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RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	EFFECTIVE DATE	REV. NO.	DESCRIPTION
Draft	01/12/2004	00-A	New Technical Basis Document for the Mound Site – Occupational External Dose. Initiated by Jeff Vollmer.
Draft	04/14/2004	00-B	Incorporates NIOSH and internal review comments. Initiated by Jeff Vollmer.
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08/11/2004	08/11/2004	00	First approved issue. Initiated by Jeff Vollmer.

ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission (a DOE predecessor agency)
AP	anterior–posterior
C	Celsius (with degree symbol)
cm	centimeter
DOE	U.S. Department of Energy
DOELAP	DOE Laboratory Accreditation Program
ERAD	External Radiation Analysis Data
EXAS	External Exposure Analysis System
IARC	International Agency for Research on Cancer
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiological Units and Measurements
keV	kilovolt-electron, 1,000 electron volts
LOD	limit of detection
MDL	minimum detectable level
MESH	Mound Environmental Safety and Health
MeV	megavolt-electron, 1 million electron volts
mm	millimeter
mo	month
MPL	maximum permissible limit
mR	milliroentgen
mrad	millirad
mrem	millirem
NBS	National Bureau of Standards
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
qtr	quarter, 3 months
R	roentgen
RBE	relative biological effectiveness
RTG	radioisotope thermoelectric generator
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code
wk	week
yr	year

6.1 INTRODUCTION AND BRIEF HISTORY OF DAYTON PROJECT AND MOUND FACILITY

This technical basis document (TBD) contains an analysis for external exposure received by Mound Laboratory workers while inside site facilities. Discussions include analysis for missed doses for monitored workers and estimated doses for unmonitored workers. The discussion covers dosimetry practices at Mound from its establishment as part of the Manhattan Engineering District project until the planned closure of the facility in 2006.

TBDs and Site Profile Documents are general working documents that provide guidance concerning the preparation of dose reconstructions at 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 the National Institute for Occupational Safety and Health (NIOSH) 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 facility" as defined in the Energy Employee Occupational Illness Compensation Program Act of 2000 [42 U.S.C. Sections 7384l(5) and (12)].

Beginning in September 1943, the Monsanto Chemical Company investigated polonium and its production at the Scioto research laboratory in Dayton, Ohio. This was the Dayton Project, a part of the Manhattan Project. The project moved to Miamisburg, Ohio, in 1948 and became the Mound Laboratory in 1949. Mound was the first U.S. Atomic Energy Commission (AEC) facility. The Mound facility supported many activities from 1946 to 1992. The name derives from the large prehistoric Adena Indian burial mound across the road from the facility.

In comparison with other AEC facilities, the Mound site was never very large, about 2 square miles in area. Of that, about 306 acres were actively used. The main use area is on a steep-sided glacial moraine jutting about 300 feet above the valley of the Great Miami River. The significance of this topography is that the wind blows over the Mound facility almost constantly. There is very little stagnant air on the Mound site, so airborne radiological releases disperse quickly. This TBD does not address airborne releases.

During the initial part of the Manhattan Project the Dayton facility separated ^{210}Po from naturally occurring materials for PoBe source neutron generators for atomic bomb initiators. By 1944 the decision was made to transmute ^{209}Bi into ^{210}Po via neutron bombardment (Warren 1944). The reaction is: $_{83}{}^{209}\text{Bi} + \eta \rightarrow {}_{83}{}^{210}\text{Bi} \rightarrow {}_{84}{}^{210}\text{Po} + \beta\text{-}$. Initially, 58-pound bismuth bricks were irradiated in the Clinton reactor at Oak Ridge. After January 1945 irradiated bismuth was the sole source of polonium (Wolf 1945). The beta radiation from the irradiated slugs was intense enough that lead gloves and tongs were necessary to handle them (Ferry 1944a). When the Mound facility opened in 1948, the bismuth was cast into slugs that were then inserted into aluminum cans, which were welded shut. The canned bismuth was then irradiated at the Hanford facility and shipped to Mound in lead casks. The casks were emptied into a pool on the second floor of the T Building. After testing mechanical cutting, chemical dissolution, and melting, it was decided that the bismuth could best be separated from the aluminum can by dissolution in a bath of 17% HCl. The bismuth was then dissolved in a bath of HCl and HNO_3. This separation occurred on the second floor of the T Building. It is Important that both the aluminum and the bismuth contained impurities including iron, silicon, cobalt, lead, tin, zinc, silver, chromium, vanadium, and gallium. During irradiation these impurities were neutron activated and produced gamma-emitting isotopes that created an external radiation hazard during the bismuth processing.

The second phase of the polonium project consisted of manufacturing polonium heat sources for radioisotope thermoelectric generators (RTGs). The SNAP 3A polonium-powered RTG was built in 1958. However, because of the short half-life of ^{210}Po, this program was halted after 1969 and cancelled in 1971 when cleanup began.

Because of the short half-life of ^{210}Po, a program was begun in the late 1940s to find other longer-lived alpha emitters that could function in bomb initiators, which began the radium and actinium programs at Mound. Actinium-227 could be made from ^{226}R via neutron irradiation. The reaction is: $^{226}Ra + \eta \rightarrow {}^{227}Ra \rightarrow {}^{227}Ac + \beta$-. All the associated research projects were carried out at Mound in the late 1940s and early 1950s. In July 1953 the program was de-emphasized.

The plutonium project at Mound began with ^{238}Pu research in the mid-1950s. Research on ^{238}Pu was transferred from the Lawrence Livermore National Laboratory to Mound in 1959. Mound produced over 500 RTGs from 1961 to 1992.

In the mid-1950s Mound was involved in a thorium refinery program. This was designed to develop a system for refining thorium for the breeder reactor program. The Monex process pilot plant was assembled in Room 1B of the SW Building in the spring of 1955. Construction on a refinery on the west side of the SW Building was begun on March 11, 1955, but was cancelled on May 9, 1955.

In November 1955 Mound received a directive from AEC to construct a facility to research the process chemistry of ^{230}Th, also called ionium. This was to be used as a tracer element in the Redwing nuclear weapons tests. This program was terminated late in 1956. There was also a brief ^{231}Pa program begun in 1954 in Room 167 of the R Building when ^{231}Pa was selected as a research surrogate for ^{233}Pa. A pilot plant was installed in the HH Building in July 1955, but after March 1956 work was moved to the SW Building and used equipment from the Monex process.

From the early 1960s through the mid 1970s Mound was involved again in the ionium and protactinium programs.

The last program at Mound was the program to produce and separate rare radioactive isotopes. It began at Mound in the mid 1950s and continued until 1985. The processes were carried out in the SW, SM, and R Buildings (DOE 1993).

Mound continued its role in nuclear weapons development and production until 1992. The U.S. Department of Energy (DOE) has transferred all nuclear work from Mound to other DOE facilities.

As an aid to understanding the health physics program at Mound, Table 6-1 lists the eight major programs, with external dose implications, that were conducted there over five decades.

6.2 BASIS OF COMPARISON

Since the Manhattan Engineering District project began in the early 1940s, a great many radiation dose concepts and quantities have been used to measure and record occupational dose. One basis of the comparison for dose reconstruction, as described in *External Dose Reconstruction Implementation Guideline*s (NIOSH 2002), 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 a weakly penetrating radiation of significance to skin dose, *d* is 0.07 mm and is noted as *Hp(0.07)*. For dose to the lens of the eye, *d* is 0.3 mm and is noted as *Hp(0.3)*. For penetrating radiation of significance to whole-body dose, *d* is 10 mm and is noted as *Hp(10)*. The International Commission on Radiological

Table 6-1. Synopsis of major programs with external dose implications.

Program	Time frame	Products	Major isotopes of interest	Building
Polonium A	1943-1959	Po-210 in PoBe & PoX neutron generators.	Bi-210, Fe-59, Sc-46, Co-60, Pb, Sn, Zn-65, Ag-110m, Cr, Va, Ga, Hg-203	T, HH
Polonium B	1953-1969	Po-210 as a heat source. SNAP 3A and Poodle RTGs.	Po-210	T, HH
Radium-actinium	1949?- 6/1953; 4/1954-12/1954	Ac-227Be neutron sources	Mallinckrodt K-65 residues, Ra-226, Ra-227, Ac-227, Th-228	R, SW including Old Cave
Plutonium	1959-1995	Pu-238 heat sources. 500+ Pu RTGs	Pu-238, Pu-238O-18	PP, WD SW
Thorium-232 Refinery (Monex process)	1954?- 5/1955; sludges stored until 7/1975	Th-232 for breeder reactor program	Th-232 containing sludges from uranium extraction and scrap	SW 1-B, stored in warehouse 15, W, G, Quonset hut, bldg. 21
Thorium-230 (Ionium)	11/1955 -1956	Tracer element for Redwing weapons test	Th-230 and Pa-231 containing sludges from uranium extraction (Cotter concentrate from St. Louis)	R
Protactinium-231 & 233	1954 – 9/1979	Pa-231 was a surrogate for study of the properties of Pa-233	Th-230 and Pa-231 containing sludges from uranium extraction (Cotter concentrate from St. Louis); products of irradiation of Th-230 & Th-232	R 167 & 145; HH '7/55-3/'56; SW 4/'56 onward
Rare isotopes	Mid 1950's-1985	Pu-238; Pa-231; Th-228,229, 230; U-233, 234; Ra-226; Ac-227; Po-209	Uranium and thorium sludges, Pu-238, U-233, target irradiation	SW 22, 132, 140; SM 1; R; bldg. 21

Units and Measurements (ICRU) has recommended *Hp(0.07)*, *Hp(0.3)*, and *Hp(10)* for use as the operational quantities to be recorded for radiological protection (ICRU 1993). In addition, DOE has used these quantities in its Laboratory Accreditation Program (DOELAP) since the 1980s for personnel dosimetry systems. In the body of this TBD, the doses have not been converted to *Hp(10)* values.

The basis for comparison for neutron radiation is more complicated because the calibration of dosimeters to measure neutron dose was based historically on such different dose quantities as first collision dose, multiple collision dose, and dose equivalent index. The starting point for neutron dose reconstruction is the recorded neutron dose values. Additions to the neutron dose would only involve adjustments for missed dose due to the limits of detection (LODs) of the dosimeters. The distribution of missed dose is log normal. Measured dose uncertainty includes fading, missed low-energy dose, and so forth, and its distribution is Gaussian. Table 6-9 later in this document sets forth the International Commission on Radiological Protection (ICRP) Publication 60 correction factors (ICRP 1991) that dose reconstructors should apply to the adjusted dose of record. Attachment 6A shows all of the doses used for reconstruction converted to *Hp(10)* values.

6.3 DOSE RECONSTRUCTION PARAMETERS

Examination of the beta, photon, and neutron radiation types, energies, and geometries of exposure, and the characteristics of the respective Mound dosimeter response are crucial to the assessment of bias and uncertainty of the original recorded dose in relation to the *Hp(10)* radiation quantity. The bias and uncertainty for current dosimetry systems is typically well documented for *Hp(10)*. At some facilities the performance of current dosimetry can be compared with performance characteristics of historic dosimetry systems in 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.

Mound operations included many different tasks in many different facilities, but almost all the work involved either experimenting with or building neutron or heat sources. Therefore, the geometry of the workers in relation to radiation sources is assumed to be anterior-posterior (AP). Unlike some other facilities, in particular Hanford and Savannah River, Mound never had a well-documented quantitative study of its external dosimetry programs. The Mound dosimetry program is clearly derivative. It began in 1948 by emulating the program at Oak Ridge National Laboratory (Meyer 1994, Volume I, 1948 Appendix III, pp. 31-34).[1] Twenty years later Mound was emulating the Nevada Test Site thermoluminescent dosimeter (TLD) program (Meyer 1994, Volume II, p. 104). By 1980, Battelle Columbus Laboratory was implementing the Mound TLD system (Meyer 1994, Volume V, p. 286). In between, there were comparisons with the Hanford and Savannah River systems.

Under NIOSH guidelines, the overall accuracy and precision of the original recorded and individual worker doses and their comparability depend on four factors:

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

- Dosimetry technology, which includes the such physical capabilities of the dosimetry system as the response to different types and energies of radiation (mixed radiation fields in particular)

- Calibration of the respective monitoring systems and similarity of the methods of calibration to sources of exposure in the workplace

- Workplace radiation fields that can include mixed types of radiation as well as variations in exposure geometries and environmental conditions

6.3.1 Mound Administrative Practices

Administrative practices germane to dose reconstruction include policies to:

- Assign dosimeters to workers
- Exchange dosimeters
- Record notational dose
- Estimate dose for missing or damaged dosimeters
- Replace destroyed or missing records
- Evaluate and record dose for incidents
- Obtain and record dose from exposures while working for another employer

Mound had policies for all these administrative practices, although the policies changed over time.

1. *History of Personal External Dosimetry Program at the Dayton Project and Mound Laboratory* (Meyer 1994) is a 2,614-page compilation covering the 46 years from 1946 to 1993. The volume numbers and appendixes are from the Meyer report. Appendix numbers begin anew for each year. There are no page numbers in the Meyer report itself; the cited page numbers are from the Adobe Acrobat Reader electronic copy of the report furnished to the TBD authors.

6.3.1.1 Dosimeter Assignment Policies and Dosimetry

Beginning as early as February 1944, the Dayton Project undertook a personnel monitoring program to measure penetrating gamma radiation received by employees in the process of extracting ^{210}Po from irradiated bismuth slugs from the Clinton reactor at Oak Ridge. Table 6-2 lists the history of Mound dosimetry. In Table 6-2 and the remainder of this document *1 wk* means a 40-hr workweek in a 7-day period ending Friday unless otherwise noted.

Table 6-2. Dosimeter assignment policies.

Date	Photon dosimetry
February 1944	Finger ring (beta) and whole-body film badges provided to some workers. Weekly limits & reports.
August 1946	Wrist film badges provided to production employees. No individual employee data recoverable until January 17, 1947.
February 21, 1949	Operations began in T Building. Film badges, one sensitive and one insensitive film, with 1-mm cadmium filter read weekly and two pocket ion chambers read daily. Beta window not read.
December 1951	Film badges read every 2 wk.
May 1966	Use of pocket ion chambers discontinued.
September 1968	New dosimeters with security credential. Based on Nevada Test Site badges but with different filters. Modified later with TLD photon dosimeters plus Nevada Test Site neutron dose film. In 1977, questions were raised about low-energy photon dose underestimates with tantalum shields.
1972	Routine extremity dosimetry began.
December 1977	All-TLD dosimeters introduced.
October 1986	New soft-pack dosimeters.
June 1991	New hard-pack dosimeters with neutron track etch capability.
June 1993	Added neutron track etch capability for future use.
Date	**Neutron dosimetry**
Before September 1949	No neutron dosimetry data found. Doses estimated at 50 mrem/40-hr wk based on historic modal dose.
September 1949	NTA track etch film for fast neutrons first used in T and R Buildings. Read 10 fields at 980 power magnification and averaged readings.
September 1956	Began reading 10 fields at 430-power magnification with projection microscope and averaged values.
December 2, 1957	Returned to using 980-power projection microscope to read NTA film.
January 21, 1963	Began routine monitoring of night maintenance staff in Building P.
March 1963	Began using 400-power projection microscope. Reading 64 fields and averaging.
October 1964	Began using new projection microscope with better light.
March 1966	Began badging all hourly Engineering Department staff members who spent a portion of their time in radiation control areas of plant.
April 1967	Began using another new projection microscope, first at 500 power, then at 1,000 power.
August 1, 1968	Exchange frequency for Buildings R and SW personnel changed to 4 wk.
Nov./Dec. 1977	All-TLD dosimeters introduced. Began using TLDs for neutron exposure monitoring.
October 1986	New soft-pack dosimeters.
June 1991	New hard-pack dosimeters with neutron track etch capability.
June 1993	Added neutron track etch capability for future use.

6.3.1.2 Historic Dose Limit Standards

The record on historic dose limit standards is ambiguous. As a consequence, a great deal of the record must be inferred. Table 6-3 lists the best set of dose limit standards that can be derived from the record.

6.3.1.3 Dosimeter Exchange Policies

By February 1944 the rings and film badges were exchanged weekly (Ferry 1944b). Between February 1949 and May 1966, pocket ion chambers were exchanged and read daily. After November

1951, film badges were exchanged biweekly. Later, film badges were exchanged monthly or quarterly for those who worked in lower radiation areas. Table 6-4 lists the details.

Table 6-3. Historic dose limit standards.

Period	Radiation type	Dose limits
12/1943-1946(?)	Photon	100 mrem/d, 26rem/yr γ; 500 mrem/d-3.5/wk β, 182 rem/yr β a
August 1946–November 1970	Photon	300 mrem/40-hr wk; 15 rem/yr
December 1970–December 1988	Photon	3 rem/qtr; 12 rem/yr not to exceed an accumulated value of 5(N-18), N = age in years; 200 mrem/wk
January 1, 1989–1997	Photon + neutron	5 rem/yr
August 1, 1949–January 1, 1985	Neutron	300 mrem/40-hr wk; 15 rem/yr
January 1985–December 31, 1988	Neutron	200 mrem/40-hr wk; 12 rem/yr; 3 rem/qtr
January 1, 1989–1997	Neutron + photon	5 rem/yr
1997–2006	Neutron + photon + internal dose	5 rem/yr

a. Source: Ferry (1944b). The doses are from finger ring (beta) and body badges (gamma); 26 rem/yr gamma and 182 rem/yr extremity beta are imputed (52 × weekly limits). The records appear to indicate that only weekly dose limits were imposed.

Table 6-4. Dosimeter exchange frequency.

Period	Dosimeter type	Dosimeter holder	Exchange frequency	Comments
1943-1946(?)	Dental film	Ring and brass badge	Weekly	Not all workers were monitored
8/1946–1/1949	Kodak dental films	Unknown	Weekly	Films worn on wrist only
2/1949–11/1951	DuPont D552	Oak Ridge/steel	Weekly	All radiation workers
12/1951–1957	DuPont D552	Oak Ridge/steel	Biweekly	All radiation workers
1957–1960	DuPont (model unknown)	Oak Ridge/steel	Biweekly	All radiation workers
1961–1962	DuPont 558	Oak Ridge/steel	Biweekly	All radiation workers
1963–1968	DuPont D556	Oak Ridge/steel	Weekly	Some radiation workers
			Biweekly	Most radiation workers
			Monthly	General area workers
1968–1969	DuPont D556	Oak Ridge/steel	Biweekly	Dependent on work area
			Monthly	
			Quarterly	
1970–1977	Kodak Type 3	Mound holder	Biweekly	Dependent on work area
			Monthly	
			Quarterly	
1977–1986	Harshaw 8810 TLD-700	Cycolac	Biweekly	Dependent on work area
			Monthly	
			Quarterly	
1986–1987	Harshaw 8810 TLD-700	Cycolac	Monthly	Dependent on work area
			Quarterly	
1987–1991	Harshaw 8810 TLD-700	Cycolac	Monthly	All employees monitored
			Quarterly	
1991–present	Harshaw 8801 TLD-700	Cycolac	Monthly	Dependent on work area
			Quarterly	

6.3.1.4 Policies To Record Notational Dose

By February 22, 1944, extremity beta doses using finger ring film badges and whole-body photon doses using film badges were reported by worker name (Ferry 1944b). The dose limits were per workday and week, so there is no indication that a continuous record of the doses was kept, only that weekly reports were issued. Beginning in 1946, all doses were recorded. The 1946 results were

entered by code rather than by worker name. With the exception of two names entered for the week of July 19, 1946, the code-name listing is no longer available (Author unknown 1947). The records that begin with the workweek ending Friday, January 17, 1947, have names associated with the recorded doses. The historical threshold of film response to photons was 40 mrad. Several entries greater than 40 mrad in the 1946 data cannot be assigned to anyone because of the lost coding.

After polonium operations began in February 1949, the results of the pocket dosimeter measurements were entered in each employee's radiation exposure record on Form 1015-X, which remained in use until December 1959. Beginning on May 4, 1959, neutron exposure data were entered on punch cards and processed by the External Exposure Analysis System (EXAS) program. Beginning on January 2, 1960, results of both photon and neutron monitoring film were entered on punch cards (Meyer 1994, Volume I, 1960 Appendix I, pp. 133–138). After this time, no film exposure or film dose data were entered on Form 1015-X.

Beginning on March 17, 1963, pocket dosimeter results were entered into a file-card system. The use of punch cards for recording pocket dosimeters ended, and a Kardex file cabinet was purchased for the file cards. The file cards were used from March 25, 1963, until December 27, 1963 (Meyer 1994, Volume I, 1963 Appendix III, p. 263). Beginning on December 30, 1963, pocket dosimeter data were entered on Form 1333, which carried a revision date of March 19, 1963. This form, which permitted the use of a Rolodex V-File for more efficient handling of daily records, remained in use through May 1966.

The External Radiation Analysis Data (ERAD) program replaced EXAS in 1978, and the Mound Environmental Safety and Health (MESH) program replaced ERAD in September 1989. The MESH database contains all radiation doses since 1947, although only the annual summary dose is available for years before 1974.

6.3.1.5 Policies To Estimate Dose from Lost or Damaged Dosimeters

Beginning in 1949, each person carried a film dosimeter and two pocket ion chambers every day. The ion chambers were read the next day and their readings recorded. The program included two pocket ion chambers because they were subject to false readings, usually high, from mechanical stress and heat. The system was, therefore, redundant in relation to damaged or lost pocket dosimeters.

The available records do not indicate any policies for recording dose due to lost or damaged film or TLD photon or neutron dosimeters.

Some records were missing or destroyed. For example, at the end of 1977, the Dosimetry group was unable to recover any individual monitoring data for the previous years from the mainframe computer. Therefore, the system generated a summary report of the annual exposures of all monitored employees from 1947 through 1977 (Guido 2003; Meyer 1994, Volume III, 1973 Appendix 3, pp. 207-211).

Reports written for each incident at the plant contain descriptions of the incident, health physics data for the individuals affected, and recommendations for improved safety for the operations involved.

There were provisions for reporting radiation doses received by individuals who worked at other sites before working at Mound (Meyer 1994, Volume III, 1973 Appendix 3, p. 210).

6.3.1.6 Unmonitored Doses at Mound

Until February 1949, Mound monitored the production workers but not researchers or administrative personnel. Production workers wore the wrist film badges. Therefore, the dose of record before February 1949 is extremity dose only rather than whole-body dose. Because the body is usually farther from the radiation source than the wrist, this analysis assumed that the unmonitored whole-body dose would be less than the monitored extremity dose.

The earliest documented reference to neutron dose monitoring is from a March 26, 1946 letter from J. Russell Hayes to Dr. B.S. Wolf (Hayes 1946). Hayes stated that neutron monitoring experiments had been carried out during the two previous months but recommended that Hayes' lab continue to read the Dayton neutron monitoring film. Writing on August 24, 1948, John E. Bradley stated that the tolerance level for neutrons was 0.1 R/8 hr. He states that 150 n/cm^2/8-hr was considered to equal 0.1 R, which is lower than the 200 n/cm^2/8-hr in effect until the year before (Bradley 1948). However, no neutron dosimetry records have as yet been found for periods before September 1949, so neutron dose before that date is considered to be unmonitored. (Neutron dose monitoring began on August 17, 1949, but was not reported until the Monthly Information Health Report of September 1949.) For the period from 1943 through August 1949, dose reconstructors should assign a neutron dose of 50 mrem/wk. This estimate is based on the modal value of the historic dose distribution recorded after September 1949 (see Table 6-5).

Neutron Dose
The analysis for neutron dose incorporated certain assumptions. First, the analysis assumed a 40-hr wk in a radiation environment. If the workweek was longer, the dose reconstructor should adjust the neutron doses appropriately. Second, the analysis assumed that worker posture during exposure was AP, so the recorded exposure would result in the highest dose for a specific workweek.

After September 1949, when both photon and neutron doses were recorded, the basic dose is the dose of record. Additions should be from missed dose, lost or damaged dosimeters or records, and other such unrecorded or flawed results.

There is a discrepancy in the records about when Mound began to manufacture neutron sources. Meyer (1994) states that the Mound Laboratory was commissioned in August 1948 and that polonium operations did not actually begin at the T Building until February 21, 1949. Meyer further states that monitoring for neutron radiation did not begin until August 1949 when the fabrication of PoBe sources began (Meyer 1994, Volume I, pp. 2, 28, and 84). However, a progress report covering October 1 to 31, 1948, states, "Three sources (WS-9, WS-10, and WS-11) have been prepared and shipped on October 25, 1948 to Unit IV" (Richmond 1948). The neutron emissions of sources WS-9 and WS-10 were counted on October 15, 1948. The emissions of all three sources were counted on October 20 and 25, 1948. These records indicate that Mound Laboratory was manufacturing PoBe sources at least as early as October 15, 1948.

Richmond (1948, pp. 5–6) indicates that Mound shipped a ^{210}PoBe neutron source to Brookhaven National Laboratory on October 25, 1948. The opening paragraph of Richmond (1948, p. 4) references a report (John H. Birden, *Work Done in Preparing Neutron Sources from Polonium and Beryllium between September 5, 1945 and May 25, 1947*, NIM-187) and implies that PoBe sources were manufactured at one or more of the Mound precursor sites between September 5, 1945, and May 25, 1947. Whenever the manufacture of the first PoBe source occurred, Meyer (1994) is clear that monitoring for neutron dose began in August 1949. However, there are no records of the August 1949 neutron monitoring doses. The first report of neutron doses did not occur until the September 1949 Monthly Health Information Report, dated October 18, 1949.

The significance of the discrepancy for dose reconstructors is that they must estimate neutron doses incurred before September 1949. There are records neither for individuals nor for worker cohorts, and

Table 6-5. Dose distribution from 1948 to 1959.[a]

	Photon dose, mrem/exchange				Neutron dose, mrem			
Year	0-50 (0-100)	50-150 (>100)	150-300	300-600 (>500, >300)	0-100	100-300	>300	Data completeness[b]
1948	Note: 1948 is extremity dose, not whole-body dose.							
Workers	95.39%	3.08%	NA	0.85%				11 mo
1949	Note: Whole-body dose measured after January 1949; neutron data began 9/49.							12 mo
Workers	98.06%							
Visitors	100%				(0-120)	(120-300)		
Neutrons	Note: increments 0-0.4 MPL = 0-120 mrem, etc.				99.23%	0.55%	0.22%	
1950								12 mo
Workers	99.53%							
Visitors	99.78%				(0-120)	(120-300)		
Neutrons	Note: Increments 0-0.4 MPL = 0-120 mrem, etc.				99.23%	0.61%	0.17%	1.6X max
1951					(0-120)	(120-300)	<thru 8/51	12 mo
Workers	99.01%	0.72%	0.19%	0.08%				
Visitors	99.72%	0.13%	0.01%	0.13%				
Neutrons	Note: Increments changed to 10-100 mrem 9/51				99.22%	0.78%	0%	
1952	Biweekly badge changeouts began 12/51.							11.5 mo
Workers*	94.23%	2.28%	1.98%	0.15%	*13 received >600 in 1 mo			
Visitors	99.86%	0.14%	0%	0%	*Nov low-dose data missing.			
Neutrons	Note: Increments are 0-100 and >100 mrem				99.60%	0.07%		
1953								11.5 mo
Workers	92.80%	6.39%	1.41 %	0.61 %	Low-dose data unavailable for			
Visitors	99.26%	0.5 7%	0.12%	0.04%	February and June.			
Neutrons					99.51%	0.49%	0%	
1954								3 mo, 3 qtr
Workers	91.74%	5.65%	1.75%	0.94%				
Visitors	98.53%	1.47%	0%	0%				
Neutrons					98.45%	1.55%	0%	
1955								2.5 qtr
Workers***	88.81%	6.10%	2.49%	2.04%	***5 received >600 mrem in 1 qtr			
Visitors	93.29%	6.71%	0	0				
Neutrons					97.55%	2.26%	0.19%	
1956								2 qtr
Workers	92.86%	6.84%	0.30%	0%				
Visitors	93.27%	6.73%	0%	0%				
Neutrons					98.57%	1.43%	0%	
1957								3.5 qtr
Workers	91.23%	8.72%	0.05%	0%				
Visitors	98.96%	1.04%	0%	0%				
Neutrons					93.72%	4.19%	2.09%	
1958								4 qtr
Workers	98.20%	1.75%	0%	0%				
Visitors	97.90%	1.95%	0%	0%				
Neutrons					87.82%	7.44%	4.75%	
1959								2 qtr
Workers	94.80%	5.20%	0%	0%				
Visitors	97.54%	2.46%	0%	0%				
Neutrons					92.86%	5.29%	1.85%	

a. Historic neutron doses at Mound were calculated using the quality factor of 7. See Attachment 6A for ICRP 60 (1991) converted doses.
b. Months and/or quarters of available health physics reports per year

source terms are not available. Therefore, in the absence of measured doses, dose reconstructors should apply the historic modal dose of 50 mrem/wk for all employees for periods before 1949.

Between the beginning of neutron dose monitoring in August 1949 and some indeterminate date (probably the end of 1969), Mound used three terms to set worker exposure limits: *maximum*

permissible exposure, *maximum permissible rate of* exposure, and *maximum permissible level* (MPL) of exposure. The value of this measure was set consistently at 300 mrem/40-hr wk (3.75 rem/qtr or 15 rem/yr) (Meyer 1959; Bigler 1959). Hogerton (1963, Section 7.10) reaffirms this standard.

By November 1970, the maximum allowable external exposure was 3 rem/qt or 12 rem/yr (Author unknown 1970, p. 1). A notation for when this standard changed to 100 mrem/wk or 5 rem/yr was not identified. The 3-rem/qtr standard was still in use on July 15, 1985 (Daily and Wallace 1985), but it was superseded by March 1989. Dose reconstructors should assume that it changed on January 1, 1989.

Table 6-6 lists the types of neutron dosimeters used at Mound.

Table 6-6. Mound neutron dosimeters.

Period	Dosimeter type	Dosimeter holder	Exchange frequency	Comment
1946–1949	None	None	None	No neutron monitoring
1949–8/1951	Kodak NTA	Oak Ridge/steel	Weekly	All radiation workers
8/1951–1957	Kodak NTA	Oak Ridge/steel	Biweekly	All radiation workers
1957–1960	Kodak NTA	Oak Ridge/steel	Biweekly	All radiation workers
1961–1962	Kodak NTA	Oak Ridge/steel	Biweekly	All radiation workers
1963–1968	Kodak NTA	Oak Ridge/steel	Weekly	Some radiation workers
			Biweekly	Most radiation workers
			Monthly	General area workers
1968–1977	Kodak NTA	Mound holder	Weekly	Dependent on work area
			Biweekly	
			Quarterly	
1977–1986	Harshaw TLD-600 TLD-700	Cycolac	Weekly	Dependent on work area
			Biweekly	
			Quarterly	
1986–1987	Harshaw TLD-600 TLD-700	Cycolac	Monthly	Dependent on work area
			Quarterly	
1987–1991	Harshaw TLD-600 TLD-700	Cycolac	Monthly	Dependent on work area
			Quarterly	
1991–2003	Harshaw TLD-600 TLD-700	Cycolac	Monthly	Dependent on work area
			Quarterly	

6.3.2 Dosimeter Types and Badge Distribution

Mound used a film badge external dosimetry monitoring system from 1946 to 1977. From 1977 to the present, Mound has used a TLD system.

Before use, dosimeters were placed in low-risk areas of men's and women's exchange rooms in the different buildings. The dosimeters were on wooden racks with name identification with a section for the film dosimeter and a section for two pocket ionization chambers. The ionization chambers were exchanged daily and read the next morning. The use of pocket ionization chambers stopped in 1966. Film badges were collected on Friday and developed on Monday of the following week (see Table 6-4 for exchange frequency).

Every film packet consisted of two films, one sensitive and one insensitive. If evaluation of the sensitive film was not possible, the insensitive film was used to evaluate exposure (Meyer 1994, Volume I, p. 121). The batch number, week number, and an "HP" number were marked on each film using a 1- or 2-keV X-ray machine.

The neutron flux, which constituted 300 mrem/40-hr wk, underwent a series of changes over this same period. Table 6-7 lists the chronology of how many neutrons per second per centimeter squared per 40 hours constitutes 300 mrem of dose. The term *millirem* came into use at Mound on May 4, 1959. This TBD uses this term for convenience in relation to earlier neutron dose quantities.

Table 6-7. Neutron flux values for 300 mrem/40-hr wk dose.

Date of flux standard	Flux/300-mrem neutron dose
1946?-7/1947	200 $n^0/s/cm^2$/40 hr = 2.873E+07 neutrons/cm^2 = 500 mrem/40-hr workweek through 7/1947
8/1947	150 $n^0/s/cm^2$/40 hr = 2.160E+07 neutrons/cm^2 PoBe sources.
10/1951	75 $n^0/s/cm^2$/40 hr = 1.080E+07 neutrons/cm^2 PoBe and Po-n sources.
1/1955	35 $n^0/s/cm^2$/40 hr = 5.040E+06 neutrons/cm^2.
1/1956	30 $n^0/s/cm^2$/40 hr = 4.320E+06 neutrons/cm^2 PoBe, PoCaF, and Po-n sources.
4/13/1959	55 $n^0/s/cm^2$/40 hr = 6.480E+06 neutrons/cm^2 PoBe, PoCl, and Po-n sources.
8/1963	70 $n^0/s/cm^2$/40 hr = 1.008E+07 neutrons/cm^2 PuF_4 sources measured at 0.75-MeV workplace average energy.
7/15/1968	Track fading correction applied to all neutron film read after this date. Some film (1 wk?) corrected for 36% fading. Two-wk film corrected for 56% fading.
1/1/1969	Exposed neutron film for 4 wk for calibration to compensate for effects of track fading. Percentage corrections for track fading were discontinued after this date.
1/12/1969	Effective date on which 55 $n^0/s/cm^2$/40 hr = 7.92E+06 neutrons/cm^2. 1.3-MeV neutron energy of bare PuF_4 source.
11/12/1997	TLDs used for dosimetry, assume 100 mrem/wk.

Meyer (1994) claims that each neutron flux value from 150 $n^0/s/cm^2$/40 hr to 30 $n^0/s/cm^2$/40 hr to 55 $n^0/s/cm^2$/40 hr equals 300 mrem/wk. Meyer states these changes without explaining why the changes occurred. It might have been that the true workweek was longer than 40 hr assumed by the National Bureau of Standards (NBS 1957), so the 300-mrem/wk flux was reduced to reflect the longer period. The changes might reflect the manufacture of neutron sources that used polonium in combination with elements other than beryllium that had lower neutron energies. For example, on November 26, 1956, there was an incident during the manufacture of a PoCaF source (Richmond 1956). All that is known is that these changes occurred.

According to Meyer (1959), the energy of a neutron from a PoBe source is about 5 MeV. [The 4.2-MeV value is from Shleien, Slaback, and Birky (1998, Table 7.5).] The neutron energy of a PoF neutron is 1.4 MeV, and that of a PoLi source is 0.42 MeV (Shleien, Slaback, and Birky 1998, Table 7.2). The neutron energy from a PoCaF source is lower than the energy from a PoBe source, probably close to the 1.4-MeV value for PoF.

All other values in Meyer (1994) through the beginning of the PuF_4 neutron calibrations in December 1963 have been accepted as stated. The PuF_4 calibrations for 1.3-MeV neutrons have been normalized to 55 $n^0/s/cm^2$/40 hr being equal to 300 mrem/wk.

It is difficult to document the neutron energy assumptions that might have driven the early standard values set forth above. Meyer (1959, footnote 2) stated that the energy of PoBe neutrons was about 5 MeV and their relative biological effectiveness (RBE) was 7, for which he cited four references to NBS Handbook 63 (NBS 1957; see Figure 6-1). However, differing neutron energy assumptions drove the values for 1963 and following years. *Quality factor* and *weighting factor* are more recent terms than RBE for the same concept. Table 6-8 lists contemporary quality factors, which neutron dose reconstructors should consider. Table 6-9 lists energy types and groups for the Dayton Project and Mound Laboratory.

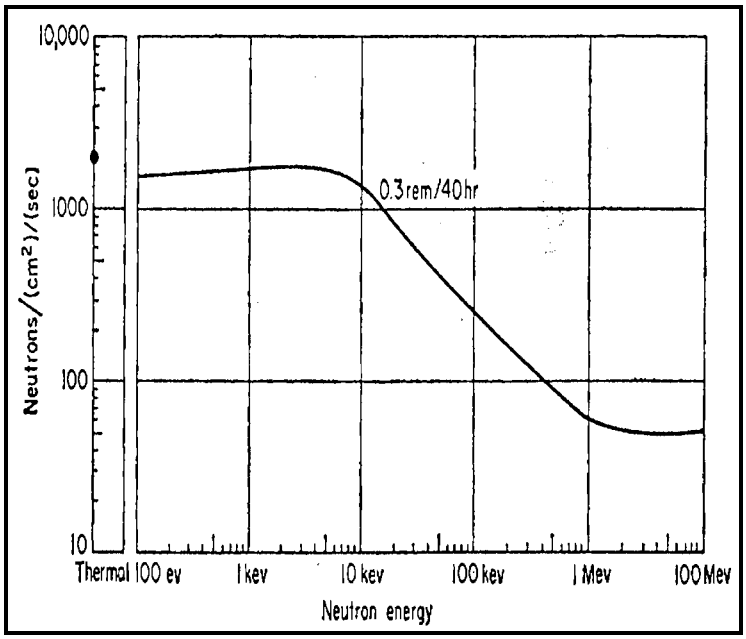

Figure 6-1. Neutron flux producing 300 mrem/40-hr exposure rate versus neutron energy (NBS 1957).

Table 6-8. Radiation weighting factors for neutrons.

Energy	Historic mean quality factor	Mound quality factor	ICRP weighting factor
<10 keV	2,10	7	5
10 keV – <100 keV	10	7	10
100 keV – <2 MeV	10	7	20
2 MeV – <20 MeV	10	7	10
≥ 20 MeV	10	7	5

For example, in August 1963 health physicist John B. Kahle measured neutron levels in the SM Building (from a PuF_4 source) using a DePangher-type instrument he had assembled. He found the average neutron energy in SM Building to be 0.75 MeV after accounting for energy lost to the laboratory environment. Bigler (1963) cited NBS Handbook 63 (NBS 1957; see Figure 6-1), which indicated that a 0.75-MeV neutron flux of 70 $n^0/s/cm^2$ would result in a dose rate of 300 mrem/40 hr. This is the first citation in Mound data of a reference for the conversion of a neutron flux to a dose. The corresponding number of neutrons equal to 300 mrem/40 hr is 1.008×10^7 neutrons/cm^2 or a flux of 70 $n^0/s/cm^2$/40 hr (Bigler 1963; Meyer 1994, 1963 Appendix I, Neutron Film Calibration, pp. I, 255).

In August 1969 (effective December 1, 1969), the unmoderated neutrons from a PuF_4 source were measured with an energy of 1.3 MeV. For 1.3 MeV, the number of neutrons equivalent to 300 mrem was reduced to 7.92×10^6 neutrons/cm^2 or a flux of 55 $n^0/s/cm^2$/40 hr. Even though the average energy of the dosing neutrons might actually have been closer to 0.75 MeV than to 1.3 MeV, taking into account collisions that would occur before the neutrons hit a person, Mound dosimetrists thought it conservative to assume the maximum neutron energy and reduce the number of neutrons equivalent to 300 mrem.

The original (August 1949) neutron source for calibration of films was a PoBe source. Therefore, the energy of the neutrons used for calibration and the energy of the neutrons to which workers were exposed were the same. It is unlikely that lowering of the neutron flux per 300 mrem in 1951 reflected

Table 6-9. Radiation energy intervals and ICRP 60[a] correction factors by facility and process.

Facility	Process type	Period	Radiation type	Energy interval	Percentage	ICRP 60 correction factor
Unit 3	Made PoBe and Po-*n* sources	Oct. 1943–1948	Photon	30–250 keV >250	25 75	
			Neutron	100–2,000 keV 2–20 MeV	25 75	0.72[b] 1.1
Unit 4	Calibrated PoBe sources	Feb, 1944–late 1948	Photon	30–250 keV >250	25 75	
			Neutron	100–2,000 keV 2–20 MeV	25 75	0.72 1.1
Mound Facility		August 1949–2000				
Buildings T, HH, WD, R, B	Po operations PoBe sources	Feb/May 1949–1963				
HH Building			Beta	>15 keV	100	
HH 3, 4, 5, 8	Separation of He-3; Kr-85	1960–1995	Photon	30–250 keV >250 keV	50 50	
HH 5, 6	Pa-231/sludge separation	1955–1956				
HH 8,10-12	Hydrolysis of Al and Bi chlorides	1949–1958				
PP Building	Plutonium processing	12/1967–1995	Beta	>15 keV	100	
Waste Handling Area	Th-232 storage & redrumming	1955–1975	Photon	30–250 keV >250 keV	75 25	
			Neutron	100–2,000 keV 2–20 MeV	75 25	2.2 0.36
R Building	R&D for Po program	1948–1951	Beta	>15 keV	100	
R 117	Storage vault	1949–1990	Photon	30–250 keV >250 keV	50 50	
			Neutron	100–2,000 keV 2–20 MeV	50 50	1.43 0.72
SW Building			Beta	>15 keV	100	
SW 8	Separation of xenon isotopes	1957–1960	Photon	30–250 keV >250 keV	50 50	
SW 11-14 & 16 (area 1B)	Decon of $BiSO_4$ Pa-231 purification	1951–1953 1956	Neutron	100–2,000 keV 2–20 MeV	50 50	1.43 0.72
SW 19 (Old Cave)	Radium-actinium separation	1951–1953				
SW 140 New Cave, SW-132, 136, 137	Processing of residue from pitchblende processing	1970–1979				
SW 146-147	Metrology laboratory	1967–1985				
SW 219	Neutron source production	1962–1965				
T Building			Beta	>15 keV	100	
All but T43,44,48, 50-51, 57-59, & 348-359	Po neutron source program	1949–1973	Photon	30–250 keV >250 keV	50 50	
			Neutron	100–2,000 keV 2–20 MeV	25 75	0.72 1.1
H Building	Hot laundry		Photon	30–250 keV >250 keV	25 75	
WD Building	Waste handling		Beta	>15 keV	100	
WD 1, 8, 101,104	Wastewater treatment	1949–1990	Photon	30–250 keV >250 keV	50 50	
WD 107	Ultra filtration	1976–1981				
WD 112, 113	Analytical work	1966–1979				
WD 113, 118 A&B	Storage, waste incineration	1979–1994				
WD Penthouse	Filter banks	1949–1993				
B Building	Internal dose research	1950–1955	Photon	30–250 keV >250 keV	25 75	

a. ICRP (1991).
b. Sample calculation: Let fraction df = 0.25 for neutron energy between 0.1 and 2.0 MeV. ICRP weighting factor wf60 = 20 sieverts/gray. Mound historic weighting factor mwf = 7 sieverts/gray. Correction factor = (df × wf60)/mwf = (0.25 × 20)/7 = 0.72.

a change in the neutron energy to which workers were exposed, because PoBe sources were still being made.

The PoBe source was last used for calibration before August 9, 1965, for T and SW Buildings (Meyer 1994, Volume I, p. 308). After December 1 and December 19, 1963, respectively, a plutonium fluoride source was used for calibration of film badges worn in the R and SM Buildings (Meyer 1994,

Volume I, p. 274). This analysis assumed that this was because polonium sources were no longer processed in those buildings (Meyer 1994, 1963 Appendix VI, Volume 1, p. 282). However, there was a significant polonium inhalation incident on July 22, 1968 (Storey 1969). Although no new polonium neutron sources were made after early 1963, a 1969 summary report indicates that research and

development work was provided to the AEC. Among other things this work consisted of "... the isotopic separation and purification and sales of highly purified stable noble gases, carbon-13, uranium-234, and polonium-210" (Author unknown 1969, p. 7). However, lowering the 300-mrem/wk neutron flux in years after 1959 probably represents the manufacture of lower energy neutron sources.

Plutonium operations began in the SM Building early in 1962. On March 8, 1963, a PuF_4 source was used for a study of neutron calibration. This was the first neutron calibration using a plutonium source. The effective date of this calibration was retroactive to January 1, 1963. On March 12, 1963, a weekly report noted that, for an equivalent exposure, 2.35 times as many tracks were observed from a PoBe source as from a PuF_4 source (Meyer 1994, 1963 Appendix II, Volume 1, p. 258). This meant that dosimetrists had been underestimating neutron exposures received by personnel in the SM Building. Bigler reported that underestimates would go back to January 1, 1963, which they did. Meyer (1994, Volume 1, pp. 257–258) believed that underestimates should go back to the beginning of plutonium work in SM Building, or early 1962. On August 9, 1965, Bigler wrote, "As of August 9, 1965, all neutron exposures received in the plant were to be estimated on the basis of PuF (sic) neutron calibrations. Before this time we have used PoBe calibrations for exposure estimates in the 'T' and 'SW' Buildings" (Meyer 1994, Volume 1, p. 308).

On December 2, 1969, the value of 55 $n^0/s/cm^2$/40 hr or 7.920×10^6 neutrons/cm^2/40-hr wk was chosen as the Mound standard for a 300-mrem/wk neutron dose. In promulgating this standard Sheehan (1969a) commented, "Although the value is arbitrary, we now feel that it is more appropriate to use the value for 1.3-MeV neutrons since this energy is closer to that emitted from PuO_2, which is the major source of our neutron emissions in the radiation areas." This is the first available record that describes the rationale for using a particular value of neutron flux as a dosimetry standard. The arbitrary nature of this value is confirmed in Phillabaum (1973), which reported that the average neutron energy at Mound was less than 1 MeV based on experience at a Minnesota dosimetry school.

An outline of a publication about a Mound dosimeter provided perspective on neutron energies at Mound: "The neutron spectra in working areas at Mound Facility vary from heavily moderated neutrons averaging 0.5-MeV in production hoods to >2-MeV neutrons from transferring bare sources. NTA [neutron track emulsion, type A] film was not adequate to measure the lower-energy neutrons" (Crain 1978).

Table 6-10 lists the components of neutron TLDs at Mound.

Table 6-10. Neutron TLD card components.

Period	Back filter		TLD Chips		Front filters	
1977–1991	Cd	None	TLD-600	.Absent	Sn	None
	Sn	Sn	TLD-700	TLD-600	Sn	Cd
1991–present	Cd/ABS	ABS	TLD-600	Absent	Sn/ABS	ABS
	Sn/ABS	Sn/ABS	TLD-700	TLD-600	Cd/ABS	Sn/ABS

The energy spectrum of the neutrons has a direct bearing on another persistent problem at Mound, that of track fading in the NTA film. Table 6-11 lists track fading versus neutron energy. While the

relationship is not linear, it is clear that tracks from higher energy neutrons fade less than tracks from lower energy ones.

Table 6-11. Neutron track fading in NTA film versus neutron energy.

Source	Neutron energy	Percent fading/time
PoBe	4.2 MeV	9%/wk (?)
Moderated $^{238}PuO_2$	≈1.3 MeV	16%/1 wk 30%/2 wk
PuF_4	1.3 MeV (bare source)	33%/1 wk 56%/2 wk

a. Meyer (1994, Volume III, p. 23) indicates that the neutron emission energy of this $^{238}PuO_2$ source and the PuF_4 source were about the same.
b. Source: Meyer (1994, E. N. Arnett, Volume II, pp. 107–113).
c. Source: Meyer (1994, C. T. Meyer, Volume II, pp. 96–102).

Table 6-12 lists the 40-yr history of neutron track and TLD signal fading at Mound.

Table 6-12. Neutron track and signal fading study and corrective action history.

Period	Dosimeter type	Study/corrective action taken
1951	NTA film	Meyer (1951) PoBe source track-fading study. No action taken.
Summer 1967	NTA film	Meyer (1968) PuF_4 source track fading study.
July 15, 1967	NTA film	Films corrected for track fading: 33% for 1 wk, 56% for 2 wk.
January 13, 1969	NTA film	Films calibrated over 4 wk to reduce track fading.
March 15, 1976	NTA film	All neutron exposures of record 1970 through 1976 doubled.
Nov/Dec 1977	TLD	Better low neutron energy response than NTA film.
July 16, 1981	TLD	Annealing begun to eliminate 5%/wk for 6 wk signal fading.
January 1, 1983	TLD	Ca-252 used for neutron calibrations.
1991	TLD	DOELAP-approved dosimeters.

The first mention of fading of neutron tracks in NTA film at Mound is in *Experiment for Fading of Latent Image on Type NTA Film Emulsions* (Meyer 1951). The primary purpose of the experiment was "to determine the percentage of proton tracks [proton recoil tracks] which will fade out after a lapse of varying amounts of time between exposure and developing." The secondary purpose was "to [find] out if increasing the developing time for 'old' films will bring out any of the faded tracks." The details of the experiment are set forth carefully, but the available records do not contain the results.

The amount of neutron track fading measured must have been accepted in 1951, or Meyer would have made some changes to the calibration procedure to minimize it. The important point is the recognition of the issue of neutron track fading as early as September 1951. Nothing was done to address the issue until July 15, 1968, which turned out to be significant.

Meyer (1994, 1967 Appendix VII, p. 82, through 1967 Appendix X, p. 119) discusses neutron track fading studies for NTA film in detail, including studies of PoBe, PuF_4, and $^{238}PuO_2$ sources. A conclusion noted that, for exposure to plutonium-fluoride neutrons, an evaluation error of approximately 9% results for each week the worker wore the film due to latent image fading (Meyer 1994, Volume II, pp. 67, 104).

On July 15, 1968, management directed correction for track fading of results of all neutron film processed on and after that date (Meyer 1994, Volume II, p. 119). This included correction of 1-wk film badges for 33% fading and 2-wk badges for 56% fading based on C. T. Meyer (1968). Beginning on January 13, 1969, neutron calibration films were exposed progressively over 4 wk to match the times that different groups of workers wore their badges. This compensated for track fading.

During late 1969 and early 1970, there were experiments on signal fading with TLD-200 phosphors (CaF_2:DY) exposed to ^{137}Cs gamma photons. By February 1970, it had become clear that TLD-200 was not suitable for routine long-term photon monitoring because of signal fading (Meyer 1994, "TLD-200 Signal Fading Studies," Volume III, pp. 86–91). Thereafter, only TLD-600 (^{6}LiF:Mg Ti for neutron detection) and TLD-700 phosphors (^{7}LiF:Mg Ti for photon detection) were investigated for use. Lithium-6 is sensitive to neutrons via the alpha,n reaction. Lithium-7 is sensitive only to thermal and epithermal neutrons but not to higher energy neutrons. Lithium-7 neutron sensitivity was not an issue at Mound because there were no thermal or epithermal neutron sources. The important conclusion is that the neutron energy spectrum must be known to calibrate dosimeters or assign dose accurately.

Figure 6-2 shows the cross-section versus neutron energy for several common neutron-detecting processes. The neutron cross-section of ^{6}Li is linear over almost 6 orders of magnitude of change in neutron energy. However, it has a very pronounced resonance peak at about 200 keV and another smaller peak at about 2,500 keV. In other words, the most nonlinear portion of the ^{6}Li neutron response lies in those portions of the neutron energy spectrum that were important at Mound after 1962 when plutonium sources were manufactured.

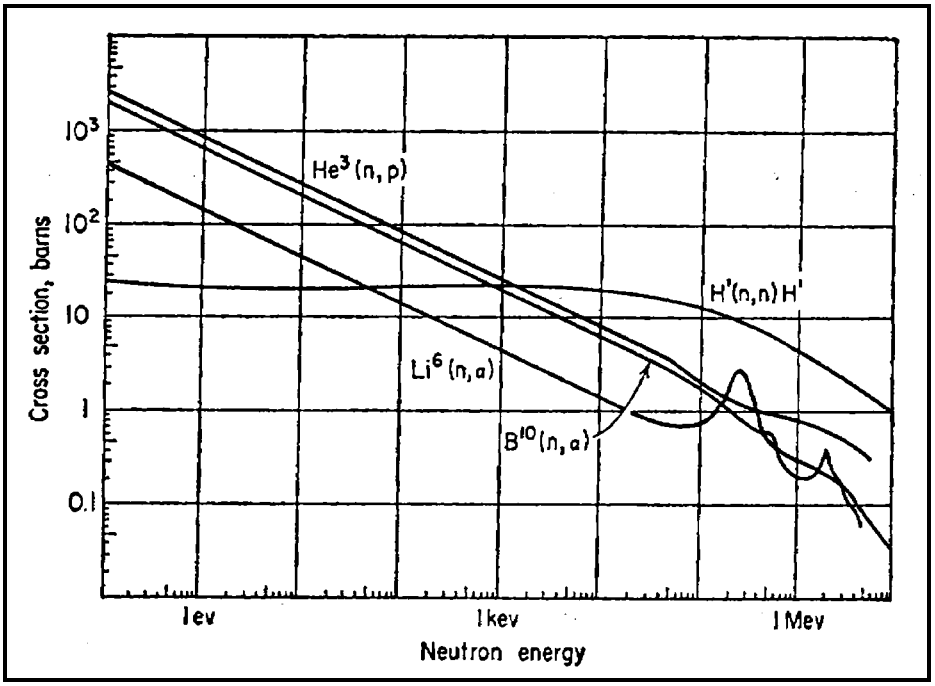

Figure 6-2. Cross-section versus neutron energy for several common neutron-detection processes (Price 1964, p. 312).

In January 1973, *Thermoluminescent Dosimeter (TLD) Fade Study of ^{7}LiF Phosphors* (Bigler 1973), a study of gamma photons and TLD-700 phosphors, indicated that track fading amounted to only about 6%/qtr, which was insignificant (Meyer 1994, Volume III, pp. 200–201). Gamma signal fading on TLD-700 phosphors might have been insignificant but neutron track fading on NTA film was not. On March 15, 1976, Mound management concluded that neutron exposures for 1970 through 1976 were low by a factor of 2 and required adjustment to include a doubling of recorded neutron dose assessments for those years (Meyer 1994, Volume IV, p. 170).

Documentation of Variables in the Assessment of Neutron Doses at Mound Laboratory (Bigler 1978) is an overview of the history of neutron dosimetry at Mound and as such is invaluable in fitting the

documented pieces into the whole picture. One of the many important comments is that Mound began working with ^{238}Pu in 1959 and began manufacturing RTGs in 1960. The PoBe sources manufactured previously had average energies of about 4.5 MeV, whereas the PuO_2 RTG sources had an average energy of about 1.0 MeV. This work occurred in either the R or SM Building until the PP Building became operational in 1970. RTG manufacture in the PP Building in 1970 allowed the stripping of ^{16}O and ^{17}O from ^{18}O before the manufacture of PuO_2 RTG sources, which lowered the neutron dose from the RTG sources significantly (Meyer 1994, Volume IV, pp. 169–185).

From 1970 to 1977, workers wore a TLD photon dosimeter and a separate NTA film neutron dosimeter. November and December 1977 saw the introduction of the new all-TLD dosimeter. Because the TLDs responded well to the lower energy neutrons that characterized the Mound working environment, it seemed that doses were finally being measured accurately. The signal fading problem now affected both neutron and photon dose measurements. Specifically, there was an observed 25% to 30% stored signal fading on both photon and neutron (TLD-600) chips. On June 3, 1981, fading was about 5%/wk for 6 wk (Meyer 1994, Volume V, pp. 310–320), after which it stopped, which meant that some people would get slightly larger doses of record after the TLDs were annealed to stop the signal fading. In addition, Meyer stated that the workers receiving the highest neutron doses were in decontamination and decommissioning in Building PP and that their neutron doses were about 30 mrem/2 wk. This means that they would receive an extra 30 mrem over the span of the second half of 1981, which is not significant.

The penultimate change in neutron dosimetry at Mound was on July 16, 1981. At that time, management decided to anneal the TLDs for 6 hr at 80 ˚C to eliminate signal fading (Meyer 1994, Volume V, p. 344). As of January 1, 1983, ^{252}Cf was used as the neutron calibration source (Meyer 1994, Technical Manual MD-21766, Issue 1, Volume IV, p. 43). In 1991, Mound adopted an all-TLD hard pack DOELAP-approved dosimeter.

Photon Dosimetry

This analysis assumed that workers spent 40 hr/wk in a radiation environment and that their posture was AP, so they received the maximum positional dose for any specific workweek. Dose reconstructors should reconstruct unrecorded dose from coworker doses, area surveys, source terms, or historic summary data. Corrections to the dose of record would be additions to the dose of record.

Table 6-13 lists beta photon dosimeter characteristics. Table 6-5 lists historic dose distribution. Dose reconstructors should use the modal values of this dose distribution to assign unmonitored photon and neutron doses.

Incomplete individual dosimetry has been found from Febuary through June, 1944, but none after that until May, 1946. In the 1946 dosimetry, worker names were numerically coded in the record and the code key has been lost. As a consequence, individual dose records before January 17, 1947, when exposures were again logged by worker name, are not recoverable. No worker cohort doses, records of area monitoring, or source terms are available for this period. Therefore, based on data from 1948 to 1959, this analysis assigned a modal dose of 50 mrem/wk (see Table 6-14).

Recovery of ^{227}Ac from neutron-irradiated ^{226}Ra began in SW Building in the early 1950s. In the range of 500 mR, the film overresponded to the actinium gamma by a factor of 1.7. However, because the gammas from ^{226}Ra, ^{227}Ac and ^{228}Th could not be separated on the dosimeter film, the radium calibration graph was used and all increased film density was treated as radium equivalent. This was a conservative dosimetric assumption. By 1952, the minimum detection for film badges was 34 mrem (Author unknown 1952), perhaps because of the improved film and the low dose calibration (Meyer

1994, Volume I, p. 28). The low-energy window was not read and its dose was not recorded until January 1960 (Meyer 1994, 1960 Appendix III, Volume I, p. 250). After that, the window was read

Table 6-13. Beta-photon dosimeter characteristics.

Period	Packet type	Film component	Exposure range(R)	Filter type	Comment
1944-1946?	Brass, coin envelopes	Dental	Unknown	Brass; none	Too many uncertainties to quantify
1946–1948	Dental size film packet	Unknown	Unknown	Unknown	Possibly Kodak Type K film
1949–1957	DuPont D552	502	0.02-10	Cd	1-mm Cd filter, one on front of film packet
		510	5-800		
1957–1960	DuPont D/Unknown model	508	0.03-5	Cd	1-mm Cd filter, one on front of film packet
		510	5-50		
1961–1962	DuPont D558	502	0.02-10	Cd	1-mm Cd filter, one on front of film packet
		1290	20-3000		
1963–1968	DuPont D556	508	0.03-5	Cd	1-mm Cd filter, one on front of film packet
		834	5-1000		
1968–1969	DuPont D556	508	0.03-5	Cd	--
				Te	
		834	5-1000	ABS	
				Ta	
July 1970–1977	Kodak Type 3	Single-coated	0.030-10	Cd	--
				Te	
		Double-coated	10-800	ABS	
				Ta	

Table 6-14. Unmonitored photon dose at Mound.

Period	Dose reconstruction action
Any facility before January 17, 1947	Assign photon dose of 50 mrem/wk, based on modal dose from Table 6-5.
January 17, 1947, through June 8, 1963	Use average of individual known doses or worker cohort data or modal dose.
June 8, 1963 onward	Use average of individual known doses, worker cohort data, or area monitoring data in R, SM, SW, and T Buildings.

and its dose recorded, so the doses in the records were correct. Table 6-5 lists dose distribution at Mound from 1948 to 1959.

Based on whole-body exposure data from 1965 through July 1969 (Sheehan 1969b), dose reconstructors should retroactively assign maintenance staff 38 mrem/2-wk badge exchange period or 1 rem/yr for the unmonitored period before March 22, 1966 (Meyer 1994, Volume I, 1966 Appendix II, pp. 320-325).

Area monitoring began in the T, R, SM, and SW Buildings between May 25 and June 8, 1963 (Meyer 1994, Volume I, pp. 264-270). If a worker was in these buildings after these dates, dose reconstructors should substitute area-monitoring results for missing doses of record.

Mound introduced new dosimetry on September 1, 1968. Meyer (1994, Volume II, pp. 104–133) asserted that the new dosimeter represented a technical advance in that it incorporated filters to differentiate among the various radiation fields present in the work environment. There are no specifics about how different types of radiation were measured for the record or what the radiation standard was at that time. The training program for November 1970 stated that the radiation dose limits were 3 rem/qtr and 12 rem/yr, with a cumulative dose not to exceed 5 (age 18 yr) rem.

At some point after July 1985, dose standards came into conformance with the International Commission on Radiological Protection recommendation of a maximum of 5 rem/yr (ICRP 1977). The effective date of this change is uncertain, but it was after July 15, 1985, and before March 1989. DOE issued Order 5480.11, "Radiation Protection for Occupational Workers" (updated as DOE 1992) to implement the recommendations in 1987. This analysis assumed that use of the 5-rem/yr standard began at Mound on January 1, 1989.

6.3.3 Energy Spectra

Dosimeter calibration performed at Mound was in-air calibration. Mound did not start to use phantom calibration until the late 1970s. Since the Mound dosimeter database contains only annual summary doses for the years through the end of 1977, dose reconstructors should use the Exposure to Organ Dose DCFs for dose conversions through 1977. Photon calibration was performed by exposing a set of films for the same period but at different distances from the source. Neutron calibrations were performed for the same distance but for different times. This section explains calibration from the start of the Dayton Project in 1946 until the present.

6.3.3.1 Beta/Photon Calibration

A photon calibration strip consisted of eight films. One film was left unexposed and seven were exposed to ^{226}Ra and its decay products at equilibrium to identify a calibration curve of net optical density and exposure. The calibration was performed in an ^{26}Al calibration well with a diameter of 65 cm. Seven film holders were affixed to the calibration well. Film packets were inserted in steel holders distributed about the well at different distances from and angle to the source and exposed for 7 hr. A calibration strip was created with every batch of film processed. The exposure was performed on Friday of every week or the last day of the exchange period. No beta calibration was performed before 1979.

6.3.3.2 Neutron Energy Calibration

Fast neutron calibration was based on exposing a set of five NTA films at a fixed distance from the source but at different exposure times. Calculation of the neutron fluence rate was based on a source strength that yielded 300 mrem/40-hr wk. A set of 10 fields of vision for each film was counted and averaged to derive the number of tracks per field. The number of tracks was plotted against exposure, and the slope of the line was used to calculate the exposure by multiplying the number of tracks per field times the slope of the line.

6.3.3.3 Neutron Energy Spectra

Neutron energy spectra depend on the neutron source. Mound manufactured ^{210}PoBe neutron sources and measured the neutron energy at about 5 MeV. Mound calculations assumed this energy and an RBE of 7. In addition, Mound experimented with other polonium compounds for creating neutrons (for example, a PoCaF source in 1956; Richmond 1956). According to the *Handbook of Health Physics and Radiological Health, 3rd Edition* (Shleien, Slaback, and Birky 1998, Table 7.2), the energy of a PoF source is 1.4 MeV. In the late 1950s, Mound was making PoCl sources (Incident Report 22 1961).

When Mound switched from polonium to plutonium neutron source manufacturing, neutron energies dropped. This was reflected in the lowering of the neutron flux, which constituted 300 mrem/40-hr wk. In 1963, the average energy to which workers on the PuF_4 manufacturing line were exposed was 0.9 MeV (Meyer 1994, Volume VIII, p. 107). In December 1969, management decided that the proper

average neutron energy to use for dosimetry of PuF_4 sources was 1.3 MeV (Meyer 1994, 1969 Appendix VIII, Volume III, pp. 9-10). The calculations and energy spectrum for a $^{238}PuF_4$ source are in Meyer (1994, Volume VIII, pp. 71–72). On February 18, 1974, a health physics technician reported a neutron energy survey in R and PP Buildings. The average neutron energy was 1.01 MeV (Meyer 1994, Volume IV, p. 888). On March 6, 1989, Fix (1989, p. 2) recommended the use of a bare ^{252}Cf spontaneous fission source for neutron dose calibrations.

6.3.3.4 Photon Energy Spectra

That photographic film overestimates the dose from low-energy photons (50-175 keV) has been known for decades. A Manhattan Project report entitled *Photographic Film as a Pocket Radiation Dosimeter* (Perdue, Goldstein, and Wollan 1944) contains a graph of the response of DuPont D502 film to photons in the energy range of about 50 to 1,000 keV. The graph shows an overresponse of about 2 at 50 keV decreasing to 1 at about 175 keV. A recent study by the International Agency for Research on Cancer (IARC; Thierry-Chef et. al. 2002) determined that the overestimation was by a factor of 3 at 118 keV and 1.2 at 208 keV.

There is a family of photon energy-versus-dosimeter response curves from May 25, 1977. A memorandum and accompanying graph show the photon energy and responses of the TLD photon dosimeter (Anderson 1977). Anderson stated that the tantalum shield in the TLD caused an underestimate of the 60-keV photon from ^{241}Am, which he noted was a dose contributor in Building PP. In addition, he noted that some low-energy photon dose from plutonium would be underestimated.

6.3.3.5 Dose Calculation for Film Badges

Photon dose for the two-element dosimeter was calculated as high- and low-gamma dose. The dose under the cadmium filter was the high-gamma dose. The low-gamma dose was calculated by subtracting the high dose from the open-window dose. No beta dose was calculated before 1979. The following have been used to calculate whole-body and skin doses in the periods specified:

- 1946-1952: High-energy gamma dose was the slope of the line of calibrated photon film times the reading of the field film under the cadmium shield. Low-energy gamma dose was not calculated.

- 1953-1959: High-energy gamma dose was the slope of the line of calibrated photon film times the reading of the field film under the cadmium shield.

  Low-energy gamma dose was the slope of the line of calibrated film under the open window times the reading of the field film under the open window.

- 1960-1967: Whole-body gamma dose was the slope of the line of calibrated photon film times the reading of the field film.

  Skin gamma dose was the slope of the line of the calibrated film under the open window times the reading of the field under the open window.

- 1968-1977: Use of a multielement film badge began during this period. Whole-body gamma dose was calculated as follows:

Whole-body gamma dose was the slope of line under the tantalum filter of calibrated film times the reading of the field film under the tantalum filter.

Skin gamma dose was the open window reading times the calibration factor.

Neutron doses were calculated as follows:

- 1949-1977: The neutron dose was calculated by the product of the slope of the tracks per millirem line from calibrated neutron film and the number of tracks per field of the dosimeter film.

  Skin dose was calculated by adding skin gamma dose and neutron dose.

6.3.3.6 Dose Calculation for Thermoluminescent Dosimeters

Table 6-15 lists the history of TLD card components.

Table 6-15. Beta/photon TLD card components.

Period	Back filter		TLD chips		Front filters	
1977–1991	Brass	None	TLD-700	TLD-700	Brass	Open window
	None	None	Absent	Absent	None	None
1991–2006	Cd/ABS	ABS	TLD-700	TLD-700	Cu/ABS	Teflon/ABS
	ABS	ABS	TLD-700	TLD-700	Mylar	ABS

Three photon doses were calculated using TLDs. These were deep dose, shallow dose, and dose to the lens of the eye. Beta dose was calculated in certain parts of the laboratory. The dose evaluations were performed as follows:

- 1977 – 1991: The whole-body gamma dose or penetrating dose was calculated using the following equation:

$$\textit{Whole-body gamma dose}\ (\text{mrem}) = \frac{PG7\text{-}BGR}{CF}$$

where

PG7 = the penetrating gamma dose measured under the brass filter; which is the value of the TLD-700 chip in position 1 on the gamma card

BGR = the background of the gamma cards

CF = the correction factor of the TLD reader

The skin dose is calculated as follows:

$$\textit{Skin dose} = \textit{Skin gamma dose} + \textit{neutron dose} + \textit{beta dose}\ (\text{if measured}).$$

The skin gamma dose due to low-energy gamma is calculated as follows:

$$\textit{Skin gamma dose} = \frac{1.20\text{x}\ (OW7\text{-}BGR)}{CF}$$

where

OW7 = the value of TLD-700 chip in position 2 on the gamma card

1.20 = the correction factor for overresponse of the chip at low energies.

If the calculated skin dose is less than whole-body gamma dose, skin dose is recorded as equal to whole-body gamma dose.

To calculate neutron dose the following equation is used:

$$Neutron\ dose = 0.4 \times (FS6 - BGR) \times R^{1.87}$$

where

$$R = \frac{(FS6 - BGR) - (NG7 - BGR)}{(BS6 - BGR) - (NG7 - BGR)}$$

and

BS6 = TLD -600 in position 1 (Cd shielded on the back of neutron card close to worker's body)

NG7 = TLD 700 in position 4 in the neutron card (Sn shielded on both sides)

FS6 = TLD-600 in position 3 in the neutron card (Cd shielded on the front)

- 1991-2006: Calculation of the whole-body gamma dose and skin dose uses the same equations used for the period from 1977 to 1991. The neutron dose is calculated by the NDOSE computer program, which implements the following calculation (FS6, BS6, and NG7 are as before):

$$Neutron\ dose = N \times 0.4 \times (FS6 - NG7) \times \left(\frac{(FS6 - NG7)}{(BS6 - NG7)}\right)^{1.87}$$

where

$N = 0.739$

If (*FS6-NG7*) is less than zero or (*BS6 - NG7*) is less than zero, the neutron dose is equal to zero.

If $\frac{(FS6 - NG7)}{(BS6 - NG7)}$ is less than 0.5, then $\frac{(FS6 - NG7)}{(BS6 - NG7)} = 0.5$.

If $\frac{(FS6 - NG7)}{(BS6 - NG7)}$ is more than 2.3, then \ = 2.3.

6.4 MISSED OR UNDERREPORTED PHOTON OR BETA DOSE

Table 6-16 lists missed photon doses at Mound. There are four possible sources of missed or underreported photon or beta dose:

1. **Unread beta or low-energy photon doses.** The narrative is not certain, but it seems that the clear portion of the film badges, which would record beta and low-energy photon dose, was not read until at least January 1953 (Meyer 1994, Volume I, p. 90). For example, in a memorandum dated September 1, 1948, Meyer describes the film badge system he had gone to Oak Ridge to study. His report states in part, "Film exposed to gamma rays are developed and read on a densitometer" (Meyer 1994, Volume I, 1948 Appendix III, p. 33). There is no mention of exposure to anything other than gamma rays. On the other hand, the next document (Meyer 1994, Volume I, 1948 Appendix IV, pp. 35-40), by a health physicist from Oak Ridge, states that Oak Ridge used uranium metal to calibrate film badges for beta exposure (Meyer 1994, Volume I, 1948 Appendix IV, pp. 39).

Table 6-16. Missed photon dose.

Type of dosimeter	Period of use	Mode of missed dose	Annual exchange frequency	Mean annual missed dose (mrem)
Two-element film: D502/ D510	Jan 17, 1947–Nov 1951	MDL 40	52	1,040
Two-element film: D502/ D510	Dec 1951–1957	MDL 34	26	442
Two-element film: D508/ D510	1957–1963	MDL 10	26	130
Two-element film: D508/ D834	1963–Dec 1, 1965	MDL 30	26	390
Two-element film: D508/ D834	Dec 1, 1965–1968	MDL 30	26	390
Two-element film: D508/ D834	1968–Nov 13, 1970	MDL 30	12	180
			26	390
Kodak type 3 film only	Nov 13, 1970–Apr 21, 1976	MDL 13	12 (R & SW Bldgs.)	78
			4	26
TLD with Ta shield	Apr 21, 1976–Jul 6, 1981	MDL 20	12	120
		Signal fade[a] 2, 6	4	40
		Tantalum shield loss[b]	26 Bldg. PP	260
			12	24
			4	24
			26	NA
			26, 12, 4	312
			Total 26	572
			Total 12	456
			Total 4	376
TLD without Ta shield	July 6, 1981–1991	MDL 20	Monthly	120
			Quarterly	40
			Biweekly	260 (Bldg PP)

a. Source: Bigler (1973).

b. Anderson (1977) contains graphs showing that the dose recorded by the TLD with the tantalum shield in place underestimates photons below 500 keV. At 200 keV the underestimation is 35%; at 110 keV it is 90%. The 61-keV ^{241}Am photons would have been completely missed. Taylor et al. (1995) identified calibration corrections of 1.119 for *Hp(10)* for Savannah River Site TLD doses before 1985. Because the energy spectrum of photons is unknown, this analysis assumed 11.9% of the permissible dose of 100 mrem/wk, 12 mrem/wk, or 24 mrem/ 2 wk for biweekly badge holders in Building PP. For biweekly badge holders, the geometric mean dose is 24 mrem ÷ 2 wk × 26 biweekly badges = 312 mrem. For monthly badge holders, the geometric mean is 12 mrem/wk × 4.33 wk/mo = 52 mrem/mo ÷ 2 × 12 mo = 312 mrem/yr.

It is clear that it was possible to use the open window of the film badge system to measure beta exposure. It is also clear that when Mound was dealing only with polonium there was no beta radiation. Because there were no beta emissions, there was no beta monitoring. Later, a few areas of the plant had significant beta fields; these were areas in R and T Buildings that

worked with materials containing ^{90}Sr-^{90}Y. On December 1, 1965, technicians began to read the open window as well as the shielded area, and insensitive film as well as sensitive film. The purpose of the additional measurements was to permit better evaluation of low-energy gamma photons (Meyer 1994, Volume I, p. 310). This analysis assumes that Mound evaluated all gamma doses after this date.

2. **The 40-mR (40-mrem) threshold for the film dosimeter response.** The 40-mR (40-mrem) threshold for the photon film dosimeter response is significant. However, a November 1952 memorandum on film darkening measurement comparisons between ^{226}Ra and ^{227}Ac uses 40 mR as the minimum measure for film darkening by ^{226}Ra (Meyer 1952). Film dosimeters were exchanged and read on a weekly basis. Therefore, in a 52-wk yr, 2,080 mrem could have been missed. Because the distribution is lognormal, its geometric mean is [(52 × 40) ÷ 2] 1,040 mrem annual missed dose.

   When operations began at Mound in 1949, the combination of films could cover a gamma radiation range of 20 to 100 R (Meyer 1994, Volume I, p. 90). However, a March 1952 memorandum identified the lowest calibration mark as 40 mR (Meyer 1952).

3. **The pocket ion chambers were read only to the nearest 5 mrem.** This analysis assumed that this means the nearest 5 mrem higher or lower than the actual reading. For example, a value of 22 mrem would be read as 20 mrem but a value of 23 mrem would be read as 25 mrem. The greatest dose that could be underreported would be 2 mrem/dosimeter reading or 10 mrem/wk. If the values were read on the high side of a measurement that was 3 or 4 mrem greater than the nearest lower 5-mrem mark, the low and high readings would result in a net of zero over time. Therefore, this analysis neglected this source of error.

4. **The cadmium or tantalum shield blocked photons below 200 keV from the TLD chip.** The cadmium or tantalum shield blocked the recording of low-energy photons. The original purpose of the cadmium shield was twofold: First, to allow imprinting of identifying codes on the monitoring films using a 1- or 2-keV X-ray machine (Meyer 1994, Volume I, p. 90); and second, "to avoid any contribution by low energy photons" (Meyer 1994, Volume I, p. 20).

   As stated in Section 6.3.3.3, when Mound switched to TLDs, the tantalum shield caused a significant underrecording of gamma photons below about 200 keV. Anderson (1977) contains graphs of TLD response versus gamma photon energy from 10 to 1,000 keV. The graphs make clear that the tantalum shield would have completely attenuated any gamma photons below about 110 keV, and any photons below about 200 to 300 keV would be significantly unrecorded. In particular, this would include the 60-keV gamma from ^{241}Am in area PP. Anderson's recommendation was to read photon doses exclusively from the open-window TLD. P. C. Adams wrote a note on his copy of Anderson (1977) indicating a request for management opinion on the recommendation. There is no record of what action, if any, management took in response to this recommendation.

6.5 MISSED OR UNDERREPORTED NEUTRON DOSE AT MOUND

There are six possible sources of missed or underreported neutron dose at Mound:

- Track fading in NTA film
- Minimum detectable level (MDL) of 50 mrem for NTA film

- Underresponse of NTA film to lower energy neutrons, particularly those less than 500 keV, including albedo neutrons
- Signal fading in TLD neutron dosimeters
- MDL of 10 mrem for TLDs
- Underresponse of TLDs to high-energy neutrons

Table 6-17 lists specific values for missed or unreported neutron doses. Tables 6-18 and 6-19 list MDL values for photon and neutron dosimeters.

Table 6-17. Missed or underreported neutron dose.

Dosimeter	Period of use	Mode of missed dose[a]	Annual badge exchange frequency	Missed dose per badge exchange (mrem)	Maximum annual missed dose (mrem)
NTA film	9/1949–11/1951	1a	Weekly	16.5	858[b]/yr
		2	Weekly	50	2,600[c]/yr
		3	Weekly	7	364[d]/yr
				73.5 total/wk	**3,822 max total/yr**
NTA film	12/1951–1967	1b	Biweekly	28	728/yr
		2	Biweekly	50	1,300/yr
		3	Biweekly	14	364/yr
				92 biweekly total	**2,392 max total/yr**
NTA film	1967–1976	1b	Biweekly	28	728/yr
		2	Biweekly	50	1,300/yr
		3	Biweekly	14	364/yr
				92 biweekly total	**2,392 max total/yr**
		1c	Monthly	19.5 [e]	234/yr
		2	Monthly	50	600/yr
		3	Monthly	100	1,200/yr
				169.5 monthly total	**2,034 max total/yr**
TLDs	1976–1981	4	Monthly	11	132/yr
		5	Monthly	10	120/yr
		6	Monthly	Can't quantify	
				21 monthly total	**252 max total/yr**
		4	Quarterly	15	60/yr[f]
		5	Quarterly	10	40/yr
		6	Quarterly	Can't quantify	
				25 quarterly total	**100 max total/yr**
TLDs	1981–1991	5	Monthly	10	**120 max/yr**
		5	Quarterly	10	**40 max/yr**
		6	Any	Can't quantify	
TLDs	1991–present	5	Quarterly	10	**40 max/yr**

a. Modes of missed dose: 1a, weekly track fading; 1b, biweekly track fading; 1c, monthly track fading; 2, MDL 50 mrem; 3, poor low-energy response; 4, signal fading; 5, minimum detection limit 10 mrem; 6, poor high-energy response.
b. 33% track fading per week calculated as 50 mrem/wk × 0.33 = 16.5 mrem/wk × 52 wk/yr = 858 mrem/yr. For 2-wk badge exchanges, the fading was 56%/2-wk period (50 mrem/wk × 0.56 × 26 badge changes) = 28 mrem/2 wk or 728 mrem/yr.
c. Unrecorded dose due to 50-mrem minimum detection limit calculated as 50 mrem/wk × 52 wk/yr = 2,600 mrem/yr for weekly badge exchanges, 50 × 26 = 1,300 mrem/yr for biweekly badge exchanges, and 50 × 12 = 600 mrem/yr for monthly badge exchanges.
d. Poor low-energy response calculated from the Savannah River Site correction factor of 1.14 neutrons in the energy range of 0.1 to 2 MeV. 50 mrem/wk × 0.14 = 7 mrem/wk or 364 mrem/yr.

e. Calculated as 50 mrem/wk × 52 wk/yr × 4.33 ÷ 12 × 0.09/wk = 19.5 mrem/mo or 234 mrem/yr.
f. Signal fade calculated as 50 mrem/wk × 0.05/wk × 4.33 wk/mo = 11 mrem/mo or × 6-wk fade/qtr = 15 mrem for the first 6 wk of each quarter × 4 qtr = 60 mrem/yr.

6.6 DOSIMETER UNCERTAINTY ANALYSES

6.6.1 Photon Dosimeters

This section discusses laboratory uncertainty. Dosimeter response uncertainty has a normal distribution. Laboratory uncertainty includes the exposure of film to laboratory sources, the developing process, the densitometer reading process, and the calibration values used to calculate film exposure to film net optical density. Those uncertainties are calculated and combined using the propagation of error and assuming that all variables are independent. Dosimeter uncertainty is a function of exposure: As the exposure gets closer to the dosimeter LOD, the uncertainty becomes ±100%. Table 6-20 lists relative uncertainty at the 95% confidence level for a study performed at the Nevada Test Site, which used the same type of film as Mound (NTS 2003). Similar values were assumed for films that were different.

Table 6-18. Photon dosimeter limits of detection.

Period	Dosimeter type	LOD (mR)[a]
1946–1949	Dental Film	40
1949–1957	DuPont D552	34
1957–1960	DuPont unknown model	10
1961–1962	DuPont 558	20
1963–1968	DuPont D556	30
1968–1969	DuPont D556	30
1970–1977	Kodak Type 3	13
1977–1991	Harshaw TLD-700	20
1991–2006	Harshaw TLD-700	20

a. Photon LODs based on Mound historical record.

Table 6-19. Neutron dosimeter limits of detection.

Period	Dosimeter type	LOD (mrem)[a]
1949-1957	Kodak NTA	50
1957-1960	Kodak NTA	50
1961-1962	Kodak NTA	50
1963-1968	Kodak NTA	50
1968-1977	Kodak NTA	50
1977-2006	Harshaw TLD-600	10

a. NTA film LOD value based on Wilson et al. (1990).

An IARC study simulated different exposure geometries and three photon energies (Thierry-Chef et al. 2000). Irradiation was performed on a slab phantom and the anthropomorphic Alderson RANDO phantom. The amount of air kerma used in this study was 5.0 milligray. Table 6-21 lists the IARC comparison between measured dose and *Hp(10)*. The mean ratio reflects the ratio between reported dose and the *Hp(10)* delivered. For the two-element film dosimeter at 118 keV, the measured dose overestimates the *Hp(10)* delivered by a factor of 3.0 for the AP geometry. At higher photon energies the measured dose and delivered dose are the same for the AP geometry.

6.6.2 Neutron Dosimeters

Calculation of neutron uncertainty is based on the simplified method in *External Dose Reconstruction Implementation Guidelines* (NIOSH 2002, p.28), which also considers laboratory uncertainty. The major uncertainty source in neutron film is the reading of tracks per field. At Mound, the number of fields and field size changed over time. At the beginning of the neutron-monitoring program in 1949, the number of fields read was 10 or 11; later it was 40, then 64. In addition, the area changed from 1.22 mm^2 to 1.88 mm^2 (from Meyer 1994, Volume VIII, *Neutron Film Calibrations,* pp. 5-9, 11-12). The relative uncertainty was calculated and tabulated based on the dose range and the number of films at each dose level. When information for a year was unavailable, uncertainty was assumed from the years for which information was available. Table 6-22 lists the 95% confidence level uncertainty. Uncertainty becomes large, almost 100%, as dose level gets closer to the dosimeter LOD.

Table 6-20. Photon dosimeter relative uncertainty.

Period	Dosimeter type	Exposure range (mR)	95% confidence level uncertainty
1946–1948[a]	Dental films	10-30	±100%
		30-1,000	±28%
		Above 1,000	±10-15%
1949–1956	DuPont D552	10-20	±100%
		20-1,000	±28%
		Above 1,000	±10-15%
1957–1960	DuPont/unknown model, may be D552	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1961–1962	DuPont D558	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1963–1969	DuPont D556	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1970–1977	Kodak Type 3	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1978–1991	Harshaw TLD-700	10-30 mrem	± 100%
		30-100 mrem	±30%
1992–2003	Harshaw TLD-700	10-30 mrem	± 100%
		30-100 mrem	±30%

a. Dental film was used until January 1949.

Table 6-21. IARC testing for three photon qualities performed on US beta/photon dosimeter.

Geometry	Phantom	118 keV		208 keV		662 keV	
		Mean ratio*	SD/mean %	Mean ratio*	SD/mean %	Mean ratio*	SD/mean %
US-2 (two-element film dosimeter)							
A-P	Slab	3.0	2.1	1.3	1.0	1.0	0.8
A-P	Anthropomorphic	3.0	4.2	1.2	1.9	1.0	1.8
Rotational	Anthropomorphic	2.2	2.0	1.4	3.0	1.2	3.2
Isotropic	Anthropomorphic	1.5	4.4	1.1	1.6	1.0	2.7
US-8 (multielement film dosimeter)							
A-P	Slab	1.0	1,5	1.0	0.8	0.8	1.7
A-P	Anthropomorphic	0.8	9.5	0.9	6.0	0.8	1.8
Rotational	Anthropomorphic	1.2	1.9	1.2	17	1.1	1.8

* Column title altered by C. Wesley Proctor.

Uncertainty in neutron TLD card response depends on several sources, including TLD reader sensitivity, variability of LiF crystal responses, energy of the neutron spectrum, interference of photon radiation on neutron dose, and level of exposure to be detected by the TLD.

Reader sensitivity and LiF crystal response can be estimated at about 10%. At low neutron energies (around 200 keV), the estimated overall uncertainty due to overresponse is about 120% unless corrected for in calibration (see Figure 6-2). At very low exposure levels close to background, the overall uncertainty approaches 100%.

Missed Dose Uncertainty Analysis

Doses reported as zero or less than the LOD can be calculated using the LOD/2 method suggested in NIOSH (2002). The missed dose is a function of dosimeter exchange frequency, the dose of record reporting format, and whether the number of zeros is known. Table 6-18 lists photon dosimeter LOD values. Table 6-19 lists LOD values for neutron dosimeters. The modeling of uncertainties in annual

Table 6-22. Neutron dosimeter relative uncertainties.

Period	Dosimeter type	Dose range (mrem)	95% confidence level uncertainty
9/1949-1957	Kodak NTA	10-20	±100%
		20-1,000	±28%
		Above 1,000	±10-15%
1957-1960	Kodak NTA	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1961 -1962	Kodak NTA	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1963-1969	Kodak NTA	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
1970-11/1977	Kodak NTA	10-30	±100%
		30-1,000	±20%
		Above 1,000	±10-15%
12/1977-1991	Harshaw TLD	10-30 mrem	± 100%
		30-100 mrem	±30%
1992-2003	Harshaw TLD	10-30 mrem	± 100%
		30-100 mrem	±30%

missed photon dose uses a lognormal distribution with a median dose equal to the product of LOD/2 and the number of zero measurements. The upper 95% dose is calculated by the product of LOD and number of zero measurements. When applying this method, the dose reconstructor must keep in mind that the LOD/2 methodology does not apply to *neutron* doses when they are large in relation to photon doses, as is the case at Mound (NIOSH 2002, p. A38).

6.6.3 General Field Characterization

Two sources of radiation in the facilities are considered:

- Process Radiation Field: This source is dependent on the process and time.
- Cumulative radiation source due to accidents and engineering control failures: This source is deposited on walls and floors in the facility where radiation work occurs, is different for each facility, and accumulates with time. In accordance with NIOSH dose reconstruction project direction, only the AP body geometry is to be considered in assigning dose, so this analysis does not address these sources.

Uniform radiation fields were assumed for this analysis and were considered routine fields. Accidental fields and nonuniform fields were not considered. All site facilities were characterized by assumptions or from energy measurements performed at the sites (Meyer 1994, Vol. III, 1974 Appendix I, pp. 217-222). Energy measurements of neutrons were performed in certain years; a grid of measurement would be performed and average neutron energy would be calculated for the entire building. Assumptions for other energy groups are based on the type of isotope and possible energies emitted per decay. Table 6-23 lists the facilities and the corresponding energy ranges.

Table 6-23. Externally hazardous radionuclide matrix [a]

Facility	Process type	Period	Externally hazardous radionuclides
Unit 1	Po separation research	1943–1945	Ra-226, Sc-46, Zn-65, Hg-203, Ag-110m, Fe-59, Co-60, Bi-210
Unit 2	Chemical	1943–1945	No radioisotopes
Unit 3	Po production; made PoBe and Po-*n* sources	Oct. 1943–1948	Sc-46, Zn-65, Hg-203, Ag-110m, Fe-59, Co-60, Bi-210; PoBe sources and other Po-*n* sources
Unit 4	Po production, calibrated PoBe sources	Feb, 1944–late 1948	Sc-46, Zn-65, Hg-203, Ag-110m, Fe-59, Co-60, Bi-210; PoBe sources
Warehouse	Bioassay	1946–1949	None
Mound Facility		August, 1949–2000	
Buildings T, HH, WD, R, B	Po operations PoBe sources	Feb/May 1949 – 1963	PoBe sources, Ra calibration sources, Co-60, Cr-55, Sr-90, Pb-210, Cs-137
HH Building			
HH 3, 4, 5, 8	Separation of He-3; Kr-85	1960–1995	Xe-131 from reactor fission, Kr-85
HH 5, 6	Pa-231/sludge separation	1955–1956	Co-60
HH 8,10-12	Hydrolysis of Al & Bi chlorides	1949–1958	Co-60, Fe-55, Cr-55, Sr-90, 100-mrem gamma at 1 foot
PP Building	Plutonium processing	12/1967–1995	Pu-238,239 plus trace amounts of Am-241
Waste Handling Area	Th-232 storage & redrumming	1955–1975	Th-232 and daughters, Pu-238, 239
R Building	R&D for Po & Pu programs	1948–2002	
R 117	Storage vault	1949–1990	PoBe, ^{238}PuBe and ^{239}PuBe neutrons
SW Building			
SW 8	Separation of xenon Isotopes	1957–1960	Xe-131 from reactor fission (process moved to HH Building later)
SW 11-14 & 16 (area 1B)	Decon of $BiSO_4$ Pa-231 purification	1951–1953 1956	Implementation of HH Building pilot project. Sr-Y-90, Cs-137, High gamma activity. Fe-59, Co-60
SW 19 (Old Cave)	Radium-actinium separation	1951–1953	Ra-226, Ac-227. By 1957, area was filled with concrete for external radiation protection. High gamma.
SW 140 New Cave, SW-132, 136, 137	Processing of residue from pitchblende processing	1970–1979	Ra-223, -224, -226
SW 146-147	Metrology laboratory	1967–1985	Co-60 source
SW 219	Neutron source production	1962–1965	PoBe, ^{238}PuBe, ^{239}PuBe neutron sources
T Building			
All but T43,44,48, 50-51, 57-59, & 348-359	Po neutron source program	1949–1973	Co-60, Cs-137, Bi-210, Sr-90, Y-90, Sc-46, Zn-65, Hg-203, Ag-110m, Fe-59, Bi-210
H Building	Hot laundry		Possibly trace Ra-226
WD Building	Waste handling		
WD 1, 8, 101,104	Wastewater treatment	1949–1990	$PoCl_2$; Fe-55; Co-60; Cs-137; Sr-90; Y-90; Am-241; Ra-224, -226, -228; K-40, Pu-238, 239
WD 107	Ultrafiltration	1976–1981	Cs-137, Am-241
WD 112, 113	Analytical work	1966–1979	Cs-137, Co-60
WD 113, 118 A&B	Storage, waste incineration	1979–1994	Cs-137, Co-60, Sr-90
WD Penthouse	Filter banks	1949–1993	Cs-137, Co-60, Sr-90, Am-241
B Building	Internal dose research	1950–1955	Minor Ra-226 contamination

a. Plutonium emits both spontaneous fission neutrons and gamma photons.

6.6.3.1 Photon Field

Sources of photons exist in almost all Mound facilities (see Table 6-1). The assumption of the two different groups was based on the processes and the surrounding shielding of each component of the facility and work areas. When photons are created, they are at high energies. As they slow down due to their interaction with air and shielding materials, the energies decrease due to Compton scattering. K and L fluorescent X-ray photons are produced.

6.6.3.2 Beta Field

Based on site isotopic inventory, most betas are created with energies above 14 keV. Polonium-210 does not emit betas. Strontium-90 was present in some places at Mound (see Table 6-22) during this period (King 1995).

In addition, there were several beta-emitting contaminants of the irradiation process that produced ^{210}Bi slugs in production reactors, including ^{210}Bi itself. The slugs were shipped to Mound for the extraction of polonium. For example, a shipment of irradiated slugs was received from Hanford on June 19, 1956. After the slugs were removed from the shipping casks, the water in the casks was drained and analyzed. The beta activity of 1 lambda of water from each cask was too high to count (Meyer 1956, p. 5). Another bismuth slug shipment from Hanford, received on April 12, 1957, had beta-contaminated water (Meyer 1957, p.4).

According to Wilcox (1965) the polonium production slurry, which had been aged from 6 months to a year, contained the following beta emitters: Sc-46, Zn-65, Se-75, Hg-203, Ag-110m, Fe-59, and Co-60. Significantly, Wilcox stated that there was no Sr-90 or Cs-137 in the slurry. The slug shipments themselves almost certainly contained radiologically significant quantities of ^{210}Bi, but because ^{210}Bi has a half-life of 5 days it was gone by the time the waste slurry had been aged for disposal. The electron emission from Se-75 has an energy of 12 keV. It is not externally hazardous and will not be considered further. Wilcox wrote that between October 1961 and July 1964, 7,599 30-gallon drums of ^{210}Po slurry had been shipped to Oak Ridge for burial and that burials before that time were "comparable in quantity and content." It was anticipated that 2,000 more barrels would be shipped in 1965, each containing less than two curies (Wilcox 1965). In 1971, a pilot unit was constructed to explore improvements in the processing of gross alpha and beta materials passing through the Mound Waste Disposal Facility (Flitcraft 1971, p. 15). Table 6-24 lists the beta emmiters of concern from polonium production.

Table 6-24. Externally hazardous beta emitters from polonium production at Mound.

Isotope	Maximum energy (MeV)	Average energy (MeV)	Half-life
Sc-46	0.357	0.112	84 days
Zn-65	0.329 (β+)	0.143	244 days
Hg-203	0.213	0.580	47 days
Ag-110m	0.531	0.165	250 days
Fe-59	1.565	0.615	45 days
Co-60	0.317	0.096	5.27 yr
Bi-210	1.161	0.389	5 days

Because of the quantity of bismuth processed, the contaminating isotopes listed above are the source of most of the potential beta dose at Mound through the decommissioning and cleanup of polonium operations in 1971. As early as October 1944, Captain Ferry reported that lead-lined gloves and tongs were needed to handle the irradiated bismuth slugs because of the beta radiation they emitted (Ferry 1944a) In 1944 the tolerance level for beta dose to the hands was 500 mrem/8-hr day or 3.5 rem/40-hour week (Ferry 1944c). Therefore, the fact that lead lined gloves and tongs were necessary for handling bismuth slugs must mean that there was such a magnitude of beta radiation that even these lax extremity dose limits could not be met without them. A 1995 study performed at Mound (EG&G 1995) shows a lower LOD for beta particles to be about 53 mrem. This MDL for beta particles is based on a quarterly monitoring interval (Mound 2002).

6.6.3.3 Neutron Field

Mound has dealt with polonium-based neutron sources of all kinds, principally PoBe sources, as well as plutonium-based sources, principally PuF_4 and PuO_2. In the early years, Mound experimented with liquid and gaseous polonium neutron sources, and finally settled on solid-state sources. These products were used for initiators for nuclear weapons, calibration, and electric power for spacecraft.

Neutrons were generated by the reaction of an alpha particle with an atomic nucleus, the (alpha,n) reaction. Polonium and plutonium produce alpha particles. In the early years, Mound settled on the use of beryllium as a target for alpha particles. With its low atomic mass number, beryllium produces neutrons with very high energies, between 4.0 and 4.5 MeV. After about 1959, Mound made sources with higher atomic mass numbers, such as oxygen and fluorine, which produced neutrons with lower energies, around 1.3 MeV. For the manufacture of RTGs for spacecraft, Mound selectively used plutonium and ^{18}O, the highest common atomic mass of oxygen, to minimize neutron emissions from the RTGs. The use of plutonium as a component of neutron and electricity sources added a minor component of spontaneous fission neutrons to the neutron energy mix.

Neutron weighting factor adjustments
At Mound a quality factor of 7.0 is used with all neutron energies (Meyer 1959). To obtain the correction factors, the dose fraction per neutron energy is multiplied by the ICRP Publication 60 weighting factor (ICRP 1991) and the product is divided by the Mound quality factor. For example, a dose fraction of 25% for neutrons with energies between 0.1 and 2.0 MeV with a Publication 60 weighting factor of 20 and a Mound quality factor of 7.0 results in a correction factor of 0.72. Neutron doses must be adjusted accordingly. Table 6-23 lists the correction factors.

6.6.3.4 Mixed Field

Most Mound facilities have or had mixed fields of neutrons and photons. The beta field probably is not a concern for external radiation protection because the shielding around the glovebox or process shielding can stop the range of the maximum beta. For researchers who deal with samples of beta-emitting isotopes, gloves and a laboratory coat would stop most beta radiation. In general, the ratio of neutrons to photons produced at Mound was 2 to 1 (Anderson and Crain 1981; Anderson 1985).

6.7 WORKDAY HOURS AND EXPOSURE GEOMETRY

The amount of time spent at each task is based on the lowest amount of exposure. A health physicist determines the amount of time required for the task and assigns the number of workers for the task that will yield the minimum amount of exposure. To be claimant-favorable, an 8- to 10-hr workday is assumed.

All worker geometry is assumed to be AP for 100% of worked hours for all workers.

6.8 GUIDE TO IMPORTANT TABLES

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GLOSSARY

absorbed dose
The energy absorbed per unit mass at a specific place in a material. The historical unit of absorbed dose is the rad; the International System unit of absorbed dose is the gray, which is joules per kilogram; 1 gray equals 100 rad.

accident dosimetry
Determination of high levels of deep absorbed dose resulting from uncontrolled conditions.

albedo effect
As used in this document, the neutron dosimeter response caused by the moderating and backscattering properties of a phantom or the human thorax for neutron radiation.

algorithm
A computational process for calculating dose equivalent from the response of individual elements in a dosimeter.

angular dependence
The response of a dosimeter as a function of the angle of incidence of the radiation detected compared with its response at normal incidence.

backscatter
Scattered radiation with an angle more than 90 degrees from the incident direction.

beta particle
An electron or positron emitted from a nucleus during beta decay.

beta radiation
Radiation consisting of beta particles.

blackness
The effect of radiation on a film dosimeter.

calibration
Adjustment or determination of the response or reading of an instrument relative to a standard or a series of conventionally true values.

deep dose
Deep dose equivalent at a tissue depth of 1,000 milligrams per square centimeter.

densitometer
A device used to measure the amount of blackness on a film dosimeter.

density reading
The reading obtained from the densitometer when a film badge is read. It is the log of the ratio of reference light intensity to the transmitted light intensity of the film.

DOE Laboratory Accreditation Program (DOELAP)
Laboratory accreditation program administered by the U.S. Department of Energy.

dose equivalent
The product of absorbed dose and radiation quality factor at the point of interest in tissue. The historic unit of dose equivalent is the rem. When absorbed dose is expressed in rad, dose equivalent is expressed in rem. When absorbed dose is expressed in gray, dose equivalent is expressed in sieverts, where 1 sievert equals 100 rem.

dosimeter
Complete assembly consisting of dosimeter card containing radiation sensitive phosphors or a film packet inserted into a dosimeter holder.

dosimeter card
An aluminum card containing one or more radiation responsive phosphors.

dosimeter holder
A plastic holder used to contain the dosimeter card. The holder typically has one or more metallic filters used to modify the response of the phosphor to radiation.

dosimetry system
A system used to assess dose equivalent from external radiation. This system includes the selection, placement, and processing of the dosimeters; interpretation and recording of results; and the means by which the quality of results is assured.

External Radiation Analysis Database (ERAD)
Contains exposure history of a radiation worker. Used at Mound from 1978 to 1989.

External Exposure Analysis System (EXAS)
Contains exposure history of a radiation worker. Used at Mound from 1958 to 1978.

external dosimetry
Theory and application of the principles and techniques involved in the measurement and recording of radiation absorbed dose, dose equivalent, and effective dose equivalent from external sources of radiation.

extremities
The hand and arm below the elbow, or the feet and legs below the knee

eye dose
Refers to dose at a tissue depth of 300 milligrams per square centimeter.

facility-specific calibration factor
The dosimeter calibration factor applicable to a particular occupational environment. These factors are determined by comparison of reference instrument with dosimeter response measurements. Both measurements are performed in the workplace.

fast neutrons
Neutrons with energies greater than 10 keV and less than 10 MeV.

field calibration
The calibration of dosimeters based on radiation types, intensities and energies of the work environment.

film
A radiation-sensitive medium used to measure radiation absorbed by radiation worker.

film density
See optical density.

Form 1015-X
The form on which the worker dose record is coded. It was used at Mound before 1958.

free field dose equivalent
The dose equivalent assigned for neutron irradiation as if it were performed in free space with no background due to air and room scattering and no source asymmetry.

high gamma dose
Penetrating gamma dose measured under the shielded portion of film badge.

in-air exposure
As used in this document, exposure of a dosimeter without any phantom.

ionizing radiation
Any radiation capable of displacing electrons from atoms or molecules, thereby producing ions

isotopes
Different forms of the same element that contain the same atomic number.

lower limit of detection
The minimum evaluated dose equivalent for which the readout value of a dosimeter is significantly different at the 95% confidence level from the readout value at the detection threshold.

low gamma dose
Nonpenetrating gamma dose.

Manhattan Engineering District (MED)
A government-based project to develop a nuclear bomb and study the characteristics of all elements of interest associated with all elements of the program.

MESH database
A Mound environmental, safety, and health database that includes radiation exposure history of an individual radiation worker. It has been used at Mound from 1989 to the present.

radiation monitoring
Actions intended to detect and quantify radiological conditions.

neutron activation
The process in which atomic nuclei become radioactive by absorption of neutrons.

neutron radiation
One of the fundamental particles of the atomic nucleus with a neutral charge.

nonuniform fields
The condition when a portion of the body is expected to receive a radiation dose equivalent that varies by more than 50% from dose equivalent expected at a reference location.

nonpenetrating dose
As used in this document, the photon dose of long wavelength measured under the open window.

on-phantom
As used in this document, exposure of dosimeters affixed to a phantom to simulate the dosimeter response while the dosimeter is being worn by a person.

open window
The part of a dosimeter that contains no metallic filter and no holder mass. The only material between radiation and film is the wrapping paper of the film.

optical density
A measure of a degree of blackness of film dosimeter. It is the log of the ratio of reference light intensity to the transmitted light intensity of the film.

penetrating dose
Deep photon dose measured at 1,000 milligrams per square centimeter.

phantom
A slab of plastic, typically measuring either 30 by 30 centimeters square by 15 centimeters deep or 40 by 40 centimeters square by 15 centimeters deep, used to simulate the effect of the body on dosimeter response. Can also refer to an anthropomorphic phantom used for the same purpose.

photon radiation
Either X- or gamma radiation.

protection dosimetry
Routine estimation of the shallow and deep dose.

quality factor
A modification factor used to obtain dose equivalent form absorbed dose.

radiation
As used in this document, ionizing radiation.

radiation worker
An occupational worker whose job assignment requires work on, with, or in the proximity of radiation–producing machines or radioactive materials and/or who has the potential of being routinely exposed above 0.1 rem per year, where the total annual dose is the sum of the annual effective dose equivalent from external irradiation and the committed effective dose equivalent from internal irradiation.

radioactivity
Unstable isotopes that release energy in the form of particles and/or electromagnetic radiation by a process of disintegration.

rad

The historical unit of absorbed dose. One rad is equal to 100 ergs per gram. The word derives from *radiation absorbed dose*.

relative biological effectiveness (RBE)

The ratio of dose of X-rays required for a biological effect to dose of other radiation that produces the same effect.

roentgen

A special unit of radiation used to quantify ionization in air from photon radiation. One roentgen is equivalent to 2.58×10^{-4} coulomb per kilogram.

rep

The amount of energy absorbed per unit mass of tissue; 1 rep is equal to 93 ergs per gram of absorbed in tissue. The term derives from *roentgen-equivalent-physical*.

rem

The historical unit of dose equivalent. The word derives from *roentgen equivalent [in] man*.

scattering

A process by which particles can change direction and have a momentum and energy change.

sievert

The special name for the International System unit of dose equivalent; 1 sievert equals 1 joule per kilogram, which equals 100 rem.

shallow dose equivalent

Dose equivalent measured at 7 milligrams per centimeter squared.

skin dose

Shallow dose equivalent at a tissue depth of 7 milligrams per centimeter squared.

superficial dose

Another term for skin dose.

thermal neutrons

Neutrons in thermal equilibrium in the medium. The mean energy of thermal neutrons is 0.025 electron-volts.

TLD chip

A compound made of lithium fluoride and activated by manganese and thallium that stores energy in crystal imperfections.

thermoluminescent dosimeter (TLD)

A type of dosimeter that relies on excitation of the crystalline lattice by radiation of certain fluorescent materials that emit light when heated.

whole-body dose equivalent

The dose equivalent that results when the whole body is irradiated. If the irradiation is uniform, whole-body dose equivalent is the same as effective dose equivalent. Whole-body dose equivalent is expressed in the same units as dose equivalent.

whole-body irradiation

Uniform radiation exposure of the gonads, active blood-forming organs, head, trunk, lens of the eye, arms above and including the elbow, and legs above and including the knee.

ATTACHMENT 6A
SUMMARY INSTRUCTIONS FOR MOUND DOSE RECONSTRUCTORS

The entire record of weekly, biweekly, or monthly doses to individuals between 1947 and the end of 1977 has been lost (Guido 2003). As a consequence, unless other records are found or the claimant can provide detailed records, all dose records for 1947 through 1977 consist only of annual dose summaries for each monitored worker. Therefore, missed dose increments through the end of 1977 are given in annual units so the dose reconstructor can add them directly to the annual dose summaries that comprise the extant dose of record. These missed dose increments are the maximum possible missed doses calculated from the most frequent badge exchanges for each period. If there is no annual dose of record, dose reconstructors should assume that the base annual dose for this period is the cohort dose or the modal neutron and photon dose for 1949 through 1959 (i.e., 50 mrem/wk for 52 wk/yr is 2,600 mrem/yr for neutrons or 1,040 mrem/yr for photons).

Corrected neutron doses: The base and missed neutron doses are multiplied by the ICRP 60 correction factors (ICRP 1991) to obtain the corrected neutron doses. Table 6A-1 lists the corrected doses.

Table 6A-1. Corrected neutron doses.

Period	Base dose[a]	Missed neutron dose/unit time[a]	ICRP 60 correction factors	Corrected base neutron dose mrem/unit time	Corrected missed neutron dose mrem/unit time
1943-8/1949	2,600 mrem/yr[b] imputed	3,822 mrem/yr[c]	25% 0.l-2.0 MeV = 0.72, 75% 2.0-20 MeV = 1.1	1,872+2,860 = 4732/yr	2,751+4,204 = 6,955/yr
9/1949–11/1951	Dose of record or cohort dose	3,822 mrem/yr[d]	25%: 0.72; 75%: 1.1	(DOR[f] × CF)	2,751+4,204/yr = 6,956/yr
12/1951–1960	Dose of record or cohort dose	2,392 mrem/yr[e]	25%: 0.1-2.0 MeV = 0.72; 75%: 2.0-20 MeV = 1.1	(DOR × CF)	1,722+2,631/yr = 4,353/yr
1960-12/1973	Dose of record or cohort dose	2,392 mrem/yr[e]	50% 0.1-2.0 MeV = 1.43; 50% 2.0-20 MeV = 0.72	(DOR × CF)	3,420+1,722/yr = 5,142/yr
1/1974–12/1976	Dose of record or cohort dose	2,392 mrem/yr[e]	75% 0.1-2.0 MeV = 2.2; 25% 2.0 - 20 MeV = 0.36	(DOR × CF)	(2,392 × 2.2) +(2,392 × 0.36) = 6,123/yr
1977	Dose of record or cohort dose	21/mo = 252 mrem/yr[e]	2.2	(DOR × CF)	(252 × 2.2) = 554/yr
1978–1981	Dose of record or cohort dose	21/mo or 25/qtr	2.2	(DOR × CF)	46/mo or 55/qtr
1981–1991	Dose of record or cohort dose	10/mo or 10/qtr	2.2	(DOR × CF)	22/mo or qtr
1991–2002	Dose of record or cohort dose	10/qtr	2.2	(DOR × CF)	22/mo or qtr

Sample calculation, 1943-8/1949: 2,600 mrem/yr imputed dose and 3,822 mrem/yr missed dose. ICRP 60 corrected dose assumes that 25% of the dose lies in the energy range 0.1 to 2.0 MeV whose integrated correction factor is 0.72 and 75% of the dose lies in the energy range 2.0 to 20 MeV whose integrated correction factor is 1.1. The calculation is: [(2,600 × 0.72) + (2,600 × 1.1)] = 1,872 + 2,860 = 4,732 mrem/yr. The correction factors change over time as the neutron energy mix changes.

a. Based upon the historic Mound neutron RBE of 7.
b. Dose imputed from 50 mrem/wk historical modal neutron dose, 9/1949-1959 calculated as follows: (50 mrem/wk × 52 wk/yr) = 2,600 mrem/yr.
c. Assumes a weekly badge exchange frequency and 52 exchanges.
d. Assumes a biweekly badge exchange frequency and 26 exchanges.
e. Assumes a biweekly badge exchange frequency and 26 exchanges.
f. DOR = Dose of Record or Cohort Dose; 7 CDOR = Corrected Dose of Record.

Corrected photon doses: The base and missed photon doses are multiplied by the photon correction factors to obtain the corrected photon doses. Table 6A-2 lists the corrected doses.

Table 6A-2. Corrected photon doses.

Period	Base dose	Missed photon dose	Photon energy interval in keV
1943–1/1949	2,600 mrem/yr imputed[a]	1,040 mrem/yr	30–250: 25% >250: 75%
2/1949–11/1951	Dose of record or cohort dose	442 mrem/yr	30–250: 50%[c] >250: 50%
12/1951–1957	Dose or record or cohort dose	442 mrem/yr	30–250: 50%[c,d] >250: 50%
1957–1963	Dose of record or cohort dose	130 mrem/yr	30–250: 50%[d] >250: 50%
1963–1968	Dose of record or cohort dose	390 mrem/yr	30–250: 50%[d] >250: 50%
1968–11/12/1970	Dose of record or cohort dose	390 mrem/yr	30–250: 50%[d] >250: 50%
11/13/1970–12/31/75	Dose of record or cohort dose	78 mrem/yr	30–250: 50%[d] >250: 50%
1976-1977	Dose of record or cohort dose	572/yr[e]	30–250: 50% >250: 50%
01/01/1978–7/6/1981	Dose of record or cohort dose	572/2 wk, 456/mo or 376/qtr	30–250: 50% >250: 50%
7/7/1981–1991	Dose of record or cohort dose	260/2 wk (bldg PP)[d], 120 monthly, 40/qtr	30–250: 50% >250: 50%
1992-2006	Dose of record or cohort dose	Not applicable	30–250: 50% >250: 50%

a. Dose imputed from 50 mrem/wk historical modal photon dose, 9/1949-1959 calculated as follows: (50 mrem/wk × 52 wk/yr) = 2,600 mrem/yr.
b. For years before 1978, only annual dose summaries are available from the record. Therefore, all the corrections through the end of 1977 are in terms of annual additions to the dose of record.
c. The internal dose research section in B Building from 1950 to 1955 had a photon energy interval of (30 to 250 keV: 75%, >250: 25%).
d. The waste handling in Building PP from 1955 to 1975 had a photon energy interval of (30 to 250: 75%, >250: 25%).
e. This is the maximum missed dose for 1976 to 1977 assuming tantalum-shielded badges and 26 badge exchanges throughout the entire period. Even though tantalum-shielded badges came into use on April 21, 1976, this analysis assumed their use for the entirety of both 1976 and 1977 for ease of computation.