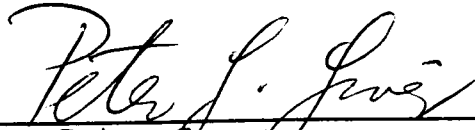


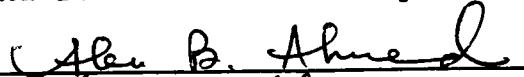
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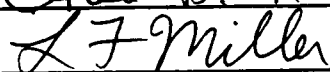
I am submitting herewith a thesis written by Kimberly Janet Nugent entitled "Evaluation of Thermoluminescent Dosimeters (TLDs) of Two Different Designs for Beta Particle and Low Energy Photon Dosimetry." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.



Dr. Peter Groer
Major Professor

We have read this thesis
and recommend its acceptance:





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EVALUATION OF THERMOLUMINESCENT DOSIMETERS (TLDs)
OF TWO DIFFERENT DESIGNS FOR BETA PARTICLE
AND LOW ENERGY PHOTON DOSIMETRY

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Kimberly Janet Nugent
December 1992

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ABSTRACT

The purpose of this research was to compare the response of the thermoluminescent dosimeters (TLDs) currently used at Martin Marietta Energy Systems with that of a newly designed TLD which is now under consideration. The new TLD consists of a thicker chip in element #3 and a thinner, more opaque mylar filter over this same element. The goals were to determine if the new (proposed) TLD would perform significantly different than the old (current) TLD when measuring dose equivalents from beta particles and low energy photons (x-rays) and to find out if changing from the old to the new design would require that modifications be made to the calibration factors currently used in the dose calculation algorithm. To accomplish these objectives, tests were performed using both types of dosimeters placed under identical conditions. Their responses were then compared and analyzed.

It was concluded that the new TLDs would allow for the detection of lower levels of radiation and give more precise readouts at very low (i.e., background) levels in addition to the obvious advantages of the new design, such as, a thicker, more durable chip and a more opaque mylar. It was also determined that no adjustments to the calibration factors would be necessary in switching to the new design.

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1. INTRODUCTION

1.1 BACKGROUND

The term thermoluminescence refers to light that is emitted when excitation, caused by ionizing radiation, is thermally removed from a material (Horowitz, 1984). Thermoluminescent dosimeters (often referred to as TLDs) are used to measure an individual's exposure to ionizing radiation. The individual wears the TLD on his clothing for an extended period of time, after which the TLDs are returned for processing. In a TLD reader, TL elements are heated while positioned under a photomultiplier tube. This heating releases any energy stored in the element traps and results in thermoluminescence. The amount of light emitted is proportional in intensity to the amount of radiation exposure received by the elements (Horowitz, 1984). Only certain materials, known as thermoluminescent (TL) materials, will respond in this manner. One of the most commonly used TL materials is lithium fluoride (LiF) and it is also the TL material that will be used in the experiments discussed throughout this report. The light that is emitted from the TL material is converted into electrical current through the use of the photomultiplier tube. Measuring this current, or its integral over time, indicates the amount of radiation exposure

that was received by the material. The fact that LiF is nearly tissue-equivalent and possesses the property of thermoluminescence, makes it suitable for use in external dosimetry. This procedure is known as thermoluminescent dosimetry.

The external dosimetry program at Martin Marietta Energy Systems, Inc. (Energy Systems) uses thermoluminescent dosimeters (TLDs) to monitor radiation exposure to personnel. Since Energy Systems manages research, development, and production facilities that include the use of radioactive materials and radiation generating equipment, there is a potential for exposure to ionizing radiation in the workplace. While only the radiation workers are likely to receive a detectable dose, all employees are monitored to ensure that they are not subjected to excess occupational health risk and to verify that Energy Systems is in compliance with Department of Energy requirements (Chapman, 1991). Each employee is assigned his or her own TLD and is required to wear it, along with an employee identification badge, during working hours. At the end of each calendar quarter, or upon termination, the dosimeters are turned in to the Centralized External Dosimetry System (CEDS) Distribution Center in exchange for another dosimeter. The dosimeters are then sent to one of two CEDS Processing Centers where they are read, the results evaluated, and the dosimeters are prepared to be used again.

The dosimeters measure beta-gamma exposure and consist of four small LiF chips encased in a plastic holder, with each chip shielded by its own unique attenuator. Each attenuator discriminates against certain types of radiation and allows the dose algorithm to determine which types of radiation exposure were received by the dosimeter and, therefore, by the person wearing the dosimeter. Also, the magnitude of radiation dose received by the dosimeter is measured and provides an approximation of the dose received by the dosimeter wearer.

1.2 STATEMENT OF PROBLEM

The primary purpose of this project is to evaluate the responses of LiF chips of two different thicknesses to beta particles and low energy photons (x-rays). The TLDs used at Energy Systems for personnel dosimetry consist of 4 LiF chips that are referred to as elements 1, 2, 3, and 4. Element #3 in the current dosimeter is a 3.6 mil (24 mg/cm²) LiF chip that is shielded by a light-transparent mylar foil placed over the opening in the dosimeter holder. Several problems associated with element #3 include: (1) a low signal-to-noise ratio because of the very small amount of TL material; (2) occasional cracking of the chip after repeated use; and (3) light entering through the light-transparent mylar foil (which could cause a false positive reading).

In response to these problems, a new TLD design is being considered. This new design would consist of a thicker, 6.0 mil (40 mg/cm^2), chip in element #3 and a new mylar with a black-colored backing to prevent light from passing through the foil. It has been discovered, however, that this new mylar is also thinner (5.1 mg/cm^2) than the old, which is 7.5 mg/cm^2 (Sonder, 1991 [2]). The scope of this project is to determine whether or not the response of the modified dosimeter is significantly different from the current dosimeter when measuring beta particles and low energy photons. This project will also determine whether the current dose algorithm needs to be changed for the new dosimeter and will discuss the relative performances of both types of dosimeters. Specifically, the dosimeters will be evaluated for the differences in (1) raw response, (2) calculated dose-equivalent, (3) accuracy and precision, (4) background signal accumulation, and (5) lower limit of detection, L_D , values.

2. DESCRIPTION OF EQUIPMENT AND RADIATION SOURCES

2.1 EQUIPMENT

2.1.1 Thermoluminescent Dosimeter (TLD)

Thermoluminescent dosimeters used at Energy Systems to measure beta-gamma exposure to personnel are manufactured by Harshaw Crystals and Electronic Products of Solon Technologies, Inc. The dosimeters are referred to as Harshaw Model 8805 Beta-Gamma Dosimeters.

The dosimeter consists of two major components: (1) the card containing the TL elements (chips) and (2) the card holder (see Figure 1). The card is made of an anodized aluminum substrate and contains four holes, one for each TL element. In each hole, a LiF (lithium flouride) chip is suspended between two thin sheets of teflon. The element card in the proposed design is identical to the one in the current TLD except for the thickness of chip #3. Chip #3 in the current design is 3.6 mil (24 mg/cm²) thick whereas, in the proposed design TLD, chip #3 is 6.0 mil (40 mg/cm²) thick.

The TLD holder is made of ABS (acrylonitrile butadiene styrene) plastic and consists of a front and back which snap

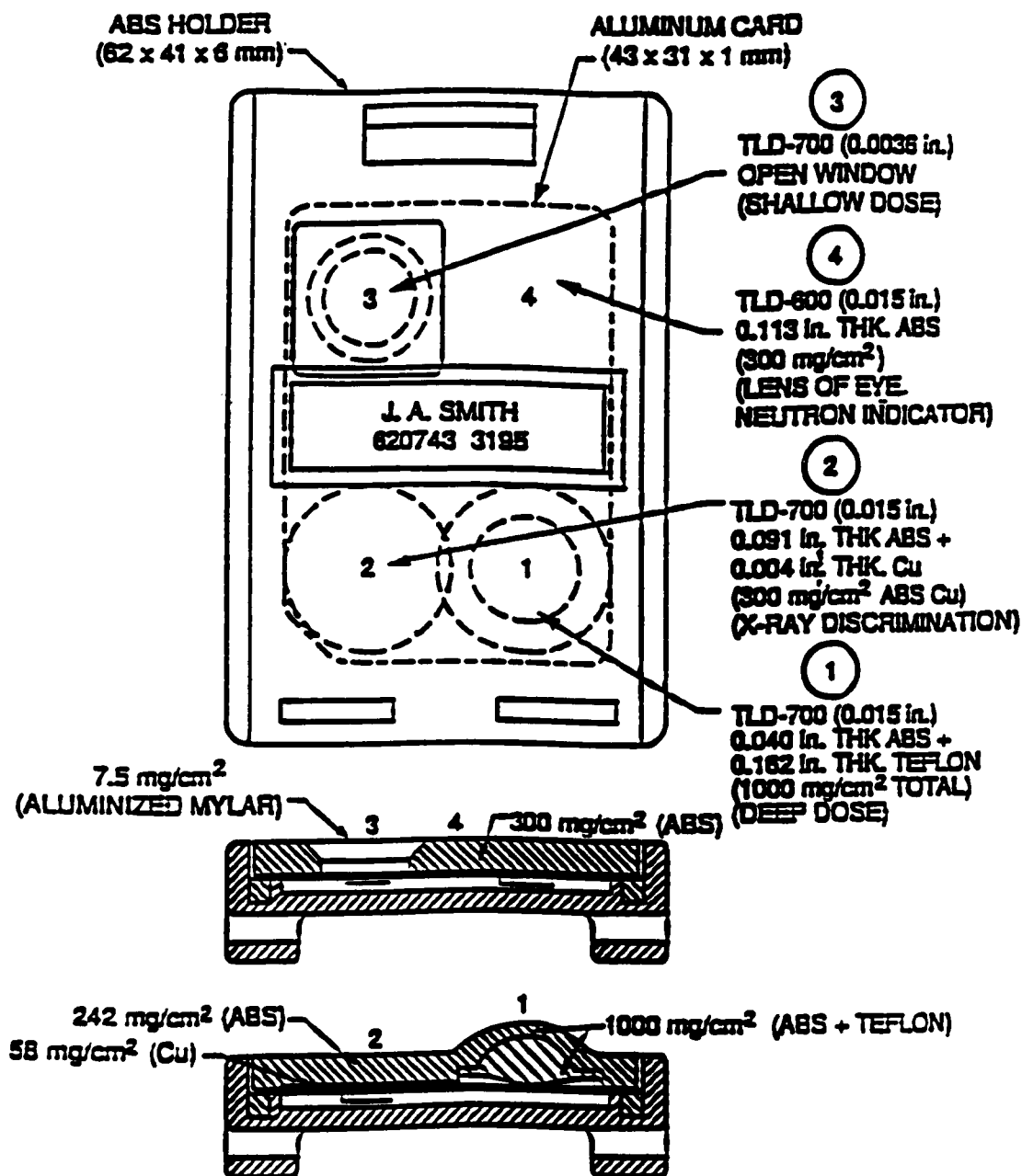


Figure 1. CEDS Beta/Gamma Dosimeter Assembly Configuration
 [Taken from "Technical Basis for the Centralized External Dosimetry System," p. 411 (MMES, 1991)]

together, holding the element card in place between them. The front part of the holder contains four different filters, each aligning with one of the four TL chips. The purpose of the filters is to modify the amount and type of radiation reaching each element in order to approximate the defined deep and shallow reporting depths and determine which types of radiation are present, if any. Element #1 is shielded by 1000 mg/cm² combined teflon and ABS plastic and measures deep dose equivalent. Element #2 is covered by 300 mg/cm² combined copper and ABS plastic and is used for low energy x-ray discrimination. Element #3 is aligned with an open window that is covered with 7.5 mg/cm² aluminized mylar. This element measures shallow dose equivalent. Element #4 is shielded by 300 mg/cm² ABS plastic and can be used to estimate the dose equivalent to the lens of the eye and to give indication of neutron exposure. The only difference between the holder to be used for the proposed TLD and the one that is currently in use is that the proposed TLD holder has a thinner (5.1 mg/cm²) and more opaque mylar. The information presented here, along with further details, on the Harshaw type 8805 dosimeter can be found in Harshaw Product Specification Sheets.

2.1.2 TLD Reader

The instrument used to read and anneal TLD cards at

Martin Marietta Energy Systems, Inc. is the Harshaw TLD System 8800 card reader. This reader is fully automatic and has the capacity to sequentially process up to 1400 TLD cards without reloading. TLD cards are removed from their holders and loaded into a carrousel containing eight magazine racks designed to hold the cards in sequential stacks. As the cards are processed, they are individually transferred to an identical carrousel for unloading.

The reader consists of four major components: (1) a heat supplying medium; (2) electronics to control the temperature and heat rate; (3) a set of four photomultiplier tubes to convert light into electrical charge (nC); and (4) a data acquisition system. The heat for the TL elements is supplied by a jet of hot nitrogen gas in an enclosed chamber (Chapman, 1991). This method of heating is used because it offers the following advantages over other heating methods (MMES, 1991):

- * fast and efficient
- * reduces incandescent light emission
- * reduces degradation to TL elements
- * provides accurate heating

Electronics are used to maintain the amount and rate at which heat is supplied to the TL elements. A set of four photomultiplier tubes (one for each TL element) is used to

convert light from the TL elements into electrical charge (nC) that is fed into a data acquisition system. This data acquisition system is connected to an IBM - compatible 80286 personal computer. The computer then generates a plot (for each TL element in each card) of the measured electrical current as a function of time and temperature. These plots, known as glow curves, appear on the computer monitor as they are generated and may also be printed. All of the output is stored into a database where it may be accessed later and run through a computer algorithm to determine the dose equivalents.

2.2 SOURCES

2.2.1 ^{204}Tl

One of the beta sources that was used in this project was ^{204}Tl ($E_{\text{MAX}} = 760 \text{ keV}$). This source was manufactured by Amersham Buchler in Germany. The source activity, as specified by the manufacturer, was 0.18 mCi at the time of purchase. A PTW (Pychlau Technical Works) extrapolation ionization chamber was used to calibrate the source at RASCAL (Radiation Standards and Calibration Laboratory) (Halliburton, 1991). The source had a point geometry and was positioned at a distance of 30 cm from the TLDs during exposure. See Figure 2 for an illustration of the set-up. The TLDs were placed on

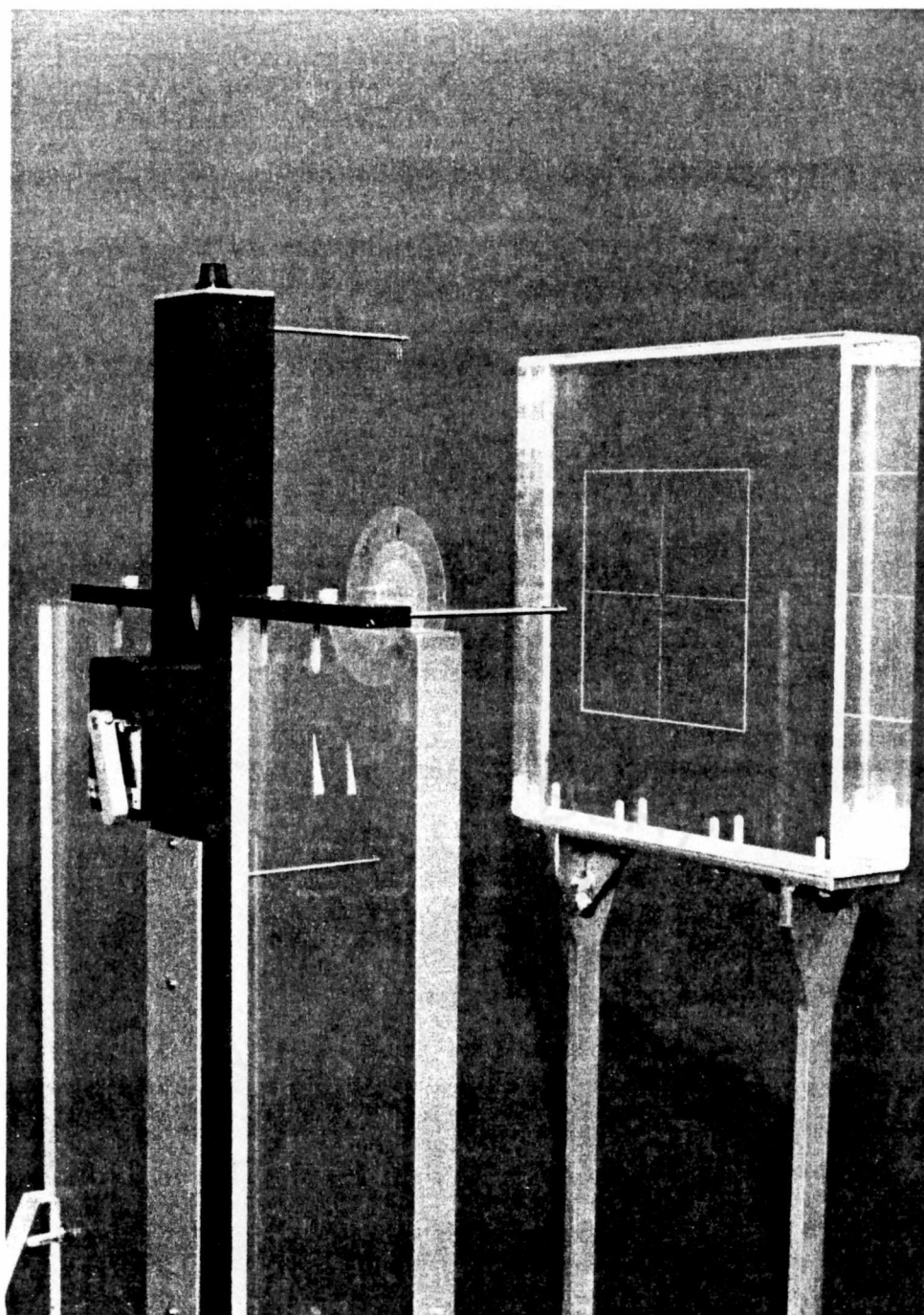


Figure 2. Equipment Set-up for ^{204}Tl Exposures

a tissue-equivalent phantom which holds up to 6 dosimeters at a time. The dimensions of the phantom are: length = 30.5 cm; width = 30.5 cm; depth = 6.5 cm. The area in which the TLDs are placed, known as the "useful area", is 15 cm. x 15 cm. Each TLD was exposed to 250 mrem of ^{204}Tl at a dose rate of 0.602 mrem/min for a total of 415 minutes each.

2.2.2 Depleted Uranium (DU)

Depleted Uranium ,or DU, ($E_{\text{MAX}} = 2300 \text{ keV}$) was the other beta source that was used in this project. The DU sources were manufactured by Eberline Corporation and had a slab geometry with dimensions as follow: length = 4"; width = 4"; thickness = 1/8". As with Thallium, a PTW extrapolation chamber was used to calibrate the Uranium sources at RASCAL (Halliburton, 1991). There was a total of five DU slabs used for irradiation of the TLDs, with each slab having a capacity to hold 2 TLDs at a time. The TLDs were laid directly onto the surface of the slabs, facing downward. In order to make the face of the TLDs parallel to the slab surface, a stick of balsa wood (with a 1/8" square cross section) was inserted between them. Each TLD was exposed to 250 mrem at a dose rate of 3.9 mrem/min for a total of 64 minutes each.

2.2.3 K17 X-ray

The x-ray irradiations used in this project were provided by Battelle Pacific Northwest Laboratories in Richland, Washington. A Phillips 323, continuous voltage, industrial type x-ray machine was used to produce the x-rays. K17 is a monoenergetic 17 keV K-fluorescent x-ray. In producing this x-ray, a secondary target made of molybdenum was used along with a Zirconium filter (which eliminated low-energy x-rays). The TLDs were exposed to 500 mrem of shallow dose equivalent K17 x-rays at a dose rate of 100 mrem/min. The distance from the source (at the secondary target) to the TLDs was 50 cm (BPNL, 1991).

2.2.4 M30 X-ray

The other type of x-ray that was used is referred to as the M30 x-ray. M30 is a bremsstrahlung x-ray with an average energy of 20 keV. A 0.5 mm thick aluminum filter was used to filter out the low energy x-rays, thus narrowing the source spectrum. The half-value layer (HVL) for M30 x-rays is 0.36 mm of aluminum with a homogeneity coefficient (ratio of the first HVL to the second HVL) of 0.64. The delivered dose equivalent of M30 x-rays was 500 mrem at a dose rate of 250 mrem/min. The distance from the source to the TLD's was 100 cm (BPNL, 1991).

3. EXPERIMENTAL PROCEDURES

3.1 CARD CALIBRATION

Although each TL element is designed to be identical to all other elements of the same type, slight variations in size, shape, density, and composition are inevitable. These variations (no matter how slight) must be compensated for in order to ensure that all TL elements, of the same type, respond consistently to different amounts of radiation. To make up for such variations in TL elements, Element Correction Coefficients (ECC's) are developed for each element in each TLD prior to their use. For this procedure, all of the TLD cards are irradiated by ^{137}Cs to a level of 500 mR*. The unit, mR*, is a generic unit used by Energy Systems to indicate the amount of gamma exposure received by the elements in the cards. This unit is essentially equivalent to mR, but must be used instead since mR is only defined for exposure in air. The amount of gamma exposure received by the chips is controlled using a predetermined exposure rate which is measured using an air-filled ionization chamber at the same distance as the elements are from the source. The cards are then read and the mean element response is determined for each of the four element positions. The response of each individual element is then divided by the mean response for

its element position (MMES, 1989). This gives the ECC values for the individual elements. An ECC value is then permanently assigned to each element in each card. Every time that element is read, its response is multiplied by its ECC to insure uniform response among all TL elements that share the same position in a TLD card. (The ECCs were developed prior to the tests performed in this report.)

3.2 READER CALIBRATION

As with the TL elements, it is also necessary to normalize the response of the TLD reader to ensure that it responds consistently. This is done by developing a Reader Calibration Factor (RCF) each day that cards are read. For this procedure, a set of cards is irradiated by ^{137}Cs to a level of 500 mR*. These cards are then read to determine the mean response (in nC). The RCF is determined as the mean response of each TL element (in nC), divided by the known exposure of 500 mR* (MMES, 1990 [2]). All readings performed by the reader are automatically divided by the daily RCF (for each corresponding element) and are therefore given in units of mR*. (The RCFs were developed prior to the tests performed in this report.)

3.3 IRRADIATION WITH ^{204}Tl

This part of the project was carried out in two separate, yet identical, groups. For each group, 36 dosimeter cards were annealed. Among these 36 cards, 18 contained a 3.6 mil chip in element #3 (referred to as thin chip cards) and the other 18 contained a 6 mil chip in element #3 (referred to as thick chip cards). These 36 cards were placed in TLD holders in the following configuration:

- 9 old (thin) chip, old mylar [type OC/OM]
- 9 old (thin) chip, new mylar [type OC/NM]
- 9 new (thick) chip, old mylar [type NC/OM]
- 9 new (thick) chip, new mylar [type NC/NM]

These dosimeters were then divided into 9 sets with each set consisting of 1 type OC/OM card, 1 type OC/NM card, 1 type NC/OM card, and 1 type NC/NM card, for a total of 4 cards per set. All 9 sets were sent to RASCAL (Radiation Standards and Calibration Laboratory) where 4 sets were exposed to 250 mrem of ^{204}Tl and the other 5 sets served as control (or background) sets. Dosimeters were placed on a tissue-equivalent phantom (one set at a time) and exposed to ^{204}Tl , as described in Section 2.2.1. The time between anneal and exposure was six to seven days. This was to minimize the variation in pre-exposure fading (also referred to as loss of sensitivity).

Once the exposures were complete, the dosimeters were returned and all 36 cards were read using the Harshaw 8800 reader. The time from exposure to readout was five to six days. This allowed for minimum variation in post-exposure fading.

3.4 IRRADIATION WITH DU

Forty dosimeter cards were annealed (20 thin chip, 20 thick chip) and placed in TLD holders as follows:

10 type OC/OM

10 type OC/NM

10 type NC/OM

10 type NC/NM

These TLDs were then divided up into 5 sets of 4 dosimeters each for 250 mrem of exposure to DU slabs. The remaining 20 TLD's were divided into 4 sets, each containing 5 dosimeters of the same type and were used as control sets. All 9 sets were then sent to RASCAL. At RASCAL, 5 different DU slabs were used to irradiate the dosimeters. Each slab can hold 2 dosimeters at a time during exposure. Instructions were given to RASCAL personnel to ensure that each dosimeter within a set (of 4) was exposed to the same slab, for uniformity. In order to accomplish this goal, each set was divided into 2 subsets (with one consisting of 1 thin chip and

1 thick chip with the old mylar; and the other having 1 thin chip and 1 thick chip with the new mylar). Both subsets were exposed to the same slab at separate times. The time between anneal and exposure was 5 days. Four days following exposure, the 40 cards were read on the Harshaw 8800 reader.

3.5 IRRADIATION WITH LOW ENERGY X-RAYS

A total of 60 cards were annealed (30 thin chip, 30 thick chip) and placed in TLD holders. All 60 holders used in this experiment had the new (thinner, opaque) mylar. Responses due to the variation of mylar thickness was not tested for x-ray categories since the small difference in thickness (~ 2 mg/cm²) would produce insignificant (if any) effects on the penetration of the x-rays. The dosimeters were divided into sets as follow:

30 type OC/NM

- 10 - for exposure to K17 x-rays
- 10 - for exposure to M30 x-rays
- 10 - control (or extra) TLD's

30 type NC/NM

- 10 - for exposure to K17 x-rays
- 10 - for exposure to M30 x-rays
- 10 - control (or extra) TLD's

All 60 dosimeters were shipped to Battelle Pacific Northwest Laboratories in Richland, Washington. The 40 TLDs that were exposed received 500 mrem of shallow dose equivalent x-rays. The time span from annealing to exposure was 8 to 9 days and the time from exposure to readout was 7 to 8 days.

3.6 CUMULATIVE BACKGROUND AND LOWER LIMIT OF DETECTION (L_D) EXPERIMENT

Since the purpose of wearing a TLD is to measure occupational or "on-the-job" exposure, it is necessary to subtract natural and system background signals from the TLD readings in order to determine the actual occupational exposure. At many nuclear facilities, employees leave their TLDs in a designated storage area when leaving work. The background radiation can then be determined by maintaining control dosimeters at the storage site to measure the amount of background radiation present there and subtracting this amount from the employees' TLD readings (Sonder, 1991 [1]). However, this is not the case at Energy Systems where employees take their dosimeters, which are attached to their identification badges, home with them. Since background radiation varies from one location to another, it becomes difficult to estimate the amount of radiation that was received from "off-the-job" exposure. Therefore, in this study, the background was determined by distributing TLDs to

10 different locations (including employees' homes and on-site locations) to simulate the way in which TLDs are actually stored and to determine an "average" background reading for the TLDs. This average cumulative background was calculated each month for up to 5 months. A 5-month period was selected because that is the average amount of time between annealing and reading for an assigned dosimeter. System background was determined by reading a random sample of cards immediately following their anneal.

For this experiment, 200 cards were annealed (100 thin chip, 100 thick chip). Twenty of these cards (10 of each thickness) were randomly selected and read immediately following the anneal cycle to determine the residual background signal (from the reader and the TLDs). The remaining 180 cards were placed in TLD holders for use in the Cumulative Background Exposure and L_D Experiment. All holders used in this experiment had the new type of mylar. The dosimeters were divided, for exposure, in the following way:

90 type OC/NM

20 - for exposure to ^{204}Tl

20 - for exposure to DU slabs

50 - control TLDs for measuring background radiation

90 type NC/NM

20 - for exposure to ^{204}Tl

20 - for exposure to DU slabs

50 - control TLDs for measuring background radiation

The 80 cards that were selected for exposure were sent to RASCAL and received 250 mrem shallow dose equivalent.

Following the exposures, all 180 cards were divided into groups for distribution to 10 different locations. Each location received an assortment of 18 TLDs to be stored and returned on the dates specified on the TLD labels. Table 1 shows how these TLDs were distributed and which ones were due back each month (over a five-month period). While the TLD's were being held at the 10 different sites, they were stored in open boxes in a single layer with their labels and mylar foils facing in an upward direction. The dosimeters were placed in areas where they would not be exposed to heat, direct light, or sources of radiation. The purpose of sending the TLDs to the different locations was to determine the average amount of background radiation that the typical TLD accumulates while being stored between working hours and the amount of variation that exists in these amounts. In addition to determining the average background accumulation, the response of dosimeters used for background study were also used to calculate the Lower Limit of Detection (L_D). The L_D is the lowest level of

**Table 1. Distribution of TLD's Per Location
With Due Dates**

CHIP TYPE	EXP TYPE	# OF TLD's	# OF TLD's DUE PER MONTH				
			MAY	JUNE	JULY	AUG	SEP
THIN	²⁰⁴ TL	2	0	1	0	0	1
THICK	²⁰⁴ TL	2	0	1	0	0	1
THIN	DU	2	0	1	0	0	1
THICK	DU	2	0	1	0	0	1
THIN	NONE	5	1	1	1	1	1
THICK	NONE	5	1	1	1	1	1
TOTALS		18	2	6	2	2	6

dose equivalent at which the dosimeter readout is significantly different (with 95% confidence) from the readout value at the detection threshold (USDOE, 1986 [1]). Appendix E shows the equation used to calculate the L_D and gives definitions for each of the variables used in the equation.

4. DATA ANALYSIS AND RESULTS

4.1 METHODS OF STATISTICAL ANALYSIS

There were two separate methods of statistical analysis used to evaluate the difference in the mean values for the thin and thick chip dosimeters. More specifically, these methods were used in evaluating the raw responses (sec. 4.2), the calculated dose equivalents (sec. 4.3), and the cumulative background results (sec. 4.5).

The first method is approximate and is based on the Student's t-distribution. This test was performed at the 95% confidence level and involved the following steps (Sachs, 1982).

- (1) Establish the null and alternative hypotheses (H_0 and H_1 , respectively) for a two-sided t-test:

$$H_0: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where: μ_1 = mean for thin chip

μ_2 = mean for thick chip

- (2) Calculate the test statistic (t'):

$$t' = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where: $\bar{x}_1$ = sample mean for thin chip

$\bar{x}_2$ = sample mean for thick chip

s_1^2 = sample variance for thin chip

s_2^2 = sample variance for thick chip

n_1 = sample size for thin chip

n_2 = sample size for thick chip

(3) Calculate the degrees of freedom (ν):

$$\nu = n - 1 + \frac{2n - 2}{\frac{s_1^2}{s_2^2} + \frac{s_2^2}{s_1^2}}$$

where: $n = n_1 = n_2$

and ν is rounded to the nearest integer.

(4) Locate value of $t_{\nu, .05}$ in a t-table.

(5) Compare t' with $t_{\nu, .05}$. If $t' > t_{\nu, .05}$, then reject H_0 and conclude that the means are significantly different at the 95% confidence level. Otherwise, the means do not differ significantly at the 95% confidence level.

The results of the t-tests are shown in the tables of results for sections 4.2, 4.3, and 4.5 under a column titled "SIGNIF DIFF" where, 'YES' means there is a significant difference at the 95% confidence level and 'NO' means there is not.

The second method of statistical analysis that was used is based on the Behrens-Fisher distribution (Box, 1973). This method allows for inferences to be made concerning the difference between two means with unequal variances by generating a distribution of the differences that can be visually represented by a probability density that resembles a t-density (see Figure 3). On such a plot, which we will refer to as a Behrens-Fisher plot, the x-axis represents the difference in the two means, γ , and the y-axis is related to the probability that the difference is γ given the data, D .

The mathematical methods that follow were derived from Box and Tiao (1973). To begin with, it was assumed that the n_1 values for the thin chip were as if drawn from a Normal population, $N(\theta_1, \sigma_1^2)$, and that the n_2 values for the thick chip were as if drawn from another Normal population, $N(\theta_2, \sigma_2^2)$, with both means (θ_1 & θ_2) and both variances (σ_1^2 & σ_2^2) unknown. The goal was to obtain the posterior distribution of $\gamma = \theta_2 - \theta_1$, the difference in the means.

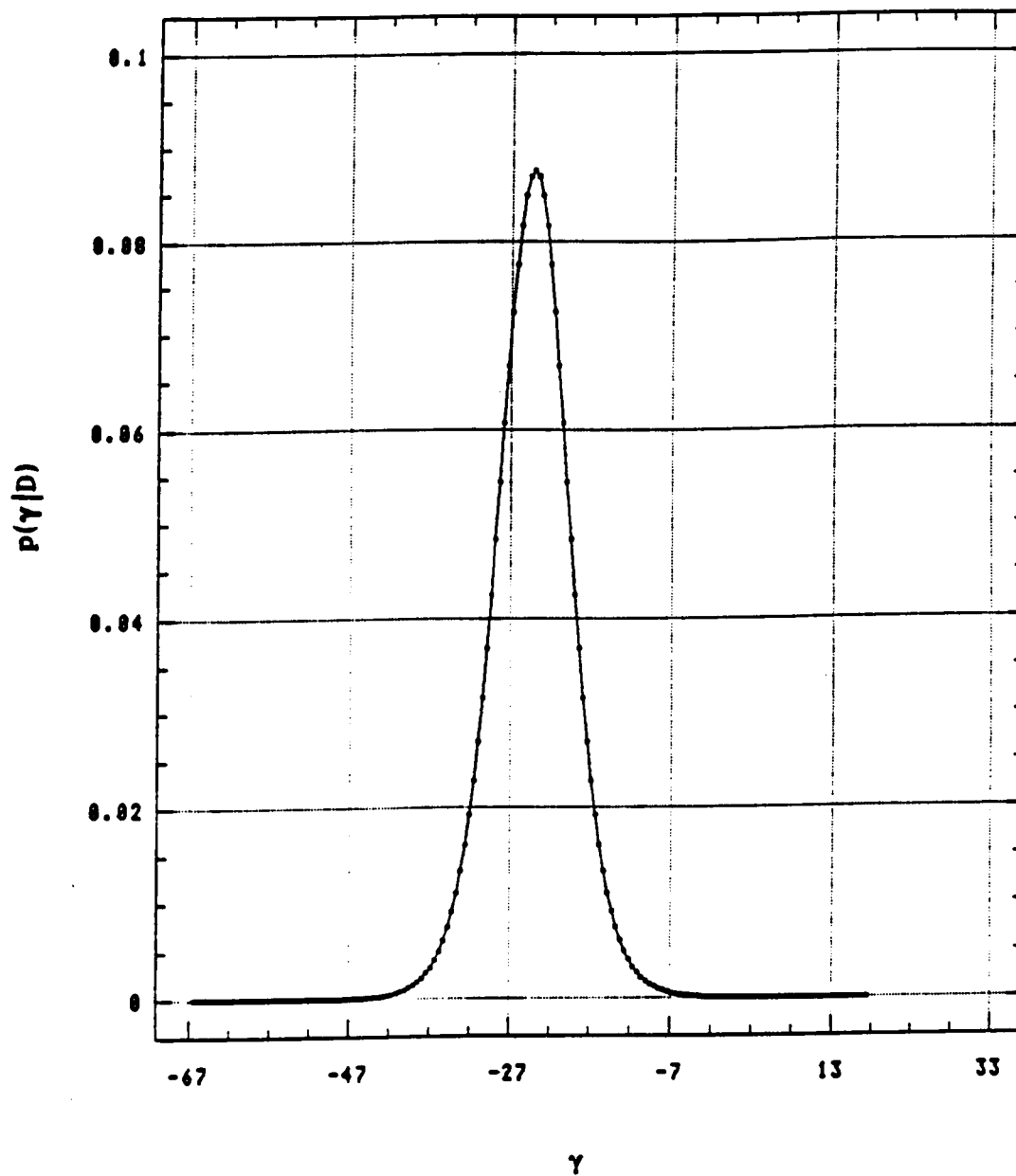


Figure 3. Example of a Behrens-Fisher Plot.
 This plot shows the difference in means for the thin
 vs. thick chip exposed to ^{204}Tl using the new mylar.
 (note: γ is in units of mR^*)

Since the distribution of $\gamma = \theta_2 - \theta_1$ cannot be given analytically, it was necessary to compute it via numerical integration. First, consider the equation (Box, 1973)

$$\tau = \frac{\gamma - (\bar{x}_2 - \bar{x}_1)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

in order to generate values for γ . Simple algebraic manipulation made it possible to derive from this equation the following relationship

$$\gamma = \tau \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} + (\bar{x}_2 - \bar{x}_1)$$

For each value of γ , the difference in the means, it was necessary to compute $p(\gamma|D)$, which is the posterior probability density of γ given the data, in order to generate the so-called Behrens-Fisher plots. According to Box and Tiao, $p(\tau|D)$ can be found using the integral that follows

$$p(\tau|D) = k \int \left[1 + \frac{z \cos \phi - \tau \sin \phi^2}{v_1} \right]^{-\frac{1}{2}(v_1+1)} \times \left[1 + \frac{z \sin \phi - \tau \cos \phi^2}{v_2} \right]^{-\frac{1}{2}(v_2+1)} dz$$

over the range $-\infty < \tau < \infty$, where

$$k^{-1} = B\left(\frac{1}{2}v_1, \frac{1}{2}\right) B\left(\frac{1}{2}v_2, \frac{1}{2}\right) (v_1 v_2)^{\frac{1}{2}}$$

and

$$\tan \phi = \frac{\frac{s_1}{\sqrt{n_1}}}{\frac{s_2}{\sqrt{n_2}}}$$

After finding $p(\tau|D)$, it was necessary to convert this quantity to $p(\gamma|D)$. This was done using the following equation for the density of a function of a random variable (Renyi, 1970)

$$p(\gamma|D) = \frac{p(\tau|D)}{\frac{d\gamma}{d\tau}}$$

Since the mathematical procedure involved solving a complicated integral several times, a program was written in

FORTTRAN to perform this task using the Trapezoidal Rule. A complete listing of this program can be found in Appendix A. The output data generated by the FORTTRAN program was then transferred into StatGraphics (a statistical graphics software package) to generate the plots.

4.2 INTERPRETATION OF RAW RESPONSES

The averages and standard deviations of the raw readings for each type of radiation and for each dosimeter design are given in Table 2. These readings came directly from the TLD reader and are in units of mR*. (The unit, mR* was explained in section 3.1.) In Table 2, the column titled "% DIFF" gives the percent difference between the response of the thin-chip dosimeters and the thick-chip dosimeters using the following equation:

$$P = \frac{\text{response of thick chip} - \text{response of thin chip}}{\text{response of thin chip}} \times 100$$

From observing these percentages, it becomes obvious that the differences were largest for ^{204}Tl . A Student's t-test was performed to see if any of the percent differences (between thin and thick-chip dosimeters) were significant at the 95% confidence level. The t-test revealed that the only time a significant difference in response occurred was when ^{204}Tl was

Table 2. Means and Standard Deviations of the
Raw Readings (in mR)

TYPE OF EXPOSURE	TYPE OF MYLAR	RAW READINGS $\pm$ STD. DEV.		% DIFF	SIGNIF DIFF	P VALUE
		THIN CHIP	THICK CHIP			
²⁰⁴ Tl	OLD	175.7 $\pm$ 11.3	153.7 $\pm$ 1.82	-12.5 %	YES	< .05
	NEW	190.9 $\pm$ 5.85	166.7 $\pm$ 10.4	-12.7 %	YES	< .05
		CURRENT		PROPOSED		
		175.7 $\pm$ 11.3	166.7 $\pm$ 10.4	-5.12 %	NO	< .05
DEPL. U.	OLD	139.7 $\pm$ 4.96	138.5 $\pm$ 2.18	-.859 %	NO	< .05
	NEW	136.2 $\pm$ 2.88	135.9 $\pm$ 5.16	-.220 %	NO	< .05
K17	NEW	659.6 $\pm$ 27.5	667.1 $\pm$ 12.9	1.14 %	NO	< .05
M30	NEW	656.4 $\pm$ 19.7	655.5 $\pm$ 5.17	-.137 %	NO	< .05

the source of exposure. In order to examine this difference in response more closely, the current TLD design (old mylar, thin chip) was compared with the proposed design (new mylar, thick chip). This comparison resulted in a lower percent difference than observed when keeping the mylar the same. In fact, the difference was determined to be statistically insignificant (at the 95% confidence level). Apparently, the effects of the change in mylar and the change in chip thickness cancel one another to a certain degree. In addition to the t-test results given in Table 2, Behrens-Fisher plots, showing a distribution of the difference in the means for each comparison made, are given in Appendix B. The plots support the results discussed above.

4.3 CALCULATED DOSE EQUIVALENTS

The TLD reader-generated raw data was analyzed using the PC-based dose algorithm (Harshaw-Solon, 1989) to convert the raw responses, in units of mR^* , to dose equivalents, in units of mrem. (See Appendix F for a brief description of the dose algorithm.) This was done to determine whether the calculated dose equivalents, for different dosimeter designs, varied differently than the raw responses. Any significant differences between the raw reading results and the dose equivalent results would indicate the need for changes in the dose calculation algorithm when using the new dosimeter.

Table 3 shows the means and standard deviations of the calculated dose equivalents. It can be seen that the dose equivalent values show variances similar to those of the raw readings. Thus, it appears that any changes to the calibration factors for calculating dose equivalents for the new TLDs will not be needed. The corresponding Behrens-Fisher plots for the data in Table 3 support these findings and can be found in Appendix C.

4.4 ACCURACY AND PRECISION

An accuracy and precision test was run to determine if the performance of one dosimeter type was better than the other. This test was performed using the dose equivalent values. First, a performance quotient was computed for each individual dosimeter using the following formula (USDOE, 1986[1]):

$$P_i = \frac{(R_D - D_D)}{D_D}$$

where, P_i = performance quotient

R_D = reported dose

D_D = delivered dose

i = dosimeter number

Table 3. Means and Standard Deviations of the
Dose Equivalents (in mrem)

TYPE OF EXPOSURE	TYPE OF MYLAR	DOSE EQUIV. $\pm$ STD. DEV.		% DIFF	SIGNIF DIFF	p VALUE
		THIN CHIP	THICK CHIP			
²⁰⁴ Tl	OLD	256.9 $\pm$ 19.1	226.3 $\pm$ 2.71	-11.9 %	YES	< .05
	NEW	280.8 $\pm$ 8.60	245.4 $\pm$ 15.2	-12.6 %	YES	< .05
		CURRENT		PROPOSED		
		256.9 $\pm$ 19.1	245.4 $\pm$ 15.2	-4.5 %	NO	< .05
DEPL. U.	OLD	250.0 $\pm$ 9.0	248.0 $\pm$ 4.0	-0.8 %	NO	< .05
	NEW	243.0 $\pm$ 5.0	243.0 $\pm$ 9.0	0.0 %	NO	< .05
K17	NEW	561.1 $\pm$ 21.0	566.0 $\pm$ 8.77	0.87 %	NO	< .05
M30	NEW	586.6 $\pm$ 16.7	*593.6 $\pm$ 37.0	1.19 %	NO	< .05

* If an outlier value is omitted, this value becomes: 582.6 $\pm$ 12.9
& the % difference is -0.68 %

Once the performance quotients were calculated and the dosimeters were divided into groups according to mylar type, chip thickness, and type of exposure, the bias (accuracy) and standard deviation (precision) values were obtained for each type (or group) of dosimeters. The following formulas were used (USDOE, 1986 [1]) to calculate bias and standard deviation values:

$$B = \frac{1}{n} \times \sum P_i$$

$$S = \frac{\sqrt{\sum (P_i - B)^2}}{\sqrt{n-1}}$$

where, B = bias (accuracy)

S = standard deviation (precision)

P_i = performance quotient

n = number of dosimeters in the group

i = dosimeter number (1,2,...,n)

Table 4 shows the results of these calculations. Observing these values gives no indication that one type of dosimeter performs better than another for any given type of exposure. The " $|B| + SD$ " (bias + standard deviation) values are very similar for the thin and thick chip dosimeters in

Table 4. Comparison of Dosimeter Performance in Terms of Accuracy and Precision of Measurement

EXP.	MYLAR	THIN CHIP				THICK CHIP			
		BIAS	S.D.	B +SD		BIAS	S.D.	B +SD	
²⁰⁴ Tl	OLD	.028	.077	.105		-.095	.011	.106	
	NEW	.123	.034	.157		-.019	.061	.080	
DEP U	OLD	-.001	.036	.037		-.008	.017	.025	
	NEW	-.007	.035	.042		-.028	.037	.065	
K17	NEW	.132	.040	.172		.142	.017	.159	
M30	NEW	.172	.033	.205		.183	.073	.256	

each exposure category. It is also possible to compare the current dosimeter design (old mylar, thin chip) with the new design (new mylar, thick chip) for the beta exposures. For ^{204}Tl , the old design has a " $|B| + \text{SD}$ " value of .105 and the new design gives a value of .080. Similarly, the old and new design values for depleted uranium are .037 and .065, respectively. Again, the values are very similar in both cases. Therefore, it appears that performance level is not an appropriate decision criterion in selecting the better TLD design since this level is approximately the same for both chip and mylar types.

4.5 BACKGROUND RESULTS

Table 5 shows the results of the Average Cumulative Background Study. This study was run to determine if there is a difference in the accumulation of background signal, due to chip thickness, over a five-month period. A five-month period was selected because that is the average amount of time between annealing and reading for an assigned dosimeter. Figure 4 shows a graph of the average background values for each month along with their corresponding standard deviations. From looking at the resulting equations for each estimated regression line, it can be seen that the slopes (or rates-of-change) are nearly equal for both types of chip; but, the extrapolated system background (y-intercept) is higher for the

Table 5. Average Cumulative Background (in mR')

MONTH	AVG .BKGD. ± STD. DEV.		% DIFF	SIGNIF DIFF	p VALUE
	THIN CHIP	THICK CHIP			
1	18.47 ± 7.28	11.37 ± 2.88	-38.4 %	YES	< .05
2	20.86 ± 4.59	14.39 ± 1.61	-31.0 %	YES	< .05
3	22.16 ± 2.39	15.63 ± 1.93	-29.5 %	YES	< .05
4	26.71 ± 5.20	20.64 ± 3.09	-22.7 %	YES	< .05
5	31.48 ± 4.11	23.75 ± 3.04	-24.6 %	YES	< .05

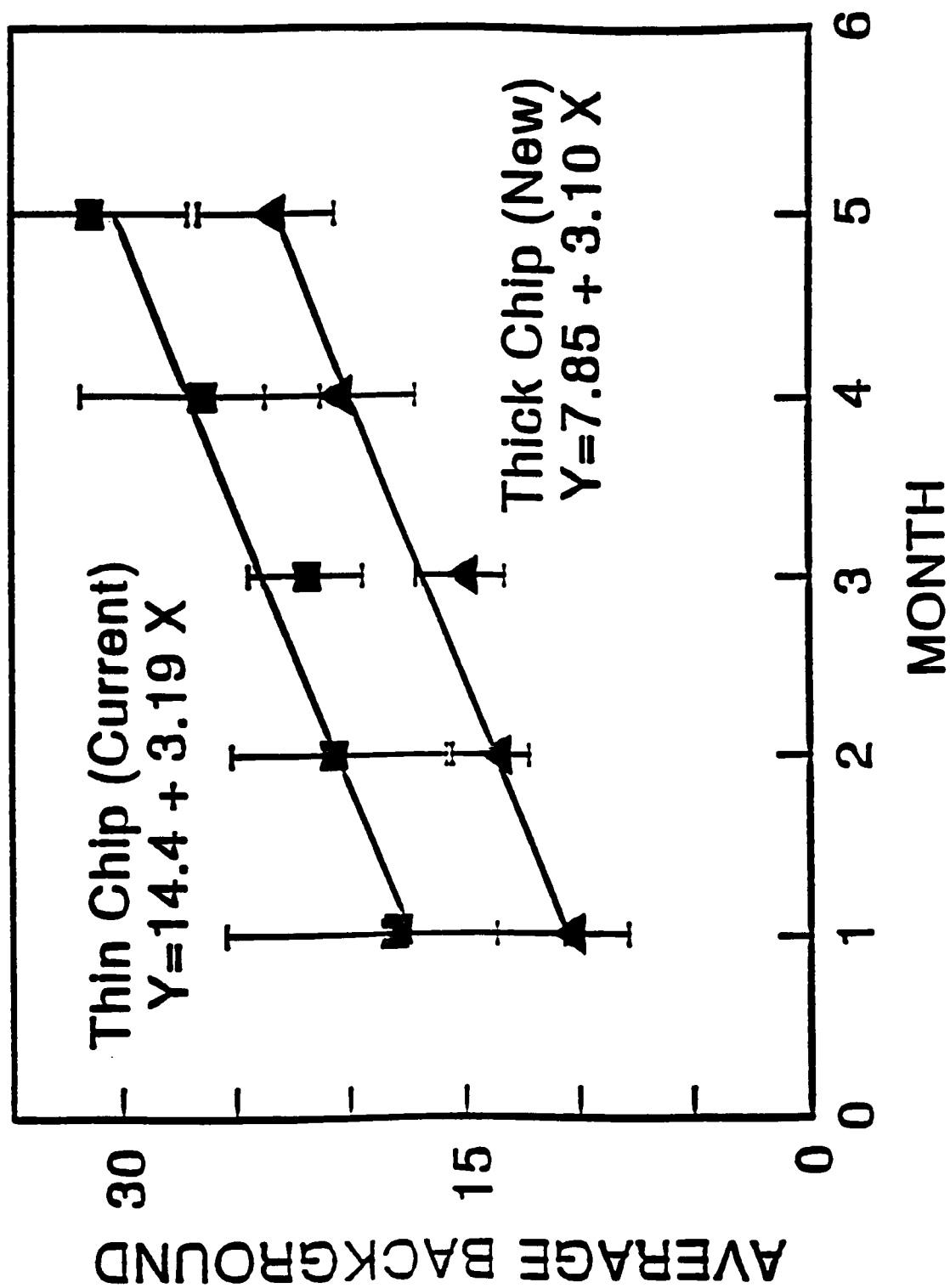


Figure 4. Background Radiation Accumulation

thin chip than for the thick. Also, the thin chip has a higher standard deviation each month which causes less certainty in the readings. A t-test revealed a significant difference (at the 95% confidence level) between the average background values for the two types of chips as a result of the higher system background in the thin chip. The results of this study favor the thick chip since a lower level of system background will allow for detection of lower levels of radiation and a smaller standard deviation, for background, will result in more accurate readouts at background levels. See Appendix D for the Behrens-Fisher plots that correspond to data in Table 5. Once again, the plots support the findings.

4.6 LOWER LIMITS OF DETECTION

As stated earlier, the Lower Limit of Detection (L_D) is the lowest level of dose equivalent at which the dosimeter readout is significantly different (with 95% confidence) from the readout value at the detection threshold (USDOE, 1986 [1]). This study, as with the Average Cumulative Background Study, was performed over a total of five months. L_D values were calculated for dosimeters out in the field for two months and five months. Table 6 shows the parameter values used in the L_D equation and the resulting L_D values for the two-month period. (Refer to Appendix E for the L_D equation and definitions of the variables.) This study compared the thin and thick chips for both ^{204}Tl and depleted uranium. As can be

Table 6. Parameter Values for I_b Equation and Resulting I_b s
for June (in mrem)

SOURCE	^{204}Tl		DEPLETED URANIUM	
	THIN	THICK	THIN	THICK
H_0	-.004	.001	-.005	.002
S_0	6.44	2.26	7.83	2.75
H_0	18.53	14.54	22.53	17.68
H_1	244.4	203.5	210.1	198.4
S_1	11.6	8.528	5.685	23.28
** t_p	1.833	1.833	1.833	1.833
I_b	24.07	8.51	28.89	12.29

** p-value < 0.05, degrees of freedom = 9

seen from Table 6, the L_D values were much lower for the thick chip for both types of radiation. The five-month calculations are shown in Table 7. As with the two-month calculations, the thick chip had a considerably lower L_D value. This again proves that the thick chip is able to detect lower levels of radiation than the thin chip.

Table 7. Parameter Values for I_p Equation and resulting I_p s
for September (in mrem)

SOURCE	^{204}Tl		DEPLETED URANIUM	
	THIN	THICK	THIN	THICK
H_0	.004	-.003	.005	-.004
S_0	5.77	4.26	7.01	5.18
H_0	34.25	28.39	41.65	34.51
H_1	214	190.3	180	181.2
S_1	19.03	16.43	32.58	23.24
** t_p	1.833	1.833	1.833	1.833
I_p	23.60	17.48	39.18	24.14

** p-value < 0.05, degrees of freedom = 9

5. DISCUSSION AND CONCLUSIONS

Based on the results of this study, the only time that the difference in chip thickness affected the response of the chip to radiation was when measuring low energy betas, such as ^{204}Tl ($E_{\text{MAX}} = 760 \text{ keV}$). However, when comparing the old TLD design (thin chip, old mylar) to the new (thick chip, new mylar), there was no significant dosimetric difference, even for ^{204}Tl , due to the counteracting effect of the difference in mylar thickness. Converting the raw responses to dose equivalents, via the PC-based dose algorithm, did not affect the way in which responses varied from one type of dosimeter to another. Therefore, the same calibration factors that were used to calculate dose equivalents for the old-design TLDs could also be used for the new-design TLDs.

In terms of accuracy and precision, no TLD design performed better than another. This held true when comparing both chip and mylar differences. Therefore, changing from the old TLD design to the new would neither increase nor decrease the performance level of the dosimeters.

Chip thickness had no effect on the rate at which the dosimeters accumulated background radiation from the environment. However, the system background (i.e., residual signal coming from the reader and the TLDs) was higher for the

thin chip than for the thick chip, which resulted in a consistently higher total background for the thin chip. Furthermore, the standard deviation of the background was higher for the thin chip, indicating less certainty when measuring background levels for the thin-chip dosimeters. Therefore, based on these background study results, the thick chip is favored for the following two reasons: (1) it can detect lower levels of radiation; (2) it gives more precise readouts at very low (i.e., background) levels.

The Lower Limit of Detection study indicated a lower L_D for the thick chip for both DU and ^{204}Tl . This reconfirms the fact that the thick chip can detect lower levels of radiation than the thin chip, as shown in the background study.

In summary, the new dosimeter design has been proven to be an improvement over the old design based upon the following: (1) improved L_D ; (2) more precise readouts at background levels; (3) higher signal-to-noise ratio; (4) lower tendency to break or crack; and (5) improved blockage of external light. Furthermore, switching to the new design would not require any adjustments to the calibration factors currently used in the dose algorithm and would not affect the performance level of the dosimeters.

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APPENDICES

APPENDIX A

FORTRAN PROGRAM

USED TO PERFORM BEHRENS-FISHER CALCULATIONS

The program on the next page was written to perform the Behrens-Fisher calculations described in section 4.1 and print out corresponding values of γ and $p(\gamma|D)$. The program used the Trapezoidal Rule to approximate the integral. The resulting values printed out by the program were then transferred into StatGraphics, a statistical graphics software package, to generate the Behrens-Fisher plots in Appendices B,C,D and E.

FORTRAN PROGRAM USED TO PERFORM BEHRENS-FISHER CALCULATIONS

```

DIMENSION VALUE(1000), GAMMA(1000), GAMVAL(1000)
REAL B, A, Z, FZERO, FEND, COSPHI, SINPHI, NUONE, NUTWO, FOFZ, TAU
REAL XONE, XTWO, VARONE, VARTWO, NONE, NTWO
INTEGER L, M, T
OPEN(UNIT=1, FILE='I.OUT', STATUS='NEW')
TAU = - 10.
COSPHI = .92057
SINPHI = .39056
NONE = 20.
NTWO = 12.
NUONE = NONE - 1.
NUTWO = NTWO - 1.
XONE = 50.
XTWO = 55.
VARONE = 12.
VARTWO = 40.
M = 3000.
T = 160
B = 1000.
A = - 1000.
L = 1
DO 100 I = 1, T
  Z = A
  FOFZ = 0.
  GAMMA(L) = TAU*(VARONE/NONE + VARTWO/NTWO)**.5 + (XTWO - XONE)
  FZERO = (1+((Z*COSPHI-TAU*SINPHI)**2)/NUONE)**(-.5*(NUONE+
+ 1))*(1+((Z*SINPHI+TAU*COSPHI)**2)/NUTWO)**(-.5*(NUTWO+1))
  DO 200 J = 1, M - 2
    Z = Z + (B - A)/FLOAT(M)
    FOFZ = FOFZ + 2*(1+((Z*COSPHI-TAU*SINPHI)**2)/NUONE)**
+ (-.5*(NUONE + 1))*(1+((Z*SINPHI+TAU*COSPHI)**2)/NUTWO)
+ **(-.5*(NUTWO+1))
200  CONTINUE
    Z = Z + (B - A)/FLOAT(M)
    FEND = (1+((Z*COSPHI-TAU*SINPHI)**2)/NUONE)**(-.5*(NUONE+
+ 1))*(1+((Z*SINPHI+TAU*COSPHI)**2)/NUTWO)**(-.5*(NUTWO+1))
    VALUE(L) = 0.153566*(FZERO + FEND + FOFZ)*(B - A)/(FLOAT(M)*2.)
    GAMVAL(L) = VALUE(L)/1.983263
    TAU = TAU + .125
    L=L+1
100  CONTINUE
WRITE(1,600) (GAMMA(L), GAMVAL(L), L=1, T)
600  FORMAT(5X, F10.6, 5X, F10.6)
STOP
END

```

APPENDIX B

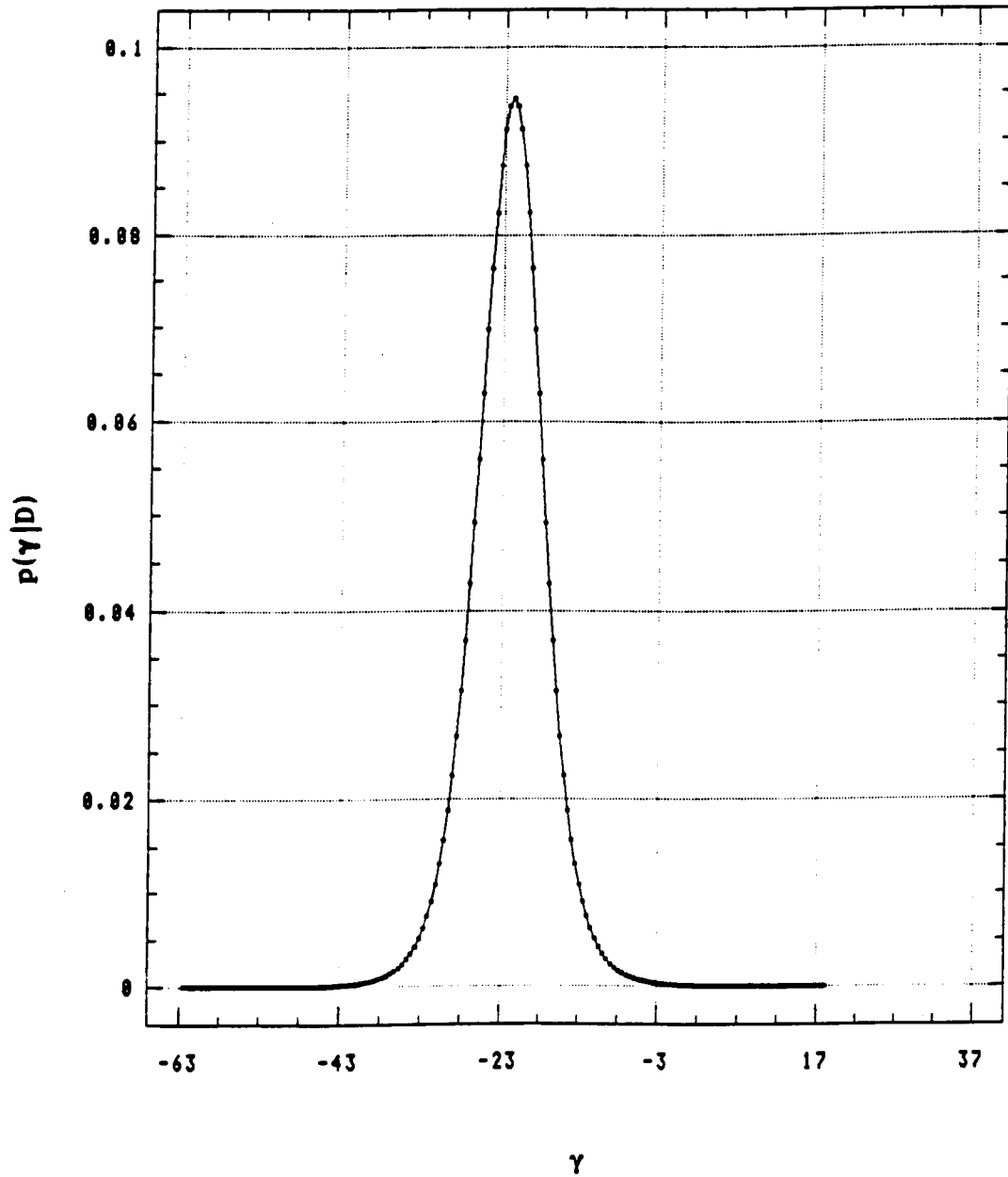
BEHRENS-FISHER PLOTS FOR RAW RESPONSES

PLOT B-1

Source of Exposure: Tl-204

Comparison: Thin chip vs. thick chip with old mylar

(note: γ is in units of mR^{*})

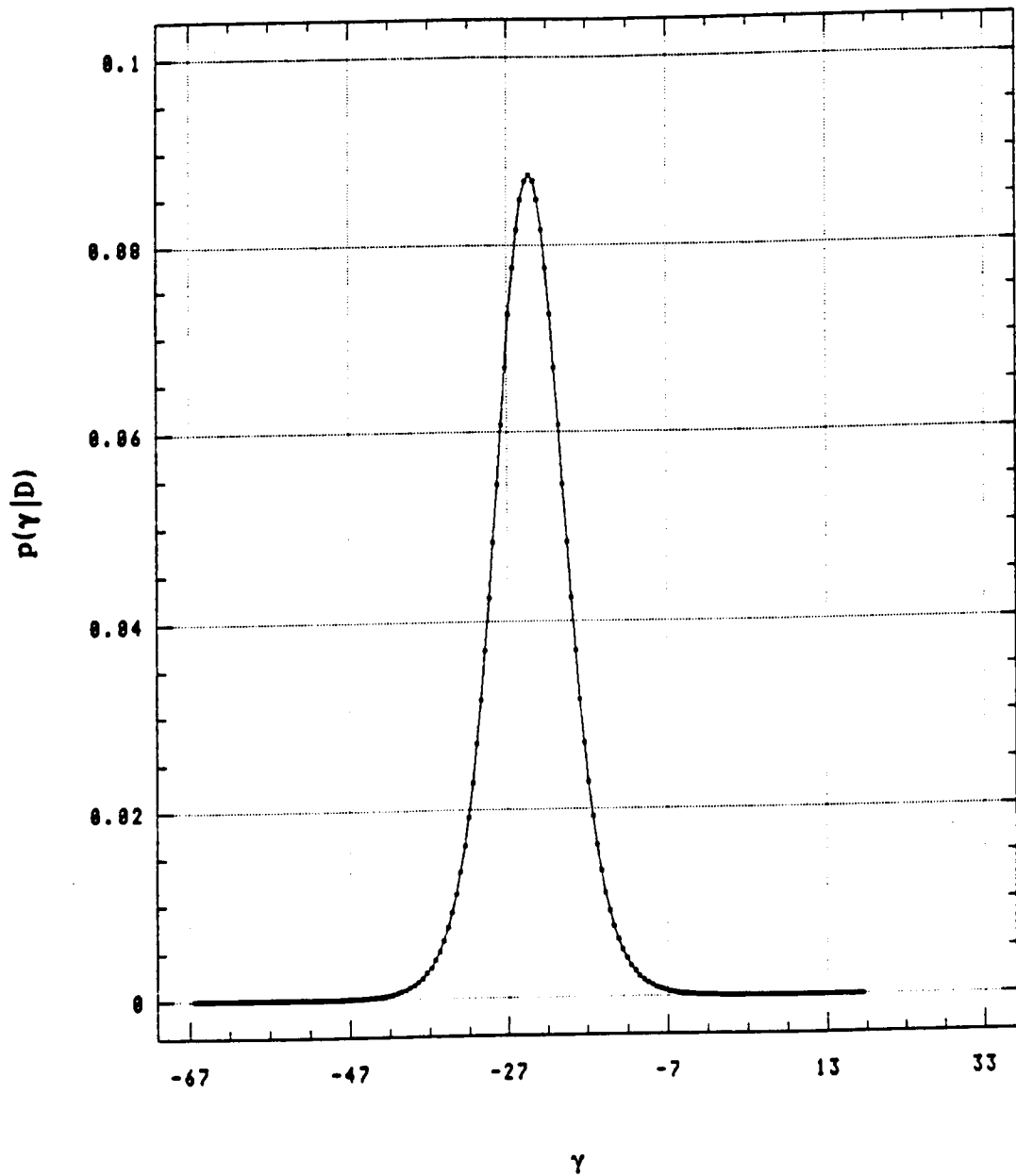


PLOT B-2

Source of Exposure: Tl-204

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)

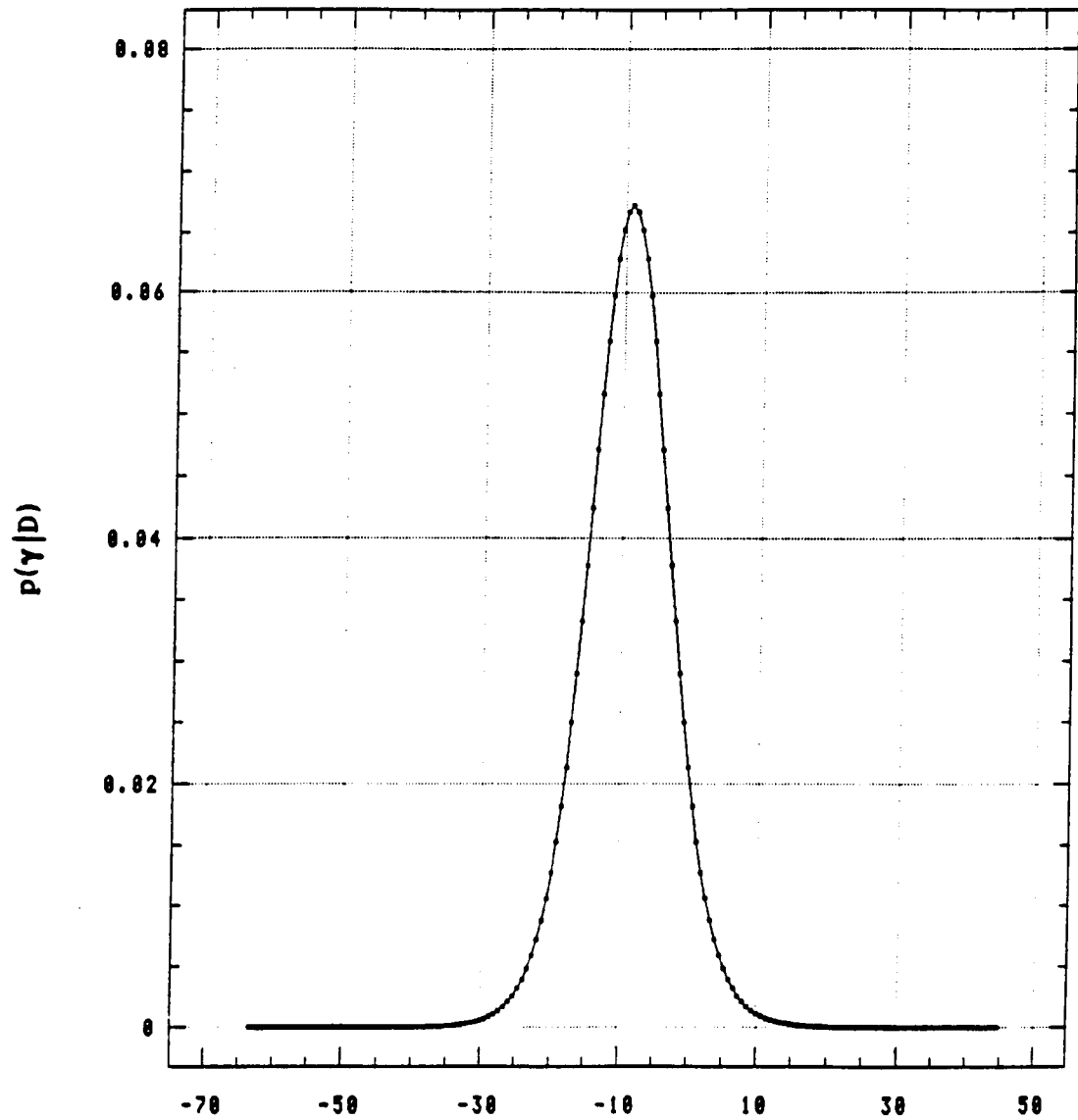


PLOT B-3

Source of Exposure: Tl-204

Comparison: Current vs. proposed dosimeter

(note: γ is in units of mR)



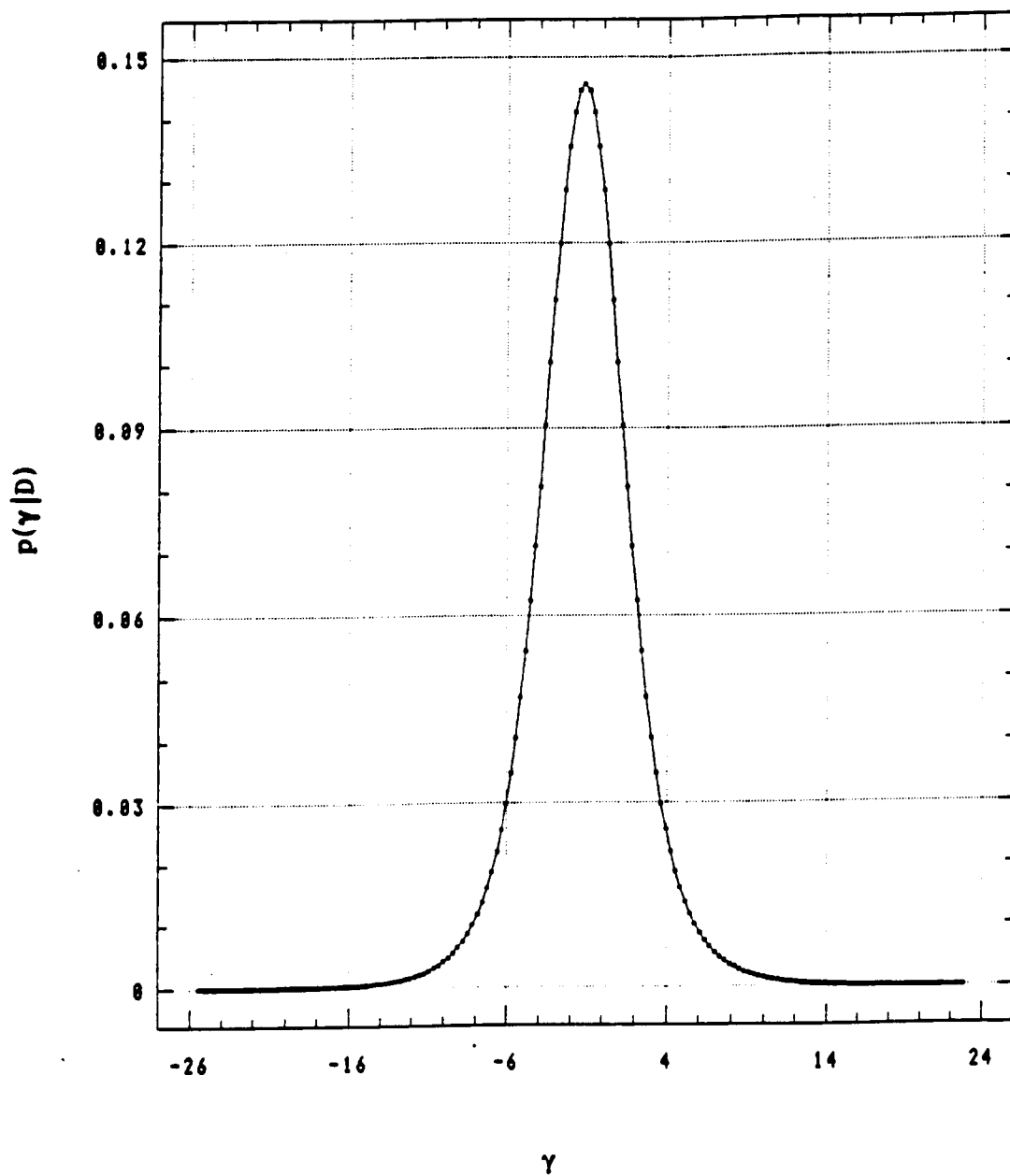
γ

PLOT B-4

Source of Exposure: Depleted Uranium

Comparison: Thin chip vs. thick chip with old mylar

(note: γ is in units of mR)

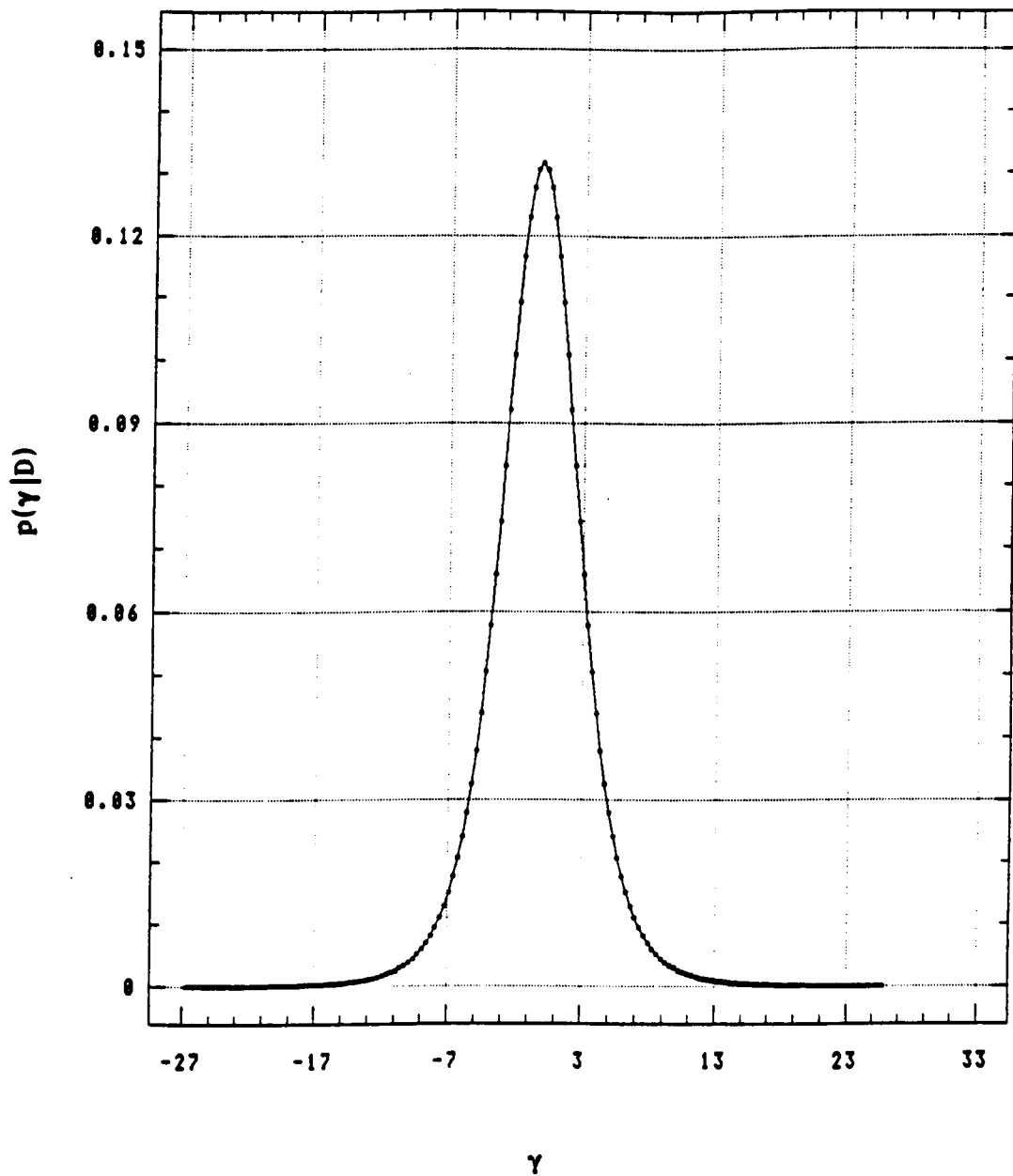


PLOT B-5

Source of Exposure: Depleted Uranium

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR')

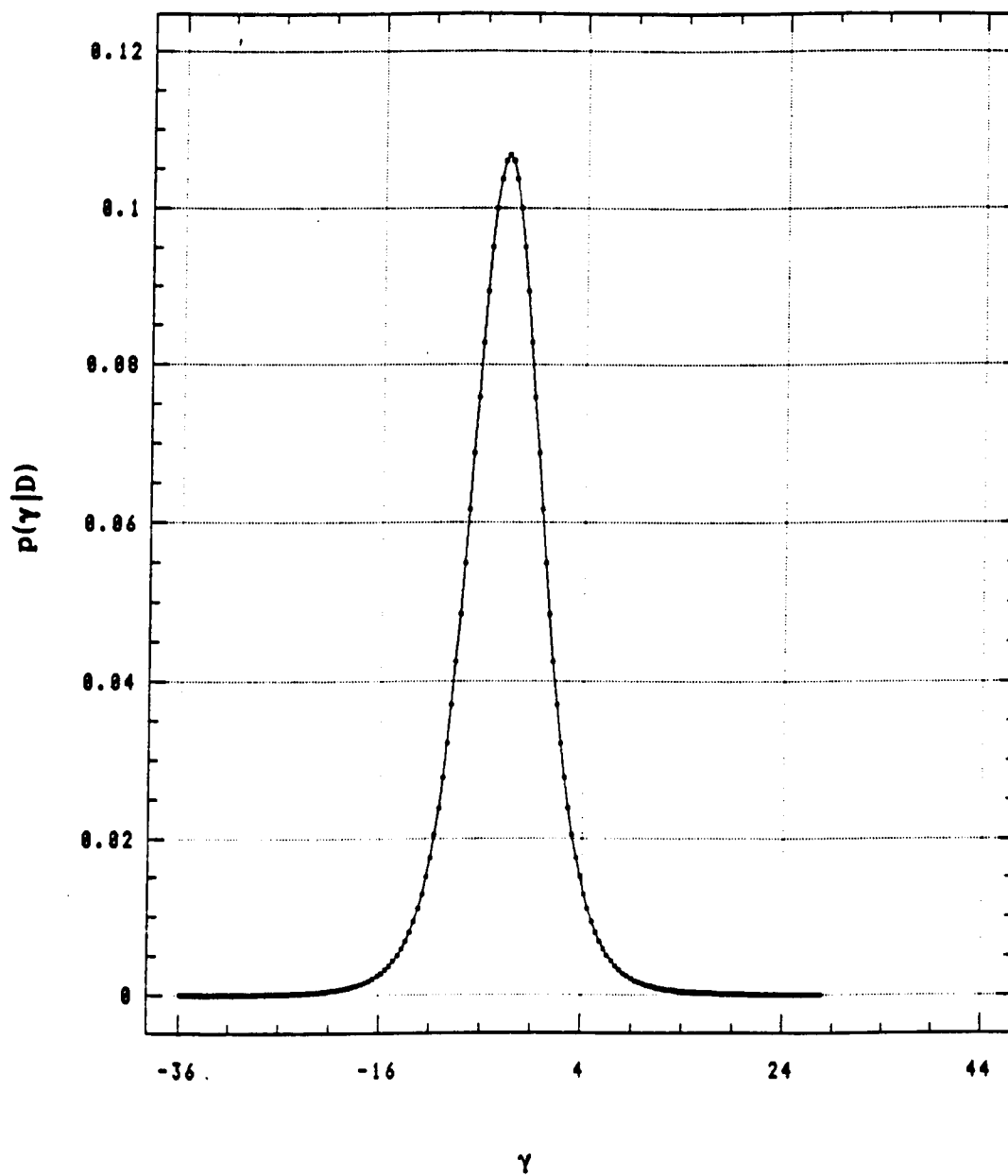


PLOT B-6

Source of Exposure: Depleted Uranium

Comparison: Current vs. proposed dosimeter

(note: γ is in units of mR)

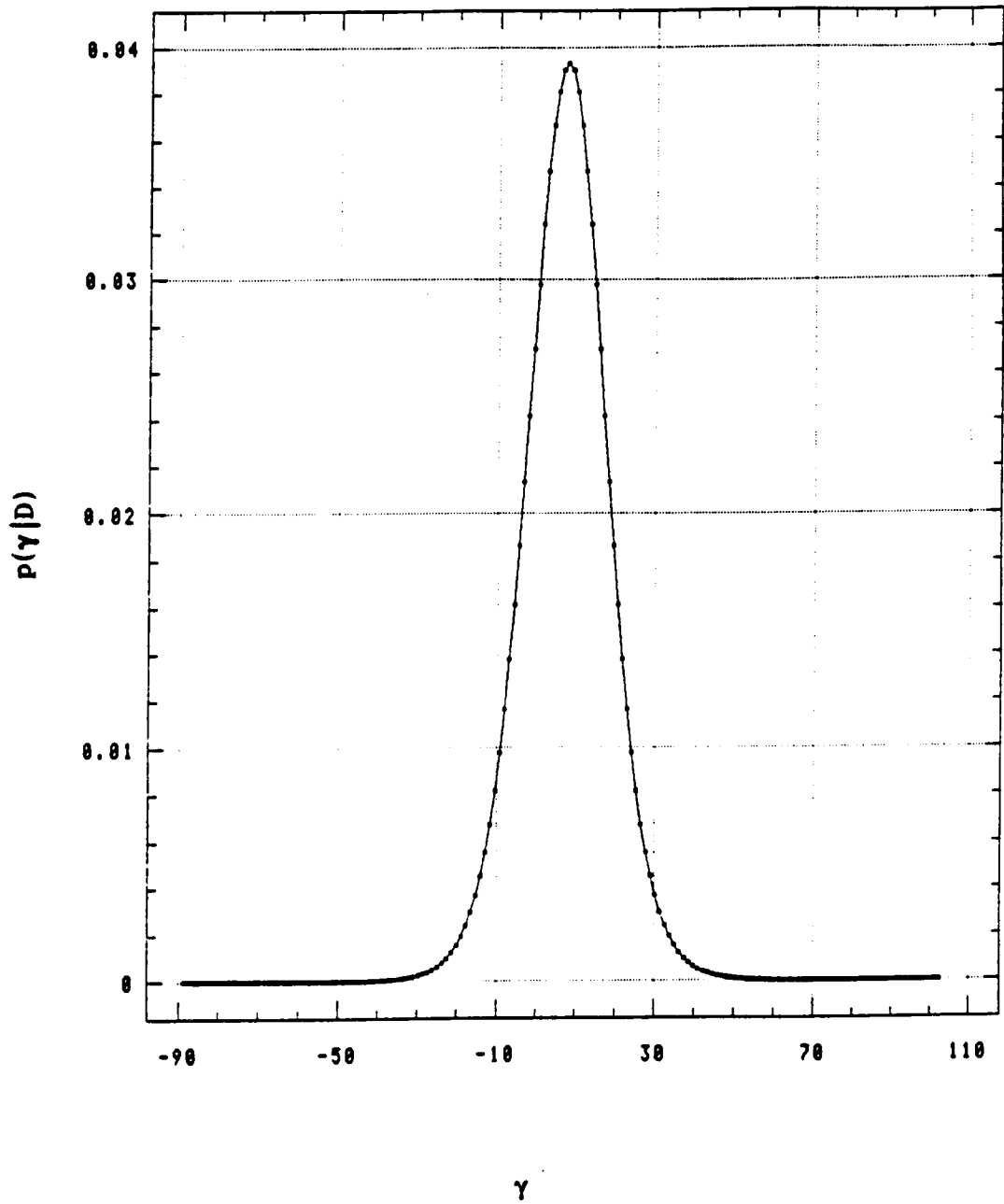


PLOT B-7

Source of Exposure: K17 x-ray

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR)

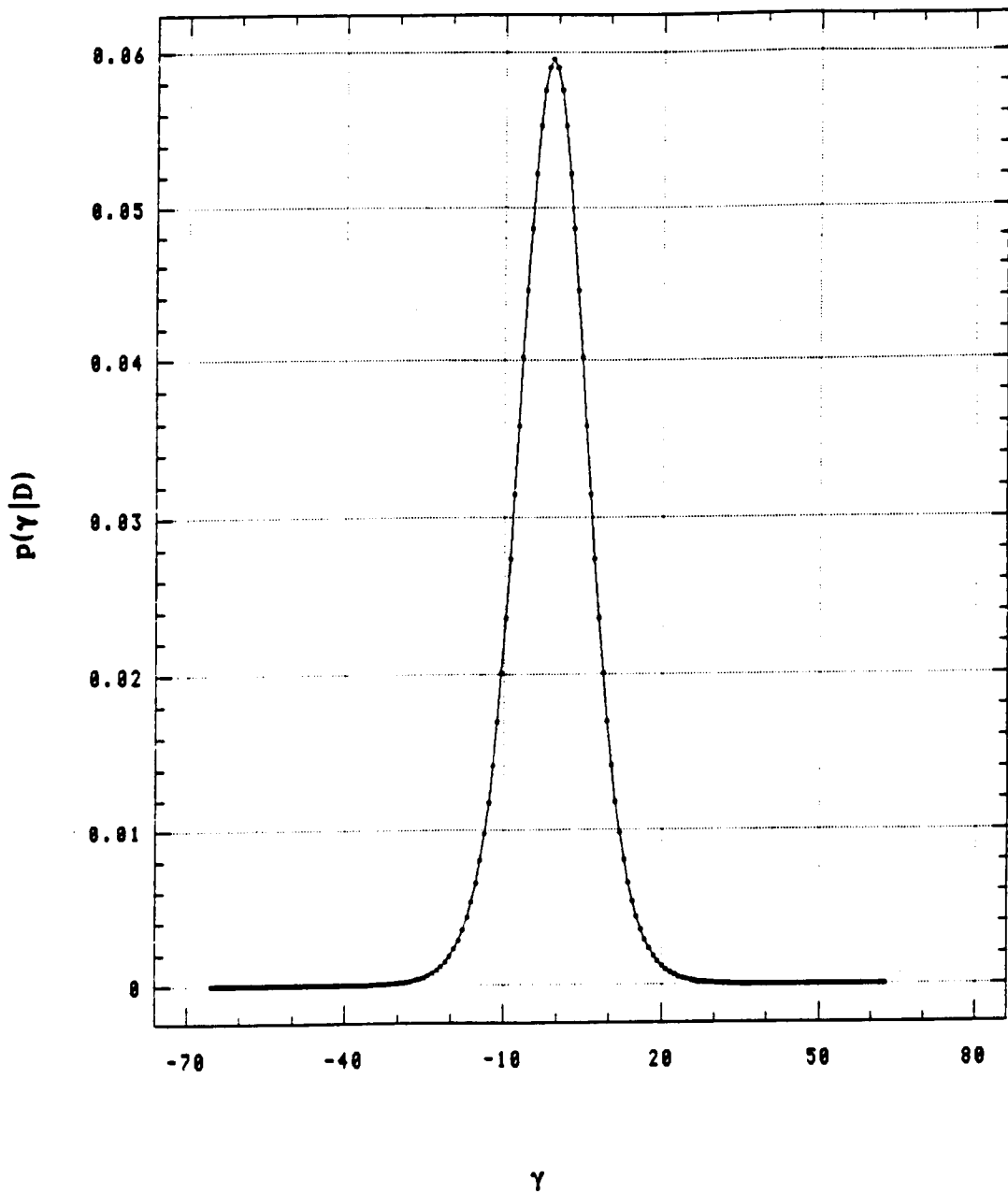


PLOT B-8

Source of Exposure: M30 x-ray

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)



APPENDIX C

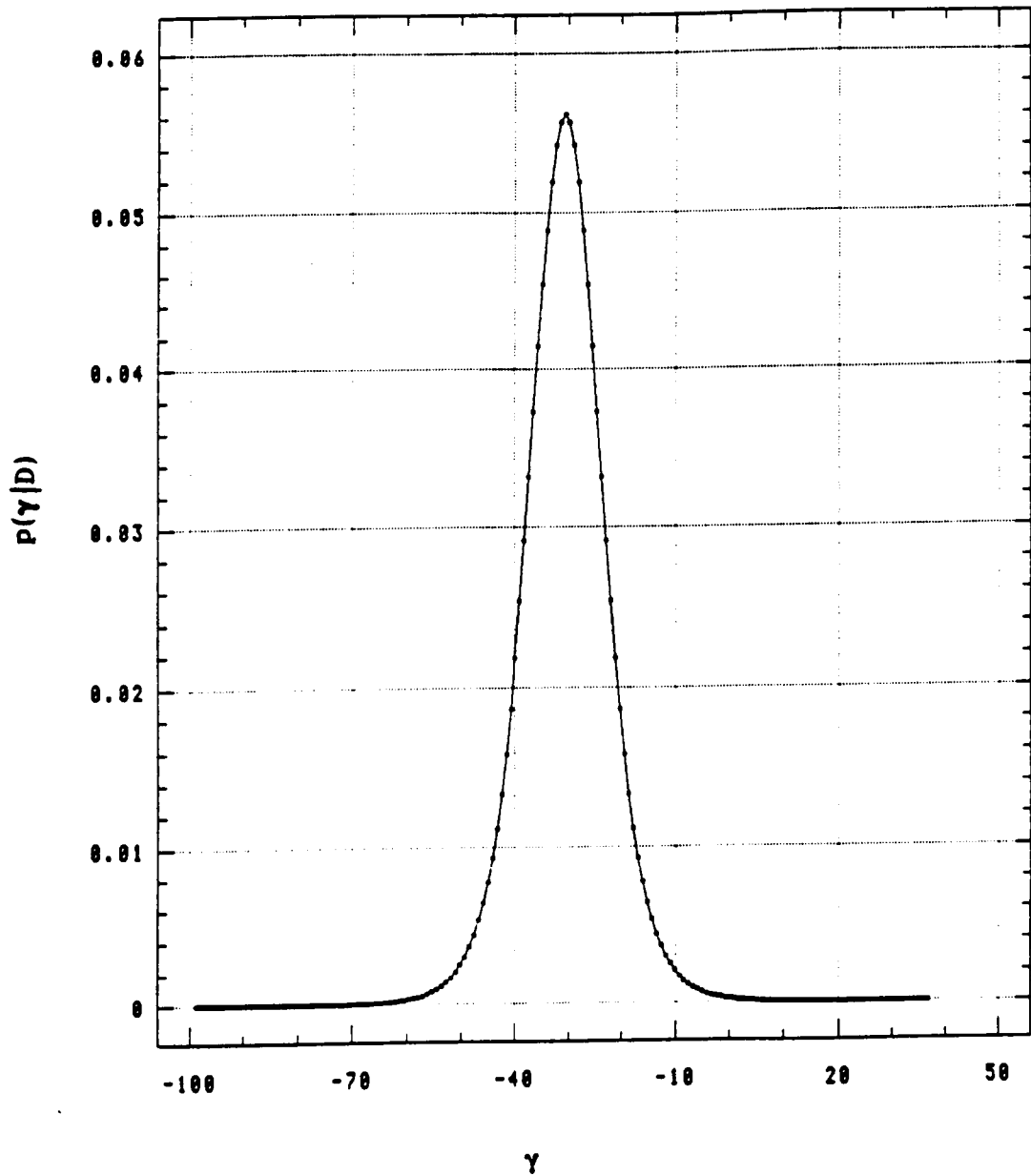
BEHRENS-FISHER PLOTS FOR CALCULATED DOSE EQUIVALENTS

PLOT C-1

Source of Exposure: Tl-204

Comparison: Thin chip vs. thick chip with old mylar

(note: γ is in units of mrem)

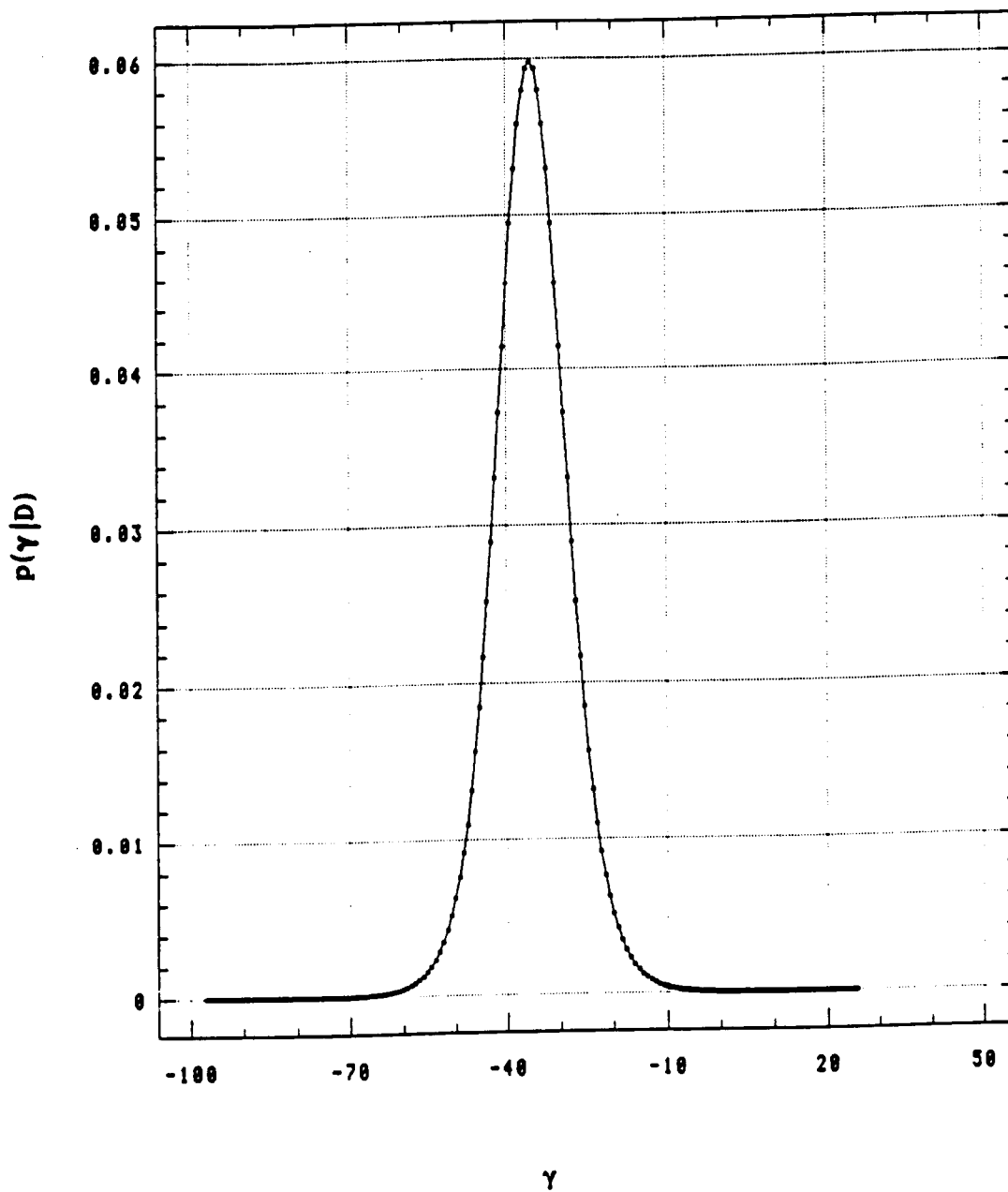


PLOT C-2

Source of Exposure: Tl-204

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mrem)

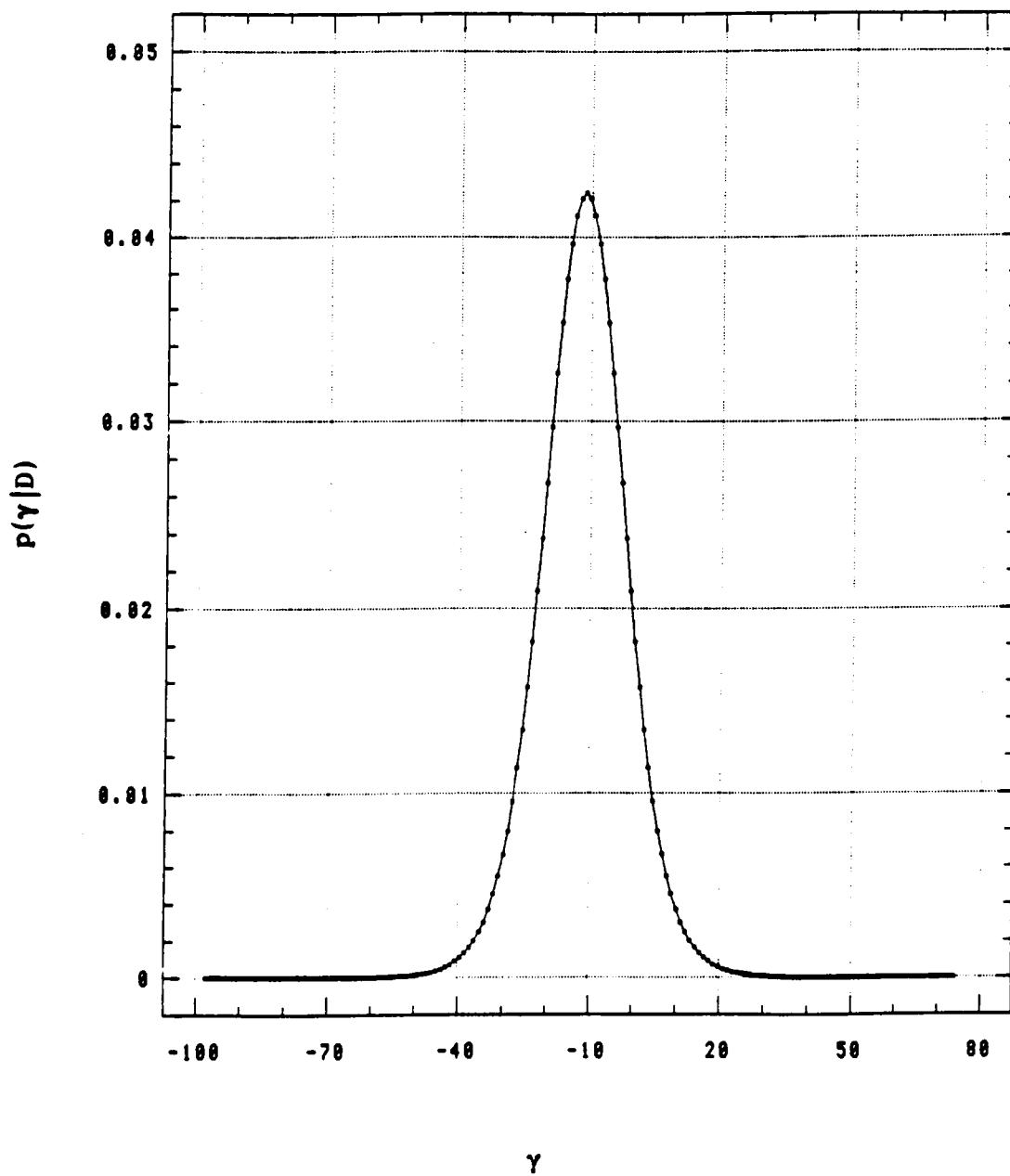


PLOT C-3

Source of Exposure: Tl-204

Comparison: Current vs. proposed dosimeter

(note: γ is in units of mrem)

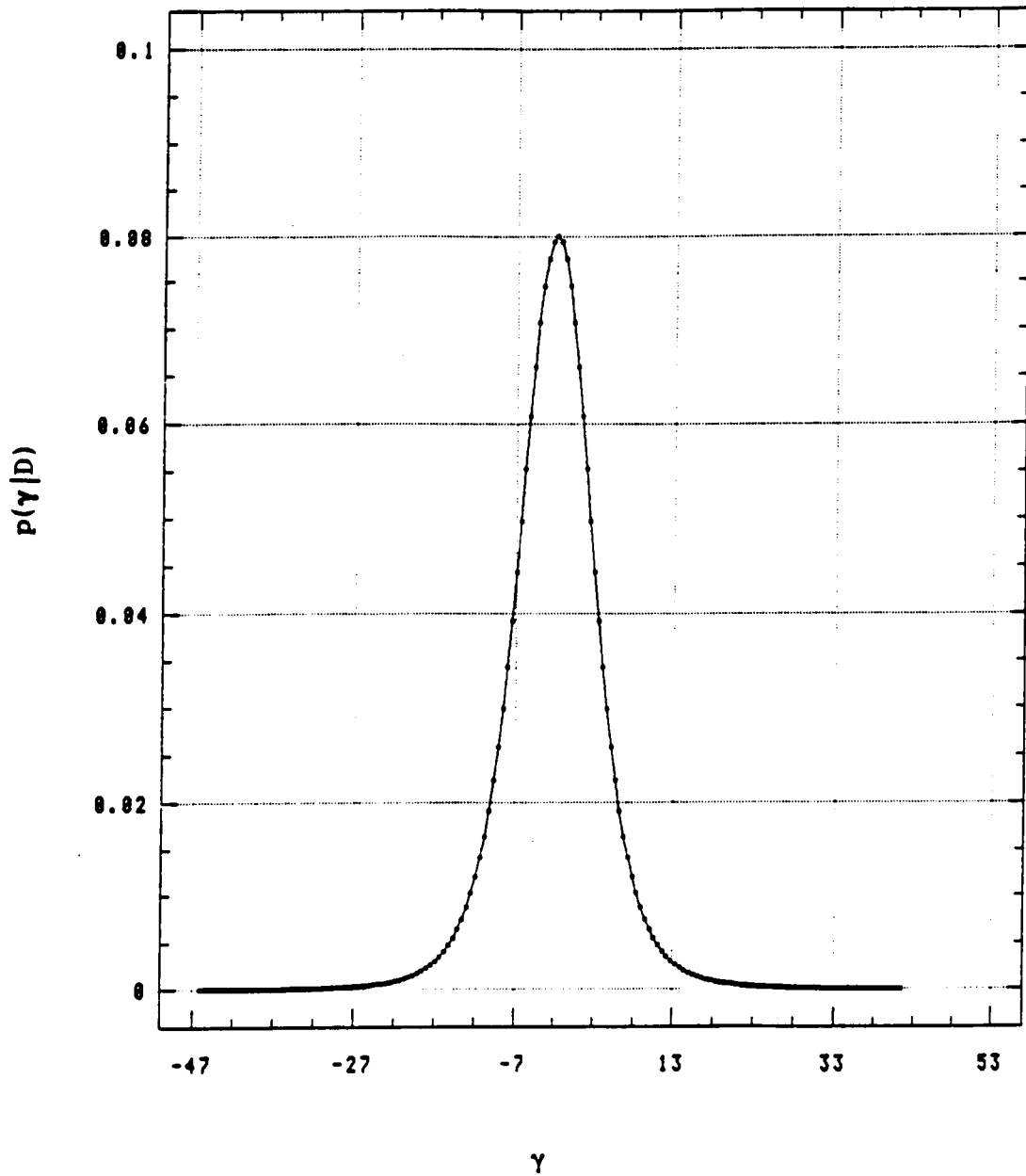


PLOT C-4

Source of Exposure: Depleted Uranium

Comparison: Thin chip vs. thick chip with old mylar

(note: γ is in units of mrem)

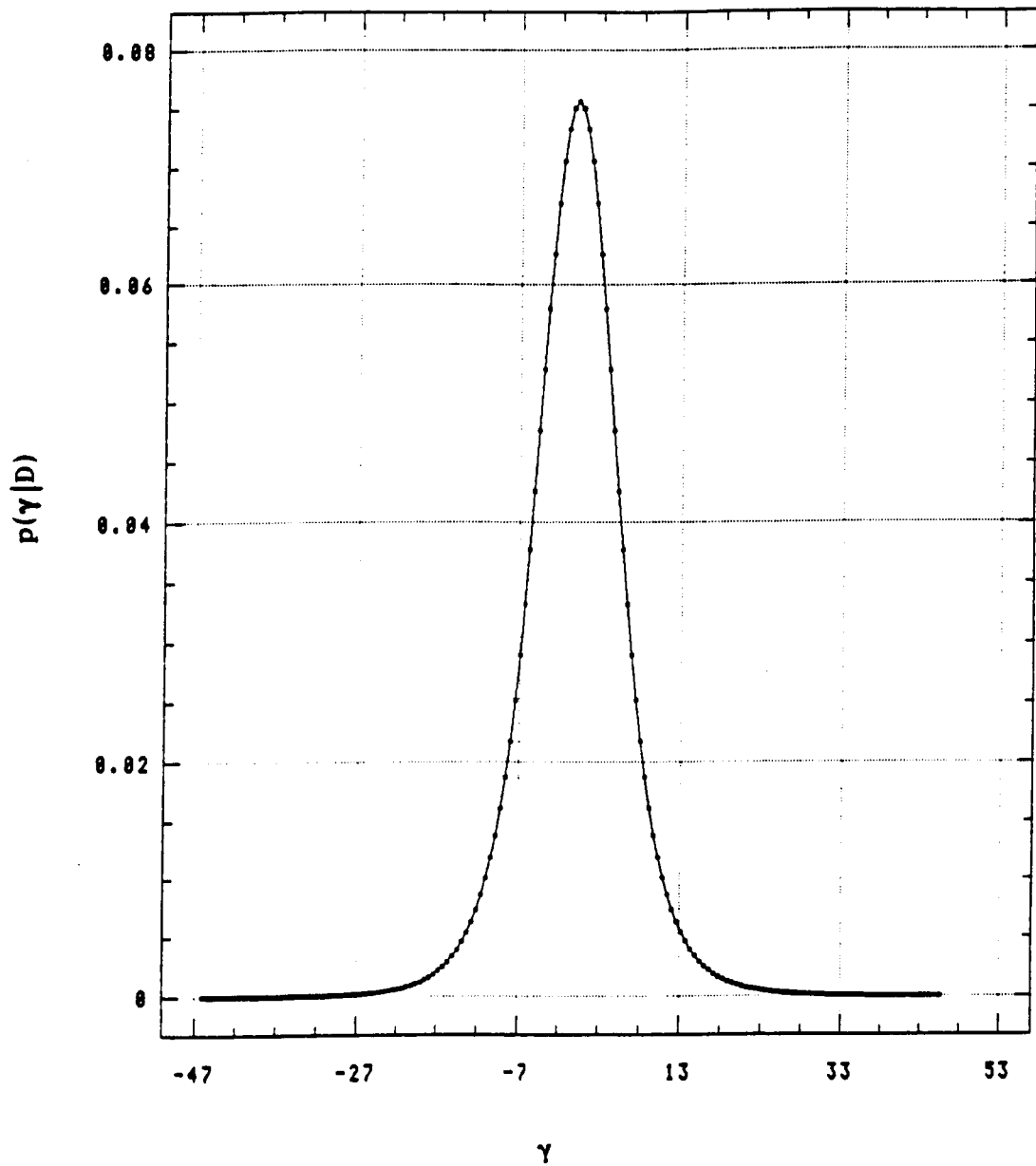


PLOT C-5

Source of Exposure: Depleted Uranium

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mrem)

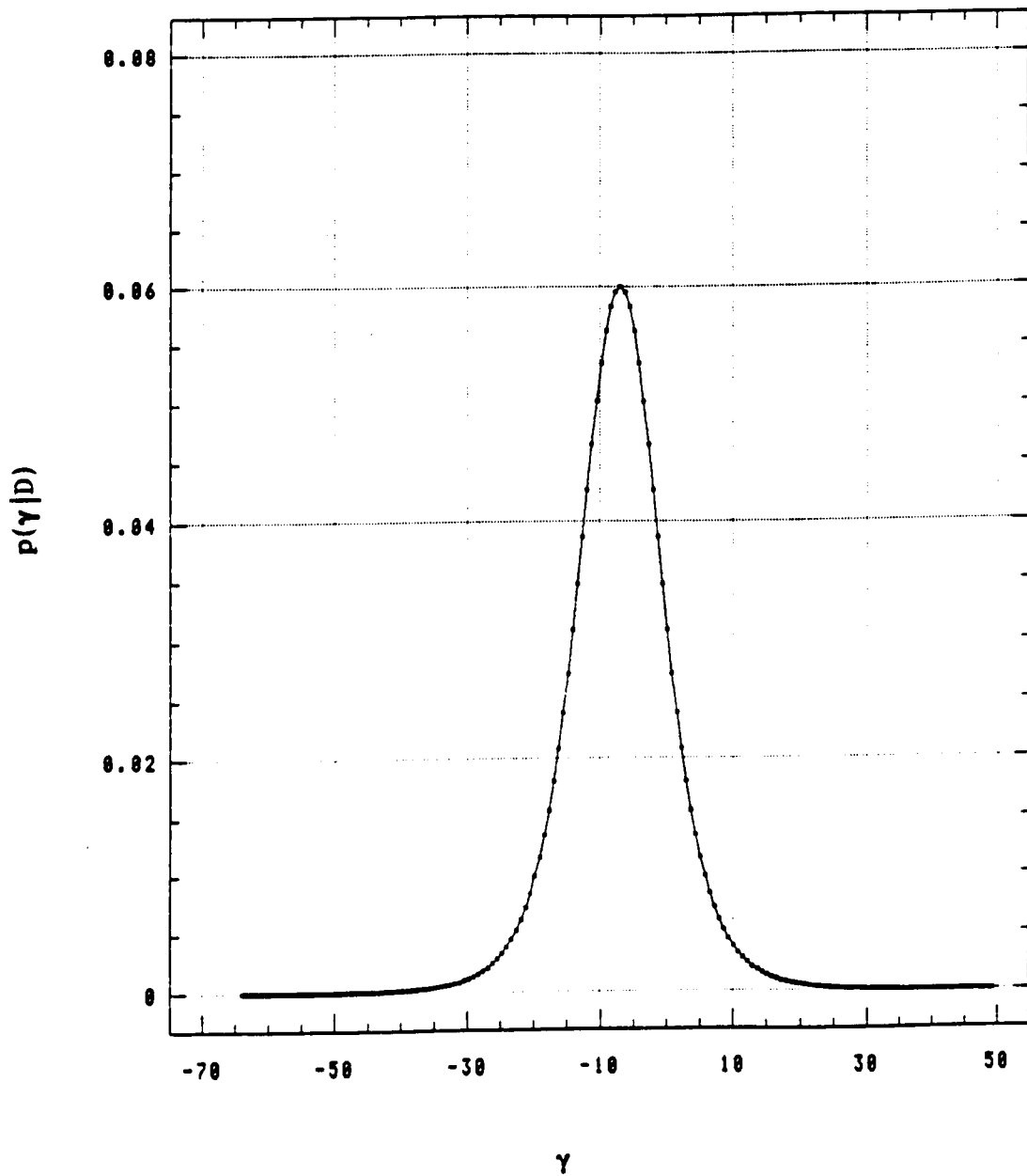


PLOT C-6

Source of Exposure: Depleted Uranium

Comparison: Current vs. proposed dosimeter

(note: γ is in units of mrem)

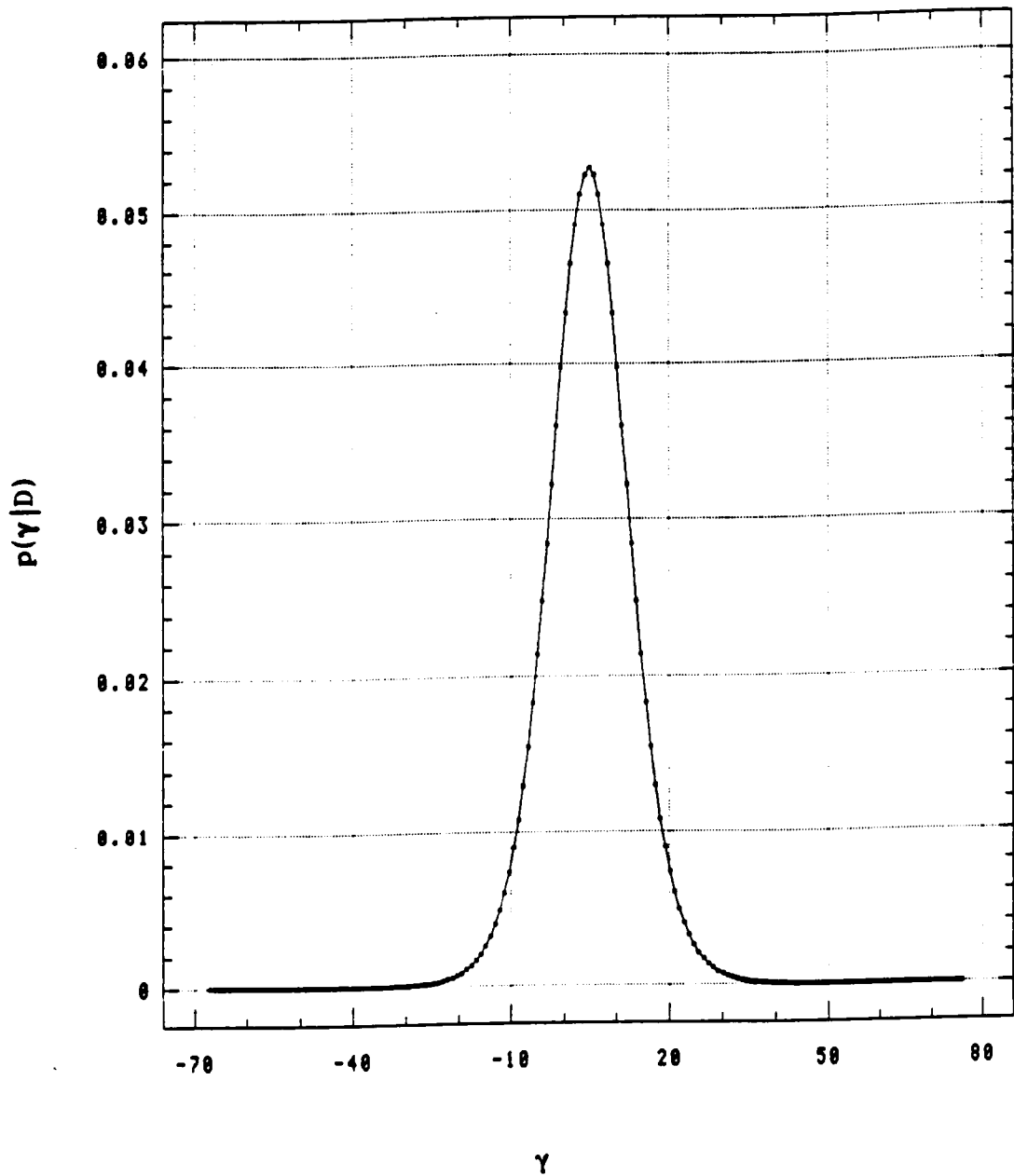


PLOT C-7

Source of Exposure: K17 x-ray

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mrem)

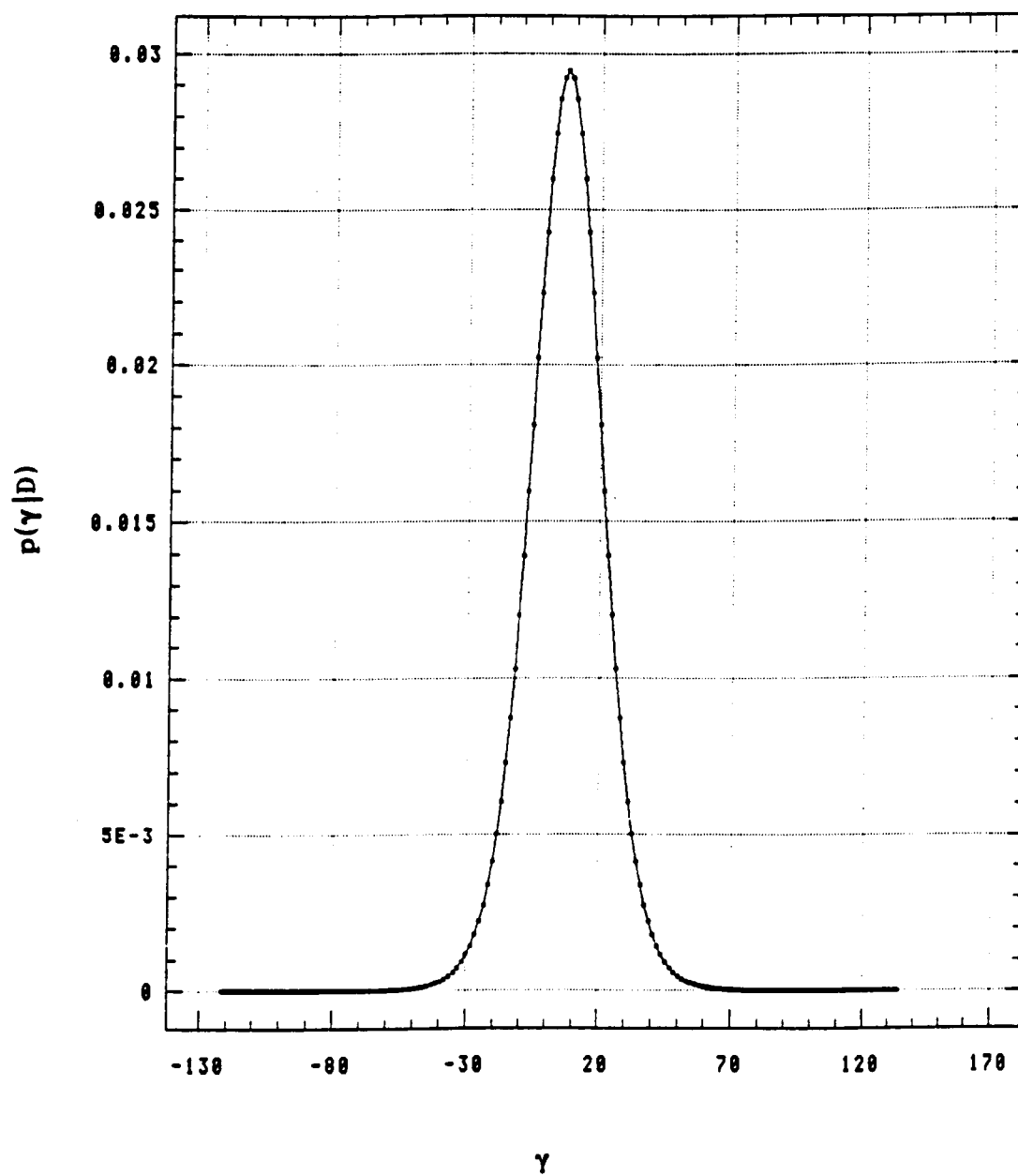


PLOT C-8

Source of Exposure: M30 x-ray

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mrem)



APPENDIX D

BEHRENS-FISHER PLOTS FOR AVERAGE CUMULATIVE

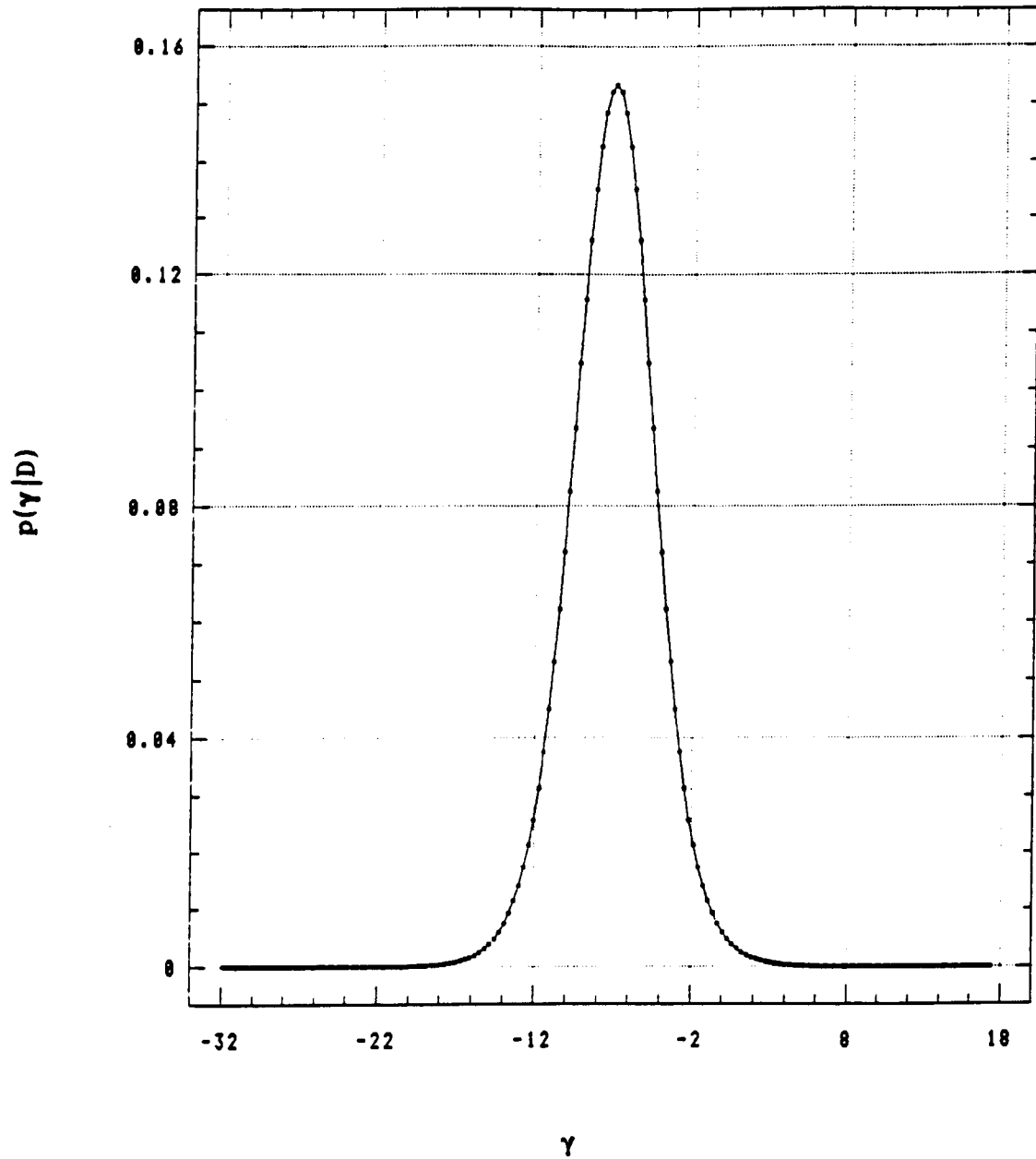
BACKGROUND RESULTS

PLOT D-1

Month: 1

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)

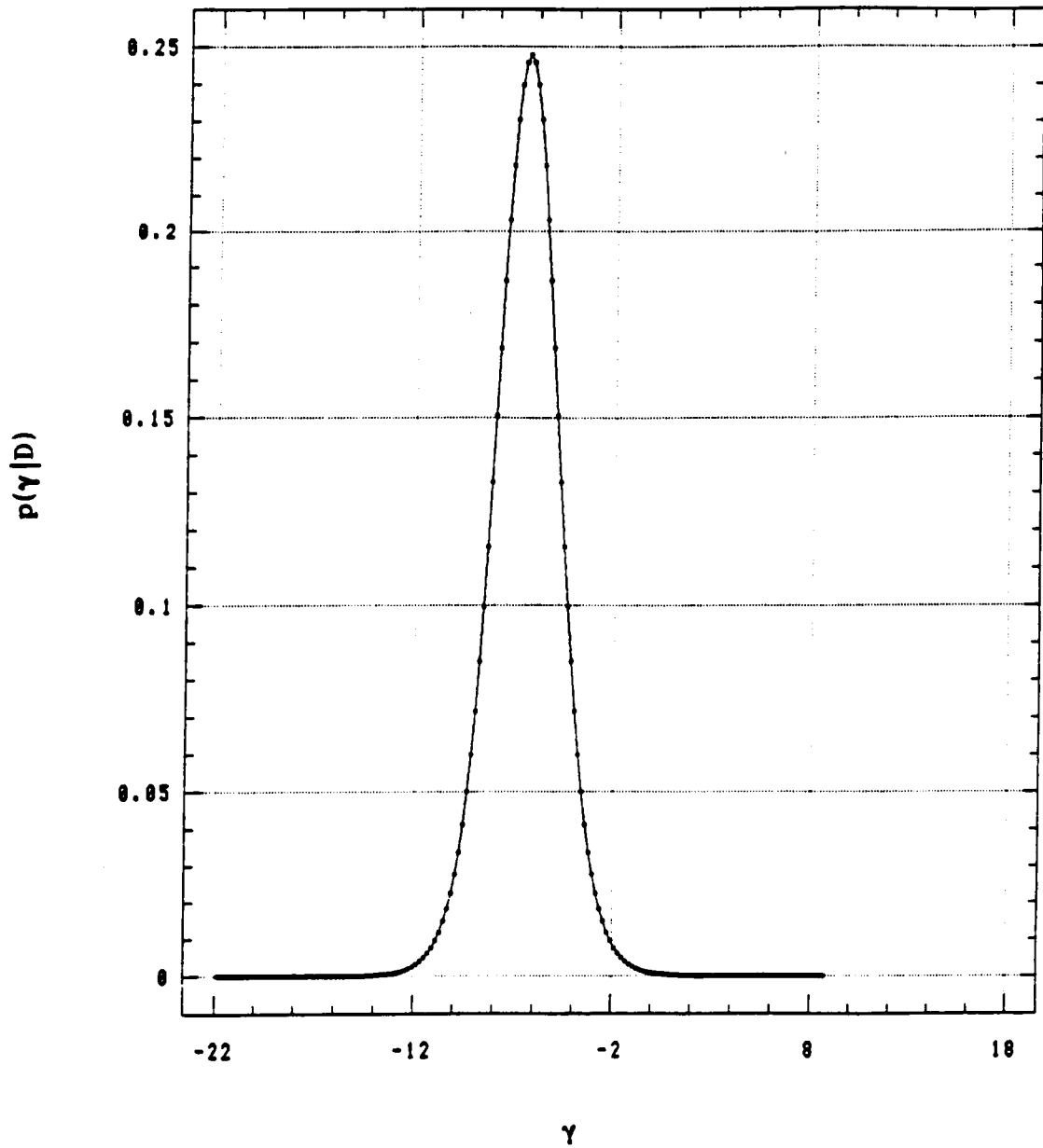


PLOT D-2

Month: 2

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)

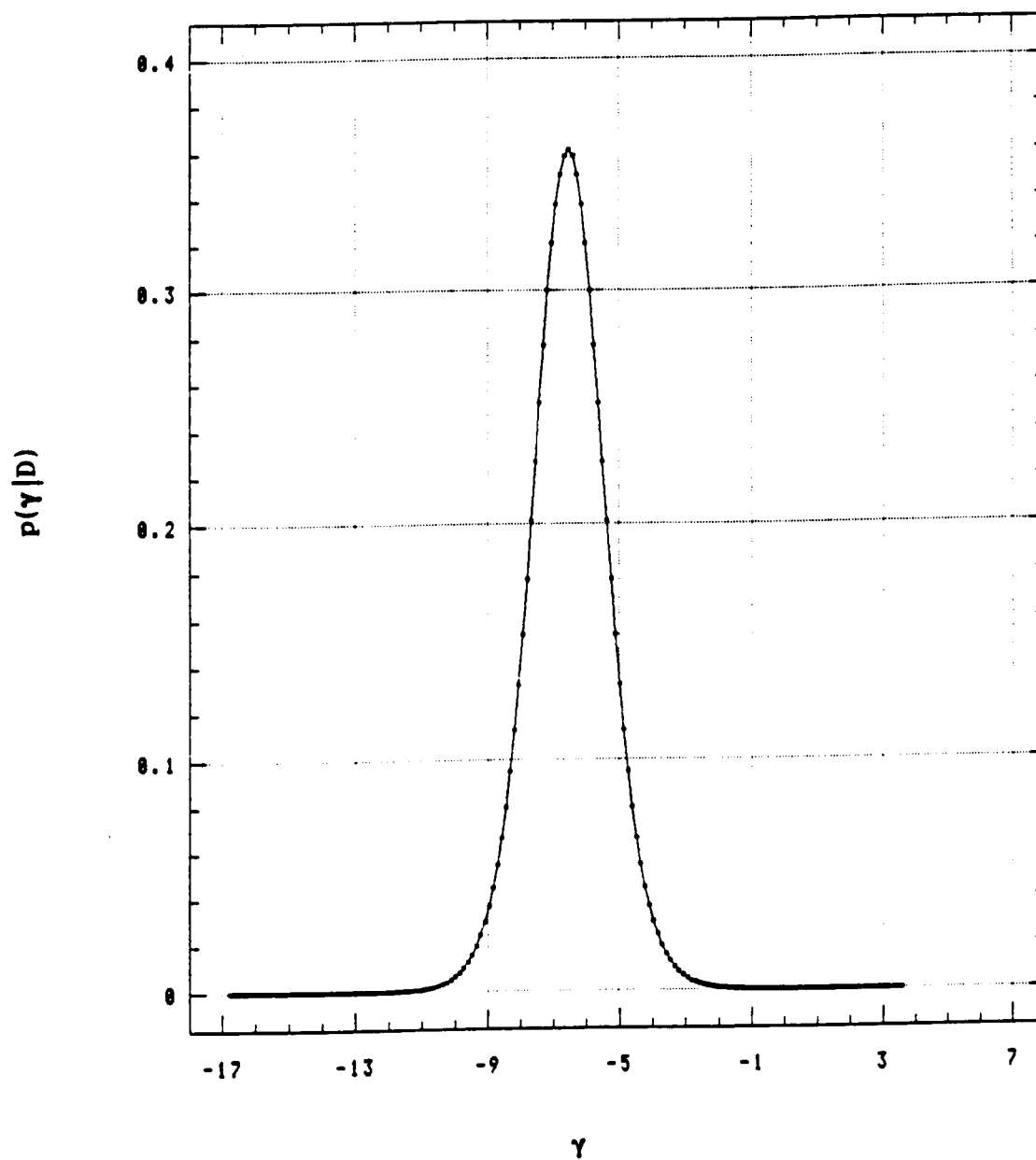


PLOT D-3

Month: 3

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)

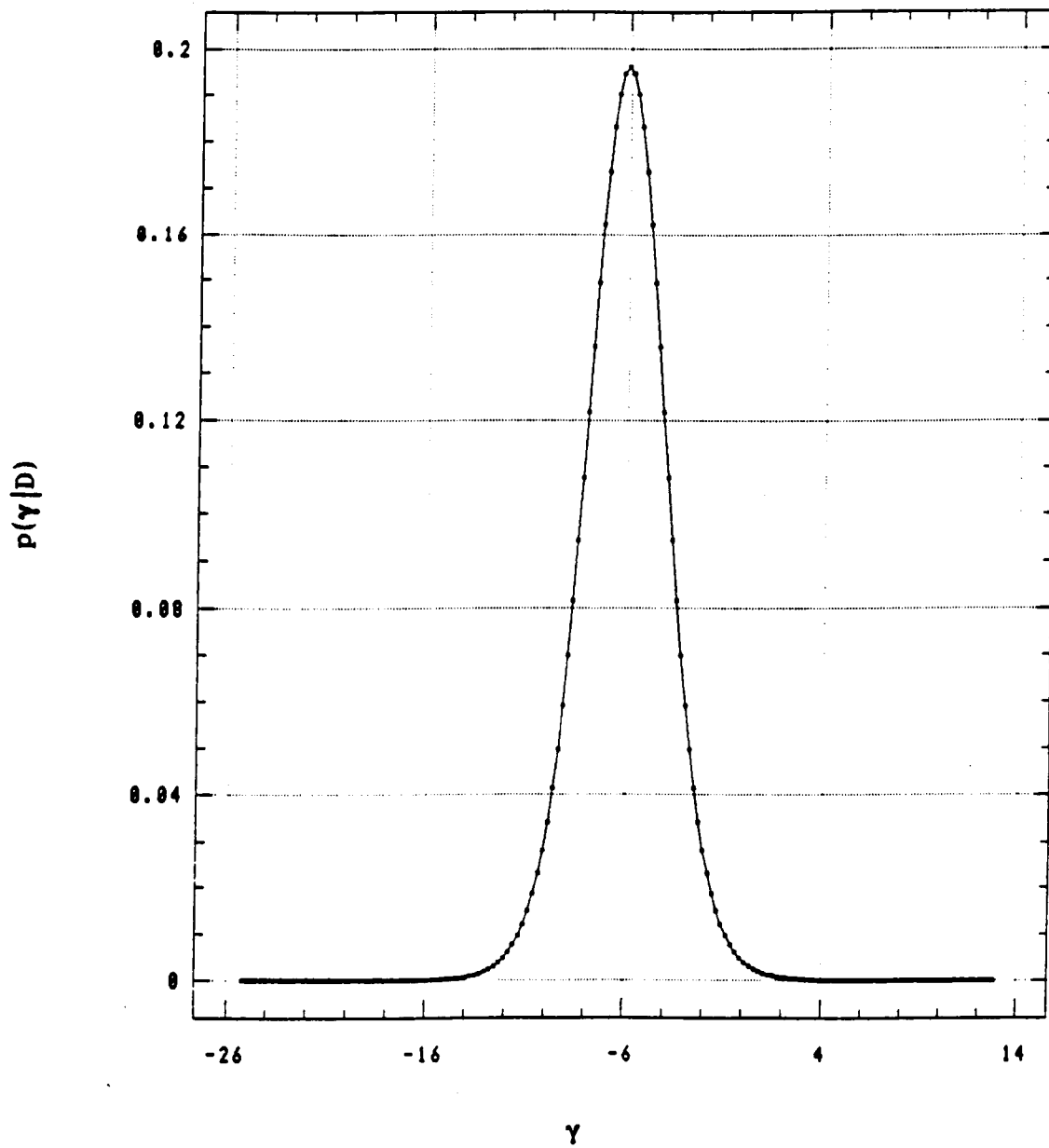


PLOT D-4

Month: 4

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)

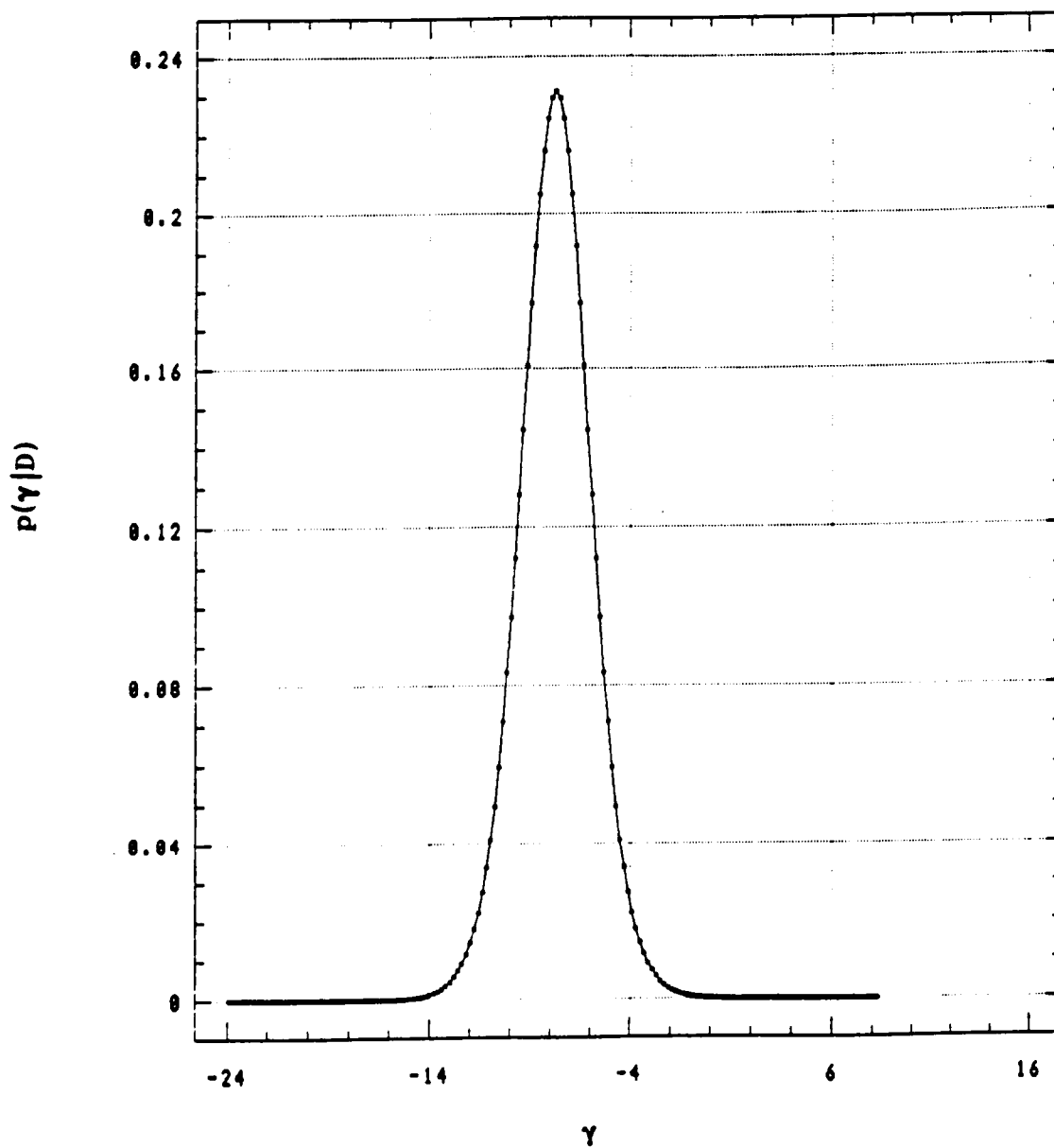


PLOT D-5

Month: 5

Comparison: Thin chip vs. thick chip with new mylar

(note: γ is in units of mR^*)



APPENDIX E

LOWER LIMIT OF DETECTION EQUATION AND

DEFINITIONS OF VARIABLES

LOWER LIMIT OF DETECTION (L_D) EQUATION

$$L_D = 2 \times \frac{(t_p S_0) + \frac{(t_p S_1)^2}{(H_1)^2} \times H_B}{1 - \frac{(t_p S_1)^2}{(H_1)^2}}$$

Definitions of Variables:

L_D - Lower Limit of Detection

H_0 - average reading (mrem) of unirradiated dosimeters,
calculated by "hand calculation" after subtracting
background

S_0 - standard deviation of H_0

H_B - average reading (mrem) of unirradiated dosimeters,
calculated by "hand calculation" without subtracting
background

H_1 - average reading (mrem) of irradiated dosimeters run
through the dose algorithm

S_1 - standard deviation of H_1

t_p - t distribution for $n - 1$ degrees of freedom and a p-value
of $< .05$

APPENDIX F

DOSE CALCULATION ALGORITHM

DOSE CALCULATION ALGORITHM

The dose calculation algorithm used in this project was developed by Harshaw Crystals and Electronic Products of Solon Technologies, Inc. It is designed to meet the requirements of the Department of Energy Laboratory Accreditation Program (DOELAP) for personnel dosimetry. The purpose of the algorithm is to identify radiation fields and determine the shallow and deep dose equivalents based on the output from the Harshaw 8800 TLD reader. The algorithm is usually calculated on a PC, but may also be computed by hand. The following is a brief overview of the steps involved in performing the dose algorithm. For a complete description of the algorithm, refer to Harshaw-Solon (1989).

The first step consists of entering the ECC corrected output from the reader (in units of mR^{*}) for each element position in the card and then subtracting the corresponding background values (obtained from the control dosimeters). Eight element ratios are then computed using the background-subtracted raw readings for each of the four element positions. A "decision-tree" type logic is used to compare the ratios to specified numerical ranges and, thereby, determine the type(s) of radiation to which the dosimeter was exposed .

Once the radiation field composition has been determined, the appropriate calibration factors (in units of mR^*/mrem) are calculated for the shallow and deep dose equivalents for that particular radiation field. The calibration factors which are referred to as r_{d1} (for deep dose) and r_{s3} (for shallow dose) are calculated using an existing data bank of calibration factors for different radiation fields. The background-corrected raw reading (in mR^*) for element position #1 is then divided by r_{d1} to determine the deep dose equivalent (in mrem). Similarly, the background-corrected raw reading for element position #3 is divided by r_{s3} to determine the shallow dose equivalent (in mrem). Fading and supralinearity corrections are then applied to get the final shallow and deep dose equivalents, which are in units of mrem.

V I T A

The author, Kimberly Janet (Loope) Nugent, was born in Knoxville, Tennessee on March 21, 1963. She attended elementary school, junior high school, and high school in the Knox County School District. She entered the University of Tennessee in 1980 to study Graphic Design. Because of her fascination with math and science, her interests later turned to engineering and she changed her major to Industrial Engineering in 1983 and received her B.S. degree in 1987. Upon completion of her B.S., she enrolled at U.T. as a graduate student in Industrial Engineering. She completed the coursework for her M.S. in 1989 and began looking for a full-time job while working on a thesis project. While looking into job prospects, she became increasingly aware of the Radiation Protection field and its importance in the local area. She then decided to apply her strong engineering background towards a M.S. degree in Nuclear Engineering with a concentration in Radiation Protection at U.T. She began working towards this degree in 1990 and did her thesis research at Oak Ridge National Laboratory. She expects to earn her M.S. degree, in Nuclear Engineering, in 1992.