**Radiation Characterization,
and Exposure Rate Measurements
from Cartridge, 105-mm,
APFSDS-T, XM774**

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November 1979

Prepared for
the U.S. Department of the Army

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ ____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

3 3679 00053 1766

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under a Related Services Agreement
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Contract EY-76-C-06-1830

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PREFACE

This study was conducted on the recommendation of the Joint Technical Coordinating Group for Munitions Effectiveness, Working Group on Depleted Uranium Munitions, and was supported by the Office of Assistant Project Manager for Tank Main Armament Development, XM1 Tank System, under Army Project Number IL663608D060. The technical monitors were the Working Group Chairman, E. W. Bloore, and E. F. Wilsey, both of the U.S. Army Armament Research and Development Command, Dover, New Jersey.

This study is one of three studies recommended by the JTCG/ME Working Group. The first study, Radiological and Toxicological Assessment of an External Heat (Burn) Test of the 105-mm Cartridge, APFSDS-T, XM774 (PNL-2670), has been distributed, while the third study, Characterization of Airborne Uranium from Test Firings of XM774 Ammunition (PNL-2944), is in preparation.

The authors wish to acknowledge the support of personnel of the Material Testing Directorate of the Testing and Evaluation Command, especially K. Ruff, in conducting the part of the study at the Aberdeen Proving Ground, Maryland. The authors also wish to acknowledge the following people without whose help this report would not have been possible: L. D. Hooker and J. P. Holland (Pacific Northwest Laboratory), and O. R. Mulhern (Eberline Instrument Corporation).

SUMMARY

In response to a recommendation from the Joint Technical Coordinating Group for Munitions Effectiveness, Working Group on Depleted Uranium Munitions, the Department of the Army contracted with Pacific Northwest Laboratory (PNL) to investigate the health physics problems associated with the assembly, storage, and use of 105-mm, APFSDS-T, XM774 ammunition. Each round of this ammunition contains a penetrator rod of 3.4 kg of depleted uranium (DU), which is classified as a radioactive source material.

The study carried out by PNL included laboratory and field analyses and an assessment of current health physics practices. The data sought included: the characteristics of radiation emitted from a penetrator and an assembled projectile; a comparison of film and thermoluminescent dosimeters; a comparison of radiation detection instruments; and the exposure rates from a single XM774 round, a loaded storage container, a standard pallet, and a loaded tank.

The results of the study show the following:

- The components of the assembled XM774 round effectively shield out beta radiation from the uranium; however, photons can penetrate the components of the round and are therefore the predominant emission.
- Both film and TL dosimeters adequately measure radiation emissions from the assembled round, but thermoluminescent dosimeters are best for measuring low exposure rates over a long period of time.
- The radiation levels associated with the XM774 ammunition are extremely low. The photon emissions measured did not exceed a maximum whole-body or critical organ exposure of 0.26 mR/hr. Even if personnel were exposed for long periods to the highest levels of radiation measured, it is doubtful that their exposure would reach 25% of the maximum permissible occupational dose listed in Title 10 of the Code of Federal Regulations, Part 20.

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GLOSSARY

APFSDS-T. Armor Piercing, Fin Stabilized, Discarding Sabot with a Tracer.

Attenuation. A general term for reduction in magnitude, amplitude, or intensity of a physical quantity, arising from absorption, scattering, or geometric dispersion.

Beam Quality. The penetrating ability of a beam of radiation, measured in half-value layers.

Bremsstrahlung. Electromagnetic radiation arising from collision or deviation between fast-moving electrons and atoms.

DU. Depleted uranium.

Dose, absorbed. The energy imparted to matter in a volume element by ionizing radiation, divided by the mass of irradiated material in that volume element. The special unit of absorbed dose is the rad.

Exposure. The potential for receiving radiation, through proximity to a radioactive source.

Half-value layer. The thickness of a material that reduces the exposure rate of the beam by one-half.

Homogeneity Coefficient. The ratio of the second to the first half-value layer.

Isotope. One of a set of chemically identical species of atom that have the same atomic number but different mass numbers.

$\mu\text{R/hr.}$ Equivalent to 1×10^{-6} roentgens/hour.

mR/hr. Equivalent to 1×10^{-3} roentgens/hour.

Penetrator. Sometimes referred to as the subprojectile, the penetrator consists of a rod fabricated of depleted uranium with 0.75 weight percent titanium alloy, an aluminum windshield with a steel tip, and an aluminum fin assembly threaded onto the tail end of the rod.

Projectile. The projectile consists of the following components: the penetrator, bourrelet, sabot, obturator, base seal, and M13 tracer.

Rad. A measure of the dose of any ionizing radiation to the body tissues in terms of the energy absorbed per unit mass of the tissue. One rad is the dose corresponding to the absorption of 100 ergs per gram of tissue.

Roentgen (R). The special unit of exposure for x or gamma radiation. One roentgen is equal to 2.58×10^{-4} coulombs per kilogram of air.

Round. A projectile with shell casing, propellant, primer tube, and primer.

Secular Equilibrium. Radioactive equilibrium in which the parent element has such a long life that activities remain effectively constant for long periods.

Source Material. Uranium or thorium, or any combination of the two, in any physical or chemical form.

TL Dosimeter or TLD. Thermoluminescent dosimeter.

TLD 400s. Thermoluminescent chips made up of calcium fluoride with manganese.

TLD 700s. Thermoluminescent chips made up of lithium fluoride with manganese.

RADIATION CHARACTERIZATION, AND EXPOSURE RATE
MEASUREMENTS FROM CARTRIDGE, 105-mm, APFSDS-T, XM774

1.0 INTRODUCTION

The Department of the Army assembles, stores, and uses 105-mm, APFSDS-T, XM774 ammunition. Each round of XM774 ammunition contains a penetrator rod of 3.4 kg of depleted uranium (DU) alloyed with 0.75% titanium by weight. An aluminum windshield with a steel tip and an aluminum tailfin are attached to the DU rod, making up the penetrator. Additional components (a bourrelet, sabot, obturator, base seal, and M13 tracer), with the penetrator, make up the XM774 projectile.

Because DU is classified as a radioactive source material, the Army is concerned about any emissions from the penetrator. Therefore, on the recommendation of the Working Group on Depleted Uranium Munitions of the Joint Technical Coordinating Group for Munitions Effectiveness, the Army contracted with Pacific Northwest Laboratory^(a) (PNL) to assess any health physics problems associated with the assembly, storage, and use of XM774 ammunition.

1.1 PURPOSE OF THE STUDY AND ITS SUBTASKS

The major emphasis of the study undertaken by PNL was to assess the external radiation emission associated with XM774 ammunition and to recommend dosimeters and instruments appropriate for measuring this emission. The following tasks were carried out as part of the study:

- A laboratory analysis was performed to characterize the types of radiation emitted from a DU penetrator and an assembled projectile.
- The energy- and angular-response characteristics of film and thermoluminescent (TL) dosimeters were compared in the laboratory using radiation sources with emissions similar to those from the DU penetrator and the projectile. This portion of the study was carried

(a) Operated for the Department of Energy by Battelle Memorial Institute.

out to determine whether either dosimeter was inadequate for estimating the dose rates associated with DU.

- The history, design, and response characteristics of film and TL dosimeters were compared to evaluate their suitability for personnel monitoring of long-term, low exposure rates.
- The advantages and disadvantages of commercially available radiation detection instruments were considered. Field measurements of exposure rates from XM774 ammunition can be carried out most conveniently using portable instruments; however, the use of certain portable instruments sensitive enough to detect low exposure rates can be misleading.
- Field experiments were conducted to measure the exposure rates from a single round of XM774 ammunition, a standard storage container holding 2 rounds, a full standard pallet consisting of 30 rounds, and an M60A1 tank loaded with 32 rounds. The detection instruments used were TL and film dosimeters and the TASC-4 Environmental Radiation Monitoring System, a semiportable survey instrument.
- Information about other potential health problems associated with XM774 ammunition was provided.

The laboratory experiments were conducted at PNL's Radiological Calibrations Laboratory. The XM774 ammunition used in the laboratory study was provided by the Materials Development Section, Materials Department, PNL, with the approval of R. Davitt, Project Manager, XM774, Engineering Development Program of the Large Caliber Weapons Systems Laboratories, ARRADCOM, Dover, New Jersey.

The field experiment was performed at the Aberdeen Proving Ground, Maryland. A controlled-environment room was provided for storage of the M60A1 tank and ammunition. All field measurements were conducted in this room except those on the pallet, which were conducted in a load and pack facility at the Aberdeen Proving Ground.

Also considered in the study were the applicability of several sections of the Code of Federal Regulations. Title 10, Part 20, "Standards for Protection

Against Radiation," requires the use of personnel monitoring devices if an individual is likely to receive more than 25% of the maximum permissible dose for occupational exposures (10 CFR 20.202).

1.2 ORGANIZATION OF THE REPORT

The results of the study are presented in Section 2.0 of this report. The major tasks undertaken are discussed in the following sections, and all figures and tables are grouped at the end of the report text (beginning on p. 34). A glossary of terms is provided on pp. xiii-xiv.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Laboratory analysis showed that beta particles are the predominant radiation emissions from bare uranium; however, measurable quantities of photon emissions are also present. The beta radiation emanating from the uranium penetrator is effectively shielded by the tailfin, sabot, and windshield of the XM774 ammunition, without significant buildup of secondary or Bremsstrahlung photons. Photons, which can penetrate the tailfin, sabot, and windshield, are therefore the predominant emission from the assembled round.

2.1 PERSONNEL MONITORING AND SURVEY DEVICES

In a controlled laboratory study, the film and TL dosimeters tested responded similarly to photon and beta radiations. The film dosimeter overresponded to some low-energy photon radiations and underresponded to others; the overresponse probably parallels a slight (but not statistically significant) overresponse noted in the field use of the two dosimeters. Both dosimeters were found adequate for measuring radiation emissions from the assembled DU rounds.

The long-term monitoring of low exposure rates requires a dosimeter that is stable and not affected by environmental factors (such as temperature and humidity). Thermoluminescent dosimeters meet these criteria. They have the additional advantage of being small and therefore more convenient than film dosimeters for extremity monitoring (if bare uranium is handled during the production of ammunition) and for lamination into the security badges of non-radiation workers.

Radiation levels measured by the semiportable, energy-compensated TASC-4 survey instrument were comparable to the exposures recorded by personnel dosimeters. This comparability indicates that a portable survey instrument can provide accurate measurements of photon emissions from the DU rounds. A comparison of the TASC-4 with three smaller, less unwieldy field instruments showed that the response of the micro R meter to uranium photons was within 10% of the TASC-4's response. This difference is well within the statistical

limitations of most field radiation measurements; therefore, the micro R meter is an appropriate instrument for field survey of uranium photon radiations.

2.2 EXPOSURE RATES FROM XM774 AMMUNITION

No radiation levels exceeding 0.5 mrem/hr were detected for a storage container with two completely assembled XM774 rounds.

The highest exposure rate measured from a pallet of XM774 rounds was 0.15 mR/hr at 5 cm from the surface of the pallet. Based on this exposure rate, a theoretical calculation indicates that the exposure rate from an igloo-type stockpiled configuration of XM774 rounds should not exceed 0.3 mR/hr.^(a) A person would have to be exposed to this level of radiation for 4166 hr/yr (there are 8760 hours in a year) before reaching 25% of the annual occupational dose limit set for radiation workers.

The highest photon exposure rate measured inside an M60A1 tank loaded with 32 XM774 rounds was 0.26 mR/hr. A person would have to be exposed to this radiation level for about 4800 hr/yr before reaching 25% of the annual whole-body dose limit set for radiation workers.

2.3 APPLICABILITY OF CODE OF FEDERAL REGULATIONS

The Code of Federal Regulations, Title 10, Part 20, requires that personnel monitoring devices be used if the dose received by an individual is likely to exceed 25% of the maximum permissible dose (10 CFR 20.202). Based on the highest exposure rate measured in the laboratory study, it was considered unlikely that a person could receive 25% of the maximum permissible dose. The field study results also indicated that the radiation levels associated with the XM774 ammunition are extremely low. Even if personnel were exposed for

(a) This calculation was made using seven pallets as the base of the igloo, with five pallets as the middle layer and three as the top layer. The front surface of the pallets was assumed to give a uniform exposure of 0.15 mR/hr at 5 cm from the surface. The inverse square law and an equation for a plane surface were used, and the exposure rate was calculated for a point 1 m up from the floor and 1 m out from the front surface of the stacked pallets.

long periods of time to the highest levels of radiation measured, their exposure would probably not exceed 25% of the maximum permissible dose.

These low exposure rates do not require occupational monitoring of workers. However, 10 CFR 20.1(c) states that every effort should be made to reduce radiation exposures to levels as low as reasonably achievable; therefore, personnel monitoring as a means of identifying variations from the norm is a matter of good health physics practices.

3.0 CHARACTERIZATION OF EMISSIONS FROM XM774 AMMUNITION

Several types of radiation are emitted from DU. In a projectile, these radiations are affected by the windshield, sabot, and tailfin that cover the DU penetrator rod. Laboratory measurement of radiation emissions from selected projectiles was made to determine the types of radiation that can be expected from a DU penetrator and a projectile.

3.1 COMPOSITION OF DEPLETED URANIUM

Depleted uranium is composed of three principal isotopes: ^{234}U , ^{235}U , and ^{238}U . Uranium-238 is the principal component of DU and makes up approximately 99.7% of its weight. This isotope gives rise to a series of daughter (or decay) products, including ^{234}U and ^{235}U (0.0034% and 0.30% by weight of DU, respectively).^(a)

During the processing of DU for penetrator production, the melting phase causes a zonal separation of many of the long-standing naturally occurring daughter products into the upper layers of the molten uranium. High dose rates are expected from the uranium only when the daughter products are concentrated. Upon solidification, the layers of uranium with a high concentration of daughter products are discarded, and the DU with a lower concentration of daughter products is used to produce the penetrator rods (Bennellick 1966). If protactinium-234 (^{234}Pa), a principal daughter product of ^{238}U , is reduced significantly in the melting phase, the activity of ^{234}Pa returns to secular equilibrium and equals 99% of the activity of ^{238}U in approximately 168 days (Hendee 1973). Previous studies (Bartlett, Mulhern and Hooker 1977) indicate that beta dose measurements made when ^{234}Pa is not in secular equilibrium with the parent isotope may be misleading with respect to the total radiation hazard.

(a) Natural uranium is composed of 99.27% ^{238}U , 0.72% ^{235}U , and 0.0057% ^{234}U by weight. The weight percent values for DU were calculated by the Energy Systems Department, PNL. The calculation takes into account a 5% enrichment process, which accounts for the reduction in ^{235}U and ^{234}U . Because of the high percentages of the ^{238}U isotope, external radiation measurements are essentially the same for natural and depleted uranium.

3.2 TYPICAL EMISSIONS ASSOCIATED WITH DEPLETED URANIUM

The principal radiation emissions from DU are alpha and beta particles, and electromagnetic radiations called photons (U.S. Department of Health, Education and Welfare 1970).

- Alpha particles have a very limited range in air and do not penetrate even the paper covering of most personnel dosimeters; they are therefore not a concern in measurements of external radiation dose.
- Beta particles, the predominant radiation emission from DU, have a much greater range than alpha particles and can be detected by most personnel dosimeters; they are easily attenuated, however, by materials such as plastics, leather, and aluminum.
- Photons, also produced by DU, are very penetrating, and are therefore attenuated only by heavy materials (materials with a high atomic number), e.g., lead or steel.

In addition to the naturally occurring photon emissions, Bremsstrahlung photons can be produced by beta particles interacting with absorbing materials. The probability of Bremsstrahlung production is low and decreases with the decreasing atomic number of the absorbing material (Chase and Rabinowitz 1968).

The most energetic beta radiation from DU (a 2.29-MeV beta from ^{234}Pa) has a maximum range of less than 0.5 cm in aluminum (U.S. Department of Health, Education and Welfare 1970). This beta emitter and other less energetic beta particles contribute most of the dose rate from bare uranium; however, measurable quantities of photons are also emitted. Because these photons easily penetrate the windshield, sabot, and tailfin of the projectile (Bartlett, Mulhern and Hooker 1977), they are the subject of most of the beam-quality analysis that follows.

3.3 BEAM QUALITY MEASUREMENTS

Measurements that indicate the relative importance of beta and photon emissions from single rounds of XM774 ammunition are reported in this section. Because the DU penetrator rods used in these laboratory measurements had been

processed several years ago, ^{234}Pa was in equilibrium with ^{238}U , making possible a "worst case" analysis of the radiation emissions involved.

3.3.1 Instrumentation Used

The photon spectra were analyzed using lithium-drifted, germanium (Ge(Li)) semiconductor (solid-state) detectors coupled to an ND100 multi-channel analyzer.^(a) Two Ge(Li) detectors were used, one with a high-energy limit of 100 keV^(b) and another with a high-energy limit of 6 MeV.^(c) A 1.27-cm polyethylene beta shield was used to eliminate the most energetic beta particles (2.29 MeV from ^{234}Pa) from the photon measurements.

The Ge(Li) detector with a high-energy limit of 6 MeV was calibrated with ^{137}Cs and ^{60}Co , while the 100-keV-limit detector was calibrated with ^{57}Co and ^{241}Am . The ND100 analyzer was coupled to a tape storage system that allowed retrieval of spectra for analysis by overlapping methods. This technique permitted determination of the presence or loss of individual photon or beta peaks.

Beta spectrometry with an NE 105 plastic detector has been used previously (Bartlett, Mulhern and Hooker 1977) to demonstrate the attenuation capabilities of the windshield. In addition to the NE 105 plastic detector, the 100-keV Ge(Li) detector was used to determine the presence of beta particles.

Thermoluminescent dosimeters (TLD 400s) (Harshaw Chemical Company 1978) were used to measure the relative exposure rate from the penetrator and the projectile in the laboratory study. Beta shields were used with the TLDs to determine penetrating radiation (predominantly photons) and nonpenetrating radiation (beta particles or low-energy photons).

The TASC-4 monitoring system (Harshaw Chemical Company 1977) and a micro R meter (Ludlum Measurements, Inc. 1975) were used for photon measurements. These instruments are described in detail in Section 5.0.

(a) Nuclear Data, Model 88-0551, Golf and Mecham Roads, Schaumburg, IL 60172.
(b) ORTEC, Model 8113-10250, 100 Midland Rd., Oak Ridge, TN 37830.
(c) Princeton Gamma-Tech, Model LGC-65D, P.O. Box 641, Princeton, NJ 08540.

3.3.2 Photon Spectra

Photon spectra were obtained, using the 100-keV Ge(Li) detector, for a penetrator with a beta shield in place, for a penetrator without the beta shield, and for a projectile. When the 6-MeV detector was used, spectra were obtained for a penetrator with no beta shield and for a projectile. In all cases, the detector was positioned above the penetrator or projectile, 6 cm from the centerline of the penetrator rod (see Figure 1).

The spectrum from the penetrator without a beta shield, obtained with the 100-keV Ge(Li) detector, showed more total counts than either of the other two spectra, indicating the counting of both beta and photon radiations. The spectrum from the projectile showed fewer counts than the spectrum from the penetrator with a beta shield, indicating that the components of the projectile shield out some photons.

The spectra obtained with the 6-MeV Ge(Li) detector showed no significant difference between photon counts from the penetrator and those from the projectile because beta radiations cannot penetrate the 6-MeV Ge(Li) detector. For both the 100-keV and the 6-MeV detectors, a slight photon buildup was shown around 100 keV in the spectra from the projectile. This small buildup does not contribute significantly to the total photon dose rate.

These measurements demonstrate that the ratio of nonpenetrating to penetrating emissions is reduced when the sabot covers the penetrator because beta particles are effectively attenuated by the sabot material. The photon spectral analysis also shows that the average photon energy from DU is approximately 1 MeV, and that this energy distribution is not significantly changed by the projectile components, indicating negligible contributions from Bremsstrahlung radiation. The higher-energy photons of DU and its daughters were not resolved because of the long counting times required (Heath 1974).

3.4 CONCLUSIONS

Beta particles are the most significant emissions from DU penetrators and are effectively eliminated by the components of the projectile. Low-level

photon emissions are not significantly shielded by the projectile components, but these photons are at energies that are easily detected and measured by the dosimeters and instrumentation used in this project.

4.0 COMPARISON OF DOSIMETERS FOR PERSONNEL MONITORING

Two types of personnel dosimeters are commonly used to measure the radiation to which individuals are exposed when working in areas containing radioactive material. These two types, thermoluminescent dosimeters (TLDs) and film dosimeters, respond differently to some of the emissions expected from DU. To determine whether one dosimeter might be more appropriate than the other for use in monitoring DU emissions, the Army personnel dosimeter^(a) (a film dosimeter) and the Hanford multipurpose dosimeter (a TLD) (Kathren, Kocher and Endres 1971) were exposed in a controlled experiment to known sources of radiation with emissions similar to those expected from a DU penetrator and from a projectile. The history and general characteristics of the two types of dosimeters were then compared to assess their suitability for general personnel monitoring of low-dose-rate emissions.

4.1 CALIBRATION OF THERMOLUMINESCENT AND FILM DOSIMETERS

The Army personnel dosimeter and the Hanford multipurpose dosimeter (MPD) were exposed to known sources of radiation. The purpose of this controlled study was to identify whether either dosimeter had inadequate energy- or angular-response characteristics, which would affect the estimation of dose rates associated with DU.

4.1.1 Dosimeters Used

The Hanford MPD has five element positions to hold thermoluminescent material and is designed to differentiate between beta particles, photons, and neutrons (Kocher et al. 1971). For this study, only two of the available positions were used: one element position was unshielded to provide a skin (non-penetrating) dose; the other element position was shielded to provide a 1-cm-depth (penetrating) tissue dose. Two ⁷LiF blocks (TLD 700s) (Harshaw

(a) Supplied by J. Starkey, TECOM, Aberdeen Proving Ground, Maryland.

Chemical Company 1978) were placed in each position to provide more data for statistical analysis. The MPDs were processed and the results reported by the Personnel Dosimetry Section, PNL.

The Army personnel dosimeter contains a film emulsion in a standard three-position holder. One position was left as an open window while the other two positions were filtered to provide energy-correction capabilities. After radiation exposure, the dosimeters were returned to the Army (Lexington-Bluegrass Depot Activity, Lexington, Kentucky) for routine processing.

4.1.2 Radiation Exposures

Seventeen multipurpose and 50 film dosimeters were used in the laboratory study. For each irradiation, one MPD and three film dosimeters were positioned together. Photon exposures were made using both National Bureau of Standards filtered x-ray techniques (U.S. National Bureau of Standards 1978) and monoenergetic k x-ray techniques, as listed below. Each dosimeter was exposed to 100 mR of photons. The exposures produced by the Moderately Filtered M (MFM) technique were found to be 8% in error, and the data for the technique were adjusted to correct for this error. Each beta exposure consisted of 100 mrad of either natural uranium or ^{90}Sr - ^{90}Y . Angular dependence was studied using ^{137}Cs photons; the reference angle was the angle between the front surface of the dosimeter and a line perpendicular to the beam direction. Dosimeters positioned at 0° , for example, received exposures directly to the front of the dosimeter. Those at 90° received exposures from the side.

Monoenergetic k X-Ray Technique

<u>Target Material</u>	<u>Energy, keV</u>
Zr	16.1
Sm-Gd	43.0

NBS Filtered X-Ray Techniques

<u>Technique</u>	<u>Energy, keV</u>	<u>Homogeneity Coefficient</u>
Moderately filtered E	34.5	0.73
Moderately filtered C	42	0.81
Moderately filtered I	64	0.88
Moderately filtered K	84	0.92
Moderately filtered M	111	0.93
Moderately filtered O	140	1.016

Photon and Beta Sources

<u>Source</u>	<u>Description</u>
^{137}Cs	0.663-MeV photons
^{90}Sr - ^{90}Y	Betas with 10-mil aluminum filter
Natural Uranium Slab	Betas and photons with 7-mg/cm filter

4.1.3 Results

Both the TL and the film dosimeters significantly overresponded to photon energies below 100 keV. Moreover, the film dosimeters' response below 100 keV was significantly higher than that of the TLDs. A plot of the energy response of both types of dosimeters, based on NBS filter techniques, is shown in Figure 2. Data comparisons were based on the results of T-test evaluations (Steel and Torrie 1960). The response of the TLDs was similar to that reported previously (Endres, Kathren and Kocher 1970).

A plot of the angular dependence of TL and film dosimeters is presented in Figure 3. The difference in the response of the two types of dosimeters is significant, but the difference between the estimated mean exposure and the actual mean exposure is not statistically significant for either dosimeter. The film dosimeters' response to beta exposures from natural uranium and ^{90}Sr - ^{90}Y was also similar to the TLDs' response.

4.2 PERSONNEL MONITORING DEVICES

Photographic film has been in wide use for monitoring personnel exposures to photon, beta, and neutron radiations. After processing, the film exhibits a darkening proportional to the amount of radiation exposure received. This

response is relatively independent of the rate of exposure, but the energy and type of radiation affect the magnitude of the darkening. The use of films with various sensitivities allows the development of film dosimeters with responses to a wide range of exposures (Dudley 1966).

Thermoluminescent material is able to trap deposited energy from ionizing radiation and store the energy in an electron lattice. When heated, the material releases a portion of this trapped energy in the form of light emissions, which can be accurately measured. Subsequently, the quantity of radiation absorbed in the material can be determined. Materials such as lithium (Li) and calcium (Ca) fluorides, which exhibit these thermoluminescent properties, have been used as TLDs (Becker 1973).

Film and TL dosimeters are the most commonly used personnel dosimeters today. Until approximately 10 years ago, film dosimeters were the dosimeter of choice because TL dosimetry was still at a rudimentary stage of development. Solutions to technical problems, such as doping of the lithium fluoride material to increase sensitivity, and commercial production of reliable TL readers, have caused the TLD to replace the film dosimeter for personnel monitoring at many large installations (Kocher et al. 1971). The TLD is now the state-of-the-art in personnel dosimetry and can be designed to provide an estimate of depth doses as required in proposed standards (Health Physics Society, Standards Committee 1977).

4.2.1 Characteristics of Thermoluminescent Dosimeters

Many sources (e.g., Becker [1973] and other references cited in this section) document in detail the characteristics of TLDs, among them the following:

- The long-term stability of TLDs has allowed their use for monitoring nonradiation workers (Becker 1973; Kocher, Kathren and Endres 1970). Although such monitoring is not required by law, it does provide health physics information about persons who have access to radiation areas or who have only a small probability of exceeding nonoccupational maximum permissible dose limits. Thermoluminescent dosimeters can be worn for long periods (3 months to 1 year) with negligible

fading of results (Kathren, Kocher and Endres 1971; Becker 1973), and the dosimeters are highly resistant to environmental factors such as temperature and humidity (Endres, Kathren and Kocher 1970). The CaF:Dy TLD, for example, has been accepted as the most appropriate dosimeter for environmental monitoring because of its stability and resistance to environmental factors (Becker 1973; Fix and Blumer 1977). By contrast, the environmental dependence of film dosimeters (Dudley 1966) is a distinct disadvantage. This assessment further strengthens the evidence that the monitoring of low-level radiation can best be accomplished with TL rather than film dosimeters.

- Single blocks of TL material are small (e.g., 3.2 x 3.2 x 0.9 mm) (Kathren, Kocher and Endres 1971), allowing the design of simple extremity dosimeters. Ring dosimeters (Kathren, Kocher and Endres 1971), for example, have proven more successful than film dosimeters in measuring hand exposures (Kocher, Kathren and Endres 1970). The TLDs used to make the measurements shown in Section 4.1 contained two blocks per element position. This doubling technique is commonly employed to improve the statistics of a single measurement. Where film is used, additional dosimeters are required.
- Compared with film dosimeters, TLDs have a less pronounced over-response to low-energy photons (Kathren, Kocher and Endres 1971; Endres, Kathren and Kocher 1970), as demonstrated in Section 4.1. In addition, a single TL block can respond to radiation exposures ranging from less than 10 mR to over 10^5 R (Kathren, Kocher and Endres 1971). This response is linear up to and above the limits for occupational workers (Kocher, Kathren and Endres 1970).
- Studies have demonstrated that TLDs have only a slight angular dependence compared with film dosimeters, especially at energies below 100 keV (Kathren, Kocher and Endres 1971). These characteristics allow the design of very simple personnel dosimeters (e.g., a single TL block mounted with an identification badge) that provide

long-term monitoring with results superior to those from film (Dudley 1966; Kocher, Kathren and Endres 1970). Currently proposed standards (Health Physics Society, Standards Committee 1977) require determination of the 1-cm-depth dose in addition to the skin dose. Thermoluminescent dosimeters have the small size and relatively stable response characteristics that will allow the design of a dosimeter to comply with these proposed requirements.^(a)

4.2.2 Characteristics of Film Dosimeters

Film (photographic emulsion) has been successfully used in personnel dosimeters for many years (Dudley 1966; Price 1964). Before the advent of TLDs, film dosimeters were the most practical personnel dosimeter, and their performance has been well characterized (Price 1964). The chief advantages of current film dosimeters are that they have been designed to compensate for some of the technical inadequacies of film and that processing techniques are well established (Dudley 1966). Detailed discussions of film dosimeters are provided by Price (1964) and Dudley (1966). Below are some of the important characteristics that should be weighed in evaluating the usefulness of film dosimeters:

- A distinct advantage of film is its high spatial resolution with respect to nonpenetrating radiations (Dudley 1966). The response sensitivity as a function of LET (linear energy transfer) is nonuniform (Dudley 1966). These characteristics, coupled with the permanent record of exposure provided by a developed film, allow analysis of the quality of the radiation exposure. This analysis may prove valuable when a radiation worker's job involves potential exposure to different qualities of radiation. Nevertheless, analysis of the radiation quality is sometimes difficult and can lead to the misinterpretation of quantitative results.

(a) The Nuclear Regulatory Commission is now considering an amendment to the Code of Federal Regulations (10 CFR 20) that would require compliance with such standards.

- The angular dependence of film to photons is extreme below 100 keV (Dudley 1966; Kocher, Kathren and Endres 1970). This dependence is less drastic at high photon energies (such as those associated with many of the daughter products of ^{238}U). For this reason, the evaluations of angular dependence (Section 4.1) were made at 0.663 MeV (from ^{137}Cs), which more closely approximates the average (1.0-MeV) photon emissions from natural uranium (ICRP 1977) than do 100-keV photons. The angular dependence of film becomes a potential problem when exposures are being monitored very close to (within a few centimeters of the surface of) a material in which low-energy photons are caused by radiation buildup. However, exposure of a personnel dosimeter in such a geometry would not be expected.
- Film can provide accurate results if the approximate conditions of exposure are known, as shown by the calibration response in Section 4.1. Two films of different sensitivities are usually contained in a film dosimeter to provide responses to a greater range of exposures (Dudley 1966). The measurements recorded by these films are always in terms of exposure because the composition of the film emulsion is significantly different from that of human tissue (Dudley 1966). The measurements recorded are not as easily converted to dose as are TLD measurements (Becker 1973). As previously mentioned, the TLDs are potentially better suited to developing depth dose information (as required in proposed standards of the Health Physics Society Standards Committee [1977]).

4.3 CONCLUSIONS

The film and TL dosimeters tested responded similarly to the various types of radiation exposures used in the laboratory calibration process. Dosimeters typically overrespond to photon energies below 100 keV, and this was the case for the two types of dosimeters evaluated. The average photon emission from the projectiles (Section 3.3.2) is 0.7 to 1.0 MeV, a response range that did not create measurement difficulties for either dosimeter.

The most important characteristic of TLDs is their suitability for monitoring personnel exposed to the low-dose-rate emissions from DU projectiles. Unlike film dosimeters, TLDs are only slightly affected by environmental factors and are reliable when worn for the long monitoring periods (3 months to 1 year) desirable for low-dose measurements. Thermoluminescent dosimeters are small and can be laminated into a security badge for use by persons not considered radiation workers. Security-badge dosimeters can be processed by commercially available automatic readers. The exposure information supplied by TLDs is as good as or better than that provided by film dosimeters.

5.0 PORTABLE RADIATION DETECTION INSTRUMENTS

The radiation exposure rate from DU projectiles is extremely low. It is this low exposure rate, rather than the characteristics of the radiation, that poses the largest problem in measuring exposures. The use of certain portable instruments sensitive enough to detect low exposure rates can be misleading. A brief description of the instruments commonly used for health physics measurements is presented in this section, along with a discussion of the major advantages and disadvantages of using these instruments to measure the low exposure rate from DU.

5.1 GEIGER-MULLER DETECTORS

The Geiger-Muller (GM) detector (Price 1964) has been widely used by health physicists and the nuclear industry. An important characteristic of this detector is its high sensitivity, which makes it useful for detecting the presence of low-exposure-rate emissions such as those associated with DU projectiles.

The GM detector is a gas-filled tube that can be triggered to discharge when traversed by nuclear radiation. An event that produces ionization within the GM tube, even the formation of only one ion pair, will cause a discharge. Therefore, any type of radiation (such as an alpha particle, beta particle, or photon) that enters the detector can cause a release of charge, which is recorded as an event by the GM instrument. The interpretation of events in terms of absorbed dose (or in terms of exposure rate) requires knowledge of the type and energy distribution of the radiation entering the detector (Emery 1966). For these reasons, GM detectors are valuable in detecting the presence of radiation, but caution should be exercised in relating the number of events counted to the exposure rate.

The GM detector is important because of its high sensitivity, versatility for detecting different types of radiation, wide variety of shapes and windows, and reasonable cost (Price 1964). The GM detector (and a similar detector, the

proportional tube) is commonly used in bench-monitor detection systems and in hand and shoe counters. This type of instrument is the instrument of choice when contamination by a radioactive material is possible.

5.2 IONIZATION SURVEY INSTRUMENTS

Ionization chambers operate by collecting ions within a cavity chamber. Quantitative measurements of exposure rate are possible by the collection of a known fraction of the charge produced within the chamber (Price 1964). Ionization-chamber detectors can be modified for special uses, for example, free-air chambers for precise exposure calibrations, chambers for the measurement of natural background radiations, and portable survey instruments (Boag 1966). A common portable survey instrument is the Cutie Pie (CP).

The typical CP is a pistol-shaped instrument with a cylindrical air-ionization chamber. The chamber is composed of a phenolic resin tube with a thin plastic window covering the outer end. When positioned over the outer end, a disc of the same phenolic resin provides a filter that prevents non-penetrating radiations from entering the chamber. Photons with energies greater than 20 keV and beta particles with energies greater than 1.1 MeV can enter the chamber with the filter in place. Additional beta shielding would be necessary to prevent all the beta particles from bare uranium from entering the chamber. With the filter removed, the thin 7-mg/cm² window will admit photons with energies greater than 8 keV and beta particles with energies greater than 65 keV. The 7-mg/cm² window by itself completely eliminates alpha radiations from the chamber (Pacific Northwest Laboratory 1969).

The CP is designed to detect exposure rates higher than those from a single round of DU ammunition. If the CP is modified to integrate the ionization collected rather than provide a measure of the exposure rate, then greater sensitivity is possible. However, the size of the CP's chamber also makes geometry considerations (orientation of the chamber and distance from the radiation source) important. If the CP is close to a source, then the measurements must be corrected to account for source size and geometry. If the CP is moved farther away to make geometry less important, then numerous DU rounds must be positioned close together to obtain measurements that are significant.

Thus, an ionization chamber such as the CP with integrating capabilities could provide useful measurements of the exposure rate from stockpiled DU rounds if due consideration were given to geometry factors.

5.3 THE TASC-4 ENVIRONMENTAL MONITORING SYSTEM

Thalium-activated sodium iodine (NaI(TL)) detectors are commonly used for photon spectrometry. They are not normally used in portable survey instruments because they are too sensitive for most health physics measurements and because their energy efficiency response is not uniform for all photon energies. With the advent of solid state electronics, however, the variable response of the NaI(TL) detector systems modified for energy response is appropriate for measurements of low photon exposure rates. Such a system is the TASC-4 Environmental Radiation Monitoring System (Figure 4) described below. (The description is provided by the Harshaw Chemical Company [1977].)

- The TASC-4 performs continuous, real-time monitoring of both natural and man-made gamma-ray (photon) emissions. Precise reliable readings of exposure rate are displayed on panel meters calibrated directly in $\mu\text{R/hr}$.
- The detector used in the TASC-4 system is a 2- x 2-in. NaI(TL) crystal optically coupled to a selected photomultiplier tube. The detector has an integral alpha source that provides continual pulses to the system electronics. These pulses are used to stabilize the gain of the system.
- Signal processing is accomplished with nuclear instrument modules (NIM). Each NIM is a discrete instrument designed to plug into a NIM bin that furnishes all required operating power. For portable operation in the field, a battery-operated inverter is used to provide 120-V ac to the TASC-4. A single coaxial cable is used for both signal and high-voltage transmission. Output pulses are decoupled from the high voltage by a decoupling network.
- Pulses are amplified and shaped by the amplifier, which contains a gain-stabilization circuit to keep the gain at a constant level. Digital feedback automatically varies the linear amplifier gain to compensate for changes in detector output caused by fluctuations in high voltage or changes in temperature. The gain is nominally set so that a 2-MeV gamma ray produces a 5-V output pulse and the reference photopeak produces a 7.5-V pulse. Pulses in the reference peak are rejected from analysis in the determination of exposure.

- For area monitoring, an analog-to-digital converter (ADC) is used to convert the linear amplifier's output pulses into a stream of digital pulses that have an average rate proportional to the average exposure of air to the input spectrum. The ADC has upper and lower discriminators so that measurements may be performed over limited portions of the gamma-ray spectrum. Because several microseconds may be involved in the processing of a single pulse, a dead-time gate (busy) is provided for use in correcting scaler and timer measurements. An analog dead-time compensation signal is also provided to compensate ratemeters. The output of the ADC drives a scaler that displays $\mu\text{R/hr}$ on a front-panel, digital readout.

The TASC-4 is a unique instrument that provides precise measurement of the low photon levels associated with DU rounds. The calculation of exposure in air using the TASC-4 is discussed in the Appendix.

5.4 MICRO R METERS

While the TASC-4 monitoring system is appropriate for determining low-level photon exposures, the large size of the detector and the electronic compensating system make it more difficult to handle than a self-contained, hand-held system. Micro R count rate meters (Figure 5) that are small and easy to handle, especially in the close confines of a tank interior, are now available commercially. These instruments use an NaI(TL) detector, as does the TASC-4; however, the detector is 1 in. by 1 in. (2.5 cm by 2.5 cm) in size, rather than 2 in. by 2 in., and has no special circuitry to convert the electronic signal to exposure rate. The limitation of this instrument is that, as with the GM detector, knowledge of the energy distribution is needed to relate the detected level to exposure rate. Micro R meters are suitable for field use in environmental analysis (and for measuring photon emissions for uranium) (NCRP 1976) when calibrated to a photon field whose exposure rate has been determined by an ionization chamber or an instrument like the TASC-4 (Harshaw Chemical Company 1977).

The Ludlum Micro R Meter used in this study is typical of most commercially available micro R meters. A brief description of the Ludlum Model 12S Count Rate Meter, quoted from the Ludlum Measurements, Inc. manual (1975), is as follows:

- The Model 12S Count Rate Meter is a Gamma Survey Meter utilizing an internally mounted NaI(TL) Gamma Scintillator as a detector. The instrument is completely self-contained and utilizes two size "D" cells for power. The instrument is suitable for operation in detecting gamma radiation from radioactive isotopes.
- Circuit functions of the Model 12S include amplifier, discriminator, high-voltage power supply, rate meter circuit, meter driver circuit and audio output circuit.
- The amplifier, discriminator and rate meter circuit are located on the outside circuit board. Remaining major circuitry is mounted in the inside circuit board.
- By using "operational" amplifier techniques in feed-back, the amplifier maintains very stable input impedance and gain characteristics for large variations in supply voltage and temperature.
- The supply has adequate power to drive scintillation detectors at 1500 volts and proportional detectors at 2400 volts.
- Instrument and probe operating point is established by setting the probe voltage and instrument sensitivity. (High Voltage and GAIN.) The proper selection of this point is the key to instrument performance. For a given detector system, efficiency, background, sensitivity and noise are fixed by the physical makeup of the detector and rarely vary from unit to unit. However, the selection of the operating point makes a marked difference in the apparent contribution of these three sources of count.
- In setting the operating point, the final result of the adjustment is to establish the system gain such that the desired signal pulses are above the discrimination level and the unwanted pulses from background radiation and noise are below the discrimination level and are not counted.

5.5 COMPARISON OF TASC-4 SYSTEM AND MICRO R METER

The TASC-4 monitoring system is a semi-portable instrument designed primarily for laboratory use. It can be used in a field situation; however, the instrument and power supply are extremely bulky and two people are required to transport the system. The TASC-4 was useful in this study for evaluating the performance of the micro R meter.

A comparison of the measurements made with the TASC-4 and the Ludlum Micro R Count Rate Meter is shown in Table 1. A single penetrator and projectile were positioned so that the distance from the side of the penetrator or the

projectile to the detector covering was as indicated. (Analysis of the photon quality for these conditions was shown in Section 3.3.) These data demonstrate that photon exposures from a DU penetrator and projectile can be measured adequately for health physics purposes by a properly calibrated micro R meter.

5.6 CONCLUSIONS

The GM detector is designed to detect radiation and is excellent for monitoring radiation contamination. It could be used from the manufacturing to the demilitarization phase of DU munitions to detect and control accidental contamination. However, unless specifically calibrated, it should not be used to measure exposure rates.

The CP air-ionization meter is useful in measuring exposure rates from stockpiled DU ammunition. However, careful attention must be paid to proper use of geometry correction factors when the CP is used. Because of the low exposure rates from the individual XM774 rounds, this instrument should not be used to measure exposure rates from fewer than four rounds. However, the CP would be useful in the transportation, storage, and research and development testing of the XM774 ammunition where more than four rounds are involved.

The TASC-4 Environmental Radiation Monitoring System is a good instrument for research and development work in the laboratory. However, it is too bulky to be used as a portable monitoring system.

The hand-held, self-contained, micro R meter would be useful for measuring exposure rates within the confines of a tank or in the field. However, this instrument should not be used to control contamination or to measure exposure rates where more than one radionuclide is present.

6.0 FIELD RADIATION MEASUREMENTS

In September 1977, PNL conducted field experiments at the Aberdeen Proving Ground, Maryland. The tests were designed to measure exposure rates from a single round of 105-mm XM774 ammunition, from two rounds in a single storage container, from a full standard pallet consisting of 30 rounds in 15 containers, and from a tank loaded with 32 rounds. In all cases, control TLDs were kept away from the test rounds for comparative purposes. In a previous study (Bartlett, Mulhern and Hooker 1977), the Radiological Calibrations Section of PNL had determined the dose rates from a DU penetrator. These measurements had been made under strict laboratory conditions at PNL using TLD 400s, in an experiment designed to measure surface radiation levels from DU penetrators (Table 2, Figure 6) and projectiles (Table 3, Figure 7). In addition, photon exposure rates had been measured with the TASC-4 instrument (Table 4).

6.1 SINGLE ROUND MEASUREMENTS

In this study, measurements were made using a 26-mm-dia round and a 28-mm-dia round of XM774 ammunition.

6.1.1 Dosimeters and Instruments Used

A specially designed TLD was constructed for the study. The dosimeter was made of polyethylene and had six locations for TLD 700 chips. One chip was placed in each hole and three of the holes were covered with a thin piece of paper. The other three holes were covered from both sides with a piece of aluminum 3 mm thick to discriminate between the dose equivalence at the skin surface and at 1-cm depth. The entire dosimeter was then secured with a piece of adhesive tape. (See Figure 8. For reference, a standard TLD holder is included in the figure.)

6.1.2 Experimental Conditions

The two XM774 rounds were placed in a low-radiation background area for the duration of this test. Twelve of the specially designed dosimeters were

taped to each round (Figure 9) for 48 hours, and three dosimeters were used as controls. At the end of 48 hours, the 24 dosimeters were removed from the rounds and, with the controls, returned to PNL for analysis.

6.1.3 Results

The three bare and three covered TL chips were averaged to give one bare (nonpenetrating) and one covered (penetrating) reading. The results of this study support the results of the previous PNL studies. The highest exposure at the surface of a projectile was found to be 5.36 mR/hr (Table 5), at location 2 in Figure 9. The exposure rate at the base of the round was not measurable.

6.2 LOADED STORAGE CONTAINER MEASUREMENTS

Radiation exposures from an ammunition container that held two XM774 rounds were measured.

6.2.1 Dosimeters and Instruments Used

Measurements were made with 15 of the specially designed TLDs containing TLD 700 chips.

6.2.2 Experimental Conditions

The storage container was placed in a low-radiation background area with 15 TLDs taped to it. The TLDs were left in place for 48 hours before being returned to PNL for analysis.

6.2.3 Results

The maximum exposure rate found was approximately 0.4 mR/hr (Figure 10) at the surface of the container. A person could not exceed the limit for occupational radiation exposure of the extremities at such a low exposure rate.

6.3 PALLET MEASUREMENTS

For shipping and storage, DU rounds are boxed two to a container and the containers are stacked on pallets. To determine the exposure rate from a pallet of XM774 ammunition, a pallet was prepared in a standard configuration containing the standard number of rounds.

6.3.1 Dosimeters and Instruments Used

Film dosimeters from the Army, the specially designed TLDs from PNL, and the TASC-4 monitoring system were used to determine exposure rates from the pallet. The film and TL dosimeters were used to measure potential contact exposures; the TASC-4 was used to measure whole-body exposures at various distances from the pallet.

6.3.2 Experimental Conditions

Thirty rounds were used in the pallet study (15 storage containers holding two rounds each). Each of the 15 containers was banded twice and placed on a pallet three boxes wide and five boxes high. The entire pallet was then banded twice. The TL and film dosimeters were taped to the sides, top, and ends of the pallet (Figure 11) for approximately 48 hours. The TASC-4 measurements were made at distances of 5 cm, 54 cm, 1 m, and 2 m from the center of one end and from the center of one side of the pallet.

6.3.3 Results

The measurements taken with the TASC-4 showed the highest exposure rate on top of the pallet directly over the projectiles (Table 6). The exposure rate was 150 μ R/hr at 5 cm above the surface. Because this exposure is localized, it is not considered a whole-body exposure. The largest whole-body exposure measured with the TASC-4 was 0.1 mR/hr, 54 cm from the center of the side of the pallet.

The highest exposure rates measured with TLDs averaged approximately 0.56 mR/hr (Table 7) at contact with the pallet. This exposure rate was found at both ends of the pallet.

6.4 TANK MEASUREMENTS

To determine the radiological hazard to which a tank crew could be exposed from XM774 ammunition, a standard tank (M60A1, Figure 12) was loaded with 32 rounds. The number and storage locations of the rounds in the tank were recommended by E. W. Bloore.^(a) The ammunition used in this study was provided by R. Davitt, Project Manager, XM774, Engineering Development Program of the Large Caliber Weapons Systems Laboratories, ARRADCOM, Dover, New Jersey.

6.4.1 Dosimeters and Instruments Used

The dose measurements within the tank were made using the TASC-4 monitoring system, 20 film dosimeters supplied and processed by the Army, and 600 TLD 600s (Harshaw Chemical Company 1978) supplied and processed by PNL.

The chips used in the TLDs were loaded into two types of dosimeters to facilitate positioning of the dosimeters within the tank. The first dosimeter was a modified version of the Hanford MPD, which can be loaded with two TL chips at each of the five filter locations (see Section 4.1.1). The second dosimeter was the specially designed polyethylene holder with six holes. The two types of TLDs and the film dosimeters were fastened to various locations in the tank with masking tape.

6.4.2 Experimental Conditions

The M60A1 tank was kept in a controlled environment during the study. The temperature was maintained at $21.1 \pm 2.7^{\circ}\text{C}$ ($70 \pm 5^{\circ}\text{F}$) to avoid heat damage to the film dosimeters. Measurements were taken with the turret and rounds in two configurations and with no rounds present (to establish a background radiation level), over a 1-week period.

The first set of measurements was taken with the barrel facing aft in the travel position (Figure 13). With the turret in this position, the loader is the crew member closest to the DU rounds. Thirteen rounds were positioned in the ready rack directly in front of the loader (Figure 14), and 19 rounds were stored in the tubular racks behind the loader (Figure 15). Both racks are approximately 50 cm from the loader. Dosimeters were taped to the front

(a) Letter from M. Falkovich.

and back of a tissue-equivalent phantom placed in the loader's seat (Figures 14 and 15). Dosimeters were also placed at each crew member's location (Figure 16) and throughout the interior of the tank (Figure 17). These dosimeters remained in place for 46 hours to achieve a high enough exposure for good statistical averaging.

The second set of measurements was taken with the barrel facing forward in the battle position (Figure 18). The loader would then receive approximately the same dose as when the turret is in the travel position. The driver would now be exposed to the rounds in the tubular storage racks on either side and in the ready rack at the rear; therefore, the phantom was placed in the driver's seat (Figures 19 and 20) with the dosimeters positioned on the phantom in the same manner as for the travel configuration. Ten rounds were loaded into the left storage rack and nine rounds were loaded into the right. The ready rack was filled with 13 rounds. Dosimeters were also placed at all crew member locations and at selected sites throughout the interior of the tank (Figure 21). The dosimeters used for this set of measurements remained in place for 41 hours and 35 minutes.

After the DU rounds had been removed, a 48-hour TLD measurement and a TASC-4 measurement were taken inside the tank to determine levels of natural background radiation and to note any emissions from radiation inherent in the armor plating or other tank components.

6.4.3 Results

The results of the tank measurements can be grouped into two categories, whole-body and extremity exposures. The whole-body exposures are defined as those from areas in the tank into which the trunk of a person can fit; the extremity exposures are based on areas into which the hands or feet can fit.

The highest exposure measured was a contact extremity exposure of 5.5 mR/hr (Table 8) measured by a specially designed TLD taped to the windshield of a round in the ready rack. This exposure agreed with previous results (Bartlett, Mulhern and Hooker 1977) of contact with the XM774 ammunition and with the contact measurements of the rounds discussed in Section 6.1.

The highest noncontact extremity exposures, 0.304 and 0.698 mR/hr (Tables 8 and 9, respectively), were measured by dosimeters located at positions not easily accessible except by an extremity; however, the measured levels are less than 25% of the maximum permissible dose for extremities allowed by 10 CFR 20.

The highest measurement in an area where whole-body exposure was possible was 0.26 mR/hr (Table 8). This reading was taken by a dosimeter on a phantom in the loader's seat. Other measurements equaled or were below (some an order of magnitude below) this value.

The penetrating (photon or gamma-ray) measurements made with the TASC-4 (Table 10) were comparable to those made with the dosimeters. The minor differences between the measurements can be accounted for by geometric factors (variations in the positioning of the detectors), the typical overresponse of TL and film dosimeters, and the low-photon-energy cutoff of the TASC-4's response.

The background TLD measurements (Table 11) indicated that no secondary sources were present. (An example of a secondary source would be excessive cobalt in the tank armor, a by-product of the smelting process.)

6.5 CONCLUSIONS

The field studies indicate extremely low radiation levels associated with 105-mm, XM774 ammunition. Even if personnel were exposed for long periods of time to the highest levels of XM774 radiation measured, their exposure would not be likely to exceed 25% of the maximum permissible limits set by 10 CFR 20.

Radiation exposure rates from a single round indicate that the round would have to be held for over 1900 hr/yr (Bartlett, Mulhern and Hooker 1977) to exceed the extremity exposure limits. This is a conservative estimate based on the highest exposure rates measured.

The results of the storage container, pallet, and tank measurements support the results of a previous study (Bartlett, Mulhern and Hooker 1977). Radiation exposure rates did not exceed 0.26 mR/hr when exposure of the whole

body or of critical organs would be probable. Personnel could be exposed to this level of radiation for approximately 4800 hr/yr without exceeding 25% of the maximum permissible whole-body exposure limit.

7.0 HEALTH PHYSICS CONSIDERATIONS OF XM774 AMMUNITION

The major emphasis of this project was to investigate the external radiation emission associated with the XM774 ammunition and to recommend dosimeters and instruments that would be appropriate for measuring this emission. This section includes information about other potential health problems associated with the ammunition.

7.1 REMOVABLE CONTAMINATION

During the course of this project, six DU penetrator rods were handled in a laboratory. No evidence of removable contamination was found.

In the production of the DU penetrator rod, milling or other processes could cause uranium contamination of work areas and equipment. Instruments designed to detect the presence of radiation should be used to monitor these areas. Specially designed hand and shoe monitors should be used to screen all persons leaving areas where removable contamination may be found.

The completed XM774 round contains no bare DU. The presence of removable contamination on such ammunition would be possible only if the round were disassembled, damaged, or exploded.

7.2 RADON RELEASE

Radon gas (^{222}Rn) is produced from the decay of ^{238}U . In uranium mining, where the decay of ^{238}U and its daughters has occurred over long periods of time, the presence of this gas requires the use of protective measures such as adequate ventilation, respirators, and special air monitors (ICRP 1977).

The DU used for the penetrator rod of the XM774 projectile is processed and fabricated to form a cylinder from which radon gas is unlikely to leak.^(a) Precautions similar to those required for uranium mining therefore appear unwarranted except where the uranium is being processed or fabricated.

(a) Private communication, L. M. Levy, National Lead Company of Ohio, Cincinnati, OH 45239. Calculations indicate that virtually no radon would be lost from within a mass of uranium 1.6 cm in diameter and 12.7 cm long.

FIGURE 1. Position of Detector Above Penetrator

FIGURE 2. Energy Response of Thermoluminescent and Film Dosimeters

FIGURE 3. Angular Response of Thermoluminescent and Film Dosimeters

FIGURE 4. TASC-4 Environmental Radiation Monitoring System

FIGURE 5. Ludlum Model 12S Micro R Meter

TABLE 1. Comparison of Exposure Measurements Using TASC-4 and Micro R Meter

Source	Source-to-Detector Distance, cm	Exposure, $\mu\text{R/hr}$	
		TASC-4	Micro R Meter
Background	—	8.70 ± 0.01	8 ± 1
Penetrator Rod	15	111.50 ± 0.41	155 ± 15
Penetrator Rod	50	43.50 ± 0.15	35 ± 4
Penetrator Rod	100	18.86 ± 0.25	15 ± 2
Projectile	15	102.82 ± 0.26	150 ± 15
Projectile	50	39.74 ± 0.16	35 ± 4
Projectile	100	17.50 ± 0.08	15 ± 2

TABLE 2. Thermoluminescent Dosimeter Measurements of Dose Rate from a Penetrator Rod with Windshield^(a)

Location of Dosimeters ^(b)	Beta and Gamma Radiations, mrad/hr			
	Projectile Number			
	1	2	3	4
A	<1.0	3.0	<1.0	<1.0
B	5.0	5.0	5.0	5.0
C	215	218	215	200
D	219	216	225	207
E	176	209	247	229

(a) Data from Bartlett, Mulhern and Hooker (1977).

(b) See Figure 6 for location of dosimeters.

FIGURE 6. Position of Thermoluminescent Dosimeters on Penetrator

TABLE 3. Thermoluminescent Dosimeter Measurements of Dose Rate from a Projectile^(a)

Location of Dosimeters ^(b)	Measurement at 1.0 cm from Surface, mrad/hr	
	Beta + Gamma	Gamma
F	9.8	<1.0
G	59.5	2.1
H	9.3	1.6
I	9.2	1.6
J	3.9	<1.0
K	54.9	2.0
L	3.4	<1.0
M	7.1	<1.0

(a) Data from Bartlett, Mulhern and Hooker (1977).

(b) See Figure 7 for location of dosimeters.

FIGURE 7. Position of Thermoluminescent Dosimeters on Projectile

TABLE 4. TASC-4 Measurements of Gamma Exposure Rate from a Penetrator and a Projectile^(a)

Detector-to-Surface Distance, cm	Exposure Rate, $\mu\text{R/hr}$	
	Center of Penetrator	Center of Projectile
15	111.50 ± 0.41	102.82 ± 0.26
50	43.50 ± 0.15	39.74 ± 0.16
100	18.86 ± 0.25	17.50 ± 0.08

(a) Data from Bartlett, Mulhern and Hooker (1977).

FIGURE 8. Thermoluminescent Dosimeters

FIGURE 9. Location of Twelve Thermoluminescent Dosimeters on an XM774 Round

TABLE 5. Thermoluminescent Dosimeter Measurements of Exposure Rate from Single XM774 Rounds

Location of Dosimeter ^(b)	Exposure, mR/hr ^(a)			
	26-mm Round		28-mm Round	
	Beta + Gamma	Gamma	Beta + Gamma	Gamma
1	0.581 ± 0.343	0.433 ± 0.208	0.197 ± 0.075	0.218 ± 0.045
2	5.358 ± 0.289	3.408 ± 0.233	5.079 ± 1.612	3.435 ± 0.468
3	1.287 ± 0.056	1.329 ± 0.091	1.337 ± 0.033	1.468 ± 0.162
4	1.350 ± 0.085	1.379 ± 0.131	1.535 ± 0.031	1.527 ± 0.047
5	0.637 ± 0.012	0.664 ± 0.033	0.745 ± 0.016	0.714 ± 0.045
6	0.616 ± 0.072	0.706 ± 0.075	0.437 ± 0.079	0.472 ± 0.091
7	0.085 ± 0.004	0.089 ± 0.004	0.052 ± 0.002	0.054 ± 0.004
8	0.008 ± 0.004	0.012 ± 0.012	0.008 ± 0.002	0.010 ± 0.004
9	<DL	<DL	<DL	<DL
10	<DL	<DL	<DL	<DL
11	<DL	<DL	<DL	<DL
12	<DL	<DL	<DL	<DL

(a) Control measurements have been subtracted from all readings.

(b) See Figure 9 for location of dosimeters.

<DL - Less than detection limit.

FIGURE 10. Thermoluminescent Dosimeter Results (mR/hr) and Locations of Dosimeters on a Storage Container

FIGURE 11. Pallet of XM774 Ammunition

TABLE 6. TASC-4 Measurements of Gamma Exposure Rate from a Standard Pallet

Measurement Location	Exposure Rate, $\mu\text{R/hr}$
5 cm from Top Surface of Pallet	150
5 cm from Top Edge of Pallet, Center	112
5 cm from Top Edge of Pallet, End	89
5 cm from Top Edge of Pallet, Opposite End	99.5
5 cm from End of Pallet, Third Row	89
5 cm from End of Pallet, Between Two Rounds	127
54 cm from Center of Side	100
1 m from Center of Side	51
2 m from Center of Side	27
54 cm from End of Pallet	46
1 m from End of Pallet	31
2 m from End of Pallet	20
Background	11

TABLE 7. Dosimeter Measurements of Exposure Rate at Contact with a Standard Pallet

Location of Dosimeters ^(b)	Exposure, mR/hr ^(a)		Film Gamma ^(c)
	Specially Designed TLD Beta + Gamma	Gamma	
<u>Center of Box #3 - East Side</u>			
10.2 cm from End	0.125	0.125	
45.7 cm from End	0.562	0.583	
78.7 cm from End	0.270	0.270	
102 cm from End	0.083	0.083	
<u>Center of Box #3 - West Side</u>			
10.2 cm from End	0.166	0.166	0.520
45.7 cm from End	0.541	0.562	0.770
78.7 cm from End	0.312	0.291	
102 cm from End	0.083	0.083	
<u>North End of Box #3</u>			
15.2 cm from East Side	0.145	0.125	
53.3 cm from East Side	0.166	0.145	0.395
88.9 cm from East Side	0.104	0.104	
<u>South End of Box #3</u>			
15.2 cm from East Side	0.145	0.125	
53.3 cm from East Side	0.145	0.145	
88.9 cm from East Side	0.104	0.083	
<u>Top of Pallet - 15.2 cm from North End</u>			
7.62 cm from East Side	0.125	0.125	
27.9 cm from East Side	0.125	0.125	
45.7 cm from East Side	0.145	0.145	
61.0 cm from East Side	0.187	0.187	0.520
78.7 cm from East Side	0.166	0.166	
99.1 cm from East Side	0.166	0.166	
<u>Top of Pallet - 15.2 cm from South End</u>			
7.62 cm from East Side	0.104	0.125	
27.9 cm from East Side	0.187	0.145	
45.7 cm from East Side	0.166	0.187	
61.0 cm from East Side	0.208	0.229	
78.7 cm from East Side	0.208	0.187	
99.1 cm from East Side	0.125	0.125	

(a) Control measurements have been subtracted from all readings.

(b) See Figure 11 for location of dosimeters.

(c) Measurements were taken only in the locations for which data are provided.

FIGURE 12. M60A1 Tank

FIGURE 13. Schematic of Tank in Travel Configuration

FIGURE 14. Phantom in Loader's Seat with Ready Rack

FIGURE 15. Phantom in Loader's Seat with Storage Rack

FIGURE 16. Dosimeters on Tank Commander's Seat

FIGURE 17. Dosimeters on Driver's Periscope

FIGURE 18. Schematic of Tank in Battle Configuration

FIGURE 19. Phantom in Driver's Seat with Left Storage Rack

FIGURE 20. Phantom in Driver's Seat

FIGURE 21. Dosimeters Above Ready Rack

TABLE 8. Dosimeter Measurements of Exposure Rate from XM774 Ammunition in an M60A1 Tank with the Gun Barrel Facing Aft^(a)

Location of Dosimeters	Exposure, mR/hr ^(b)				Film Gamma ^(c)
	Hanford MPD ^(c)		Specially Designed TLD		
	Gamma	Beta + Gamma	Gamma	Beta + Gamma	
Phantom in Loader's Seat					
Phantom Front Left			0.239	0.260	
Phantom Front Left			0.217	0.239	
Phantom Front Center	0.195	0.195	0.152	0.173	0
Phantom Front Center	0.195	0.195	0.130	0.108	0.195
Phantom Front Right			0.065	0.087	
Phantom Back Center	0.065	0.087	0.065	0.065	0
Phantom Back Center	0.087	0.087	0.065	0.043	0.195
Phantom Back Right			0.043	0.021	
Phantom Back Right			0.087	0.087	
Phantom Back Left			0.152	0.152	
7.62-mm Ammunition Rack					
Above Ready Rack	0.152	0.152	0.152	0.152	0.130
Storage Rack Behind Loader			0.087	0.087	
Driver's Periscope			0.021	0.021	
Gunner's Seat			0.108	0.087	
Tank Commander's Seat			0.065	0.065	0
Windshield of Round in Ready Rack			3.108	5.565	
Side of Turret Beside Loader			0.195	0.217	
Metal Plate, Left Side of Breech			0.304	0.391	0.195
Side of Turret Beside Tank Commander			0.065	0.043	0

(a) Thirteen rounds were placed in the ready rack and 19 rounds in the storage rack behind the loader.

(b) Control measurements have been subtracted from all readings.

(c) Measurements were taken only in the locations for which data are provided.

TABLE 9. Dosimeter Measurements of Exposure Rate from XM774 Ammunition in an M60A1 Tank with the Gun Barrel Facing Forward^(a)

Location of Dosimeters	Exposure, mR/hr ^(b)				Film Gamma ^(c)
	Hanford MPD ^(c)		Specially Designed TLD		
	Gamma	Beta + Gamma	Gamma	Beta + Gamma	
Phantom in Driver's Seat					
Phantom Front Left			0.168	0.144	
Phantom Front Left			0.168	0.168	
Phantom Front Center	0.192	0.192	0.168	0.144	0.216
Phantom Front Center	0.144	0.144	0.192	0.192	0.289
Phantom Front Right			0.168	0.144	
Phantom Back Right			0.144	0.120	
Phantom Back Center	0.144	0.144	0.120	0.096	0.144
Phantom Back Center	0.096	0.096	0.096	0.072	0.144
Phantom Back Left			0.096	0.072	
Phantom Back Left			0.096	0.072	
Driver's Center					
Periscope			0.096	0.144	
7.62-mm Ammunition Rack					
Above Ready Rack			0.240	0.289	0.289
Storage Rack Behind					
Loader			0.072	0.048	
Gunner's Seat			0.048	0.120	0
Tank Commander's Seat			0.048	0.048	0
Side of Turret Beside					
Loader			0.096	0.096	
Metal Plate, Left Side					
of Breech			0.313	0.385	0.361
Side of Turret Beside					
Tank Commander			0.048	0.024	
Storage Cylinder Left					
of Driver			1.036	1.060	
Instrument Panel Right					
of Driver			0.698	0.722	

(a) Thirteen rounds were placed in the ready rack, 9 rounds were placed in the storage rack to the right of the driver, and 10 rounds were placed in the storage rack to the left of the driver.

(b) Control measurements have been subtracted from all readings.

(c) Measurements were taken only in the locations for which data are provided.

TABLE 10. TASC-4 Measurements of Gamma Exposure Rate from an M60A1 Tank with the Gun Barrel Facing Aft^(a)

Measurement Location	Exposure, $\mu\text{R/hr}$	
	Loaded Tank ^(a)	Unloaded Tank ^(b)
Gunner's Seat	48.9	10.0
Tank Commander's Seat	40.8	10.6
Driver's Seat	20.3	10.3
Loader's Seat	(c)	10.2
Loader's Seat, on Top of Phantom	88.1	(c)
Loader's Seat, in Front of Phantom	121	(c)
Front of Storage Rack Behind Loader	50.6	9.9
Interior of Storage Rack Behind Loader	134	(c)
Between Rounds in Ready Rack	187	(c)
Inside Top of Turret at Rear	(c)	11.1

(a) Thirteen rounds were placed in the ready rack and 19 rounds in the storage rack behind the loader—background was not subtracted.

(b) All rounds were removed.

(c) No measurements were taken.

TABLE 11. Measurements of Radiation Background in an M60A1 Tank

Location	Exposure, $\mu\text{R/hr}$ ^(a)		
	TLD		Film Gamma ^(b)
	Beta + Gamma	Gamma	
Loader's Seat	10.4	6.3	0
Gunner's Seat	14.6	12.5	0
Tank Commander's Seat	4.2	2.1	16.7
Driver's Seat	6.3	2.1	0
Storage Rack Behind Loader	10.4	4.2	
Side of Turret Beside Loader	14.6	4.2	
7.62-mm Ammunition Rack	8.3	4.2	
Metal Plate, Left Side of Breech	6.3	2.1	
Turret Beside Tank Commander	2.1	2.1	
Periscope in Front of Driver	2.1	4.2	
Right Storage Tube by Driver	16.7	10.4	
Left Storage Tube by Driver	14.6	4.2	

(a) Control measurements have been subtracted from all readings.

(b) Film measurements were taken only in the locations for which data are provided.

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APPENDIX

CALCULATION OF EXPOSURE RATE USING THE TASC-4 SYSTEM

APPENDIX

CALCULATION OF EXPOSURE RATE USING THE TASC-4 SYSTEM^(a)

A block diagram of the TASC-4 system is shown below.

- (a) This material is taken from the Harshaw Chemical Co., TASC-4 Environmental Radiation Monitoring System Operation and Maintenance - Instruction Manual.

The exposure in air is computed by using the relationship that exists between energy fluence and exposure. While such computations can be made by using matrix unfolding or stripping methods operating on spectra accumulated to high statistical significance, it is possible in certain size categories of high atomic number scintillators to operate directly on each pulse, so as to calculate the contribution of each pulse to the exposure. The exposure attributable to photons having energies between E_1 and E_2 is given by Equation 1.1.

$$\epsilon = \sum_{E_1}^{E_2} \frac{1.6 \times 10^{-6}}{87} \mu_a \phi E \quad \text{Eq. 1.1}$$

Where: μ_a is the mass energy absorption coefficient for air.
 ϕ is the photon number fluence,
 E is the energy of the photons.

In practice, real scintillators do not have unit efficiency for detection of gamma-rays having high energies and some systematic method must be devised for calculating the exposure from the number of pulses and their distribution which are actually observed. A sufficient method has been found when Equation 1.1 is modified to the form shown in Equation 1.2.

$$\epsilon = \sum_{E_1}^{E_2} A \cdot g(E) \cdot N \cdot H \quad \text{Eq. 1.2}$$

Where: A is a pre-calibration constant,
 N is the number of pulses having height H .

For a 2 x 2 inch NaI(Tl) scintillator $g(E)$ has been found to be:

$$g(E) = \frac{\mu_a}{1 - \exp(-B\mu)} \quad \text{Eq. 1.3}$$

Where: B is 11,
 μ is the mass energy absorption coefficient for gamma rays in NaI.

The product $N \cdot H$ is formed electronically by measuring the time required for a capacitor charged to the pulse height H to be discharged at a constant current and summing that time over all times. This is accomplished by a Wilkinson analog to digital converter circuit.

The nonlinearity $g(E)$ is generated by causing the discharge current for the storage capacitor to be smaller for higher values of pulse height. The ADC is adjusted using a pulse generator to provide output count rate as a function of input pulse height having the variation shown in Figure B-1.

FIGURE B-1. Output Characteristics of Charge Digitizer

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