BNL 17452

Conf-720614--5

HEALTH PHYSICS AND SAFETY DIVISION

DEVELOPMENTAL STUDY OF PERSONNEL NEUTRON DOSIMETRY AT THE AGS

Carl H. Distenfeld and Joseph R. Klemish, Jr.

December 12, 1972

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

MASTER

IN
F
O
R
M
A
L

R
E
P
O
R
T

DEVELOPMENTAL STUDY OF PERSONNEL NEUTRON DOSIMETRY AT THE AGS *

Carl H. Distenfeld

and

Joseph R. Klemish, Jr.

Health Physics & Safety Division
Brookhaven National Laboratory
Upton, New York 11973

Presented at the
Seventeenth Annual Meeting of the Health Physics Society
Stardust Hotel, Las Vegas, Nevada on 12-16 June 1972

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

* Research carried out at Brookhaven National Laboratory under Contract with the U. S. Atomic Energy Commission.

MASTER

REPRODUCED FROM THE NATIONAL ARCHIVES
14

ABSTRACT

Neutron exposure at Brookhaven National Laboratory is primarily received by the occupants of the experimental facilities associated with the Alternating Gradient Synchrotron. The exposure field is composed mainly of neutrons and gamma rays of differing composition and energy spectra.

Natural thorium fission track detectors and ^6LiF TLD materials are capable of responding to different parts of the neutron spectra. This provides a discrete response for each exposure spectrum. The personnel monitoring value of a fission track-TLD system depends on consistent dose equivalent response with field location. A multisphere Bonner neutron spectrometer was used to determine the maximum neutron dose equivalent. Concurrently, ^{232}Th fission track detectors and TLD (^6Li and ^7Li) were exposed. This procedure was repeated to establish the variation of calibration constants with field location. The constants weighted over field spectral variations are 3.5 mrem/spark for the Th fission track detector and 0.2 to 0.04 mrem/mR for the TLD difference detectors, depending on spectrum softness defined as TL to track ratio.

The most significant difficulty in employing thorium fission track detection involves the radioactivity of the detector and the prejudice against monitoring exposure with a radioactive dosimeter. In this regard the fission track efficiency was studied with different foil thicknesses down to about one micron. It was observed that the production of fission fragments is optimum for foils of about 5 microns and thicker. The personnel exposure from a minimally shielded foil of about 5 microns thickness (5 cm^2) is about 1.3 to 2.1 mR/40 hour week at 0.5 cm for foils about 2 to 15 years old.

DEVELOPMENTAL STUDY OF PERSONNEL NEUTRON DOSIMETRY AT THE AGS

- I. INTRODUCTION
- II. OTHER PERSONNEL NEUTRON DOSIMETRY SYSTEMS STUDIED
 - A. TSEE
 - B. Radiophotoluminescence
 - C. TLD
 - 1. Mixed γ -n Response
 - 2. Neutron Energy Spectra Response
 - a) Area Factors
 - b) Response Modifications
- III. THE BROOKHAVEN EXPERIMENTAL NEUTRON DOSIMETER, BEND
 - A. Introduction
 - B. Energy Response
 - 1. Neutron Fission
 - 2. Photofission
 - C. Prototype Personnel Dosimeter and Experimental Holder
 - D. Post Irradiation Processing
 - E. Spark Counting
 - F. Fission Radiator Comparison
 - G. Efficiency of Different Radiator Thicknesses
 - H. Dosage Response
 - I. Background
 - J. Miscellaneous Studies
 - 1. Prespark Neutralizing
 - 2. Multiple Spark Counting
 - 3. Spark Time Dependence
 - 4. Foil Thickness
 - 5. Additional Studies
- IV. AGS EXPOSURE SPECTRA
 - A. Air Scatter
 - B. Ground and Heavy Shield Wall Scatter
 - C. Secondary Beam Lines and End Stops
- V. FIELD EVALUATION
 - A. East Experimental Area
 - B. Spectrometer
 - 1. General
 - 2. Accuracy

C. Method

1. Experimental
2. Calculational

D. Discussion and Results

1. General
2. Gamma Dosimetry
3. Film Neutron Dosimetry
4. BEND Results
5. Summary

VI. CONCLUSION

VII. ACKNOWLEDGMENTS

I. INTRODUCTION

A suitable personnel neutron monitoring detector must be capable of integrating the exposure, storing the information for periods of two or more weeks, and be easily and accurately evaluated thereafter. Information storage requires the dosimeter to be free of significant fading for time periods equal to the integration time. Fig. 1 describes the results of a fading study⁽¹⁾ on the present personnel neutron dosimeter at Brookhaven National Laboratory, BNL. The work defined fading of neutron track film (Kodak, Type A, NTA) as a function of time and humidity.

The average on-site summer relative humidity, RH, is about 70%⁽²⁾. This time integrated average reflects limits approaching 100% RH during the late evening, night and early morning, and lesser amounts during the late morning, afternoon and early evening.

Fig. 2 is a replot of the earlier information for a 3-week wearing (storage) period. Assuming the loss of original tracks, fading, to be exponentially related to relative humidity for values $\geq 60\%$ RH, 10% RH increments further reduce the tracks by e^{-1} .

K. Becker⁽³⁾ argued that the fading rate vs. humidity should be larger. He suggested that a few days were required for the film, normally stored at low temperature and humidity, to come into equilibrium with the wearer's humidity.

The Alternating Gradient Synchrotron (AGS) accounts for 81.6%⁽⁴⁾ of BNL's personnel gamma exposure, and 88.6%⁽⁴⁾ of the Laboratory's neutron exposure (1971). Most of the neutron exposure is received in the non-air conditioned experimental buildings. The structures are well-ventilated aircraft hangar type metal buildings with inside atmospheric conditions similar to those outside. Normal film wearing period at the AGS is 2 weeks; however, the average wearing period is longer and 3 weeks is assumed. Considering an average humidity of 70%, and wearing period of 3 weeks, 80 to 90% fading is predicted for exposures occurring early in the wearing cycle.

This violates a basic requirement of personnel neutron dosimeter, storability, and prompted a developmental investigation of other systems.

II. OTHER PERSONNEL NEUTRON DOSIMETRY SYSTEMS STUDIED

A. Thermally stimulated Exoelectrons (TSEE)

Attempts were made to experimentally evaluate TSEE methods for personnel neutron dosimetry. A reader was constructed by adapting a Nuclear Measurement Corporation (NMC) gas flow proportional counter chamber to a BNL alpha

counter base. The sample slide assembly was converted to heater service. Temperature was controlled by a thermocouple sensor in a servo loop with a linear ramp heater power supply. Ceramic discs of beryllium oxide, Thermolox 995⁽⁵⁾ 0.04" thick by 0.47" diameter, and plated films of graphite powder and beryllium oxide⁽⁶⁾ on graphite discs were tested for radiation response. The following is a listing of some of the measurements made after 1350°C. activation:

1. Plateau with 2 counting gases
 - a) CH₄
 - b) 99.5% He + 0.5% isobutane
2. Counting rate vs. temperature for different irradiations and heating rates.
3. Temperature studies across the heated ceramic dosimeter disc in air, He and CH₄.
4. Effect of counting gas flow rate.
5. Post reading annealing temperature studies.

It was concluded that the BNL reader, annealing procedure, and detectors were not reproducible enough for dosimetry purposes.

B. Radiophotoluminescence

A Toshiba reader⁽⁷⁾ was used to study reproducibility and precision. Dosimeter glasses were obtained from the Toshiba Electric Company of Japan (8 x 8 x 4.5 mm FD PB-1). The glass stock contained about 43% lithium phosphate by weight, and only the natural isotopic mixture of lithium was available.

Wearer exposure was derived by taking differences between present and past determinations. Measurements⁽⁸⁾ indicated that a precision of 250 ± 20 mR could be achieved for gamma exposure.

Mixed gamma and neutron dosimetry could be performed as follows:

1. Determine response between Cd filtered and unfiltered Low-Z Toshiba glasses. This requires separate gamma energy correcting filters. Cd filtered dosimeters will read too high due to thermal neutron activation of Cd.
2. A neutron response can be gained by differences between Schulman

and Toshiba low-Z glass. Advantage can be taken of the neutron insensitivity of Schulman glass. This also requires separate gamma energy correcting filters.

Many of the above problems could be eliminated by compounding the lithium glass with ^6Li and ^7Li phosphate. This sophistication was routinely available in thermoluminescent materials. This reason, together with the uncertain U.S. availability of readers, parts, and dosimeter glasses, was the basis for considering thermoluminescence.

C. Thermoluminescent Dosimeters

The neutron response of ^6LiF thermoluminescent (TL) dosimeters, TLD 600, made by the Harshaw Chemical Company, is well known⁽⁹⁾. Unrestricted use of this material for mixed field dosimetry depends on a clear gamma and neutron sensitivity and a neutron energy spectra response that follows the ICRP-20 recommendations for maximum dose equivalent (M A D E).

1. Mixed Gamma-neutron Response

A gamma adjustment⁽⁹⁾ can be made by using a co-exposed second dosimeter which is much less neutron sensitive. This dosimeter is composed of ^7LiF (Harshaw TLD 700). The atomic similarity of the ^6Li and ^7Li fluoride allows subtraction without regard to gamma energy spectra corrections. Thus TLD 700 dosimeters that are first neutron response batched and then rebatched for gamma response, can be subtracted from neutron and gamma batched TLD 600 material, netting a response clearly due to neutrons.

2. Neutron Energy Spectra Response

^6LiF is a thermal neutron detector. $^6\text{Li} (n, \alpha) ^3\text{He} + 4.78 \text{ MeV}$, has a thermal cross section of about 1,000 barns⁽¹⁰⁾. The cross section follows the reciprocal of velocity to about 100 KeV, thereafter increasing in a small resonance, 0.3 MeV, and further declining at about the previous rate. Due to the large thermal cross section, most of the thermoluminescence displayed by ^6LiF is caused by reaction with the thermal fraction of a continuous neutron spectra. Use of this mechanism for personnel neutron dosimetry requires the energy spectrum to be spatially invariant, and this is unlikely in a large and heterogeneous laboratory. Two solutions are possible,

as follows:

- a) Area Factors - Assign calibration factors reflecting a building or area energy spectrum. This requires a stable radiation worker population.
- b) Response Modifications - Filter, partially moderate, or otherwise modify the thermal response of ^6LiF detector to induce M A D E spectral independence. The contribution of albedo (backscattered) neutrons⁽¹¹⁾ is included. Detailed Monte Carlo calculations⁽¹²⁾ have been made quantifying the backscattered thermal and total neutrons per unit incident neutron within the energy range 3×10^{-7} to 10^1 MeV. The calculations include isotopic and normal particles incident on a tissue-like 30 cm semi-infinite slab. For both cases, the thermal neutron fraction of the albedo neutrons monotonically declines with increasing incident neutron energy. At 3 eV, 65% of the normally incident neutrons are returned thermalized. This decreases to about 6.5% at 10 MeV. Unfortunately, the dose per neutron increases with energy, so that the two are counterproductive. Albedo neutrons cannot be used to distinguish between a given fluence of intermediate energy neutrons and a larger number and dose equivalent of fast neutrons⁽¹³⁾. Fortunately, many practical exposure spectra are energetically limited and quasi-stable. Thus, two or more different portions of a restricted energy spectrum, permit use of an appropriate spectrally weighted calibration factor. This technique is widely used in a number of laboratories^(14,15,16,). Present methods⁽¹⁵⁾ allow the energy spectrum to be divided into <0.4eV thermal, >0.4eV epicadmium, and albedo portions. The "windows" through which the energy spectrum must be viewed are adequate for heavy metal processing plants and some reactor installations^(14,15,16,17). This is true, since the epithermal and thermal portions of the energy spectra encountered in shielded glove box and some reactor facilities dominate the energy spectra, and allow a sensitive determination of the M A D E via, an appropriate area calibration factor.

III. THE BROOKHAVEN EXPERIMENTAL NEUTRON DOSIMETER (BEND)

A. Introduction

Leakage, radiation-produced by a high energy accelerator, establishes a broad exposure spectrum ranging to 100's of MeV. This requires that dosimeters be able to respond to the whole or major fraction of the exposure spectrum.

The method employed used a TLD 600 and 700 pair to respond to the soft components and another dosimeter for the fast. The fast neutron detector selected employed natural thorium (n, fission), recorded on thin polycarbonate foils. The spark detection method basically followed the earlier work of W. Cross and L. Tammasino^(18,19). A schematic drawing of the BNL reader is shown in Fig. 3.

Some important features of the damage track detector follow:

1. No observable fading at room temperatures for at least a year⁽³⁾.
2. Adequate sensitivity.
3. Spark counting provides easy readout.
4. Adequate energy response.
5. Low background.
6. Fissioning radiator may be radioactive, causing some personnel exposure.

B. Energy response

1. Neutron Fission

The basic response of the damage-pit dosimeter depends on the fission radiator used. Fig. 4 describes the fission energy response of ^{238}U and ^{232}Th . Apparently ^{238}U would make a more sensitive fission radiator, since the fission cross section is everywhere larger. Unfortunately, the excessive background of uranium precludes its use as a practical detector material. Detector background depends on cosmic ray induced fission and spontaneous fission decay of the detector material. The spontaneous fission half-life of ^{238}U is 0.8 to 1.3×10^{16} years, while thorium⁽²⁰⁾ is reported to be $>10^{20}$ years, about 10^4 less probable. Experimental measurements⁽²¹⁾ employing ^{238}U reflect a rate of about 1 spark/cm² per day. Considering an AmBe laboratory exposure spectrum, this corresponds to about 1.5×10^6 n/cm²/day

or 11 mrem/day. This is about 50% of the daily chronic exposure limit, prohibiting consideration of uranium as a fission fragment radiator.

An energy comparison (Fig. 4) can be made between NTA film and thorium. The experimental NTA film badge data⁽²²⁾ are presented per unit neutron per cm² for normal incidence on a water filled thorax phantom. Cross section is similar, permitting curve shape comparisons and suggesting the following:

- a. NTA film has a useful response above about 0.6 MeV.
- b. The 20 MeV film response is unspecified.
- c. The general shape for all detectors is similar.
- d. Th can usefully detect neutrons above 1.5 MeV.
- e. The (n,f) and (p,f) tie points are very good.
 $\leq 35 \text{ MeV}^{(10)}$; $>35 \text{ MeV} \leq 120 \text{ MeV}^{(23)}$; $120 \text{ MeV} \leq 320 \text{ MeV}^{(24)}$, $>320 \text{ MeV}^{(25)}$.
- f. Thorium can be used $\geq 1 \text{ GeV}$.

The practical exposure spectrum is expected to be continuous from 10^{-8} to about 10^2 MeV . Approximately 2 orders of magnitude are covered by the Th detector. The remaining eight must be detected by TL material.

2. Photofission

Photofission may compete with neutron induced fission. Fig. 4 illustrates the energy dependence above 100 MeV. The photofission cross section <100 MeV smoothly declines to a minimum of about 1 mb at 70 MeV, and thereafter increases (giant resonance) to a maximum of about 51 mb at 14.1 MeV. Below 15 MeV the photofission cross section falls to <1 mb at about 5 MeV.

The importance of photofission can be evaluated by comparing the energy weighted neutron and photon fission cross section for similar field conditions. Both the neutron⁽²⁶⁾ and photon⁽²⁷⁾ spectra were determined, and the field weighted cross sections are as follows:

$$\text{Photofission} = 12.1 \text{ mb} = \frac{\int_{5.4 \text{ MeV}}^{640 \text{ MeV}} \phi_{(E)} [\sigma_{\gamma-f}]_{(E)} dE}{\int_{5.4 \text{ MeV}}^{640 \text{ MeV}} \phi_{(E)} dE}$$

where:

$\sigma_{\gamma-f}$

$<17.5 \text{ MeV}^{(28)}$

$35 \text{ to } 240 \text{ MeV}^{(29)}$

$>300 \text{ MeV}^{(30)}$

$$\text{Neutron Fission} = 605.2 \text{ mb} = \frac{\int_{1.5 \text{ MeV}}^{1.26 \text{ GeV}} \phi(E) [\sigma_{n-f}(E)] dE}{\int_{1.5 \text{ MeV}}^{1.26 \text{ GeV}} \phi(E) dE}$$

Stray photon energy spectra were determined and normalized⁽²⁷⁾ to the measured neutron fluences at 3 AGS locations. Results indicate that an average integral photon fluence is about 1.2 γ per. Neut. Considering the foregoing neutron induced fission clearly dominates the fission processes. The field location selected is known to have a relatively thin shield, hence a fairly intense hard neutron spectrum, and the most intense photon spectrum. Since this case is assumed to be the limit, it is concluded that photofission can be neglected.

C. Prototype Personnel Dosimeter and Experimental Holder

Two exposure containers (Fig. 5) were used. The larger, termed a holder, accommodated more samples and was extensively used to provide the data base for this study. The smaller was worn as a personnel dosimeter badge. Both containers feature a lucite face and aluminum back of approximately the same thickness. The transparent faces allow wrinkle-free loading of the 10 micron thick, 3 cm diameter, discs of Kimfol⁽³¹⁾ foil. The holders and badges were loaded on either side of the thorium metal fission radiator in a sandwich-like structure.

D. Post Irradiation Processing

After irradiation, the foils were removed and etched in 6N KOH at 65°C for 75 minutes. Minimum stirring on a 15-minute cycle seemed adequate to prevent foil to foil and foil to etching chamber adhesion. The etched foils were

removed and washing in distilled water for 15 minutes and oven dried at 100°C for another 15 minutes. The dried foils were allowed to equilibrate to room ambient conditions for at least one hour prior to spark counting.

E. Spark Counting

Etched foils contained holes corresponding to the passage of the fission fragments. Hole dimensions, for constant etching conditions, depended on the incident energy and angle of the fission fragments. Normal variations in both resulted in a spectrum of hole sizes establishing a counting-voltage plateau with a relatively large slope. Precount sparking at 1060 Volts served to improve the efficiency and stability of a subsequent spark counting at 560 Volts⁽³²⁾. Fresh cathode foils of metalized Kimfol were used for all sparking operations.

F. Fission Radiator Comparison

1. Some Additional Selection Criteria

Fission cross section energy relationships limit selection of an appropriate radiator to alloys or metal films of neptunium or thorium. Uranium was previously discounted due to excessive background by spontaneous fission. The remaining materials are compared in Table 1.

²³⁷Np has a significantly larger fission cross section⁽¹⁰⁾. The ratio of ²³⁷Np to ²³²Th neutron fission cross sections weighted over the O'Brien spectrum⁽²⁶⁾ is 8.12. Table 1 compares ²³²Th and ²³⁷Np assuming a uniform radiator foil of 5 mg/cm² thick and 3 cm in diameter. Clearly ²³⁷Np could be alloyed to approximate the lower fission sensitivity of thorium, and thereby reduce the relative internal and external hazard (²³⁷Np/²³²Th) to 266 and 308 respectively. AEC derived ²³⁷Np⁽³³⁾ usually contains <0.1% ²³³U and 0.03% Pu. The latter should produce a strong response to thermal and epithermal neutron fission.

It is clear that thorium is considerably less hazardous, less expensive, and more easily available.

2. Wearer's Exposure

The magnitude of the decay gamma exposure to the wearer depends on the mass of thorium required (Fig. 6). This may be contrasted with the radiator thickness needed for acceptable track registration (Fig. 7). Thus a 5 mg/cm^2 radiator of 5 cm^2 area could cause a 4 week, 40 hour exposure of about 5 mR (slope = 1) to a point 0.5 cm from the radiator center. Assuming a badge (as above) is worn on the breast pocket, and the critical organ is the skin, the dose delivered would be 5 mrad/4 weeks. Taking natural cosmic and gamma ray yearly background as 98 mR, the skin would receive an exposure of $98(\frac{4}{52}) = 7.5 \text{ mR}$ due to background, while the thorium decay gamma rays would deliver an additional exposure of 5.0 mR, a 70% additional exposure delivered to a small fraction of the organ.

G. Efficiency of Different Radiator Thicknesses

Evaluation of absolute radiator efficiency allows direct determinations of fluence from an observed quantity of sparks, knowing both cross section and energy of the incident neutrons. The number of fissions detected, S , is related to efficiency as follows:

$$S = N_{\text{th}} E_x \int (\phi(E) \sigma_f(E)) dE$$

where

N_{th}	= thorium atoms
$\sigma_{f(i)}$	= fission cross section
$\phi_{(i)}$	= fluence
E_x	= restricted efficiency
E_x	= $E_D E_R$
E_D	= detector efficiency
E_R	= radiator efficiency

Efficiency is dependent on both the detector foil and fission radiator thickness. Passage of fission fragments through foil and radiator are impeded by ionization loss, charge transfer, and nuclear collision. Restricted efficiency is the combined efficiency of a given radiator and detector. Radiator efficiency can be determined by extrapolating detector response (per unit

radiator thickness) to zero thickness with radiator thickness (Fig. 8). The value noted, 44.4%, is attributed to the 6.4 mg/cm^2 radiator; detector efficiency can be determined by solving the fission production equation for known values of the variables. This calculation was performed for a 10 micron Kimfol detector; results indicated a restricted 2π efficiency of 22.2% and a detector efficiency of 50%, $(\frac{22.2}{44.4})$.

An interdependence should exist between radiator and detector efficiencies due to the angular dependence of the emerging fission fragments and its variation with radiator thickness. The number of straight ahead to total fragments should decrease with decreasing thickness. Assuming the detector foil efficiency to be inversely related to angular divergence it was expected that a sublinear deviation would occur near this ordinate. Considering Fig. 8, a linear relationship exists within the experimental error noted. The constant slope suggests that an interdependence effect is either small or not present.

H. Dosage Response

Each spark passing through the detector foil causes the evaporation of aluminum film from the electrode foil. The evaporated area depends on the following:

1. Maximum potential difference, 1060V and 560V.
2. Energy available for sparking, .002 mfd $(V^2/2)$.
3. Detector foil hole diameter, 2 to 10 microns.
4. Detector foil hole length, ≥ 10 microns.
5. Electrode pressure, $100 \text{ gm}/4.46 \text{ cm}^2$.

The present pre-spark counting parameters produce easily visible evaporated areas of 0.5 to 1.4 mm in diameter on the cathode metalized foil. This is about 30 times larger than the spark enlarged detector foil holes. Since the number of fission fragments is proportional to dose, for a given spectrum, the number of sparks should also be. Deviation from proportionality appears above about 270 sparks/cm^2 (Fig. 9). This is true of foil number 1 on either side of the thorium radiator. Additionally, the error limits, standard deviation of the mean (SD), increase with dose. The slope shift and expansion of experimental error is due to electrical isolation⁽³²⁾ of unsparked portions of the electrode foil by perimeters of evaporated aluminum. Taking the average

value of 0.99 mm for the diameter of holes produced by the pre-count spark 1060 Volts treatment, the total evaporated area of 1000 sparks should be 7.7 cm^2 . This compares with 4.46 cm^2 of electrode area, indicating that the mean diameter of the evaporated areas must decrease with increasing sparks and that the total evaporated area competes with the total available area, accounting for the departure from linearity.

The linear dose-spark limit can be extended by reducing the stored energy available for sparking, conducting the sparking operation at elevated pressure⁽³²⁾, or using a second "piggy-back" foil (Fig. 9). Foil 2 has a linear, slope one, detector response to >50 rem delivered to a 5 gallon water phantom. The first foil acts as a factor of 50 attenuator allowing only the most energetic, nearly normal incident particles to be etched through the second or "piggy-back" foil. Assuming a neutron exposure spectrum similar to AmBe and a 1200 spark linearity limit, the second foil should be linear to about 80 rad, $[50 (\frac{1200}{100})/7.6]$, and have a useful response to about 362 rads, $[50 (\frac{3300}{60})/7.6]$. The present overall reproducibility of the "piggy-back" foil is about 20% SD. First foil results vary between 5 and 10% SD for about the same number of sparks. Apparently the mechanism responsible for at least part of the first foil deviation affects the second foil. This mechanism may be variations in detector foil thickness. 20% SD is considered to be acceptable in practical accident dosimetry.

I. Background

Background sparks are a composite of holes or pits caused by cosmic ray and terrestrial neutron fission and holes, creases, or other defects in the foil. Measurements of 151 unirradiated bare foil samples established a bare foil background of $0.96 \pm 1.13 \text{ SD sparks}/4.46 \text{ cm}^2$. Composite Th-foil backgrounds were measured over an 28-week period, and $9.2 \pm 4.4 \text{ SD sparks}/4.46 \text{ cm}^2$ determined for a group of 10 samples. This composite background reflects a monthly M A D E of about 5 mrem, and should offer no difficulty in determining occupational exposure. For low exposures, the 560 Volt sparked metalized foil can be visually scanned (Fig. 10) with a light box or built-in light source under the sparking device. Interconnected tracks in a near background field are certainly due to mechanical defects in the foil. A more correct spark value can be determined by simple visual counting, taking all connected tract groups as unity.

J. Miscellaneous Studies

Standard exposure etching and spark evaluation provide reproducible, dosimetrically useful data of about 10% $\overline{SD}$. The expected deviation for a normal distribution is generally better than the observed precision. Congel⁽³⁶⁾ has studied this effect and determined a deviation associated with the method and device of about 12% for his etching and reading conditions. A number of studies were made to define the source of error.

1. Pre-spark Neutralizing

Some counting error could reasonably be attributed to trapped KOH solution within the etched holes. Svensson⁽³⁷⁾ used to dilute acetic acid rinse before sparking to aid removal. Hankins⁽³⁷⁾ recommended an acetic acid rinse to improve dosimeter reproducibility. An acid rinse required rewashing or one electrolyte is replaced by another. This was avoided by titrating to a phenolphthalein end-point with acetic acid.

Surprisingly, the results, Table 2, suggest a loss of sensitivity without an observable improvement in precision.

2. Multiple Spark Counting

Hankins, Svensson, Griffith, and Backer⁽³⁷⁾ report improved spark counting precision by record sparking each foil several times and averaging. This was tried for a range of spark densities from 80 to 1000 sparks per 4.46 cm² (Table 3). Results indicate that the 2 to 5 respark average is always less than the first spark value. A density dependence is suggested since the ratio of the 2 to 5 respark average to the first respark value depends on density. The precision, % $\overline{SD}$, of the first spark group appears to be similar to slightly better than the 2 to 5 spark group, while the latter had a larger sample advantage. Multiple sparking appears to have no value when evaluated with the BNL spark reader.

3. Spark Time Dependence

One study aimed at spark reading variations with time was made (Table 4). Time was varied between the 1060 volt pre-spark and the 560 volt record spark from 30 seconds to 1½ minutes. The same time interval was maintained for each respark from 2 to 5. The controls were advanced in the normal time of about 20 seconds per sparking operation. No time dependence was observed.

4. Foil Thickness

Effects of foil thickness was studied by weight grouping punched foils prior to standard irradiation, etching, and reading. No statistically significant weight effects were noted.

5. Additional Studies

- a) Humidity effects on sparking ---- this important study is continuing.
- b) Spark voltage polarity ---- no effect at 1060 and 560 Volts.
- c) Comparison of optically projected and spark counted holes ---- within 0.5%.
- d) Foil-radiator sandwich ---- smoothness important.
- e) Alloying thorium with 5% (weight) titanium ---- improved radiator life.

IV. AGS EXPOSURE SPECTRA

Most of the neutron exposure at BNL is due to the AGS, a 30 GeV accelerator. Lindenbaum⁽³⁷⁾ pointed out that energetic proton nuclei (above several hundred MeV) generate a nucleonic cascade in a target nucleus. The cascade contains high-energy (≥ 100 MeV) neutrons and protons, low-energy neutrons and protons (evaporation), heavier nuclear fragments, pi mesons and K mesons, etc. The most penetrating is the high-energy neutron component, since all charged particles undergo energy loss by ionization along with (similar probability) the usual nuclear interactions that remove neutrons.

The energy spectrum⁽²⁶⁾ of the neutrons streaming through the heavy shielding extends above 100 MeV. Air, ground, and heavy shield wall scatter alter the energy spectrum to preclude sole use of the thermal and epithermal window method of applying reasonable spectrally weighted values of dose-response factors.

A. Air Scatter

Neutrons emerging from the relatively thinner roof shielding of the heavily shielded biological enclosure radiate away from the ground. A large fraction⁽³⁸⁾ of this population is energetically able to transfer energy to oxygen and nitrogen nuclei to cause an isotropic⁽³⁹⁾ release of evaporation neutrons and protons. This neutron rain is termed skyshine⁽³⁷⁾. The evapor-

ated neutrons and/or protons produce an energy spectrum that abruptly peaks about 1 to 2 MeV and tails down in energy to about 10 MeV where the population approaches zero. The range in air of a 10 MeV proton is about 150 mg/cm^2 , or roughly 150 cm. Therefore the protons "inhabit" the immediate area of their formation while the neutrons have a much longer range⁽³⁸⁾. Skyshine is thus composed of neutrons above 1 MeV.

B. Ground and Heavy Shield Wall Scatter

This phenomenon is familiar to all and needs no additional discussion; however, a variation exists that should be considered. The AGS has more than 15 entrances into the accelerator and primary beam transport areas. Each of the resulting ducts are of the labyrinth type and average about 40 ft^2 in cross sectional area. During accelerator operation soft neutrons diffuse out of the entrances and dominate the local neutron energy spectrum.

C. Secondary Beam Lines and End Stops

A high energy research accelerator is a source of radiation. As such, beams of high energy particles are piped through the heavy biological shielding. The unshielded beam lines, presently 8 lines, limited to about 10^6 particles/sec, are contained in vacuum chambers. The particles leave the chamber through a thin window and pass through 10 to 100 gms/cm^2 of Cerenkov counters, collimators, spark chambers, plastic scintillation paddles, Rodoscopes, targets, and finally, an end stop. The stop is thick enough to absorb most of the particles; however, all of the detectors, stops and beam collimators constitute sources of high energy particles that are not in equilibrium with their lower energy secondaries (evaporation).

FIELD EVALUATION

A. East Experimental Area

A large portion of the 4 major AGS experimental areas are occupiable. The target building and east experimental area is representative of the remaining 3 areas. Referring to Fig. 11, heavy shielding is oriented across the building diagonal. The clear portion on the left contains a magnet and power supply works area. The building below the works area serves as office space. All of the experimentation in the east area is performed on the right

side of the shield diagonal. The experimental personnel spend a majority of time in heavily instrumented house trailers owned by their respective universities. Four trailers are shown unsymmetrically placed around the beam lines and the main biological shield. This produces differences in the contribution of air scatter, ground, and heavy wall scatter, and scatter from secondary beam lines and end stops, as noted in Section IV. Exposure spectra variations are expected and must be considered in determining the calibration value and general utility of the BEND device.

B. Spectrometer

1. General

Knowledge of the energy spectra is basic to all other quantities. Exposure is relatable to the energy spectra by the application of the appropriate fluence-dose conversions listed in ICRU-20. Conversion values are flexible as they reflect the best radiobiological input at a given time. Additionally energy spectra determinations allow the calculation of the intertissue point of maximum dose or dose equivalent; since this quantity is energy dependent. A modified Bonner⁽⁴⁰⁾ multisphere neutron spectrometer serves as the detector. This consists of a ^6LiI scintillation crystal or a TLD 600-TLD 700 pair moderated by a series of polyethylene spheres, and modified by addition of the Th damage track portion of the BEND device as follows:

- a) Bare
- b) Cadmium covered
- c) 2" polyethylene special moderator
- d) 3" " " "
- e) 5" " " "
- f) 8" " " "
- g) 12" " " "
- h) Thorium fission track detector

An energy spectrum is determined by unfolding⁽⁴¹⁾ the integral results of as many detectors as are used. The original BON 4 code⁽⁴²⁾ was improved by incorporation of the minimum variance and $\frac{1}{E}$ starting point suggestions of Stevenson⁽⁴³⁾ and Awschalom⁽⁴⁴⁾. Detector responses for the 2, 3, 5, 8, and 12" spheres were taken from HASL⁽⁴⁵⁾; bare and cadmium covered detector responses were derived from Burrus⁽⁴⁶⁾, and the thorium detector response can be found in Table 5. The output (Fig. 12 and Table 6) includes the following:

- a) 12" sphere calibration (Counts/mrem)
- b) NTA film calibration⁽²²⁾ (mrem/track per 25 F)
- c) Calculated thorium fission pits (sparks)
- d) Maximum absorbed dose (mrad)
- e) M A D E (mrem)
- f) Neutron Q (mrem/mrad)
- g) Integral fluence (n/cm^2)
- h) Fluence energy spectra printout and curve (n/cm^2 per energy bin)
- i) Sum fluence energy spectra printout (n/cm^2)
- j) M A D E energy spectra printout and curve (mrem per energy bin)
- k) Sum M A D E energy spectra printout (mrem)
- l) Comparison of detector input data to synthesized (calculated) input data.

2. Accuracy

The basis for all field dose measurements was the modified Bonner spectrometer. Therefore, something must be known about its reliability for unfolding spectra, evaluating fluence, and calculating absorbed dose and M A D E. Stevenson⁽⁴³⁾ studied the overall spectrometer performance by comparing the calculated spectrum with the given spectrum for 5 different cases. He concluded that the degree of fit was a good measure of spectrometer performance; better than 1% spectrum match could be achieved when the synthesized detector values agree with the given detector values to within

3 to 5%. Weinstein et al.⁽⁴⁷⁾ considered Stevenson's work. They suggested that close agreement between the calculated and given spectrum usually indicates good agreement between the synthesized and given detector values, but the converse is not necessarily assured.

Awschalom⁽⁴⁴⁾ tested 10 known spectra in a similar way, and concluded that the method provided a satisfactory means of calculating the dose equivalent in a radiation field.

Weinstein et al.^(47,48) considered the effect of experimental detector error as propagated by the spectrometer method. Standard deviations of $\leq 10\%$ for a given detector set were stated to not unduly impair the unfolding capability of the multisphere spectrometer. Mr. Weinstein restricted his conclusion to wide energy range smooth continuous spectra requiring a low resolution as outside of a high energy accelerator shield. This conclusion was supported by the specific dose equivalent determination of the following spectra:

- a) Cosmic ray
- b) Proton accelerator (Cosmotron)
- c) ²³⁹PuBe source
- d) ²⁵²Cf source
- e) 15.85 MeV monoenergetic neutrons

The above largely different and independently determined spectra were folded into the response matrices to obtain synthetic detector values. These values were perturbed by Monte Carlo methods to include 1, 5, and 10% SD. The disturbed detector values were used to unfold and develop an envelop of spectral variation. Perturbed detector values of 1 and 10% SD produced ratios of $0.99 \pm 6\%$ respectively of the spectrometer derived to the known specific dose equivalent.

Actual detector error is difficult to determine. Counting errors were easily reduced to $\approx 2\%$. Overall error, due to counting, experimental, and systematic errors, should be reflected in the agreement between the given and synthesized detector values. The

unfolding process smooths the synthesized values to agree with smooth continuous accelerator spectra. The individual synthesized detector values thus constrained by the experimental detector set and smooth unfolded spectra requirement, are assumed to reflect overall individual detector error. The perturbed detector values discussed by Weinstein et al.^(47,48) were related to individual detectors. From statistics, deviation of a detector set is the square root of the sums of the squares of the individual detector deviation. 10% $\overline{SD}$ detector error thereby results in a 26.5% $\overline{SD}$ 7 detector set error. A measure of conservatism is adopted by assuming the $\overline{SD}$ of an experimental 7 detector set, calculated by comparing given to synthesized values, is equivalent to the detector deviation considered by Weinstein et al.

Summarizing all of the foregoing, better than 1% fit results can be expected if the given-synthesized detector values agree to better than 5%. Detector errors $\leq 10\%$, $\overline{SD}$ should provide a M A D E within 9% of the true value. Table 7 lists the synthesized to given detector values for all of the locations and detectors used. GT is within 5% for the worst single detector; the remaining location tabulations range to a worst single detector error of 23%. In nearly all cases the 2" and 3" detectors deviate the most. They will perturb the spectrum below about 100 eV and 10 KeV⁽⁴⁹⁾ respectively, dosimetrically an unimportant region. The spectral disturbance appears to oscillate about the true spectrum. This can be observed in all cases listed in Table 7. The deviation of the worst detector is compensated for by an opposite and somewhat smaller deviation of the two adjacent detectors. This should produce local spectrum errors and should not importantly effect the dose equivalent, since this quantity slowly varies with energy. This conclusion is supported by considering that detector perturbations of 10% $\overline{SD}$ ⁽⁴⁷⁾ lead to an average of $3\% \pm 6\%$ $\overline{SD}$ error in the dose equivalent. Table 7 indicates that only location G7, Run 2 is much above the 10% $\overline{SD}$, and this value was 13.7% $\overline{SD}$.

Assuming the experimental counter detector errors to be governed by total detector counts, less than 2% counter error is expected. The location most likely to have suffered detector deviation was the G90-TLD. This data set consisted of a single run with one TL pair in each detector. TL readout precision with the Eberline⁽⁵⁰⁾ TLR-5 reader is about $\pm 7\%$. Table 7 indicates a spectrum fit of about 1%, assuming the Stevenson criteria. The original detector response calculations⁽⁴⁶⁾ assumed a ${}^6\text{Li}$ kernel at the center of a variety of moderating spheres. Certainly, a ${}^6\text{LiI}$ scintillation counter mounted on a long (6") lucite light pipe is a poor representation of a bare or cadmium covered bare ${}^6\text{Li}$ kernel.

The overall spectrometer was tested by unfolding a high energy spectrum experimentally measured on the 1000 gm/cm^2 heavy concrete shield top above the G-10 target. This spectrum was compared (Fig. 13) with a theoretical spectrum derived⁽²⁶⁾ for the surface of a 1000 gm/cm^2 earth shield. Table 8 lists some of the pertinent values normalized to the experimental measurement. Good agreement exists above 1.5 MeV. The O'Brien spectrum correctly predicts less neutrons below 1.5 MeV than exist emerging from the concrete shield. This is due to the smaller hydrogen composition of concrete compared with soil. At least 4 of the spectrometer detectors are sensitive in this region and the spectrum fit is better than 1%, suggesting the O'Brien spectrum reports too few low energy neutrons.

It is concluded that 2 TL detectors of the 10 data sets are accurate to about 1%, 7 accurate to better than 9%, and 1 certainly more accurate than 15% of the true M A D E.

C. Method

1. Experimental Method

A variety of dosimeters were tape-mounted along the horizontal periphery of a rotating 12" Bonner sphere. The following dosimeters were included:

- a) Two BNL film badges containing (NTA and γ film)

- b) Three MBE dosimeters⁽⁵¹⁾
- c) One Eberline TLD holder⁽⁵⁰⁾ containing 1 TLD-700 in the open window and a TLD-600 and 700 high sensitivity ribbon in the remaining two aluminum filtered positions.
- d) Three self reading pocket ionization chambers
- e) Two TLD-600 and 700 pairs in the center of the 12" sphere
- f) One experimental thorium damage track holder

Two spectra measurement methods were used. GT and G90 TLD runs employed the full sphere set oriented around the central 12" sphere and rotating with it. The second method required two exposures. The first with the ⁶LiI counter loaded multisphere spectrometer. The spectrometer was normalized through the 12" sphere. The second method was much faster, but less accurate, than the first.

2. Calculational Method

None of the personnel neutron detectors considered responds to the entire spectrum. NTA film is responsive above 600 KeV, while thorium fission becomes effective above 1.5 MeV (Fig. 4). The M A D E is partitioned into two groups $\gtrsim 0.6$ MeV for the NTA system and $\gtrsim 1.5$ MeV for the BEND. Referring to Table 6, the integral dose fraction from 10^{-8} MeV to 1.58 MeV is 0.183. The lower partition is 129 mrem, (0.183×702.7) , and this must be determined by the TL pair part of the BEND. Conversely, the thorium fission tk. detector must respond to the upper partition of 574 mrem, $[(1.00 - .183) 702.7]$.

Since NTA film is not responsive below 0.6 MeV, an additional detector was needed. Maintaining an all film dosimeter for comparison, thermal neutron exposure was estimated from darkening of the B- γ film. A comparison of darkening under the aluminum filter yielded a difference value attributable to the incident thermal and albedo neutrons similar to the response of the TL pair described in Section III c).

D. Discussion and Results

1. General

Table 8 is a listing of the various detector data and interpretation. The list is location ordered in ascending softness, defined as the ratio of the TL pair to the thorium fission track response. Locations are coded and designated on Fig. 10.

To allow intersite comparisons, all TL pair information, $[Tl_G(NyO)]$, is reported as equivalent gamma. The information was derived by normalizing the gamma responding TLD 700 to the TLD 600 basis and subtracting the gamma response. The remainder, due to neutron interaction, was reported in TLD 600 gamma exposure units obviating the need to discuss non-standard reader-neutron units.

Gamma comparisons were made with TLD 700 and gamma film and the MBLE⁽⁵¹⁾ calcium fluoride dosimeter type PNP 292. This dosimeter was adopted as standard due to its negligible neutron⁽⁵²⁾ sensitivity.

2. Gamma Results

Ratios of the MBLE dosimeter to the film evaluated under the cadmium, Cd γ , and aluminum, Al γ , filter and the TLD 700 detector are listed in Table 8. The averages and $\overline{SD}$ noted should be supplemented by an inspection of the MBLE to detector ratio with hardness. As expected, the Cd γ is hardness dependent, and the Al γ also appears to be. The TLD 700 detector appears to be most precise with little or no suggestion of hardness dependence.

3. Film Neutron Dosimetry

The standard BNL personnel neutron dosimeter is NTA film interpreted as 100 mrem/track for 25 fields scanned. Employing this interpretation, the NTA dosimeter overestimated the M A D E by an average factor of about 2.4. The $\overline{SD}$ for this set of data is 81% reflecting limits of 1/2 to 4 times the spectrometer derived M A D E.

Much of the deviation and need for a conservative NTA calibration is based on the lack of response below 0.6 MeV. Table 8 compares the NTA + (Cd γ - Al γ) to the calculated M A D E system. This dosimetry system overestimates the dose equivalent by about

40% with a $\overline{SD}$ of 50%, when using a calibration of 3 mrem/NTA tk. and 3 rem (Cd γ - Al γ). This indicates that the (Cd γ - Al γ) composite dosimeter considerably improves the film system. Selection of the $\overline{K}$ values was somewhat subjective and determine the average accuracy. Adoption of different values could improve the average accuracy, but was considered to be unproductive due to the $\pm 50\%$ average precision of the method.

Unfortunately, the test exposures were generally larger than the normal personnel exposures. Considering the M.I.T. trailer location (Cd γ - Al γ) = 25 mR reflects a net optical density difference of 0.02 determined with an Ansco densitometer, and is near the limit of detection.

4. BEND Results

Combining a thorium fission tk. detector and a TL pair resulted in a 9% overestimate of the dose equivalent with a $\overline{SD}$ of 25%. This was achieved by using a constant interpretation of 3.5 mrem/spark for the upper M A D E compartment and a variable interpretation (Fig. 14) for the lower TL pair compartment. The reader is invited to refer to section IV D 3 for a discussion of $\overline{K}$ value significance. In one case, W-19, The BEND system underestimated the calculated M A D E by a factor of 2.6. This was attributed equally to both compartments, suggesting an error in the M A D E but not in the spectrum. Since one determines the other, one must look elsewhere. The W-19 exposure geometry was unique, as this was the only point source in the data set. Further, W-19 reflected the maximum intensity, too high for occupancy. All of the occupiable areas were broadly illuminated, exposing the trial dosimeters over a large angular fraction of the rotating phantom exposures. Spectrum determination depended on detector responses at the center of a sphere, whereas the W-19 trial dosimeters were shielded for about 40% of a revolution.

5. Summary

The thorium fission-thermoluminescent system, modified film, and standard NTA film neutron dosimetry systems were compared to the

maximum average dose equivalent, M A D E. Additionally, the M A D E 1.5 MeV was presented for the fission-TL system, and ≥ 0.6 MeV for the modified film system.

Referring to Fig. 15, the histograms are location ordered in decreasing spectral hardness. The shaded upper portion of each bar reflects the M A D E fraction reported by the lower energy detector, < 1.5 and < 0.6 MeV. The unshaded portion accounts for the higher energy M A D E fraction. The magnitude of the low energy fraction varies from 10 to 20% for a hard spectrum to 80 to 90% for the softer spectra. This transference of dosimetry importance from high to low energy responding detectors compares the value of a two detector system.

The fission damage track - thermoluminescent personnel neutron dosimetry system more closely responds to the field M A D E at the locations tested. Film neutron dosimetry suffers prohibitive fading. Attempts by American laboratories to package NTA film have never prevented excessive fading⁽³⁾. The authors recommend that the damage track-TL system should replace NTA film at the Brookhaven National Laboratory AGS.

VI. CONCLUSION

Personnel neutron dosimetry can be considerably improved by employing two detectors sensitive to largely different parts of the energy spectrum. A dosimetry system utilizing thermoluminescent ^6LiF material for the lower energy compartment, and natural thorium damage track detection for the higher energy compartment was developed. The combination device was able to report the field maximum average dose equivalent of the locations tested to an average accuracy of 25%.

The low background and lack of fading permit quarterly or annual determination for low risk personnel, improving personnel monitoring workloads.

VII. ACKNOWLEDGEMENTS

The study leading to and the development of the damage track-TL system involved members of the Personnel Monitoring Group, who evaluated all of the film. The remaining effort was supplied by the AGS Health Physics Group. Mention is

gratefully made of the shift Health Physics men for their work in rotating the spectrometer and phantom assemblies. J. Ash is thanked for his counter spectrometer data, and T. Malinowski for evaluating much of the TL dosimeters. D. Thompson deserves commendation for decoding the first draft into a working manuscript.

Frank Karasek, Argonne National Laboratory, supplied the thorium foils that transformed the damage track detector into a practical personnel neutron dosimeter. Mr. Karasek's outstanding metallurgical ability made the fission pit-TL dosimetry system possible.

REFERENCES

1. L.F. Phillips, et al., Unpublished data (1967), Personnel Monitoring Group, Health Physics & Safety Division, Brookhaven National Laboratory.
2. Private Communication for 1971, Meteorology Group, Brookhaven National Laboratory.
3. K. Becker, J. Nagpal, J. Cheka, et al., "Fading Characteristics of Various Film and Solid State Dosimeters in a Warm and Humid Climate". Paper 58, 1972 Annual Health Physics Society Meeting, Las Vegas, Nevada.
4. L.F. Phillips, Private Communication (7/14/72), Personnel Monitoring Group, Health Physics & Safety Division, Brookhaven National Laboratory.
5. Catalog Number BBD-470-40, Brush Beryllium Inc., Ceramic Non-Metallic Division, Elmore, Ohio.
6. K. Becker, "Some Studies in Radiation Dosimetry by Thermally Stimulated Exoelectron Emission (TSEE)", 2nd Int. Conf. on Luminescent Dosimetry, 1968, Conf. 680920.
7. Borrowed from Stanford University, California, by courtesy of R. Barrall, P. Rago.
8. J. Davis, Unpublished data (1971), AGS Health Physics Group, Health Physics & Safety Division, Brookhaven National Laboratory.
9. C. Distenfeld, W. Bishop and D. Colvett, "Thermoluminescent Neutron-Dosimetry System", 1st Int. Conf. on Lum. Dosim., 8th AEC Symposium Series, Stanford University, Stanford, Calif., 1965.
10. Neutron Cross Sections, BNL 325, 2nd ed and Supplements, 1958.
11. B. Price, C. Horton and K. Spinney, Radiation Shielding, Pergamon Press, 1957.
12. P. Nagarajan and D. Krishnan, Neutron Personnel Monitoring, Health Physics Journal, Vol. 17, No. 2, pp. 323-329, 1967.
13. R. Alsmiller, Jr. and J. Barish, Calculated Response of the TLND Personnel Dosimeter to Neutrons with Energies 400 MeV, Neut. Phys. Div. Ann. Rept., pp. 67-69, ORNL-4800 (May 1972).
14. R. Falk, Personnel Neutron Dosimetry Using LiF Thermoluminescent Dosimeters, RFP-1581, 1971.
15. L. Kocker, G. Enders, L. Nichols, et al., Hanford Thermoluminescent Multipurpose Dosimeter, BNWL-SA-3955, 1971.
16. J. Hoy, Personnel Albedo Neutron Dosimeter with Thermoluminescent ^6LiF and ^7LiF . DP-1277, 1972.

17. D. Hankins, Factors Affecting Design of Albedo-Neutron Dosimeters Containing LiF Thermoluminescent Dosimeters, LA-4832, 1972.
18. W. Cross and L. Tammasino, Rapid Reading Technique for Nuclear particle Damage in Thin Foils, Proc. of Int. Top. Conf. on Nuc. Trk. Reg. in Inst. Solids and Appl., Conf-690522, Vol. 1, 1969.
19. W. Cross, L. Tommasino, A. Rapid Reading Technique for Nuclear Particle Damage Tracks in Thin Foils Radiation Effects 5, pp 85-89 (1970).
20. Reactor Physics Constants, ANL-5800, 2nd Ed., 1963.
21. C. Distenfeld, Continuing Work on Personnel Neutron Dosimeter At BNL, 2nd AEC Workshop on Personnel Neutron Dosimetry, New York, June 8-9, 1971, BNWL 16161
22. C. Distenfeld and A. Nappi, NTA Film Neutron Response, BNL HP Div. Internal Report, Dec. 1961.
23. Data compiled by National Neutron Cross Section Center, May 1972.
24. Steiner, Jungerman, Proton Induced Fission Cross Section for ^{233}U , ^{235}U , ^{232}Th , ^{209}Bi , and ^{197}Au . Phys. Rev. 101, 807, 1956.
25. H. deCarvalho, Fission of U, Th, and Bi by 20 GeV protons, Il Nuovo Cimento, Vol. 27, 46B, 1963.
26. K. O'Brien, Neutron Spectra in the Side-Shielding of a Large Particle Accelerator, HASL-240.
27. B. Bennett, J. McLaughlin, K. O'Brien, M. Weinstein, Estimating stray photon spectra and Dose Above 25 MeV near the transverse shielding of 2 proton synchrotron, HASL-226 (1970).
28. L. Lazareva, B. Govrilov, et al. Neut. Held in Photodisintegration of v and Th, Akademia Nauk SSSR. Conf. on Peaceful Uses of At. Eng (1955).
29. E. Minarik, V. Novikov, Fission of U, Th, Bi, and Tl Induced by High Energy γ -Quando, Sov. Phys. JETP, Vols. 5, #2, P. 253 (1957).
30. F. Carbonara, H. de Carvalho, et al., Photofission of v and Th Between 300 and 1000 MeV, Nuc. Phys. 73, 385-95 (1965).
31. Kimfol, 40 gauge, plain and metalized, Kimberly Clark, Schwitzer Div., N.Y. (1970).
32. W. Cross and L. Tammasino, Improvements in the Spark Counting Technique for Damage Track Neutron Dosimeters, Symposium on Neutron Dosimetry in Biology and Medicine, Munich, Germany (1972).
33. M. Sohrsbi, K. Becker, Fast Neutron Personnel Monitoring by Fission Fragment Registration From ^{237}Np , Nuc. Inst. and Meth. 104, pp. 409-411 (1972).

34. 1972 Catalog Amersham-Searle, Inc., Illinois.
35. ICRP, Committee II, Permissible Dose for Internal Radiation HP Vol. 3, June 1960.
36. F. Congel, J. Roberts, D. Dreiss, et al., Automatic System for Counting Etched Holes in Thin Dielectric Plastics, Nuc. Inst. & Meth. 100, pp. 247-252 (1972).
37. R. Griffith, Letter to Participants of the July 1971 AEC Neutron Dosimetry Workshop Survey Summary on Spark Counting (Oct. 1971), LRL, Livermore, California.
38. C. Distenfeld, R. Colvert, Skyshine Considerations for Accelerator Shielding Design, Nuc. Sc. and Eng. 26, 117-121, 1966.
39. D. Skyrme, The Evaporation of Neutrons from Nuclei Bombarded with High Energy Protons, Nuc. Phy. 35, pp. 117-193, 1962.
40. R. Bramblett, R. Ewing and T. Bonner, A New Type of Neutron Spectrometer, Nuc. Inst. & Meth. 9:1 (1960).
41. R. Gold, An Iterative Unfolding Method for Response Matrices, USAEC Rept. ANL-6984 (1964).
42. K. O'Brien, Cards and Information supplied by HASL, USAEC (1965).
43. G. Stevenson, Neutron Spectrometry from 0.025 eV to 25 GeV, RHCL/R 154.
44. M. Awschalom, The Use of the Multisphere Neutron Detector for Dosimetry of Mixed Radiation Fields, PPAD 596 E.
45. J. McLaughlin, Private Communication (July 31, 1968), HASL, USAEC.
46. W. Burrus, Bonner spheres and Threshold Detectors for Neutron Spectrometry, ORNL 3360 (1962).
47. M. Weinstein, R. Sanna and J. McLaughlin, Tests of Experimental Error Propagation in Unfolded Stray Neutron Spectra, 2nd Int. Conf. on Accel. Dosi. and Experience, CONF-691101 (1969).
48. M. Weinstein, F. Hajnal, J. McLaughlin, and K. O'Brien Neutron Dose Equivalents from Multisphere Accelerator Shield Leakage Spectra, HASL 223 (1970).
49. S. McGuire, A Dose Monitoring Instrument for Neutron From Thermal to 100 MeV, LA-3435 (1966).
50. Eberline Instrument Corporation, Santa Fe, New Mexico.

- S1. M. B. L. E. (Manufacture Belge de Lampes et de Matériel Electronique), Brussels, Belgium.
- S2. W. Haring and M. Schoen, Dosimetry of Ionizing Radiation with the Aid of Thermoluminescence, Selected Topics in Radiation Dosimetry, IAEA, Vienna (1961).

LIST OF TABLES

Table 1	Fission Radiator Comparison
Table 2	Neutralized Final Wash Results
Table 3	Value of Multiple Sparking
Table 4	Sparking Time Effect
Table 5	Thorium Damage Track Multisphere Spectrometer Response Matrix
Table 6	Spectrometer Output, G-10 Ring Top, GT
Table 7	Multisphere Spectrometer Detector Input-Output Comparison
Table 8	Detector Data and Results

TABLE I
Fission Radiator Comparison

Item	^{238}Th	^{237}Np
Cost ⁽³⁴⁾	\$75.00/gm (metal form) \$22.00/radiator*	\$295.00/100 mg (oxide)
Natural Abundance	100%	Manufactured
Max. Perm. Burden ⁽³⁵⁾ (MPB)	0.02 μC (bone)	0.06 μC (bone)
Specific Activity, $\mu\text{C/gm}$	1.09×10^{-1}	7.06×10^2
Calc. Radiator** Activity MPB	1.9×10^{-1}	4.2×10^2
Relative Internal Hazard	1	2160
Calc. ** Ext. γ Exposure, MeV/sec for 2 π	9.2	2.3×10^4
Relative External Hazard	1	2500

*Quotation, 5/8/72

1 to 100, 95% Th, 5% Ti, $5 \pm 0.2 \text{ mg/cm}^2$ by 3.5 x 3.5 cm, \$22.00 each.

Micromatter Co.
197-34th E.
Seattle, Washington

**Assumed radiator - 3cm disc, 5 mg/cm^2 thick

TABLE 2

Neutralized Final Wash

Spark Number	Neutralized Final Wash (Acetic Acid)						Average
1	807	892	883	787	784	861	836 ± 49
2	760	734	703	694	714	665	
3	748	790	704	678	613	677	
4	729	742	702	652	616	689	
5	706	719	685	651	641	695	709 ± 72

Spark Number	Control						Average
1	1132	922	1003	861	1086	956	993 ± 102
2	844	848	825	842	928	778	
3	825	784	819	869	866	790	
4	810	786	809	795	900	794	
5	808	807	828	786	914	798	827 ± 42

TABLE 3

Value of Multiple Sparking

1st. spark value	1st. spark/avg. 2 to 5		± % error	
			1st. spark	2 to 5
1000	1.17±	.08	10.3, 8.0	5.1, 6.6
800	1.20	.06	5.9	10.2
600	1.16	.05	7.9, 4.8	7.9, 6.7
300	1.07	.02	5.1, 1.1	7.0, 2.4
200	1.07	.04	5.9, 7.3	5.0, 7.7
80	1.03	.03	6.3	8.0

TABLE 4

Sparkling Time Effect

spark number	time between successive sparkings (min)						average
	.5	1.0	2	4	8	16	
1	1094	1098	980	1030	1107	899	1035± 83
2	940	947	841	872	1026	764	
3	947	1009	900	893	971	802	
4	963	975	863	837	951	774	
5	1002	965	854	880	940	781	904± 60

spark number	control						average
1	1132	922	1003	861	1086	956	993± 102
2	844	848	825	842	928	778	
3	825	784	819	869	866	790	
4	810	786	809	796	900	794	
5	808	807	828	786	914	798	827± 42

TABLE 5

Thorium Damage Track Multisphere Spectrometer Response Matrix

Since $P_i = \phi_i \sigma_i (N_{eff})$ where $(N_{eff}) = 1.956 \times 10^{19}$

Energy Bin, MeV	σ_i , barns	$(1.956 \times 10^{19})\sigma_i$	Card No.	Format, F9.8
1.0	.017	3.33×10^{-7}	41	.00 00 00 33
1.6	.052	1.017×10^{-6}	42	.00 00 01 02
2.5	.119	2.328×10^{-6}	43	.00 00 02 33
4.0	.134	2.328×10^{-6}	44	.00 00 02 62
6.3	.229	4.479×10^{-6}	45	.00 00 04 48
10	.29	5.672×10^{-6}	46	.00 00 05 67
16	.405	7.922×10^{-6}	47	.00 00 07 92
25	.888	1.7369×10^{-5}	48	.00 00 17 37
40	1.018	1.9912×10^{-5}	49	.00 00 19 91
63	1.0	1.956×10^{-5}	50	.00 00 19 56
100	1.0	" "	51	.00 00 19 56
160	1.0	" "	52	.00 00 19 56

TABLE 6

G-10 RING TOP, GT

3252.0 Sphere Counts /MREM

127.6 MRAD

4.7 MREM/Track NTA Reading

702.7 MREM

232.068 Sparks

QF (Neut.) = 5.5

$$\phi = 4.465 \text{ E } + 07 \text{ N/cm}^2$$

ENERGY	N(E)	FLUX AND INTEGRAL		DOSE AND INTEGRAL	
1.00E-02	2.408E+05	.005	.005	0.000	0.000
1.50E-02	3.143E+05	.007	.012	.000	.000
2.51E-02	3.957E+05	.009	.021	.000	.001
3.92E-02	4.808E+05	.011	.032	.001	.001
6.31E-02	5.819E+05	.013	.045	.001	.002
1.00E-01	6.296E+05	.014	.059	.001	.003
1.50E-01	6.827E+05	.015	.074	.001	.004
2.51E-01	6.853E+05	.015	.089	.001	.005
3.92E-01	5.781E+05	.013	.102	.001	.005
6.31E-01	4.966E+05	.011	.113	.001	.006
1.00E-01	4.529E+05	.010	.123	.001	.007
1.50E-01	4.254E+05	.010	.133	.001	.008
2.51E-01	4.119E+05	.009	.142	.001	.008
3.92E-01	4.115E+05	.009	.151	.001	.009
6.31E-01	4.242E+05	.010	.161	.001	.009
1.00E-01	4.493E+05	.010	.171	.001	.010
1.50E-01	4.819E+05	.011	.182	.001	.011
2.51E-01	5.190E+05	.012	.193	.001	.011
3.92E-01	5.601E+05	.013	.206	.001	.012
6.31E-01	5.995E+05	.013	.219	.001	.013
1.00E-01	6.314E+05	.014	.234	.001	.014
1.50E-01	6.469E+05	.014	.248	.001	.014
2.51E-01	6.446E+05	.014	.262	.001	.015
3.92E-01	6.270E+05	.014	.276	.001	.016
6.31E-01	6.023E+05	.013	.290	.001	.017
1.00E-01	5.743E+05	.013	.303	.001	.018
1.50E-01	5.496E+05	.012	.315	.001	.018
2.51E-01	5.324E+05	.012	.327	.001	.019
3.92E-01	5.253E+05	.012	.339	.001	.019
6.31E-01	5.293E+05	.012	.351	.001	.020
1.00E-01	5.440E+05	.012	.363	.001	.021
1.50E-01	5.712E+05	.013	.376	.001	.021
2.51E-01	6.001E+05	.014	.389	.001	.022
3.92E-01	6.554E+05	.015	.404	.002	.024
6.31E-01	7.150E+05	.016	.420	.003	.027
1.00E-01	7.410E+05	.018	.438	.004	.032
1.50E-01	8.864E+05	.020	.458	.006	.038
2.51E-01	1.001E+06	.022	.480	.010	.048
3.92E-01	1.125E+06	.025	.505	.016	.064
6.31E-01	1.241E+06	.028	.533	.026	.090
1.00E+00	1.320E+06	.030	.563	.039	.129
1.50E+00	1.340E+06	.030	.593	.053	.183
2.51E+00	1.295E+06	.029	.622	.080	.243
3.92E+00	1.206E+06	.027	.649	.059	.302
6.31E+00	1.116E+06	.025	.674	.056	.357
1.00E+01	1.032E+06	.023	.697	.052	.410
1.50E+01	9.820E+05	.022	.719	.050	.459
2.51E+01	1.008E+06	.023	.741	.050	.509
3.92E+01	1.203E+06	.027	.768	.056	.564
6.31E+01	1.736E+06	.039	.887	.075	.639
1.00E+02	2.973E+06	.067	.874	.123	.763
1.50E+02	5.643E+06	.126	1.000	.237	1.000

.090

.183

TABLE 7

Multisphere Spectrometer Detector Input-Output Comparison

Location	Bare	Cd	2"	3"	5"	$\frac{D_{SYN}}{D_{GIV}}$		Th	Worst Detector	Error %	$\overline{DS/DG}$	$\overline{SD}, \%$
						8"	12"					
GT	.998	1.015	.977	1.022	1.011	.976	1.021	.991	2	2.4	1.001	1.9
ST, Run 1	.972	*	1.080	.891	1.088	.914	1.041	.984	3	11	.996	7.8
ST, Run 2	.972	*	1.080	.891	1.088	.914	1.041	.096	3	11	.996	7.8
G90,TLD	.953	1.005	1.061	1.002	.970	1.017	1.009	.992	2	6.1	1.001	3.3
G90 Cntr	.949	*	1.089	.938	1.045	.929	1.051	.985	2	8.9	.998	6.4
W-19	.968	*	1.057	1.036	.786	1.126	.979	1.052	5	21	1.001	10.8
G7, Run 2	.947	*	1.063	1.018	*	.765	1.172	.941	8	23	.984	13.7
G7, Run 1	.941	*	1.124	.877	1.037	*	1.001	1.048	3	12	1.005	8.7
R	.933	*	1.095	.983	.967	.969	1.064	.983	2	9.5	.999	5.8
GA-A	.941	*	1.085	.971	.997	.952	1.070	.978	2	8.5	.999	5.7

*No Detector Used

Detector Data and Results

[illegible]

TABLE 8 (Continued)

	Location		Location		Location		Best Results
	G-10 + 7° (G-7)		Rutgers (R)	M.I.T. (M)	SES (SA-A)		
	Run 1	Run 2	Trailer	Trailer	Crate		
Spectrum	medium	medium	medium	soft	soft		
TL ₆ (Ny)/Pit	26.2	42.8	47.1	65.7	309		
TL ₆ (Ny), mR	495	557	1078 ± (3%)	578	2506		
TL ₇ (y), mR	117	119	117 ± (5%)	28	62		
Fission Fit, Sparks	18.9 ± 29%	13 ± 27%	22.9 ± 30%	8.8 ± 15%	8.1 ± 20%		
NTA, Tks./25F	13.4 ± 19%	12.4 ± 30%	5 ± 34%	11.5 ± (22%)	5.5 ± (46%)		
Film Cdγ, mR	275	235 ± (2%)	147.5 ± (2%)	70 ± (0)	210 ± (9.5%)		
Film Alγ, mR	205	175 ± (11%)	110 ± (0)	45 ± (0)	103 ± (8%)		
MBLE, mR	168.5 ± (12%)	128.5 ± (11%)	96.5 ± (1%)	22.3 ± (1%)	69.8 ± (8.5%)		
Calc. Neutron M A D E, mrem	150.2	112.0	227.9	133.8	113.7		
Film	mrem ≥ 0.63 MeV	(35%) 52.6	(71%) 79.9	(47%) 106.2	(47%) 62.5	(18%) 20.2	$\bar{K}_1 = 3 \text{ mrem/tk}$ $\bar{K}_2 = 3 \text{ mrem/(Cd } \gamma - \text{ Al)}$
	mrem/NTA = K_1	3.9	6.4	21.2	5.4	3.7	
	mrem ≤ 0.63 MeV	97.6	32.1	121.7	71.3	93.5	
	mrem/(Cd γ - Al γ) = K_2	1.4	.54	3.3	2.9	.87	
	mrem (NTA) = Tracks · K_1	40	37	15	35	17	
	mrem (Cd γ - Al γ) = mR · $\bar{K}_2$	<u>210</u>	<u>180</u>	<u>140</u>	<u>75</u>	<u>321</u>	
Film M A D E	250	217	155	110	338		
Film, Pit-TLD	mrem ≥ 1.5 MeV	(17%) 25.5	(57%) 63.3	(26%) 58.6	(25%) 33.6	(12%) 13.2	$\bar{K}_3 = 3.5 \text{ mrem/Pit}$ $K_4 = f(\text{hardness})$
	mrem/Pit	1.4	4.9	2.6	3.8	1.6	
	mrem ≤ 1.5 MeV	124.7	48.7	149.3	100.2	100.5	
	mrem/TL ₆ (Ny)	.25	.09	.16	.17	.04	
	mrem (Pit) = Pit · $\bar{K}_3$	66	46	80	31	28	
	mrem [TL ₆ (Ny)] = mR ³ · K_4	<u>87</u>	<u>84</u>	<u>151</u>	<u>73</u>	<u>113</u>	
Pit-TL M A D E	153	130	231	104	141		
Gamma Results	MBLE/Cd γ	.61	.55	.65	.32	.33	.69 ± 48%
	MBLE/Al γ	.82	.73	.88	.50	.68	.96 ± 39%
	MBLE/TL ₇ (y)	1.44	1.08	.83	.79	1.13	.97 ± 22%
Neut. Results	NTA Tks. × 10/Calc. M A D E	.89	1.11	.22	.86	.48	2.39 ± 81%
	Film M A D E /Calc. M A D E	1.66	1.94	.68	.82	2.97	1.39 ± 50%
	Pit-TL M A D E /Calc. M A D E	1.02	1.16	1.01	.77	1.24	1.09 ± 25%

NOTE: K_4 = variable depending on hardness refer to Fig. 14

ERROR LIMITS: ± % = Std. dev. of mean 4 numbers: ± (%) = Max. dev. of data 2 or 3 values; Plain number = Single value;

(*) = Data smoothed in 7 × 14 matrix; (N) = M A D E in indicated energy group

FIG. 1

BNL FILM BADGE
PROTON RECOIL TRACK FADING IN NTA FILM
PuBe NEUTRON SOURCE

FIG. 2

FIG. 3

BROOKHAVEN NATIONAL LAB EXPERIMENTAL
DAMAGE TRACK SPARK READER

FIG. 4

FIGURE 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIGURE 10

FIG. 11

FIG. 12

G-10 RING TOP, GT

FIG. 12

G-10 RING TOP, GT

FIG. 13

FIG. 14

FIG. 15