm}}{\text{mGy h}^{-1}}$ (15.5 cm ²)
PTB Sources					
⁹⁰ Sr 30 cm	6.41	700	304353	47,481	579,491
⁹⁰ Sr 50 cm	3.84	665	186652	48,607	593,234
²⁰⁴ Tl	0.30	240	5907	19,690	240,311
¹⁴⁷ Pm	0.05	60	1080	21,600	263,622
VARSKIN Sources and ²³⁸U slab					
¹⁴ C	0.64	50	15488	24,200	295,354
¹⁴⁷ Pm	0.12	62	2428	20,233	246,938
⁹⁹ Tc	0.23	85	3989	17,343	211,666
³⁶ Cl	0.51	251	8205	16,088	196,349
²¹⁰ Pb	0.39	389	7769	19,921	243,130
⁹⁰ SrY	1.04	565	19492	18,742	228,740
²³⁸ U slab	2.30	600	57200	24,870	303,531

* The net count rates are for irradiation of a 1.27 cm² area of the pancake probe.

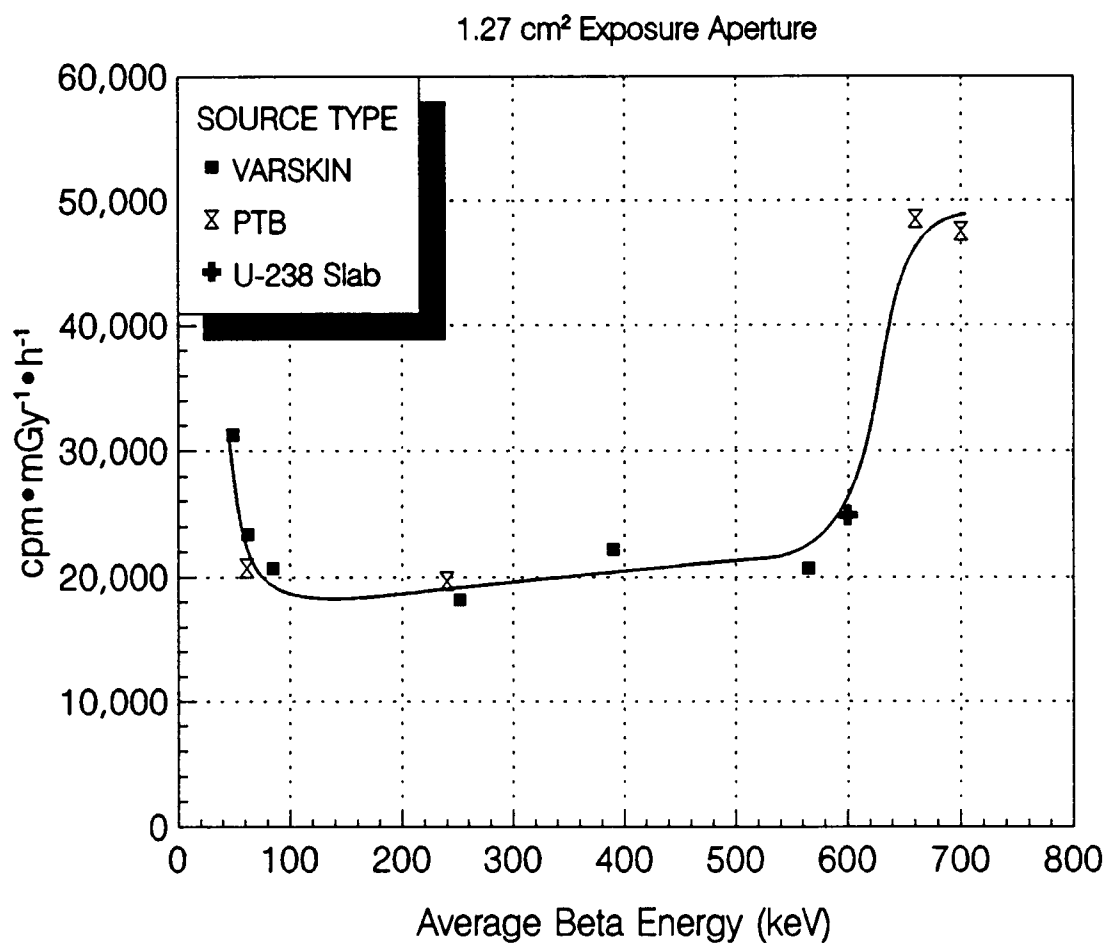


Figure 14 Dose rate response of pancake probe as a function of average β energy while irradiated through a 1.27 cm² aperture.

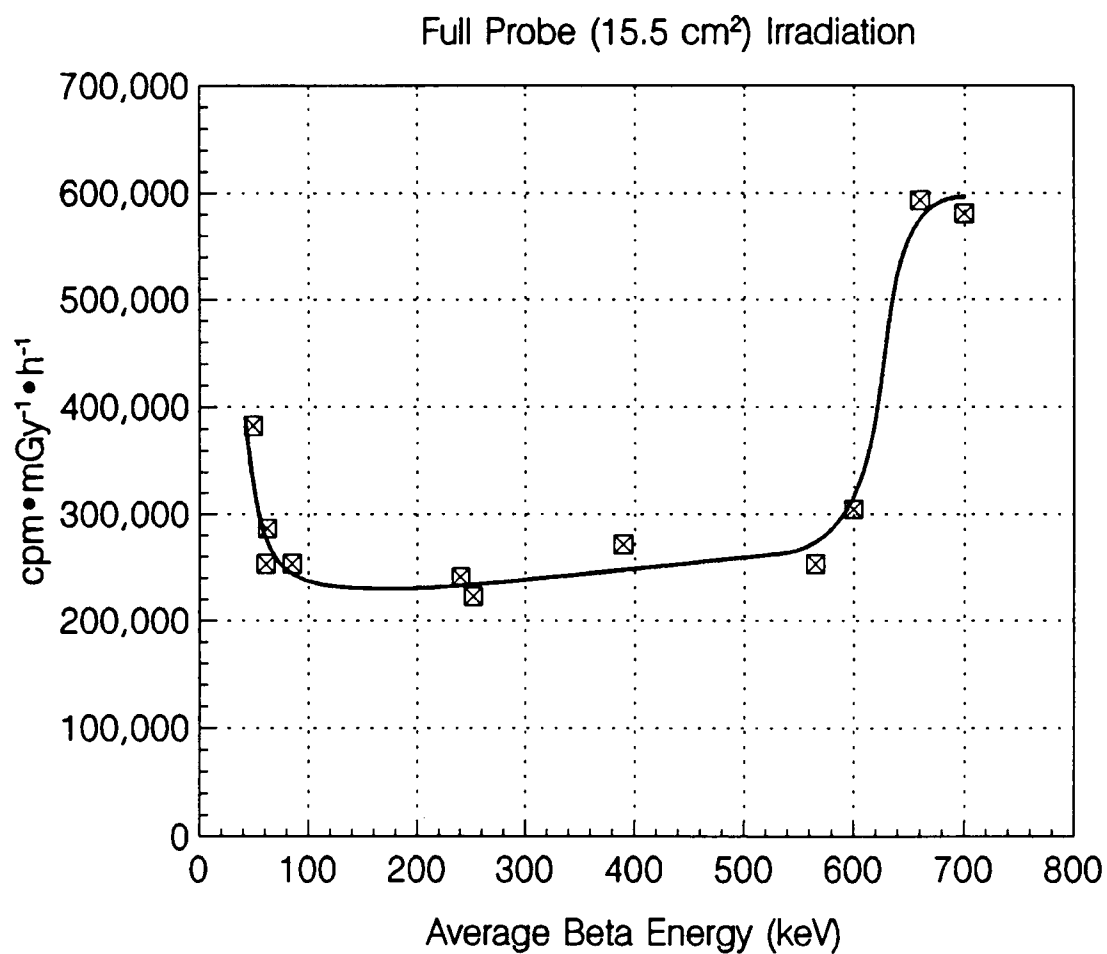


Figure 15 Dose rate response of pancake probe as a function of average β energy assuming full irradiation of the entrance window with a 16 mesh stainless steel protective screen.

Table 16 Separation of filtered measurements into count rate bands.

Source	Dose Rate (mGy h ⁻¹)	Net Corrected Count Rate (cpm)			Count Rate (cpm)		
		6.5 mg cm ⁻²	13.5 mg cm ⁻²	44.3 mg cm ⁻²	Band 1	Band 2	Band 3
PTB Sources							
⁹⁰ Sr, 30 cm	6.41	202318	201295	200835	1,023	460	200,835
⁹⁰ Sr, 50 cm	3.84	132735	132409	129534	326	2,875	129,534
²⁰⁴ Tl	0.30	6689	5741	3305	948	2,436	3,305
¹⁴⁷ Pm	0.05	380	112	29	268	83	29
VARSKIN Sources and ²³⁸ U Slab							
¹⁴ C	0.49	2172	169	0	2,003	169	0
¹⁴⁷ Pm	0.10	826	228	0	598	228	0
⁹⁹ Tc	0.19	2208	1129	52	1,079	1,077	52
³⁶ Cl	0.45	7118	5809	3543	1,309	2,266	3,543
²¹⁰ Pb	0.35	6920	5791	3885	1,129	1,906	3,885
⁹⁰ SrY	0.94	14785	12591	9443	2,194	3,148	9,443
²³⁸ U Slab	2.30	56460	55046	49054	1,414	5,992	49,054

150 keV. The count rate in band 2 was expected to be due to β particles with incident energies between 150 and 300 keV and the count rate in band 3 was expected to be due to β particles with incident energies greater than 300 keV. The PTB ^{90}Sr sources showed unexpected results when broken into the successive bands. The count rates in the first and second bands were extremely low relative to the count rate in the third band and did not accurately reflect the true spectral distribution for the sources. The data for these sources were measured on three separate occasions and the same results were obtained each time. The cause of the discrepancies could not be determined.

The computer software package Statgraphics^{®†} was used to perform a multivariate regression of the dose rate versus the three count rate bands. The input model parameters were set as follows:

- The resultant dose rate was assumed to be linearly dependant on each of the count rate bands.
- The regression was weighted by the inverse of the dose rates to prevent the larger values from dominating the results. Although it is common practice to weight regressions by the inverse of sample variances to prevent large numbers from dominating results, the variance was not known for the point estimates being used in this study and therefore could not be used.

[†] Statgraphics is a registered trademark of Statistical Graphics Corporation, Rockville MD.

- The regression model was set to have a dependant variable constant equal to zero since a zero net count rate would be expected to yield a zero dose rate.

The model was tested with many different input parameters, but these gave the best overall results without compromising the model integrity. A summary of the output from the regression model is presented in Table 17. Figure 16 shows the observed dose rate values plotted against dose rates fitted from the regression results.

The test statistics showed that each of the independent variables, i.e. the count rate bands, accounted for over 98% of the variability in the model. The computed f value for each variable was compared to a $f_{0.05}[1,7]$ value of 5.6 (Walpole et al 1989). The computed f values for the independent variables ranged from 61 to 440 which was significantly higher than the minimum expected $f_{0.05}[1,7]$ value of 5.6 indicating a strong dependence of the model on each independent variable. The standardized residuals were averaged and tested for outliers. No outliers were observed beyond 3σ . It was concluded that the regression model represented a good fit between the count rate bands and the measured dose rates and that no single data point was causing excessive weighting on the resulting parameters. Equation 9 shows the results of the regression fit in explicit mathematical form.

Table 17 Summary of Statgraphics™ results for regression analysis of filtered pancake measurements.

Model statistics

R^2 = 0.99
F-Ratio = 243

Independent variables statistics

Variable	Coefficient (mGy h ⁻¹ cpm ⁻¹)	Sum of Squares	F-Ratio
Band 1	2.6×10^{-4}	5.3	227
Band 2	2.0×10^{-5}	1.3	61
Band 3	3.0×10^{-5}	9.5	440

Regression data points

Observed Value (mGy h ⁻¹)	Fitted Value (mGy h ⁻¹)	Residual (mGy h ⁻¹)	% Error	Standardized Residual
0.64	0.51	-0.13	-20	1.12
0.05	0.07	0.02	40	-0.58
0.12	0.15	0.03	25	-0.69
0.23	0.30	0.07	30	-0.93
0.31	0.38	0.07	23	-0.95
0.51	0.48	-0.03	-6	0.26
0.39	0.44	0.05	13	-0.55
1.04	0.90	-0.14	-13	0.92
2.30	1.97	-0.33	-14	1.49
3.84	4.08	0.24	6	0.08
6.41	6.38	-0.03	-0	-0.84

Dose Rate Regression

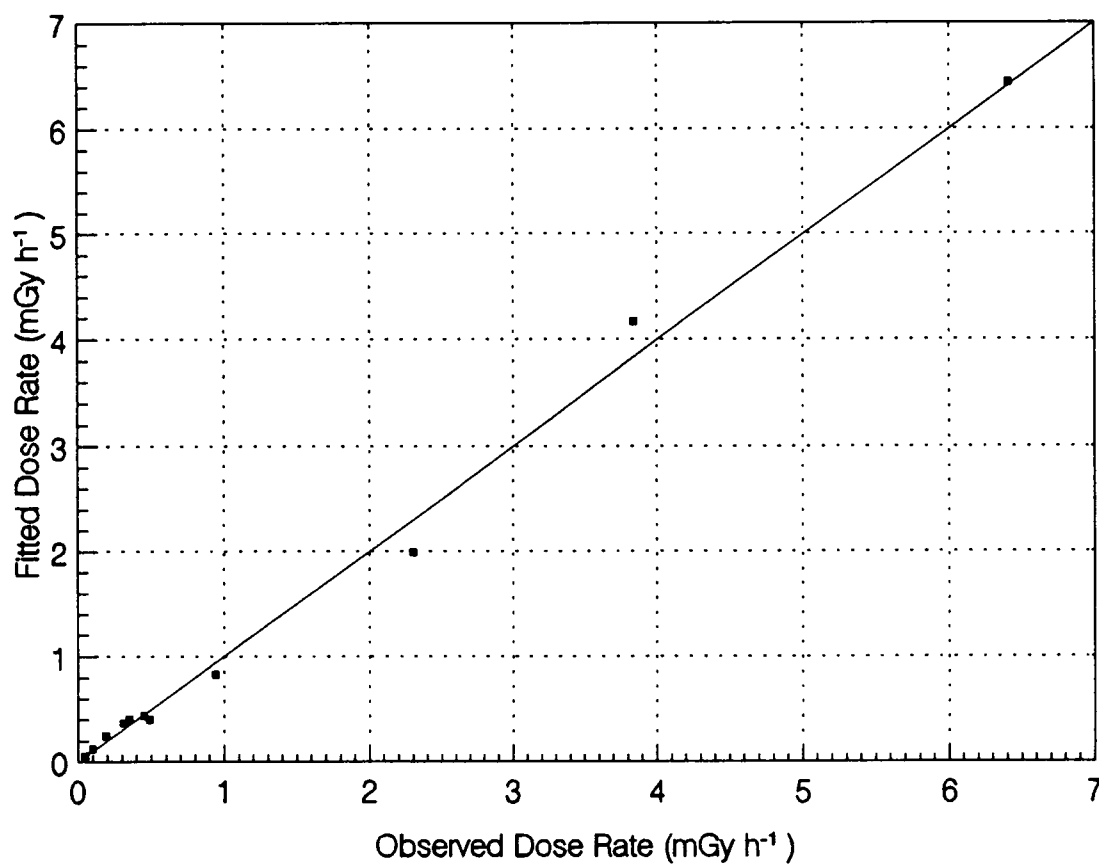


Figure 16 Graphical representation of the dose rate fit obtained by multivariate analysis of the filtered pancake measurements.

$$D = 2.6 \times 10^{-4} B_1 + 2.0 \times 10^{-5} B_2 + 3.0 \times 10^{-5} B_3 \quad \text{Equation 9}$$

Where:

B_1 , B_2 , and B_3 are the count rates (cpm) in band 1, band 2, and band 3 respectively and D is the resulting dose rate (mGy h^{-1}).

V. CONCLUSIONS and RECOMMENDATIONS

1. Pancake measurements with stainless steel protective screen

The resulting dose rate response curve in Figure 15 should be valuable for estimating β dose rate conversion factors during field survey operations with pancake probes using a 16 mesh stainless steel protective screen. When β field characteristics are unknown, the use of a single conversion factor should be chosen such that the resulting dose rate is sure to be conservative. A conversion factor of $2.4 \times 10^5 \text{ cpm} \cdot \text{mGy}^{-1} \cdot \text{h}^{-1}$ ($2400 \text{ cpm} \cdot \text{mrad}^{-1} \cdot \text{h}^{-1}$) will usually yield a dose rate estimate equal to or higher than the true dose rate when the full entrance window of the probe is being irradiated. The use of this conversion factor will usually yield results that are within 20% of the true dose rate, however dose rate overestimates of up to 100% are expected for very low energy β spectra and overestimates of up to 300% are expected for very high energy β spectra. It is important that count rates be corrected for both dead time losses inherent to the detection system and for background counts from high photon radiation fields. The dead time constant needs to be measured for each type of detection system employed since it will vary depending on how the scaler or ratemeter is configured. Dead time correction will only be important for count rates greater than approximately 20,000 cpm. Background data can be taken by making a measurement with a 1 cm thick (1 g cm^{-2}) piece of lucite or other suitable plastic placed over the probe.

The shape of the dose response curve has an unexpected sharp rise as the average β energy increases past ~500 keV. A calculational model could be designed to compute a theoretical dose response function of the probe to test this phenomena. Such a model would have to consider the transport and energy deposition of electrons through both tissue and the probe detection volume. The mere complexity of such a model lends itself to only being carried out by Monte Carlo simulation. The model would indeed require advanced software code with a large library of electron transport and energy deposition parameters.

2. Filtered pancake measurements

A good empirical fit between the filtered pancake measurements and the β dose rate to the 70 μm layer of the skin was established. A valid dose rate evaluation technique would be to make one measurement at the point of interest with each of three plastic filters in place through a 1.27 cm (0.5 in) diameter aperture plus one background measurement with a 1 cm thick plastic shield over the probe. The aperture assembly would need to be designed similar to the one used during this study (Figure 10) and the plastic filters would need to have density thicknesses of:

- 1) 6.5 mg cm^{-2}
- 2) 13.5 mg cm^{-2}
- 3) 44.3 mg cm^{-2}

All count rates would have to be corrected for dead time losses inherent to the detection system being used and the background count rate would have to be subtracted from each. The dead time constant would have to be measured for each type of detection system since it would vary depending on how the scaler or ratemeter was configured. The measured count rates would then need to be broken into bands as follows:

$$B_1 = \text{cpm}_{6.5} - \text{cpm}_{13.5}$$

$$B_2 = \text{cpm}_{13.5} - \text{cpm}_{44.3}$$

$$B_3 = \text{cpm}_{44.3}$$

Where:

$$\text{cpm}_{6.5} = \text{Count rate measured with the } 6.5 \text{ mg cm}^{-2} \text{ filter.}$$

$$\text{cpm}_{13.5} = \text{Count rate measured with the } 13.5 \text{ mg cm}^{-2} \text{ filter.}$$

$$\text{cpm}_{44.3} = \text{Count rate measured with the } 44.3 \text{ mg cm}^{-2} \text{ filter.}$$

The β dose rate would then be calculated by use of Equation 9 by substituting B_1 through B_3 as the unknown parameters. Dose rates measured by this method should be within approximately 40% of the true dose rate based on the data points used in this study.

These results could be tested by making measurements on other β sources that were not used as part of this study to allow independent comparison of the derived mathematical fit. The number of filters used or the thicknesses of the filters could also possibly be adjusted to achieve better results, however the number of filters would have to be limited to a practical level for field use.

LIST OF REFERENCES

REFERENCES

- American National Standards Institute (ANSI) *American National Standard Radiation Protection Instrumentation Test and Calibration. ANSI N323; 1978*
- Heinzelmann, M.; Keller, M. *An Energy-Independent Dose Rate Meter for Beta and Gamma Radiation. Radiation Protection Dosimetry 14, No 2: 179-182; 1986*
- Herbaut, Y.; Oliveira, Heeren de; Vivian, R.; Delahaie, M.; Leroux, J.B. *Response of Different Survey Instruments in Beta Radiation Fields. Radiation Protection Dosimetry 14, No 2: 199-203; 1986*
- International Commission on Radiological Protection. *Recommendations of the ICRP. Publication 26. Pergamon Press; 1977*
- International Commission on Radiological Protection. *1990 Recommendations of the ICRP. Publication 60. Pergamon Press; 1990*
- Knoll, Glenn F. *Radiation Detection and Measurement. John Wiley and Sons; 1979*
- Kocher, David C. *Radioactive Decay Data Tables DOE/TIC-11026, National Technical Information Service; 1981*
- Loevinger, Robert *Extrapolation Chamber for the Measurement of Beta Sources. The Review of Scientific Instruments, Vol. 24, No 10: 907-914; 1953*
- Martz, D.E.; Rich, B.L.; Johnson, L.O. *A Portable Beta Spectrometer for Tissue Dose Measurement. Radiation Protection Dosimetry 14, No 2: 183-186; 1986*
- Martz, D.E.; Rich, B.L.; Johnson, L.O. *Measuring the Skin Dose Protection Afforded by Protective Apparel with a Beta Spectrometer. Radiation Protection Management: 61-70; Oct 1986*
- Martz, D.E.; Johnson, L.O.; Rich, B.L.; Daniel, S.H. *Field Tests of a Tissue-Equivalent Beta Survey Meter. Radiation Protection Dosimetry 14, No 2: 117-121; 1986*
- Martz, D.E.; Rich, B.L.; Darois, E.L.; McWilliams, F.F.; Sannel, M.J.; Turner, J.E. *Experimental Verification of a Theoretical Algorithm for Converting β Spectral Measurements to Skin-dose Equivalent. Health Physics 52, Suppl. 1:S34; 1987*
- National Bureau of Standards. *Calibration of Beta-Particle Radiation Instrumentation and Sources Publication 250-21; 1988*

Reaves, Kevin L., Oak Ridge National Laboratory, *Personal communication to Robert L. Coleman*, Oak Ridge National Laboratory. 1992

The Chemical Rubber Company (CRC) *Handbook of Chemistry and Physics*. 52nd Edition; 1972

Traub, R.J.; Reece, W.D.; Scherpelz, R.I.; Sigalla, L.A. *Dose Calculation for Contamination of the Skin Using the Computer Code VARSKIN*. NUREG/CR-4418; Pacific Northwest Laboratory publication 5610; 1987. Source code and IBM PC compatible executable code are available at the Radiation Shielding Information Center, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge TN 37831.

Turner, J.E.; Hamm, R.N.; Souleyrette, M.L.; Martz, D.E. *Calculations for β Dosimetry Using Monte Carlo Code (OREC) for Electron Transport in Water*. Health Physics 55, No 5: 741-750; 1988

Turner, James E. *Atoms, Radiation, and Radiation Protection*. Pergamon Press Inc.; 1986

Walpole, Ronald E.; Myers, Raymond H. *Probability and Statistics for Engineers and Scientists*. Macmillian Publishing Co.; 1989

APPENDICES

APPENDIX I

Pancake Detector Systems Calibration Procedure

Feb, 23 1993

R.L. Coleman
Measurement Applications & Development Group
Oak Ridge National Laboratory

1. PURPOSE

The purpose of this procedure is to provide a method for the laboratory calibration of portable pancake detector systems.

2. ABBREVIATIONS

cpm counts per minute
dpm disintegrations per minute
ES&H Environmental and Health Compliance Division, ORNL
MAD Measurement Applications & Development Group, ORNL

3. RESPONSIBILITIES

The health physics instrument technologist is responsible for the implementation of this procedure and for all records generated by the enactment of this procedure.

4. EQUIPMENT & SUPPLIES

Bicron Analyst scaler/ratemeter or equivalent
Eberline HP-260/210 pancake detector or equivalent

5. RADIATION SOURCES

All calibration sources are to be NIST/NBS traceable.

- Calibration Sources

Required: ^{14}C , ^{99}Tc , ^{36}Cl , ^{90}Sr
Optional: ^{147}Pm , ^{210}Pb

- Check Sources

Any sealed β emitting isotope with a half live ≥ 20 years.

6. STANDARDS & REFERENCES

1. ANSI 323-1978, Radiation Protection Instrumentation Test & Calibration
2. Ludlum 2221 users manual

7. CALIBRATION FREQUENCY

Primary calibration will be performed at least annually and immediately following any repair or modification to the instrument which may have voided the calibration validity.

8. CALIBRATION PROCEDURE

8.1 SCALER / RATEMETER

The scaler/ratemeter is tested and adjusted in accordance with ANSI N323-1978 by ORNL Instrumentation and Controls Division laboratory technicians or an equivalently approved organization. The testing procedure insures that all functions and settings are correct and in tolerance.

8.2 PANCAKE DETECTOR

The radiation calibration of the pancake detector may be performed by either MAD personnel or ORNL ES&H health physics calibration personnel or an equivalently approved organization.

8.2.1 EXTERNAL ORGANIZATION

If the calibration is performed by ES&H or another external organization, the calibration procedures and quality assurance responsibilities will be handled by that organization. The resulting calibration values will be reported to the MAD instrument technologist and properly recorded in pertinent records. It will be the MAD instrument technologist's responsibility to ensure that the calibration date, calibration technician or organization, and calibration due date are properly labeled on the instrument. It will also be the responsibility of the MAD instrument technologist to review the organizations calibration procedures to ensure continuity with MAD calibration requirements as outlined in section 8.2.2.

8.2.2 MAD PERSONNEL

GENERAL

- The response of all pancake detectors must be within 10% of the following isotope efficiency values at contact with the source:

^{14}C	6.5%
^{99}Tc	12.0%
^{36}Cl	37.0%
^{90}Sr	88.0%

- Record all results on Form #1, "Pancake Calibration Form".

- Record the instrument number.
- Adjust the high voltage on the scaler/ratemeter to 900V.
- Record the meter data for the scaler/ratemeter being used during the calibration.
- Record the source #, nuclide, and current activity (dpm) for each of the required calibration isotopes: ^{14}C , ^{99}Tc , ^{36}Cl , and ^{90}Sr .
- Take a one minute background count and record the result.
- Place the ^{14}C calibration source at contact with the pancake screen cover and take a one minute scaler count. Record the result and repeat for the remaining isotopes.
- Calculate the corrected count rate (dead time correction) for each isotope with a count rate $\geq 20,000$ cpm by use of the following formula and record:

$$c = \frac{c_o}{1 - (1.7 \times 10^{-6} c_o)}$$

Where: c_o = measured count rate

- Calculate the parent nuclide efficiency for each isotope by use of the following formula and record:

$$Eff = \frac{c}{d}$$

Where: c = corrected count rate (cpm)
 d = activity of parent nuclide (dpm)

- Ensure that the average beta efficiency values fall within 10% of the isotope efficiencies listed in section 8.2.2-General.
- Perform a one minute count with the chosen beta check source and record the result under "Instrument Source Check Data" along with the source reference number.

12. Calculate the minimum and maximum acceptable source response for future source check by use of the following formulae and record:

$$Min = R(1 - m/100)$$

$$Max = R(1 + m/100)$$

Where:

Min	=	minimum acceptable response for future operational response checks
Max	=	maximum acceptable response for future operational response checks
m	=	Min/Max acceptance range percent (%)

13. Record your initials, the calibration date, the calibration due date, the check source number, and the minimum and maximum acceptable response values for the source on the pancake instrument.
14. File the calibration results and update all pertinent calibration records for the instrument.

APPENDIX II

Pancake Calibration

Date 03/10/92

Instrument # THESIS SYSTEM

Meter Data. Calibration Date 02/11/92
 Calibrated by I&C, ORNL
 Voltage 900 Volts
 Notes INPUT SENSITIVITY ADJUSTED TO 50 mV

Voltage	BKG (cpm)	SOURCE (cpm)

Average Beta Efficiency Values

Isotope	Contact
C-14	6.5%
Pm-147	12.0%
Tc-99	18.0%
Cl-36	37.0%
Pb-210	38.0%
Sr-90	88.0%

Calibration results must fall within
10% of these values.

Probe Dead Time..... 100 us
 Background 38 cpm

Source #	Nuclide	Activity (dpm)	Response (cpm)	Corrected Response (cpm)	Parent Nuclide Efficiency	
371-67-8	C-14	230655	15488	15898	6.9%	PASS
396-75-1	Cl-36	21911	8245	8360	38.0%	PASS
371-72-8	Sr-90	21369	18774	19380	90.5%	PASS
371-68-8	Tc-99	22289	3996	4023	17.9%	PASS
396-75-2	Pm-147	20628	2416	2426	11.6%	PASS
371-70-8	Pb-210	20269	7685	7785	38.2%	PASS

Source #	7503-2
Response	30123
Min/Max %	15%
Min	25605
Max	34641

< === Instrument Source Check Data

Notes: SYSTEM CALIBRATED WITH #16 MESH SS SCREEN IN PLACE

Cal Date 03/10/92 Due Date 03/10/93 Name... R.L. COLEMAN, 30476

VITA

Mr. Robert Lloyd Coleman was born in Dayton, Tennessee on March 30, 1966 to Mr. George H. Coleman and Mrs. Charlotte A. Coleman. He graduated from Rhea County high school in June of 1984 and entered into the A.S. radiation protection program at Chattanooga State Technical Community College the following September which he successfully completed. He transferred to the University of Tennessee at Chattanooga in the Fall of 1986 and graduated with a Bachelor of Science in Physics in December of 1988. During this time, he worked summers at Oak Ridge National Laboratory (ORNL) and after graduation became a full time employee. He entered the University of Tennessee, Knoxville in the Fall of 1989 as a part time student and received a Master of Science degree in Nuclear Engineering in August of 1993.

He is presently employed as a radiation protection specialist at Oak Ridge National Laboratory.