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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
07/27/2006	00	New Technical Basis Document for the Pantex Plant National Security Complex – Occupational External Dose. First approved issue. Training required: As determined by the Task Manager. Initiated by Jerome B. Martin.
06/22/2007	01	Approved revision initiated to incorporate Attributions and Annotations section. Constitutes a total rewrite of the document. Added references and made editorial changes. Modified Table 6-1 average total dose for 1958, 1977, 1983, and 1997. Modified Table 6-9 to add Radiography NDE. No further changes occurred as a result of formal internal review. Incorporates formal NIOSH review comments. This revision results in no change to the assigned dose and no PER is required. Training required: As determined by the Task Manager. Initiated by Jack J. Fix.
11/24/2015	02	Revision initiated to add section detailing the Special Exposure Cohort classes for the Pantex Plant. Includes editorial changes. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Dale D. Thomas III.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ALARA	as low as reasonably achievable
AP	anterior-posterior
CFR	Code of Federal Regulations
Ci	curie
cm	centimeter
DHHS	U.S. Department of Health and Human Services
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
DOL	U.S. Department of Labor
DU	depleted uranium
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
eV	electron-volt
GSD	geometric standard deviation
HE	high explosive
HERS	Historical Exposure Records System
HEU	highly enriched uranium
Hp(0.07)	personal dose equivalent at 0.07 millimeters depth in tissue
Hp(10)	personal dose equivalent at 10 mm depth in tissue
Hp(d)	personal dose equivalent at depth *d* (deep dose at 10 mm; shallow at 0.07 mm)
Hp,slab(10)	personal dose equivalent (slab phantom) at 10-mm depth in tissue
hr	hour
IOP	Iowa Ordnance Plant
IARC	International Agency for Research on Cancer
ICD	International Classification of Diseases
ICRP	International Commission on Radiological Protection
IREP	Interactive RadioEpidemiological Program
ISO	isotropic
keV	kiloelectron-volt, 1,000 electron-volts
MCNP	Monte Carlo N-Particle
MDL	minimum detectable level
MED	Manhattan Engineer District
MeV	megaelectron-volt, 1 million electron-volts
mg	milligram
mm	millimeter
mrad	millirad
MRD	minimum recordable dose
mrem	millirem
n	neutron
NCRP	National Council on Radiation Protection and Measurements
NDE	nondestructive evaluations
NIOSH	National Institute for Occupational Safety and Health

NTA	nuclear track emulsion, type A
ORAU	Oak Ridge Associated Universities
PNNL	Pacific Northwest National Laboratory
POC	probability of causation
PPD	Pantex Personnel Dosimeter
ROT	rotational
RPG	radiation protection guideline
RST	Radiation Safety Technician
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
TLD	thermoluminescent dosimeter
TLD-600	LiF TLD with enriched ^{6}Li
TLD-700	LiF TLD with enriched ^{7}Li
TLND	thermoluminescent neutron dosimeter
U.S.C.	United States Code
yr	year
Z	atomic number
α	alpha particle
β	beta particle
γ	gamma ray
§	section or sections

6.1 INTRODUCTION

Technical basis documents and site profile documents are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular Department of Energy (DOE) or Atomic Weapons Employer (AWE) facilities or categories of DOE or AWE facilities. They will be revised in the event additional relevant information is obtained about the affected DOE or AWE facility(ies). These documents may be used to assist NIOSH staff in the evaluation of Special Exposure Cohort (SEC) petitions and the completion of the individual work required for each dose reconstruction.

In this document the word “facility” is used to refer to an area, building, or group of buildings that served a specific purpose at a DOE or AWE facility. It does not mean nor should it be equated to an “AWE facility” or a “DOE facility.” The terms AWE and DOE facility are defined in sections 7348l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000 (EEOICPA), respectively. An AWE facility means “a facility, owned by an atomic weapons employer, that is or was used to process or produce, for use by the United States, material that emitted radiation and was used in the production of an atomic weapon, excluding uranium mining or milling.” 42 U.S.C. § 7384l(5). On the other hand, a DOE facility is defined as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the [DOE] (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program),” and with regard to which DOE has or had a proprietary interest; or “entered into a contract with an entity to provide management and operation, management and integration, environmental remediation services, construction, or maintenance services.” 42 U.S.C. § 7384l(12). The Department of Energy (DOE) determines whether a site meets the statutory definition of an AWE facility and the Department of Labor (DOL) determines if a site is a DOE facility and, if it is, designates it as such.

Accordingly, a Part B claim for benefits must be based on an energy employee’s eligible employment and occupational radiation exposure at a DOE or AWE facility during the facility’s designated time period and location (i.e., covered employee). After DOL determines that a claim meets the eligibility requirements under EEOICPA, DOL transmits the claim to NIOSH for a dose reconstruction. EEOICPA provides, among other things, guidance on eligible employment and the types of radiation exposure to be included in an individual dose reconstruction. Under EEOICPA, eligible employment at a DOE facility includes individuals who are or were employed by DOE and its predecessor agencies, as well as their contractors and subcontractors at the facility. Unlike the abovementioned statutory provisions on DOE facility definitions that contain specific descriptions or exclusions on facility designation, the statutory provision governing types of exposure to be included in dose reconstructions for DOE covered employees only requires that such exposures be incurred in the performance of duty. As such, NIOSH broadly construes radiation exposures incurred in the performance of duty to include all radiation exposures received as a condition of employment at covered DOE facilities in its dose reconstructions for covered employees. For covered employees at DOE facilities, individual dose reconstructions may also include radiation exposures related to the Naval Nuclear Propulsion Program at DOE facilities, if applicable. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction.

NIOSH does not consider the following types of exposure as those incurred in the performance of duty as a condition of employment at a DOE facility. Therefore these exposures are not included in dose reconstructions for covered employees (NIOSH 2010):

- Background radiation, including radiation from naturally occurring radon present in conventional structures
- Radiation from X-rays received in the diagnosis of injuries or illnesses or for therapeutic reasons

6.1.1 Purpose

Pantex Plant was one of the last plants built during World War II to load, assemble, and pack high-explosive (HE) ordnance. The plant began operations in September 1942 – only 9 months after groundbreaking – and operations stopped the week after the war ended on August 14, 1945 (Mitchell 2003). The purpose of this technical basis document (TBD) is to describe the external dosimetry systems and practices at Pantex beginning in December 1951 when U.S. Atomic Energy Commission (AEC) operations began. This document discusses historical and current practices in relation to the evaluation of external radiation exposure of monitored and unmonitored workers.

6.1.2 Scope

Pantex operations play an important role in the U.S. nuclear weapons program. Historically, Pantex has filled several roles associated with the assembly, disassembly, retrofit, and modification of nuclear weapon systems (Mitchell 2003). Today, Pantex continues to fabricate high explosives HE and assemble nuclear weapons. The principal operations at this site, however, are the dismantling of retired nuclear weapons and the maintenance of the nation's nuclear weapons stockpile. Pantex, which is operated by the DOE Office of Defense Programs, is the only facility in the United States that performs these operations.

The methods and concepts of measuring occupational external doses to workers have evolved since the beginning of Pantex operations. An objective of this document is to provide a technical basis to evaluate external radiation exposure to workers that can reasonably be associated with Pantex operations under EEOICPA. Consistent with NIOSH guidelines, this document identifies options to adjust historical recorded occupational external dose to account for current scientific methods and protection factors. In particular, this document presents the methods to prepare worker dose information for input to the NIOSH Interactive RadioEpidemiological Program (IREP).

Attributions and annotations, indicated by bracketed callouts and used to identify the source, justification, or clarification of the associated information, are presented in Section 6.9.

6.1.3 Special Exposure Cohort

6.1.3.1 January 1, 1958, through December 31, 1983

On December 21, 2011, the Secretary of the U.S. Department of Health and Human Services (DHHS) designated the following class of employees as an addition to the Special Exposure Cohort (SEC) (DHHS 2011):

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Pantex Plant in Amarillo, Texas, during the period from January 1, 1958 through December 31, 1983, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees included in the SEC.*

As stated in (DHHS 2011), DHHS found that it lacks sufficient personnel or area monitoring data, source term data, and operational information to support completely reconstructing internal dose with sufficient accuracy at the Pantex Plant from January 1, 1958, through December 31, 1983. However, the letter indicates that the principal sources of external radiation doses for members of the evaluated class were plutonium, uranium, and thorium components in weapons systems, radiation-producing machines used in non-destructive examination of components, and medical x-ray examinations. The letter further indicates that the Board and NIOSH determined that these external doses can be reconstructed with sufficient accuracy based on dosimeter measurements, workplace measurements in order to estimate early neutron doses, and complex-wide approaches for reconstructing medical x-ray exposures. Although DHHS found it is not possible to completely reconstruct internal radiation doses for the proposed class, NIOSH can use any reliable internal and external monitoring data that may be available for an individual claim during this period (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures). Therefore, dose reconstruction for individuals employed at the Pantex Plant, during the period from January 1, 1958 through December 31, 1983, but who do not qualify for inclusion in the SEC, can be performed using these data as appropriate to support partial dose reconstructions.

6.1.3.2 January 1, 1984, through December 31, 1991

On September 30, 2013, the Secretary of DHHS designated the following class of employees as an addition to the SEC (DHHS 2013):

> *All employees of the Department of Energy, its predecessor agencies, and their contractors and subcontractors who worked at the Pantex Plant in Amarillo, Texas, during the period from January 1, 1984 through December 31, 1991, for a number of work days aggregating at least 250 work days, occurring either solely under this employment or in combination with work days within the parameters established for one or more other classes of employees included in the SEC.*

As stated in (DHHS 2013), DHHS found that it lacks specific biological monitoring data, air monitoring data, process and radiological source information, and surrogate data from similar operations at other sites to support completely reconstructing internal dose with sufficient accuracy at the Pantex Plant from January 1, 1984 through December 31, 1991. However, the letter indicates that the principal sources of external radiation doses for members of the proposed class were plutonium pits and depleted uranium and thorium components. Secondary sources of external exposure included other radioactive materials present in smaller quantities (typically microcurie levels) as calibration sources or in larger quantities (up to curie levels) as radiography sources (ORAUT-TKBS-0013-2). The letter further indicates that NIOSH concluded that it is feasible, using methods in existing NIOSH procedures, to reconstruct external radiation doses, including the x-ray dose, when appropriate, for all Pantex workers from January 1, 1984 through December 31, 1991. Based on this information, the Board and NIOSH concluded that the external doses could be reconstructed for all years, using the available external monitoring data for Pantex workers, adjusted during some periods to account for the performance of the monitoring devices. Although DHHS found it is not possible to completely reconstruct internal radiation doses for the proposed class, NIOSH can use any reliable internal monitoring data that may be available for an individual claim during this period (and that can be interpreted using existing NIOSH dose reconstruction processes or procedures) and external monitoring data as described above. Therefore, dose reconstruction for individuals employed at Pantex Plant, during the period from January 1, 1984 through December 31, 1991, but who do not qualify for inclusion in the SEC, can be performed using these data as appropriate to support partial dose reconstructions.

6.1.4 Pantex Workers at Other AEC/DOE Facilities

Due to the nature of the work at Pantex, workers were sometimes required to temporarily perform their duties at other AEC/DOE facilities (e.g., the Nevada Test Site, which is now Nevada National Security Site, modification centers, national laboratories, etc.) and might have been monitored for occupational radiation exposures by Pantex, the temporary work location, or concurrently by both facilities. In such cases, all available monitoring records should be used to assign worker doses.

6.2 EXTERNAL DOSIMETRY

Information on the history of Pantex Plant nuclear weapons assembly activities involves classified information, so a complete description of events is not publicly available. AEC built two nuclear weapons assembly plants to supplement assembly activities at Sandia National Laboratories that began in about 1945 (DOE 1997). One of these was at the Iowa Ordnance Plant (IOP) in 1947; the second was the Pantex Plant in 1951. Pantex was originally a conventional munitions factory loading HE into bombs and artillery shells (DOE 1997); it was converted to nuclear weapons work during 1951 and 1952. In 1975, IAAP nuclear weapons assembly work transferred to the Pantex Plant. The Pantex Plant remains operational as the sole DOE facility for nuclear weapons assembly, modification, and dismantling (DOE 1997). This TBD summarizes information from the Pantex Plant and other sources about radiation doses Plant workers received from external sources.

Details of Pantex workers handling sources of radiation, such as depleted uranium (DU), plutonium, and other nuclear weapon materials, involves classified information. Work activities undoubtedly varied over time. Analysis of historical information showed that assembly activities at Pantex began in 1952, which corresponds with the first record of personnel monitoring (Carr ca. 1992). The nature of the radiation fields a Pantex worker could have encountered depends on the type of facility in which the work occurred. Nuclear weapons components emit alpha, beta, X-ray, gamma, and neutron radiation; however, doses to workers depend strongly on the configuration (i.e., material and shielding) of the source of radiation and the work that was performed (BWXT Pantex 2001). In addition, industrial radiography operations had the potential to expose some workers to X-ray or gamma radiation. Workers were potentially exposed to various radiation fields from DU. This TBD addresses the significance of these radiation fields.

OCAS-IG-001, *External Dose Reconstruction Implementation Guideline* (NIOSH 2007) determined that external personnel dosimetry results are the highest quality record for assessing historical doses from external sources to individuals and their organs. The DOE Laboratory Accreditation Program (DOELAP) accredited the current Pantex dosimetry system in 1993. Before 1993, several dosimetry systems measured radiation doses to workers from external sources (ORAUT 2003a). Early dosimetry practices were based on experience from several decades of radium and X-ray use in medical diagnostic and therapeutic applications. These methods were generally well advanced at the start of the Manhattan Engineer District (MED) project to develop nuclear weapons in the 1940s (Morgan 1961; Taylor 1971). The primary difficulties encountered in MED efforts to measure worker doses to external radiation were (1) the potential for large quantities of high-level radioactivity that had not been encountered previously and (2) mixed radiation fields involving beta particles, photons (X- and gamma rays), and (3) neutrons with a broad spectrum of energies. This TBD summarizes what is known about dosimetry systems used at Pantex and their technical performance in measuring dose to workers.

6.2.1 Potential for Workplace Exposures Based on Job Categories

Knowing the job title and a brief description of duties for that title can be helpful in determining the correct information to use for assessing dose. Production Technicians (also called Assembly Operators) and Radiation Safety Technicians (RSTs) typically had the highest potential for occupational external doses. Other workers could have received external dose, but the probability of receiving external exposure was smaller. Claimant interview files might not state the same job title because the interviewee could have described the type of job rather than the job title and because job titles have changed over the years. Table 6-1 summarizes job titles, descriptions, and relative potential for receiving occupational external exposures.

Table 6-1. Job titles and descriptions of work with possibility for occupational exposures.

Job title	Description of work	Possibility for Exposure (1 highest)[a]
Production Technician, Assembler, Assembly Operator, Assembly Fabrication	Assembles, disassembles, reassembles, inspects components.	1
Quality Assurance Technician I	Conducts nondestructive evaluations (NDEs) with linear accelerators, X-ray machines, etc.; conducts telemetry testing; performs confirmatory measurements on components, assemblies, containers, etc.	1
Quality Assurance Technician II	Performs NDEs, electronic, destructive, telemetry, and radiation measurement testing.	1
RST (entry)	Performs monitoring and sampling; collects samples; assists RST in monitoring personnel.	1[a]
RST	Performs monitoring and sampling; collects samples; performs radiation and contamination surveys; conducts surveillance work.	1
RST (Senior)	Responds to contamination or radiation alarms; performs surveillance, monitors radiation conditions in workplace.	1
Firing Site Technician	Includes hydroshot operators, drivers, anyone involved with cleanup of hydroshot contamination.	2
Not known, possibly drivers or teamsters	Includes burning of HE and cleanup of ash at burning ground.	2
Material Handler (pits and cans)	Operates material handling/moving equipment; transports material; loads and unloads materials and containers.	2
Operations Manager, Production Supervisor	Supervises personnel engaged in manufacturing, assembly, packaging, material control, etc.	2
Quality Control Inspectors/ Auditors	Conducts special audits; different from quality assurance technicians.	2
Security, protective force, guard	Performs per job title.	2[b]
Engineer, engineering	Performs variety of tasks associated with design, testing, procedure development.	2[c]
Machinist	Machining on components	2[a]
Metrology laboratory staff	Performs nonradiological metrology calibrations.	On-site Ambient only
Fireman	Performs per job title.	On-site Ambient only
Computer Programmer, Electronic Data Processing Analyst	Performs computer programming, maintenance.	On-site Ambient only
Secretary, Administrator, Technical Writer, nonoperations management, Planner	Performs per job title.	On-site Ambient only
Tool and die maker	Performs per job title.	On-site Ambient only
Food service	Performs tasks associated with operation of cafeteria.	On-site Ambient only
Stores Stockman, Clerk, Supervisor	Performs tasks associated with general stores.	On-site Ambient only

a. Based on actual contact with components.

b. In general, security personnel had lesser risks of occupational external exposures. However, some potential for exposures can be inferred from working inside the cells, pit vaults, igloos, and gravel gerties. The default assumption is to place security personnel in category 2; however, based on other information in the file, dose reconstructors may assign on-site ambient dose only if they believe the worker's tasks did not involve entry into cells, pit vaults, gravel gerties, igloos, or locations within the material access areas.

c. Engineering tasks cover a wide range, and most have little or no potential for occupational external exposures. However, some tasks might have involved observations during assembly or disassembly work. If the engineer did not have a dosimeter or never had recordable dose, only assign environmental dose unless there is information in the file to indicate otherwise.

6.3 BASIS OF COMPARISON

Since the initiation of the MED project in the early 1940s, various concepts and quantities have been used to measure and record occupational radiation dose at MED/AEC/DOE facilities. A common basis of comparison has been selected to assess the consistency of the available recorded dose at Pantex operations in comparison to current dosimetry performance and field-tested capabilities. The dates of change in the Pantex dosimetry systems are known (ORAUT 2003a); comparisons of recorded doses before and after these changes provide the ability to assess consistency. Similar radiation sources have been used historically to calibrate and conduct performance testing of dosimetry systems (AEC 1955; Unruh et al. 1967; McDonald et al. 1983). This basis, to be used in dose evaluation or reconstruction, is the personal dose equivalent [$Hp(d)$], where d identifies the depth in millimeters and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 mm and the personal dose equivalent is noted as $Hp(0.07)$. For penetrating radiation of significance to whole-body dose, d = 10 mm and the personal dose equivalent is noted as $Hp(10)$. Both $Hp(0.07)$ and $Hp(10)$ are recommended for use as operational quantities to be recorded for radiological protection by the International Commission on Radiological Units and Measurements (ICRU 1993). DOE has used these radiation quantities in the DOELAP since the 1980s to accredit personnel dosimetry systems in the Complex (DOE 1986).

6.4 EXTERNAL RADIATION EXPOSURE RECORDS

Pantex maintains a database that contains monthly, annual, and career dose information for workers from 1952 to the present. Annual dose data include the whole-body dose equivalent from photons and neutrons, individually and collectively (Prather 2004). In 2015, a detailed evaluation of this data was performed and resulted in the development of an external coworker model (ORAUT 2015). The results of this evaluation are summarized in Attachment A. At first, Pantex issued dosimeters only to workers likely to receive a radiation dose. From 1952 through 1957, this included only radiographers (ORAUT 2003b). From 1958 through 1988, only radiation workers were monitored (ORAUT 2003b). The variations in numbers of radiation workers reflect changes in weapon production rates (Carr ca. 1992). Since 1989, all Pantex workers who enter a radiologically controlled area have been monitored for external radiation exposure (Griffis 1988). Figure 6-1 shows the number of monitored workers and the number who had recorded annual doses of zero from external sources. For most of this period, very few workers received significant external doses. From 1960 to 1980, however, a larger fraction of the workers received nonzero external doses [1]. The increase was probably a result of increased production and increased handling of nuclear components.

From 1989 to 1991, Pantex implemented the Historical Exposure Records System (HERS) to capture past radiation dose records and ensure complete documentation (Rawlston 1991). Exposure records were retrieved from the archives, reviewed, and summarized. Individual workers were interviewed and their records were checked for accuracy. Missing records or anomalies were analyzed, with worker assistance, and appropriate notes were entered in the record (Rawlston 1991). The HERS project produced the best possible set of radiation exposure records attainable in 1991.

In late 1992, the algorithm Pantex used to calculate doses was changed to resolve performance issues during the 1989 Department of Energy Laboratory Accreditation Program (DOELAP) performance testing. This algorithm, called the “Stanford Algorithm,” was used to successfully pass DOELAP performance testing during 1993. The recalculated doses have been linked to individual claimant files and are typically present in the worker’s records in addition to the original site-reported doses. These records should be compared, and the result most favorable to the claimant should be used for each dose reconstruction.

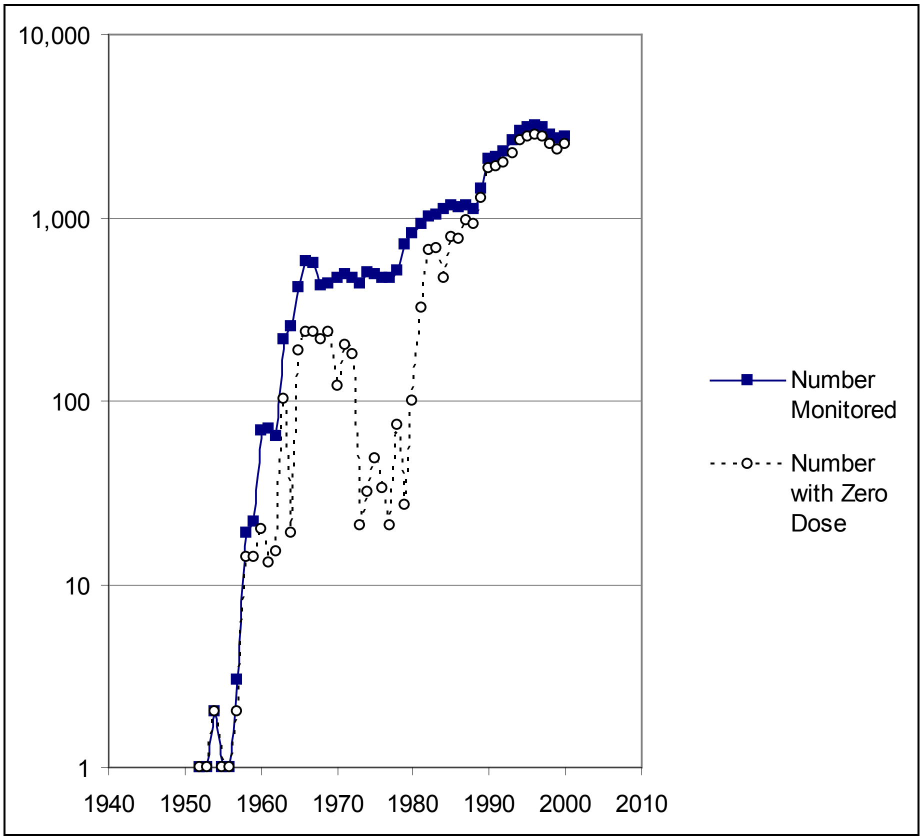

Figure 6-1. Number of workers monitored as a function of time and number of workers with zero recorded annual dose (ORAUT 2003b).

6.5 DOSE RECONSTRUCTION PARAMETERS

Examinations of the beta, photon (X- and gamma ray), and neutron radiation types, energies, and workplace exposure geometries, and the characteristics of Pantex Plant dosimeter responses, are crucial for the assessment of bias and uncertainty of the original penetrating dose of record in relation to the radiation quantity *Hp(10)*. The bias and uncertainty for current dosimetry systems are typically well documented for *Hp(10)* (BWXT Pantex 2002). The performance of current dosimeters can often be compared to performance characteristics of historical dosimetry systems in the same, or highly similar, facilities or workplaces. In addition, current performance testing techniques can be applied to earlier dosimetry systems to achieve a consistent evaluation of all dosimetry systems (BWXT Pantex 2002).

Overall, the accuracy and precision of original individual worker doses of record and their comparability to be considered in using NIOSH (2007) guidelines depend on:

- **Administrative practices** that were adopted by facilities to calculate and record personnel dose based on technical, administrative, and statutory compliance considerations;

- **Dosimetry technology** that was used, including the physical capabilities of the dosimetry system, such as response to radiation type and energy, especially in mixed radiation fields;

- **Calibration methods** that were used for monitoring systems and the similarity of the methods of calibration to sources of exposure in the workplace; and

- **Workplace radiation fields** that can include mixed types of radiation, variations in exposure geometries, and environmental conditions.

An evaluation of the original doses of record based on these parameters is likely to provide the best estimate of *Hp(0.07)*, as necessary, and *Hp(10)* for individual workers with the least relative overall uncertainty.

6.5.1 Historical Administrative Practices

Pantex started monitoring workers for radiation exposure in 1952 (ORAUT 2003a,b). Dosimeters that were used at that time to measure worker radiation doses were contracted from a commercial service. Table 6-2a summarizes the monitoring technique and exchange frequency. Table 6-2b lists reasonable MDLs for most applications for film and TLD dosimeters based on era of use and processor (ORAUT 2015).

Pantex Plant administrative practices important to dose reconstruction include historical policies for:

- Assigning dosimeters to workers (Rawlston 1991),
- Exchanging dosimeters (Rawlston 1991),
- Recording notional dose (i.e., a dose that was added to a record when the dosimeter for a monitoring period was lost or damaged) (Reissland 1982),
- Investigating missed dose (i.e., a dose that was added to a record when the dosimeter for a monitoring period was lost or damaged) (Watson et al. 1994),
- Replacing destroyed or missing records (Rawlston 1991),
- Evaluating and recording doses for incidents or accidents (Rawlston 1991), and
- Obtaining and recording occupational dose to workers for other exposures (Rawlston 1991).

At a minimum, Pantex routine practices appear to have required assigning dosimeters to personnel designated as radiation workers who could receive an external radiation dose greater than 10% of the Radiation Protection Guideline (RPG) of 5 rem/yr [2]. Dosimeters were exchanged on a routine schedule [3]. Beginning in 1980, if dosimeters were lost or damaged, investigations were conducted and doses were recorded that reflected the results of the investigation (ORAUT 2003b). Before 1980, there appear to be missing dose components for some workers based on such designations as “not available” or “damaged film” in worker records. These missing components can be reconstructed from other recorded dosimeter data using methods in Watson et al. (1994) and based on examination of continuity in worker job activities, or by using the recommended methods in later sections of this TBD.

6.5.2 Dosimetry Technology

Pantex Plant dosimetry methods evolved with the development of improved technology and a better understanding of the complex radiation fields in the workplace. The adequacy of dosimetry methods

Table 6-2a. Dosimeter type, period of use, and exchange frequency (ORAUT 2003a).

Dosimeter type/ provider	Period and Exchange frequency[a]
βγ film/Tracerlab	1/1952–12/1959, Weekly
βγ film and NTA film/ Tracerlab	1/1960–3/1961, Weekly 4/1961–5/1963, Monthly
βγ film and NTA film/ Eberline	6/1963–9/1964, Monthly
βγ film and NTA film/ Landauer	10/1964–12/1968, Twice per month
βγ film and NTA film/ Landauer	1/1969–12/1972, Monthly
TLD 2-element/in-house and NTA film/Landauer[b]	1973–1976, Monthly
TLD 6-element/in-house	1977–1980, Monthly
Panasonic 802/in-house	1980–1991[c], Monthly
Panasonic 802/in-house	1992–2000[c], Monthly
Panasonic 802/in-house	1992–2000[b], Quarterly
Panasonic 809/812/in-house[d]	1994–present, Monthly
Panasonic 809/812/in-house[d]	1994–present, Quarterly

a. Exchange frequencies were established from dosimetry reports. The initial weekly exchange frequency was changed to monthly in March 1961 (Tracerlab 1962–1963). A monthly exchange frequency continued with Eberline (Ashton 2003). An exchange frequency of twice per month for both beta/gamma and neutron films was established with Landauer in October 1964; this frequency changed, for both beta/gamma and neutron films, to monthly in January 1969 (Adams 2003). Nuclear track emulsion, type A (NTA) film provided by Landauer was used with the two-element TLD and exchanged monthly (Adams 2003).

b. The Pantex in-house two-element TLD was implemented in 1973 for monitoring only beta/gamma radiation exposures. Use of NTA film continued for monitoring neutron exposures until the implementation of the six-element TLD system in 1977.

c. In 1992, the algorithms were changed for the Panasonic 802 to the Stanford algorithms (BWXT Pantex 2002). The dosimeter exchange frequency for nonradiation workers was changed from monthly to quarterly in 1992.

d. Beginning in January 1994, the Panasonic 809/812 dosimeter was provided to radiation workers and exchanged monthly. The Panasonic 802 dosimeter was provided to all other Pantex workers and exchanged quarterly. Between 1994 and 2000, Panasonic 802 dosimeters were gradually phased out and replaced by Panasonic 809/812 dosimeters for all workers.

Table 6-2b[a]. Dosimeter LOD/s for Dose Reconstruction by Period (ORAUT 2015).

Years	LOD/2s for Dose Reconstruction (mrem)		
	Gamma	Skin	Neutron
1952 - 1959	5	15	NA[b]
1960–1963	5	15	7.5
1964–1972	5	20	10
1973–1976	2	5	5
1977–1979	2	5	25
1980–1991	10	10	25
1992–1993	7.5	10	42.5
1994–2010	7.5	7.5	5

a. Adapted from Table A-3, ORAUT (2015).
b. Neutron dosimetry was not performed prior to 1960 (ORAUT 2003a).

to measure radiation dose accurately, as discussed in later sections, depends on radiation type, energy, exposure geometry, etc. (BWXT Pantex 2001). Dosimeter exchange frequency gradually lengthened and corresponded to downward reductions in RPGs (Morgan 1961). During the early stages of the program to monitor individual Pantex workers, a weekly dose control of 0.3 rem was in effect (NBS 1951). Table 6-2a summarizes major changes in Pantex external dosimetry systems and routine dosimeter assignment periods for workers.

The first dosimeter used at Pantex was a two-element film badge from Tracerlab for measuring beta, X-ray, and gamma exposures (Tracerlab 1962–1963). Beginning in 1960, Pantex used a multielement film badge that incorporated NTA film to measure beta, X-ray, gamma, and fast neutrons (Tracerlab 1962–1963). From 1972 to 1976, a two-element in-house TLD system was used to measure beta, X-ray, and gamma exposures, while NTA film was retained to measure fast neutrons (Adams 2003; Alexander, Hess, and Canada 1973). From 1977 to 1980, Pantex used a six-element in-house TLD system that included personal nuclear accident dosimeter elements (DOE 1980; ORAUT 2003a). Beginning in 1980, Panasonic TLD systems with automatic readers were used; the UD-802 TLD was used from 1980 to 1993. The UD-809/ UD-812 TLD system was DOELAP-accredited and used for radiation workers beginning in 1994 (BWXT Pantex 2002). The UD-802 was used for all other workers until it was phased out in 2001. All Pantex workers who have entered radiologically controlled areas have been monitored with the UD-809/UD-812 TLD since 2001 (ORAUT 2003b).

A few documents or results of studies describe earlier dosimetry systems (AEC 1955; Roberson et al. 1983; McDonald et al. 1983). For the current TLDs, MRDs are precisely defined in *Pantex Plant Technical Basis Manual for External Dosimetry* (BWXT Pantex 2002). The MRDs are not necessarily equivalent to the MDL or lower limit of detection (L_D) described in NIOSH (2007) or in the DOELAP standard (DOE 1986). Dosimeter readings that indicated a dose less than these MDLs were judged to have high uncertainty. For earlier dosimetry systems, there were similar quantities below which doses were not recorded. Others might have been MRDs based on expert judgment. In either case, dosimetry results less than the MRD were recorded as zero [4]. Table 6-2b lists the MRDs of dosimeters that were used at the Pantex Plant to monitor for neutron deep doses and beta/gamma skin and deep doses.

The term MDL, which is widely used in NIOSH documents, can vary depending on many conditions including dosimeter type, processing equipment, calibration techniques, and procedures. Because of these variations, NIOSH has evaluated external beta/photon film (ORAUT 2006a) and thermoluminescent (ORAUT 2006b) dosimetry capabilities and has established standard MDLs for missed beta/photon dose and a correction factor for variability. The standard MDLs (missed dose) per exchange cycle for beta/photon dose for film and thermoluminescent dosimeters are 40 and 30 mrem, respectively. A typical MDL (missed dose) per exchange cycle for neutrons is 50 mrem for both NTA film (ORAUT 2006c) and thermoluminescent neutron dosimeters (TLNDs; Wilson et al. 1990).

6.5.2.1 Beta/Photon Dosimeters

Figure 6-2 shows the response of a film badge to photon radiation of different energies; it also shows the *Hp(10)* response. The figure shows two responses for film badges: one for a sensitive DuPont 502 emulsion in a two-element badge (Pardue, Goldstein, and Wollan 1944), and one for a sensitive DuPont 555 emulsion in the multielement badge (Thornton, Davis, and Gupton 1961). The response of the sensitive Eastman Type 2 film in a multielement film badge is similar to that of the sensitive

DuPont 555 emulsion. The film badges show an over-response at photon energies around 100 keV, due primarily to relatively (in comparison to tissue) high atomic numbers (*Z*) [silver (47) and bromine (35)] in the film emulsions. The film badges under-respond to lower energy photons, but the relative response of the two-element film badge to 60-keV photons from ^{241}Am is nearly unity. The multielement film badge typically over-responds to 60-keV photons.

The response of newer TLD badges provides a better match to the *Hp(10)* response in the soft tissues of the body due to the lower *Z* of the lithium (3) and fluorine (9) in the chips (Horowitz 1984; Cameron, Sunthanalingham, and Kennedy 1968). The two-element TLD badges that were used at Pantex from 1973 to 1976 had LiF (TLD-700) chips that were covered by a 7-mg/cm^2 plastic film over an open window and a 290-mg/cm^2 aluminum filter for beta/photon discrimination (ORAUT 2003a; Alexander, Hess, and Canada 1973). The six-element TLD badges that were adopted for use in 1977 were patterned after a Sandia design (DOE 1980; ORAUT 2003a). Figure 6-3 shows the TLD holder, chips, and filters. The open window for measuring skin dose was covered by a 7-mg/cm^2 polyester

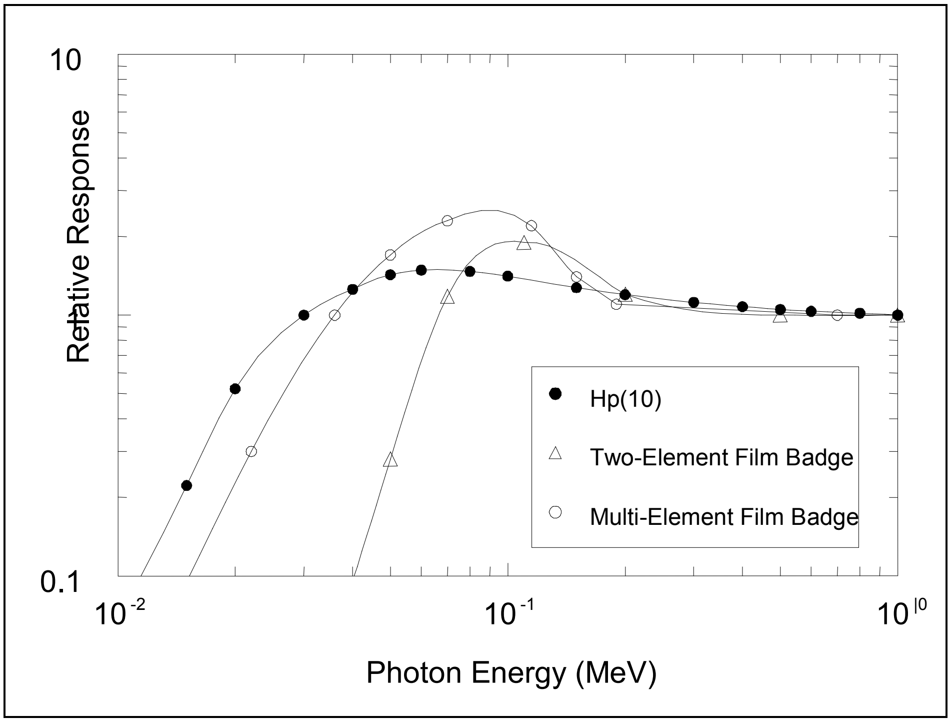

Figure 6-2. Comparison of *Hp(10)* for photons with energy responses for sensitive DuPont 502 emulsion in MED two-element film badge (Pardue, Goldstein, and Wollan 1944) and sensitive DuPont 555 emulsion in Oak Ridge National Laboratory multielement film badge (Thornton, Davis, and Gupton 1961).

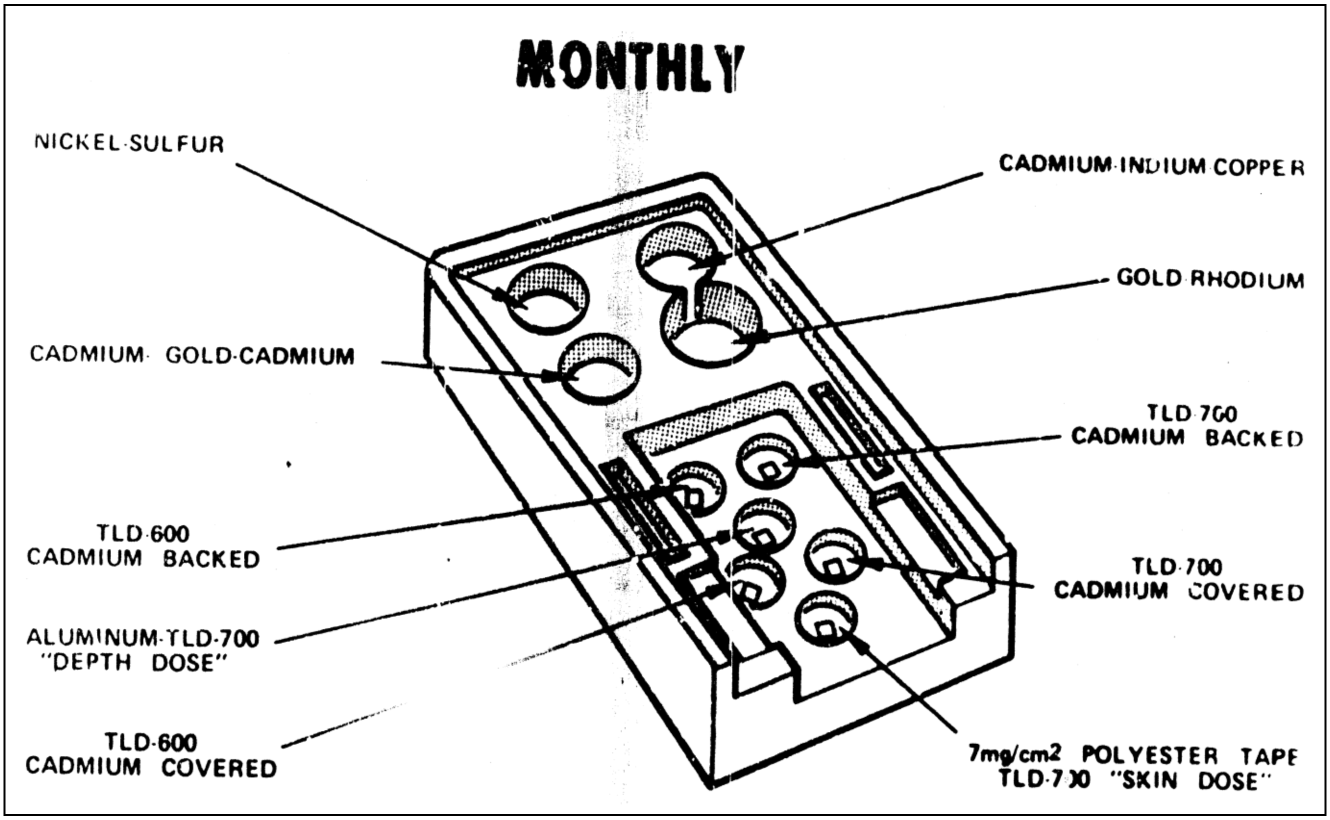

Figure 6-3. Six-element TLD holder (DOE 1980).

tape over the TLD-700 chip. The aluminum-backed TLD-700 chip was used to measure deep dose. One TLD-700 chip was covered by cadmium and the other was backed by cadmium to discriminate between photon exposures from the front and back. The two TLD-600 chips were similarly backed and covered by cadmium to discriminate between neutron exposures from the front and back. In addition, nickel-sulfur, cadmium-gold, cadmium-indium-copper, and gold-rhodium foils were included to provide a personal nuclear accident dosimeter capability.

The first commercial TLD badge, which was implemented at Pantex in 1980, was the multielement Panasonic Model UD-802 (BWXT Pantex 2002). The UD-802 TLD is capable of measuring beta, photon, and thermal and albedo neutron radiations. Table 6-3 lists phosphor and filter data for the UD-802 TLD and its holder. In general terms, elements E1 through E4 are used as follows: E1 is used for beta response, E2 is used for photon dose and beta energy determination, and E3 and E4 are used for photon energy characterization. The thin phosphor layer and minimal filtration over E1 enable excellent sensitivity to beta radiation and good response to photons and thermal neutrons. E2 is under approximately 300 mg/cm^2 of plastic, which provides a reasonably tissue-equivalent response to photons and penetrating beta radiation and thermal neutrons. The $CaSO_4$ in E3 demonstrates a sharp over-response to lower energy photons due to the high effective Z of the material in relation to tissue. This element is sensitive to suitably penetrating beta radiation, but it has no response to neutrons. A lead filter in E4 compensates for the over-response of $CaSO_4$ to lower energy photons. This filter preferentially removes the lower energy photon component, which reduces the over-response because it is insensitive to neutron radiation and is beyond the range of expected beta radiation. E4 is used for reporting environmental exposure. The UD-802 TLD system was DOELAP-accredited in 1993 for all tested radiation categories, including neutrons and mixtures of radiations. However, neutron doses can be overestimated by as much as 8 times because the fixed unmoderated ^{252}Cf correction factor is used for neutron responses (BWXT Pantex 2002).

Table 6-3. UD-802 dosimeter characteristics (BWXT Pantex 2002).

Characteristic	E1	E2	E3	E4
Phosphor	$^6Li_2B_4O_7$	$^6Li_2B_4O_7$	$CaSO_4$	$CaSO_4$
Filtration	Plastic	Plastic	Plastic	Plastic/lead
Filter thickness (mg/cm^2)	20	300	300	1,000
Primary sensitivity	Beta, gamma, neutron	Gamma, neutron	Gamma	Gamma

The Panasonic UD-809/UD-812 TLD system was fully implemented in January 1994 (BWXT Pantex 2002; ORAUT 2003b). This system was DOELAP-accredited in all beta, photon, and neutron radiation testing categories in 1993 [5]. The UD-812 TLD is the same as the UD-802 in phosphor type and filtration. The notable exception is that the lithium-borate phosphor in this dosimeter is depleted of the neutron-sensitive ^{6}Li and ^{10}B, so signals from E1 and E2 are due only to photon and beta radiation. This makes the final dose determination more straightforward and precise. Table 6-4 lists phosphor and filtration data for the UD-812 TLD and holder used at Pantex. The response of the UD-812 is essentially the same as that of the UD-802 with the exception of the neutron fields, for which the UD-812 has no response.

The UD-809 TLD was designed for determination of neutron dose (BWXT Pantex 2002). It uses four lithium-borate phosphors under different filters of approximately the same density thickness.
Table 6-4 lists phosphor and filtration data for the UD-812/UD-809 and holder used at Pantex. The first position, E5, is $^7Li_2{}^{11}B_4O_7$ depleted of the neutron-sensitive ^{6}Li and ^{10}B. This element is used to estimate the photon response on the remaining three elements. Because the effective measurement depths of E6, E7, and E8 are beyond the range of expected beta radiation, the nonphoton response is due solely to neutrons. E6, with the tin filter on the front side (facing away from the worker's body), responds to incident thermal neutrons; however, with the cadmium filter on the back side, the response to albedo neutrons is minimized. E8 has the opposite filtration, so its response to incident

Table 6-4. UD-812/UD-809 dosimeter characteristics (BWXT Pantex 2002).

Element	Phosphor	Filtration (front/back)	Filter thickness (mg/cm^2)	Sensitivity	Primary use
E1 (812)	$^7Li_2{}^{11}B_4O_7$	Plastic	17	Beta/gamma	Beta
E2 (812	$^7Li_2{}^{11}B_4O_7$	Plastic	150	Beta/gamma	Beta
E3 (812)	$CaSO_4$	Plastic	300	Beta/gamma	Gamma
E4 (812)	$CaSO_4$	Plastic + lead	1,000	Gamma	Gamma
E5 (809)	$^7Li_2{}^{11}B_4O_7$	Cd/Cd	900	Gamma	Gamma
E6 (809)	$^6Li_2{}^{10}B_4O_7$	Sn/Cd	900	Gamma/thermal neutron	Neutron
E7 (809)	$^6Li_2{}^{10}B_4O_7$	Cd/Cd	900	Gamma/neutron	Neutron
E8 (809)	$^6Li_2{}^{10}B_4O_7$	Cd/Sn	900	Gamma/albedo neutron	Neutron

thermal neutrons is minimized. E7, which is not currently used in Pantex dose algorithms, has cadmium on front and back, so its response indicates that neutrons pass through the cadmium and still create a signal. The general application of this dosimeter design is to use the ratio of the albedo neutron signal to the incident thermal neutron signal to characterize the neutron field [6].

Analyses of dosimeter performance data and workplace collective dose patterns in Tables 6-2a and Table 6-2b enable some judgments about consistency in historical measured radiation doses. The International Agency for Research on Cancer (IARC) conducted a comparison study of 10 commonly used dosimetry systems from around the world (Thierry-Chef et al. 2002). Three of the designs were from the United States: a two-element film dosimeter previously used at the DOE Hanford Site (identified as US-2), a multielement film dosimeter previously used at Hanford (US-8), and the Panasonic 802 TLD used at the DOE Savannah River Site (US-22) (and at Pantex from 1980 to 2001). The study concluded that exposure to workers could be characterized as a combination of anterior-posterior (AP), rotational (ROT), and isotropic (ISO) irradiation geometries. Dosimeter responses for these geometries were investigated using two phantoms to represent the torso of the body. The first phantom was a water-filled slab phantom with polymethyl methacrylate walls, an overall width of 30 cm, an overall height of 30 cm, and an overall depth of 15 cm. This phantom is widely used for dosimeter calibration and performance testing by the International Standards Organization. The second phantom was an anthropomorphic Alderson Rando Phantom. This realistic man-type phantom has a natural human skeleton cast inside material that has a tissue-equivalent composition. Table 6-5 lists the results of this study for the U.S. dosimeters. The two-element film dosimeter significantly overestimated *Hp(10)* at the lower photon energies of 118 keV and 208 keV. As noted above, the multielement film badge was used at Pantex in essentially the same manner as the two-element film badge (ORAUT 2003b).

To evaluate the dosimeter response to lower energy (i.e., less-than-100-keV) photons that are significant in plutonium operations, Hanford conducted intercomparison testing of all Hanford historical dosimeter film designs (Wilson et al. 1990) using AP irradiations only. Although there are differences in films and filters in multielement dosimeters, good comparison in energy response for both Pantex and Hanford dosimeters is probably based on similar design characteristics. The results of this testing for energies greater than 100 keV are consistent with the IARC results, showing an overestimate of *Hp(10)* for the two-element dosimeter used from 1944 to 1956.

6.5.2.2 Neutron Dosimeters

The two general types of neutron dosimeters that were used at the Pantex Plant differ significantly in their response to neutrons of different energies (Figure 6-4) (IAEA 1990). NTA film was included in the holder for the Pantex beta/gamma dosimeter from 1960 through 1976 (ORAUT 2003a). In general, the response of the NTA film decreases with decreasing neutron energies greater than a minimum threshold energy for laboratory studies [estimated to be about 500 keV (IAEA 1990)], and the neutron TLD response increases with decreasing neutron energy as shown in Figure 6-4 (IAEA 1990). The minimum threshold energy for routine use in Pantex mixed photon and neutron radiation fields is probably about 1 MeV. Results reported at the first AEC Neutron Dosimetry Workshop indicated that laboratory dose measurements made with NTA film were about one-half to one-fourth of

Table 6-5. IARC study results for U.S. beta/photon dosimeters (Thierry-Chef et al. 2002).

US-2 (Two-element film dosimeter)

Geometry	Phantom	118-keV mean[a] and SD/Mean[b]	208-keV mean[a] and SD/Mean[b]	662-keV mean[a] and SD/Mean[b]
AP	Slab	3.0, 2.1	1.3, 1.0	1.0, 0.8
AP	Anthropomorphic	3.0, 4.2	1.2, 1.9	1.0, 1.8
ROT	Anthropomorphic	2.2, 2.0	1.4, 3.0	1.2, 3.2
ISO	Anthropomorphic	1.5, 4.4	1.1, 1.6	1.0, 2.7

US-8 (Multielement film dosimeter)

Geometry	Phantom	118-keV mean[a] and SD/Mean[b]	208-keV mean[a] and SD/Mean[b]	662-keV mean[a] and SD/Mean[b]
AP	Slab	1.0, 1.5	1.0, 0.8	0.8, 1.7
AP	Anthropomorphic	0.8, 9.5	0.9, 6.0	0.8, 1.8
ROT	Anthropomorphic	1.2, 1.9	1.2, 1.7	1.1, 1.8
ISO	Anthropomorphic	1.0, 3.0	1.2, 9.0	1.0, 2.3

US-22 (Multichip TLD)

Geometry	Phantom	118-keV mean[a] and SD/Mean[b]	208-keV mean[a] and SD/Mean[b]	662-keV mean[a] and SD/Mean[b]
AP	Slab	0.9, 4.4	0.9, 3.9	0.9, 3.5
AP	Anthropomorphic	0.8, 3.1	0.9, 2.1	0.9, 3.9
ROT	Anthropomorphic	1.1, 3.1	1.2, 1.5	1.0, 4.1
ISO	Anthropomorphic	0.9, 0.3	1.0, 2.5	0.9, 1.6

a. Ratio of dose of record to *Hp(10)*.
b. Ratio of standard deviation (SD) to the mean.

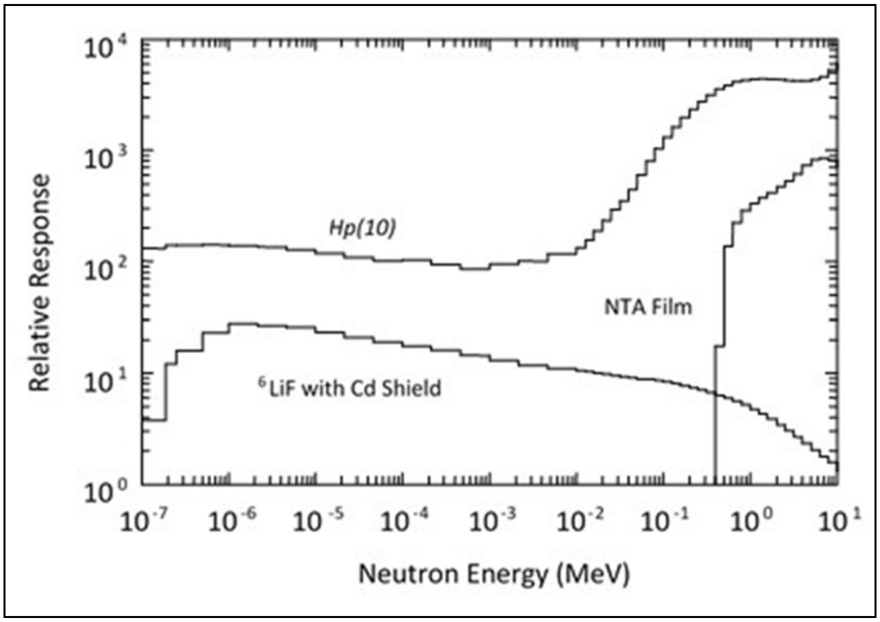

Figure 6-4. Comparison of *Hp(10)* from normally incident neutrons to energy responses of NTA film and neutron albedo dosimeter containing neutron TLD chip made of ^{6}LiF and shielded by cadmium (IAEA 1990).

those measured with other methods, including the neutron TLD (Vallario, Hankins, and Unruh 1969). The response of both dosimeters is highly dependent on the neutron energy spectra, and both dosimeter types require the matching of laboratory calibration neutron spectra to workplace neutron spectra for reliable results.

The neutron response of the six-element, in-house TLD system was similar to the response of the Sandia TLD system (Thompson 1977). The dosimeter responded well to thermal neutrons, but under-responded to neutron energies above 10 keV.

Roberson et al. (1983) measured the Panasonic UD-802 dosimeter response to thermal and fast neutron beams. Neutron doses measured by the UD-802 between 1980 and 1992 are likely to be underestimated (BWXT Pantex 2002). The performance of the UD-802 for measuring neutron doses was improved in 1992 and 1993 when the Stanford algorithm was applied (Stanford et al. 1994). However, neutron doses derived from this version of the algorithm could be overestimated by as much as 8 times because the fixed unmoderated ^{252}Cf correction factor is used for neutron responses (BWXT Pantex 2002).

6.5.2.3 Effects of Changing Early Dosimetry Services

Pantex has historically used different dosimetry technology, different film-based commercial dosimetry services, and in-house TLD capabilities. There have been only limited and incomplete Pantex studies that compared the performance of the early dosimetry systems or services. However, in 1954 the AEC conducted performance testing of several commercial (including Tracerlab) and in-house film dosimeter services with exposures that were provided by the National Bureau of Standards (AEC 1955); this document includes specific dosimeter design specifications. The testing included 40-, 70-, and 210-keV narrow spectral beam X-ray techniques, ^{60}Co gamma radiation, and selected mixtures of these beams. The report provides measured response data for each of the dosimeter open-window and filtered regions of the film. This information exhibits the significant over-response of the open-window and lightly filtered regions of the film at lower photon energies (i.e., 40 and 70 keV). The data certainly illustrate the ability, in spite of many differences in organizations, emulsion types, and dosimeter designs, to reasonably detect and measure photon radiation levels and energies Pantex workers could have received.

Examination of the Pantex cumulative dose records for the periods of use suggests that changes in the ratio between neutron and photon doses did occur. Without precise knowledge of the workplace radiation fields, the exact cause or effect is uncertain. However, a reasonable explanation is improved photon dosimetry with the TLD system that has nearly a tissue-equivalent response and significantly improved neutron dosimetry with the implementation of the TLND, as noted in Table 6-6 [7]. The ratio of the measured neutron-to-photon dose has increased during the periods of improving dosimetry capabilities from film beta/photon and NTA neutron dosimeters to sophisticated TLD systems [8]. Figure 6-5 shows a plot in cumulative Pantex worker photon and neutron doses from 1952 through 2000 and the years of implementation of new dosimetry methods. It is apparent that little neutron dose was measured before about 1963. The trend in the recorded photon dose is comparatively smooth during the transition from film to TLDs in 1977. The trend in the neutron dose fraction (in comparison with the photon dose) implies a significantly increased neutron dose fraction

Table 6-6. Ratio of neutron-to-photon cumulative dose.

Dosimeter technology	Neutron cumulative dose (person-rem)	Photon cumulative dose (person-rem)	Ratio[a]
Film + NTA, 1952–1972	41.67	595.66	0.070
TLD + NTA, 1973–1976	31.01	238.61	0.130
TLND, 1977–1993	303.45	1,142.09	0.266
809/812 TLND, 1994–2004	65.51	261.75	0.250

a. Rounded to three significant figures.

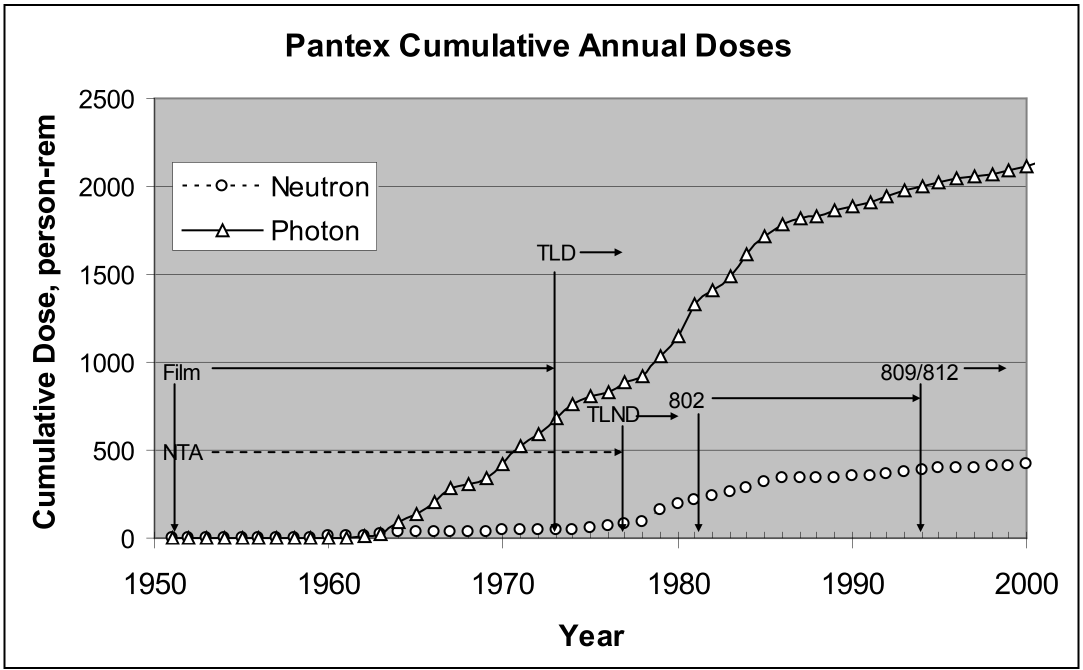

Figure 6-5. Cumulative plot of annual photon and neutron recorded dose (Prather 2004; ORAUT 2003b).

after 1977 when TLDs were used. However, the ratio between neutron and photon doses is significantly variable, particularly before the mid-1980s [9].

6.5.3 Dosimeter Calibration Procedures

Potential error in doses of record depends on the dosimeter calibration methods and the extent of the similarity between the radiation fields for calibration and those in the workplace. The potential error is much greater for dosimeters with significant variations in response, such as film dosimeters for lower energy photon radiation and NTA and neutron TLDs for neutron radiation.

6.5.3.1 Beta/Photon Dosimeters

Pantex Plant film badges and TLDs were originally calibrated with ^{60}Co and ^{137}Cs sources, Victoreen R chambers to measure the exposure (MHSMC 1972). Deliberately irradiated film badges were sent periodically to R. S. Landauer, Jr., and Company beginning in 1970, and reported doses were compared with measured doses for calibration (ORAUT 2003a). Similar calibration procedures were used with the development and operation of the in-house film and TLD systems between 1973 and

1980 (see Tables 6-2a and 6-2b). Table 6-7 lists sources of bias in the calibration parameters for beta/photon dosimeters.

In the 1970s, during the development of the two-element and six-element TLD systems, a 60-Ci ^{137}Cs source in a well facility in the 12-2 Building was used to calibrate TLD-700 chips (DOE 1980). A 2-µg ^{252}Cf source was used to calibrate TLD-600 chips for measuring fast neutron dose (DOE 1980). Records indicated that photon calibrations occurred in March 1978 and neutron calibrations occurred in September 1978 (DOE 1980). Additional neutron response testing with a Pu-Be neutron source and a thermal neutron source occurred in April and October 1980 (DOE 1980). Calibration methods were similar to those used at Sandia National Laboratories. In the mid-1980s, a 0.5-Ci ^{137}Cs source in the 12-10 Building was used to calibrate Panasonic UD-802 dosimeters [10]. Element correction factors were determined for each chip in each dosimeter, which were used for improved photon dosimetry (BWXT Pantex 2002).

Table 6-7. Common sources of laboratory bias in calibration parameters for beta/photon dosimeters.[a]

Parameter	Description	Anticipated laboratory bias[b]
Free-in-air calibration	In 1970s, Pantex began exposing calibration dosimeters on phantom to simulate worker body. There were no on-phantom calibrations before 1970.	Dose of record is too high; however, effect of backscattered radiation from worker body is highly dependent on dosimeter design and actual geometry of radiation fields in workplace.
Radiation quantity	Photon dose quantities used to calibrate Pantex beta/photon dosimeters have varied.	Because of higher energy, Ra-226 gamma radiation used to calibrate dosimeters at Pantex caused only slight (about 3%) under-response in dose of record.
Depth of tissue dose	Pantex used selected depth of 1 cm (i.e., depth of testes) to estimate deep dose.	No significant effect because Pantex dosimeter designs had filtration density thicknesses of about 1,000 mg/cm^2 that is equivalent to 1-cm depth in tissue.
Angular response	Pantex dosimeters were calibrated using AP laboratory irradiation.	Dose of record is probably too low because dosimeter response is lower at non-AP angles. Effect is highly dependent on radiation type and energy.
Environmental stability	Pantex film and TLD dosimeters are subject to signal fade with time, heat, humidity, light, etc.	Dose of record is probably too low; however, this depends strongly on when calibration dosimeters were irradiated during dosimeter exchange cycle. Midcycle calibration minimizes overall uncertainty.

a. Judgment based on Pantex dosimeter response characteristics (BWXT Pantex 2002).
b. Dose of record compared to *Hp(10)*.

Calibrations for the Panasonic 802 and 809/812 TLD systems have occurred in the Pantex Radiation Safety Department Calibration Facility. This facility, first used in 1996, has 5- and 0.5-Ci ^{137}Cs sources, a 120-µg ^{252}Cf source, a dosimetry-type X-ray machine, and two ^{90}Sr and one ^{204}Tl sources, which are used for DOELAP calibration and quality control (BWXT Pantex 2001).

6.5.3.2 Neutron Dosimeters

A complete account of the historical aspects of the calibration of Pantex neutron dosimeters is not available. It is known, however, that NTA films and in-house TLDs were originally calibrated with ^{239}Pu:Be and ^{252}Cf sources (DOE 1980). Deliberately irradiated NTA quality control film badges were sent periodically to Landauer beginning in 1970, and reported doses were compared with measured doses for calibration (ORAUT 2003a). Similar calibration procedures were used with the development and operation of the 6-element, in-house TLD system between 1977 and 1980 (DOE 1980).
Table 6-8 lists common sources of expected laboratory bias for personnel neutron dosimeters based on comparison of the dose of record with *Hp(10)*.

6.5.4 Workplace Radiation Fields

The main workplace radiation fields at Pantex arise from the handling of nuclear weapons components containing plutonium, thorium, and highly enriched uranium (HEU), the radioactive progeny of those elements, and DU. The highest dose rates are encountered when handling bare pits. Dose rates are lower when handling full weapons, physics packages, and pits in storage containers [11]. Other workplace radiation fields involve industrial radiation-generating equipment (X-ray machines and electron accelerators) and isotopic gamma-ray and neutron sources for radiography and testing purposes (^{60}Co and ^{252}Cf) [12]. The nuclides in the sealed nuclear weapon component pits emit beta, X-, gamma, and neutron radiation. From an external dosimetry perspective, the radiations of concern are beta particles, photons (X- and gamma rays), and neutrons. Radiation exposure to workers depends significantly on the processes in the preparation, design, and construction of the weapons [13].

Table 6-8. Common sources of laboratory bias in calibration parameters for neutron dosimeters.[a]

Parameter	Description	Anticipated laboratory bias[b]
Source energy spectrum	In 1970, Pantex began using dosimeters calibrated on phantoms to simulate worker body and neutron spectra that represented workplace. ^{239}Pu:Be and ^{252}Cf sources were used. There were no on-phantom calibrations before 1970.	Delivered dose was uncertain, as noted in Section 6.4.2.2.
Radiation quantity	Neutron dose quantities used to calibrate Pantex neutron dosimeters have varied historically. *First collision dose* for fast neutrons and *quality factor* of 10 was used for many years.	Effects of neutron dose quantities used to calibrate Pantex dosimeters are uncertain. In particular, fluence-to-dose conversion factors have varied over time. Exact values used before 1980 are not known.
Angular response	Pantex dosimeters are calibrated using AP laboratory irradiation.	Dose of record is probably too low because dosimeter response is lower at non-AP angles. Effect is highly dependent on neutron energy and actual geometry of radiation fields in workplace.
Environmental stability	Pantex NTA film and neutron TLD dosimeters are subject to signal fade with time, heat, humidity, light, etc.	Dose of record is probably too low; however, this depends strongly on when calibration dosimeters are irradiated during dosimeter exchange cycle. Midcycle calibration minimizes overall uncertainty.

a. Judgment based on Pantex Plant dosimeter response characteristics (BWXT Pantex 2002).
b. Dose of record compared to *Hp(10)*.

As a good practice to comply with the DOELAP accreditation process for the Panasonic 809/812 TLD system, field measurements were made to characterize radiation fields in the Pantex workplace and to document the performance of the dosimetry system (BWXT Pantex 2002). Radiation fields were measured with TLDs on a polymethylmethacrylate phantom that were exposed under controlled conditions. The radiation fields were also characterized with several instruments to measure the photon, neutron, and beta dose rates. Each characterized weapon program was measured in each of four configurations: full weapon, physics package, bare pit, and pit in storage container (BWXT Pantex 2002). The data derived from these measurements are classified; however, some generalized unclassified conclusions can be stated.

The photon dose rates were measured with a Victoreen Model 530 electrometer in conjunction with the Victoreen Model 550-3 ion chamber. The ion chamber was calibrated by Victoreen and is traceable to the National Institute of Standards and Technology using four different X-ray techniques: M50 (22 keV), M100 (39 keV), M200 (90 keV), and M250 (180 keV) (BWXT Pantex 2002). The appropriate correction factors were chosen based on gamma spectroscopy measurements during the field measurements. Beta dose rates were measured with a Victoreen 450BE instrument with an open window (BWXT Pantex 2002). Neutron dose rates were measured with tissue-equivalent proportional counters, and multisphere measurements were analyzed to characterize the neutron spectra (BWXT Pantex 2002).

The predominant source of radiation dose at Pantex is photons from ^{241}Am, with the 60-keV photon being the most significant (BWXT Pantex 2002). The photon dose rate is very dependent on the configuration of the weapon. The more material that is added to the component, or the more complete its assembly, the lower the photon dose rate [14]. In general terms, the neutron component of the radiation field begins as a standard spontaneous fission spectrum and then is degraded and moderated as the assembly process adds more material to the weapon. Beta dose is not limiting in the Pantex workplace. The primary sources of beta radiation are DU and thorium (BWXT Pantex 2002). Total dose rates in the workplace are generally low, less than 10 mrem/hr, unless very close work is being performed (BWXT Pantex 2002).

With very few exceptions, the following sections show that for external dose reconstruction purposes all beta radiation fields are greater than 15 keV, all photon radiation fields are between 30 and 250 keV, and all neutron fields are between 0.1 and 2 MeV. Assuming that 100% of the radiation fields are within these ranges is a simplifying conservative assumption that is generally favorable to claimants.

6.5.4.1 Depleted Uranium

Pantex workers handled DU (primarily ^{238}U) during assembly and disassembly of weapon components and during and after testing. An important progeny for potential worker exposure in the ^{238}U decay is ^{234}Th with a half-life of 24.1 days. In a matter of a few months after purification, DU components have ^{234m}Pa activities nearly equal to that of ^{238}U. Protactinium-234m emits beta radiation 99.87% of the time when it decays to ^{234}U with a maximum energy of 2.29 MeV and an average energy of 0.825 MeV (Shleien, Slaback, and Birky 1998; ICRP 1983). An additional source of exposure in the Pantex workplace is from bremsstrahlung that high-Z materials produce during interactions with higher energy beta particles. Beta particles emitted by ^{234m}Pa excite both bremsstrahlung and characteristic X-rays in DU or ^{238}U (Shleien, Slaback, and Birky 1998).

Beta radiation from DU can contribute to extremity and skin dose to workers unless precautions are taken to protect workers from the radiation. Protective clothing and gloves provide a protection factor of 2 or more depending on the thickness (DOE 2001). A bare slab source of DU contributes an *Hp(0.07)* dose of approximately 230 mrad/hr at the surface (BRH 1970) in comparison with an *Hp(10)* dose of approximately 2 mrad/hr (NIOSH 2010b). However, based on a review of shallow and deep dosimetry data, significant beta exposures to Pantex workers were rarely detected by film badges or TLDs [15].

6.5.4.2 Photon Radiation

Photon radiations at Pantex have had widely varying energies that have ranged from about 30 keV to a few MeV [16]. Sources of photon radiation have included weapon components, analytical devices that use X-rays from radiation-generating devices, and low-activity radioactive sources such as those used to check or calibrate radiation detectors [17]. These sources could have included alpha, beta, photon, and neutron emitters and were of the types and source strengths typical of mainstream industrial or process-related users [18]. Doses from the proper, and widespread, use of small check sources are negligible.

Weapons assembly at Pantex has been performed with nuclear components of purified metals. The purification process separates natural progeny radionuclides from their parent metals, which provides some insight into potential sources of radiation. Plutonium is purged of progeny radionuclides when it is purified [19]. However, ^{241}Am starts growing in immediately as its parent radionuclide ^{241}Pu decays with a half-life of 14.4 years. The ^{241}Am, which emits 60-keV photons, reaches a maximum activity after about 80 years, but it reaches about 85% of this maximum in 40 years [20]. Therefore, for nuclear weapons activities, this is increasingly significant with weapons disassembly, which often occurs many years after assembly [21].

A sample of purified ^{232}Th would initially contain an equal activity of ^{228}Th and ^{232}Th with no progeny radionuclides. The reappearance of the progeny is complex (Stannard 1988, p. 237). The governing radionuclide in the ^{232}Th-to-^{228}Th chain is ^{228}Ra, which has a half-life of 5.75 years. The half-life of ^{228}Th is 1.9 years, and none of its progeny has a longer half-life. The gross activity of an initially pure mixture of ^{232}Th and ^{228}Th would rise for about a month, decline for about 4 years, and rise to nearly complete equilibrium after 20 years (Stannard 1988). Thorium progeny emit many energetic beta particles (1 to 2.25 MeV) and many energetic gamma rays, including the 2.61-MeV gamma emitted by ^{208}Tl in 100% of its decays (Shleien, Slaback, and Birky 1998).

The Monte Carlo N-Particle (MCNP) program was used to model spectral characteristics of bremsstrahlung photons from 1- and 30-cm-diameter ^{238}U spheres (Booth et al. 2005). The results were similar for both spheres. Figure 6-6 shows the MCNP-calculated photon spectrum emitted from ^{238}U as excited by the ^{234m}Pa beta spectrum on a logarithmic vertical axis. Note the smooth bremsstrahlung spectrum and the uranium characteristic K X-rays at 90 to 109 keV and the L X-rays in the range of 13 to 19 keV. The vertical axes in Figures 6-6 through 6-8 represents the energy of the photon emission, i.e. MeV per photon emission.

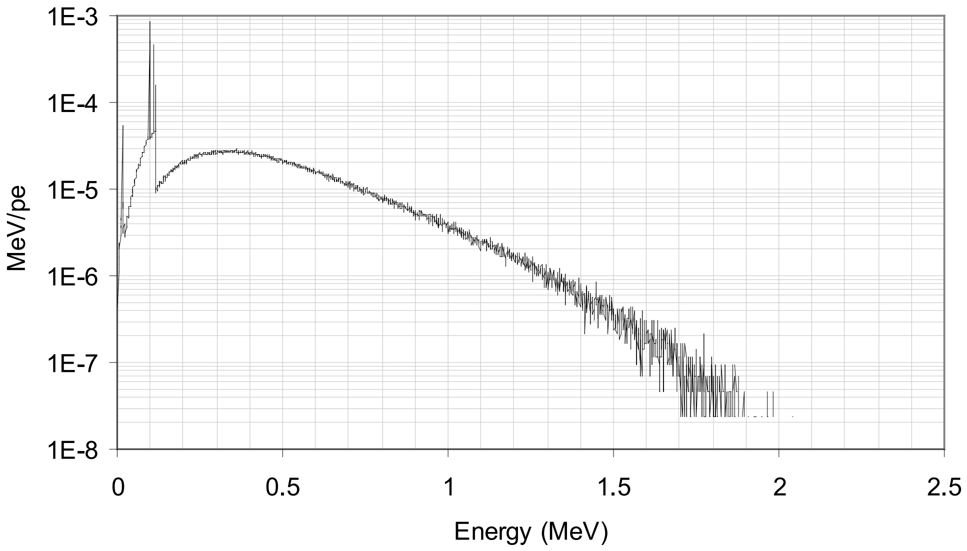

Figure 6-6. MCNP-calculated photon spectra emitted from ^{238}U as excited by ^{234m}Pa beta in ^{238}U spheres. Source: Calculations made using Booth et al. (2005).

The linear vertical axes in Figures 6-7 and 6-8 show the bremsstrahlung and characteristic X-ray components, respectively, of the calculated spectrum in Figure 6-6. The average energy of the photon spectrum is 0.41 MeV. The spectrum below 30 keV is insignificant [22]. The characteristic X-ray photons produce their own Compton-scattered photons, which are visible as elevated fluences underlying the characteristic X-rays. For workers near the older plutonium pits, the ^{241}Am 60-keV gamma photons are the most significant source of photon radiation [23]. Assembled weapon components were encased in a metallic cladding that significantly attenuated photon radiation (particularly at lower energies) (Shleien and Terpilak 1984). Measured photon energy spectra in Pantex workplaces have confirmed that a major fraction of the photon dose rate near weapons is from the 60-keV photons from ^{241}Am (BWXT Pantex 2002).

Much of the interior surfaces of the buildings in which nuclear components are handled or stored are concrete. Most elements that constitute ordinary concrete have a low *Z*. The elemental composition of concrete is 50% oxygen ($Z = 8$) and 32% silicon ($Z = 14$) (Shleien, Slaback, and Birky 1998). Higher energy photons scatter within such a facility lose energy in each collision and result in photons of lower energy. Gamma radiation of 2.2 MeV results from ^{1}H (n,γ) ^{2}H interactions caused by neutron radiation scattering (i.e., moderation) and absorption in the hydrogen-rich materials in the nuclear components and building materials (concrete) (Shleien, Slaback, and Birky 1998). This gamma field should be well dispersed where pits are stored or handled and hydrogenous material is nearby.

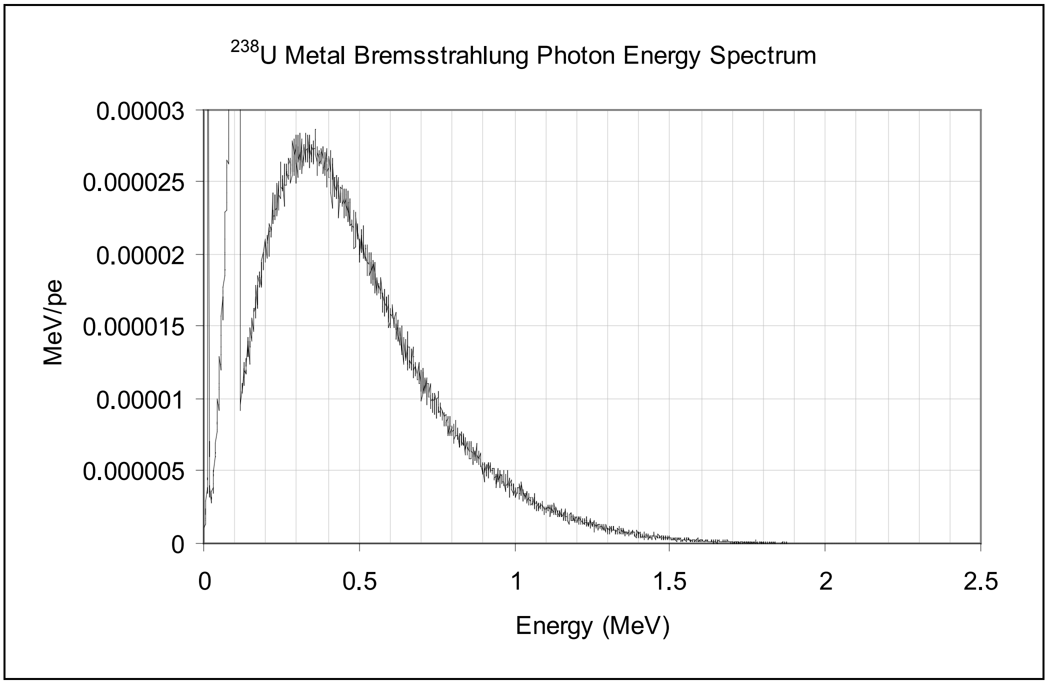

Figure 6-7. Bremsstrahlung component of calculated spectrum from ^{238}U spheres on linear vertical axis. Source: Calculations made using Booth et al. (2005).

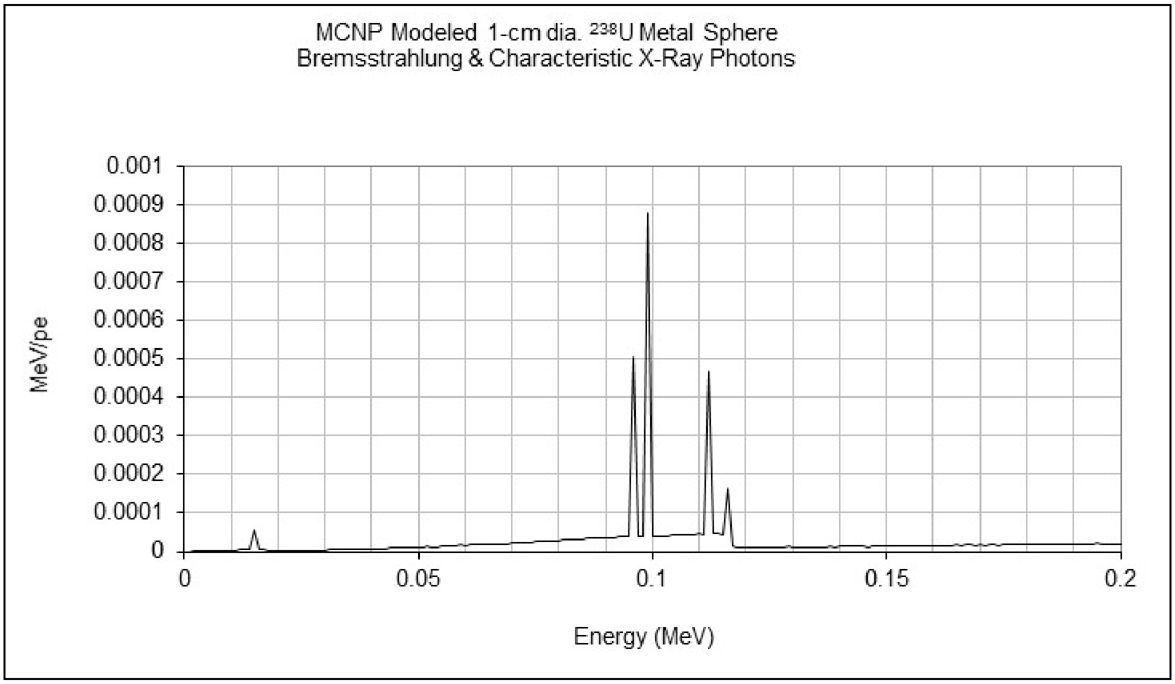

Figure 6-8. Characteristic X-ray component of calculated spectrum from ^{238}U spheres on linear vertical axis. Source: Calculations made using Booth et al. (2005).

Photon radiation in the workplace would have been readily measured at Pantex, with available dosimeter technology, during all years of operation. With few exceptions, photon energies in the Pantex workplace are all within the range of 30 to 250 keV [24]. An assumption that all photons are in this range is a simplifying conservative assumption that is generally favorable to claimants.

6.5.4.3 Neutron Radiation

There have been three main types of facilities or activities at Pantex with potential for neutron exposure to workers: (1) bays and cells, (2) vaults and igloos (storage facilities), and (3) transportation (BWXT Pantex 2001). The specific workplace neutron fields for selected types of nuclear weapon components are classified. Unclassified information on neutron spectra from fission and sealed plutonium sources is available.

Plutonium pits that are not associated with HE are referred to as “bare pits,” although all pits are sealed or encapsulated (Carr 2004). Assembly and disassembly operations that occur in cells comprise the only times workers have been exposed to neutrons from bare pits [25]. The average energy is higher for unshielded plutonium and beryllium (α,n) interactions than for fission neutrons. Figure 6-9 shows examples of unshielded fission and Pu-Be spectra and the respective average energies. In the workplace, these spectra are significantly changed through scattering in nuclear weapon components, equipment, and building materials [26]. The 809/812 dosimeter system was designed and calibrated for neutrons in the Pantex workplaces (BWXT Pantex 2002).

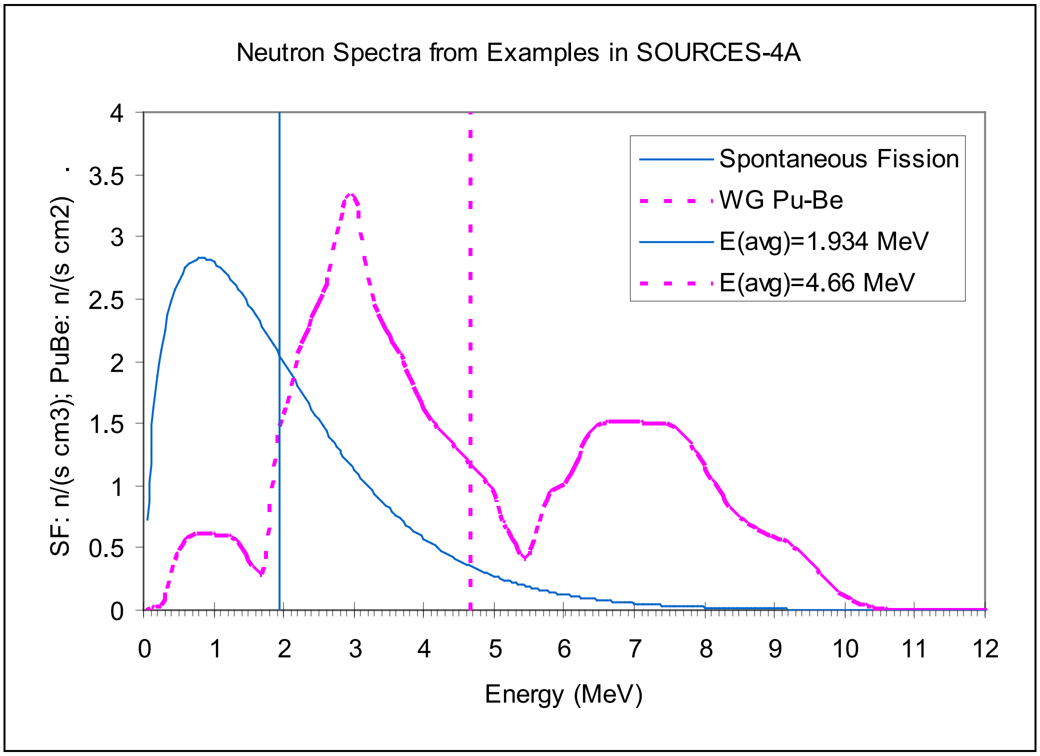

Figure 6-9. Unmoderated neutron spectra calculated by SOURCES-4A (Wilson et al. 1999).

Maximum radiation dose rates occur when workers handle bare pits [27]. The operations often involve direct hands-on manipulation where the distance from the surface of the pit to the dosimeter is approximately 30 cm [28]. Lead aprons or other shielding has been used to reduce photon dose rates. In other assembly or disassembly operations, where HE or other materials surround the pit, photon and neutron dose rates decrease significantly, although photon dose rates decrease more rapidly with increased shielding [29].

Assuming that 100% of the neutron doses were delivered by neutrons in the 0.1- to 2-MeV energy range is a simplifying conservative assumption that is generally favorable to claimants. Although there are neutrons with higher energies (which are more penetrating) at Pantex, the POC for deeper organs, such as the liver, is much larger from the higher neutron fluence in the 0.1- to 2-MeV range than in any other energy group (NIOSH 2007). Radiation fields characteristic of Pantex facilities (beta/photon and neutron) can be generally defined based on historical information on processes, locations, operating periods, and radioactive materials in each, as listed in Table 6-9.

Table 6-9. Beta, photon, and neutron radiation energies and percentages for Pantex facilities.

Process/ buildings	Description	Operations period	Radioactive material	Radiation type	Energy selection	Percent (notes)
Bays, cells	Assembly/ disassembly of nuclear weapons	1952–2005	DU	Beta	>15 keV	100[a]
				Photons	30–250 keV	100[b]
Bays, cells	Assembly/ disassembly of nuclear weapons	1958–2005	Tritium	Beta	<15 keV	100[c]
Bays, cells	Assembly/ disassembly of nuclear weapons	1958–2005	Plutonium, HEU	Photons	30–250 keV	100
				Neutrons	0.1–2 MeV	100[d]
Bays, cells	Assembly/ disassembly of nuclear weapons	1958–2005	Thorium	Beta	>15 keV	100
				Photons	30–250 keV	100[e]
Pit vaults, igloos	Staging of plutonium pits	1958–2005	Plutonium, HEU	Photons	30–250 keV	100
				Neutrons	0.1–2 MeV	100[d]
Tritium vault	Staging of tritium reservoirs	1958–2005	Tritium	Beta	<15 keV	100[c]
Transportation	Movement of weapons	1952–2005	DU, HEU, thorium, plutonium	Photons	30–250 keV	100[b]
				Neutrons	0.1–2 MeV	100[d]
Radiography, nondestructive examination	Radiography	1952–2005	Weapon components	Photons	30–250 keV	100[b]
				Neutrons	0.1–2 MeV	100[d]
QA/QC, Cell 8	Pit testing	1958–2005	Plutonium, HEU	Photons	30–250 keV	100[e]
				Neutrons	0.1–2 MeV	100[d]
Warehouse, production stores	Packaging components	1952–2005	Weapon components	Beta	>15 keV	100[a]
				Photons	30–250 keV	100[b]
				Neutrons	0.1–2 MeV	100[d]
Warehouse, production stores	Packaging components	1958–2005	Tritium	Beta	<15 keV	100[c]

a. Workplace beta radiation has energy greater than 15 keV [30].

b. Most photons from DU have energies greater than 30 keV; some have energies greater than 250 keV. If shielding materials are present, fewer photons are in the categories less than 30 keV, or greater than 250 keV. The assumption that 100% of the photons from DU are between 30 and 250 keV is recommended as a simplifying conservative assumption that is generally favorable to claimants [31].

c. Beta particles from tritium are classified in the “less-than-15-keV” category [32].

d. The energy of neutrons in the workplace is predominately in one of two ranges: 0.1 to 2 MeV or 2 to 20 MeV. In some cases, with significant moderating materials, some neutrons are less than 0.1 MeV. However, assuming that 100% of the neutrons are between 0.1 and 2 MeV is a simplifying, conservative assumption that is generally favorable to claimants [33].

e. Four weapons programs included thorium components assembled during the 1960s and disassembled during the 1990s. Beginning in about 1960, there was handling of recently purified thorium that was not in secular equilibrium with its progeny and had emission of predominantly lower energy photons. The assumption that 100% of these photons were between 30 and 250 keV is recommended. Although the thorium components were in secular equilibrium during the disassembly period and the 2.6-MeV photons from ^{208}Tl are dominant, this represented a small fraction of the total worker photon dose. The assumption that the photon energy was between 30 and 250 keV is conservative [34].

6.5.5 Dosimeter Response to Radiation Fields

6.5.5.1 Beta/Photon Film Dosimeter Response

The Pantex Plant used film for beta and photon dosimetry from 1952 to 1973 (see Table 6-2a). Three companies provided dosimetry services during this period; the services and dosimeters were essentially the same [35]. The dosimeters provided an open window with little filtration, a lower energy window for allowing beta particles and lower energy photons to enter a film area with a plastic filter, and a film area with a metal (usually aluminum) filter (AEC 1955). The open window enabled measurement of beta particles and lower energy photons. The plastic filter enabled measurement of intermediate-energy photons, and the metal filter enabled measurement of higher energy photons (1-cm depth) (AEC 1955).

The AEC tested film badges provided by Tracerlab (AEC 1955) with exposures to 40-, 70-, and 210-keV X-rays, ^{60}Co gamma rays, and mixed-energy exposures of all four radiations. The film badges generally responded well "with a tendency to interpret most exposures too high." The over-response (in the 100- to 200-keV region) tended to yield conservatively high results. This testing, in combination with the data from Figure 6-2 and the pattern in recorded doses with progressively more sophisticated dosimetry systems, leads to the conclusion that film-badge measured photon doses at Pantex were reliable. Moreover, photon exposures from 60-keV ^{241}Am photons were not underestimated, and the total photon dose was probably slightly overestimated because of the over-response to photons in the 100- to 200-keV energy region [36].

Table 6-10 summarizes typical beta/photon personnel dosimeter parameters important to *Hp(10)* performance in the workplace.

Table 6-10. Typical workplace beta/gamma dosimeter *Hp(10)* performance.[a]

Parameter	Description	Potential workplace bias[b] [37]
Exposure geometry	Pantex dosimeter system calibrated using AP laboratory irradiations.	Dose of record probably too low because dosimeter response is lower at angles other than AP. Effect is highly dependent on radiation type and energy.
Energy response	Pantex film deep dose response is too low for photon energies less than about 35 keV and too high for photon energies between 35 and 200 keV (see Figure 6-2).	Positive bias in dose of record is expected, because photon energy is typically >35 keV in workplaces and performance testing shows positive bias.
Highly divergent fields	Dosimeter worn at collar could underestimate deep dose at waist.	Dose of record could be too low for workers performing waist-level uranium handling jobs.
Mixed fields	Pantex dosimeters respond to beta and photon radiation.	Filtration of about 1,000 mg/cm^2 over dosimeter region used to measure deep dose minimizes dosimeter response to beta radiation.
Missed dose	Doses less than MDL recorded as zero dose.	Dose of record probably too low. Impact of missed dose would be greatest in earlier years because of dosimeter exchange frequency and film dosimeter with higher MDLs.
Environmental effects	Workplace environment (heat, humidity, etc.) fades dosimeter signal.	Dose of record is probably too low.

a. Judgment based on Pantex Plant dosimeter response characteristics and workplace radiation fields (BWXT Pantex 2002).

b. Dose of record in comparison with *Hp(10)*.

6.5.5.2 Beta/Photon TLD Dosimeter Response

The Pantex external dosimetry program has used Panasonic TLD systems for personnel dosimetry, with the exception of the in-house period (1973 to 1980) when the Plant implemented the Pantex Personnel Dosimeter (PPD) based on the Harshaw Model 2000 TL analyzer system (DOE 1980). The first PPDs had open windows for beta and lower energy photons (7 mg/cm^2) and a window of 290 mg/cm^2 Al (DOE 1980). In 1977, Pantex implemented an improved six-element TLD program, which had several filters up to a density thickness of about 1,000 mg/cm^2 (i.e., nearly equivalent to 1-cm depth in tissue) for measurement of the whole-body (deep) dose, *Hp(10)* (see Figure 6-3).

The Panasonic UD-802 system at Pantex was tested by Roberson et al. (1983) and found to respond very well to ^{137}Cs photons, to overestimate dose from 60-keV ^{241}Am photons, and to underestimate the dose from fast neutrons. Adjustments were made to the calibrations and algorithm, and the UD-802 system was accredited by DOELAP in 1993 for all beta and photon testing categories. The Panasonic UD-809/UD-812 dosimeter system was accredited by DOELAP in 1993 for all testing categories applicable to Pantex [38].

The dosimeter testing described in Section 6.4.5.1 (AEC 1955) and above (Roberson et al. 1983) and the DOELAP accreditations show widespread technical capabilities to measure photon doses reliably. The intercomparison studies provide evidence that film badges and TLDs responded adequately, during the entire 1952-to-present period at Pantex, to the 60-keV photons from ^{241}Am and the film badges probably over-responded to photons between 100 and 200 keV [39]. Based on this information, the photon dose of record is likely to be favorable to claimants, assuming the dose of record is adjusted upward for missed dose (i.e., recorded zero dose when less than MDL) [40].

The exposure orientation of workers in the various Pantex facilities is primarily AP, and dosimeters are normally worn on the front of the torso [41]. An assumption that exposure orientations are 100% AP is a simplifying and conservative assumption that is generally favorable to claimants. However, other exposure orientations (ROT and ISO) do occur for a limited number of workers in some work situations. If the claim file provides information to suggest a geometry for which the dosimeter would receive appreciably less dose than the region of interest (e.g. work at a benchtop) then a correction factor should be applied in accordance with the guidance of OCAS-TIB-0010, *Best Estimate Dose Reconstruction for Glovebox Workers* (NIOSH 2011).

6.5.5.3 Neutron Dosimeter Response

Tracerlab provided NTA film dosimetry service from 1958 through April 1963 (ORAUT 2003b). According to routine dose reports, the film was sensitive to neutrons with energies from 1 to 10 MeV. The stated MRD value of the film was 15 mrem for neutrons. Between April 1963 and September 1964, Eberline provided similar film badge services (Ashton 2003); the stated MRD was 10 mrem. From October 1964 through 1976, Landauer provided similar services (Adams 2003). MRDs were 20 and 10 mrem, respectively, for fast and thermal neutrons.

Based on current knowledge of the general characteristics and response of NTA film, and the expected under-response in workplace conditions with significant scattering of neutrons, use of the film for personnel neutron dose monitoring can have the biases listed in Table 6-11. Testing of NTA film clearly showed that neutrons with energies below 500 keV were not measurable, and overall neutron doses were probably underestimated (ORAUT 2006c). Based on this, correction factors are applied to the recorded NTA film results to account for threshold response (1.4), angular dependence (1.33), and uncorrected fading (1.56). Combining these factors, the total correction factor of 2.9 is applied to the NTA film results in addition to the ICRP correction factor (1.91) (ORAUT 2015).

Table 6-11. Typical workplace neutron dosimeter performance (BWXT Pantex 2002).[a]

Parameter	Description	Potential workplace bias[b] [42]
Workplace neutron energy spectra	NTA dosimeter response decreases and TLND response increases with decreasing neutron energy.	Depends on workplace neutron spectra. NTA dose of record probably too low because of high 500-keV energy threshold for detection of neutrons.
Exposure geometry	NTA dosimeter response increases and TLND response decreases with increasing exposure angle.	NTA dose of record probably too high because dosimeter response is higher at angles other than AP. TLD dose of record is lower at angles other than AP. Effect is highly dependent on neutron energy.
Missed dose	Doses less than MDL recorded as zero dose.	Dose of record probably too low. Impact of missed dose is greatest in earlier years because of higher MDLs of neutron dosimeters.
Environmental effects	Workplace environment (heat, humidity, etc.) fades dosimeter signal.	Dose of record probably too low.

a. Judgment based on Pantex Plant dosimeter response characteristics [43].
b. Dose of record in comparison with *Hp(10)*.

The six-element, in-house TLD system Pantex used from 1977 to 1980 responded well to thermal neutrons but under-responded to neutrons with energies above about 10 keV (Thompson 1977). Therefore, this system did not measure a significant fraction of the neutrons in the Pantex workplace.

The response of the Panasonic UD-802 TLD to thermal and fast neutron radiation was measured by Roberson et al. (1983) using a bare and moderated ^{252}Cf sources. These measurements showed that the UD-802 significantly under-responded to fast neutrons. Therefore, UD_802-measured neutron doses between 1980 and 1993 are likely to be underestimated. DOELAP accredited the Panasonic UD-809/UD-812 TLD system in 1993 for all neutron categories applicable at Pantex. Measured neutron doses at Pantex since 1994 are reliable, and dose reconstructors should use the dose of record [44]. In addition, the Pantex site retrospectively reanalyzed all neutron dosimeter results from 1977 through 1993 using the dosimeter algorithm that was accredited by DOELAP. These results have been linked to individual worker records and should be used for dose reconstruction [45].

6.5.5.4 Neutron Dose Weighting Factor

An adjustment to the neutron dose is necessary to account for the change in neutron quality factors between historical and current scientific guidance, as discussed in NIOSH (2007). At Pantex, TLNDs were calibrated with measurements based on fluence-to-dose conversion factors and quality factors similar to those from International Commission on Radiological Protection (ICRP) Publication 21 (ICRP 1973) and National Council on Radiological Protection and Measurements (NCRP) Report 38 (NCRP 1971). These quality factors are point-wise data because they were calculated for a broad parallel beam of monoenergetic neutrons incident on a 30-cm-diameter cylindrical phantom representing the torso. Figure 6-11 compares NCRP (1971) quality factors to those used in Pacific Northwest National Laboratory (PNNL) measurements at the Y-12 Plant (Soldat et al. 1990). To convert from NCRP (1971) quality factors to ICRP (1991) radiation weighting factors, a curve was fit that described the quality factors as a function of neutron energy. A group average quality factor was calculated, as

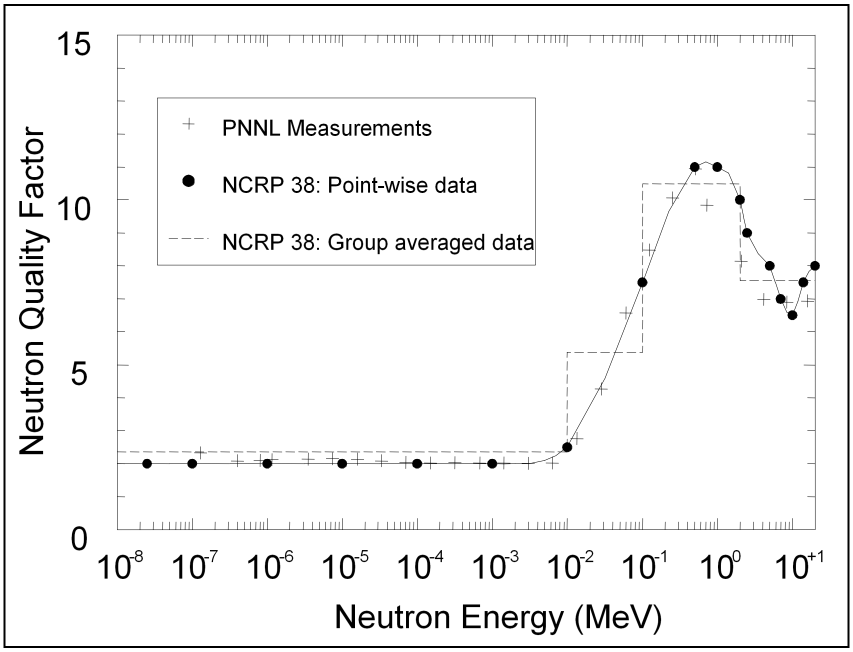

Figure 6-11. Comparison of neutron quality factors used in PNNL neutron spectrum measurements (Soldat et al. 1990) and neutron quality factors from NCRP (1971), shown as point-wise data, and grouped, averaged data over four neutron energy groups used in dose reconstruction for Y-12 Plant workers.

shown in Figure 6-11, for each neutron energy group used to define the radiation weighting factors in ICRP (1991). Table 6-12 summarizes the group-averaged NCRP (1971) quality factors that were used in the dose reconstruction. In addition, this table compares these quality factors with dosimetry guidelines from the First Tripartite Conference in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994).

Table 6-12. Neutron quality factor or weighting factor.

Neutron energy	**Historical dosimetry guideline**[a]	**NCRP (1971) group averaged quality factor $Q_{avg}(E_n)$**[b]	**ICRP (1991) neutron weighting factor $w_R(E_n)$**	**Correction factor ICRP (1991)/NCRP (1971) $w_R(E_n)/Q_{avg}(E_n)$**
Thermal	5	2.35	5	2.13
0.5 eV–10 keV	10	Not applicable	Not applicable	Not applicable
10 keV–100 keV	10	5.38	10	1.86
100 keV–2 MeV	10	10.49	20	1.91
2 MeV–14 MeV	10	7.56	10	1.32
14 MeV–60 MeV	10	Not applicable	5	Not applicable

a. First Tripartite Conference in 1949 (Warren et al. 1949; Fix, Gilbert, and Baumgartner 1994).

b. ORAUT (2009).

Table 6-12 lists average quality factors for the four energy groups for inputting dose to IREP, which encompass potential neutron exposures. The neutron dose equivalent correction factor for each energy group, $C_f(E_n)$, can be calculated by the use of the following equation (ORAUT 2006d):

$$C_f(E_n) = \frac{w_R(E_n)}{Q_{avg}(E_n)} \times D_f(E_n) \tag{6-1}$$

where

$D_f(E_n)$ = the dose fraction for the specific neutron energy group of interest

$Q_{avg}(E_n)$ = the group average NCRP (1971) neutron quality factor for that specific group
$w_R(E_n)$ = the ICRP (1991) neutron weighting factor for that specific group

Using this method, the dose equivalent of record is a combination of all neutron energies. To calculate the neutron dose input to IREP, the neutron dose of record must be separated into neutron energy groups. Table 6-9 summarizes the dose fractions by neutron energy group for the neutron exposure areas at Pantex. Dose reconstructors should apply the correction to recorded, unmonitored, and missed neutron dose before 1994 using the ICRP (1991) correction factor from Table 6-13. Beginning on January 1, 2010, Pantex incorporated the ICRP correction factor into the reported neutron doses. Therefore, the correction factor is not applied for any reported doses after 2009.

Table 6-13. Neutron dose energies, percentages, and associated correction factors for nuclear weapons component assembly and disassembly.

Process	Neutron energy (MeV)	Default dose fraction[a] (%)	Correction factor from Table 6-12
Nuclear weapons component assembly	0.1–2 MeV	100	1.91

a. The assumption (see Table 6-9) that all neutron energies are between 0.1 and 2 MeV typically results in a higher organ dose assignment and is therefore favorable to claimants.

6.5.5.5 Use of Lead Aprons

Lead aprons were available to early radiography workers at Pantex. However, because radiography machines were inside shielded facilities, workers did not use the aprons routinely [46]. Monitored radiation doses for radiographers in the early years were usually zero [47]. In the late 1950s when work with pits began, there were higher measured photon radiation doses and workers began wearing lead aprons [48]. However, the use of lead aprons was not included in procedures until the mid-1980s [49]. Present instructions for workers wearing aprons are to wear whole-body dosimeters “under the lead apron to make the best estimate of the delivered dose equivalent to the major portion of the body” (BWXT Pantex 2002). However, there was no enforcement to ensure that dosimeters were worn under the apron [50].

Three types of lead aprons have been worn by Pantex workers over the years (Passmore 1995a,b,c). Some covered only the front of a worker’s body. Some covered the front and back but not the sides. In 1995, the use of aprons that wrap entirely around the body began, but use of the other two types continued. Figure 6-12 shows the areas of the body a lead apron typically covers (Memmler and Rada 1970).

In 1995, a series of studies were performed at Pantex on the effects of apron use on dosimeter readings (Passmore 1995a,b,c). The studies placed a dosimeter on the front of a phantom in an aisleway near the middle of an igloo in which plutonium pits were stored in cans. The photon spectrum in this isotropic field was “hardened” by the steel cans and included the 2.2-MeV photons that are generated when a thermal neutron is captured by hydrogen [51]. This exposure scenario was chosen to represent the radiation fields where lead aprons were least effective in reducing photon dose [52]. Dose measurements were made with no apron and with the dosimeter under and over each type of apron. The results summarized in Table 6-14 are the percent reduction when wearing an apron in comparison with the measurement with no apron. A surprising result was that placing dosimeters outside the apron indicated a reduction in the dosimeter readings. One possible explanation for this effect is that some radiation getting to the dosimeter on the phantom came through the back of the phantom and was reduced by the shielding in the apron that it encountered before it would have reached the dosimeter.

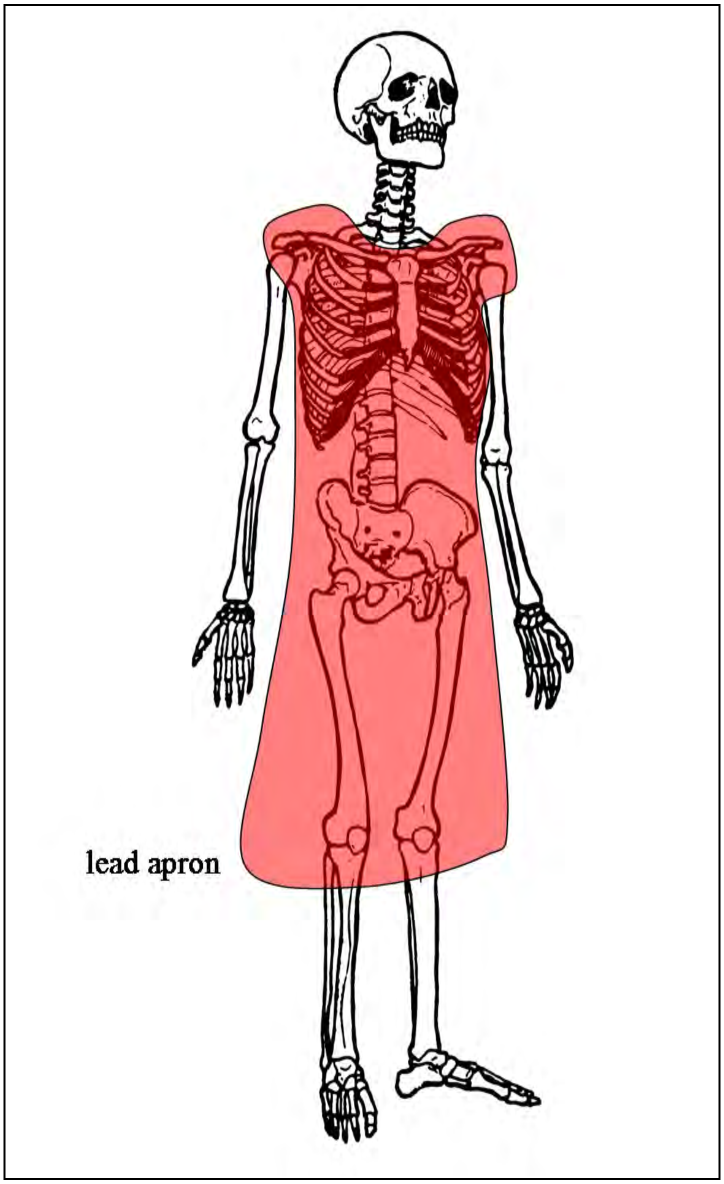

Figure 6-12. Body areas covered by lead apron (skeletal figure from Memmler and Rada 1970).

Table 6-14. Percent reduction in measured photon dose provided by lead aprons (Passmore 1995a,b,c).

Apron type	Apron thickness (mm lead equivalent)	Dosimeter location[a]			
		Deep dose		Shallow dose	
		Under	On top	Under	On top
Front only	0.50	30	13	29	12
Front and back	0.50	35	8	23	7
Wrap-around	0.25	27	7	19	8

a. In relation to dosimeter response with no apron.

Production Technicians, Material Handlers, Radiography Technicians, and Quality Control Technicians routinely wore aprons during work in the 1980s and 1990s, and perhaps earlier [53]. More recently, the use of lead aprons has been required by procedure and enforced by management. Production Technicians and Material Handlers in facilities that contained plutonium generally wore aprons [54]. Workers in other job classifications generally did not wear aprons.

An adjustment factor was derived from the largest relevant dose reduction data in Table 6-14 and applied to the location of cancer sites listed in Table 6-15 [55]. If the cancer site is in an area protected by a lead apron, an adjustment factor of 1 applies to a worker who wore the dosimeter under the apron [56]. If a worker received dose while not wearing an apron, applying this factor of 1 to the measured dose is still favorable to claimants. If the cancer site is in an area not protected by a lead apron, an adjustment factor of 1.5 should be applied, regardless of the location of the dosimeter [57].

Table 6-15. Cancer sites protected or unprotected by apron (42 CFR Part 81).

ICD-9 code	Cancer description	Cancer site[a]
140	Malignant neoplasm of lip	U
141	Malignant neoplasm of tongue	U
142	Malignant neoplasm of major salivary glands	U
143	Malignant neoplasm of gum	U
144	Malignant neoplasm of floor of mouth	U
145	Malignant neoplasm of other and unspecified parts of mouth	U
146	Malignant neoplasm of oropharynx	U
147	Malignant neoplasm of nasopharynx	U
148	Malignant neoplasm of hypopharynx	U
149	Malignant neoplasm of other and ill-defined sites within lip, oral cavity, and pharynx	U
150	Malignant neoplasm of esophagus	U
151	Malignant neoplasm of stomach	P
152	Malignant neoplasm of small intestine, including duodenum	P
153	Malignant neoplasm of colon	P
154	Malignant neoplasm of rectum, rectosigmoid junction, and anus	P
155	Malignant neoplasm of liver and intrahepatic bile ducts	P
156	Malignant neoplasm of gall bladder and extrahepatic bile ducts	P
157	Malignant neoplasm of pancreas	P
158	Malignant neoplasm of retroperitoneum and peritoneum	P
159	Malignant neoplasm of other and ill-defined sites within digestive organs and peritoneum	P
160	Malignant neoplasm of nasal cavities, middle ear, and accessory sinuses	P
161	Malignant neoplasm of larynx	P
162	Malignant neoplasm of trachea, bronchus, and lung	P
163	Malignant neoplasm of pleura	P
164	Malignant neoplasm of thymus, heart, and mediastinum	P
165	Malignant neoplasm of other and ill-defined sites within respiratory system and intrathoracic organs	P
170	Malignant neoplasm of bone and articular cartilage	F
171	Malignant neoplasm of connective and other soft tissue	F
172	Malignant melanoma of skin	F
173	Other malignant neoplasms of skin	F
174	Malignant neoplasm of female breast	P
175	Malignant neoplasm of male breast	P
179	Malignant neoplasm of uterus, part unspecified	P
180	Malignant neoplasm of cervix uteri	P
181	Malignant neoplasm of placenta	P
182	Malignant neoplasm of body of uterus	P
183	Malignant neoplasm of ovary and other uterine adnexa	P
184	Malignant neoplasm of other and unspecified female genital organs	P
185	Malignant neoplasm of prostate	P
186	Malignant neoplasm of testis	P
187	Malignant neoplasm of penis and other male genital organs	P
188	Malignant neoplasm of urinary bladder	P

ICD-9 code	Cancer description	Cancer site[a]
189	Malignant neoplasm of kidney and other unspecified urinary organs	P
190	Malignant neoplasm of eye	U
191	Malignant neoplasm of brain	U
192	Malignant neoplasm of other and unspecified parts of nervous system	F
193	Malignant neoplasm of thyroid gland	U
194	Malignant neoplasm of other endocrine glands and related structures	P
195	Malignant neoplasm of other and ill-defined sites	F
196	Secondary and unspecified malignant neoplasm of lymph nodes	P
197	Secondary malignant neoplasm of respiratory and digestive organs	P
198	Secondary malignant neoplasm of other tissue and organs	F
199	Malignant neoplasm without specification of site	U
200	Lymphosarcoma and reticulosarcoma	U
201	Hodgkin’s disease	U
202	Other malignant neoplasms of lymphoid and histiocytic tissue	U
203	Multiple myeloma and other immunoproliferative neoplasms	U
204	Lymphoid leukemia	U
205	Myeloid leukemia	U
206	Monocytic leukemia	U
207	Other specified leukemia	U
208	Leukemia of unspecified cell type	U

a. F = apron covered from shoulders to below the knee but not the arms; P = protected by apron; U = unprotected by apron. Dose reconstructors should use Figure 6-11 and knowledge of cancer site to determine U or P.

6.6 ANALYSIS OF CLAIMS FILED BY PANTEX WORKERS

An analysis of job titles, worker classifications, and external dose parameters from Pantex claims was performed to better determine dose reconstruction recommendations. There are three primary sources of information in each claim that provide information of interest to reconstruction of external dose: (1) DOL claim documentation, (2) DOE medical X-ray, dosimetry, and incident archive records, and (3) records of interviews with claimants and coworkers, as available. This information is used to identify the employment period, job title and work activities, coworkers, supervisors, etc., for use in dose reconstruction. Analysis of the historical radiation monitoring and dose documentation for the respective claims provides insight into Pantex dosimetry practices, such as assignment of dosimeters, exchange periods, and dose recording levels.

For purposes of dose reconstruction, it is recognized that while “average” and “routine” activities are important and probably represent most exposure scenarios, there could be unusual circumstances in some claims that require special evaluation [58].

6.6.1 Years with a Claim

A sample of 316 claims that were filed with the U.S. Department of Labor (DOL) by Pantex workers was analyzed to examine trends in the data. These claims were assembled into a dataset with one line of data for each year of employment for each worker. Information for workers that had more than one job title in a given year was entered into additional lines. Overall, a total of 6,396 lines of data was assembled for the 316 claims. Claimants reported a total of 692 different job titles or job codes. The average period of employment for workers was 20.2 years [59]. The records (with and without a recorded radiation dose) were examined for each year for the respective claims. Figure 6-13 illustrates the frequency of claims in each year. It is evident that the very early years have fewer claims. The peak in the number of claims for a year occurs in the late 1970s to early 1980s.

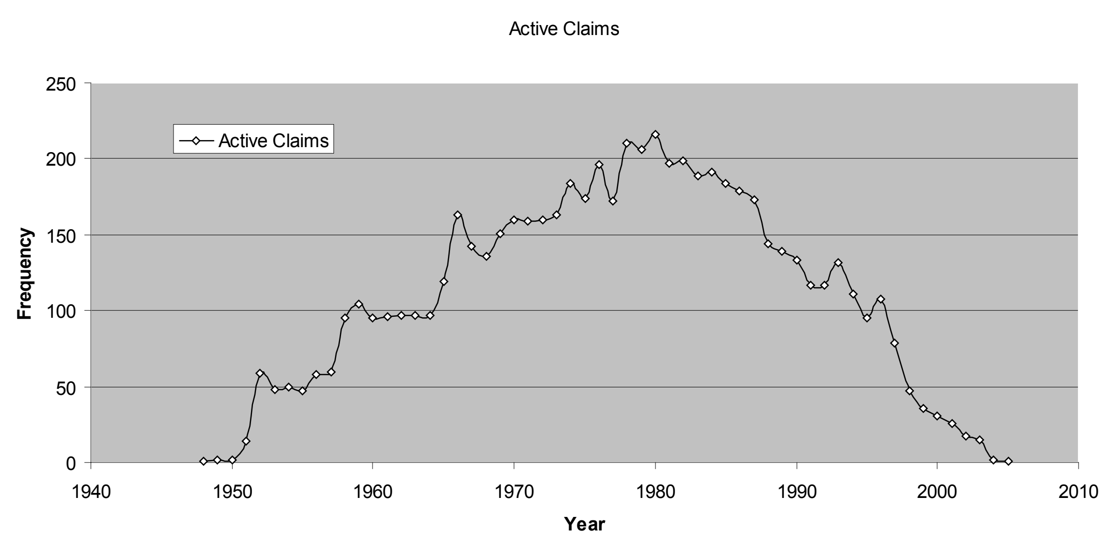

Figure 6-13. Frequency distribution of claims that encompass the respective years [61].

6.6.2 Collective Dose by Job Title

Analysis of the available claim documentation showed a wide spectrum of job titles and job descriptions for the workers. Many descriptive occupational titles, including Pantex-specific numerical identifiers for positions, are found in the respective claim documentation. Nearly 700 different job titles were identified for the 316 workers during the years of employment [60]. Similar job titles were grouped into the assigned job titles listed in Table 6-16, and collective photon and neutron doses were tabulated to examine the dose distribution in relation to job titles [62]. This analysis confirmed that most of the collective dose was received by assembly, inspection, and warehouse operators, who were generally designated as radiation workers. Another interesting feature of these data is the nearly equal collective photon and neutron doses that were recorded for warehouse operators, which is not evident for any other group of job titles. Detailed analysis of these data revealed that most of the collective neutron dose to warehouse operators was received by fewer than 10 workers in 1960 and 1979 [63].

Table 6-16. General categories of job titles for Pantex workers and recorded collective doses (person-mrem) [64].

	Collective photon dose		**Collective neutron dose**	
Category of job title	**Collective dose**	**% of total**	**Collective dose**	**% of total**
Assembly/Production	103,197	61.8	17,248	44.9
Clerk	2,460	1.5	2,390	6.2
Disability	330	0.2		0.0
Engineering	3,837	2.3	237	0.6
Explosives Handler	490	0.3	20	0.1
Inspection	19,567	11.7	3,431	8.9
Management	2,625	1.6	70	0.2
Material Hander	1,060	0.6	370	1.0
Metrology	3,971	2.4	405	1.1
Quality	9,430	5.6	2,150	5.6
Radiation Safety	345	0.2		0.0
Security	910	0.5		0.0
Support Services	2,260	1.4	50	0.1
Tradeworker	4,431	2.7	650	1.7
Warehouse Operator	12,205	7.3	11,393	29.7
Total	167,118	Not applicable	38,414	Not applicable

6.6.3 Analysis of Recorded Doses

Radiation doses were examined for these workers for years before March 1989, when monitoring began for all employees. A total of 1,754 lines of data showed recorded doses (including zeros) for monitored workers and accounted about 27% of the data. A total of 3,577 lines of data had no recorded doses (blank), which represented unmonitored workers and accounted for about 56% of the data. The remaining 1,065 lines of data represent workers who were monitored after March 1989 and accounted for about 17% of the database. Overall, about 44% of the records contained results (including zeroes) of dose monitoring (i.e., 2,819 lines, the sum of 1,754 and 1,065 lines, respectively, from before and after March 1989). Further analysis of monitored worker data (2,819 lines) showed that about 48% had nonzero recorded doses. The recorded photon and neutron collective dose for the Pantex claims is presented in Figure 6-14. Based on this information, the earliest recorded photon dose occurred in 1958 and the earliest neutron dose in 1960. The relatively high collective neutron dose in 1960 is interesting because it is higher than the recorded collective photon dose. The majority of the recorded neutron dose in 1960 was recorded for just a few workers [65]. One possible explanation is that there could have been an effort to correct for the known underestimation of neutron dose as measured by NTA films.

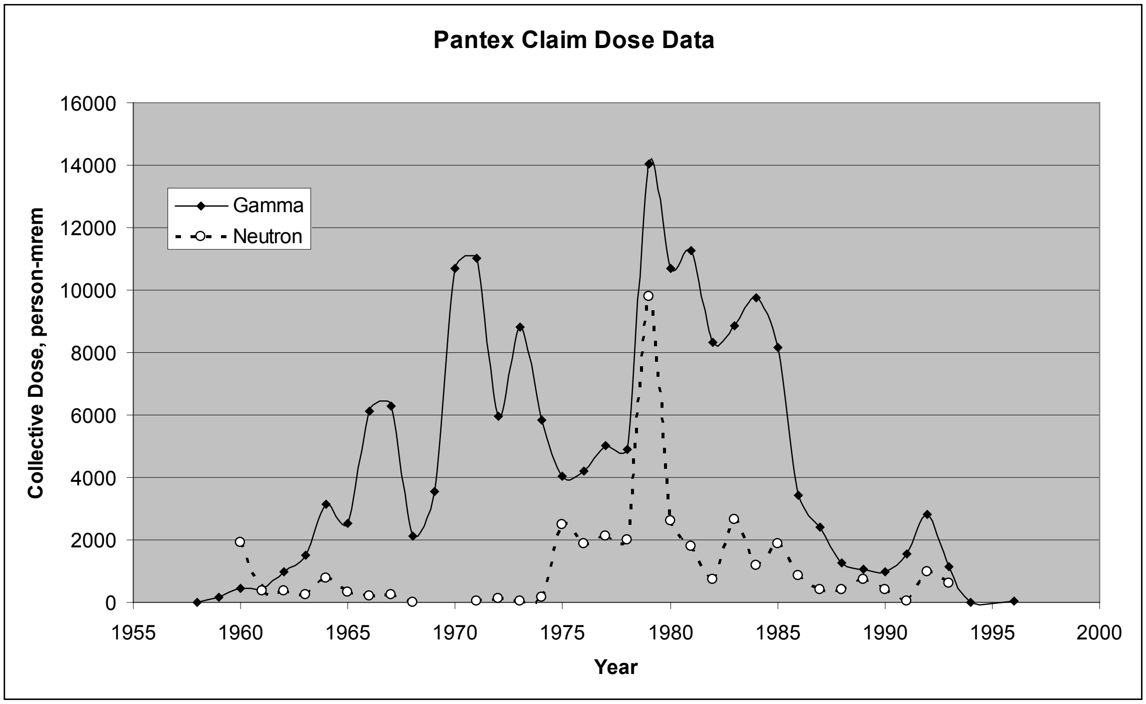

Figure 6-14. Distribution of annual photon and neutron dose for Pantex claims.

An attempt was made to associate group job titles with specific worker job activities that were expected to involve radiation exposure. However, meaningful analysis was not feasible with the data available because worker job titles changed significantly over the years and many workers had several titles during their employment at Pantex. It is evident that the respective workers represent a broad spectrum of work functions at Pantex.

6.7 RECOMMENDATIONS FOR PANTEX WORKER EXTERNAL DOSE RECONSTRUCTION

Dose reconstruction for Pantex workers is based on the foregoing information, which requires assessment of additional dose to be added to the dose of record from four primary causes as follows [66]:

- Dose to unmonitored workers with potential for occupational external exposures before the routine use of personnel dosimeters by all workers,
- Adjustments to reported photon dose associated with the use of protective lead aprons,
- Missed dose for monitored workers for low dose results (less than MDL of the personnel dosimeter), and
- Unmeasured neutron dose to monitored and unmonitored workers.

6.7.1 Unmonitored External Dose

Figure 6-5 implies there is comparatively little collective measured dose, particularly before about 1960. This occurred because there was limited potential for exposure and few workers were monitored [67]. Figure 6-17 shows a statistical analysis of the history of recorded Pantex gamma doses in a lognormal probability plot. A detailed statistical analysis of the available external monitoring results for the Pantex Plant was published in 2015 (ORAUT 2015). The analysis for ORAUT-OTIB-0086, *Pantex External Coworker Model*, resulted in the development of unmonitored photon, electron, and neutron doses which are listed in Attachment A. It is recommended that dose reconstructors assign a dose to an unmonitored worker, who would otherwise be monitored by today's standards, equal to the geometric mean or 95th-percentile coworker doses for each year of unmonitored employment [68] for the operational years through 1988 (i.e., 1952 through 1988). This is favorable to claimants because unmonitored workers are expected to have lower exposure because Pantex practice was to monitor all radiation workers before March 1989. For years before 1960 when no measured gamma dose equal to or greater than 40 mrem was measured, dose reconstructors should use the median dose for 1960 for each year of employment [69]. In presumptively noncompensable cases, unmonitored doses can be applied for periods after 1988 if deemed warranted by the dose reconstructor.

6.7.2 Adjustment for Protective Lead Aprons

Adjustment to dose for use of protective lead aprons depends on the location of the cancer site as determined from Figure 6-12 [70]. The aprons covered the body from the shoulders to below the knee, but not the arms. If the cancer site is under the lead apron, there is no adjustment factor (or the adjustment factor is 1.0) because a dosimeter under the apron will reasonably measure a dose to the cancer site. If the cancer site is in an area not protected by an apron, and for which the dosimeter-measured dose might be too low, the recommended adjustment factor is 1.5, as described in Section 6.5.5.6. This factor is applied only to the assigned photon dose components because electrons would essentially be absorbed by the apron and the apron would not have an effect on incident neutrons. In the absence of extremity monitoring information, dose reconstructors should apply the higher of the recorded shallow dose or the 95th-percentile external shallow dose for the skin of the hands and forearms.

6.7.3 Photon and Neutron Dose Adjustments

Pantex worker neutron dose measurements with the Panasonic 809/812-accredited and workplace performance-validated TLND implemented in 1994 are considered accurate [71]. NTA film neutron dose results are adjusted by the factor of 2.9 as discussed in Section 6.5.5.3 from 1958 through 1976. For 1977 through 1993, the doses recalculated using the Stanford algorithm are considered accurate and are used for reconstructing worker doses.

For monitored workers whose occupational activities involved handling nuclear weapons components (e.g., Production Technicians and Material Handlers), options to estimate the dose include:

1. Adjust the measured photon and neutron doses for dosimeter response uncertainty as outlined in Section 6.8. If the cancer site is in an area not protected by an apron, apply the lead apron adjustment factor of 1.5 to the adjusted photon dose.

2. Details in the claim file and/or interview should be used to determine if unique work activities and exposure geometries should be a consideration, particularly for non-uniform fields generally associated with bench-top operations. For example, statements in some worker's files indicated that they performed pit maintenance operations with the pit on their lap in a sitting position. This could result in a low bias to the organs of the lower torso. In these cases, the 95th-percentile glovebox correction factor listed in OCAS-TIB-0010 (NIOSH 2011) are recommended to ensure an analysis favorable to the claimant. This type of activity was generally limited to a relatively small fraction of time during the average workday. Because of this, a scaling factor should be applied to the 95th percentile glovebox correction. For example, the actual pit handling activity likely took no more than one to two hours per day. Assuming that the claimant actually performed pit handling maintenance operations for one hour per day, five days per week, the appropriate correction to apply would equate to the 95th percentile correction multiplied by 0.125 (5 hours per day divided by the 40 hour work week). If the worker's dosimetry records indicate that they were monitored for extremity doses, the extremity dosimetry records may represent a more accurate indication of the actual dose to the lower torso organs than the whole body dosimeter worn underneath a lead apron worn at the chest or collar level. In such cases, the uncorrected extremity dose applied to the lower torso organ shall be compared to the lower torso organ dose determined using the whole body dosimeter result obtained using the scaled 95th percentile correction factor. The highest dose to the lower torso organ should be assigned for the dose reconstruction. In either case, the correction should be applied using a constant distribution for measured dose and a lognormal distribution with a geometric standard deviation of 1.520 for missed dose.

3. From 1977 through 2009, no adjustment in measured neutron dose is needed other than standard adjustments for dosimeter response uncertainty and ICRP Publication 60/NCRP Report 38 neutron weighting factors adjustments from Table 6-13 (ICRP 1991; NCRP 1971). For 2010 and later years, the site incorporated the ICRP weighting factor into the reported dose. Therefore, additional weighting factors are not required after 2009.

6.7.4 Skin Dose

For years before 1981, the skin dose records included only beta doses [72]. For 1981 and subsequent years, the skin dose has been calculated as the sum of the beta, gamma, and neutron doses. In cases where no nonpenetrating dose was recorded, the skin dose is assumed to be equal to the whole-body penetrating dose [73]. Based on this, recorded deep doses for 1981 and before should not be subtracted from the reported shallow dose. For 1981 and subsequent years of employment, electron doses are the difference between the reported shallow and deep doses and should be applied with an energy range of 100% >15 keV. Additional guidance on determining skin dose can be obtained from ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (ORAUT 2005).

6.7.5 Extremity Dose

Wrist-type extremity dosimeters have been assigned to radiation workers who directly handled nuclear weapon components, such as pits (BWXT Pantex 2002). Since 1980, a Panasonic UD-802 dosimeter with a wristband has been used for extremity dose monitoring [74]. Between 1972 and

1980, a wrist-type TLD badge was used; before 1972, a wrist-type film badge was used [75]. More recently (since 1991), two 802 wrist dosimeters (labeled right and left) have been assigned to radiation workers for use when working “hands on” with pits, uranium, or thorium components (BWXT Pantex 2002).

The actual use of extremity dosimeters at Pantex has not always been rigorously managed, and there were times when workers did not wear the assigned extremity dosimeters [76]. If an extremity dosimeter was worn and the measured dose was less than the skin dose measured by the whole-body dosimeter, the assumption was made that the extremity dosimeter was not worn at least part of the time; therefore, the skin dose was assigned as the wrist dose. If the extremity dosimeter did measure a dose greater than the whole-body dosimeter, the extremity dose was assigned to the wrist. If wrist dosimeter results were obtained for both wrists, the higher result was recorded as the extremity dose (BWXT Pantex 2002).

Durham and Hickey (1994) established that the average ratio between finger and wrist doses was 2.5. Finger rings were exposed on a hand phantom to the surface of a bare pit. Beginning in 1994, wrist doses were multiplied by 2.5 to calculate the extremity dose of record. Measured wrist doses from before 1994 should be multiplied by 2.5 to calculate the maximum extremity dose, if necessary.

A standard practice in operational health physics is to use a factor of 10 between whole-body and extremity exposures (Battelle 2006, p. 5). That is, if the measured contact dose rate is 10 times (or more) the measured dose rate at the location of the whole-body dosimeter, extremity dosimeters should be assigned for the work. In the case of missing extremity dose data, the whole-body dose can be multiplied by 10 and the result assigned as a conservative extremity dose.

Examination of the worker data revealed that, of 316 claims, only 42 had recorded extremity dose data greater than 100 mrem in a given year [77]. The 95th-percentile value of this distribution of wrist/extremity to whole-body photon dose ratios was approximately 6. If the cancer site involves the hands, forearms, feet, or legs below the knees, the extremity dose of record should be used. For any periods when the extremity dose of record is missing, the whole body dose multiplied by 10 can be used, if necessary.

6.7.6 Radiation Dose Fraction

Table 6-9 summarizes the recommended fractions for Pantex dose according to facility, worker occupational classification, and IREP-required energy categories. Because of the uncertainty in actual workplace fields, the energy fractions for worker dose estimation in Table 6-9 are recommended:

- 100% of the photon deep dose to the worker results from 30- to 250-keV photon radiation.
- 100% of the neutron dose to the worker results from 0.1- to 2-MeV neutrons.

These assumptions will generally result in estimates of organ dose that are favorable to claimants.

6.7.7 Organ Dose

Once the adjusted doses have been calculated for each year, the values are used to calculate organ doses of interest using the external dose reconstruction implementation guideline (NIOSH 2007). Consistent with NIOSH direction, it is recommended that the 100% AP (front-to-back) geometry should be assumed for the irradiation geometry and for conversion to organ dose. Exceptions to this include the red bone marrow, esophagus, lung, and bone surface. To determine the organ dose conversion factor most favorable to the claimant, a comparison must be made between the AP and ROT exposure geometries. For photon doses, the exposure to organ dose conversion factor should be applied through 1972 and the personal dose equivalent [*Hp(10)*] should be applied for 1973 and all subsequent years [78]. The deep dose equivalent *Hp,slab(10)* dose conversion factor should be used for neutron doses for all years.

6.8 UNCERTAINTY IN PHOTON AND NEUTRON DOSES

For the usual analysis of measured film badge doses, MDLs in the literature range from about 30 to 50 mrem for beta/photon irradiation (West 1993; Wilson et al. 1990). It is possible to read a photon dose of 100 mrem to within ±15 mrem if the exposure involved photons with energies between several keV and several MeV (Morgan 1961). The estimated standard error in recorded film badge doses from photons of any energy is ±30% (ORAUT 2006a). The estimated uncertainty in TLD-recorded doses is ±20% before 1994 (ORAUT 2006b) and ±10% for 1994 and after (BWXT Pantex 2002).

The correction factor of 2.9 accounts for uncertainties in neutron doses during the NTA film period (i.e., through 1976). Therefore, no uncertainty corrections should be applied to NTA film neutron dose results. For all other years, the neutron dosimeter results are accurate to ±30% based on DOELAP performance testing (ANSI 1993). Therefore, an uncertainty correction of ±30% should be applied to the recorded neutron dose results for the years of 1977 through the present.

6.9 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in this document, bracketed callouts have been inserted to indicate information, conclusions, and recommendations provided to assist in the process of worker dose reconstruction. These callouts are listed here in the Attributions and Annotations section, with information to identify the source and justification for each associated item. Conventional References, which are provided in the next section of this document, link data, quotations, and other information to documents available for review on the Project's Site Research Database (SRDB).

Jerry Martin served as the initial Document Owner of this document. Mr. Martin was previously employed at the Pantex site and his work involved management, direction, or implementation of radiation protection and/or health physics program policies, procedures, or practices in relation to atomic weapons activities at the site. This revision has been overseen by a new Document Owner, who is fully responsible for the content of this document, including all findings and conclusions.

[1] Martin, Jerome B. Oak Ridge Associated Universities (ORAU) Team. Senior Health Physicist. August 2006.
A larger fraction of the workers received nonzero external doses between 1960 and 1980, which was determined by inspection of Figure 6-1.

[2] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
AEC Manual Chapter 0524 (e.g., AEC 1958) required personal external dosimetry for radiation workers with the potential to exceed 10% of the RPG of 5 rem/yr. A comparison of the data in Table 6-2a, Table 6-2b, and Figure 6-1 for monitored workers to the total plant population generally indicated that radiation workers with a potential to exceed 500 mrem/yr were monitored while other workers were not.

[3] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The dosimeter exchange frequency was determined from dosimetry reports (Tracerlab 1962–1963; Ashton 2003; Adams 2003).

[4] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Examination of external dosimetry reports (Tracerlab 1962–1963; Ashton 2003; Adams 2003;

Martin 2003a) revealed that results less than the MRD were recorded as zero. Any results equal to or greater than the MRD were reported as nonzero results.

[5] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Pantex received its DOELAP certificate indicating successful completion of testing of the 809/812 TLD system in all beta, photon, and neutron radiation testing categories on September 1, 1993 (personal knowledge).

[6] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The discussion of UD-809 TLD elements is from BWXT Pantex (2002); however, the element numbers E5 through E8 are used here instead of E1 through E4 to distinguish between the similar element numbers in the UD-812 TLD.

[7] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
An examination of the collective neutron and collective gamma doses in Table 6-16 and their ratios indicates trends in the ratios as stated in the text. The improved TLD and TLND used between 1977 and 1993 (see Table 6-6) gave an overall ratio of 0.266, which is similar to the 0.25 ratio obtained with the DOELAP-accredited 809/812 TLND system currently used.

[8] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The ratios in Table 6-6 have increased with improvements in the dosimetry systems.

[9] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A calculation of neutron-to-photon dose ratios for the data in Figure 6-5 shows that the ratios after about 1985 are fairly constant, while the ratios before 1985 are quite variable.

[10] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A 0.5-Ci ^{137}Cs source in the 12-10 Building was used to calibrate the UD-802 dosimeters from the mid-1980s to 1996, when the Radiation Safety Department Calibration Facility was commissioned (ORAUT 2003a).

[11] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The highest dose rates are encountered when handling bare pits. In all other configurations (full weapons, physics packages, or pits in storage containers), some shielding is provided that reduces the dose rates to workers.

[12] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Information on other radiation fields at Pantex is based on personal knowledge of radiation-generating machines and the radioactive materials inventory.

[13] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Radiation dose rates vary considerably with the different weapon designs. Dose rates also vary during assembly and disassembly as components that provide shielding are added or removed (personal knowledge).

[14] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Radiation dose rates decrease during assembly as components that provide shielding are added (personal knowledge).

[15] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The statement about beta exposures being rarely detected by film badges or TLDs is based on personal knowledge of routine annual analyses of exposure data relative to worker

assignments to ensure proper assignment of radiation worker status and the type of dosimeter to provide.

[16] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Of the various photon radiation sources at Pantex, the lowest energy (about 30 keV) is produced by X-ray diffraction machines and the highest energy (2.6 MeV) is produced by the thorium decay product ^{208}Tl.

[17] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Information on sources of photon radiation at Pantex is based on personal knowledge of radiation-generating machines and the radioactive materials inventory.

[18] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Information on radiation sources at Pantex is based on personal knowledge of the radioactive materials inventory.

[19] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
When plutonium metal is purified, its decay products and other radionuclides are removed. However, weapons-grade plutonium contains several isotopes of plutonium, including varying amounts of ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu. With a half-life of 14.4 years, ^{241}Pu immediately begins to decay to ^{241}Am.

[20] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
With a half-life for ^{241}Pu of 14.4 years, ^{241}Am will reach equilibrium in about 80 years, but it will reach about 80% of this maximum in 40 years.

[21] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Disassembly of nuclear weapons often occurs 20 or more years after assembly. The longer the interval between assembly and disassembly, the more significant is the exposure from ^{241}Am photons.

[22] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
As can be seen in Figure 6-8, there are very few photons with energies less than 0.05 MeV (50 keV).

[23] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Disassembly of nuclear weapons often occurs 20 or more years after assembly. The longer the interval between assembly and disassembly, the more significant is the exposure from ^{241}Am photons.

[24] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Of the various photon radiation sources at Pantex, the lowest energy (about 30 keV) is produced by X-ray diffraction machines and the highest energy (2.6 MeV) is produced by the thorium decay product ^{208}Tl. The predominant source of radiation dose at Pantex is photons from ^{241}Am, with the 60-keV photon being the most significant. Although there are photons with energies greater than 250 keV in the Pantex workplace, the dose workers received from higher energy photons is insignificant in comparison with the dose from 60-keV photons. An

assumption that all photons are in the 30- to 250-keV range is a simplifying assumption that is generally favorable to claimants.

[25] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Bare pits are only handled in cells. Pits are surrounded by other weapon components or storage containers in all other Pantex facilities.

[26] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The spectra shown in Figure 6-9 are unmoderated neutrons. In the workplace, with moderation caused by nuclear weapons components, equipment, and building materials, the moderated spectra are shifted to lower energies.

[27] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Radiation dose rate surveys are routinely conducted in Pantex workplaces where radioactive materials are handled or radiation-generating machines are operated. The highest radiation dose rates to workers usually occur when workers handle bare pits. In all other workplace scenarios, bare pits are covered by some shielding material, which reduces the dose rate to workers.

[28] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Workplace measurements have been made to simulate typical worker exposure scenarios. The nominal distance from the surface of a pit to the worker's dosimeter location is 30 cm during hands-on operations.

[29] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
When any shielding or moderating material is added to a bare pit, both the photon and neutron dose rates are decreased, but the lower energy photon dose rates are reduced the most.

[30] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although there are some beta particles emitted by DU and its progeny that have energies less than 15 keV, these lower energy beta particles cannot penetrate the dead layer of the skin and do not contribute to external dose.

[31] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Footnote b is the explanation for the recommended simplifying assumption.

[32] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The maximum energy of beta particles from tritium is 18 keV and the average energy is 6 keV. Most of the beta particles from tritium are less than 15 keV. In any case, beta particles from tritium do not contribute to external dose.

[33] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although there are neutrons with higher energies (which are more penetrating) at Pantex, the POC for deeper organs, such as the liver, is much larger from the higher neutron fluence in the 0.1- to 2-MeV range than in any other energy group (NIOSH 2007).

[34] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
This conclusion was reached by review of AEC (1955) and inspection of Figure 6-2 that shows an over-response to photons with energies greater than 30 keV for the multielement film dosimeter that was used at Pantex from 1958 to 1976. The two-element film dosimeter, which

was used at Pantex between 1952 and 1958, shows a slight under-response at 60 keV but an over-response to photons between 70 and 200 keV.

[35] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The three companies that provided film badge service to Pantex between 1952 and 1976 were Tracerlab, Eberline, and Landauer. A review of the radiation dosimetry reports from all three suppliers and the explanatory notes on the back of each page of the reports indicated the frequency of exchange, film type, absorbers, MRDs, energy response, units of exposure, and other factors that demonstrated the similarities between the services.

[36] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Footnote e is the explanation for the recommended simplifying assumption.

[37] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The statements about potential workplace dosimeter bias are based on Tables 8.1, 8.2, and 8.3 in Wilson et al. (1990). Professional judgment was used to evaluate dosimeter response in Hanford facilities and predict the potential workplace dosimeter bias. The same method was used to evaluate dosimeter response to Pantex workplace radiation fields and to predict potential workplace dosimeter bias.

[38] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Pantex received its DOELAP certificate indicating successful completion of testing of the 802 TLD system in all beta and photon radiation testing categories, and of the 809/812 TLD system in all beta, photon, and neutron radiation testing categories, on September 1, 1993 (personal knowledge).

[39] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
This conclusion was reached by review of AEC (1955) and inspection of Figure 6-2 that shows an over-response to photons with energies greater than 30 keV for the multielement film dosimeter that was used at Pantex from 1958 to 1976. The two-element film dosimeter, which was used at Pantex between 1952 and 1958, shows a slight under-response at 60 keV but an over-response to photons between 70 and 200 keV.

[40] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The photon dose of record is considered to be reliable. If additions to the dose of record are made to account for missed dose, the adjusted dose is likely to be favorable to claimants.

[41] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
In most Pantex workplace scenarios where workers handle radioactive materials, they do so while facing the source in an AP orientation and they routinely wear the dosimeter on the front of the torso. An assumption that the exposure orientations are 100% AP is a simplifying and conservative assumption that is generally favorable to claimants.

[42] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The statements about potential workplace dosimeter bias are based on Tables 8.1, 8.2, and 8.3 in Wilson et al. (1990). Professional judgment was used to evaluate dosimeter response in Hanford facilities and predict the potential workplace dosimeter bias. The same method was used to evaluate dosimeter response to Pantex workplace radiation fields and to predict potential workplace dosimeter bias.

[43] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The statements about potential workplace dosimeter bias are based on Tables 8.1, 8.2, and 8.3 in Wilson et al (1990). Professional judgment was used to evaluate dosimeter response in

Hanford facilities and predict the potential workplace dosimeter bias. The same method was used to evaluate dosimeter response to Pantex workplace radiation fields and to predict potential workplace dosimeter bias.

[44] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The UD-809/UD-812 dosimeter used by Pantex was accredited by DOELAP in all neutron categories tested on September 1, 1993. Neutron doses measured and recorded at Pantex since 1994 are reliable, and the dose of record should be used in dose reconstructions.

[45] Thomas, Dale D. III. ORAU Team. Senior Health Physicist. December 2013.
The Pantex site retrospectively processed all neutron dosimeter results for 1977 through 1992 using the revised dosimeter algorithm that was accredited by DOELAP. These revised results have been linked to the individual worker records and should be used for external dose reconstruction.

[46] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Most radiography was done with radiography machines or sources inside shielded rooms, in which case the radiographers were outside the shielded room during radiation exposures and lead aprons were not worn. In some limited situations, radiography was done with portable X-ray machines or sources where a shielded room was not available. In these cases, the radiographers were supposed to wear lead aprons, but it was not required by procedure or enforced.

[47] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
From 1952 to 1957, only radiographers were assigned dosimeters, and the recorded doses were mostly zeros.

[48] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
In 1958, Pantex began to assemble nuclear weapons with pits from Rocky Flats. Higher photon dose rates were measured by radiation surveys, and lead aprons were provided to radiation workers.

[49] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The Pantex ALARA program and increased awareness of radiation exposure in the mid-1980s led to the revision of Pantex procedures to require the use of lead aprons while handling bare pits.

[50] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
In 1994 with the introduction of the 809/812 TLD system and increased concern about the accurate reading of neutron dose, the requirement to wear the dosimeter under lead aprons was explained and enforced (personal knowledge).

[51] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The photon spectrum from older pits includes a significant component of 60-keV photons from ^{241}Am. The steel pit storage cans effectively attenuate the lower energy photons from pits and “harden” the spectrum. Neutrons from pits interact with low-*Z* materials in the pit storage igloos, and 2.2-MeV photons are produced by the neutron moderation reaction.

[52] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A lead apron is most effective for attenuating low-energy photons (Shleien, Slaback, and Birky

1998). A lead apron is far less effective for attenuating the higher energy photons described in attribution 69.

[53] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Production Technicians, Material Handlers, Radiography Technicians, and Quality Control Technicians are the job titles most often designated as radiation workers at Pantex. Lead aprons were provided to radiation workers for pit handling during weapon disassembly in the 1980s and 1990s. Lead aprons were also available at earlier times, but records about their use were not found.

[54] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Lead aprons were most often used during the handling of plutonium pits, and this work was done by Production Technicians and Material Handlers. Workers who did not handle plutonium pits were not required to wear lead aprons.

[55] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The purpose of the conservative adjustment factor is to take into account various effects that occur with three different kinds of lead aprons and the dosimeter location (under or outside the apron). A dosimeter under a lead apron measures a lower dose than one outside an apron, and the lower dose varies depending on the thickness and type of apron. The data in Table 6-14 indicate a maximum reduction of 35% in the measured photon dose from use of a lead apron. This was rounded up to 50% (a factor of 1.5) to be favorable to claimants, and this factor was applied to the organs in Table 6-15 if the organ was outside the area protected by the lead apron.

[56] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
If the cancer site was in an organ that was protected by the lead apron and the dosimeter was worn under the lead apron, the photon dose measured by the dosimeter was assumed to be an accurate measure of the dose received by the organ (i.e., the adjustment factor was 1).

[57] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
If the cancer site was in an organ that was not protected by a lead apron, the adjustment factor of 1.5 was applied regardless of whether the worker wore a lead apron and regardless of whether the dosimeter was worn under or outside of the lead apron. Applying the adjustment factor of 1.5 for any of these circumstances is favorable to claimants.

[58] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although “average” or “routine” activities apply to most radiation exposure scenarios, many workers were involved in one or more radiation incidents during their radiation worker careers. Many of these incidents involved radioactive contamination that was readily cleaned up with little or no dose consequence. However, some incidents involved higher than normal radiation exposures or an uptake of radioactive material and an internal dose. The records for each worker must be carefully reviewed for any evidence of such radiation incidents, and the incidents must be evaluated to produce an accurate dose reconstruction.

[59] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The total person-years of employment at Pantex were divided by 316 claims to give the average of 20.2 years of employment per person.

[60] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The claims associated with 316 workers reported nearly 700 different job titles. Many workers

had more than one job title, and many job titles have changed since Pantex began operations in 1952 to reflect changes in job duties and union negotiations.

[61] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
For each worker, the period of employment begins and ends in a given year. The data points for each year in Figure 6-13 represent the number of workers that were employed during that year. The plot indicates that few workers were employed in the early 1950s and few were still employed after 2000.

[62] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although there were nearly 700 different job titles, many were similar so they could reasonably be grouped into the 15 job categories in Table 6-16. The photon and neutron doses for each worker were summed within the job categories to give the collective photon and neutron doses in Table 6-16. The purpose of this tabulation was to facilitate an analysis of dose distribution in relation to job categories.

[63] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The near equality of collective photon and neutron doses for warehouse operators was unusual, and they were examined in detail to try to determine the cause. A large fraction of the neutron dose was received by a small group (fewer than 10) warehouse operators. One of the job duties of some warehouse operators involved handling pit containers in the pit storage vaults where neutron dose rates were relatively high. It is possible that some extensive operations occurred in pit storage vaults, but records of this were not found.

[64] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although there were nearly 700 different job titles, many were similar so they could reasonably be grouped into the 15 job categories in Table 6-16. The photon and neutron doses for each worker were summed within the job categories to give the collective photon and neutron doses in Table 6-16. The purpose of this tabulation was to facilitate an analysis of dose distribution in relation to job categories. The near equality of collective photon and neutron doses for warehouse operators was unusual, and they were examined in detail to try to determine the cause. A large fraction of the neutron dose was received by a small group (fewer than 10) of warehouse operators. One of the job duties of some warehouse operators involved handling pit containers in the pit storage vaults where neutron dose rates were relatively high. It is possible that some extensive operations occurred in pit storage vaults, but records of this were not found.

[65] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The relatively high collective neutron dose in Figure 6-14 in 1960 was examined in detail to try to determine the cause. Most of the collective neutron dose was recorded for just a few workers. It is possible that these workers were involved in some extensive operations and that the recorded neutron doses were accurate. It is also possible that there was an effort to correct for the known underestimation of neutron doses as measured by NTA films, but no records of such an adjustment were found.

[66] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
There are four primary situations where the recorded dose for Pantex workers might be underestimated: (1) There were a number of workers who were unmonitored before 1989 and who could have been incidentally exposed to radiation. The median photon dose for monitored workers before 1989 should be added to the dose of record. (2) If a cancer site is in an area not protected by a lead apron, an adjustment factor of 1.5 should be applied regardless of whether the worker wore a lead apron and regardless of whether the dosimeter was worn under or outside the lead apron. (3) When a dosimeter reading was less than the

MDL, the dose was recorded as a zero when it could have actually been some nonzero value less than the MDL. All such zero results should be adjusted by adding a value of MDL/2. (4) Before 1994, the neutron dosimeters at Pantex could have underestimated the neutron dose; therefore, all recorded neutron doses from before 1994 are considered unreliable. For this period, neutron doses should be calculated by multiplying the reliable photon dose of record by a neutron-to-photon dose ratio of 1.7.

[67] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Between 1952 and 1957, only a few radiographers were monitored (see Table 6-1). In 1958 and 1959, after sealed pits were introduced, the number of monitored radiation workers increased to just 19 and 22, respectively. Therefore, the collective measured dose for this small group of workers was low in comparison with later periods.

[68] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The recommendation is based on the assumption that unmonitored workers (who were not expected to receive measurable radiation dose) would not likely receive incidental dose in excess of the median measured dose for monitored workers.

[69] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
To apply the same recommendation to unmonitored workers for years before 1960, when there was no measured gamma dose equal to or greater than 40 mrem, the median gamma dose for 1960 should be used.

[70] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Figure 6-12 illustrates the areas of the body that would be protected by a lead apron. If a cancer site is outside the areas protected by a lead apron, the adjustment factor for a lead apron should be used.

[71] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Pantex received its DOELAP certificate on September 1, 1993, indicating successful completion of testing of the 802 TLD system in all beta and photon radiation testing categories and successful completion of testing of the 809/812 TLD system in all beta, photon, and neutron radiation testing categories (personal knowledge). Only DOELAP-accredited dosimeters have been used at Pantex since January 1994.

[72] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The method for recording beta and skin doses changed in 1981. Before 1981, dosimetry records included beta, X-ray or gamma, and neutron doses, and the skin dose was taken to be the beta dose only. In 1981 and after, the skin dose has been calculated as the sum of the beta, gamma, and neutron doses, and the whole-body tritium dose.

[73] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Radiation that results in a whole-body penetrating dose must also pass through the skin. Although the skin dose would probably be less than the whole-body penetrating dose, the assumption that it is equal is favorable to claimants.

[74] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A Panasonic UD-802 TLD with a wrist band has been used for extremity dosimetry since 1980 (BWXT Pantex 2002; ORAUT 2003a).

[75] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A wrist-type TLD dosimeter was used for extremity dosimetry between 1972 and 1980; a wrist-type film badge was used before 1972. The earliest evidence of a nonzero extremity dose

result was from 1964 (ORAUT 2003a). There was no evidence that confirmed the use of extremity dosimeters before 1964.

[76] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
There are numerous examples in the dosimetry records where a worker received a nonzero whole-body dose, but the assigned extremity dosimeters were zero. This scenario suggests the worker wore the whole-body dosimeter but did not take the extremity dosimeter(s) into the workplace. In other examples, a worker received a nonzero whole-body dose and a nearly equal extremity dose. This scenario suggests the worker had both the whole-body and extremity dosimeters in the workplace, but did not wear the extremity dosimeter(s) on the wrists.

[77] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The extremity dose data for 316 Pantex claims were examined, and only 42 claims had extremity doses that were greater than 100 mrem in a given year. The ratios of wrist/extremity dose to whole-body photon dose were calculated, and a lognormal distribution analysis of the ratios showed that the 95th-percentile value of this distribution was approximately 6. This value is consistent with the rule-of-thumb used in operational health physics that if the measured contact dose rate is 6 times (or more) than the measured dose rate at the location of the whole-body dosimeter, extremity dosimeters should be assigned for the work.

[78] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Radiation doses that were measured by film badges were generally reported in units of exposure. Doses measured by TLDs were generally reported in units of deep dose equivalent. NIOSH (2007) recommends the use of the conversion factor from exposure to organ dose for data from film badges. NIOSH (2007) recommends the use of the conversion factor from deep dose equivalent to organ dose for data from TLDs. Film badges were used at Pantex until 1972; TLDs have been used since 1973.

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GLOSSARY

beta dose

Designation (i.e., beta) on some records for external dose from beta and less-energetic X-ray and gamma radiation, often for shallow dose or dose to the lens of the eye.

beta particle (β)

See beta radiation.

beta radiation

Charged particle emitted from some radioactive elements with a mass equal to 1/1,837 that of a proton. A negatively charged beta particle is identical to an electron. A positively charged beta particle is a positron.

bremsstrahlung

Electromagnetic radiation released as a result of inelastic scattering of a moving charged particle within the nucleus of an atom. X-rays produced in a typical medical X-ray tube frequently originate from inelastic scattering of accelerated electrons in the anode material.

curie (Ci)

Traditional unit of radioactivity equal to 37 billion (3.7×10^{10}) becquerels, which is approximately equal to the activity of 1 gram of pure ^{226}Ra.

depleted uranium (DU)

Uranium with a percentage of ^{235}U lower than the 0.7% found in natural uranium. As examples, spent (used) fuel elements, byproduct tails, residues from uranium isotope separation, and some weapons materials contain DU. DU can be blended with highly enriched uranium to make reactor fuel or used as a raw material to produce plutonium. Pantex lists the isotope activity fractions for use in nuclear weapons components as:

Isotope	Activity fraction
^{234}U	0.0840
^{235}U	0.0145
^{238}U	0.9015

dose equivalent (*H*)

In units of rem or sievert, product of absorbed dose in tissue multiplied by a weighting factor and sometimes by other modifying factors to account for the potential for a biological effect from the absorbed dose.

dose of record

(1) Dose records that the U.S. Department of Energy provided to the National Institute for Occupational Safety and Health as part of each worker's file. (2) Individual recorded dose such as that on a dosimetry card or in a dosimetry database.

dosimeter

Device that measures the quantity of received radiation, usually a holder with radiation-absorbing filters and radiation-sensitive inserts packaged to provide a record of absorbed dose received by an individual.

dosimetry

Measurement and calculation of internal and external radiation doses.

dosimetry system

System for assessment of received radiation dose. This includes the fabrication, assignment, and processing of external dosimeters, and/or the collection and analysis of bioassay samples, and the interpretation and documentation of the results.

exchange period (frequency)

Period (weekly, biweekly, monthly, quarterly, etc.) for routine exchange of dosimeters.

exposure

(1) In general, the act of being exposed to ionizing radiation. (2) Measure of the ionization produced by X- and gamma-ray photons in air in units of roentgens.

extremities

Portion of the arm from and including the elbow through the fingertips and the portion of the leg from and including the knee and patella through the toes.

film

In the context of external dosimetry, radiation-sensitive photographic film in a light-tight wrapping. See *film dosimeter*.

film dosimeter

Package of film for measurement of ionizing radiation exposure for personnel monitoring purposes. A film dosimeter can contain two or three films of different sensitivities, and it can contain one or more filters that shield parts of the film from certain types of radiation. When developed, the film has an image caused by radiation measurable with an optical densitometer. Also called film badge.

gamma radiation

Electromagnetic radiation (photons) of short wavelength and high energy (10 kiloelectron-volts to 9 megaelectron-volts) that originates in atomic nuclei and accompanies many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Gamma photons are identical to X-ray photons of high energy; the difference is that X-rays do not originate in the nucleus.

gamma ray, particle, or photon (γ)

See gamma radiation.

gray (Gy)

International System unit of absorbed radiation dose, which is the amount of energy from any type of ionizing radiation deposited in any medium; 1 gray equals 1 joule per kilogram or 100 rads.

highly enriched uranium (HEU)

Uranium enriched to at least 20% ^{235}U for use as fissile material in nuclear weapons components and some reactor fuels. Also called high-enriched uranium. Pantex lists the isotope activity fractions as:

Isotope	Activity fraction
^{234}U	0.9806
^{235}U	0.0194
^{238}U	0.0000

ionizing radiation

Radiation of high enough energy to remove an electron from a struck atom and leave behind a positively charged ion. High enough doses of ionizing radiation can cause cellular damage.

Ionizing particles include alpha particles, beta particles, gamma rays, X-rays, neutrons, high-speed electrons, high-speed protons, photoelectrons, Compton electrons, positron/negatron pairs from photon radiation, and scattered nuclei from fast neutrons. See *alpha radiation*, *beta radiation*, *gamma radiation*, *neutron radiation*, *photon radiation*, and *X-ray radiation*.

minimum detectable activity or amount (MDA)

Smallest amount (activity or mass) of an analyte in a sample that can be detected with a probability β of nondetection (Type II error) while accepting a probability α of erroneously deciding that a positive (nonzero) quantity of analyte is present in an appropriate blank sample (Type I error).

minimum detectable level (MDL)

See minimum detectable activity.

minimum recordable or recording dose (MRD)

See minimum reporting level.

minimum reporting level (MRL)

Level below which an analytical dose is not recorded in the worker's dose record, usually based on a site-specific policy decision. The recording level is not necessarily the same as the minimum detectable amount or activity for that measurement. Also called less-than value, minimum reportable dose, minimum recordable or recording dose, recording level, and reporting level.

neutron (n)

Basic nucleic particle that is electrically neutral with mass slightly greater than that of a proton. There are neutrons in the nuclei of every atom heavier than normal hydrogen.

neutron, fast

Neutron with energy equal or greater than 10 keV.

neutron, thermal

Strictly, neutrons in thermal equilibrium with surroundings; in general, neutrons with energy less than about 0.5 eV.

neutron film dosimeter

Film dosimeter with a nuclear track emulsion, type A, film packet.

nuclear emulsion

Thick photographic coating in which the tracks of various fundamental particles show as black traces after development. The number of tracks in a given area is a measure of the dose from that radiation. See *nuclear track emulsion, type A*.

nuclear track emulsion, type A (NTA)

Film sensitive to fast neutrons made by the Eastman Kodak Company. The developed image has tracks caused by neutrons that become visible under oil immersion with about 1,000-power magnification. The number of tracks in a given area is a measure of the dose from that radiation. Pantex apparently used NTA film at one time to measure alpha radiation from radon progeny in air.

open window

Designation on Pantex film dosimeter reports that implies the use of little (i.e., only security credential) shielding. It commonly is used to label the film response corresponding to the open window area.

personal dose equivalent [*Hp(d)*]

Dose equivalent in units of rem or sievert in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personal dosimetry are 0.07 millimeters (7 milligrams per square centimeter) and 10 millimeters (1,000 milligrams per square centimeter), respectively, for the skin (shallow) and whole-body (deep) doses. These are noted as $H_p(0.07)$ and $H_p(10)$, respectively. The International Commission on Radiological Measurement and Units recommended $H_p(d)$ in 1993 as dose quantity for radiological protection.

photon

Quantum of electromagnetic energy generally regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime. The entire range of electromagnetic radiation that extends in frequency from 10^{23} cycles per second (hertz) to 0 hertz.

photon X-ray

Electromagnetic radiation of energies between 10 keV and 100 keV whose source can be an X-ray machine or radioisotope.

quality factor (Q, QF)

Principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose. The quality factor multiplied by the absorbed dose yields the dose equivalent.

radiation worker

Employee who works on, with, or in the proximity of radiation-producing machines or radioactive materials.

radioactivity

Property possessed by some elements (e.g., uranium) or isotopes (e.g., ^{14}C) of spontaneously emitting energetic particles (electrons or alpha particles) by the disintegration of their atomic nuclei.

rem

Traditional unit of radiation dose equivalent that indicates the biological damage caused by radiation equivalent to that caused by 1 rad of high-penetration X-rays multiplied by a quality factor. The sievert is the International System unit; 1 rem equals 0.01 sievert. The word derives from roentgen equivalent in man; rem is also the plural.

roentgen (R)

Unit of photon (gamma or X-ray) exposure for which the resultant ionization liberates a positive or negative charge equal to 2.58×10^{-4} coulombs per kilogram (or 1 electrostatic unit of electricity per cubic centimeter) of dry air at 0 degrees Celsius and standard atmospheric pressure. An exposure of 1 R is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (generally greater than 100 kiloelectron-volts).

shallow dose equivalent [*Hp(0.07)*]

Dose equivalent in units of rem or sievert at a depth of 0.07 millimeters (7 milligrams per square centimeter) in tissue equal to the sum of the penetrating and nonpenetrating doses.

shielding

Material or obstruction that absorbs ionizing radiation and tends to protect personnel or materials from its effects.

skin dose

See shallow dose equivalent.

thermoluminescence

Property that causes a material to emit light as a result of heat.

thermoluminescent dosimeter (TLD)

Device for measuring radiation dose that consists of a holder containing solid chips of material that, when heated, release the stored energy as light. The measurement of this light provides a measurement of absorbed dose.

U.S. Atomic Energy Commission (AEC)

Federal agency created in 1946 to assume the responsibilities of the Manhattan Engineer District (nuclear weapons) and to manage the development, use, and control of nuclear energy for military and civilian applications. The U.S. Energy Research and Development Administration and the U.S. Nuclear Regulatory Commission assumed separate duties from the AEC in 1974. The U.S. Department of Energy succeeded the U.S. Energy Research and Development Administration in 1979.

whole-body dose

Dose to the entire body excluding the contents of the gastrointestinal tract, urinary bladder, and gall bladder and commonly defined as the absorbed dose at a tissue depth of 10 millimeters (1,000 milligrams per square centimeter). Also called penetrating dose.

X-ray radiation

Electromagnetic radiation (photons) produced by bombardment of atoms by accelerated particles. X-rays are produced by various mechanisms including bremsstrahlung and electron shell transitions within atoms (characteristic X-rays). Once formed, there is no difference between X-rays and gamma rays, but gamma photons originate inside the nucleus of an atom.

ATTACHMENT A
UNMONITORED EXTERNAL DOSE TABLES

LIST OF TABLES

ATTACHMENT A
UNMONITORED EXTERNAL DOSE TABLES (continued)

The following tables were taken from ORAUT-OTIB-0086 (ORAUT 2015) and modified for years for which no data was listed (i.e., years before 1960 and 1983).

ATTACHMENT A
UNMONITORED EXTERNAL DOSE TABLES (continued)

Table A-1. Annual Pantex external photon doses (rem).

Year	GM	GSD	95th percentile	*N*
1952–1960	0.030	2.38	0.127	59
1961	0.040	2.77	0.211	61
1962	0.056	3.10	0.362	57
1963	0.018	4.79	0.240	217
1964	0.112	3.70	0.968	253
1965	0.037	4.31	0.406	416
1966	0.052	3.54	0.416	581
1967	0.057	3.62	0.471	562
1968	0.046	2.90	0.264	423
1969	0.042	3.22	0.289	432
1970	0.076	3.64	0.635	467
1971	0.070	4.05	0.700	495
1972	0.068	3.44	0.515	467
1973	0.125	2.43	0.537	441
1974	0.068	3.40	0.509	500
1975	0.039	2.99	0.237	493
1976	0.045	2.79	0.241	463
1977	0.080	2.15	0.281	465
1978	0.032	4.03	0.318	518
1979	0.087	2.81	0.478	714
1980	0.012	6.28	0.247	772
1981	0.072	4.63	0.900	908
1982	0.044	4.00	0.429	1,002
1983	0.051	3.68	0.431	1,093
1984	0.051	3.68	0.431	1,093
1985	0.043	3.95	0.415	1,172
1986	0.040	3.05	0.253	1,128
1987	0.027	2.83	0.147	1,160
1988	0.032	2.56	0.148	1,121
1989	0.023	3.13	0.151	1,437
1990	0.025	2.58	0.119	2,090
1991	0.027	2.40	0.115	2,126
1992	0.039	2.11	0.134	2,316
1993	0.020	2.27	0.077	2,633
1994	0.010	2.85	0.057	2,978
1995	0.010	2.78	0.056	3,107
1996	0.010	2.82	0.055	3,162
1997	0.009	2.65	0.043	3,000
1998	0.009	2.66	0.046	2,786
1999	0.010	2.57	0.045	2,686
2000	0.009	2.60	0.044	2,642
2001	0.009	2.53	0.042	2,770
2002	0.009	2.62	0.043	2,947
2003	0.009	2.46	0.040	2,996
2004	0.009	2.45	0.038	3,168
2005	0.009	2.44	0.039	3,210
2006	0.009	2.50	0.039	3,237
2007	0.008	2.73	0.040	3,183
2008	0.008	3.03	0.052	2,159
2009	0.009	2.95	0.054	2,110
2010	0.007	3.12	0.047	2,067

ATTACHMENT A
UNMONITORED EXTERNAL DOSE TABLES (continued)

Table A-2. Annual Pantex external neutron doses (rem).

Year	GM	GSD	95th percentile	*N*
1960–1963	0.063	5.66	1.099	284
1964	0.049	4.33	0.542	249
1965	0.020	3.38	0.146	415
1966	0.027	2.63	0.133	581
1967	0.025	2.12	0.085	563
1968	0.026	1.81	0.069	423
1969	0.005	4.83	0.066	66
1970	0.022	1.96	0.066	465
1971	0.024	1.78	0.062	494
1972	0.026	1.67	0.060	464
1973	0.040	1.63	0.090	59
1974	0.052	3.99	0.508	29
1975	0.618	2.61	2.986	54
1976	0.004	4.62	0.044	463
1977	0.003	13.54	0.230	465
1978	0.003	11.51	0.155	518
1979	0.020	5.77	0.364	714
1980	0.003	5.71	0.058	772
1981	0.023	3.44	0.178	908
1982	0.024	3.41	0.182	1,002
1983	0.024	3.41	0.182	1,002
1984	0.020	3.36	0.150	1,093
1985	0.025	4.01	0.241	1,172
1986	0.027	3.50	0.216	1,128
1987	0.019	2.84	0.105	1,160
1988	0.020	2.71	0.100	1,121
1989	0.016	3.10	0.101	1,437
1990	0.017	2.72	0.090	2,090
1991	0.019	2.49	0.084	2,126
1992	0.038	2.68	0.192	2,316
1993	0.033	2.51	0.151	2,633
1994	0.006	2.56	0.030	2,978
1995	0.006	2.56	0.030	3,107
1996	0.006	2.56	0.029	3,162
1997	0.006	2.45	0.024	3,000
1998	0.006	2.35	0.023	2,786
1999	0.006	2.28	0.022	2,686
2000	0.006	2.35	0.023	2,642
2001	0.006	2.35	0.023	2,770
2002	0.006	2.37	0.023	2,947
2003	0.006	2.25	0.021	2,996
2004	0.005	2.27	0.021	3,168
2005	0.006	2.22	0.021	3,210
2006	0.005	2.26	0.021	3,237
2007	0.005	2.45	0.021	3,183
2008	0.005	2.52	0.025	2,159
2009	0.005	2.36	0.022	2,110
2010	0.004	2.60	0.021	2,067

ATTACHMENT A
UNMONITORED EXTERNAL DOSE TABLES (continued)

Table A-3. Annual Pantex external skin doses (rem).

Year	GM	GSD	95th percentile	*N*
1952–1963	0.011	3.72	0.100	230
1964	0.057	1.82	0.152	249
1965	0.037	2.67	0.186	414
1966	0.053	2.00	0.164	579
1967	0.055	1.97	0.168	559
1968	0.061	1.97	0.187	421
1969	0.059	1.79	0.155	393
1970	0.116	2.66	0.582	119
1971	0.139	3.20	0.942	97
1972	0.199	2.95	1.176	83
1973	0.028	3.58	0.231	409
1974	0.022	5.29	0.345	423
1975	0.016	2.78	0.084	483
1976	0.007	5.13	0.097	463
1977	0.008	5.44	0.134	466
1978	0.007	6.27	0.143	519
1979	0.021	4.01	0.207	714
1980	0.027	5.75	0.473	772
1981	0.131	4.71	1.675	908
1982	0.088	4.55	1.057	1,002
1983	0.106	3.83	0.968	1,093
1984	0.106	3.83	0.968	1,093
1985	0.093	4.97	1.296	1,172
1986	0.100	4.22	1.072	1,128
1987	0.059	3.72	0.508	1,160
1988	0.061	3.32	0.435	1,121
1989	0.041	3.34	0.298	1,437
1990	0.040	2.39	0.169	2,090
1991	0.040	2.04	0.130	2,126
1992	0.023	3.46	0.179	2,316
1993	0.012	3.83	0.109	2,633
1994	0.012	2.98	0.072	2,978
1995	0.012	2.92	0.070	3,107
1996	0.012	3.00	0.072	3,162
1997	0.010	2.86	0.058	3,000
1998	0.011	2.84	0.061	2,786
1999	0.011	2.72	0.059	2,686
2000	0.011	2.77	0.058	2,642
2001	0.011	2.68	0.055	2,770
2002	0.011	2.75	0.056	2,947
2003	0.011	2.57	0.051	2,996
2004	0.010	2.57	0.049	3,168
2005	0.010	2.46	0.045	3,210
2006	0.010	2.56	0.048	3,237
2007	0.009	2.80	0.049	3,183
2008	0.010	3.20	0.069	2,159
2009	0.011	2.95	0.063	2,110
2010	0.008	3.21	0.058	2,067