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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
ANSI	American National Standards Institute
Do	dose observed
DOE	U.S. Department of Energy
DOELAP	U.S. Department of Energy Laboratory Accreditation Program
EEOICPA	Energy Employees Occupational Illness Compensation Program Act of 2000
FEMP	Fernald Environmental Management Project
FMPC	Feed Material Production Center
HF	hydrogen fluoride
ICRP	International Commission on Radiological Protection
INEL	[DOE] Idaho National Engineering Laboratory
keV	kilovolt-electron, 1,000 electron volts)
MDL	minimum detection limit or level
MED	Manhattan Engineering District
MeV	megavolt-electron, 1 million electron volts
mg	milligram
mm	millimeter
mR	milliroentgen
mrad	millirad
mrem	millirem
mrep	millirep
mSv	millisievert
MTU	metric tons uranium
NIOSH	National Institute for Occupational Safety and Health
NLO	National Lead of Ohio, Inc.
ORNL	[DOE] Oak Ridge National Laboratory
PNL	[Battelle] Pacific Northwest Laboratories
R	roentgen
Rd	dose read
rem	roentgen equivalent man
rep	roentgen equivalent physical
rpm	revolutions per minute
TBD	technical basis document
TLD	thermoluminescent dosimeter
U.S.C.	United States Code

6.0 OCCUPATIONAL EXTERNAL DOSE

This section provides the technical basis for estimating worker radiological dose based on exposure to occupational external radiation sources at the U.S. Department of Energy (DOE) Fernald Environmental Management Project (FEMP).

6.1 INTRODUCTION

FEMP (formerly known as the Feed Materials Production Center, or FMPC) was a rather late addition to the Manhattan Engineering District/U.S. Atomic Energy Commission (MED/AEC) weapons complex, although it was a very important one. The site included chemical processing, foundries, machine shops, storage yards, a uranium recycler, and a variety of other capabilities. In addition, FEMP was assigned a mission that to date had never been preformed before, at least on such a large scale. Processing such large quantities of radioactive material, in this case uranium, up to 10,000 MTU annually and small amount of thorium with a staff of up to almost 2,900 (ASI date unknown), was a new type of endeavor.

When operational, FEMP was a large integrated facility that produced uranium metal products used as feed materials in DOE defense program facilities throughout the United States (RAC 1995). FEMP utilized a number of processes that involved a variety of forms of uranium, such as uranium ore concentrate, uranium hexafluoride (UF_6), and recycled uranium scrap generated throughout the DOE complex. The products were "variously sized, highly purified uranium metal forms of assorted standard isotopic assays" (Unknown 1988) ranging from depleted to slightly enriched uranium metal products. The primary facilities, referred to as plants, are described in detail in Section 2, Site Description, of the FEMP Technical Basis Document (TBD) and are addressed in this section of the FEMP TBD by reference. The radiological hazards associated with these processes and products resulted from the radioactivity of uranium, thorium and their daughter products, and in some instances impurities in the recycled material.

The occupational dose received by workers at FEMP was a function of the physical location of the workers on the site, the process, and the type and quantities of materials. The dose also varied with the "age" (with respect to radiological decay) of the material being processed. The concerns with aging and processing involve the disequilibria of the radioactive material daughter products that often are affected by the process to which the parent is subjected. For example, the temperature of the process can volatilize a daughter product in the parent radioactive decay chain (such as thorium) which in turn can, until equilibrium is reestablished, affect the resulting dose rates. These and other factors are often encountered in the processing of radiological materials, all of which can affect the amount and magnitude of external dose.

Many cycles of activities took place throughout the operational lifetime of FEMP. The throughput of material varied considerably as did the sources of feed materials, one of which was ore from the Belgian Congo. This ore, pitchblende, contained large quantities of radium that required shielding (EPA 2000). Wastes from this process were stored on the site in the K-65 silos. These silos also received waste from a site near Niagara Falls, New York. The silos became a large contributor to site background dose rates and probably to resultant doses to individuals.

The introduction of recycled uranium at FEMP, mostly from the DOE Hanford Site, started in 1958 (DOE 2003) and reached a peak in 1970. This material contained some "carryover" fission products and minute quantities of transuranics. One of the carryover products of interest for occupational external exposure is ^{99}Tc, which has 0.292 MeV beta energy at a yield of 100%. It is important because its specific activity is approximately 4 orders of magnitude greater than that of uranium, and

FEMP received an estimated 135 kilograms of ^{99}Tc. Technetium-99 is a major contributor to shallow dose because it contributes most of its energies at tissue depths used in defining shallow dose. The same is true of the similar beta energy found in ^{234}Th, the first daughter product of the ^{238}U decay series.

A more penetrating beta energy occurs with the decay of protactinium, the product of ^{234}Th decay (the first daughter radionuclide of ^{238}U decay), which undergoes a metastable state as ^{234m}Pa, which in turn decays (0.13% of time) to ^{234m}Pa with a 2.29 MeV beta at a yield of 98%, and two lesser energy betas of 1 MeV each. Complete decay chain diagrams are provided in *Table of Isotopes* (Lederer et. al 1978) or the decay diagrams of the *Radiological Health Handbook* (PHS 1970) that are provided in tables at the end of this section.

There are several beta particles in the ^{235}U decay chain, most of which are associated with ^{231}Th, the first daughter product of ^{235}U. The maximum beta energy is 0.3 MeV ±0.005 and several lesser energies. In addition, several gammas and X-rays are emitted during the decay process. Table 6-1 lists the radiations of major concern.

Table 6–1. Uranium beta and gamma emissions of interest.

Radionuclide	Beta energy, MeV (Max)	Gamma energy, MeV
U-238	None	None
Th-234	0.103 (21%)	0.063 (3.5%)
	0.193 (79%)	0.093 (4%)
Pa-234m	2.29 (98%)	0.765 (0.3%)
		1.00 (0.6%)
U-235	None	0.144 (11%)
		0.186 (54%)
		0.205 (5%)
Th-231	0.140 (45%)	0.026 (2%)
	0.220 (15%)	0.084 (10%)
U-234	None	0.053 (0.2%)

Workers at FEMP who might have been exposed to the sources of radiation discussed in this TBD were employed during the period starting in late 1951. Of most concern are those employed during the peak production years, from the late 1950s to mid-1970s, peaking in 1960 at an annual rate of approximately 10,000 metric tons of uranium (MTU) (RAC 1995). Individual worker monitoring methods were implemented by work locations, length of time, and facility monitoring. No early radiological policy documentation at FEMP was found during the TBD investigations. However, individual doses from personal dosimeters worn by the workers are available, and this TBD pertains to the analysis of these records.

6.2 BASIS OF COMPARISON

Occupational whole-body doses at the time of FEMP startup in 1951 were controlled to 0.3 R/wk and an extremity dose of 1.5 R/wk. The annual limit for maximum whole-body dose for any one year period was limited to12 rem, and the annual extremity limit was 75 rem; both values had associated administrative limits that were fractions of the annual limits per calendar quarter. In 1955, the whole body dose limits were reduced to 3 rem per 13 weeks, not to exceed 5 rem per year. The terms roentgen, rad, rem, and rep (roentgen equivalent physical) often are used interchangeably and in this document the claimant favorable assumption was made that they are considered equal.

Various radiation dose concepts and quantities have been used to measure and record occupational dose since the start of FEMP in 1951. A basis of comparison for dose reconstruction is the concept of

Personal Dose Equivalent, Hp(d), where d identifies the depth (in mm) and represents the point of reference for dose in tissue. For penetrating radiation of significance to whole body dose (e.g. high-energy photons), d=10 mm and is noted as Hp(10). For weakly penetrating radiation of significance to skin dose, d=0.07 mm, and is noted as Hs(0.07). These are the radiation quantities recommended by the ICRU Report 51 (ICRU1993), and the radiation quantities used in DOELAP (DOE Laboratory Accreditation Program; DOE 1986) to accredit personal dosimetry programs at DOE sites. FEMP was the first DOE site to become DOELAP accredited (in 1987). While this accreditation is of significant value in validating data from 1987 and later, there is no analogous validation for data obtained before 1987 and especially back to the 1950s. The accuracies of the dosimetry system(s), their recorded doses, and their comparability to current systems depend on:

- Administrative practices based on technical, statutory, and administrative requirements;
- Workplace radiation fields, materials, quantities, etc.;
- Dosimetry technologies and calibrations;
- Process technologies; and
- Training programs and practices.

6.3 SITE HISTORIC DOSIMETRY PRACTICES

This section provides a summary of external dosimetry practices utilized throughout the history of FEMP operations and activities.

6.3.1 Site Historic Administrative Practices

FEMP started operation in October 1951 (DOE 2000) using a variety of chemical and metallurgical processes to perform its mission of supplying uranium metal products to the AEC and its successor agencies. This included fuel cores for production reactors at the Hanford and Savannah River Sites and uranium metal products for Y-12 at Oak Ridge National Laboratory (ORNL) and Rocky Flats Plant operations. Raw uranium-bearing ores, ore concentrates, and later recycled uranium compounds were received primarily from the Hanford and Savannah River Sites.

Some of the raw uranium ore (especially ores from the Belgium Congo) contained considerable amounts of radium that later became a waste problem, while recycled material had trace quantities of transuranics and some fission products. Fernald Receipts Data (DOE 2003) presented in Table 6-2 lists the quantities of recycled materials along with other radionuclides and their sources from key shipping sites.

Figures 6-1 and 6-2 (at the end of this TBD section) present decay schemes for ^{235}U and ^{238}U, respectively. Of prime importance is Figure 6-2 (^{238}U) because its decay scheme includes ^{234m}Pa, a major contributor to FEMP worker dose since FEMP processed only low-enrichment uranium (i.e., <2% ^{235}U). For the most part, only uranium that had been subjected to processing (primarily concentration) that resulted in the disruption of its decay chain was the main feed material. Typically, only the first two daughter products of ^{238}U are of importance, and in particular ^{234m}Pa with its 2.29 MeV beta energy 98% of the time. The FEMP processed only low-enriched uranium (i.e. typically <2% ^{235}U) but it varied between <0.7 and 5% (in limited quantities).

The FEMP also became the storage site for thorium in the U.S. and processed some thorium into reactor fuel for the weapons complex. The radiological properties of thorium are different than those of uranium since it has higher energy gamma rays and a shorter time to reestablish equilibrium with its daughters after processing.

Table 6–2. FEMP recycled materials receipts (DOE 2003)

	Key shipping sites (MTU)				Contaminants			
Year	Hanford	Savannah River	West Valley	Total	Plutonium (g)	Neptunium (g)	^{236}U (kg)	Technetium (kg)
1953	0			0	0.0	0		0.0
1954	0			0	0.0	0		0.0
1955	0			0	0.0	0		0.0
1956	0			0	0.0	0		0.0
1957	0			0	0.0	0		0.0
1958	5			5	0.0	2		0.0
1959	19			19	0.1	7		0.2
1960	21			21	0.1	7		0.2
1961	50	1		51	0.2	18		0.4
1962	170			170	0.8	60		1.4
1963	1,002			1,002	4.5	351		8.0
1964	1,097	1		1,097	4.9	384		8.8
1965								
1966	2,025	202	48	2,274	9.7	752		17.1
1967	1,458	859	101	2,418	8.7	679		15.0
1968	1,692	412	168	2,273	9.1	690		15.5
1969	1,870	706	124	2,700	10.3	799		17.8
1970	2,237	22	78	2,336	10.4	798		18.2
1971	0	60	69	129	0.4	21		0.4
1972		0	31	31	0.1	4		0.1
1973			3	3	0.0	0		0.0
1974		15		15	0.0	3	17	1.2
1975								
1976		12		12	0.0	2	14	1.0
1977	0	14		15	0.0	3		0.4
1978		28		28	0.1	5	23	1.0
1979		66		66	0.1	12		0.2
1980		36		36	0.1	7	17	2.5
1981		0		0	0.0	0		0.0
1982								
1983		23		23	0.0	4		0.1
1984	706	27		733	3.2	252		5.7
1985	918			918	4.1	321		7.3
1986	1,151			1,151	5.2	403		9.2
1987	314			314	1.4	110		2.5
1988	123			123	0.6	43		1.0
1989	0			0	0.0	0		0.0
Total	**14,859**	**2,486**	**621**	**17,966**	**74.3**	**5,735**	**71**	**135**

The dosimetry requirements for uranium and thorium are similar; i.e., the first two daughter products of ^{232}Th decay by emission of beta particles along with a few photons. Since the daughter products are volatile, when thorium is processed the equilibrium is disrupted and considerable time is required for the processed material to again reach equilibrium. Figure 6-3 (at the end of this TBD section) provides the decay scheme for ^{232}Th. Later in plant operations ^{99}Tc became a contributor to external dose when the FEMP started processing recycled materials that included small quantities of transuranics and fission products, (e.g., ^{237}Np, plutonium, and ^{99}Tc). The transuranics shown in Table 6-2 contributed to the internal dose, but only on a limited basis (DOE 2003). Technetium contributed

primarily to external exposure (skin or extremity) dose due to the quantities present, and probably was contacted through contamination of apparel (in particular gloves).

The use of a dosimeter for production workers has always been employed at FEMP. After the security credential and the dosimeter were combined, all employees wore them. However, exposures have not always been determined for all employees. During certain periods, female employees were not routinely monitored. Periods when male and female employees were monitored were:

1951 – 1960: male employees only

1961 – 1968: male and female employees

1969 – 1978: male employees only

1979 - present: male and female employees.

Female employees were not monitored during certain periods because "the potential did not exist for them to exceed 10% of the quarterly standards" (Dugan 1981). Additional information and data are provided in Section 6.6.2 on missed dose for unmonitored employees and Table 6-14, "Missed dose for unmonitored employees."

FEMP used several types of personnel dosimeters throughout its operational period. There were also several changes in occupational and administrative exposure limits during that period, including dosimeter exchange periods. Table 6-3 lists details of these changes.

Table 6–3. FEMP MED/AEC/DOE dosimeter characteristics.

Years	Dosimeter	Filters	MDL (mRad)	Routine exchange
1951-54	Two-element film	Open, Cd 1 mm	40	Weekly
1954-58	ORNL dosimeter	Cu, Cd, plastic, Pb, open	30	Bi-weekly
1959-85	ORNL dosimeter	Cu, Cd, plastic, Pb, open	30	Monthly
1985-92	Commercial Panasonic TLD	Multiple	30	Monthly
1993-present	Commercial Panasonic TLD	Multiple	20	Quarterly

Table 6-4 summarizes the calibration practices, calibration sources, quantity, and background correction use for FEMP dosimetry.

Table 6–4. FEMP dosimetry calibration practices.

Years	Calibration source	Dosimetric quantity	Air or phantom	Natural background correction?
1952-?	Ra--U slab	Exposure & rep	Air	Yes
?-1985	Ra--U	Exposure & rad	Air	Yes
1985-present	Commercial	Rem	Phantom	Yes

During these periods dose or exposure limits changed with the lowering of limits as more knowledge was gained with respect to radiation protection practices. Exposure limits to the whole body were established at 0.1 R per day in the early 1940s, and were reduced in 1948 to 0.05 R per day to the whole body and 0.3 R per week to blood-forming organs. Skin and extremities limits were established at 0.6 and 1.5 R per week respectively. By 1955, whole-body exposure was reduced to 3 rem per 13-week period and 5 rem per year from all sources of radiation. In 1959, the International Commission on Radiological Protection issued ICRP-2 (ICRP 1959), which recommended a limit for

employees over 18 years old as 5(N-18) rem total lifetime, where N is the age in years. This limit included an annual restriction of 10 rem. The extremity limit remained constant at 75 rem per year, but was later reduced to 50 rem per year. Fernald established site-specific lesser values as a guide to ensure that workers would not exceed limits. The guides were often one-fourth to one-third of the annual limits per dosimeter wearing period or per calendar quarter. Additionally, exposures sometimes were controlled using other types of dosimeters such as pocket-type ion chamber "pencil dosimeters." Time limits were based on the product of measured dose rates and time (Noyes 1968).

While current minimum detection limits (MDLs) as listed in Table 6-3 are well defined (Cooper 1988), earlier limits were not. Since it is difficult to estimate MDLs for the early dosimetry systems, the values provided in this TBD are those given for the analogous ORNL system. Important dose reconstruction parameters for FEMP workers are based on the following administrative practices:

- Dosimeter exchange policies
- Dosimeter assignment policies
- Lost dosimeter and dose assignment policies
- Incident handling policies and information on how results were recorded
- Past exposure records for new employees

6.3.2 Site Dosimetry Technology

The dosimetry technology at FEMP was approximately equivalent to that used throughout the nuclear industry at the time. FEMP followed the ORNL program for dosimeter design and calibration. The exception was the lack of a requirement for neutron dosimetry at FEMP. Table 6-3 lists data used at FEMP, including dosimeter type, period of exchange, and MDLs, while Table 6-4 lists calibration data over the same periods.

Extremity dosimetry at Fernald involved the use of wrist dosimeters (rather than finger dosimeters) together with application of an appropriate correction factor. There is some evidence that a factor of 3 was used as observed in the review of early worker exposure records. Documentation of the correction factor was not established until a study by Jones (Jones 1988) determined that a factor of 2.06 times the wrist dosimeter value should be used to estimate the dose to the extremity. The wrist dosimeter in use at the time of the Jones study was a Teflon disk embedded with $CaSO_4$: Dy; however, records indicate that film previously had been used at FEMP.

The method of using wrist-to-finger ratios to estimate extremity doses is not a particularly accurate practice. This approach was used at many DOE sites, with each site determining its own correction factor. Extremity Hs(0.07) doses could be over estimated by this method by as much as 20% due to shielding by protective clothing on the extremities (e.g. gloves) since the wrist dosimeter is worn out side of any clothing. Therefore, the recorded extremity doses should be claimant favorable and should provide the best estimate of Hs(0.07) for individual monitored employees.

This reasoning is also true for whole-body doses. After reviewing the tables in this TBD it is possible to determine that the preponderance of the radiation consists of beta particles, and while this form of radiation can deliver substantial doses to bare skin in proximity it does not penetrate deeply into the body. The dose rate from the photon component associated with the radioactive decay of uranium is "minor compared to the beta dose rate" (Alvarez et al. 1984). In addition, protective measures such as distance, shielding, clothing, gloves, etc., reduce beta dose rates appreciably without excessive bulk by approximately 20%.

Individual exposure records indicate an “open window” design for personnel monitoring devices that allows both beta and photon radiations to reach the measuring element [film or thermoluminescent dosimeter (TLD)]. Some DOE sites, including FEMP, incorporated a security credential in the dosimeter holder that in some instances covered the open window of the dosimeter. However, FEMP did not cover the open window with their security credential (Dugan 1981) which provided more accurate results than if the window had been covered.

An additional radiological concern at several locations at FEMP occurred when workers were subjected to high levels of radioactive material-bearing dust. This widespread source of contamination was a concern for personal dosimeters, so at times the dosimeters were enclosed in plastic bags for protection against dust contamination. The manner in which these contaminated dosimeters were handled was not identified; however, this should not be an issue in dose reconstruction because the dosimeters were calibrated in plastic bags and no adjustments were made to the dosimeter results for either Hs(0.07) or Hp(10).

Because Hp(10) may be of predominant interest in dose reconstruction, uranium beta radiation can be considered insignificant. An evaluation of original recorded doses for FEMP workers based on these parameters should yield a good (best available) estimate of Hp(10). Where necessary, Hs(0.07) for those individual workers who came in direct contact with radiological source materials can also be obtained because open window results were recorded with no adjustments to those readings.

6.3.2.1 Multielement Film Dosimeters

At startup in late 1951, FEMP used the two-element beta/photon dosimeter developed at the Metallurgical Laboratory at the University of Chicago (Pardue, Goldstein, and Wollan 1944). This dosimeter was basically the same as the Clinton Laboratory dosimeter used at Oak Ridge. It utilized DuPont 552 film, an open window, and a cadmium filter. The open window was recorded as skin dose, beta plus gamma and the filtered response as whole body gamma dose. The Pardue dosimeter was processed offsite from start up in 1951 to June 1952, when on-site processing began. In mid-1953, FEMP converted to an advanced ORNL dosimeter, which consisted of 552 film, an open window, with cadmium, lead, copper, and plastic filters. However, there are discrepancies in the documentation with regard to the use of this dosimeter at FEMP. A letter dated September 11, 1981, in response to a Dosimetry Assessment Fact Sheet (Dugan 1981) states that in “January 1971 the ORNL badge meter, Model II was put into service at this site.” Regardless, all designs were calibrated for each batch of film, with the optical density of the film determined after irradiation. The unknown exposure was compared optically to the known calibration and recorded accordingly. Therefore, any multielement dosimeter would be adequate since only the “open window” and the element that provided approximately 1000 mg/cm^2 shielding was used.

6.3.2.2 Thermoluminescent Dosimeters

TLDs were introduced in or around 1978 or 1979, but only on an experimental basis. An exception was the extremity dosimeter program, which introduced TLDs in 1977; however, no data were found in the literature that described these TLDs other than “they were the Teledyne Teflon impregnated with calcium sulfate type” (Dugan 1981). Therefore, this TBD has assumed that the TLD was used in a wrist dosimeter configuration, and that dose calculations involved use of a modifying factor to provide some estimate of actual extremity exposure. The sampling of records reviewed showed that while extremity doses were often near limits, the imposed whole-body restrictions limited worker extremity exposure to less than the extremity limit. It was concluded that the dose of record is the best to use for reconstruction of the extremity dose. At FEMP, extremity doses were calculated by

correcting the wrist dosimeter results utilizing a modifying factor of 3 for film and 2.06 as per the Jones study (*ibid*). FEMP did not retrofit the calculated extremity dose based on the new modifying factor.

Whole-body TLDs using the commercial Panasonic system were placed in service in January 1985. The whole system was subjected to an extensive study starting in the fall of 1981 (Plato and Miklos 1982). The study included screening of 1,800 dosimeters, calibration of a manual reader, development of correction factors for each of the four TLD chips (E1–E4) in the dosimeter, and the development of an algorithm and the calibration of FEMP ^{137}Cs source. The TLD used was the Panasonic UD-802 model, some of which were modified by National Lead of Ohio, Inc. (NLO, the Fernald operating contractor at the time) by removal of the plastic filter over element E2 on the front of the dosimeter. This modification was to improve the difference in the E1:E2 ratio to provide a better differential of the beta energies.

The algorithm developed by this study proved to be less than adequate, although the system did satisfy American National Standards Institute (ANSI) Standard N13.11-1983 (ANSI 1983). The system lacked sufficient precision in estimating beta energies. Alvarez (Alvarez et al. 1984) found that, on average, skin dose was in error by about 1%. At a given location, this error could vary between -36% and +45%, and the review of the algorithm used for calculating skin dose indicated that individual TLD readings of approximately 4% caused variation in skin doses of 15% to 25%. This led to the development of a new algorithm and the previously mentioned change in the plastic filter in the dosimeter. These changes had an impact on skin dose and in some cases eye dose, but had no effect on deep dose since neither the filter nor the evaluation of deep dose was changed.

6.3.3 Calibration

It is always prudent and technically defensible to calibrate to the same types and energies of the radiations to be measured. For FEMP, this would involve uranium and its daughter products, in some cases ^{99}Tc and (perhaps early in FEMP operations) ^{226}Ra. Potential errors in recorded doses depend not only on the response of the specific dosimeter to the radiation to which it is exposed and calibrated, but also on the dosimeter geometry, how it is worn, and the simple variables in shielding afforded by clothing and other materials. The shielding effect is especially significant when the radiations are primarily beta particles or low-energy photons, both of which are predominant with uranium.

6.3.3.1 Beta/Photon Dosimeters

FEMP dosimeters were originally calibrated using a slab of natural uranium for beta energy and low-energy photons and ^{226}Ra for gamma energy. The uranium calibration determined the nonpenetrating or skin dose by measuring the film density behind the open window of the dosimeter. The penetrating dose was determined by measuring the film density behind the metal filter. All calibrations were made “in air” (i.e., no phantom) and for each batch of film. From a review of the available documentation, exposures were made for ^{226}Ra gamma radiation at 50, 150, 450, 1,356, and 4,077 mR. Uranium slab exposures were made at 40, 80, 160, 320, 642, and 3,840 mrep (*Film Calibrations* 1971, 1974, 1977).

By January 1977, calibration values had changed to a range of 25 to 4,077 mR in 10 increments for ^{226}Ra and to a range of 20 to 3,840 mrep for beta emissions (for a uranium slab). All dosimeters were calibrated with and without “bags”. It was not determined when bags were first incorporated in the calibration process; however, calibration data from September 1974 indicated that five gamma exposures ranging from 50 to 4,077 mR ^{226}Ra and 10 uranium slab exposures ranging from 40 to 8,000 mrep were conducted “with bags.”

This TBD assumes that when FEMP began the practice of using bags for contamination control, attendant calibration procedures were revised to accommodate the new practice. Small changes in film density can mean large changes in recorded exposure. Therefore, it is desirable to calibrate dosimeters using the same radiological sources and energies to which worker dosimeters will be exposed; this practice was implemented at FEMP.

6.3.3.2 FEMP Beta/Photon Dosimeter

As previously stated, FEMP beta/photon dosimeters were calibrated using ^{226}Ra for gamma energy and uranium for beta and low-energy photons. All calibrations were in air (i.e., no phantom was used). This practice continued until the change to TLDs in January 1985. When participation in DOELAP performance testing was required in the mid to late 1980s (DOE 1986), FEMP began using ^{137}Cs as the gamma calibration source while continuing to use the uranium slab. In addition, the use of a phantom was required at this time. Whether a change was determined to be necessary in the recorded penetrating radiation dose as a consequence of this change has not been determined. It is probable that a decrease in Hp(10) would result from these actions because most other sites experienced similar results. No change in the recorded dose is proposed to account for what could be a 10% decrease in dose.

The use of the mrep unit is somewhat unique to FEMP because it declined in use after the 1950s. There are few references, including the *Radiological Health Handbook* (PHS 1970), so this TBD assumes that a rep is approximately 93 ergs/g of tissue. Because FEMP used this term interchangeably with rad (100 ergs/g of any receptor), there is a further inherent conservativeness of approximately 7%.

6.3.4 Workplace Beta/Photon Radiation Fields

Alvarez et al. (1984) characterized typical FEMP radiation fields in preparation for introduction of the TLD system. The radiation fields consisted of a complex mixture of beta, X-rays, and gamma energies. These were supplemented by higher energy gamma radiation associated with ^{226}Ra transitions that account for the dose rates associated with the K-65 silos.

6.3.4.1 FEMP Beta/Photon Dosimeter Response Testing

No data or evidence has been identified of early response testing of FEMP dosimeters, but the site used both the Pardue and ORNL dosimeters since the beginning of operations. Tests performed on these or similar dosimeters indicated an overestimate for Hp(10) with energies greater than 100 keV for the two-element dosimeter and an underestimate of dose for energies less than 100 keV (unless an adjustment is made using a fraction of the response of the shielded portion of the dosimeter). It is reasonable to assume that the early versions of the FEMP dosimeters reacted similarly to the ORNL dosimeter system, given that FEMP used the ORNL system until changing to a commercial system in 1985.

In December 1983, there was an intersite comparison of the FEMP system between FEMP, Pacific Northwest Laboratories (PNL), and the Idaho National Engineering Laboratory (INEL) (Hayes 1983). The dosimeters were exposed in air, mounted on a 3/8-inch plywood disk and rotated at 2 rpm during exposure to several different uranium or uranium-bearing materials. Conclusions reached as a result of these tests were:

- NLO skin dose results were usually high but satisfactory.

- Penetrating dose compared to within ± a few percent (<10%) and NLO results were usually high.

- All three systems were satisfactory for adequate determination of both types of exposures.

After these tests, NLO conducted several projects to improve its ability to determine incident beta energies. NLO contracted with INEL to characterize FEMP radiation fields (Alvarez et al. 1984). These actions, along with the conclusion and attendant suggestions resulted in changing the algorithm developed by Plato and Miklos (1982). Documentation indicates that official use of TLDs began on January 1, 1985; however, the tests took place in the late 1983–early 1984 period. The documentation review for preparation of this TBD determined that FEMP used the total response of the unshielded or open window for skin dose and the response behind the shield for penetrating dose prior to the introduction of the TLD system. This approach is consistent with accepted practices of the time throughout the AEC complex, especially in nonplutonium facilities. This results in a conservative dose estimate that is claimant-favorable.

6.3.4.2 FEMP Workplace Beta/Gamma Dosimeter Response

Results of tests of FEMP dosimeters used during the 1960s (Heatherton 1960) included the conclusion that the half-value thickness of absorption of UX-2 (^{234}Pa) beta energy was approximately 110 mg/cm^2. It was determined that "the combined dose rate from the surface of uranium metal in equilibrium with its two daughters, UX-1 (^{234}Th) and UX-2 (^{234}Pa), is about 240 mrad/hr." It was also determined that approximately 95% of the surface dose rate, or approximately 228 mrad/hr, originated from the UX-2 in the metal. The processing of the metal resulted in separation of uranium daughter products, which produced much higher dose rates in portions of the product, process equipment, and byproducts. The reason for this increase in dose rates is the loss of self-shielding afforded by the mass of the in-process uranium. Further studies involved the absorption afforded by such materials as film wrapping paper, polyethylene, cardboard, and Lucite. These materials were used because they were assumed to be nearly tissue equivalent. It was determined that the half value thickness for tissue was approximately 110 mg/cm^2 and, therefore, the dose to the eyes or gonads was approximately 15% of the skin dose. It was also determined that coveralls worn by workers (about 30 mg/cm^2) reduced uranium beta exposure to the skin by approximately 20%. Figure 6-6, at the end of this TBD, summarizes these data.

While it was not explicitly stated in the documentation (Heatherton 1960), it is assumed that the dosimeter in use at FEMP was the ORNL version and that the film used was a DuPont type (Johnson 1963). There is some general data of results between film and TLD dosimeters dated November and December 1982. After review of these data, the conclusion is that the two types of dosimeters did not agree and that the ratio of film to TLD varied with the location of the exposure. In some instances the ratio was greater than 1, and in others it was less than 1. Most often film results provide higher dose estimates than TLD results, which support the conclusion that early film dosimeter results are claimant-favorable. However, TLD results have been documented to be more accurate than film dosimeters, and provide a more representative measure of the true exposures (this is particularly true when measuring beta and low-energy photons). ICRU Report 43 (ICRU 1988) concludes (pg. 9) that TLDs, when placed under an appropriate absorber "…will constitute a dosimeter having a spectral and angular response close to the ideal", while in regard to film, it states, "Dosimeters based on sensing elements that are not tissue equivalent (e.g. photographic film) can also be used, though in general it is more difficult to ensure that the variation of response with energy and angle of incidence is correct. Such problems are often enhanced for beta and low-energy x rays".

The forms of radiation encountered at FEMP varied from plant to plant with Plants 5 and 9 exhibiting the highest potential workplace dose rates. These plants were involved with metal reduction, casting, and rolling, and these processes generated the separation and migration of daughter products ^{234}Th and ^{234}Pa (UX-1 and UX-2). As stated above, ^{234}Pa contributes approximately 95% of the total beta dose rate; therefore, any location in the process where this material accumulated resulted in the potential for higher exposure rates. Other areas of potential high radiation exposure included areas where daughter products contaminated other materials (i.e., crucibles, saws, and rolling mills), or where large quantities of the parent material were present.

Studies conducted in May 1984 (Boback 1984) of various activities in Plant 5 indicated that the whole-body dose rate Hp(10) ranged from 0.1 to 1 mrem/hr. Studies conducted in November and December 1982 using the same criteria (i.e., 80% of the time workers were performing their jobs) indicated that dose rates ranged from 0.08 to 16.5 mrem/hr. These dose rates were established for Plants 5, 6, and 9, with Plant 9 exhibiting the highest rate and Plant 5 the lowest. The dose rate values were derived using dosimeter data and applying the 80% work rate rule. These values were not intended to be precise measurements of actual dose rates and resultant doses to workers, but rather as representations of the dose rate ranges that were present. These and other studies resulted in the use of shielding and establishment of material limits that could be present at any time in certain locations. There is discussion in the documentation of the use of improved housekeeping to assist in reducing worker exposure (Boback 1984). There is also discussion of process changes (i.e., “ingot pickling” to remove “beta emitting daughters from the use of Lucite face shields, rubber matting, ingots surface”). Robinson (2002) contains information on dosimeter response data after 1984.

Table 6-5 lists the lower limits of detection for DOELAP categories for FEMP and Table 6-6 lists the maximum viable dose ranges for DOELAP categories.

Table 6–5. Lower limits of detection for DOELAP categories.

Category	Shallow Hs (mrem)	Deep Hd (mrem)
Cesium	<5	<5
M30 (X-ray L)	<16	<16
S60 (X-ray M)	<16	<16
M150 (X-ray H_1)	<16	<16
M150 (X-ray H_2)	<16	NA
Sr/Y-90 (Beta)	<16	NA

Table 6–6. Maximum viable FEMP category dose ranges.

Category	Hs (rem)	Hd (rem)
Acc gamma (Cs)	5,150	5,150
Acc X-ray H_1	7,050	7,350
X-ray L	5,400	2,250
X-ray M	5,750	5,350
X-ray H_1	7,050	7,350
X-ray H_2	7,050	7,050
Gamma (Cs)	10.3	10.3
B\B+G	1,257	10.3
X-ray L+B	10.2	5.9
X-ray M+B	5,188	10.2
X-ray H_1+B	5,625	11.2
X-ray H_2+B	5,513	11
X-ray L+G	10.4	6

Category	Hs (rem)	Hd (rem)
X-ray M+G	10.6	10.4
X-ray H_1+G	11.3	11.4
X-ray H_2+G	11.3	11.3

The angular dependence of the FEMP dosimeter satisfied the DOELAP Angular Dependence Requirements (Hinnefeld 1989). The system was DOELAP-accredited in 1987 by meeting all requirements at that time. It has maintained accreditation as indicated in the *FEMP External Dosimetry Technical Basis Manual* (Robinson 2002). FEMP has further improved its dosimetry by the addition of an improved computer for the system that enables it to generate element correction factors for each TLD chip in each dosimeter. New correction factors are generated on a biannual basis.

Table 6-7 lists average annular responses for the DOELAP energies of importance at FEMP.

Table 6–7. Angular response for DOELAP energies of importance to FEMP.

Energy*	Angle	Plane	Hp(10) Rd/Do Avg.**	Hs(0.07) Rd/Do Avg.**
M30	0	H	1.02	1.012
M30	±20	H	1.012	0.997
M30	±40	H	0.967	0.955
M30	±60	H	0.769	0.764
M30	±60	V	0.928	0.918
S60	0	H	1.019	1.021
S60	±20	H	1.028	1.031
S60	±40	H	1.021	1.017
S60	±60	H	0.964	0.967
S60	±60	V	0.893	0.896
M150	0	H	1.026	1.026
M150	±20	H	1.061	1.068
M150	±40	H	1.102	1.102
M150	±60	H	1.02	1.02
M150	±60	V	1.058	1.058
Cs137	0	H	0.964	0.964
Cs137	±20	H	0.973	0.972
Cs137	±40	H	0.966	0.966
Cs137	±60	H	0.934	0.934
Cs137	±60	V	0.890	0.891
Sr90/Y90	0	H	0.995	N/A
Sr90/Y90	±20	H	0.982	N/A
Sr90/Y90	±40	H	0.720	N/A
Sr90/Y90	±60	H	0.367	N/A
Sr90/Y90	±60	V	0.340	N/A
M30	±60	V	0.928	0.918
S60	0	H	1.019	1.021
S60	±20	H	1.028	1.031
S60	±40	H	1.021	1.017
S60	±60	H	0.964	0.967
S60	±60	V	0.893	0.896
M150	0	H	1.026	1.026

Energy*	Angle	Plane	Hp(10) Rd/Do Avg.**	Hs(0.07) Rd/Do Avg.**
M150	±20	H	1.061	1.068
M150	±40	H	1.102	1.102

* The entries for M30, S60, and M150 represent calibration energy categories utilized by DOELAP.
** "Rd: is "dose read" or the value read from the dosimeter; "Do" is dose observed, or the value given by DOELAP.

The Hp(10) response is accurate for up to ±60 degrees, while Hs(0.07) varies drastically (as would be expected). Clothing, etc., may offer some reduction in Hs(0.07); however no adjustments were made to dosimeter results for any exposure, e.g., Hp(10) or Hs(0.07). The logical conclusion is that the recorded doses are claimant-favorable. The selection of beta and photon energies for the major FEMP facilities is summarized in Table 6-8.

Table 6–8. Beta and photon energies and percentages for FEMP.

Building	Description	Radiation	Energy, keV	Percentage
Plants 2/3	Production of UO_3	Beta Photon	>15 >30 and <250 >250	100 40 60
Plant 7*	Reduction of UF_6 to UF_4	Beta Photon	>15 >30 and <250 >250	100 40 60
Plant 1	Sampling plant	beta photon	>15 >30 and <250 >250	100 40 60
	Refinery	beta photon	>15 >30 and<250 >250	100 40 60
Pilot Plant[b]	Scrap recovery	beta photon	>15 >30 and <250 >250	100 40 60
	UF_6 to UF_4 reduction	beta photon	>15 >30 and <250 >250	100 40 60
Plant 8[b]	Scrap recovery	beta photon	>15 >30 and <250 >250	100 40 60
Plant 5[a]	Metal production	beta photon	>15 <30 >30 and <250 >250	100 13 33 54
Plant 6[a]	Metal fabrication	beta photon	>15 <30 >30 and <250 >250	100 13 33 54
Plant 9[a,b]	Special products	beta photon	>15 <30 >30 and <250 >250	100 13 33 54

Building	Description	Radiation	Energy, keV	Percentage
Plant 4[b]	UF_4	beta photon	>15 >30 and<250 >250	100 40[b] 60[b]

a. Alvarez et al. 1984. b. For Plants 4, 8, 9 and the pilot plant the years processing thorium are: Plant 4, (1954); Plant 8, (1967-71); Plant 9, (1954-55); and Pilot Plant (1964-80) and for those workers employed there, the energy range is 25% >30 and <250 KeV and 75% >250 KeV. *Operated only two years June 1954-May 1956.

Alvarez (Alvarez et al. 1984) also estimated dose rates typical for the spectra measured at several locations on the plant. Those values are 0.35 mR/hr for low-energy photons <20 keV (typical for shallow skin dose); for photons >30 keV and <300 keV a dose rate of 0.86 mR/hr was assigned. For energies >300 keV a deep dose rate of 1.4 mR/hr was calculated. These values are provided here for example only and if ratioed yield 13, 33, and 54 percent respectively for the energy categories used in dose reconstruction. The average photon radiation dose would be much lower and is “almost negligible compared with the beta skin dose” as previously stated.

6.3.5 FEMP Neutron Dosimetry

The documentation for FEMP did not include any reference to neutron dosimetry with the exception of high-range, gamma-sensitive 1290 film. This film was packaged with the sensitive 508 film and exchanged on an annual basis. There was some concern expressed in AEC audit letters (Johnson and Heacker 1963) that mention “the badge also contains components to evaluate personnel exposure from criticality accidents” (an event that never occurred at Fernald). There was no established need for neutron dosimetry at FEMP even though there were large quantities of UF_4 and UF_6. Enrichments were low enough (typically <2% ^{235}U) that alpha neutron reactions were limited. The limitations of NTA film were well documented including an MDL of approximately 40 mrem for fast neutrons. Based on studies and calculations it was concluded that fast neutron exposures at FEMP would be less than the MDL (Robinson 2001). The purpose of the following section is to discuss and develop a neutron to photon ratio for estimating neutron doses at Fernald. A possible source of low level neutron exposure at Fernald is the alpha,n reaction from the uranium alpha particle interactions with fluorine atoms. This reaction primarily occurs with the production and storage of UF_4 (green salt). The areas at Fernald which produced and/or stored green salt include the Pilot Plant, Plant 4, Warehouse 4B and any other warehouse at Fernald for which the material stored is unknown. The neutron to photon ratio described below should only be applied to workers who were exposed to Uranium – Fluorine materials (i.e. UF_4, UF_6) at Fernald.

6.3.5.1 Development of the Neutron to Photon Ratio

Neutron exposures at Fernald were evaluated by Baker (1995). This survey was conducted in Warehouse 4B using bubble dosimeters to measure the neutron dose rate on UF_4 (green salt) canisters of different enrichments. Table 6-9 presents the average measured neutron dose rate for depleted and low enriched uranium (1.25% – 2%).

Table 6-9. Measured neutron dose rates at Fernald (Baker 1995).

Location	Depleted Uranium Dose Rate (mrem/hr)	Location	Low Enriched Uranium Dose Rate (mrem/hr)
1	0.085	3	0.1069
2	0.063	4	0.1069
5	0.080		
Average	0.076 ± 0.012	Average	0.1069

Measurements also were conducted for 10% enriched uranium; however, based on enriched material receipt information contained in the DOE Recycled Uranium Reports (DOE 2003), it was determined that the vast majority of the enriched material at Fernald was of approximately 1% enrichment.

To develop a neutron to photon ratio for UF_4 (green salt), photon survey data also is required. Unfortunately, Baker (1995) only measured the neutron dose rate of individual canisters. Photon surveys were conducted in 2001 on 56 drums of UF_4 (Fernald 2001). The drum midline dose rate varied from below detection limits to 1.5 mrem/hr, with a mean and standard deviation of 0.79 ± 0.26 mrem/hr on contact. The photon dose rate at the bottom of the drum ranged from below detection limits to 3.5 mrem/hr, with a mean and standard deviation of 1.71 ± 0.82 mrem/hr. These two datasets were combined in order to estimate an overall uncertainty. The photon dose rate variability is primarily the result of differences in the fill level of the individual drums. The top of the drums were discarded from this analysis since the measured general photon dose rate was below detection limits. After combining of the datasets, a distribution was fit to the data. The combined datasets resulted in a log-normal distribution with a geometric mean of 1.1 mrem/hr and a geometric standard deviation of 1.7.

The neutron to photon ratio ($R_{n/\gamma}$) is calculated by dividing the neutron dose rate found in Table 6-9 by the photon dose rate (Equation 6-1).

$$R_{n/\gamma} = \frac{Neutron\ Dose\ Rate}{Photon\ Dose\ Rate} \qquad \text{(Equation 6-1)}$$

To propagate the uncertainty, a Monte Carlo simulation was conducted using distributions in place of each constant dose rate value. Figure 1 depicts the frequency distribution of the simulated neutron to photon ratios for depleted and low enriched uranium.

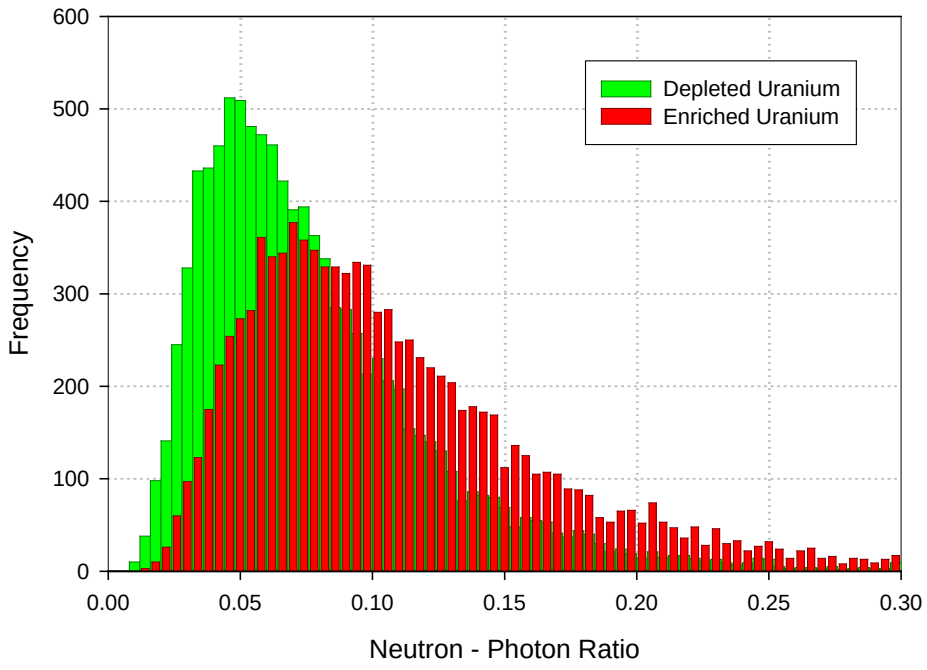


Figure 6-1. Comparison of neutron-photon ratio distributions for depleted and low enriched UF_4.

Statistical parameters of the distributions depicted in Figure 6-1 are provided in Table 6-10. The geometric mean of the low enriched uranium neutron-photon distribution was 0.10 with a geometric standard deviation of 1.71 and an upper 95th% confidence of 0.23.

Table 6-10. Statistical parameters of neutron to photon ratio distributions.

Enrichment	Geometric Mean	GSD	Upper 95th%
Depleted Uranium	0.07	1.74	0.17
Low Enriched Uranium	0.10	1.71	0.23

There are multiple approaches that can be used to estimate the neutron dose using the neutron to photon ratios as presented. The factors that affect an individual's neutron dose include: 1) the quantity of uranium processed, 2) the enrichment, and 3) the time an employee worked with in a process or storage area. The recorded photon dose is also a function of the quantity of uranium processed and the exposure duration. The uranium enrichment has some small effect on the recorded photon dose in that enriched uranium generally has a higher photon dose rate than depleted uranium. This effect is ignored in this analysis for simplicity and is considered a claimant favorable simplification since a higher photon dose rate would decrease the neutron to photon ratio rather than increase the ratio (see Equation 6-1). Using the measured and missed photon dose should correctly account for changes in exposure resulting from decreases in uranium production and changes in an individual's exposure duration.

Through the years Fernald workers conducted operations with enriched uranium, natural uranium, and depleted uranium. Figure 6-2 depicts the percentage of total uranium that was received and processed by Fernald in each of these three categories (DOE 2003).

The receipt for the maximum year (1967) was 24.4 x 10^3 metric tons of uranium.

It should be noted that although natural uranium is not presented in Table 6-10 or calculated in this analysis, the neutron to photon ratio for natural uranium would fall in between the depleted and low enriched ratios. This is because the alpha-n reaction is directly proportional to the alpha activity of the sample. Depleted uranium has the least amount of ^{235}U which has a significantly higher specific activity than ^{238}U and therefore an overall lower specific activity when comparing natural and enriched uranium. Natural uranium has a slightly higher specific activity compared to depleted uranium and enriched uranium has the highest specific activity of the three forms.

As can be observed from the Figure 6-2, most of the uranium work prior to about 1965 was natural uranium with a decrease beginning around 1960 at which time the percentage of enriched uranium received increased. By 1970, relatively little work with natural uranium was conducted at Fernald. Beginning in the mid 1960s, work with depleted uranium began to increase. By the mid 1970s, work with depleted uranium constituted the majority of the uranium work at Fernald. During the transition periods (1965-1975), work with enriched uranium initially increased such that by 1968 enriched uranium work constituted about 50-60% of the uranium work at Fernald. Following this peak, work with enriched uranium decreased to about 10-20% of the total uranium work at Fernald.

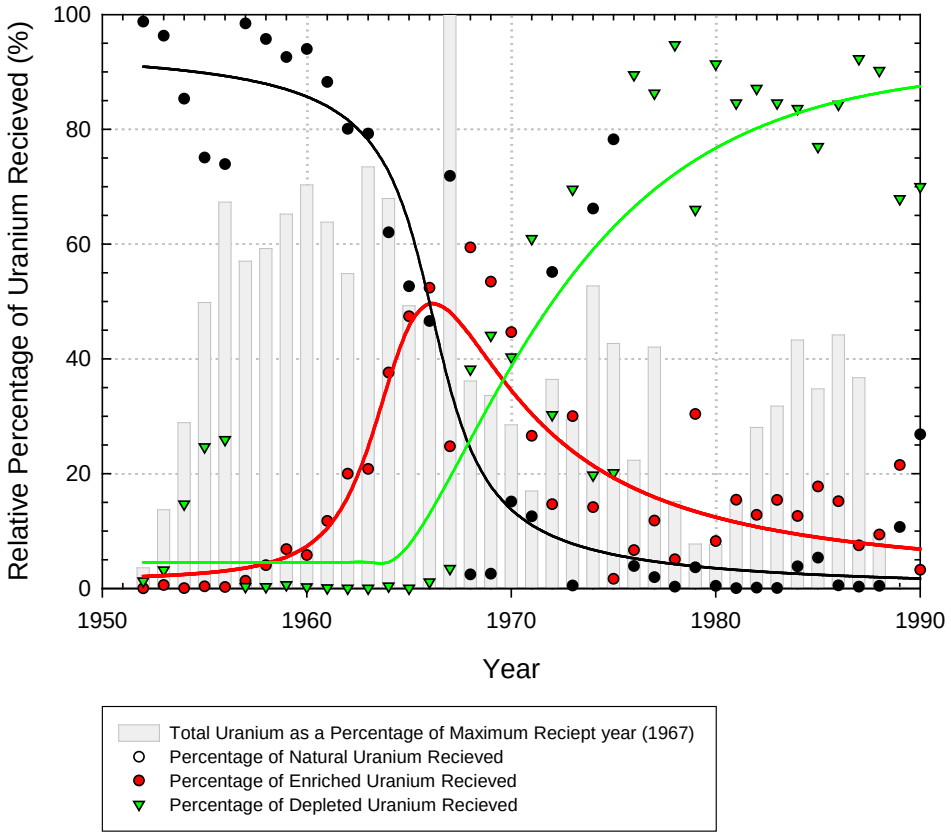


Figure 6-2. Relative Percentage of Uranium Receipts by Material Category (Natural, Enriched, and Depleted).

While the data in Figure 6-2 could be used to estimate annual neutron to photon ratios based on the percentage of enriched, natural, and depleted uranium work conducted, to do so would unreasonably complicate the dose reconstruction and introduce additional uncertainty. The additional uncertainty stems from whether an employee might have worked predominately with one type of material or another. Since this uncertainty cannot be properly tracked without detailed job history and material tracking information, and in order to simplify the dose reconstruction, the low enriched uranium neutron to photon ratio should be used. This assumption will tend to slightly overestimate the actual neutron to photon ratio and is considered a reasonable but necessary claimant favorable assumption, given the limited data available.

While there is a low probability that all of an employee's photon dose would result from exposure to green salt (especially since Fernald is known to have processed large quantities of uranium metal, yellow cake, black oxide, etc.), the probability is not zero and cannot be excluded on an individual basis without significant job history information. As a result, the neutron to photon ratio should be applied to all measured and missed photon dose for employees who worked in the Pilot Plant, Plant 4, any warehouse or other area known to store UF_4 or any of the onsite warehouse for which the stored material is not known. This claimant favorable assumption is a necessary to account for the uncertainty in the origin of the photon dose.

6.3.5.2 Workplace Neutron Radiation Fields

To date, specific neutron energy spectra of UF_4 has not been located or modeled. According to the DOE Health Physics Manual of Good Practices for Uranium Facilities (Rich et. al 1988), neutrons of approximately 2 MeV are generated from uranium alpha particle interactions with fluorine. If the neutrons are generated at this energy, through scattering interactions with surrounding materials, some fraction of the neutrons will have energy less than 2 MeV.

The probability of causation calculations in IREP uses a Radiation Effectiveness Factor (REF) to estimate the probability of causation. The most claimant favorable neutron energy group (i.e., the neutron energy group with the largest REF) is the 0.1 – 2.0 MeV energy group. Since the neutrons at Fernald are assumed to be generated (born) in this energy group and although some fraction will scatter to a lower (less claimant favorable) energy groups, all of the neutron dose should be assumed to result from the 0.1 – 2 MeV energy group. In the absence of data, this is a reasonable and claimant favorable assumption. The default neutron dose fractions are given in Table 6-11.

Table 6–11. FEMP facility default neutron dose fractions.

Facilities with Neutron Radiation	Source	Neutron Energy (MeV)	Default dose %
Pilot Plant, Plant 4 and Warehouses	UF_4, UF_6 and Various enrichments	0.1 to 2.0	100%

6.4 RECORDED DOSES

FEMP recorded both skin and penetrating doses by determining film densities behind the open window and a single filter of approximately 1000 mg/cm^2. The FEMP historical dose record practices are given in Table 6-12.

Table 6–12. Historical recorded dose practices.

Year	Dosimeter Measured Quantities	Compliance Dose Quantities
1951-54 Film	OW-Open Window-mrep S=Cd - mR	Skin=OW+S WB=S
1954-85 Film	OW - mR S - mrem	Skin=OW+S WB=S
1985-present TLD	Non-penetrating (Npen) Penetrating (Pen)	Skin=Npen+WB WB=Pen

6.5 ADJUSTMENTS TO RECORDED DOSE

Corrections to the FEMP reported dose are required due to uncertainties in the recorded data and lack of significant data, especially prior to 1980. To satisfy the claimant-favorable criteria for dose reconstruction and considering the variability in radiation due to the FEMP processes, it is suggested that the corrections identified in the following discussion be considered.

A review of available data and documentation identified no mention that suggested the need for corrections to recorded whole-body dose. However, due to uncertainties in the dosimeter responses and the extended use of the two-element (or effectively two-element) dosimeter, a correction to pre-1985 recorded dose data is suggested. While there was a change to a multielement dosimeter, the penetrating dose was evaluated by the response behind the heavy metal filter. The heavy metal

filter was cadmium in both dosimeters, which attenuated the lower energy photons (see Table 6-8), and should have resulted in an underestimated response behind that filter for measured dose and Hp(10). Because most, but not all, penetrating radiations are above 30 keV, it is suggested that adjustments are necessary to satisfy claimant-favorable dose reconstruction criteria of pre-1985 recorded penetrating whole-body doses due to the contribution to Hp(10) from low energy photons which include the L-X-rays from both uranium and thorium. It is estimated that a correction equal to 10% of the <250 keV values given in Table 6-8 be added to the Hp(10) dose due to the contribution of these low energy photons to penetrating dose but are absorbed in the thick filter.

Exposures were measured for the years that film dosimeters were used; therefore to obtain organ doses (as required for dose reconstruction), the exposure to organ dose conversion factors provided in External Implementation Guide (NIOSH 2002) should be used.

6.6 MISSED DOSE

6.6.1 Missed Beta/Photon Dose

It can be assumed with some certainty that there have been missed doses in the recorded doses for FEMP workers. This could have resulted when a dosimeter was lost or a worker was not monitored, or a zero was entered because the dosimeter result was less than the MDL. Various methods were used to estimate lost dosimeter results such as using coworker results, products of time and dose rate, or previously recorded results for similar work. All of these required considerable review and examination. Missed dose from MDLs is especially important when there were short exchange periods, generally through the 1950s and 1960s. That period also had higher MDLs. The recommended procedure for missed dose is to assign with a log-normal distribution, with zero as a minimum value, (LOD/2 * the number of zero measurements) as the central tendency and (LOD * the number of zero measurements) as the upper 95% estimate. This procedure is applicable to both Hs(0.07) and Hp(10) since the same dosimeter was used for both until the introduction of a TLD finger dosimeter. The MDL per period and exchange frequencies along with the product (LOD * exchanges) are listed in Table 6-13. The other values can be obtained from this data and the individual exposure record.

Table 6-13. FEMP missed beta/photon dose.

Years	MDL (mrem/period)	Exchange frequency	Product (mrem/yr)
1951-53	40	Weekly	2,080
1954-58	30	Biweekly	780
1959-84	30	Monthly	360
1985-present	20	Quarterly	80

6.6.2 Missed Neutron Dose

It is not known for certain how the neutron dosimeters used by Baker (1995) were calibrated. The typical practice in 1995 was to use neutron flux to dose rate conversion factors in NCRP 38 (1971). Some DOE facilities, however, used a standard quality factor of 10 to convert from absorbed dose (rad) to dose equivalent (rem). For dose reconstruction purposes, the NCRP 38 doses must be converted to ICRP 60 values. If the dosimeters were calibrated based on NCRP 38, then the conversion factor from NCRP 38 (1971) to ICRP 60 (1990) is 1.91. If the dosimeters were calibrated to absorbed dose and a quality factor of 10 was applied then the conversion factor is 2. Since there is relatively little difference between these two values and additional research would be required to

determine which method was used for the calibration, the claimant favorable assumption using a factor of 2 should be applied to the neutron to photon ratio in order to convert the estimated dose to an ICRP 60 dose equivalent value.

As an example, suppose an employee worked in Plant 4 at Fernald in 1965. The employee's measured photon dose was 400 ± 80 mrem, and there were three zero monthly dosimeter readings. The energy employees total photon dose would be 449 ± 82 mrem. Applying the low enriched neutron to photon ratio and the conversion to ICRP 60 (1990) radiation weighting factors would result in an estimated neutron dose of 89 mrem. The neutron dose distribution is a lognormal distribution with a geometric standard deviation of 1.77.

Summary of reasonable but claimant favorable assumptions:

1. Neutron to photon ratio developed using the average midline and bottom photon dose rates.
2. Neutron to photon ratio developed using the low enriched uranium neutron dose rate
3. Assumption that all recorded and missed photon dose was the result of exposure to enriched UF_4 material
4. Assumption that all of the neutron energies are between 0.1 – 2 MeV
5. Assumption that neutron dosimeter used a quality factor of 10 to convert rad to rem.

6.6.3 Missed Dose for Unmonitored Employees

As noted previously (Dugan et. al 1981) in a response to a dosimetry assessment fact sheet, Dugan indicated that female employees at FEMP at times were not routinely monitored. This situation existed although the female workers wore a combined security and dosimeter badge. It is reasonable to postulate that there may have been other circumstances where women and men may have not been monitored. For unmonitored workers, 500 mrem per year will be assigned as an upper bound limit. This is several times above the mean doses observed for monitored workers. Since this dose is considered an overestimate, this upper bound will only be used in cases that will likely result in a Probability of Causation (PC) less than 50%. The applicable years this dose may be assigned are shown in Table 6-14.

Table 6 –14. Missed dose for unmonitored employees.

Years	Dose to be Assigned for Unmonitored Employees (mrem/yr)
1951 – 1960 1969 – 1978	500

6.7 ORGAN DOSE

Once the Hp(10) doses have been calculated for each year, these values are used according to NIOSH (2002) to calculate the organ dose distribution. Reference NIOSH 2002 describes the methodology used to calculate organ dose using identified exposure geometries. Worker orientation is a primary consideration for this process; however, no definitive method is available to evaluate this factor. Therefore, Table 6-15 lists default values that are claimant-favorable.

Table 6–15. Organ dose default geometries.

Claim Status	Job Categories	Exposure Geometry	Percentage
All Workers	All	AP	100

6.8 BIAS AND UNCERTAINTY

No information was identified to address the uncertainty in the positive recorded photon dose for FEMP workers during the years that film dosimeters were used. The FEMP film dosimeters were of the Pardue and Oak Ridge designs. A study performed by H. M. Parker in 1945 (Parker 1945) where he performed a comparison of the Hanford, Chicago and Oak Ridge dosimeters, he concluded that the agreement between the three programs ". . is considered to be satisfactory, especially with reference to the total exposure". While this study is useful, it was all based on plutonium energies which other than for L-X-ray energies, the results are not directly comparable to Fernald radiations. For those radiation energies >250 keV, the two element dosimeter does a credible job and no corrections are required. Because there are energies <250 keV, corrections of 10% are recommended as described in Section 6-5. The uncertainty information for the FEMP Multi-Element Thermoluminescent dosimeter are presented in Table 6-16 is based on DOELAP accreditation data provided in an e-mail letter (Robinson 2003).

Table 6 –16. Bias and uncertainty.

	Bias Magnitude and Range		Uncertainty Factors	
FEMP Dosimetry System	**Overall Bias[a]**	**Range in Bias[b]**	**Systematic[c]**	**Random[d]**
Multi-element Thermoluminescent (1985-Present)	1.01	0.85-1.18	1.06	1.2

a. Based on the distribution of energy levels and geometry judged most likely. Divide recorded dose by the table's bias value to calculate deep dose.
b. Range of overall bias factors based on alternative distributions of energy levels and geometry.
c. Systematic uncertainty resulting from lack of knowledge regarding actual distributions of energy levels and geometry.
d. Random uncertainty resulting from variation among workers in energy levels and geometry.

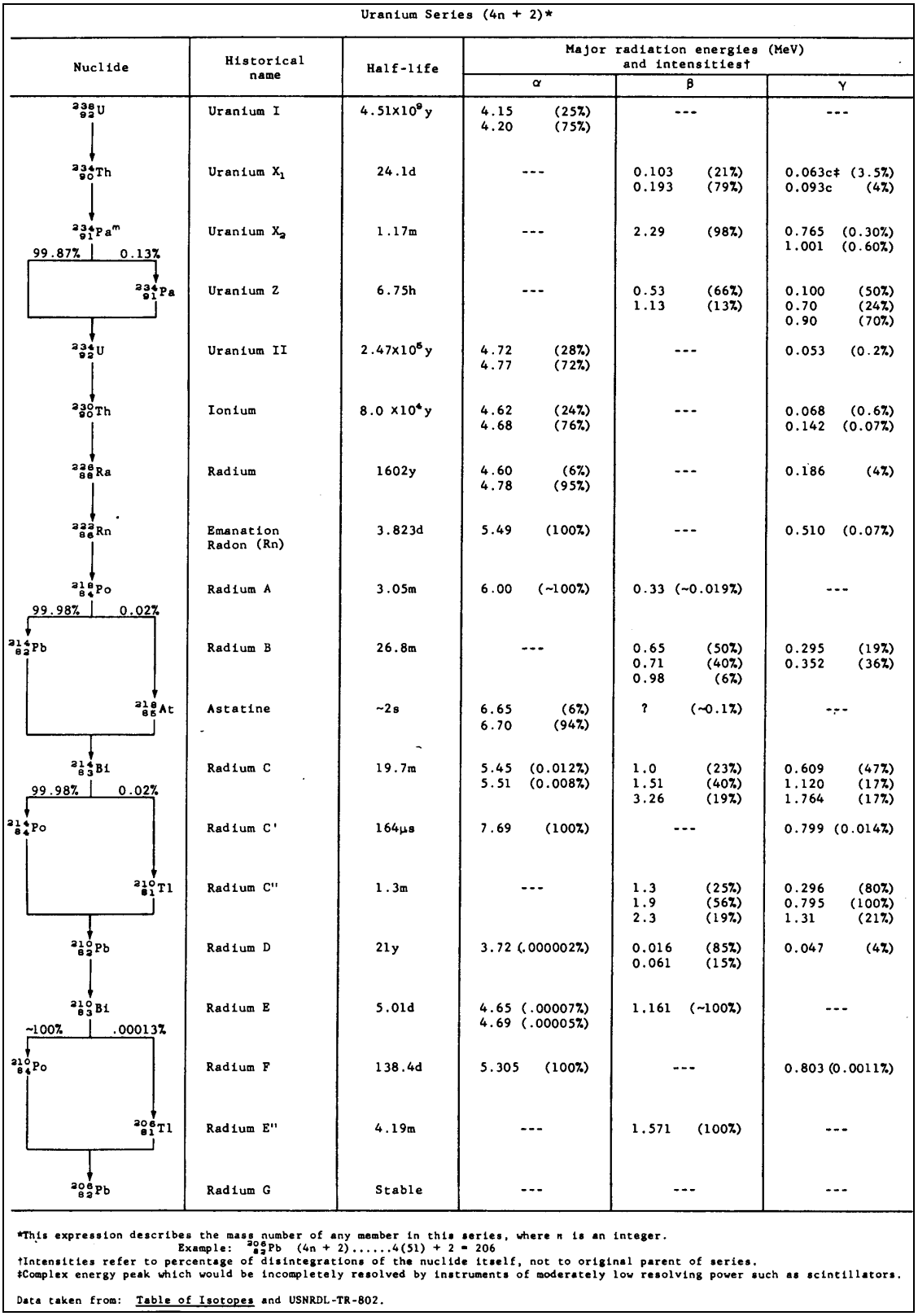
Actinium Series (4n + 3)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{235}_{92}U$	Actinouranium	7.1 x10^{8}y	4.37 (18%) 4.40 (57%) 4.58c‡ (8%)	---	0.143 (11%) 0.185 (54%) 0.204 (5%)
$^{231}_{90}Th$	Uranium Y	25.5h	---	0.140 (45%) 0.220 (15%) 0.305 (40%)	0.026 (2%) 0.084c (10%)
$^{231}_{91}Pa$	Protoactinium	3.25x10^{4}y	4.95 (22%) 5.01 (24%) 5.02 (23%)	---	0.027 (6%) 0.29c (6%)
$^{227}_{89}Ac$	Actinium	21.6y	4.86c (0.18%) 4.95c (1.2%)	0.043 (~99%)	0.070 (0.08%)
98.6% | 1.4%					
$^{227}_{90}Th$	Radioactinium	18.2d	5.76 (21%) 5.98 (24%) 6.04 (23%)	---	0.050 (8%) 0.237c (15%) 0.31c (8%)
$^{223}_{87}Fr$	Actinium K	22m	5.44 (~0.005%)	1.15 (~100%)	0.050 (40%) 0.080 (13%) 0.234 (4%)
$^{223}_{88}Ra$	Actinium X	11.43d	5.61 (26%) 5.71 (54%) 5.75 (9%)	---	0.149c (10%) 0.270 (10%) 0.33c (6%)
$^{219}_{86}Rn$	Emanation Actinon (An)	4.0s	6.42 (8%) 6.55 (11%) 6.82 (81%)	---	0.272 (9%) 0.401 (5%)
$^{215}_{84}Po$	Actinium A	1.78ms	7.38 (~100%)	0.74 (~.00023%)	---
~100% | .00023%					
$^{211}_{82}Pb$	Actinium B	36.1m	---	0.29 (1.4%) 0.56 (9.4%) 1.39 (87.5%)	0.405 (3.4%) 0.427 (1.8%) 0.832 (3.4%)
$^{215}_{85}At$	Astatine	~0.1ms	8.01 (~100%)	---	---
$^{211}_{83}Bi$	Actinium C	2.15m	6.28 (16%) 6.62 (84%)	0.60 (0.28%)	0.351 (14%)
0.28% | 99.7%					
$^{211}_{84}Po$	Actinium C'	0.52s	7.45 (99%)	---	0.570 (0.5%) 0.90 (0.5%)
$^{207}_{81}Tl$	Actinium C''	4.79m	---	1.44 (99.8%)	0.897 (0.16%)
$^{207}_{82}Pb$	Actinium D	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integar.
Example: $^{207}_{82}Pb$ (4n + 3).....4(51) + 3 = 207
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

Figure 6-3. Uranium-235 decay series (ref. PHS 1970).



Uranium Series (4n + 2)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^{9}y	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}Th$	Uranium X_1	24.1d	---	0.103 (21%) 0.193 (79%)	0.063c‡ (3.5%) 0.093c (4%)
$^{234}_{91}Pa^{m}$	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
99.87% | 0.13%					
$^{234}_{91}Pa$	Uranium Z	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}U$	Uranium II	2.47×10^{5}y	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^{4}y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}Po$	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
99.98% | 0.02%					
$^{214}_{82}Pb$	Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$	Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{83}Bi$	Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
99.98% | 0.02%					
$^{214}_{84}Po$	Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
$^{210}_{81}Tl$	Radium C''	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
~100% | .00013%					
$^{210}_{84}Po$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E''	4.19m	---	1.571 (100%)	---
$^{206}_{82}Pb$	Radium G	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{206}_{82}Pb$ (4n + 2).....4(51) + 2 = 206
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Table of Isotopes and USNRDL-TR-802.

Figure 6-4. Uranium-238 decay series (ref. PHS 1970).

Thorium Series (4n)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{232}_{90}Th$	Thorium	1.41×10^{10}y	3.95 (24%) 4.01 (76%)	---	---
$^{228}_{88}Ra$	Mesothorium I	6.7y	---	0.055 (100%)	---
$^{228}_{89}Ac$	Mesothorium II	6.13h	---	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34c‡ (15%) 0.908 (25%) 0.96c (20%)
$^{228}_{90}Th$	Radiothorium	1.910y	5.34 (28%) 5.43 (71%)	---	0.084 (1.6%) 0.214 (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64d	5.45 (6%) 5.68 (94%)	---	0.241 (3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55s	6.29 (100%)	---	0.55 (0.07%)
$^{216}_{84}Po$	Thorium A	0.15s	6.78 (100%)	---	---
$^{212}_{82}Pb$	Thorium B	10.64h	---	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
$^{212}_{83}Bi$	Thorium C	60.6m	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
64.0% / 36.0%					
$^{212}_{84}Po$	Thorium C'	304ns	8.78 (100%)	---	---
$^{208}_{81}Tl$	Thorium C''	3.10m	---	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
$^{208}_{82}Pb$	Thorium D	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{232}_{90}Th$ (4n).....4(58) = 232
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Lederer, C. M., Hollander, J. M., and Perlman, I., Table of Isotopes (6th ed.; New York: John Wiley & Sons, Inc., 1967) and Hogan, O. H., Zigman, P. E., and Mackin, J. L., Beta Spectra (USNRDL-TR-802 [Washington, D.C.: U.S. Atomic Energy Commission, 1964]).

Figure 6-5. Thorium-232 decay series (ref PHS 1970).

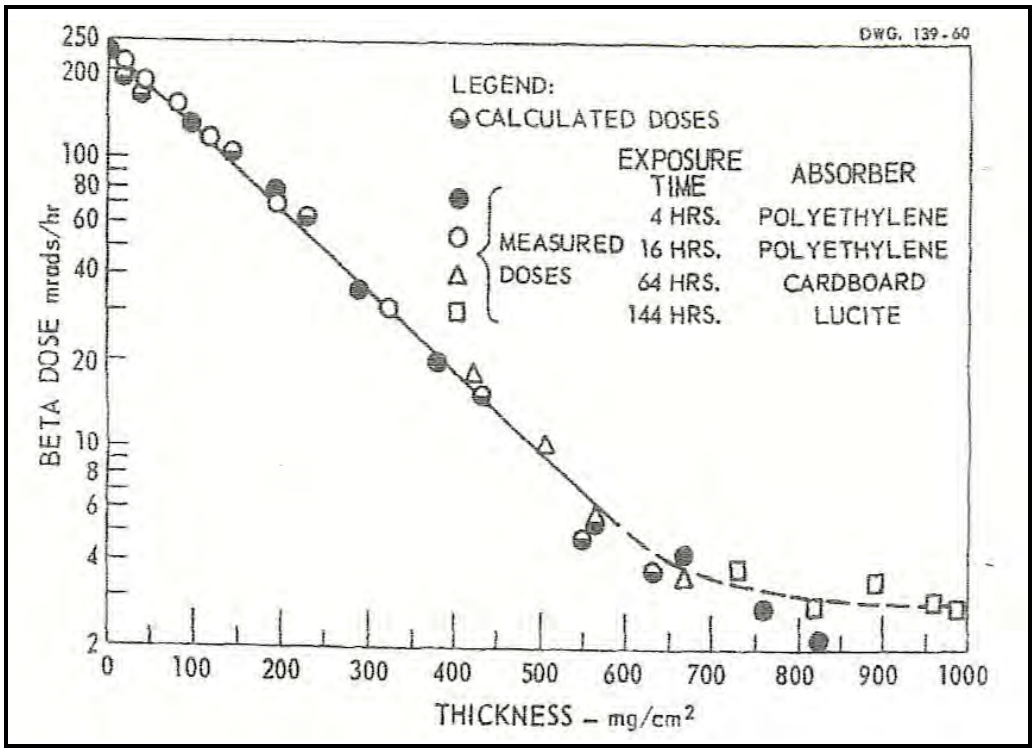


Figure 6-6. Beta dose vs. skin depth (Heatherton 1960).

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GLOSSARY

accreditation
Recognition that a dosimeter system has passed the performance criteria of the DOE Laboratory Accreditation Program (DOELAP) standard (DOE 1986) in specified irradiation categories.

accuracy
If a series of measurements has small systematic errors, they are said to have high accuracy. The accuracy is represented by the bias.

algorithm
A computational procedure.

Atomic Energy Commission
Original agency established for nuclear weapons and power production; a successor to the Manhattan Engineering District (MED) and a predecessor to the U.S. Department of Energy (DOE).

beta particle
A charged particle of very small mass emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) of the direct fission products emit (negative) beta particles. Physically, the beta particle is identical with an electron moving at high velocity.

claimant-favorable
Refers to the process of estimation based on technical considerations of the parameter significant to dose such that the estimated dose is not underestimated.

deep dose equivalent (Hd)
The dose equivalent at the respective depth of 1.0 cm in tissue.

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

DOELAP
The DOE Laboratory Accreditation Program (DOELAP) accredits DOE site dosimetry programs based on performance testing and onsite reviews performed on a 2-year cycle.

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

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

DuPont 552
A film packet containing two pieces of film: a 502 sensitive film and a 510 insensitive film.

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

exposure
A measure expressed in roentgens of the ionization produced by gamma (or X) rays in air.

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

film
Generally means a "film packet" that contains one or more pieces of film in a light-tight wrapping. The film when developed has an image caused by radiation that can be measured using an optical densitometer.

film density
See *optical density*.

film dosimeter
A small packet of film within a holder that attaches to a worker.

filter
Material used to adjust radiation response of a dosimeter to provide an improved tissue equivalent or dose response.

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

ionizing radiation
Electromagnetic radiation (consisting of photons) or particulate radiation (consisting of electrons, neutrons, protons, etc.) capable of producing charged particles through interactions with matter.

luminescence
The emission of light from a material as a result of some excitation.

Manhattan Engineering District (MED)
U.S. agency designated to develop nuclear weapons; a predecessor to the U.S. Department of Energy (DOE).

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

nonpenetrating dose

Designation (i.e., NP or NPen) on film dosimeter reports that implies a radiation dose, typically to the skin of whole body, from beta and lower energy photon radiation.

open window

Designation on a dosimeter that implies the use of little or no shielding. It commonly is used to label the film response corresponding to the open window area.

optical density

The quantitative measurement of photographic blackening the density defined as $D = \log 10 (I_o/I)$.

pencil dosimeters

A type of ionization chamber used by personnel to measure radiation dose. The results might be labeled “Pen” dose. Other names: pencil, pocket dosimeter, pocket ionization chamber.

penetrating dose

Designation (i.e., P, Pen, or Gamma) on Fernald film dosimeter reports that radiation.

Personal Dose Equivalent, Hp(d)

Radiation quantity recommended for use as the operational quantity to be recorded for radiological protection purposes by the International Commission on Radiological Units and Measurements. The Personal Dose Equivalent is represented by Hp(d), where d identifies the depth in millimeters and represents the point of reference for dose in tissue. For weakly penetrating radiation of significance to skin dose, d = 0.07 millimeter and is noted as Hp(0.07). For penetrating radiation of significance to “whole-body” dose, d = 10 millimeters and is noted as Hp(10).

photon

A unit or “particle” of electromagnetic radiation consisting of X- and/or gamma rays.

rad

A unit of absorbed dose equal to the absorption of 100 ergs per gram of absorbing material, such as body tissue.

radiation

One or more of beta, neutron, and photon radiation.

radioactivity

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

rem (roentgen equivalent in man)

A unit of dose equivalent equal to the product of the number of rads and the “quality factor” and any other modifying factors.

rep (roentgen-equivalent-physical)

Historically, the rep has been used extensively for the specification of permissible doses of ionizing radiations other that X-rays or gamma rays. Several definitions have appeared in the literature but in the sense most widely adopted, it is a unit of absorbed dose with a magnitude of 93 ergs per gram.

roentgen

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

sievert

The SI unit for dose equivalent. (1 sievert = 100 rem).

skin dose

Absorbed dose at a tissue depth of 7 milligrams per square centimeter.

tissue equivalent

Term used to imply that the radiation response of the material being irradiated is equivalent to tissue.

TLD chip

A small block or crystal made of lithium fluoride used in the TLD.

thermoluminescent

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

thermoluminescent dosimeter (TLD)

A holder containing solid chips of material that when heated will release the stored energy as light. The measurement of this light provides a measurement of absorbed energy, which can be related to dose through suitable calibration. The solid chips are sometimes called crystals.

whole-body dose

Commonly defined as the absorbed dose at a tissue depth of 1.0 centimeter (1,000 milligrams per square centimeter); also used to refer to the dose recorded.

X-ray

Ionizing electromagnetic radiation of extra-nuclear origin.