ORAU TEAM
Dose Reconstruction Project for NIOSH

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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
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
HE	high explosive
HERS	Historical Exposure Records System
HEU	highly enriched uranium
Hp(d)	personal dose equivalent at depth *d* (deep dose at 10 mm; shallow at 0.07 mm)
hr	hour
IAAP	Iowa Army Ammunition Plant
IARC	International Agency for Research on Cancer
ICD	International Classification of Diseases
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
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
mR	milliroentgen
mrad	millirad
MRD	minimum recordable dose
mrem	millirem
n	neutron
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
PNL	Pacific Northwest Laboratory

POC	probability of causation
PPD	Pantex Personnel Dosimeter
ROT	rotational
RPG	radiation protection guideline
SRDB Ref ID	Site Research Database Reference Identification (number)
TBD	technical basis document
TLD	thermoluminescent dosimeter
TLD-100	LiF TLD with natural abundance of ^{6}Li and ^{7}Li
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
µg	microgram
§	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 historic background information and guidance to assist in the preparation of dose reconstructions for particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). These documents may be used to assist NIOSH staff in the completion of the individual work required for each dose reconstruction.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility 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 Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define “performance of duty” for DOE employees with a covered cancer or restrict the “duty” to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at covered facilities in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

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[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

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 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 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.

6.2 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. The U.S. Atomic Energy Commission (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 Army Ammunition Plant (IAAP), in 1947; the second was the Pantex Plant in 1951. Pantex was originally a conventional munitions factory loading high explosives into bombs and artillery shells (DOE 1997); it was converted to nuclear weapons work in 1951–1952. 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 obtained from the Pantex Plant and other sources related to radiation doses received by Plant workers 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 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-, and gamma rays, and neutrons;

however, doses to workers depend strongly on the configuration (i.e., material and shielding) of the source of radiation and the work performed (BWXT 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.

External Dose Reconstruction Implementation Guidelines (NIOSH 2006) 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 (Martin 2003b). Early dosimetry practices were based on experience gained during 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 Engineers 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.

6.3 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 (Martin 2003b); comparisons of recorded doses before and after these changes provide the ability to assess consistency. Similar radiation beams 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; the personal dose equivalent is noted as *Hp(0.07).* For penetrating radiation of significance to whole-body dose, *d* = 10 mm; 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 containing 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). Table 6-1 summarizes the average recorded worker dose for each year along with the total collective dose and its neutron and gamma components. At first, Pantex issued dosimeters only to workers likely to receive a radiation dose. From 1952 through 1957, this included only radiographers (Martin 2003a). From 1958 through 1988, only radiation workers were monitored (Martin 2003a). The variations in numbers of radiation workers reflect changes in weapon production rates (Carr 1992). From 1989 to the present, 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 workers monitored 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 non-zero external doses [1]. The increase was probably a result of increased production and increased handling of nuclear components.

Table 6-1. Annual external radiation doses, 1952–2004 (Prather 2004; Martin 2003a).

Year	Total collective dose (person-rem)	Number of workers monitored	Average total dose (rem)	Collective neutron dose (person-rem)	Collective gamma dose (person-rem)
1952	0.00	1	0.00	0.00	0.00
1953	0.00	1	0.00	0.00	0.00
1954	0.00	2	0.00	0.00	0.00
1955	0.00	1	0.00	0.00	0.00
1956	0.00	1	0.00	0.00	0.00
1957	0.02	3	0.01	0.00	0.02
1958	0.09	19	0.005	0.00	0.09
1959	0.35	22	0.02	0.00	0.35
1960	10.35	69	0.15	9.20	1.15
1961	8.74	71	0.12	6.23	2.51
1962	5.27	64	0.08	1.53	3.74
1963	18.20	218	0.08	5.75	12.45
1964	79.91	253	0.32	7.80	72.11
1965	47.41	416	0.11	2.53	44.88
1966	70.46	581	0.12	4.39	66.07
1967	78.33	563	0.14	1.51	76.82
1968	29.64	423	0.07	0.55	29.09
1969	30.84	432	0.07	0.17	30.67
1970	85.46	468	0.18	0.43	85.03
1971	101.42	495	0.21	1.08	100.34
1972	70.84	467	0.15	0.50	70.34
1973	86.35	441	0.20	0.17	86.18
1974	75.61	500	0.15	0.95	74.66
1975	61.89	493	0.13	17.13	44.76
1976	45.77	463	0.10	12.76	33.01
1977	58.08	465	0.12	10.14	47.94
1978	50.46	518	0.10	13.12	37.34
1979	178.91	714	0.25	62.85	116.06
1980	147.52	819	0.18	30.40	117.12
1981	201.19	915	0.22	28.78	172.41
1982	110.76	1,002	0.11	23.31	87.45
1983	103.18	1,027	0.10	24.60	78.58
1984	141.71	1,113	0.13	21.54	120.17
1985	133.56	1,172	0.11	27.87	105.69
1986	85.59	1,129	0.08	20.49	65.10
1987	34.85	1,160	0.03	4.05	30.80
1988	24.98	1,121	0.02	2.74	22.24
1989	33.56	1,438	0.02	3.22	30.34
1990	23.46	2,090	0.01	1.92	21.54
1991	22.31	2,126	0.01	0.23	22.08
1992	50.59	2,317	0.02	15.41	35.18
1993	44.83	2,624	0.02	12.78	32.05

Year	Total collective dose (person-rem)	Number of workers monitored	Average total dose (rem)	Collective neutron dose (person-rem)	Collective gamma dose (person-rem)
1994	28.82	2,978	0.01	6.55	22.27
1995	36.62	3,107	0.01	10.24	26.39
1996	27.62	3,209	0.01	5.79	21.83
1997	10.99	3,120	0.004	2.46	8.54
1998	14.84	2,800	0.01	2.99	11.84
1999	25.59	2,686	0.01	4.39	21.20
2000	34.18	2,766	0.01	6.55	27.63
2001	42.82	2,770	0.02	7.70	35.11
2002	46.87	2,947	0.02	8.93	37.94
2003	35.28	2,996	0.01	5.14	30.15
2004	23.62	3,168	0.01	4.77	18.85

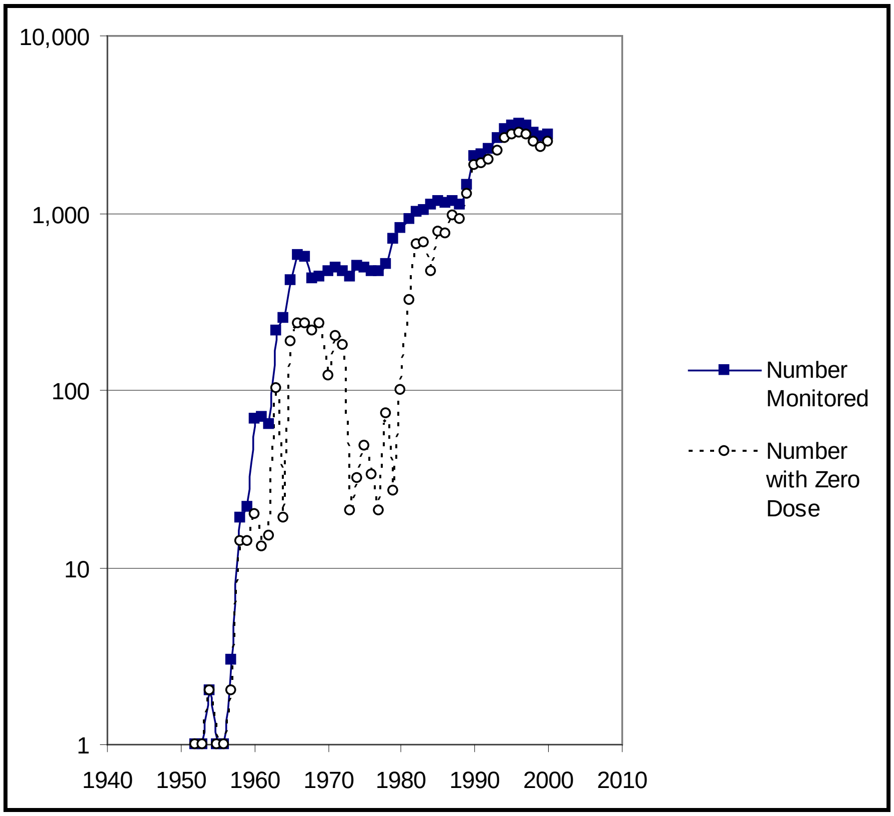


Figure 6-1. Number of workers monitored as a function of time and number of workers with zero recorded annual dose (Martin 2003a).

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.

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)* (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 (Pantex 2002).

Overall, the accuracy and precision of original individual worker doses of record and their comparability to be considered in using NIOSH (2006) guidelines depend on:

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

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

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

- **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 (Martin 2003a, Martin 2003b). Dosimeters used at that time to measure worker radiation doses were contracted from a commercial service. Table 6-2 summarizes the monitoring technique and exchange frequency. The minimum recordable dose (MRD) for nonpenetrating skin and penetrating whole-body dose, as reported by the film badge processor, were initially 30 and 10 mrem, respectively (Tracerlab 1963). Actual minimum detectable levels (MDLs) are typically higher because of additional uncertainty in field use and the use of dose recording thresholds. Table 6-2 lists reasonable MDLs for most applications for film dosimeters based on Wilson (1960, 1987), NIOSH (1993), NRC (1989), and Wilson et al. (1990) and for thermoluminescent dosimeters (TLDs) based on Fix et al. (1982) and Rathbone (2002). MRDs varied with time and processor, as listed in Table 6-2.

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)

Table 6-2. Dosimeter type, period of use, exchange frequency, MRD, and MDL (Martin 2003b).

Dosimeter type/ provider	Period	Exchange frequency[a]	MRD (mrem)			MDL (mrem)		
			Skin	β/γ deep	Neutron	Skin	Deep	Neutron
βγ film/Tracerlab	1/1952–12/1959	Weekly	30[b]	10[b]		40[c]	40[c]	
βγ film and NTA film/ Tracerlab	1/1960–3/1961	Weekly	30[b]	10[b]	15[b]	40[c]	40[c]	(d)
	4/1961–5/1963	Monthly	30[b]	10[b]	15[b]	40[c]	40[c]	(d)
βγ film and NTA film/ Eberline	6/1963–9/1964	Monthly	10[b]	10[b]	10[b]	40[c]	40[c]	(d)
βγ film and NTA film/ Landauer	10/1964–12/1968	2/month	40[b]	10[b]	10[b,e]	40[c]	40[c]	(d)
	1/1969–12/1972	Monthly			20[b,f]			
TLD 2-element/in-house and NTA film/Landauer[g]	1973–1976	Monthly	10	4	10[b,e]	30	30	(d)
TLD 6-element/in-house	1977–1980	Monthly	10	4	50	30	30	50
Panasonic 802/in-house	1980–1991[h]	Monthly	20	20	50	30	30	50
Panasonic 802/in-house	1992–2000[h]	Monthly	15	10	70	30	30	50
		Quarterly	20	15	85	30	30	50
Panasonic 809/812/in-house[i]	1994–present	Monthly	10	10	5[j]	30	30	50
					25[k]			
		Quarterly	15	15	10[j]	30	30	50
					65[k]			

a. Exchange frequencies were established from dosimetry reports. The initial weekly exchange frequency was changed to monthly in March 1961 (Tracerlab 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. Based on minimum doses recorded on dosimetry reports (Tracerlab 1963, Ashton 2003, Adams 2003).
c. Estimated MDL typical of film dosimeter capabilities (Wilson 1960, 1987; NIOSH 1993; NRC 1989; Wilson et al. 1990).
d. For years of NTA film use, before 1977, the reconstructed neutron dose is calculated using the adjusted photon dose and a neutron-to-photon dose ratio.
e. MRD for thermal neutrons (Adams 2003).
f. MRD for fast neutrons (greater than 1 MeV) (Adams 2003).
g. 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.
h. In 1992, the algorithms were changed for the Panasonic 802 to the Stanford algorithms (Pantex 2002). The dosimeter exchange frequency for non-radiation workers was changed from monthly to quarterly in 1992.
i. 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.
j. DOELAP performance testing with moderated ^{252}Cf neutrons.
k. DOELAP performance testing with unmoderated ^{252}Cf neutrons.

- 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)
- 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/year [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 reflecting the results of the investigation (Martin 2003a). 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 described by Watson et al. (1994) and based on examination of continuity in worker job activities, or by using recommended methods described 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 encountered in the workplace. The adequacy of dosimetry methods to measure radiation dose accurately, as discussed in later sections, depends on radiation type, energy, exposure geometry, etc. (BWXT 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 (ICRP 1950). Table 6-2 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 supplied by Tracerlab for measuring beta, X-ray, and gamma exposures (Tracerlab 1963). Beginning in 1960, Pantex used a multielement film badge that incorporated NTA film to measure beta, X-ray, gamma, and fast neutrons (Tracerlab 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 (Landauer 1976, 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, Martin 2003b). 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 (Pantex 2002). The UD-802 was used for all other workers until it was phased out in 2001. All Pantex workers who enter radiologically controlled areas have been monitored with the UD-809/UD-812 TLD since 2001 (Martin 2003a).

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* (Pantex 2002). The MRDs are not necessarily equivalent to the MDL or lower limit of detection (L_D) described in NIOSH (2006) or in the DOELAP Standard (DOE 1986). Dosimeter readings indicating 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 6-2 lists MRDs of dosimeters used at the Pantex Plant to monitor for beta/gamma skin and deep doses, and neutron 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 2006c) and thermoluminescent (ORAUT 2006a) 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 2006d) 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 (compared 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.

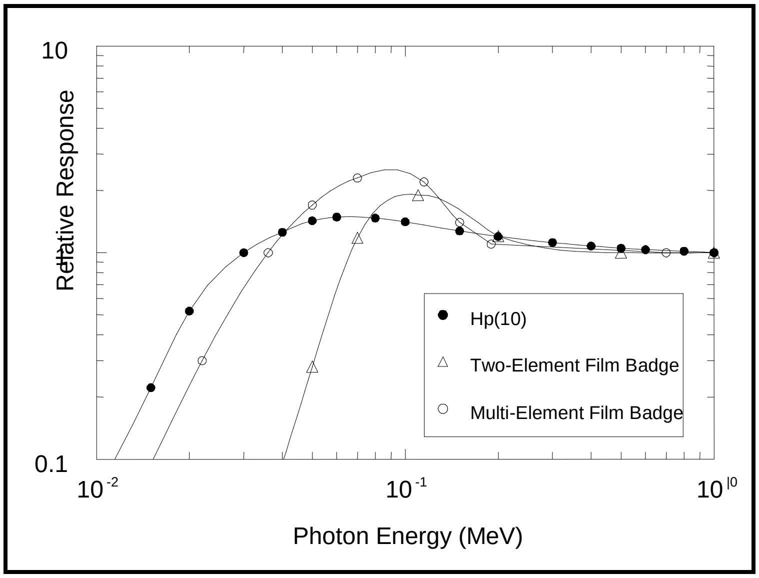


Figure 6-2. Comparison of *Hp(10)* for photons with energy responses for sensitive DuPont 502 emulsion in MED two-element film badge (Pardue, Goldstein, and Wollan 1944) and sensitive DuPont 555 emulsion in Oak Ridge National Laboratory multielement film badge (Thornton, Davis, and Gupton 1961).

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 atomic number (*Z*) of the lithium (3) and fluorine (9) in the chips (Horowitz 1984; Cameron, Sunthanalingham, and Kennedy 1968). The two-element TLD badges used at Pantex from 1973 to 1976 had LiF (TLD-700) chips 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 (Martin 2003b, Alexander, Hess, and Canada 1973). The six-element TLD badges adopted for use in 1977 were patterned after a Sandia design (DOE 1980; Martin 2003b). Figure 6-3 shows the TLD holder, chips, and filters. The open window used for measuring skin dose was covered by a 7-mg/cm^2 polyester 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.

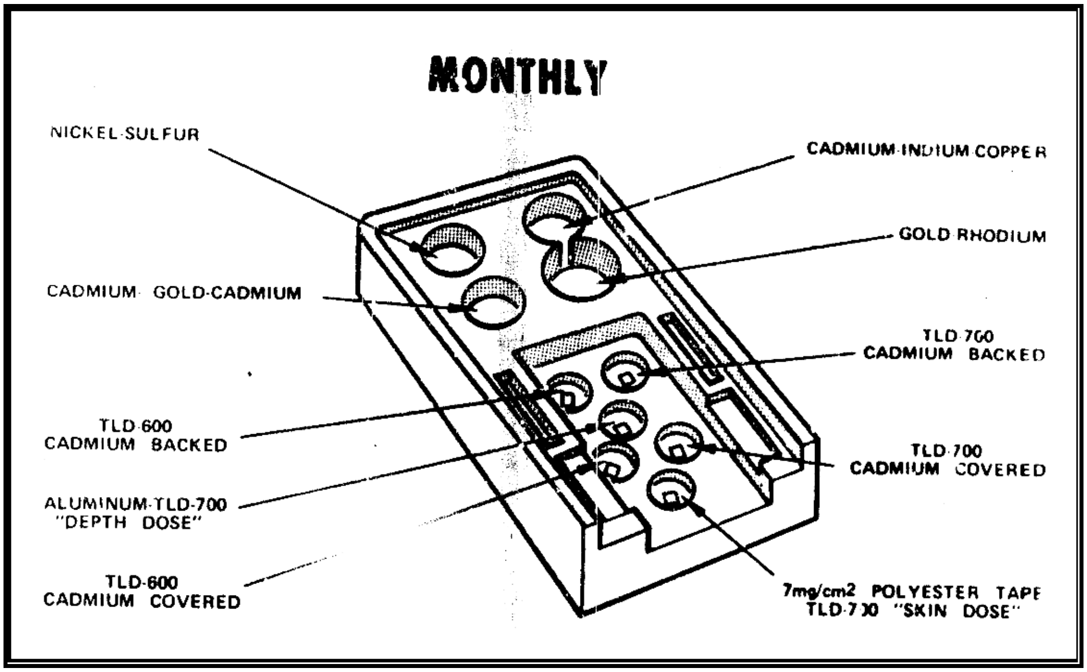


Figure 6-3. Six-element TLD holder (DOE 1980).

The first commercial TLD badge, implemented at Pantex in 1980, was the multielement Panasonic Model UD-802 (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, providing 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 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, reducing 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 radiation categories tested, 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 (Pantex 2002).

Table 6-3. UD-802 dosimeter characteristics (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 (Pantex 2002, Martin 2003a). 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.

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

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

The UD-809 TLD was designed for determination of neutron dose (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 $^{7}Li_2{}^{11}B_4O_7$ 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 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 Table 6-1 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 (Martin 2003a).

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

Geometry	Phantom	118 keV		208 keV		662 keV	
		Mean[a]	SD/Mean[b]	Mean[a]	SD/Mean[b]	Mean[a]	SD/Mean[b]
US-2 (Two-element film dosimeter)							
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)							
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)							
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.

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 used 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 used at the Pantex Plant differ significantly in their response to neutrons of different energies, as shown in Figure 6-4 (IAEA 1990). NTA film was included in the holder used for the Pantex beta/gamma dosimeter from 1960 through 1976 (Martin 2003b). 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 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 (PNL 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 (Pantex 2002). The performance of the UD-802 for measuring neutron doses was

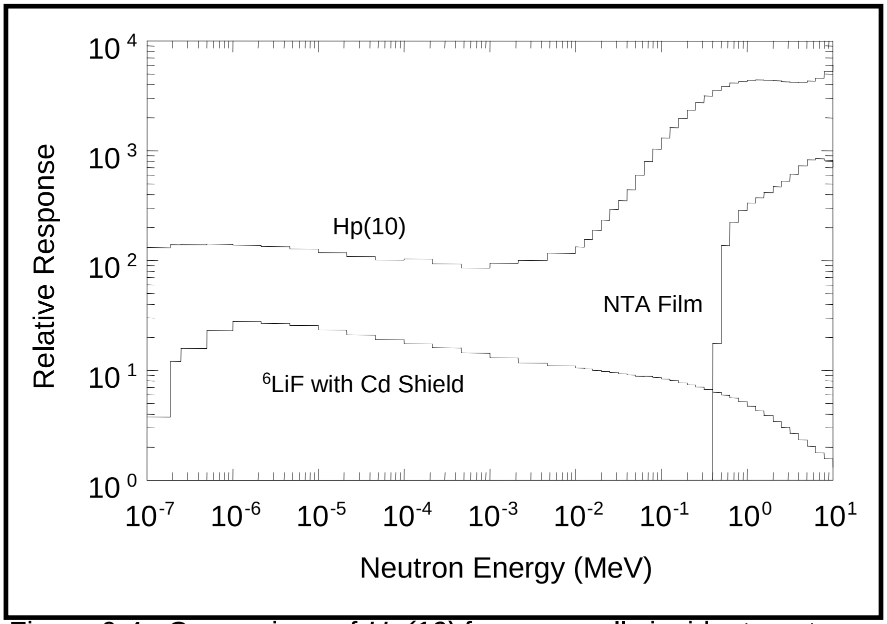


Figure 6-4. Comparison of *Hp(10)* from normally incident neutrons to energy responses of NTA film and neutron albedo dosimeter containing neutron TLD chip made of ^{6}LiF and shielded by cadmium (IAEA 1990).

improved in 1992 and 1993 when the Stanford algorithm was applied (Stanford 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 (Pantex 2002).

Neutron doses measured with the Panasonic UD-809/UD-812 dosimeter system were much improved. Neutron doses determined by means of the Stanford algorithm (Stanford 1994) are likely to be accurate based on DOELAP performance testing results and workplace validation studies (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 are only limited and incomplete Pantex studies comparing 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 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 (i.e., 40 and 70 keV) photon energies. 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 (compared to the photon dose) implies a significantly increased neutron dose fraction after 1977 when TLDs were used. However, the ratio between neutron and photon doses is significantly variable, particularly before the mid-1980s [9].

Table 6-6. Ratio of neutron-to-photon cumulative dose.[a]

Dosimeter technology	Cumulative dose (person-rem)		Ratio[b]
	Neutron	Photon	
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. Data from Table 6-1.
b. Rounded to three significant figures.

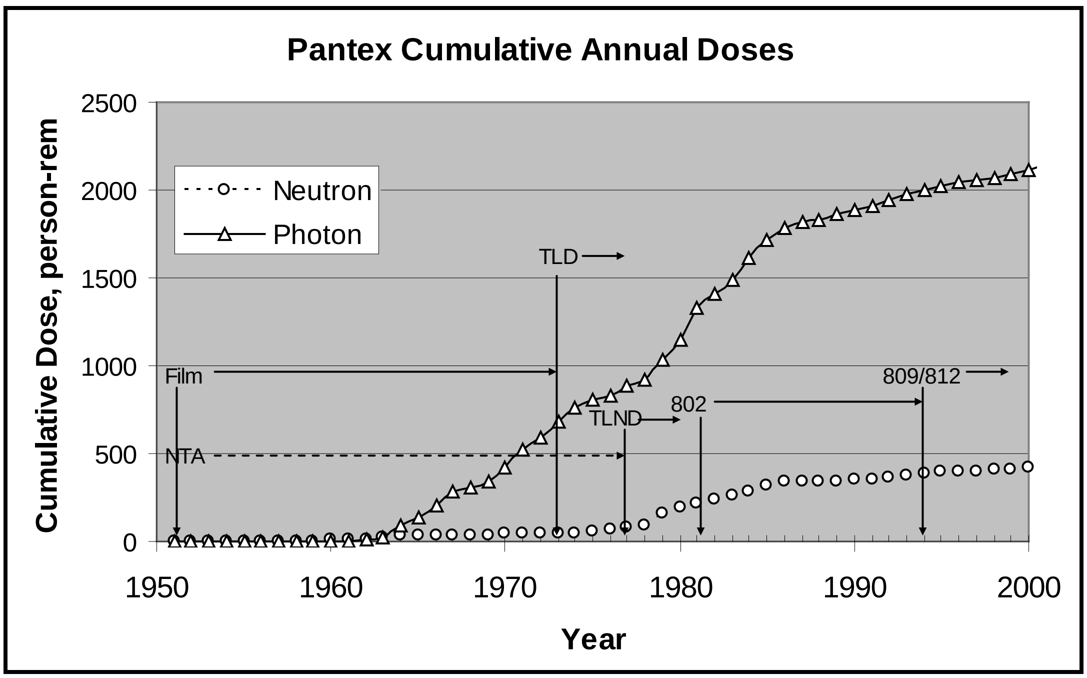


Figure 6-5. Cumulative plot of annual photon and neutron recorded dose (from data in Table 6-1). Source: Prather (2004; Martin 2003a).

6.5.3 Dosimeter Calibration Procedures

Potential error in doses of record depends on the methods used to calibrate dosimeters and the extent of the similarity between the radiation fields used for calibration and those encountered 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, with exposure measured by Victoreen R chambers (Pantex 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 (Martin 2003b). Similar calibration procedures were used with the development and operation of the in-house film and TLD systems between 1973 and 1980 (see Table 6-2). Table 6-7 lists sources of bias in the calibration parameters for beta/photon dosimeters.

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 would relate 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 (Pantex 2002).
b. Dose of record compared to *Hp(10)*.

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 (Pantex 2002).

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 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 (Martin 2003b). 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)*.

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 (Pantex 2002).
b. Dose of record compared to *Hp(10)*.

6.5.4 <u>Workplace Radiation Fields</u>

The main workplace radiation fields at Pantex arise from the handling of nuclear weapons components containing plutonium, thorium, and highly enriched uranium (HEU) and their radioactive progeny, as well as 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-rays 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 processes used in the preparation, design, and construction of the weapons [13].

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 (Pantex 2002). Radiation fields were measured with TLDs positioned on a polymethylmethacrylate phantom and exposed under controlled conditions. The radiation fields were also characterized with several instruments used to measure the photon, neutron, and beta dose rates. Each weapon program characterized was measured in each of four configurations: full weapon, physics package, bare pit, and pit in storage container (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) (Pantex 2002). The appropriate correction factors were chosen based on gamma spectroscopy measurements made during the field measurements. Beta dose rates were measured with a Victoreen 450BE instrument with an open window (Pantex 2002). Neutron dose rates were measured with tissue-equivalent proportional counters and multisphere measurements were analyzed to characterize the neutron spectra (Pantex 2002).

The predominant source of radiation dose at Pantex is photons from ^{241}Am, with the 60-keV photon being the most significant (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 depleted uranium and thorium (Pantex 2002). Total dose rates in the workplace are generally low, less than 10 mrem/hr, unless very close work is being performed (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 following testing. An important progeny nuclide 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* produced in high-*Z* materials from 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 could contribute to extremity and skin dose to workers unless precautions were taken to protect workers from the radiation. Protective clothing and gloves provide a protection factor of 2 or more, depending on the thickness (DOE 2000). A bare slab source of DU contributes an *Hp(0.07)* dose of approximately 200 mrad/hr at the surface (BRH 1970) compared to an *Hp(10)* dose of approximately 2 mrad/hr (ORAUT 2004a). However, significant beta exposures to Pantex workers were rarely detected by film badges or TLDs, based on a review of shallow and deep dosimetry data [15].

6.5.4.2 Photon Radiation

Photon radiations encountered at Pantex have widely varying energies, ranging from about 30 keV to a few MeV [16]. Sources of photon radiation have included weapon components, analytical devices employing X-rays produced by 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 typically used by mainstream industrial or process-related users [18]. Doses associated with 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 yr. The ^{241}Am, which emits 60-keV photons, reaches a maximum activity after about 80 yr, but it reaches about 85% of this maximum in 40 yr [20]. Thus, 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 and Baalman 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 yr. The half-life of ^{228}Th is 1.9 yr, 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 yr, and rise to nearly complete equilibrium after 20 yr (Stannard and Baalman 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 (Los Alamos 2003). 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 shown 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.

A linear vertical axis in Figures 6-7 and 6-8 shows 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 (particularly lower energy) radiation (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 attributed to the 60-keV photons from ^{241}Am (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

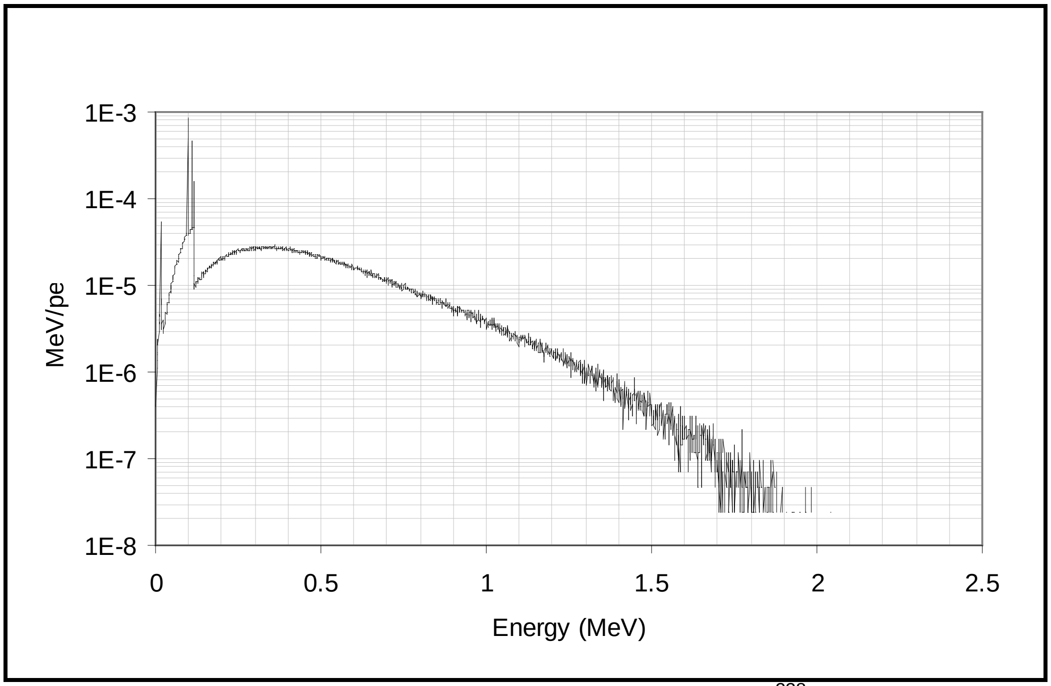


Figure 6-6. MCNP-calculated photon spectra emitted from ^{238}U as excited by ^{234m}Pa beta in ^{238}U spheres. Source: Calculations made using Los Alamos 2003.

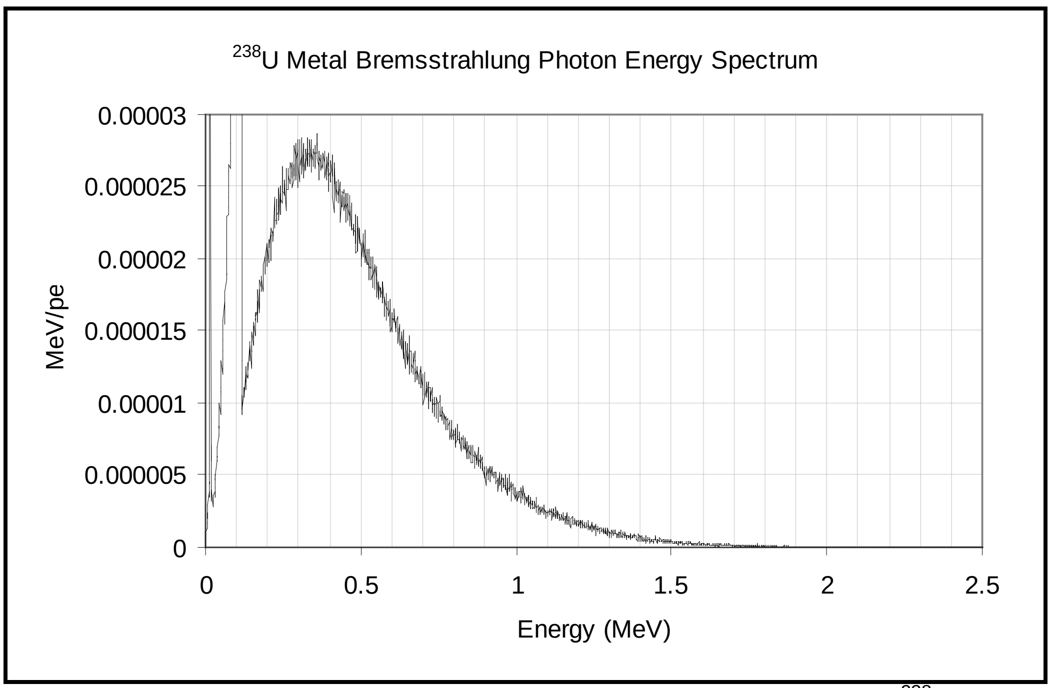


Figure 6-7. *Bremsstrahlung* component of calculated spectrum from ^{238}U spheres on linear vertical axis. Source: Calculations made using Los Alamos 2003.

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 (neutron, gamma) ^{2}H interactions caused by neutron radiation scattering (i.e., moderation) and absorption in the hydrogen-

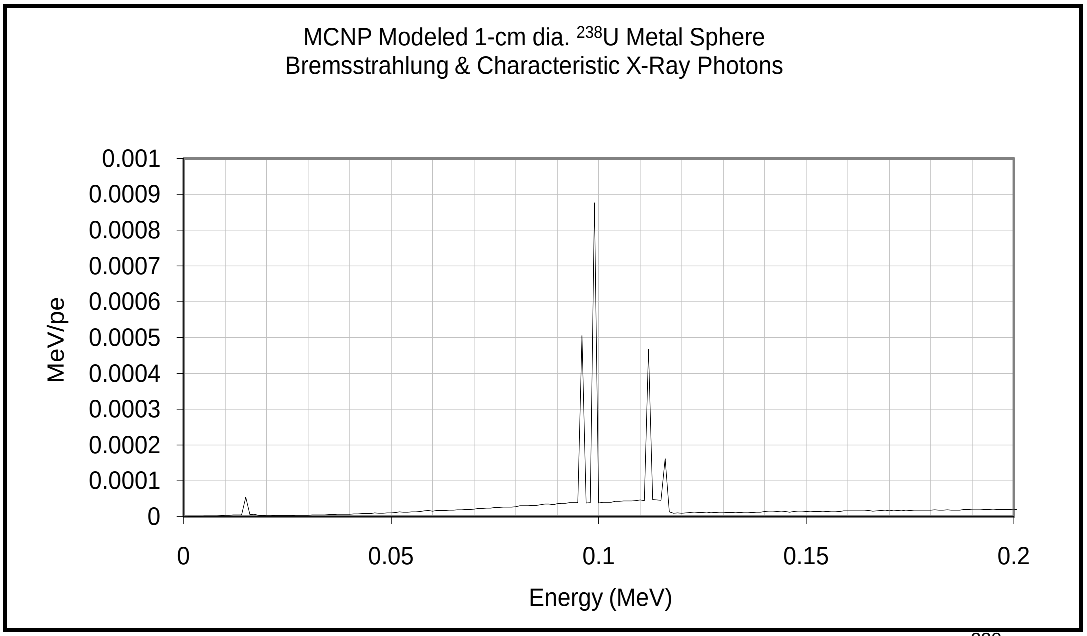


Figure 6-8. Characteristic X-ray component of calculated spectrum from ^{238}U spheres on linear vertical axis. Source: Calculations made using Los Alamos 2003.

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.

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 30-250 keV range [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 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 high explosives are referred to as “bare pits,” although all pits are sealed or encapsulated (Shipler 2004). Assembly and disassembly operations that occur in cells comprise the only times workers have been exposed to neutrons emanating 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 energy. 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 (Pantex 2002).

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

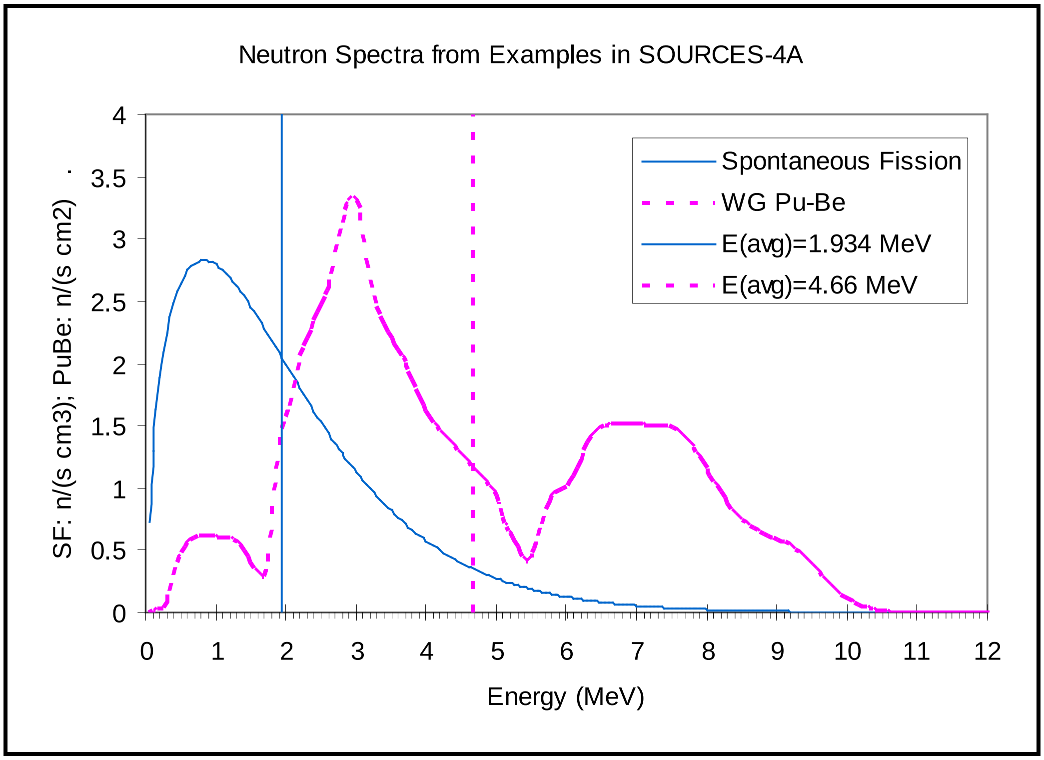


Figure 6-9. Unmoderated neutron spectra calculated by SOURCES-4A (Wilson et al. 1999).

approximately 30 cm [28]. Lead aprons or other shielding has been used to reduce photon dose rates. In other assembly or disassembly operations, where high explosives (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 2006). Radiation fields (beta/photon and neutron) characteristic of Pantex facilities can be generally defined based on historical information on processes, locations, operating periods, and radioactive materials in each, as listed in Table 6-9.

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 6-2). Three companies provided dosimetry services during this period; the services and dosimeters were essentially the same [30]. 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).

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]
		1958-2005	Tritium	Beta	<15 keV	100[c]
		1958-2005	Plutonium, HEU	Photons	30-250 keV	100
				Neutrons	0.1-2 MeV	100[d]
		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]
		1958-2005	Tritium	Beta	<15 keV	100[c]

a. Workplace beta radiation has energy greater than 15 keV [31].

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 [32].

c. Beta particles from tritium are classified in the "less-than-15-keV" category [33].

d. The energy of neutrons in the workplace is predominately in one of two ranges: Between 0.1 and 2 MeV or between 2 and 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 [34].

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 progeny nuclides 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 [35].

The AEC tested film badges provided by Tracerlab (AEC 1955) with exposures to 40-, 70-, and 210-keV X-rays and ^{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, combined with the data from Figure 6-2 and the pattern in recorded doses with progressively more sophisticated dosimetry systems, leads to the conclusion that photon doses measured at Pantex by film badges 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 (Pantex 2002).
b. Dose of record compared to *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 elements of the dosimeter used to measure the whole-body (deep) dose, *Hp(10)* (see Figure 6-3).

The Panasonic UD-802 system used 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 (NIOSH 2005).

6.5.5.3 Neutron Dosimeter Response

Tracerlab provided NTA film dosimetry service from 1958 through April 1963 (Martin 2003a). 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 2006d).

Table 6-11. Typical workplace neutron dosimeter performance (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 with increasing exposure angle 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 compared to *Hp(10).*

The six-element, in-house TLD system used from 1977 to 1980 responded well to thermal neutrons but under-responded to neutrons with energies above about 10 keV (PNL 1977). Thus, 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 a moderated ^{252}Cf source. These measurements showed that the UD-802 significantly under-responded to fast neutrons. Therefore, neutron doses measured by the UD-802 between 1980 and 1993 are likely to be underestimated.

In summary, all neutron dosimeters used at Pantex prior to 1994 underestimated actual neutron doses. The neutron doses of record are unreliable and should not be used by dose reconstructors [44].

DOELAP accredited the Panasonic UD-809/UD-812 TLD system in 1993 for all neutron categories applicable at Pantex. Neutron doses measured at Pantex since 1994 are reliable and dose reconstructors should use the dose of record [45].

6.5.5.4 Neutron-to-Photon Dose Ratios

There have been many measurements of neutron and photon spectra and dose ratios for specific facilities, weapon components, and operations at the Pantex Plant. However, details of this information are classified, other than the general statement that the instrument-measured dose ratios are less than the dosimeter-measured ratios. Assessments of neutron-to-photon dose ratios have been based on general information and measurements conducted at the Plant and at similar facilities and operations elsewhere in the DOE complex [46]. Table 6-1 lists collective total, photon, and neutron doses as well as the average total dose to monitored workers for the entire period of operation. The annual average percentages of the total dose due to neutrons for the periods of operation with positive recorded neutron dose from 1960 through 1993 and from 1994 through 2004 (with the 809/812 accredited system) from Table 6-1 are 19% and 26%, respectively [47]. However, these ratios are not directly applicable to claimants because they are derived from collective doses [48]. They do not take into account the “diluting” effect of numerous workers who had photon doses only [49].

Neutron-to-photon dose ratios were calculated from Pantex post-1993 dosimeter data. Data were provided by Pantex (Prather 2004) on all photon and neutron recorded doses (measured by the 809/812 TLDs) from 1994-2004. These data were analyzed by Strom (2004) and the neutron-to-photon dose ratios were determined where the neutron and photon doses were equal or greater than 50 mrem/yr. A log-probability plot of the grouped neutron-to-photon dose ratios is shown in Figure 6-10. The median ratio is 0.7915 (rounded to 0.8), standard deviation is 1.6, and the 95th-percentile ratio from this distribution is 1.72 (rounded to 1.7). These data represent radiation workers who were exposed to both photons and neutrons emitted from nuclear weapon components, primarily bare pits [50]. During operations with bare pits, radiation workers routinely wear lead aprons that are very effective (greater than 99%) in shielding the workers from lower energy photons, including 60-keV photons from ^{241}Am (Shleien and Terpilak 1984). Procedures in use during this period require the wearing of lead aprons, and their use has been enforced by management [51]. Thus, the dosimeter data for 1994 to 2004 includes very little contribution from lower energy (i.e., ^{241}Am) photons [52].

To reliably apply a 95th-percentile neutron-to-photon dose ratio of 1.7 to earlier periods, such as assembly operations in the 1960s, it must be shown that even higher ratios did not exist. Assembly operations in this period would have involved new pits with very little ^{241}Am ingrowth (DOE 1998), and lead aprons probably were not routinely used [53]. The neutron and photon fields around new pits would have been very similar to the fields experienced between 1993 and 2004 when radiation workers did wear lead aprons that attenuated essentially all lower energy photons [54].

During other periods when disassembly of aged weapons was conducted, the contribution of ^{241}Am photons (Traub, Sherpelz, and Taulbee 2005) to the total photon dose would have been larger and lead aprons might not have been worn. Under these conditions, the photon doses would have been

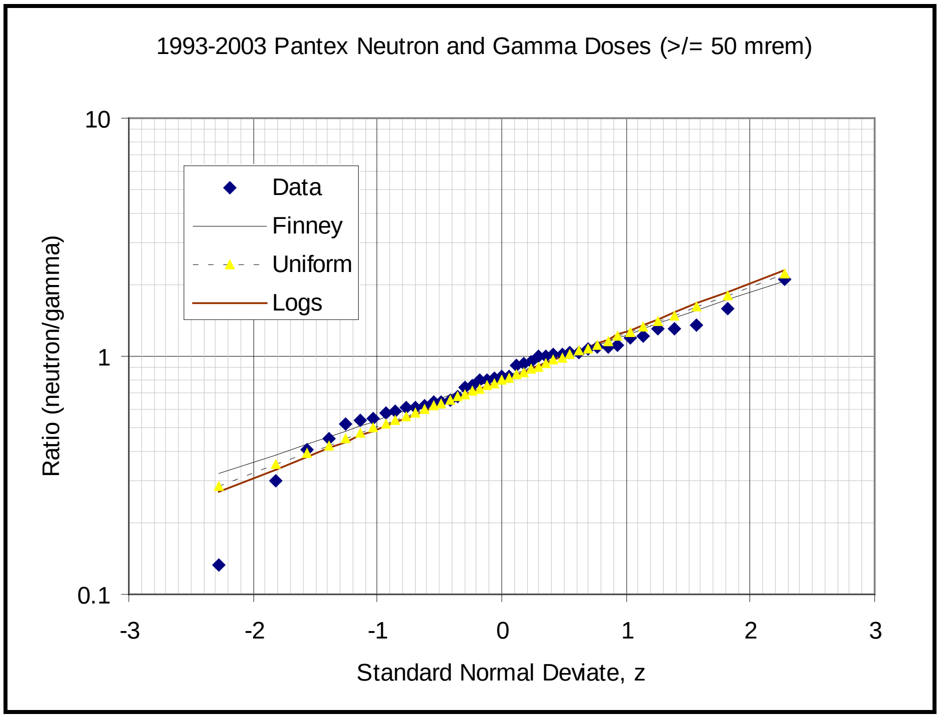


Figure 6-10. Log-probability plot of grouped neutron-to-photon dose ratios. Source: Strom 2004.

higher and the neutron-to-photon dose ratio would have been lower than that experienced with new pits. If lead aprons were worn, the ratio of neutron-to-photon dose would have been similar to those experienced during the 1994-2004 period [55].

Although the annual neutron-to-photon dose ratios have varied over the decades, the pre-1994 annual neutron-to-photon dose ratio should be bounded by the 95th-percentile value of 1.7 derived from the analysis of data from DOELAP-accredited dosimeters, with few exceptions [56]. The neutron-to-photon dose ratio of 1.7 provides a favorable to claimant method for reconstructing neutron doses over a worker's entire career at Pantex [57]. For the years when the measured neutron and photon dose exceeds a ratio of 1.7, the higher measured dose ratios should be used. For comparison, neutron-to-photon dose ratios determined at Los Alamos National Laboratory (ORAUT 2007) and Rocky Flats (ORAUT 2004b) for similar exposure scenarios are 1.4 to 1.8 and 1.79, respectively.

The definition of the 95th-percentile value means that 5% of the data exceeds the 95th-percentile value. In fact, an examination of the claimant data revealed that dosimetry records for four claimants included neutron-to-photon dose ratios greater than 1.7 in some years [58]. In these few cases, the actual recorded neutron and photon doses (and higher neutron-to-photon dose ratios) should be used to calculate the neutron dose in the respective years. In all other years when the neutron-to-photon dose ratio is less than 1.7, a favorable to claimant neutron dose should be calculated by multiplying the photon dose by 1.7.

Neutron doses at Pantex have been monitored reliably with the Panasonic 809/812 dosimeter since late 1993; however, neutron dosimeters used at Pantex prior to 809/812 TLDs generally underestimated neutron doses to some degree. The neutron doses of record measured prior to the 809/812 TLDs are unreliable and should not be used by dose reconstructors, unless the neutron-to-photon dose ratio exceeds 1.7 [59]. All photon doses of record (with appropriate corrections for lead apron use and dosimeter response uncertainty) were reliably detected and can be used with a neutron-to-photon dose ratio to calculate favorable to claimant neutron doses for years prior to 1994 [60].

Pantex radiation workers have accumulated photon doses from a variety of workplace radiation sources, including full weapon assemblies, partially shielded pits, and bare pits. Workplace measurements have shown that most neutron doses were received during the handling of bare pits [61]. The application of a neutron-to-photon dose ratio of 1.7 to the photon dose of radiation workers assumes that all photon dose received was accompanied by a conservatively high estimate of the neutron dose associated with handling bare pits [62].

Unmonitored workers at Pantex, who by today's standards would be monitored, might have been exposed to low levels of photon and neutron doses. Photon doses to unmonitored workers can be estimated from the median photon doses for radiation workers listed in Table 6-17. A neutron dose can be derived from the median value of neutron-to-photon dose ratios determined by Strom (2004). This value of 0.8 applied to the median photon dose for radiation workers will provide a favorable to claimant estimate of the calculated neutron dose to unmonitored workers. The sum of the median photon dose and the calculated median neutron dose will provide a favorable to claimant total dose estimate for unmonitored workers [63].

6.5.5.5 Neutron Dose Weighting Factor

An adjustment to the neutron dose is necessary to account for the change in neutron quality factors between historic and current scientific guidance, as discussed in NIOSH (2006). 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 Publication 21 (ICRP 1973) and National Council on Radiological Protection and Measurements 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 Laboratory 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 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 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 lists average quality factors for the four energy groups used to input dose to the Interactive RadioEpidemiological Program (IREP) computer code, 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:

$$C_f(E_n) = \frac{w_R(E_n)}{Q_{\text{avg}}(E_n)} \times D_f(E_n) \qquad \text{(ORAUT 2006e)}$$

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

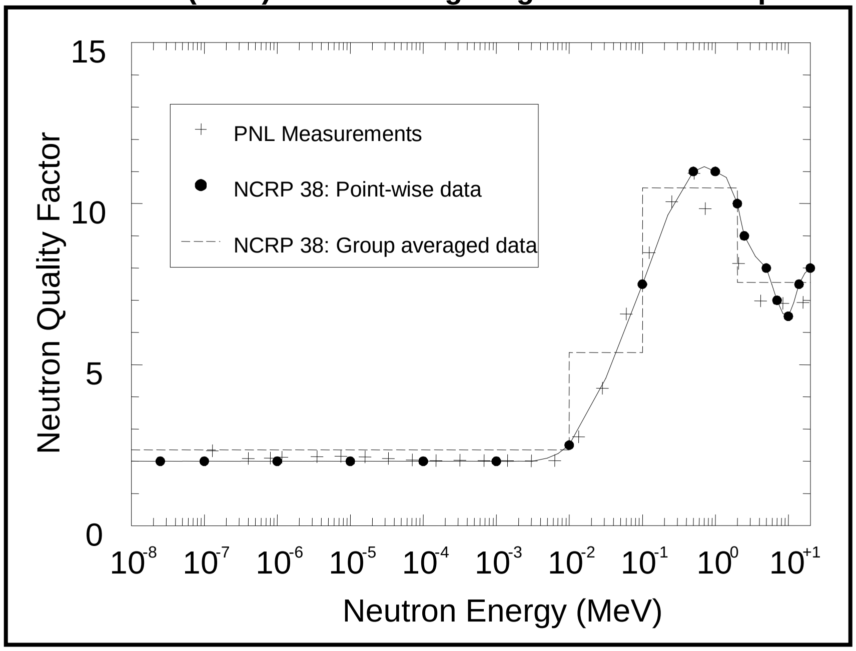


Figure 6-11. Comparison of neutron quality factors used in PNL neutron spectrum measurements (Soldat et al 1990) and neutron quality factors from NCRP (1971), shown as point-wise data and grouped averaged data over four neutron energy groups used in dose reconstruction for Y-12 Plant workers.

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			
10 keV–100 keV		5.38	10	1.86
100 keV–2 MeV		10.49	20	1.91
2 MeV–14 MeV		7.56	10	1.32
14 MeV–60 MeV		Not applicable	5	

a. First Tripartite Conference in 1949 (Warren et al. 1949, Fix, Gilbert, and Baumgartner 1994).
b. ORAUT (2006b).

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 prior to 1994 using the ICRP (1991) correction factor from Table 6-13.

Table 6-13. Neutron dose energies, percentages, and associated correction factors.

Process	Description/ buildings	Neutron energy (MeV)	Default dose fraction[a] (%)	Correction Factor from Table 6-12
Nuclear weapons	Neutron exposure associated with weapons assembly and disassembly activities			

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 thus favorable to claimants.

6.5.5.6 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 [64]. Monitored radiation doses for radiographers in the early years were usually zero [65]. In the late 1950s, when work with pits began, there were higher measured photon radiation doses and workers began wearing lead aprons [66]. However, the use of lead aprons was not included in procedures until the mid-1980s [67]. 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" (Pantex 2002). However, there was no enforcement to ensure that dosimeters were worn under the apron [68].

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 worker's 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 typically covered by a lead apron (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 were done by putting a dosimeter on the front of a phantom positioned in an aisle way 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 it included the 2.2-MeV photons generated when a thermal neutron is captured by hydrogen [69]. This exposure scenario was chosen to represent the radiation fields where lead aprons were least effective in reducing photon dose [70]. 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.

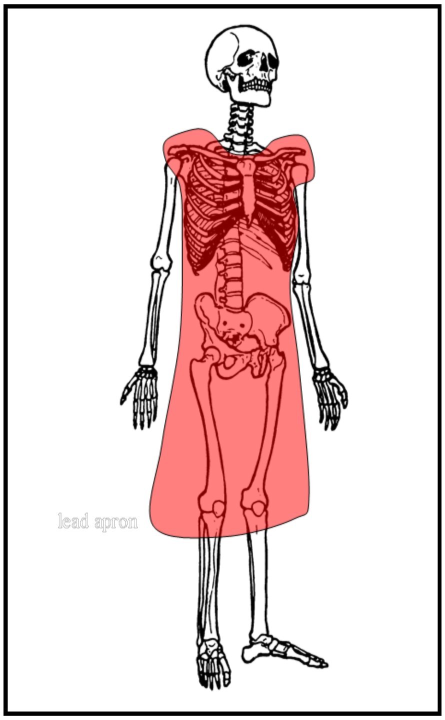


Figure 6-12. Body areas covered by lead apron (skeletal figure from Memmler and Rada 1970).

Production Technicians, Material Handlers, Radiography Technicians, and Quality Control Technicians routinely wore aprons during work in the 1980s and 1990s, and perhaps earlier [71]. More recently, the use of lead aprons has been required by procedure and enforced by management. Production Technicians and Material Handlers in facilities containing plutonium generally wore aprons [72]. 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 [73]. 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 [74].

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.

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

ICD-9 code	Cancer description	Cancer site[a]
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
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.

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 is applied, regardless of the location of the dosimeter [75].

6.6 ANALYSIS OF CLAIMS FILED BY PANTEX WORKERS

An analysis of job titles, worker classifications, and external dose parameters reported in Pantex claims was done to better determine dose reconstruction recommendations. There are three primary sources of information in each claim that provide information of interest used to reconstruct external dose: (1) DOL claim documentation, (2) DOE medical X-ray, dosimetry, and incident archive records, and (3) records of interviews with claimant 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 [76].

6.6.1 Years with a Claim

A sample of 316 claims filed with the U.S. Department of Labor (DOL) by Pantex workers was analyzed to examine trends in the data. These claims were assembled in a database with one line of data for each year of employment for each claimant. Information for claimants that had more than one job title in a given year is presented in extra 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 claimants was 20.2 years [77]. 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.

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 claimants. 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 claimants during the years of employment [78]. Similar job titles were grouped into the assigned job titles listed in Table 6-16, and collective photon and

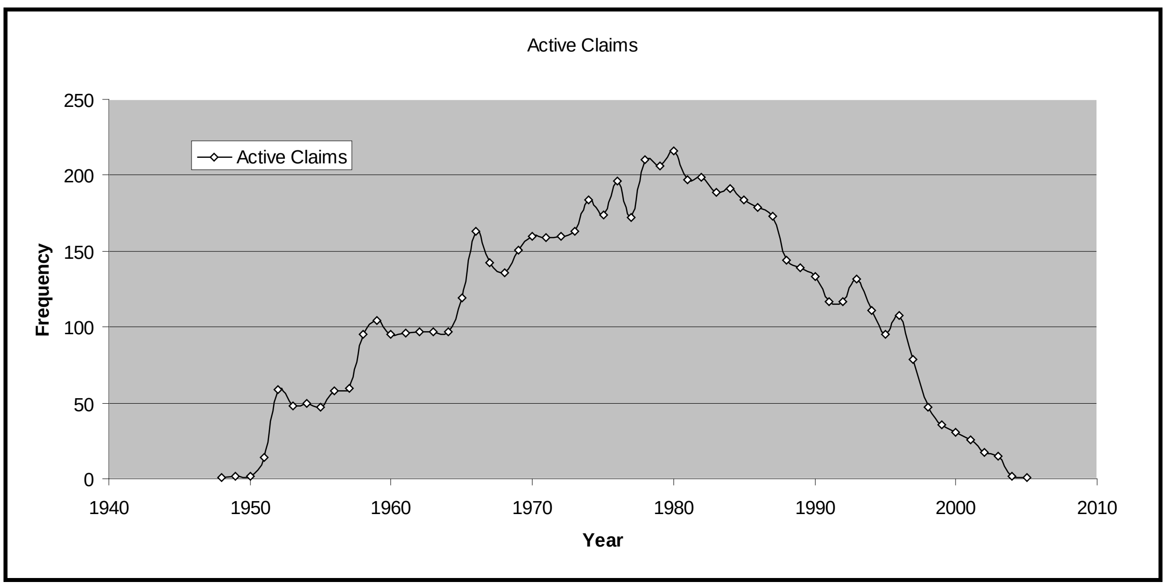


Figure 6-13. Frequency distribution of claims that encompass the respective years [79].

neutron doses were tabulated to examine the dose distribution with respect to job titles [80]. 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 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 [81].

Table 6-16. General categories of job titles for Pantex claimants and recorded doses [82].

Assigned job titles	Collective photon dose person-mrem		Collective neutron dose person-mrem	
	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		38,414	

6.6.3 Analysis of Recorded Doses

Radiation doses were examined for these claimants for years prior to March 1989, when monitoring began for all employees. A total of 1,754 lines of data showed recorded doses (including zeros) for monitored workers representing about 27% of the database. A total of 3,577 lines of data had no recorded doses (blank) representing unmonitored workers, which comprised about 56% of the database. The remaining 1,065 lines of data represent workers who were monitored after March 1989 and account for about 17% of the database. Overall, about 44% of the records contained results (including zeroes) of dose monitoring (i.e., a total of 2,819 lines calculated as the sum of 1,754 and 1,065 lines of data, respectively, from before and after March 1989). Further analysis of monitored claimant data (2,819 lines) showed that about 48% had non-zero 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 five workers (three identified as warehouse operators, one assembler, and one inspection foreman) [83]. 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.

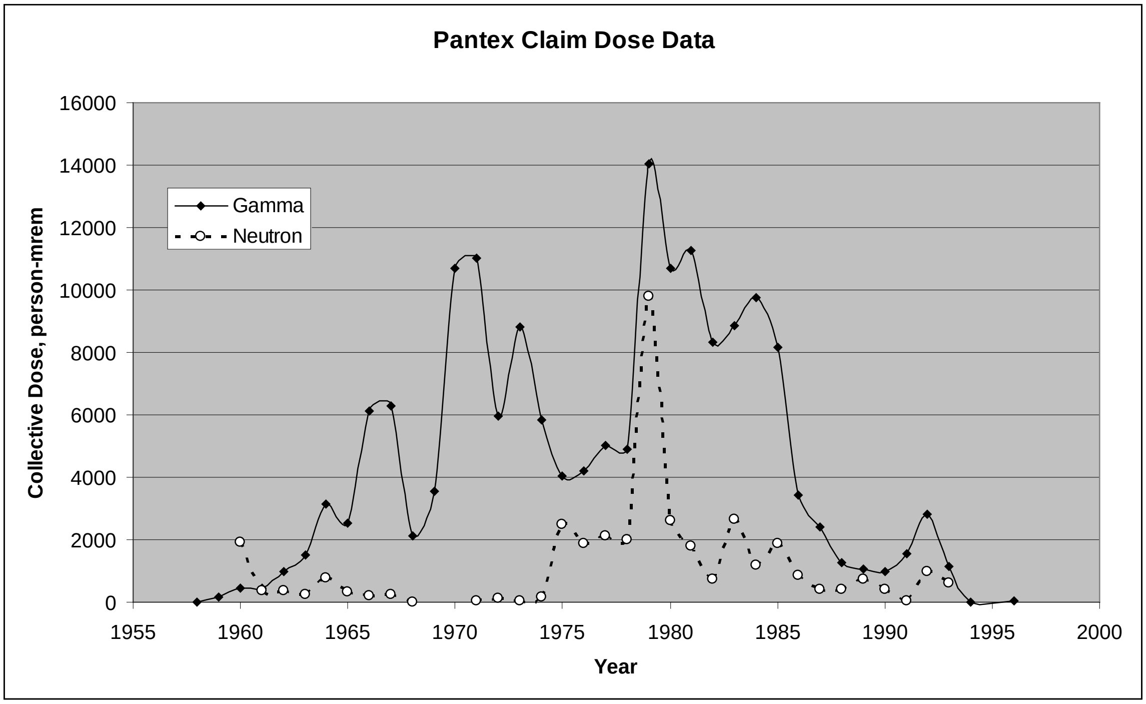


Figure 6-14. Distribution of annual photon and neutron dose for Pantex claims.

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

An examination of the worker neutron and photon dose data revealed that the 95^{th}-percentile value of the ratio was 1.3 and that only four workers received an annual photon and neutron dose for which the neutron-to-photon dose ratio was greater than 1.7 (see Section 6.4.5.4) [84]. This higher ratio was typically associated with a relatively low (i.e., less than 100 mrem) annual photon dose, so there is greater uncertainty in the analysis [85]. The workers were however associated with the Pantex job categories (i.e., inspector and warehouse operator) that typically showed the highest recorded doses [86]. For these workers with higher neutron-to-photon dose ratios, consideration of potential unique workplace factors is recommended in cases of best-estimate dose reconstruction as follows:

- The higher recorded neutron-to-photon dose ratio should be used instead of the lower calculated neutron-to-photon dose ratio (the measured neutron-to-photon dose ratio is used any time it is higher than the calculated value of 1.7) [87].

- Details of the claim file should be examined to determine if there are unique job activities or exposure geometries that could explain the higher measured neutron-to-photon dose ratio.

- Consideration should be given in cases of potential nonuniformity in the workplace radiation field to follow the guidance of the latest revision of OCAS-TIB-0010 (NIOSH 2005) to assign a correction factor based on the benchtop operations typical of some work activities at Pantex. These considerations are similar to the considerations for glovebox workers. In these cases it is recommended that the correction factors provided in this document (NIOSH 2005) be used to compensate for the greater uncertainty associated with these claims.

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 [88]:

- Dose to unmonitored workers 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]
- Unmeasured neutron dose to monitored and unmonitored workers

The application of the foregoing information and the following recommendations can be guided by the flowcharts in Figures 6-15 and 6-16 [89]. Dose reconstructors should consider the dose of record accurate for photon and neutron doses for all workers from January 1994 to the present [90].

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 [91]. Figure 6-17 shows a statistical analysis of the history of Pantex recorded gamma doses in a lognormal probability plot. Table 6-17 summarizes the respective lognormal probability statistical parameters for the period from 1952 to 2000 for Pantex annual dose results that are equal to or exceed a gamma dose of 30 mrem. It is recommended that dose reconstructors assign a favorable to claimant dose to an unmonitored worker, who would otherwise be monitored by today's standards, equal to the median (i.e., geometric mean) dose measured for monitored workers for each year of employment [92]. This is favorable to claimants because unmonitored workers are expected to be lower exposed workers since Pantex practice was to monitor all radiation workers prior to March 1989. For years before 1959, when no measured gamma dose equal to or greater than 40 mrem was measured, use the median dose for 1960 for each year of employment [93].

There should not, typically, be a significant neutron exposure to unmonitored workers. However, for an unmonitored worker with some evidence of potential neutron exposure, neutron doses can be conservatively estimated from the median photon doses for radiation workers listed in Table 6-17 by applying a median neutron-to-photon dose ratio determined by Strom (2004). This median value applied to the median photon dose for radiation workers will yield a favorable to claimant assigned neutron dose to unmonitored workers.

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 [94]. The aprons covered the body from the shoulders to below the knee, but not the arms. Figures 6-15 and 6-16 illustrate the logic for applying adjustments. 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 6.3.5.6.

6.7.3 Missed External Dose for Monitored Workers

Missed dose occurs when the dose of record is zero because the dosimeter response was less than the MDL or there is no dose of record for an assigned badge for a monitoring period. This kind of missed dose is most important for earlier years when MDLs were higher and dosimeter exchange was more frequent. Dose reconstructors should follow NIOSH (2006) guidance and use data in Table 6-18 to calculate the missed photon dose. The method recommended for estimating missed photon dose is:

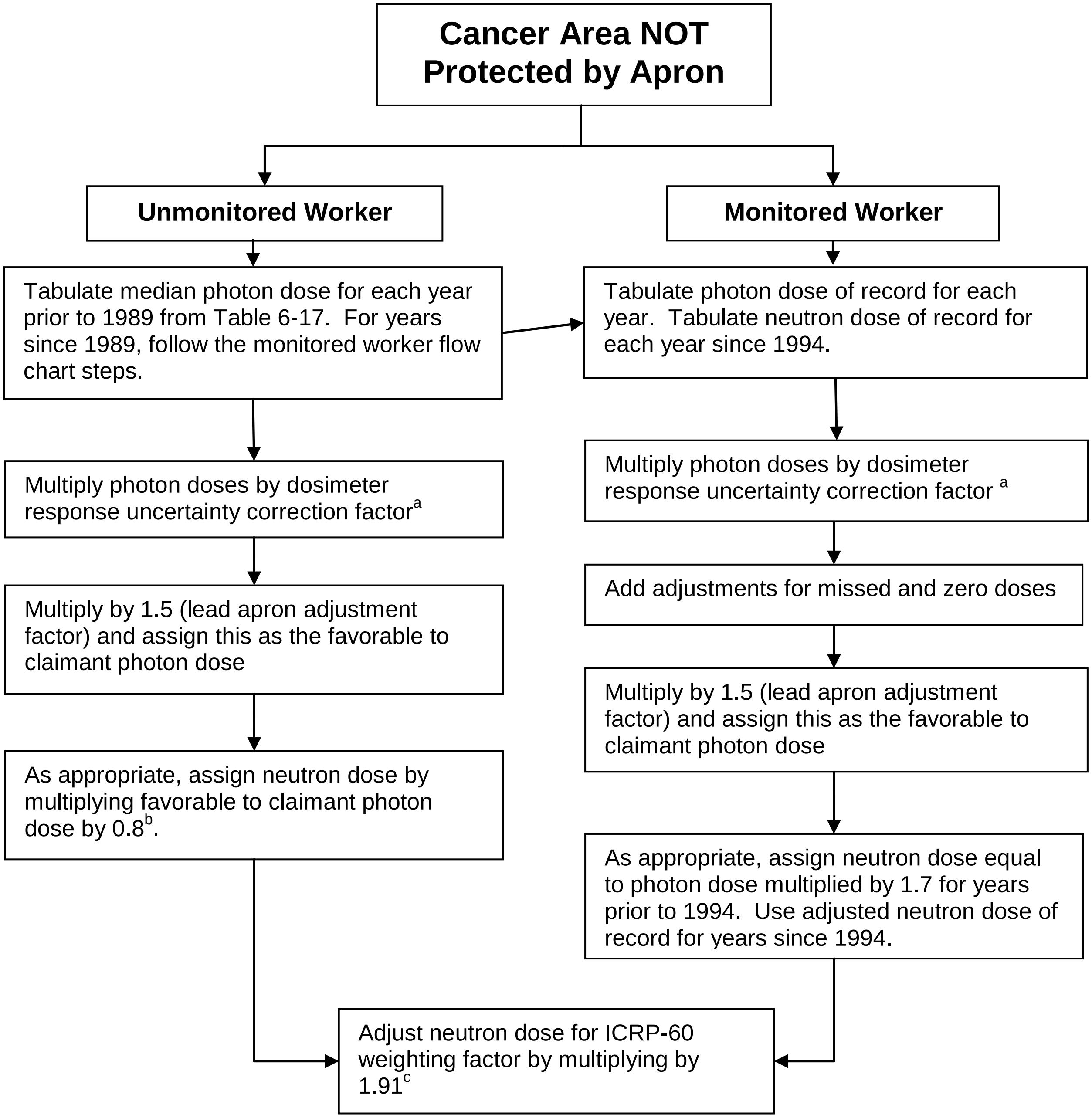
- Assign a missed photon dose based on the MDL/2 method and the number of exchange periods (NIOSH 2006) given in Table 6-18 for the respective dosimetry systems.

6.7.4 Photon and Neutron Dose Adjustments

Pantex worker neutron dose measurements with the 809/812-accredited and workplace performance-validated TLND implemented in 1994 are considered accurate [95]. Adjustments are necessary to earlier recorded neutron dose with the TLD systems used before 1994 (begun in 1977) and before 1977 with the NTA film dosimeter. The recorded neutron doses during these earlier periods are likely to be too low and should not be used in dose reconstructions [96]. The recommended approach in this TBD, as illustrated in Figures 6-15 and 6-16, is to apply a neutron-to-photon dose ratio for the period of neutron dosimeter use before 1994, as described in the following:

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

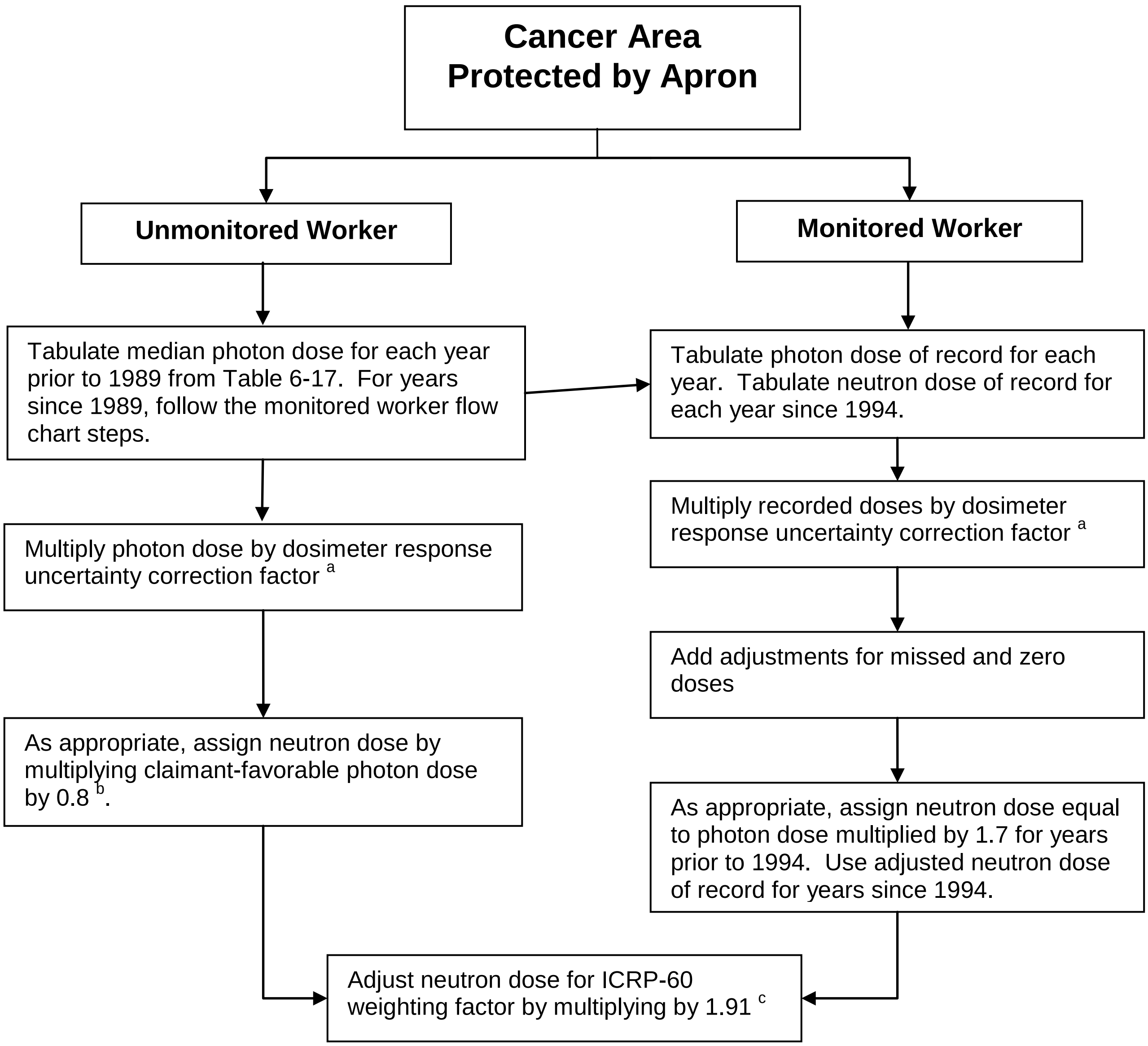
1. Adjust the measured photon and neutron doses for dosimeter response uncertainty. If the cancer site is in an area not protected by an apron, apply the lead apron adjustment factor of 1.5 to the adjusted photon dose.



a. Uncertainties and correction factors are ±30% and 1.3 for film badges, ±20% and 1.2 for TLD prior to 1994, and ±10% and 1.1 for TLDs after DOELAP accreditation, respectively.
b. Median neutron-to-photon dose ratio.
c. ICRP 1991 neutron weighting factor adjustment for neutron energies 0.1- 2 MeV.

Note: Photon and neutron organ dose conversion factors are not included in this flow chart and must be applied separately.

Figure 6-15. Dose reconstruction flowchart for cancer site not protected by a lead apron. Source: Flowchart developed by the authors.



a. Uncertainties and correction factors are ±30% and 1.3 for film badges, ±20% and 1.2 for TLD prior to 1994, and ±10% and 1.1 for TLDs after DOELAP accreditation, respectively.
b. Median neutron-to-photon dose ratio.
c. ICRP 1991 neutron weighting factor adjustment for neutron energies 0.1- 2 MeV.

Note: Photon and neutron organ dose conversion factors are not included in this flow chart and must be applied separately.

Figure 6-16. Dose reconstruction flowchart for cancer site protected by a lead apron. Source: Flowchart developed by the authors.

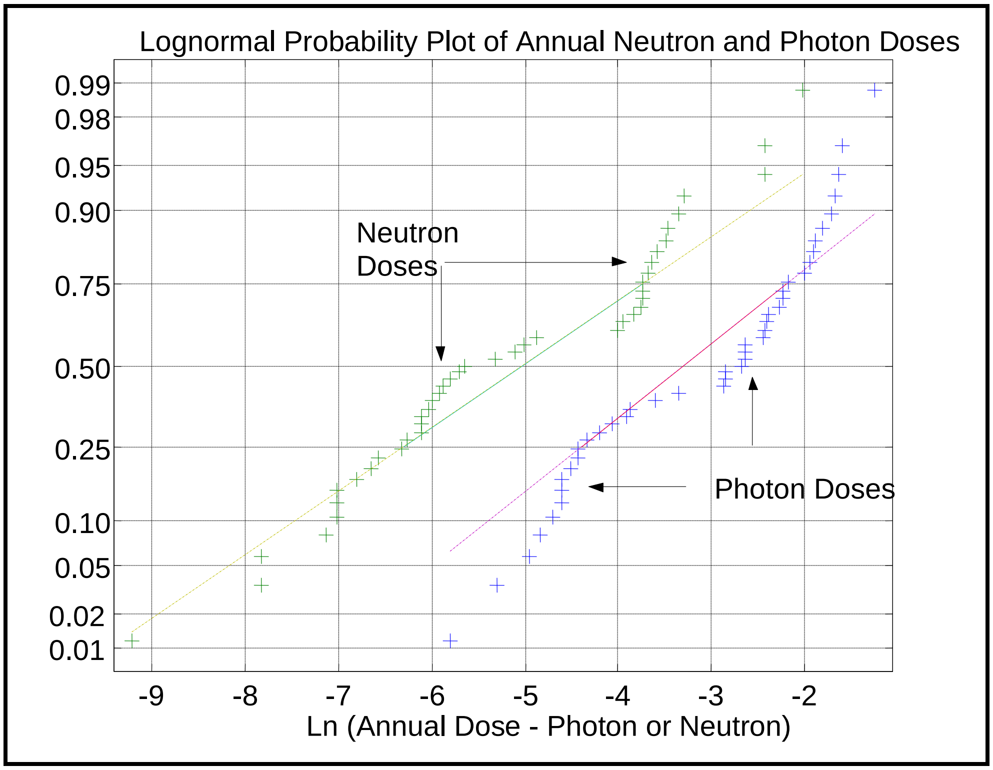


Figure 6-17. Lognormal probability plot of Pantex recorded annual photon and neutron doses. Source: Strom 2004.

Table 6-17. Pantex worker photon dose statistics (Strom 2004).

Year	Recorded photon dose data[a]			Lognormal fit		
	No. of workers reported photon dose >30 mrem	Dose (mrem)		Dose (mrem)		GSD
		Mean	Maximum	Median	95%	
1952-58	(b)					
1959	4	36.3	40	36.0	45	1.15
1960	8	69.4	170	58.0	160	1.86
1961	33	55.7	190	50.1	103	1.55
1962	58	55.5	210	50.1	101	1.53
1963	186	65.7	513	49.6	141	1.88
1964	581	120.0	1,820	74.9	306	2.35
1965	380	101.0	2,950	64.3	231	2.18
1966	708	80.0	1,300	59.2	183	1.98
1967	688	100.0	1,150	71.3	246	2.12
1968	268	90.2	1,090	63.1	220	2.14
1969	350	74.8	1,310	54.0	160	1.93
1970	815	94.2	1,120	63.0	238	2.24
1971	934	102.0	1,400	66.1	265	2.33
1972	765	79.2	540	60.0	188	2.00
1973	1,086	69.6	5,930	53.3	139	1.79
1974	706	91.2	4,990	63.1	200	2.02
1975	329	107.0	10,400	59.3	190	2.03
1976	369	85.6	990	67.1	192	1.90
1977	415	114.0	730	94.8	255	1.83
1978	323	110.0	1,000	77.1	271	2.15
1979	1,144	85.0	2,320	57.0	190	2.08

Year	Recorded photon dose data[a]			Lognormal fit		
	No. of workers reported photon dose >30 mrem	Dose (mrem)		Dose (mrem)		GSD
		Mean	Maximum	Median	95%	
1980	1,228	86.4	820	60.3	208	2.12
1981	1,605	89.7	1,260	63.2	223	2.15
1982	886	86.5	680	66.5	204	1.98
1983	850	78.9	630	59.8	184	1.98
1984	1,330	63.6	1,100	50.2	136	1.84
1985	991	89.7	1,490	62.9	214	2.11
1986	725	74.1	730	57.9	166	1.90
1987	348	73.5	480	58.4	162	1.86
1988	291	59.8	340	50.7	121	1.70
1989	395	66.1	350	55.4	137	1.73
1990	285	56.6	240	49.5	110	1.63
1991	288	55.4	240	48.6	107	1.62
1992	386	60.3	299	52.6	117	1.63
1993	310	57.5	391	52.0	104	1.52
1994	235	53.6	162	49.5	93	1.47
1995	294	50.2	157	46.8	84	1.43
1996	230	50.5	138	47.3	84	1.42
1997	59	55.4	203	48.9	104	1.58
1998	120	43.4	104	41.6	66	1.32
1999	241	53.7	164	49.5	93	1.47
2000	312	53.1	179	48.8	93	1.48

a. Individual dosimeter records analyzed only if photon dose was equal to or greater than 30 mrem.
b. All recorded doses less than 30 mrem.

Table 6-18. Potential missed dose for Pantex workers [97].

Dosimeter	Period	Exchange frequency[a]	MDL (mrem)			Missed annual mean dose (mrem)		
			Skin	Deep	Neutron	Skin	Deep	Neutron
βγ film	1/1952–12/1959	Weekly	40[b]	40[b]	(c)	1,040	1,040	
βγ film and NTA film	1/1960–3/1961	Weekly	40	40	(c)	1,040	1,040	(d)
	4/1961–9/1964	Monthly	40	40	(c)	240	240	(d)
	10/1964-12/1968	2/month	40	40	(c)	520	520	(d)
	1/1969–12/1972	Monthly	40	40	(c)	240	240	(d)
TLD two-element, in-house and NTA film	1973–1976	Monthly	40	40	(c)	240	240	(d)
TLD six-element in-house	1977–1980	Monthly	30	30	(c)	180	180	(d)
Panasonic 802	1980–1991	Monthly	30	30	(c)	180	180	(d)
	1992–2000	Monthly	30	30	(c)	180	180	(d)
		Quarterly[e]	30	30	(c)	60	60	(d)
Panasonic 809/812	1994–present	Monthly	30	30	50	180	180	300
		Quarterly	30	30	50	60	60	100

a. Exchange frequencies were established from dosimetry reports. The initial weekly exchange frequency was changed to monthly in March 1961 (Tracerlab 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). NTA film provided by Landauer was used with the two-element TLD and exchanged monthly (Adams 2003).
b. Estimated MDL typical of film dosimeter capabilities (Wilson 1960, 1987; NIOSH 1993; NRC 1989; Wilson et al. 1990).
c. The MDL for neutron doses estimated for years prior to 1994 was unreliable.
d. For years prior to 1994, the reconstructed neutron dose is calculated using the adjusted photon dose and a neutron-to-photon dose ratio [98].
e. The dosimeter exchange frequency for non-radiation workers was changed from monthly to quarterly in 1992.

2. Prior to 1994, assign a neutron dose for workers handling nuclear components by multiplying the adjusted photon dose and missed photon dose by a neutron-to-photon dose ratio of 1.7, unless the recorded neutron dose is greater (i.e., use the highest dose).

3. For some workers with best-estimate claims only, details in the claim file should be used to determine if unique work activities and exposure geometries could have been a consideration, particularly for nonuniform fields generally associated with benchtop operations. In these cases, the glovebox correction factors of OCAS-TIB-0010 (NIOSH 2005) are recommended to ensure a favorable to claimant analysis.

4. From 1994 to present, no adjustment in measured neutron dose is needed other than standard adjustments for dosimeter response uncertainty and ICRP Publication 60/NCRP 38 neutron weighting factors adjustments from Table 6-13 (per step 5 below). The missed neutron dose needs only the ICRP Publication 60 (ICRP 1991) neutron weighting factor adjustment.

5. Multiply the assigned neutron dose by a neutron weighting factor adjustment of 1.91 for neutron energies of 0.1 to 2 MeV.

It should be noted that the use of neutron to photon dose ratios to retrospectively assign a neutron dose entails substantial uncertainty and is an ongoing issue of discussion and evaluation. Further guidance is anticipated. There is the possibility that facilities where the workplace neutron spectrum is predominantly of higher energy (and thereby contributes the most significant worker dose), the NTA dosimeter may provide a realistic dose assessment with appropriate consideration of uncertainty.

For unmonitored Pantex workers, who by today's standards would be monitored, but were not directly involved in handling nuclear components, options to estimate the dose include:

1. From 1989 to present, all Pantex workers have been monitored; use the dose of record.

2. Before 1989, if there is no recorded photon dose, use the median (with geometric standard deviation) photon dose for Radiation Workers for each year from Table 6-17. Adjust these doses for dosimeter response uncertainty.

3. Apply the neutron-to-photon dose ratio to the adjusted total photon dose (step 2 above). The recommended ratio is 0.8, which is the median neutron-to-photon dose ratio determined by Strom (2004).

4. Multiply the assigned neutron dose by a neutron weighting factor adjustment from Table 6-13 of 1.91 for neutron energies of 0.1-2 MeV.

6.7.5 Skin Dose

In years before 1981, the skin dose records included beta doses only [99]. In 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 [100]. Additional guidance on determining skin dose can be obtained from ORAUT-OTIB-0017, *Interpretation of Dosimetry Data for Assignment of Shallow Dose* (ORAUT 2005).

6.7.6 Extremity Dose

Wrist type extremity dosimeters have been assigned to radiation workers who directly handled nuclear weapon components, such as pits (Pantex 2002). Since 1980, a Panasonic UD-802 dosimeter with a wristband has been used for extremity dose monitoring [101]. Between 1972 and 1980, a wrist type TLD badge was used; before 1972, a wrist type film badge was used [102]. 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 (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 [103]. 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, and 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 (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 (PNNL 2006). 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 claimant data revealed that of 316 claims, only 42 had extremity dose data greater than 100 mrem recorded in a given year [104]. The 95^{th}-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.

6.7.7 Radiation Dose Fraction

Table 6-9 summarizes the recommended fractions for Pantex dose according to facility, worker occupational classification, and energy categories required by IREP. Because of the uncertainty in actual workplace fields, the energy fractions for claimant dose estimation in Table 6-18 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 favorable to claimant estimates of organ dose.

6.7.8 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 guidelines (NIOSH 2006). 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. The calculated neutron doses should be multiplied by the conversion factors from deep dose equivalent to organ dose for AP irradiation from Appendix B of NIOSH (2006). For photons prior to 1973 (film badge era), the conversion factor from exposure to organ dose should be used. For 1973 to the present (TLD era), the conversion factor from deep dose equivalent to organ dose should be used [105].

6.7.9 Claim Analysis Methods

6.7.9.1 Minimizing Assumptions

When a claim is categorized as likely compensable, minimizing assumptions are used to process the dose assessment quickly and simply. Assumptions such as assigning no neutron dose or no missed dose are typical minimizing assumptions that can expedite processing. If the estimated dose corresponds to a POC exceeding 50%, even with minimizing assumptions, the claim is probably compensable.

6.7.9.2 Maximizing Assumptions

When a claim is categorized as likely noncompensable, maximizing assumptions are used to expedite claim processing. Assigning the maximum neutron dose, maximum missed dose, and maximum adjustment for uncertainty are typical maximizing assumptions. If the estimated dose with maximizing assumptions corresponds to a POC that does not equal or exceed 50%, the claim is probably noncompensable.

6.7.9.3 Best Estimate Assumptions

The resolution of claims that require a more realistic assessment to determine compensability should consider that the conversion of photon and neutron doses of record to organ doses requires careful evaluation without simplifying assumptions. Best available data for the claimant should be used, including actual dosimeter results, actual number of x-rays, and actual uptakes.

6.7.9.4 Summary of Correction and Adjustment Factors

The various recommended correction and adjustment factors defined above are summarized in Table 6-19 for application of minimizing assumptions, maximizing assumptions, and best estimate assumptions.

Table 6-19. Summary of recommended correction and adjustment factors [106].

	Correction and adjustment factors		
Parameters	**Minimizing assumptions**	**Maximizing assumptions**	**Best estimate assumptions**
Photons:			
Lead apron adjustment[a]	1.0	1.5	1.5
Missed dose	0	N x MDL / 2	Monte Carlo analysis
Dosimeter response uncertainty:			
Film badges	1.0	+30%	±30%[b]
TLDs	1.0	+20%	±20%[b]

TLDs after DOELAP	1.0	+10%	±10%[b]
Neutrons:			
Prior to 1994: neutron/photon dose ratio	0	1.7 x photon dose	Monte Carlo analysis
After 1994	0	Dose of record	Dose of record
Dosimeter response uncertainty after 1994	0	+30%	±30%[b]
ICRP 60 neutron weighting factor	0	1.91	1.91

a. Apply the lead apron adjustment factor if the cancer is located in an area not protected by an apron.
b. Normal distribution.

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 2006c). The estimated uncertainty in doses recorded by TLDs is ±20% prior to 1994 (ORAUT 2006a) and ±10% since 1994 (Pantex 2002).

The situation for neutrons was not as favorable as for photons [107]. With NTA films used at Pantex before 1977, the estimated standard error was larger and varied significantly with the energy of the neutrons. Therefore, measured neutron doses to workers were very likely underestimated. TLNDs used between 1977 and 1993 had some limitations [108]. The recommended approach in this TBD is to use neutron-to-photon dose ratios to estimate the neutron dose using the reliably measured photon doses. For TLNDs used at Pantex beginning in 1994, the estimated standard errors for a neutron dose of record reading of 100 mrem or more are approximately ±30% based on DOELAP performance testing (ANSI 1993).

6.9 ATTRIBUTIONS AND ANNOTATIONS

Where appropriate in the preceding text, bracketed callouts have been inserted to indicate information, conclusions, and recommendations to assist in the process of worker dose reconstruction. These callouts are listed in this section with information that identifies the source and justification for each item. Conventional references are provided in the next section that link data, quotations, and other information to documents available for review on the Oak Ridge Associated Universities (ORAU) Team servers.

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. Mr. Martin continues to serve as a site expert for this document because he possesses or is aware of information relevant for reconstructing radiation doses to claimants who worked at the site. In all cases where such information or previous studies or writings are included or relied upon by the Document Owner, those materials are fully attributed to the source. Mr. Martin's disclosure statement is available at www.oraucoc.org.

[1] Martin, Jerome B. 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 Radiation Protection Guideline of 5 rem/yr. An examination of the data in Table 6-1 and Figure 6-1 for monitored workers compared 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 1963; Eberline 1964; Landauer 1976).

[4] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Examination of external dosimetry reports (Tracerlab 1963; Eberline 1964; Landauer 1976; 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 taken from 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 6-1 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 (personal communication from Mark Prather).

[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 that are done to ensure proper assignment of radiation worker status and the type of dosimeter provided.

[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 received by workers from higher energy photons is insignificant compared to the dose received 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.
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.

[31] 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.

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

[33] 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.

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

[35] 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 multi-element 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.

[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 on September 1, 1993 (personal knowledge). 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).

[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 multi-element 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 text discusses weaknesses and underestimating of neutron doses by both the NTA film badge and TLNDs used before 1994. The text establishes that neutron doses measured and recorded before 1994 are unreliable and should not be used in dose reconstructions.

[45] 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.

[46] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A neutron-to-photon dose ratio method has been used to estimate neutron doses when measured doses are unreliable. This method has been used in the Occupational External Dose TBDs for Hanford, Savannah River, Y-12, Los Alamos, and Rocky Flats. The method used for Pantex most closely resembles the circumstances and neutron-to-photon ratios at Los Alamos and Rocky Flats.

[47] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
If the ratio of the collective neutron dose to the collective photon (gamma) dose in Table 6-1 is calculated for each year from 1960 through 1993, the average ratio over this period was 0.19, i.e., the neutron dose was 19% of the photon dose. A similar calculation for each year from 1994 though 2004 gives an average ratio of 0.26, i.e., the neutron dose was 26% of the photon dose.

[48] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
If all workers had both photon and neutron doses, the ratios of collective doses would be more meaningful in relation to claimants' doses, and a stronger case could be made for a lower neutron-to-photon dose ratio. Because this not the case, the neutron-to-photon dose ratio must be calculated from the reliable neutron and photon dose data recorded since 1994.

[49] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Some workers had both neutron and photon doses, and some had only photon doses. The neutron-to-photon dose ratio calculated for those workers who had both neutron and photon

doses would be reduced or “diluted” when the workers with only photon dose are included in the ratio calculation.

[50] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The sources of neutrons at Pantex are routinely surveyed, and it is consistently shown that bare pits have the highest neutron dose rates. It follows that handling bare pits is the major source of neutron doses.

[51] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The as low as reasonably achievable (ALARA) program at Pantex is focused on reduction of radiation doses. Analysis showed that a significant reduction in photon dose could be achieved by more consistent use of lead aprons while working with pits. Procedures were revised to require the use of lead aprons when handling pits, and management was required to enforce their use.

[52] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Since 1994, the increased use of lead aprons when handling pits has resulted in a decrease in the contribution of lower energy photons to the total photon dose.

[53] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The purpose of the discussion is to compare neutron-to-photon dose ratios in earlier periods, such as assembly operations in the 1960s, to the neutron-to-photon dose ratios that were determined from reliable data from 1994 to 2004. During assembly operations with new pits, the photon dose rates would be lower because of little ingrowth of ^{241}Am and because the use of lead aprons was not required.

[54] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The neutron dose rates were generally the same during both periods. The photon dose rates were lower during the earlier period because of little ^{241}Am ingrowth. The photon dose rates were lower from 1994 to 2004 because of the effective use of lead aprons. If both the neutron and photon dose rates were similar during both periods, the neutron-to-photon dose ratios would also be similar during both periods.

[55] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The purpose of this discussion is to consider the effect of disassembly operations during the 1980s on the neutron-to-photon dose ratios. During this period, there was significant ingrowth of ^{241}Am in pits and photon doses were higher, while the use of lead aprons was not required. The neutron-to-photon dose ratio would therefore have been lower. If lead aprons were used during this period, the neutron-to-photon dose ratio would have been about the same as that from 1994 to 2004.

[56] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A neutron-to-photon dose ratio of 1.7 was defined for the period from 1960 to 1993 and was shown to be conservative and favorable to claimants. Measured neutron doses since 1994 have been shown to be reliable. These two periods cover the entire career of any Pantex workers.

[57] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Individual claimant dose records were examined to identify any periods when a neutron-to-photon dose ratio greater than 1.7 occurred. Four claimants had a ratio greater than 1.7 in

some years. In these few cases, the actual measured neutron and photon doses (and higher neutron-to-photon dose ratios) were recommended for use in dose reconstructions.

[58] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Individual claimant dose records were examined to identify any periods when a neutron-to-photon dose ratios greater than 1.7 occurred. Four claimants had ratios greater than 1.7 in some years. In these few cases, the actual measured neutron and photon doses (and higher neutron-to-photon dose ratios) were recommended for use in dose reconstructions.

[59] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
A neutron-to-photon dose ratio of 1.7 was defined for the period from 1960 to 1993 and was shown to be conservative and favorable to claimants. Measured neutron doses since 1994 have been shown to be reliable. These two periods cover the entire career of any Pantex workers.

[60] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The purpose of this sentence is to summarize that photon doses of record are reliable, a neutron-to-photon dose ratio of 1.7 is conservative, and neutron doses that are favorable to claimants can be calculated for all years before 1994.

[61] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The sources of neutrons at Pantex are routinely surveyed, and it is consistently shown that bare pits have the highest neutron dose rates. It follows that handling bare pits is the major source of neutron doses

[62] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
There are many radiation exposure scenarios at Pantex that involve only photon dose. By applying a neutron-to-photon dose ratio of 1.7 to all photon dose, the conservative assumption is made that all photon dose was accompanied by a neutron dose and that the neutron dose was received in the highest dose rate scenario.

[63] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Some workers at Pantex were not monitored because they were not designated as radiation workers. However, some unmonitored workers could have been incidentally exposed to radiation in the workplace. The assumption was made that the dose to unmonitored workers was not likely to exceed the median dose to monitored workers. Furthermore, the assumed photon dose would then be multiplied by a neutron-to-photon dose ratio of 0.8 to calculate an additional neutron dose, even though neutron exposure to unmonitored workers was unlikely. The combination of assumed photon dose and calculated neutron dose provides a total dose estimate for unmonitored workers that is favorable to claimants.

[64] 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.

[65] 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 (see Table 6-1).

[66] 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.

[67] 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.

[68] 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).

[69] 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.

[70] 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.

[71] 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.

[72] 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.

[73] 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.

[74] 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.

[75] 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.

[76] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Although “average” or “routine” activities apply to most radiation exposure scenarios, many claimants 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 claimant must be carefully reviewed for any evidence of such radiation incidents, and the incidents must be evaluated to produce an accurate dose reconstruction.

[77] 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.

[78] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The 316 claimants reported nearly 700 different job titles. Many claimants 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.

[79] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
For each claimant, 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 claimants that were employed during that year. The plot indicates that few claimants were employed in the early 1950s and few were still employed after 2000.

[80] 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 claimant 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.

[81] 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 in 1960 and 1979. 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 in 1960 and again in 1979, but records of this were not found.

[82] 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 claimant 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 in 1960 and 1979. 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 in 1960 and again in 1979, but records of this were not found.

[83] 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 five workers. It is possible that these workers were involved in some extensive operations in pit storage vaults 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.

[84] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The annual neutron and photon dose data for all 316 Pantex claimants were analyzed, and the neutron-to-photon dose ratios were calculated for each year. A lognormal distribution analysis of the ratios showed that the 95th-percentile value was 1.3. Further analysis revealed that only four workers received an annual photon and neutron dose for which the neutron-to-photon dose ratio was greater than 1.7. This analysis of claimant data confirmed that the neutron-to-photon dose ratio of 1.7 in Section 6.4.5.4 is conservative and favorable to claimants.

[85] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
In the four cases where the neutron-to-photon dose ratio was greater than 1.7, the annual photon dose was relatively low (typically less than 100 mrem). The lower the photon dose in relation to a given neutron dose, the higher the neutron-to-photon dose ratio. The lower photon doses have a less certain measurement, so there can be a greater uncertainty in the higher neutron-to-photon dose ratios. Regardless of the uncertainty, if any recorded neutron-to-photon dose ratios are greater than 1.7, the higher recorded ratios should be used in dose reconstruction.

[86] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The four cases where the neutron-to-photon dose ratios were greater than 1.7 involved workers in the inspector or warehouse operator job categories. Workers in these job categories has some of the higher collective doses in Table 6-16.

[87] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
In the four cases where the neutron-to-photon dose ratio was greater than 1.7, the annual photon dose was relatively low (typically less than 100 mrem). The lower the photon dose in relation to a given neutron dose, the higher the neutron-to-photon dose ratio. The lower photon doses have a less certain measurement, so there can be a greater uncertainty in the higher neutron-to-photon dose ratios. Regardless of the uncertainty, if any recorded neutron-

to-photon dose ratios are greater than 1.7, the higher recorded ratios should be used in dose reconstruction.

[88] 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, 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, 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.

[89] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The flowcharts in Figures 6-15 and 6-16 were developed to summarize and guide the application of recommended adjustments to the recorded doses for Pantex workers. The correct sequence for applying the adjustments is also indicated in the flowcharts.

[90] [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.

[91] 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. Thus, the collective measured dose for this small group of workers was low in comparison to later periods.

[92] 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.

[93] 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.

[94] 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.

[95] 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.

[96] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The neutron doses that were measured by NTA film were low because of inability to detect neutrons with energies less than about 800 keV (ORAUT 2005a). Neutron doses that were measured by the Pantex six-element TLD system and the Panasonic UD-802 were also low (Roberson et al 1983 and Pantex 2002). Neutron doses from before 1994 are know to be low and should not be used in dose reconstructions, because of the low bias and large uncertainties.

[97] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Table 6-18 is simply a repeat of the dosimeter, period, exchange frequency, and MDL columns from Table 6-2, with the addition of the missed annual mean doses that were derived with the MDL/2 method in NIOSH (2006).

[98] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
Measured photon doses have been shown in Section 6.4.5.2 to be reliable and accurate. The recommended neutron-to-photon dose ratio was developed in Section 6.4.5.4. For years before 1994, the adjusted photon dose should be multiplied by a neutron-to-photon dose ratio to calculate the neutron dose.

[99] 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.

[100] 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.

[101] 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 (see Pantex 2002 and personal communication with Mark Prather)

[102] 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 (personal communication with Mark Prather). There was no evidence that confirmed the use of extremity dosimeters before 1964.

[103] 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.

[104] 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.

[105] 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 (2006) recommends the use of the conversion factor from exposure to organ dose for data from film badges. NIOSH (2006) 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.

[106] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
All of the correction and adjustment factors recommended in Section 6.6 are summarized in Table 6-19 for the convenience of the dose reconstructors.

[107] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The uncertainty in neutron doses that were measured with NTA film was much larger than the uncertainty in photon doses that were measured by film badges. The uncertainties in neutron doses are discussed in ORAUT (2006d).

[108] Martin, Jerome B. ORAU Team. Senior Health Physicist. August 2006.
The uncertainty in neutron doses that were measured with TLNDs between 1977 and 1993 was also much larger than the uncertainty in photon doses that were measured by TLDs, especially with the complex neutron spectra at Pantex.

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GLOSSARY

Atomic Energy Commission (AEC)
Agency established for oversight of nuclear weapons and power production; a predecessor to the U.S. Department of Energy.

beta (β) dose
A designation (i.e., beta) on some Pantex external dose records referring to the dose from less-energetic beta, X-ray, or gamma radiation.

beta radiation
Radiation consisting of charged particles of very small mass (i.e., the electron or positron) emitted spontaneously from the nuclei of certain radioactive elements. Physically, the beta particle is identical to an electron or positron moving at high velocity.

bremsstrahlung
A German term that means secondary electromagnetic radiation (x-rays) produced by deceleration of charged particles passing through matter.

curie
A special unit of activity. One curie exactly equals 3.7×10^{10} nuclear disintegrations per second.

dose equivalent (*H*)
The product of the absorbed dose (*D*), the quality factor (*Q*), and any other modifying factors. The special unit is the rem. When *D* is expressed in gray, *H* is in seiverts (1 sievert = 100 rem).

dose of record
The dose files provided by DOE to NIOSH as part of the individual worker files.

dosimeter
A device used to measure the quantity of radiation received. A holder with radiation-absorbing elements (filters) and an insert with radiation-sensitive elements packaged to provide a record of absorbed dose or dose equivalent received by an individual.

dosimetry
The science of assessing absorbed dose, dose equivalent, effective dose equivalent, etc., from external or internal sources of radiation.

dosimetry system
A system used to assess dose equivalent from external radiation to the whole body, skin, and extremities. This includes the fabrication, assignment, and processing of dosimeters as well as interpretation and documentation of the results.

depleted uranium (DU)
As used in components of nuclear weapons. Pantex listed isotopic activity fractions (NOTE: this is not the mass fraction) as:

Isotope	Activity fraction
U-234	0.0840
U-235	0.0145
U-238	0.9015

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

exposure
As used in the technical sense, a measure expressed in roentgen of the ionization produced by photons (i.e., gamma and X-rays) in air.

extremity
That portion of the arm extending from and including the elbow through the fingertips, and that portion of the leg extending from and including the knee and patella through the tips of the toes.

film
In this context, a film packet that contains one or more pieces of film in a light-tight wrapping. When developed, the film has an image caused by radiation that can be measured using an optical densitometer.

film dosimeter
A small packet of film in a holder that attaches to a wearer.

gamma rays (γ)
Electromagnetic radiation (photons) originating in atomic nuclei and accompanying many nuclear reactions (e.g., fission, radioactive decay, and neutron capture). Physically, gamma rays are nearly identical to X-rays but with higher energy; the only essential difference is that X-rays do not originate in the nucleus.

gray
International System unit of absorbed dose (1 gray = 100 rad).

highly enriched uranium (HEU)
Uranium with activity fraction listed by Pantex as:

Isotope	Activity fraction
U-234	0.9806
U-235	0.0194
U-238	0.0000

ionizing radiation
Electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.

minimum detectable level (MDL)
A statistically determined minimum detectable level, lower limit of detection (L_D), and related quantities.

minimum recordable dose (MRD)
The minimum dose recorded and reported; the MRD is normally based on site-specific policy.

neutron
A basic particle that is electrically neutral weighing nearly the same as the hydrogen atom.

neutron, fast
A neutron with energy equal to or greater than 10 keV.

neutron, thermal
Strictly, a neutron in thermal equilibrium with surroundings. In general, a neutron with energy less than about 0.4 eV.

neutron film dosimeter
A film dosimeter that contains a nuclear track emulsion, type A, film packet.

nuclear emulsion
Often referred to as NTA film and used to measure personnel dose from neutron radiation.

nuclear track emulsion, type A (NTA)
A film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using an appropriate imaging capability such as oil immersion and a 1000-power microscope or a projection capability.

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 $H_p(d)$
The dose equivalent in soft tissue below a specified point on the body at an appropriate depth *d*. The depths selected for personnel dosimetry are 0.07 mm and 10 mm for the skin and body, respectively. These are noted as *Hp(0.07)* and *Hp(10)*, respectively.

photon
A unit or particle of electromagnetic radiation consisting of X- or gamma rays.

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*
A modifying factor used to derive dose equivalent from absorbed dose.

radiation
Alpha, beta, neutron, and photon radiation.

radiation worker (or radiological worker)
Worker with a job assignment that requires work on, with, or in the proximity of radiation-producing machines or radioactive materials. A radiation worker has the potential of being exposed to more than 0.1 rem per year, which is the sum of the dose equivalent from external irradiation and the committed effective dose equivalent from internal radiation.

radioactivity
The spontaneous emission of radiation, generally alpha or beta particles, gamma rays, and neutrons from unstable nuclei.

rem
A unit of dose equivalent equal to the product of the number of rad absorbed and the quality factor *Q*.

roentgen (R)
A unit of exposure to gamma (or X-ray) radiation. A roentgen is defined precisely as the quantity of gamma (or X-) rays that will produce a total charge of 2.58×10^{-4} coulomb in 1 kilogram of dry air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue for higher energy photons (over 100 keV).

shielding
Any material or obstruction that absorbs (or attenuates) radiation and thus tends to protect personnel or materials from radiation.

skin dose
Absorbed dose at a tissue depth (density thickness) of 7 mg/cm^2.

thermoluminescent
Property of a material that causes it to emit light as a result of being excited by heat.

thermoluminescent dosimeter (TLD)
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.

whole-body dose
The absorbed dose at a tissue depth of 1.0 cm (density thickness of 1,000 mg/cm^2); however, this term is also used to refer to the recorded dose.

X-ray
Ionizing electromagnetic radiation that originates outside the nucleus of an atom.