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Retrospective Assessment of Personnel Neutron Dosimetry for Workers at the Hanford Site

J. J. Fix
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Executive Summary

This report was prepared to examine the specific issue of the potential for unrecorded neutron dose for Hanford workers, particularly in comparison with the recorded whole body (neutron plus photon) dose. During the past several years, historical personnel dosimetry practices at Hanford have been documented in several technical reports (Wilson 1987, Wilson et al. 1990, Fix et al. 1994). This documentation provides a detailed history of the technology, radiation fields, and administrative practices used to measure and record dose for Hanford workers. Importantly, documentation has been prepared by personnel whose collective experience spans nearly the entire history of Hanford operations beginning in the mid-1940s. Evaluations of selected Hanford radiation dose records have been conducted along with statistical profiles of the recorded dose data. The history of Hanford personnel dosimetry is complex, spanning substantial evolution in radiation protection technology, concepts, and standards.

Epidemiologic assessments of Hanford worker mortality and radiation dose data were initiated in the early 1960s. In recent years, Hanford data have been included in combined analyses of worker cohorts from several Department of Energy (DOE) sites and from several countries through the International Agency for Research on Cancer (IARC). Hanford data have also been included in the DOE Comprehensive Epidemiologic Data Resource (CEDR). In the analysis of Hanford, and other site data, the question of comparability of recorded dose through time and across the respective sites has arisen. DOE formed a dosimetry working group composed of dosimetrists and epidemiologists to evaluate data and documentation requirements of CEDR. This working group included in its recommendations the high priority for documentation of site-specific radiation dosimetry practices used to measure and record worker dose by the respective DOE sites. IARC formed a dosimetry subcommittee to evaluate comparability of radiation dose data among participants in their study.

Based on previous published assessments by the authors of this report (Wilson et al. 1990, Fix et al. 1994) the evaluations associated with the epidemiologic studies have shown recorded occupational whole body dose for Hanford to be comparable with the currently accepted deep (i.e., 1 cm in tissue) dose and with the recorded dose for other participants involved in these studies, with notable exceptions of exposure to 1) low-energy photons, 2) neutrons, and 3) internal contaminants other than tritium. This is attributable to site-specific practices, and to limitations of dosimetry systems, particularly for the earlier years when technology was less advanced.

The historical pattern of recorded neutron dose at Hanford shows essentially no recorded neutron dose prior to 1950. Relatively little neutron dose, compared to the recorded whole body dose from photon (x and gamma) radiation, was recorded prior to about 1957. Substantially more neutron dose was recorded until 1972 when, with implementation of the Hanford thermoluminescent neutron dosimeter, significantly greater neutron dose was recorded. In contrast, significant whole body dose from photon radiation is recorded throughout the history of Hanford operations.

The historical record shows that Hanford assigned personnel dosimeters to personnel with any potential for radiation exposure and assigned neutron dosimeters to employees with any significant

potential for exposure to neutron radiation. This was certainly the case following introduction of the Nuclear Track Emulsion, Type A (NTA), film dosimeter at Hanford in 1950, for which dosimeter processing records can be inspected for all assigned NTA film dosimeters. Practices used to assign neutron dosimeters prior to 1950, when boron-lined pocket ionization chambers were assigned, is not known in detail because there is no recorded neutron dose before 1950. However, it is expected that there was little worker exposure to neutron radiation before operation of the Hanford Plutonium Finishing Plant (PFP), which began operation in mid-1949.

It is evident that substantial effort was made by Hanford dosimetry organizations to conduct detailed dosimetry evaluations throughout the history of Hanford operations. There are records of many studies, evaluations, and system improvements beginning as early as 1944, as described in this report and references. For example, to improve dosimeter performance, personnel, calibration, and control, NTA film dosimeters were administered in batches, as procured from the supplier. For this report, a database was developed containing 85,000 records of processing data for 529 separate batches of NTA film used at Hanford during the period 1950-1961.

Detailed studies of personnel neutron dosimeter performance in the work environment were conducted to prepare for the first Hanford thermoluminescent dosimeter (TLD) in 1972 and again in 1994-1995 to prepare for the most recent Hanford combination neutron dosimeter. In both of these field evaluations, NTA film was evaluated along with instrument measurements of neutron spectra and dose. Based on these studies, there is undoubtedly under-recorded neutron dose for some Hanford personnel, specifically for those workers associated with plutonium-handling operations. Neutron dose was under-recorded because of lower energy neutrons in this work environment and the lower energy cutoff at about 1 MeV for the NTA film dosimeter. Although NTA film was the only generally accepted method of personnel neutron dosimetry during the 1950s and 1960s, NTA film has since been recognized to be unacceptable for use in facilities with significant lower-energy neutron radiation, such as in Hanford plutonium-handling facilities.

Based on information contained in this report and references, the following statements regarding Hanford recorded dose can be made:

- The recorded whole body deep dose, calculated as the sum of the photon deep dose and the neutron dose, is accurate for the vast majority of Hanford workers. These workers' primary radiation exposures were directly attributable to higher energy photon radiation.
- For the relatively small number of plutonium workers, the whole body deep dose from all energies of photon radiation is expected to be measured accurately, beginning with the use of the multi-element beta/photon film dosimeter in 1957. For the original two-element beta/photon dosimeter used at Hanford, beginning in 1943, under-reporting of the whole body deep dose did occur in lower energy photon fields. However, steps were taken to compensate for this effect by adding in a fraction of the measured shallow dose. As described in this report, the recorded shallow dose can be used to conservatively estimate the deep dose. As originally measured with the Hanford two-element film

dosimeter, the shallow dose from lower energy plutonium x-rays is approximately a factor of 5 too high. This was recognized by Hanford dosimetrists, and the recorded shallow dose was reduced by about a factor of 5 (multiplicative factors of 0.2 in 1952 and 0.14 in 1956 are noted in the historical documentation), based on knowledge about the work location. The deep dose was calculated as the sum of the dosimeter penetrating dose component and the corrected shallow dose.

- In this report, validation was performed of the originally recorded dose from NTA film processing. Comparisons between the official dose of record and that calculated from the processing data between 1950 and 1961 showed good agreement. In particular, neutron dose recorded in 1950 for three long-term Hanford plutonium-handling workers was validated from the raw processing data using current dose conversion factors.
- Based on current knowledge, there was under-recorded neutron dose primarily before the use of the Hanford TLD in 1972 and specifically for the relatively few Hanford workers involved with plutonium-handling operations. This occurred because of significant neutron radiation in the workplace with energies less than the energy threshold of about 1 MeV (based on a minimum of 4 grains to be counted as a track) for the Hanford NTA film dosimetry system.
- The ratio of recorded neutron to deep photon dose would be expected to vary significantly throughout Hanford facilities. However, the ratio for specific work environments and groups of workers is expected to be highly correlated, as this report shows. This has been reported previously during a national technical committee review of the Hanford personnel neutron dosimetry program in 1972, and by Watson in 1959. The 1972 national review includes tabulation of neutron to gamma (photon deep dose) ratios for several plutonium-handling operations.
- The neutron dose was under-recorded during January 1980 through January 1984 for Hanford plutonium workers when the four-element Hanford TLD was used. A study conducted at that time showed an average under-recorded whole body dose of about 25%.
- Relatively little personnel neutron dose is expected from the Hanford production reactor facilities. Personnel neutron dose was limited by the large quantities of shielding, high temperatures near the reactor core, and the general practice of limiting personnel access to areas near the core during reactor operation. Neutrons were observed in selected reactor areas such as control rod drive rooms and areas with shield penetrations where special tests were being performed. However, in general, neutrons in these areas would be expected to be of higher energy than observed in plutonium-handling facilities and to be accompanied by easily measured high energy gamma radiation. There was essentially no neutron radiation while the reactor WAS not in operation.
- Because of the concern for unrecorded neutron dose, Hanford used internal controls (such as a 3 R/year administrative level from photon radiation beginning in the latter 1950s) to limit whole body dose to personnel.

Accuracy of the recorded dose is important to the validity of Hanford exposure records, and to the conduct of worker health studies that use these records. The general quality of Hanford radiation exposure

records appears to be excellent. Under-recording of neutron dose described in this report is limited specifically to the relatively few hundred personnel who have worked in Hanford plutonium-handling facilities to date, but primarily before 1972, compared to the many tens of thousands of Hanford personnel who have worked over many years in many different radiation environments involving reactor, fuel manufacturing, processing, waste and research facilities.

A retrospective analysis of the magnitude of the unrecorded neutron dose and the change in whole body dose (i.e., photon and neutron dose) could be done. However, tremendous effort would be necessary to determine the best estimate of dose for all workers based on analysis of the type and location of work performed by each worker. If a retrospective analysis were performed for an individual worker, recommended steps in this analysis would include the following:

1. Determine if the worker was potentially affected based on a review of the person's work history, exposure history file and, if necessary, from the dosimeter processing database prior to 1957 and from recorded dose characteristics (x-ray, deep, neutron) from 1957-1971.
2. Determine the range in neutron to gamma ratios from the 1972 report, or other reference, applicable for selected time periods.
3. Calculate the neutron dose from the computerized dose record using the neutron to deep dose ratios from step 2.
4. Compare the calculated dose in step 3 with the recorded neutron dose for the same period of time.
5. Document cases where the maximum of the calculated neutron dose exceeds the recorded neutron dose.

A small refinement in the foregoing is to base the calculation of neutron dose, during the period of use of the Hanford two-element dosimeter, on neutron dose to shallow dose ratios. During this period of time, the shallow dose is considered to be a more reliable indicator of the potential dose received than the deep dose. An estimate of the range in under-recorded neutron dose associated with use of the 4-chip TLD during January 1980 to January 1984 is less significant. However, it is possible to include these years as well in any effort to calculate the range in unrecorded neutron dose for an individual worker based on existing documentation referenced in this report.

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Acknowledgment

This report is a tribute to the efforts of the many professional staff involved in the measurement and documentation of personnel neutron dose since inception of the Hanford Plant in 1943. This is a technically challenging area. Evolution in personnel neutron dosimetry technology and radiation protection practices continues to the present day as illustrated throughout this report.

Summaries of information from many other documents are presented in this report. Interested readers are encouraged to consult the many referenced technical reports and articles. Many of the historical Hanford personnel neutron dosimetry practices could not have been evaluated without the personal reference file maintained by Bob Wilson, one of the authors of this report, for the past 50-plus years of Hanford operations. Articles provided by Bob provided critically important documentation of the challenges and technical complexities associated with personnel neutron dosimetry practices at Hanford. As described in this report, these challenges were faced throughout the DOE and predecessor agency facilities involved with plutonium production.

The authors would like to thank Bill Endres and Lowell Nichols, PNNL, Roger Falk, Rocky Flats Plant, and Dale Cunningham, Westinghouse Hanford Company, for their respective reviews of this document. Bill, Lowell, and Roger were intimately involved in the development and implementation of thermoluminescent dosimetry (TLD) systems which replaced Nuclear Track Emulsion Type A (NTA) film systems at Hanford (Bill and Lowell) and the Rocky Flats Plant (Roger). They have conducted numerous laboratory and workplace validation measurements comparing the performance of both NTA and TLD. They were all involved in a 1972 technical review of the Hanford personnel neutron dosimetry program. Dale, in his operational health physics roles at Hanford, has been involved in many studies of Hanford personnel dosimeter performance in the workplace.

Significant contributions in the preparation of this report were provided by Regina Orgill and Brian Schur. Regina conducted data entry of all of the original nuclear track emulsion processing data, consisting of over 85,000 individual records, spanning the period of 1950 through 1961. Brian, a University of Washington student, analyzed this data during the summer of 1994, Christmas break 1994, and spring break 1995. Using criteria provided by the authors, he prepared several codes for analyses of the data on the Hanford External Dosimetry Project (HEDP) Digital Equipment Corporation computer system. He also evaluated the accuracy of the database information, particularly with respect to the selected sample of workers chosen for more detailed analysis.

The authors would also like to thank Joan Clarke who typed and prepared this report for publication.

Acronyms

AEC	Atomic Energy Commission
BNW	Battelle - Northwest
BNWL	Battelle - Northwest Laboratory
DOE	U.S. Department of Energy
DOELAP	U.S. Department of Energy Laboratory Accreditation Program
EPA	U.S. Environmental Protection Agency
FN	Fast Neutrons
HCND	Hanford Combination Neutron Dosimeter
HEDP	Hanford External Dosimetry Project
HMP	Hanford Multipurpose Dosimeter
HSD	Hanford Standard Dosimeter
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
LET	Linear Energy Transfer
LLD	Lower-Level-of-Detection
MDL	Minimum Detection Level
NBS	National Bureau of Standards
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology
NTA	Nuclear Track Emulsion (type A) film
PFP	Plutonium Finishing Plant
PNL	Pacific Northwest Laboratory
PNNL	Pacific Northwest National Laboratory
PUREX	Plutonium-Uranium Extraction facility, a Hanford facility for separating plutonium (Pu) and uranium from irradiated production fuels using steps of solvent extraction and ion exchange
QC	Quality Control
REDOX	Hanford facility for separating plutonium and uranium from irradiated reactor fuels by using successive steps of chemical <u>Reduction</u> <u>Oxidation</u> together with solvent extraction
RBE	Relative Biological Effectiveness
SN	Slow Neutrons
TE	Tissue Equivalent
TED	Track-Etch Dosimeter
TEPC	Tissue-Equivalent Proportional Counter
TL	Thermoluminescent
TLD	Thermoluminescent Dosimeter

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1.0 Introduction

During the past several years, retrospective evaluations of Hanford dosimetry practices have been conducted to support worker health evaluations. In recent years, combined analyses of worker cohorts from several Department of Energy (DOE) sites (Gilbert et al. 1993, 1989), from several countries through the International Agency for Research on Cancer (IARC) (Cardis et al. 1995a), and through the establishment of the DOE Comprehensive Epidemiologic Data Resource (CEDR) (DOE 1995) introduced the issue of whether recorded dose was comparable through time and across the respective sites. Dosimetry subcommittees have been formed to evaluate these issues (Cardis et al. 1985b, Fix 1994). Participation in these evaluations has shown that recorded occupational whole body dose within the selected DOE facilities are reasonably comparable, with the notable exceptions of exposure to 1) low-energy photons, 2) neutrons, and 3) internal contaminants other than tritium, where significant uncertainty in the recorded dose is anticipated. This is particularly true for the earlier years, when dosimetry technology was less advanced.

This report describes practices used to measure and estimate the dose from neutron radiation for workers at the Hanford Site. Because of the historical nature of this report, currently adopted dosimetry concepts and units are not always used. Where applicable, efforts have been made to describe the respective concepts and units as currently used. A glossary has been included to assist the reader (see Section 9.0). Previously, a description of overall personnel dosimetry practices since the inception of Hanford operations was described by Wilson (1987), and an evaluation of these practices provided by Wilson et al. (1990). More recently, an assessment of the accuracy and bias of Hanford personnel dosimetry systems for higher energy photon radiation was provided by Fix et al. (1994). These reports describe the complexity and technical features of Hanford personnel dosimeters, particularly during the earlier years. Personnel dosimetry practices similar to those at Hanford, particularly with respect to technology, have been used throughout facilities operated by the DOE and its predecessor agency (i.e., Atomic Energy Commission [AEC], and Energy Research and Development Administration [ERDA]) facilities. Brackenbush et al. (1980) describes personnel neutron concepts, instrumentation, and dosimeters used throughout DOE facilities.

1.1 Objectives of this Report

The objectives of this report are:

- to provide a comprehensive overview of all significant technical personnel neutron dosimetry practices throughout the history of Hanford operations, and
- to conduct an evaluation of the potential for under-recorded neutron dose, particularly during earlier years with less developed dosimetry technology.

The potential effect on recorded whole body dose from each change in dosimetry technology and/or calibration has been from available documentation and the expert knowledge of the authors of this report, whose combined experience spans essentially the entire history of the Hanford personnel dosimetry program.

1.2 Structure of this Report

The general structure of succeeding chapters of this report is as follows:

- Section 2.0 provides an historical description of radiation dosimetry concepts and radiation protection requirements. Original concepts of dose measurement and control are based on photon radiation because of the extensive use of x-rays and radium gamma-rays in medical applications. Concepts to be applied to neutron radiation evolved during the early years of Hanford operation.
- Section 3.0 describes the history of Hanford personnel neutron dosimetry practices, including descriptions of all dosimetry systems, significant technical changes, methods of calibration, dose calculation, etc.
- Section 4.0 contains retrospective analysis of the recorded nuclear track emulsion processing data from 1950 to 1961. This data was retrieved from the Federal repository, computerized, and used to retrospectively calculate the neutron dose using selected criteria. The calculated doses were compared to the recorded neutron and whole body dose of record for a selected sample of personnel. This period of time, prior to 1958, received particular focus because, as described later in this report, little neutron dose was recorded.
- Section 5.0 presents the results of Hanford evaluations and/or measurements conducted to validate the performance of Hanford dosimeters in the work environment. This chapter contains information which compares the performance of one or more Hanford personnel dosimeters with instrument measurements of spectra and/or dose.
- Section 6.0 describes detailed studies of neutron dose in Hanford plutonium-handling facilities which have been performed on several occasions as well as recommendations to conduct retrospective dose assessment.
- Section 7.0 summarizes the technical conclusions determined from information in Sections 2.0 - 6.0. The authors' summary is based on more than 100 years of combined professional experience evaluating Hanford dosimeter response in the laboratory and in Hanford work environments.
- Section 8.0 contains the references.
- Section 9.0 contains a bibliography.
- Section 10.0 is a glossary to assist in understanding the information contained in this report.

- The Appendix provides a detailed summary of NTA calibration data for all 529 batches of film used from 1950 to 1961.

Personnel neutron dosimetry continues to the present day to pose significant technical challenges (Fix et al. 1991). In fact, field calibration and verification of the personnel neutron dosimetry system are critically important to ensure accurate dose results for the range of neutron spectra encountered in DOE work environments (Brackenbush et al. 1980). The most recent effort to validate dosimeter performance in Hanford work environments is documented by Endres et al. (1996). Response characteristics of the Hanford combination neutron dosimeter, implemented January 1995, to laboratory and workplace radiation fields are described. Dosimeter performance in the workplace is compared with instrument measurements of neutron spectra and dose at several work locations. These data are used to describe the technical basis of the Hanford neutron dose algorithm.

1.3 Hanford Recorded Personnel Dose

Concepts used to measure and record personnel dose at Hanford have changed with the nationwide evolution in dosimetry concepts and regulatory requirements. Throughout this report, shallow and deep doses^(a) are used to describe Hanford dosimeter capabilities for beta and photon radiation. Historical Hanford dosimeter processing records refer to the shallow dose as the open-window, nonpenetrating, beta, or skin dose. Likewise, the deep dose is referred to as the penetrating, gamma, or whole body silver dose (i.e., because of the 1-mm-thick silver filter used in early Hanford film dosimeters). The neutron dose may be referred to as the thermal or fast neutron dose; however, typically only the total neutron dose (i.e., thermal plus fast) is recorded. In general, the thermal neutron dose is numerically inconsequential.

Radiation protection regulations require estimating the occupational radiation dose to the whole body and to the skin of the whole body. Typically, whole body and skin dose estimates are based on results of personnel dosimeters placed on the front of the torso. From the dosimeter results, the dose to the whole body and skin is calculated. A general approach to calculating these doses for all of the Hanford dosimeter systems for Hanford workers is represented by the following:

$$\text{Whole Body Deep Dose} = \text{deep} + 35\% \text{ x-ray} + \text{neutron} \quad (1.1)$$

$$\text{Whole Body Skin Dose} = \text{shallow} + 65\% \text{ x-ray} + \text{neutron} \quad (1.2)$$

where shallow, deep, x-ray, and neutron refer to the respective dose components determined from the dosimeter. An x-ray dose component was determined from the multi-element beta/gamma film dosimeter, described in Section 3.0, used from 1957 to 1971. Both fast and slow neutron dose results are included in the neutron dose. Equations 1.1 and 1.2 are applied to dosimeter results using the particular nomenclature for each year of record to calculate the whole body deep and skin doses, respectively.

(a) ANSI N13.11 (1993) defines the shallow and deep dose as the dose in tissue at 7 mg/cm² (0.007 cm) and 1 g/cm² (1 cm), respectively.

Hanford operations presented numerous technical challenges to health physicists because of the wide range of radiation exposure conditions. Hanford radiation fields involved fuel fabrication, reactor, irradiated fuel reprocessing, waste, and plutonium finishing facilities. Many of these facilities had the potential for significant personnel exposure at any moment. Throughout these facilities, complex mixtures of beta, photon (i.e., x- and gamma rays) and neutron radiation were encountered. Because of these challenges, significant applied dosimetry research, instrument development, and field measurements, to include administrative controls, were made from the very beginning of operations. The combination of actions was done to better ensure the adequacy of personnel dosimetry practices. As summarized in the reports by Wilson et al. (1990) and Fix et al. (1994), and specifically in this report, technical evaluations of neutron dosimetry issues were prepared by Hanford researchers throughout the history of Hanford operations. Summaries of those evaluations related to personnel neutron dosimetry are presented in this report.

The vast majority of recorded radiation dose for Hanford workers is from photon (i.e., x- and gamma rays) radiation (Buschbaum and Gilbert 1993). Personnel film dosimeters available to Hanford from the beginning of operations in 1943 were highly capable of an assured response to photon radiation, allowing a reasonable estimate of the dose to personnel nearly equivalent with practices utilized at the current time. In 1957, Wilson conducted a retroactive assessment of film dosimeter processing since 1944 (Wilson 1957). This may generally be attributable to the fact that film dosimeters had been extensively used from the early 1900s associated with medical applications of x-rays and radium, which confirmed the adequacy of the earlier processed films.

1.4 Neutron Exposure in Hanford Facilities

Upon the discovery of the neutron by Chadwick in 1932 (Fitzgerald et al. 1967), and the demonstration of a nuclear chain reaction at the University of Chicago metallurgical laboratory in 1942 (Rhodes 1986), events proceeded quickly at Hanford beginning in 1943 to build several reactors, manufacture nuclear fuel, produce irradiated fuel in one of the nuclear reactors, reprocess the irradiated fuel to separate plutonium from the many other fission and activation radionuclides, and purify the plutonium for use in nuclear weapons. Construction of facilities at Hanford for each of these operations was of the highest national priority. There were two major classes of operations at Hanford which involved the potential for significant neutron exposure to workers: 1) nuclear reactors and 2) plutonium refinement facilities. In 1944, these were entirely new facilities with little available history which could be used to guide Hanford Health Physics staff.

1.4.1 Reactor Facilities

Eventually, Hanford had nine plutonium production reactor facilities. These facilities had extensive shielding to reduce worker exposure. Neutron radiation is significant only while the reactor is operating and then, typically, only in areas where personnel are not allowed access during reactor operation. Any significant personnel exposure to neutron radiation would be expected to have an associated large higher-energy photon dose which was readily measured by dosimeters and instruments in routine use. Questions have been raised regarding significant personnel dose arising from "penetrations" through the reactor

shielding, resulting in very intense beams of radiation. These beams, which were likely of a very limited occurrence both in time and space, would be characterized by a substantial gamma component and high energy neutron radiation. It is known that a few personnel could be exposed to a high neutron dose associated with test holes in the reactor, such as during the operation of neutron spectrometer equipment.^(a) However, it appears work control practices were used to minimize any significant neutron dose. Initially, reactors were operated in a relatively "low power" status as experience and confidence in the operation of these facilities evolved. Table 1.1 provides a summary of the operating history of Hanford production reactors. During the years of operation, there were periods of shutdown and changes in the reactor power levels. Cumulative power levels from all Hanford reactors were significantly increased in the mid to late 1950s as all of the reactor systems became operational and efforts were made to operate the respective reactor systems at higher power levels. This was done because of the national priority to produce more plutonium. Figure 1.1 illustrates the operating history of the respective production reactor facilities.

1.4.2 Plutonium Finishing Plant (PFP) Facilities^(b)

In the 1940s, Hanford was the only source of plutonium for the original Manhattan Engineering District project. Plutonium from Hanford was shipped to Los Alamos National Laboratory (LANL) to be

Table 1.1. Hanford Production Reactor Operating History

Reactor	Highest Power Level ^(a)	Construction Start	Operation	
			Start	Shutdown
100-B	1940	August 1943	September 1944	February 1968
100-C	2310	June 1951	November 1952	April 1969
100-D	2005	November 1943	December 1944	June 1967
100-DR	1925	December 1947	October 1950	December 1964
100-F	1935	December 1943	February 1945	June 1965
100-H	1955	March 1948	October 1949	April 1965
100-KW	4400	November 1952	January 1955	February 1970
100-KE	4400	January 1953	April 1955	January 1971
100-N	n/a	May 1959	December 1963	January 1987

(a) December 2, 1963, reactor power level, in Megawatts, limited to the highest level previously achieved (DeNeal 1970). N Reactor was not yet operational.

(a) Wilson R. H. "Neutron Exposure at the 105-DR Reactor." Letter to file dated February 2, 1956.

(b) Significant text in this section prepared from notes provided by M. S. Gerber during June 1996, Westinghouse Hanford Company (WHC), Richland, Washington.

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Figure 1.1. Hanford Production Reactors' Comparative Operating Times

used in the construction of atomic bombs. Originally, Hanford shipped plutonium nitrate. Construction of the Hanford 234-5 building (the Plutonium Finishing Plant [PFP]) began June 1948. The PFP facility was operational on July 5, 1949. The PFP provided the Hanford capability to convert plutonium nitrate to metallic plutonium which was shipped to LANL. The initial 234-5 plutonium finishing equipment was termed the "RG" (Rubber Glove) line because it depended upon personnel working with a series of 28 stainless steel gloveboxes, measuring a total of 55 meters (180 feet) in length, to manually move the plutonium mixtures through the finishing operation.

The basic plutonium finishing operations at Hanford consisted of several standard steps, known as "tasks," described as follows:

- **Task 1, Purification or Oxalate Precipitation** (also known as Wet Chemistry or Feed Preparation). This task consisted of precipitating the Pu nitrate feed solution with oxalic acid and other agents.
- **Task 2, Hydrofluorination** (also called Dry Chemistry in the very early years). In this task, hydrogen fluoride gas was diffused through the precipitate at a very high temperature in a vacuum furnace, producing a plutonium tetrafluoride powder.
- **Task 3, Reduction.** Plutonium tetrafluoride was combined with calcium, a small percentage of gallium, and other agents and fired at very high temperature, again under vacuum, until it fused or "reduced" into Pu metal. The metal was produced in chunks roughly the size and shape of a hockey puck, and were known as "buttons."

- **Task 4, Casting.** The plutonium button was rendered molten and cast into a mold shape roughly approximating the desired weapon hemisphere shape.
- **Task 5, Machining (also known as Shaping).** The hemisphere was ground and lathed to precise, specified dimensions and configuration.
- **Task 6, Coating.** The machined Pu metal was placed on a tripod and coated with nickel carbonyl gas through three separate applications to make sure that all portions of the bare Pu metal were covered. This coating served as a contamination shield during inspection, transport, and storage.
- **Task 7, Final Inspection.** The machined and coated Pu was measured for wall thickness, uniformity of coating, neutron energy, isotopic content, dimensional precision, and any cracking.

Tasks 8 through 13 were identified as topics, not actual process steps: Task 8 was Instrumentation, Task 9 was Control, Task 10 was Ventilation, Task 11 was the Conveyor System (not present in the RG Line, but present in later 234-5 Building process lines), Task 12 was Maintenance of Equipment, and Task 13 was Sampling.

Even as the RG Line became operational at the PFP, design and construction was underway for a remotely operated, mechanized plutonium finishing line. The first line was known as the Remote Mechanical A Line (RMA) and commenced hot operations at the PFP on March 18, 1952. At first, the RMA Line performed all of the process steps in Pu metal production and fabrication except for Task 1 (feed make-up and purification). The RMA Line consisted of a row of 30 interconnected stainless steel gloveboxes, 30 control desks, 10 control cubicles, 24 instrument panels, 9 resistance furnaces, 5 induction furnaces, a sample can handling assembly, a 34-meter (110-feet) long general conveyor and manipulator, other smaller conveyors and furnace loaders, and miscellaneous support equipment. It was located in six rooms of the PFP.

During January and February 1955, in response to the rapidly growing demand for increased plutonium production, the RMA Line was shut down to complete major changes to improve the productivity of the PFP. These changes were focused on building into the RMA Line a new Task 1 process capable of bypassing the precipitation and purification activities then being conducted in Hanford's 231 Isolation Building and expansion of the PFP to complete a series of revisions to Tasks 2 and 3 (hydrofluorination and reduction). The RMA Line ran until mid-1957, when it was again closed briefly to install and activate equipment for a continuous calcination and hydrofluorination process that essentially combined the flow of Tasks 1 and 2.

Many projects were undertaken at the PFP during 1957-1961 in an effort to accommodate the vast production increases generated by the PUREX Plant and the increased reactor throughput. The most significant of these projects were the construction of the RMC Button Line and the RMC Fabrication Line. Both were undertaken officially in April 1957, and completed in late 1959. Actual operations with hot materials commenced in mid-1960. The RMC Line (both the button and fabrication components) consisted of a completely self-contained, remotely operated series of glove boxes very similar to the RMA Line. Like the A Line, the C Line functioned to convert Pu solutions to metal and then to fabricate actual

weapons shapes from the metal. It differed from the RMA Line in that it had an automatic vacuum cleaning system that served Tasks 1-4, greater radiation shielding, and improved radiography facilities. The RMC Line was placed where the former RG Line (removed in 1957) had stood, and began operation in late 1960.

Construction of the PFP facilities was done with little information available regarding personnel radiation safety considerations in handling plutonium. In fact, there are references in the historical literature where plutonium was considered to be primarily a hazard as an alpha-emitting radionuclide. By wearing surgical gloves, all of the radiation would be prevented from exposing the workers. It was known at Hanford that plutonium emitted low-energy x-rays, alpha radiation, and, upon spontaneous fission, gamma and neutron radiation (Roesch 1951).

Dosimetry problems were noted at PFP as soon as operations began in 1949,^(a) at which time an investigation was conducted to determine which radiations existed and to what extent dose from these radiations was correctly interpreted from the personnel monitoring program. Roesch (1951) describes considerations involving calibration of the NTA film. Based on the relative energy sensitivity of NTA film to the PoB calibration source and to PuF_4 , where the fluorine was known to greatly increase the neutron flux level, Roesch recommended a factor of 1.35 be applied to increase the recorded neutron dose. Roesch also described the fading expected to occur and the observation that this effect increases with decreasing neutron energy. For the two-week film exchange period, the loss of tracks was anticipated to approach 50%. Roesch recommended that a factor of 1.17 be used to increase the recorded dose for the effects of fading expected during a two-week exchange period. Based on these two effects (i.e., energy and fading), Roesch recommended an increase by a factor of 5/3 in the recorded neutron dose. Undoubtedly, this is one of the reasons Hanford calibration films were exposed at the beginning of the monitoring period, which would generally result in an overestimate of recorded dose based only on considerations of fading. Also, at the beginning, Hanford NTA film exchange periods were bi-weekly; the beta/photon film dosimeter was exchanged weekly.

Significant problems were encountered with the "soft x-ray" radiations from plutonium, and their effect on the film dosimeter. The significance of the plutonium x-ray radiations was fully understood in 1952. It was determined that the nonpenetrating (i.e., shallow) dose calibration, based on radium, must be multiplied by a factor of either 0.14^(b) or 0.2 for the open window position of the Hanford two-element dosimeter.^(c) The issue of the critical organ (i.e., eyes or gonads) for this radiation was identified and was the subject of additional study. With the implementation of the multi-element beta/photon film dosimeter during 1957, issues regarding the correct shallow and deep dose interpretation for the low energy photon radiation in the Hanford 234-5 facility became a major issue because a number of workers were anticipated to exceed the 3 R per year administrative dose limit. Wilson provided a summary of a meeting held to

(a) Keene, A. R. "Exposure Problem: 234-5 Building." Letter to G. E. Backman dated February 12, 1957.

(b) Wilson, R. H. "Meeting on External Exposure Problems." Letter to distribution dated February 28, 1957.

(c) Ebright, D. P. "Monitoring Problems." Letter to A. R. Keene dated November 15, 1955.

discuss external exposure problems during 1957.^(a) Watson^{(b),(c)} described reviews of the 40 individuals (21 from 234-5) from the 200 Work Areas who had the highest recorded shallow dose and a list of personnel from 234-5 based on their length of employment. Studies associated with this issue resulted in the adoption of the Hanford practice of adding 35% of the x-ray dose to the deep dose and 65% of the x-ray dose to the shallow dose.^(d)

In a report written during 1959, Watson describes the Hanford experience with NTA film used since 1950 and provides recommendations for its improvement (Watson 1959). From 1950 through 1958, more than 66,000 NTA films had been processed. Of this total, 107 films showed doses exceeding 90 mrem. A definite correlation was observed between NTA film with a positive neutron dose and an associated gamma dose, particularly for higher neutron doses. Based on this work, it was concluded that a sequential analysis method for NTA film should be used. Four recommendations are included in this report as follows:

1. NTA films should be evaluated for fast neutron exposure only when there is a significant gamma exposure as measured by the NTA film dosimeter.
2. Records of the gamma dose as measured with the NTA film dosimeter should be maintained for future analysis.
3. The sequential analysis based on first observing a gamma dose prior to NTA film evaluation should be adopted.
4. A research program to investigate improved personnel neutron monitoring devices is required. Such a personnel monitoring device should be capable of measuring the full spectrum of neutron energies encountered in Hanford work environments. The device should be sensitive enough to measure an annual dose of 0.5 rem and permit reporting dose information at frequent intervals, preferably every four weeks.

It is understood that these recommendations were adopted into the routine program.

Significant changes in PFP shielding were made over the years.^(e) As originally constructed, the gloveboxes contained essentially no shielding other than the stainless steel construction and the plastic hood windows. Beginning in 1956 (approximately), personnel exposure to lower energy photon radiation was reduced following installation of lighter weight shielding. This reduced the x-ray dose but did little to

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- (a) Wilson, R. H. "Meeting on External Exposure Problems." Letter to several people describing minutes of a meeting dated February 28, 1957.
- (b) Watson, E. C. "Background Information for 234-5 Exposures." Letter to A. R. Keene dated February 11, 1957.
- (c) Watson, E. C. "234-5 Exposure Histories." Letter to A. R. Keene dated February 22, 1957.
- (d) Watson, E. C. "234-5 Gamma Exposure Limits." Letter to A. R. Keene dated August 2, 1957.
- (e) Wilson, R. H. and K. R. Heid. Appendix A to Letter from M. A. Biles to T. A. Nemzak, "Ad Hoc Technical Committee Findings," dated November 23, 1972.

reduce the neutron exposure. Installation of heavy shielding materials (lead, lead glass, steel plate, etc.) was completed during 1959 (approximately). These conditions remained through 1972.

In the early 1960s, studies of the neutron dose component of the whole body dose were conducted because of the trend towards higher annual doses.^(a) There was concern for the increasing potential of exceeding an annual whole body dose of 5 rem per year. This situation conflicted with the Hanford philosophy to maintain the recorded whole body dose, primarily from photon radiation, to less than 3 rem per year to compensate for any uncertainty in measured personnel dose, particularly associated with neutron radiation.^(b) These discussions apparently led to an overall task to evaluate options to improve Hanford neutron dosimetry capabilities. Two prime objectives of the task were described in a letter from Unruh in 1962^(c) as follows:

1. to improve the personnel neutron dosimeter detection limit for fast neutrons to 1 rem per year or less, and
2. to generally improve the dose evaluation techniques including a review of calibration practices.

This led to a series of instrument and dosimeter workplace measurements to evaluate the accuracy of the recorded neutron dose. These measurements are described in Section 5.0.

1.4.3 Surface Dose Rate from Plutonium

During the latter 1940s and into the 1950s, the surface exposure rate from plutonium was measured in several chemical forms and configurations. The significant generation of neutron radiation from alpha nuclear interactions, notably with fluorine, became evident as soon as PFP became operational. A summary report of the process of producing Hanford "buttons" of plutonium metal and the surface dose rates from the respective plutonium-handling operations is presented by Helgeson (1956). The surface dose rates were observed to vary substantially, depending upon the chemical form and geometry of the plutonium. The primary emphasis in these measurements was the personnel dose from photon radiation although the presence of neutron radiation, particularly for PuF_4 , was understood. Dose rates of several hundred to thousands of mrem per hour for selected chemical forms and geometries of plutonium were observed. Roesch (1957) describes many of the technical aspects of determining the surface dose rates from plutonium nuclides and from ^{241}Am .

(a) Knights, L. M. "Personnel Exposure to Neutrons." Letter to L. I. Brecke, J. J. Courtney, C. C. Hinson and H. H. Hopkins, Jr., dated July 28, 1961.

(b) Keene, A. R. "Supervisory Authority to Allow Exposure in Excess of Daily Limits." Letter to L. M. Knights dated September 21, 1961.

(c) Unruh, C. M. "Neutron Dosimetry." Letter to A. R. Keene dated February, 1962.

1.5 Trends in Recorded Hanford Neutron Dose

Trends in recorded dose for Hanford workers have been examined in epidemiologic assessments conducted by Gilbert et al. (1993). An important consideration in these assessments was the significant change in the pattern of recorded annual whole body dose since 1943, as shown in Figure 1.2, where the number of personnel exposure records with positive annual photon (i.e., penetrating, whole body or deep dose) and positive annual neutron dose, respectively, is plotted based on information provided by Buschbaum and Gilbert (1993). The total number of monitored workers is also shown in Figure 1.2. Figure 1.3 presents the collective annual photon and neutron whole body dose since 1943. Several trends are apparent in this figure:

- Most workers had positive recorded photon dose.
- There is little neutron dose recorded prior to 1958.
- A significant change in recorded neutron dose appears to have occurred in 1958.

One of the objectives of this report is to understand the reasons for the trends shown in Figures 1.2 and 1.3.

Figure 1.2. Trend in Recorded Annual Photon and Neutron Dose for all Hanford Workers (Buschbaum and Gilbert 1993)

Figure 1.3. Trend in Annual Collective Photon and Neutron Dose for all Hanford Workers (Buschbaum and Gilbert 1993)

2.0 Personnel Dosimetry Concepts

Personnel dosimetry concepts evolved throughout the 20th century, along with increased understanding of atomic and nuclear phenomenon, effects of radiation type and intensity on living tissue, and sociopolitical considerations regarding benefit and risk. Today, 100 years after the discovery of x-rays and radioactivity, these concepts continue to evolve. A few of the more significant historical concepts related to personnel dosimetry are described in the following sections. The early history of dosimetry is focused on quantification of dose from x-rays and radium gamma-rays. Concepts to quantify absorbed dose or dose equivalent from neutron radiation evolved during the early years of Hanford operation.

2.1 Concept of Tolerance Dose

With the realization of the deleterious effects of ionizing radiation came an awareness of the need to control human exposure to radiation. During the years following the discovery of the x-ray in 1895, the concept of a tolerance (or tolerable) dose of radiation evolved. This concept contained the assumption that there was a dose rate to which a person could be exposed for prolonged periods of time without ultimately suffering injury. Such a concept was discussed by the British X-Ray and Radium Protection Committee when it was formed in 1921. In an attempt to determine the tolerance dose and dose rate, Mutscheller (1925) and others conducted studies of persons who had been exposed to ionizing radiation for years without suffering any detectable deleterious effects. Accurate measurement of the dose from x-rays could not be made for many years and, consequently, the correlation of dose and effect could not be made directly. This led to the development of several concepts to quantify dose, as described in the following sections.

2.1.1 Roentgen (R)

In 1928, the international unit of x-ray dose was originally defined at the Stockholm Congress of Radiology, as follows (Hine and Brownell 1956):

The roentgen is the quantity of x-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 cm³ of atmospheric air at 0°C and 76 cm of mercury pressure such a degree of conductivity that 1 electrostatic unit (esu) of charge is measured at saturation current.

This definition of the roentgen, which is also a prescription for its measurement, was modified at the Chicago Congress of Radiology in 1937 to a form applicable also to the dosimetry of radium gamma rays. The changed wording is:

The roentgen shall be the quantity of x- or γ -radiation such that the associated corpuscular emission per 0.001293 gm of air produces in air, ions carrying 1 esu of quantity of electricity of either sign.

The International Commission on Radiation Units and Measurements (ICRU) Report No. 19, and subsequently Report No. 33, describe exposure as:

The quotient of dQ by dm where the value of dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated in air of mass dm are completely stopped in air. The roentgen = $2.58 \times 10^{-4} \text{ Q/kg}$ (exactly).

The definition of the roentgen led to specification of the tolerance dose in roentgen/day or roentgen/week, and to a number of other intermediate units: the gram roentgen, roentgen-equivalent-physical and roentgen-equivalent man.

2.1.2 Early Tolerance Dose

In nearly all cases, the tolerance dose rate estimated from these early studies was in the range of 0.1 to 0.2 roentgen per day. Subsequently, in 1934, the International Committee on X-ray Protection adopted 0.2 roentgen/day or 1 roentgen/week as the "tolerance dose." No statement was made as to whether the dose should be measured "in air" or on the surface of the body to include back-scattered radiation. Following local practice in x-ray therapy in Europe and particularly in England, the tolerance dose was assumed to include back scatter, whereas in the United States, it was taken to represent the dose in air. In the U.S., the value of 0.2 roentgen/day was generally regarded as being too high and a value of 0.1 roentgen/day was generally used. At the time, the chief concern was protection of radiologists working with x-ray machines. As evidence accumulated through the years indicating that even small doses of ionizing radiation might be cumulative in effect, at least as regards genetic and aging processes, the concepts of tolerance dose and dose rate went into decline (Fitzgerald et al. 1967).

2.1.3 Gram-Roentgen

To express the total energy absorbed throughout a volume of irradiated tissue in terms of a unit related to the roentgen, a gram-roentgen was defined as equal to the x- or γ -ray energy absorbed when 1 gram of air is exposed to 1 roentgen. The value of the gram-roentgen is approximately 84 ergs/gram and is almost independent of the radiation quality (Hine and Brownell 1956).

2.1.4 Roentgen-Equivalent-Physical (REP)

By definition, the roentgen is unsuitable for expressing dose in the case of corpuscular radiations such as neutrons. Accordingly, Parker (Taylor 1979, Kathren et al. 1986) suggested another unit, the roentgen-equivalent-physical (rep), defined as "that dose of ionizing radiation which produces an energy absorption of 84 ergs/cm³ in tissue." This value was originally chosen to be the same as the energy absorption per roentgen per gram of air and was not identical, therefore, with energy absorption per roentgen in tissues, since this depends on both tissue composition and radiation quality. Later, the value of the rep was changed to 93 ergs/cm³ of tissue because this value represents more accurately the energy absorption per cm³ of water or tissue which has received a dose of 1 roentgen of penetrating x- or γ -rays.

2.1.5 Roentgen-Equivalent-Man (REM)

The roentgen-equivalent-man was defined originally as the dose which, delivered to man (or mammal) exposed to any ionizing radiation, is biologically equivalent to the dose of 1 roentgen of x- or γ -ray radiation. The *rem* is thus intended to take into account the relative biological effectiveness (RBE) of different types of radiation. Such factors, however, vary not only with the properties of the radiation but also with the biological effect studied. It became customary, therefore, to regard the *rem* as a "biological" unit of dose defined by the relation

$$\text{dose in rem} = \text{dose in rep} \times \text{RBE} \quad (2.1)$$

This unit was often referred to as the "RBE dose."

2.2 Concept of Maximum Permissible Dose

The concept of tolerance dose was gradually superseded in the thinking of radiation physicists and biologists by the concept of maximum permissible dose. Although this concept was widely used before 1953, it was not until 1953 that it was officially defined by the International Commission on Radiological Protection (ICRP). A maximum permissible dose was defined as that dose of ionizing radiation which, in light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during their lifetime (NBS 1954). The phrase "appreciable bodily harm" was defined as any bodily injury or effect that a person would regard as being deleterious to the health and well-being of the individual. The National Bureau of Standards (NBS) in Handbook 59, "Permissible Dose From External Sources of Ionizing Radiation" (1954), describes many facets of this concept, including considerations of radiosensitivity, biological variability, and acceptable risk. This concept resulted in the designation of "critical" tissues or organs. If exposure was controlled to such tissues or organs, it was assumed that the whole body was protected. This concept involved the introduction of a new unit of radiation absorbed dose, the rad, and discussion of the need to have one dose unit or value to measure radiation dose or detriment.

2.2.1 Absorbed Dose

In July 1953, the International Commission on Radiological Units (ICRU) at its Copenhagen meeting, recommended that a distinction be made between dose in a general sense and "absorbed dose." A new unit, the rad, defined as 100 ergs/gram, was recommended for the latter (NBS 1957). The absorbed dose is defined, for any ionizing radiation, as the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the point of interest. Prior to the use of the *rad*, the *rep* was widely used for specification of permissible doses of ionizing radiations other than x- or γ -rays. For example, the *rep* was used to record the neutron dose of record at Hanford.^(a)

(a) Watson, E. C. "Suggested Revisions of Neutron Metering Program." Letter to H. A. Meloeny dated September 1, 1950.

2.2.2 REM

At that time, the rem was not officially listed as a unit, but in recommendations of the ICRP, it was suggested that this unit should be used when necessary to add doses from different radiations. The rem is then defined in relation to the rad as:

$$\text{dose in rem} = (\text{dose in rad}) \times \text{RBE} \quad (2.2)$$

This was also referred to as the RBE dose. NBS Handbook 59 (1954) discusses the use of the rem in more detail. The introduction of the rad to replace the rep results in a small change in the magnitude of the rem (in the ratio of 93 to 100). The rem is defined as follows:

The quantity of any ionizing radiation such that the energy imparted to a biological system (cell, tissue, organ, or organism) per gram of living matter by the ionizing particles present in the region of interest, has the same biological effectiveness as an absorbed dose of 1 rad of x-radiation with average specific ionization of 100 ion pairs per micron of water in the same region.

The RBE of 1 for x-rays with this specific ionization (lightly filtered 200-kV x-rays) results in the case of 1 rem = 1 rad. Although the limits shown in NBS Handbook 59 are provided in milliroentgen, discussion indicates that the limits are to be considered as equivalent to rem limits based on the use of the rad and the RBE values provided in the Handbook.

2.2.3 Neutron First-Collision Dose

Along with other complexities of neutron radiation, the concept of dose to be used in personnel dosimetry was discussed for many years. Because the permissible limit of exposure to neutrons is related to absorbed dose, it is obviously preferable to measure this quantity directly, particularly as this can be done with little or no information on neutron energy. Like other aspects of neutron technology, dosimetry has not been developed to the point where universally applicable methods of measurement are available (NBS 1957). Perhaps the simplest calculation that can be made is one relating dose to flux through a thin layer of tissue. The resultant value, sometimes referred to as the first-collision dose, is derived from the assumption that the probability of two or more interactions per neutron is negligible (Hine and Brownell 1956). Hanford used the first-collision RBE dose (i.e., rem) to calibrate the neutron dosimeter. The relationship between the first-collision dose and the maximum absorbed dose or maximum RBE dose in a 30-cm slab is presented in Figure 2.1 (NBS 1957). The first-collision dose will underestimate the maximum RBE dose for essentially all neutron energies. However, the first-collision dose may provide a more accurate estimate of dose to the lens of the eye or to the male gonads. Several aspects of this topic were discussed by Roesch and De Pangher in 1958.^(a)

(a) Roesch, W. C. and J. De Pangher. "Neutron Flux-Dose Relations." Letter to A. R. Keene dated September 9, 1958.

Figure 2.1. Ratio of Maximum RBE Dose to First Collision RBE Dose (NBS 1957)

2.3 Concept of Dose Equivalent

Early recommendations on radiation protection were primarily concerned with x-rays and gamma rays, which were deemed to have similar biological effectiveness. When other types of ionizing radiation became important, such as neutrons, it became necessary to consider what came to be called the quality of the radiation (ICRU 1986). Quality relates to the type (i.e., beta, alpha, photons, etc.) and energy of the charged particles that produce the absorbed dose. It was envisioned that the same level of protection should be ensured for all types of ionizing radiation, regardless of their quality. On the basis of specific ionization in air, Cantril and Parker (1945) developed a scheme for dealing with the effects of different radiations, including mixed radiation fields. They assumed that one could add the hazards from the various kinds of radiation and that one could estimate the relative hazards for each kind using the product of what would now be called air kerma (free-in-air) and a relative biological factor based upon specific ionization of charged particles and their ability to penetrate tissue. On this basis, they assigned a relative biological effectiveness of 10 to neutrons and alpha particles. This scheme provided the basis for what is now called the dose equivalent. During the Tripartite Conferences (with representatives from Canada, the United Kingdom, and the United States) in 1949, 1950 and 1953, the decision was made to base the relative biological effectiveness on x-rays (Taylor 1979).

In 1962, the ICRU provided a formal statement on dose equivalent in Report 10a (ICRU 1962). The statement was made that although the concept does not cover a number of theoretical aspects, it fulfills the

immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection. In ICRU Report 19 (ICRU 1973), the expression for the dose equivalent was expanded as follows:

$$H = DQN \quad (2.3)$$

where H is the dose equivalent in rem, D is the absorbed dose in rad, Q is the quality factor, and N is the product of any other modifying factors.

2.4 Concept of Effective Dose Equivalent

In 1977, the ICRP introduced a system of dose limitation in Publication 26 which involved adding the dose equivalent from external radiation to the committed effective dose equivalent from internal radiation (ICRP 1977). To calculate the committed effective dose equivalent, a set of weighting factors was provided. The weighting factors have subsequently been updated in ICRP 60 (1991) and are summarized in Table 2.1. The weighting factors are intended to represent the fraction of overall health risk resulting from uniform, whole body irradiation, attributable to a specific tissue. The dose equivalent to the affected tissue is multiplied by the appropriate weighting factor in Table 2.1 to obtain the effective dose equivalent contribution from that tissue. In 1981, the U.S. Environmental Protection Agency (CFR 1981) proposed the use of the ICRP 26 methodology to limit occupational dose. This methodology has gradually become known as the effective dose equivalent, defined as follows:

The summation of the products of the dose equivalent received by specified tissues of the body and the appropriate weighting factors. It includes the dose from radiation sources internal and/or external to the body. The effective dose equivalent is expressed in rem.

The concept of effective dose equivalent is gradually being used for additional purposes. For example, draft ANSI N13.41 (ANSI 1996) proposes to use weighting factors to determine the effective dose equivalent from non-uniform external exposure of the whole body.

2.5 Summary of Radiation Units

More recently, with the implementation of the International Standard of Units (SI), the special units (curie, roentgen, and rad) are not consistent with this system. The National Institute of Standards and Technology (NIST) has begun using Air Kerma to describe the dose conversion factors for photons. Table 2.2 provides a summary and application for the respective radiation units.

Table 2.1. Weighting Factors^(a)

Tissue	Weighting Factor ICRP 26	Weighting Factor ICRP 60
Gonads	0.25	0.20
Breast	0.15	0.05
Red Bone Marrow	0.12	0.12
Lung	0.12	0.12
Thyroid	0.03	0.05
Bone Surfaces	0.03	0.01
Colon	-	0.12
Stomach	-	0.12
Bladder	-	0.05
Liver	-	0.05
Oesophagus	-	0.05
Skin	-	0.01
Remainder	0.30	0.05

(a) From ICRP Publications 26 (1977) and 60 (1991).

Table 2.2. Historical Radiation Quantities and Units^(a)

Unit or Quantity	Symbol	Brief Description	Application
Roentgen	R	2.58×10^{-4} C/kg	Exposure: applies only to photons in air
Radiation-equivalent-physical (REP)	rep	0.0093 J/kg (93 erg/g)	Dose: applies to corpuscular radiation
Absorbed dose	rad	0.01 J/kg (100 erg/g)	Dose: applies to any radiation
Gray	Gy	1 J/kg (=100 rad)	SI unit of dose
Linear energy transfer	LET	Energy deposition per unit of path length	To determine quality factor
Relative biological effect	RBE	Biological potency of radiation compared to biological effect from 200-keV x-rays	Radiobiology
Dose equivalent	H	Absorbed dose x Q x other modifying factors	Radiation protection (health physics)
Quality factor	Q	Factor based on radiation type and energy used to calculate dose equivalent	Radiation protection
Rem	rem	rad x Q x other modifying factors	Unit of dose equivalent
Sievert	Sv	Gy x Q x other modifying factors (1 Gy = 100 rem)	SI unit of dose equivalent
Effective dose equivalent	rem	Effective dose (annual, committed, total, etc.) based on weighting factors applied to organ dose equivalent	Unit of effective dose equivalent
Kerma	J/kg	Sum of initial kinetic energies of all charged particles liberated by indirectly ionizing particles in a volume	More precise unit being used to determine dose conversion factors for photon beams

(a) After Sanders and Kathren (1983).

3.0 History of Hanford Personnel Neutron Dosimetry Practices

Reports by Wilson (1987) and Wilson et al. (1990) describe Hanford personnel dosimetry systems and practices. These reports provide a general review of Hanford neutron dosimetry practices and detailed specifications of the respective dosimeters. This chapter specifically addresses Hanford practices used to determine the neutron component of the official whole body dose of record.

3.1 Hanford Personnel Neutron Dosimetry

Hanford has relied on three forms of widely used dosimetry technology to determine the neutron dose: 1) boron-lined Pocket Ionization Chamber (PIC) prior to 1950, 2) Eastman-Kodak Nuclear Track Emulsion, Type A (NTA) film from 1950 to 1971, and 3) thermoluminescent dosimeters (TLDs) since 1972. Boron-lined pocket ionization chambers are sensitive primarily to thermal neutrons only, which contribute relatively little dose to Hanford workers. Although PICs were used at Hanford beginning in the 1940s, no record of any recorded neutron dose from this system has been found. This is confirmed by the historical tabulation of recorded dose by Buschbaum and Gilbert (1993), which shows no neutron dose recorded prior to 1950.

Several types of dosimeter holders, processing techniques, calibration, and dose assessment methodologies were used with the nuclear track emulsion and thermoluminescent dosimetry technologies during the period of their respective use. General features of these dosimeters are described in the report by Wilson (1987). A description of Hanford practices to process, calibrate, and calculate neutron dose for NTA film and TLDs is provided in the following sections. Table 3.1 provides a chronological review of the most notable changes in the history of personnel neutron dosimetry practices at Hanford extending from the use of PICs in 1945 through the termination of NTA in 1971.

3.2 Nuclear Track Emulsion

From 1950 through 1971, Hanford personnel neutron dosimetry was based on various holders containing Eastman-Kodak Nuclear Track Emulsion Type A (NTA) film. Watson (1951, 1959) describes many technical features of Hanford NTA personnel neutron dosimetry practices. Dental-film-sized packets of NTA film were used at Hanford and at other laboratories (e.g., Los Alamos and Clinton, later to become the Oak Ridge National Laboratory) to monitor neutron radiation. The thickness of the emulsion used at Hanford was 25 microns. Thicker emulsions were available but experience at Hanford showed that the thicker emulsions were less uniform.

Fast neutrons produce recoil protons within the hydrogenous emulsion and film base. The presence of tracks created by recoil protons can be observed and counted with a microscope. The sensitivity of NTA film to fast neutrons is dependent upon the energy of the incident neutrons and upon the thickness of the emulsion, which may vary from film to film. Energy dependence of NTA film involves changes in the hydrogen cross-section with energy and the associated average range of the recoil protons. As the neutron

Table 3.1. Hanford Personnel Neutron Dosimetry Practices, 1945-1971^(a)

Year	Practice	Description
1945	Personnel neutron monitoring using PICs	Personnel neutron monitoring conducted using boron-lined pressurized ionization chambers (PICs) assigned to workers.
1950	Implemented routine NTA monitoring for neutron radiation using PoB calibration source	Eastman-Kodak Type A (NTA) emulsion placed in two-element beta/photon holder. Each reading of 40 fields of view (0.78 mm^2) was conducted at least three times. PoB used as the calibration source. Dose recorded in units of rep, which were equivalent to dose equivalent measured in mrem. NTA dosimeters assigned to all workers working in facilities with neutron fields. Effective November 8, 1950, recorded deep (penetrating) dose from beta/photon film dosimeter based on measured dosimeter response behind the silver shield.
1952	Revised deep dose	Effective March 9, 1952, recorded deep (penetrating) dose calculated as the sum of the open window response, divided by a factor of 5, plus the measured dosimeter response behind the silver shield.
1955	Calibration source changed to positive ion accelerator	The positive ion accelerator produced lower energy neutron beams, which were expected to be closer to the neutron energies observed in the work environment.
	Revised deep dose	Effective December 1, 1955, recorded deep (penetrating) dose calculated as the sum of the open window response, divided by a factor of 10, plus the measured dosimeter response behind the silver shield.
1956	Revised deep dose	Effective December 1, 1956, recorded deep (penetrating) dose calculated as the sum of the open window response, multiplied by a factor of 0.14, plus the measured dosimeter response behind the silver shield.
1957	Multi-element beta/photon film dosimeter implemented	On April 4, 1957, the multi-element beta/photon film dosimeter was implemented. Whole body deep dose calculated from 0.35 times x-ray dose plus measured deep (penetrating) component.
1958	Calibration source changed to PuF_4	In July 1958, the plutonium fluoride source was introduced. The dose factor was based on single collision neutron dose theory. This source was anticipated to be close in energy to the neutron radiation in the work environment.
1958	Multi-element dosimeter	Introduced first holder specifically designed for neutron radiation fields.
1962	Revised multi-element dosimeter	Implemented modified multi-element dosimeter, which also contained nuclear accident dosimetry components.
1965	Calibration on-phantom	Effective January 1965, calibration dosimeters were exposed on phantom to more closely simulate geometry of personnel exposure. Neutron dose calculated from a standard calibration factor of 17 mrem/track.
1965	Processing assigned to U.S. Testing	As one element of diversification of Hanford contractor responsibilities with the departure of General Electric, dosimeter processing was assigned to U.S. Testing Company using the same equipment and staff as previously done under General Electric.
1965	NTA Processing	Readout changed to 25 fields of view (0.5 mm^2) during routine processing.
1971	Terminated NTA film monitoring	Effective January 1, 1972, Hanford thermoluminescent dosimetry system replaced NTA film.

(a) Adopted from Wilson 1987.

energy increases, the cross-section decreases but the average range of the recoil protons increases. The overall effect is that NTA film is more sensitive to higher energy neutrons. The variation in emulsion thickness from film to film is associated with different production batches of film. For these reasons, Hanford assigned, calibrated, and evaluated personnel neutron dose for each specific production batch of NTA film, as obtained from the supplier.

NTA emulsions are also sensitive to thermal neutrons because of the (n,p) interaction with nitrogen in the emulsion. Therefore, methods were necessary to "shield" the NTA film from thermal neutrons. Hanford dosimeter designs such as the two-element silver holder (1-mm thick) used at Hanford from 1956 to 1957 were very capable of minimizing effects on NTA film from thermal neutrons. NTA film is also sensitive to photon radiation. The effects of thermal neutrons and photons is to increase the general difficulty of identifying specific proton recoil tracks used to calculate the fast neutron dose.

A significant characteristic of NTA film is its lack of response to intermediate neutron energies. Tracks of length less than about 3 microns are difficult to identify. A proton track appears as a series of developed grains. Since developed grains from proton recoils are the same as those from other developed grains, some criteria are necessary to identify a track. Tracks with only one or two grains may be the result of recoil protons but are impossible to identify from developed grains in the film from other sources. There is considerable uncertainty about tracks with only three grains. At Hanford, the observation of a track was confined to tracks with four or more grains (Watson 1951). As such, the lower energy threshold for the Hanford NTA film dosimeters is expected to be about 1 MeV, particularly when photon "fogging" is present.

Effective sensitivity of the film is dependent upon the elapsed time between exposure and processing of the emulsion, and upon the person counting the tracks. For a given developing process, the loss of tracks due to fading is directly proportional to the time elapsed before counting the film. This phenomenon is attributed to random fading of individual grains within a track rather than fading of the entire track. Assuming that each grain of a track has equal probability of fading, a longer track will remain distinguishable for a longer time period than a shorter track. Studies have shown that NTA film exposed to higher energy neutrons demonstrates a longer fading "half-time" than films exposed to lower energy neutrons. To compensate for this effect, control badges were prepared immediately before the personnel badges were issued. These control badges were stored along with the personnel badges at the badge exchange racks located at the entry to the respective Hanford work areas. Each control badge consisted of an exposed NTA film and an unexposed NTA film. Studies reported by Watson (1957) showed a fading "half-time" of 50 days for Hanford NTA used film, exposed to a polonium-boron source. The practice of exposing the calibration film prior to assigning the personnel dosimeter results would result in an over-estimate of the actual dose, assuming all other effects are equal. The magnitude of the over-estimate is dependent upon the length of the exchange period. For the two-week exchange used in the early 1950s, this resulted in a small effect.

Hanford employed a counting method in which different technicians would read, at least three times, 40 fields of view (0.78 mm^2) on each film. (In 1965, 25 fields of view, 0.5 mm^2 , were implemented, along with an ocular with a wider field of view.). The average of the different readings was used in the calculation of dose. If significant variations in track count were observed among the readings, then the

film was recounted. Watson (1951) describes the training and quality control process associated with counting the films. Nearly three months of training was necessary to develop the skill necessary by the technician to reproducibly count the tracks. The track densities are typically very small because of the low sensitivity of the emulsion and the relatively low neutron fluence. Counting the films day after day, particularly with little or no distinguishable neutron-induced tracks, is very tedious and can result in staff morale problems. For this reason, Watson reported that selected films were exposed to significant doses and processed without the knowledge of the technicians. Technicians were expected to count tracks only four hours per day, the remaining work time being spent on other tasks. In this manner, a technician was expected to process about 25 NTA films in a week. Watson (1951) reported the routine counting results to be reproducible within about 20%. Based on the polonium-boron neutron source exposures, it was possible to measure 1.4×10^5 neutrons/cm² to within about 30%. Using dose conversion factors of 1.3×10^{-2} mrad/hr per neutron/cm²-sec (Roesch 1954) or 3.5×10^{-5} mrem per neutron/cm²,^(a) this corresponds to doses of 0.5 mrad or 4.9 mrem, respectively, which are essentially equal.

3.2.1 Hanford Nuclear Track Emulsion Dosimeters

There were three specific Hanford NTA dosimeter holders, as described in the following sections. From 1950 to 1971, Hanford used the same Eastman-Kodak Nuclear Track, Type A (NTA) emulsion.

Dosimeter Used From 1950 to 1957. The personnel neutron film dosimeter used from 1950 to 1957 was based on NTA film enclosed in the original two-element dosimeter holder along with the beta/photon film. This holder was fabricated from silver (Ag) of 1 mm in thickness with a 1-cm² open window on the front side. Dose evaluation was based upon a direct comparison of the number of tracks observed on the personnel NTA film, minus tracks observed on background control NTA film, with a calibration curve showing track density as a function of neutron dose.

Dosimeter Used From 1957 to 1958. From April 1957 to July 1958, NTA film was used in a separate cellulose acetate butyrate holder, which was identical, except for color, to the one used for the new Hanford multi-element beta/photon dosimeter (Wilson et al. 1990). The method for interpretation of neutron dose was the same as that used from 1950 to 1957.

Dosimeter Used From 1958 to 1972. A separate multi-element neutron dosimeter was introduced in 1958 (Swanberg 1959). The appearance of this dosimeter differed only slightly from the multi-element beta/photon film dosimeter. The thickness of the holder was increased 0.254 cm (0.1 in.) to permit replacement of old materials with new, more suitable filter materials and room for two film packets. Cadmium and tin were chosen for shield materials because of their similar x-ray and gamma ray mass absorption coefficients and their different thermal neutron absorption cross-sections (high for cadmium, low for tin), thus permitting a measurement of the thermal neutron dose by comparing film density under the two filters. The prompt gamma coincident with a neutron capture in the cadmium is recorded as darkening of the film behind the cadmium shield. Photon radiation undergoes nearly equal attenuation in

(a) Brackenbush, L. W. "Dose Equivalent Conversion Coefficient for Polonium-boron Sources." Letter to W. V. Baumgartner dated July 14, 1994.

either cadmium or tin. The difference in darkening behind the cadmium and tin shields was found to be a direct measure of the slow neutron exposure. In addition, the gamma ray attenuation of these two elements compares well with silver, which was the shield material selected for the beta/photon film dosimeter. The comparable attenuation provided excellent correlation of gamma dose between the tin shields of the neutron dosimeter and the silver shield of the beta/photon dosimeter.

3.2.2 Film Processing Methodology

Watson describes several aspects of the Hanford NTA neutron dosimetry system in a letter in 1950.^(a) Hanford counting practices involved counting microscopically the tracks produced in the emulsion by recoil protons (see Figure 3.1). A magnification of 970 was obtained with a 97-power oil immersion objective and a 10-power ocular (Watson 1951). A minimum of three readings (i.e., readers) were made. Each reading counted the tracks occurring in 40 fields (0.78 mm^2) (Watson 1959) of view (i.e., a total of at least 120 fields).

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Figure 3.1. Technician Counting Tracks on Hanford NTA Film in 1950s

(a) Watson, E. C. 1956. "Suggested Revisions of Neutron Metering Program." Letter to H. A. Meloney dated September 1, 1950.

A technical report by Watson (1951) described detailed features of the Hanford NTA dosimetry system. In a letter in 1956,^(a) Watson reiterated the use of a minimum total of 120 fields to be used routinely to evaluate neutron dose. However, if a larger-than-expected number of tracks was observed, additional fields were viewed in order to more accurately determine the dose.

3.2.3 Calibration Methodology

Over the years, three different neutron-emitting sources were used to calibrate Hanford NTA film. Appendix A provides a tabulation of each calibration from 1950 through 1961. An important consideration in the calibration of the film involved the comparable energy spectra of the calibration source with the energy spectra in the work environment. Table 3.2 provides an overview of neutron sources used to calibrate NTA film at Hanford.

Table 3.2. Calibration Sources Used at Hanford

Source	Period of Use	Exposure Geometry	Average Neutron Energy, MeV
PoB	1950-9/4/1955	in-air	2.8
Positive ion accelerator	9/9/1955-1958	in-air	2.2
PuF ₄	1958-1964	in-air	1.4
	1964-1971 ^(a)	on-phantom	1.4

(a) New PuF₄ source (GWR Endres, Private Communication).

Four different PoB sources (sources number 106, 107, 182, and 304) were used to provide neutron calibrations for personnel-assigned dosimeters from 1950 through September 4, 1955. The sensitivity of the NTA emulsion, based on a PoB exposure, was approximately 1.4×10^{-5} tracks/neutron-cm² (Watson 1951). Three standard deviations is estimated based on the calibration data in Appendix A. The standard deviation of the blank calibration film ranged between 0.5 and 1 tracks. This implies a detection level of about 13 to 23 mrem.

The Van de Graaff positive ion accelerator was used to calibrate film using the reaction of deuteron on a ⁹Be target from September 9, 1955, through October 22, 1958. The energy of the accelerator neutrons produced was less than for the PoB source, as shown in Table 3.2. For neutrons produced by the Van de Graaff accelerator, the energy varied from 1.0 MeV to 6.3 MeV with an average energy of 2.2 MeV.^(b)

(a) Watson, E. C. 1956. "Fast Neutron Monitoring." Letter to A. R. Keene dated October 16, 1956.

(b) De Pangher, J. 1958. "Suggested Change in Procedure for Calibration of Neutron Film." Letter to R. W. Meisinger dated January 28, 1958.

Beginning in 1958, calibration was accomplished with a PuF_4 neutron source in which calibration films were exposed to a dose of 1075 mrem computed from first-collision theory. The average film response yielded 71.24 ± 13.51 tracks per 40 fields of view with a 95% confidence interval (Swanburg 1959). The single-collision calibration factor could be multiplied by a constant of 1.372 to obtain a multiple-collision neutron dose theory calibration factor. This source was considered to have a strength of 6.00×10^6 n/sec and an average energy of 1.4 MeV. Precision long counter measurements were used to determine the flux at a known distance. The flux was converted to dose rate by first-collision dose calculations. Calibration film was allowed to age because of the significantly fewer tracks that could be observed following the aging period. This track fading was thought to be caused by humidity. Thermal neutron calibration was done in the sigma pile, which had graphite stringers for positioning the neutron source and stringers for positioning the dosimeters for calibration. Gold foils were used to calibrate the positions for dosimeter placement. The use of the PuF_4 calibration source coincided with the introduction in 1958 of the new "double packet" dosimeter holder that accommodated two film packets.

Starting in January 1965, calibration of NTA film was done with the film dosimeter being placed on a phantom simulating the human body. This arrangement more closely measured the back scatter that affected the film and radiation dose received.

A letter by Roesch and De Pangher provides an overview for converting neutron flux to dose for the early neutron sources used at Hanford.^(a) The conversion factors used at Hanford for many years were considered to be approximately 8 n/cm²-sec per mrem/hr for fast neutrons, 48 n/cm²-sec per mrem/hr for intermediate neutrons, and 120 n/cm²-sec per mrem/hr for slow neutrons. The exact history of these numbers was not certain but is thought to have been calculated by Gamertsfelder et al. (1962).

3.2.4 Dose Interpretation

Dose interpretation from NTA involves exposing calibration emulsions to a known dose of neutron radiation, processing both the personnel-assigned and calibration emulsions, and interpreting the dose on the personnel-assigned emulsions based on the results of the calibration emulsions. Different procedures were used for the respective dosimetry systems, as illustrated in the following.

3.2.4.1 Dose Interpretation for Two-Element NTA Dosimeter

In 1950, Watson^(b) recommended that the Hanford NTA neutron dose assessment procedure be revised to utilize the statistical limits of the calibration and field dosimeters. Watson proposed that the upper statistical limit (i.e., mean number of tracks plus standard deviation) of the field dosimeter processing results and the lower statistical limit (i.e., mean number of tracks minus standard deviation) of the calibration dosimeters be used to calculate dose. This procedure would bias the calculated dose high,

(a) Roesch W. C. and J. De Pangher. "Neutron Flux-Dose Regulations." Letter to A. R. Keene dated September 9, 1958.

(b) Watson, E. C. "Suggested Revisions of Neutron Metering Program." Letter to H.A. Meloeny dated September 1, 1950.

assuming there were no other effects. He also recommended that the results of the neutron films be given in terms of mrep, which from other documentation includes a quality factor of 10. From this letter and other information, the routine procedure at the beginning of the Hanford NTA program can be understood to include the following elements:

1. Calibration film was exposed at the beginning of the exchange period to a PoB fluence equivalent to a first collision absorbed dose equivalent to 300 mrem.
2. Several readers independently read 40 fields of view each of the calibration and blank control films. From this information, the total number of tracks observed by all readers, the average and the standard deviation were calculated. This is illustrated in Appendix A based on information taken from the original calibration processing data.
3. Several readers independently read 40 fields of view each of the personnel assigned film. This was typically necessary because of the much lower number of tracks observed.
4. A total number of 60 tracks (net) was necessary, based on 10 readings, to consider the film to have a positive dose.
5. If the total number of tracks exceeded 60, based on 10 readings, then the dose would be calculated as follows:

$$\text{Dose} = \frac{[\text{mean} + \text{standard deviation} - (\text{personnel film})]}{[\text{mean} - \text{standard deviation} - (\text{calibration film})]} 300 \text{ mrem}$$

In Watson's letter, he describes the use of a table to utilize statistical derived limits based on the total number of counts observed. The statistical limits were based on 10 readers. The process described by Watson can be illustrated in the following example:

If a personnel assigned film was observed to have an average of 6 tracks/40 fields of view (expressed as 6t/40f) from the first three observations, then seven more independent observations would be made to give a total number of tracks equal to 60 at a minimum. Assuming the total number of tracks observed in ten readings was 60, this would be recorded as 6.0t/40f with 90% limits of 4.8-7.4 t/40f (a table was provided to determine the statistical limits based on the number of tracks). Then, assuming the number of tracks observed on the calibration film is 40t/40f $\pm$ 14%, the dose is calculated by using the upper limit of the personnel dosimeter and the lower limit of the tolerance value, i.e., 7.4/34 * 300 mrem = 65 mrem. If the average had been 5t/40f then the result would have been recorded as 0.

If the average had been 7.0t/40f the dose would have been calculated and recorded. The statistics of the calibration film varied slightly from film batch to batch. As such, the minimum reported dose varied also.^(a)

This procedure represents some of the complexity associated with the variation in sensitivity from batch to batch of NTA film, and the associated effort necessary to calculate personnel dose based on calibration data for each batch.

3.2.4.2 Dose Interpretation for Multi-Element NTA Dosimeter

Swanburg (1959) describes the specific steps used to calculate the fast and slow neutron doses at Hanford. This procedure was initiated with the introduction of the multi-element NTA film holder and the PuF₄ calibration source in 1958. The procedure follows:

1. Film was exposed to a PuF₄ dose of 1075 mrem computed as the first-collision dose. The average film response yielded 71.24 ± 13.51 tracks per 40 fields of view at the 95% confidence interval.
2. Personnel NTA film was processed by counting microscopically the tracks produced in the emulsion.
3. Three readings were made of the tracks occurring in 40 fields of view (i.e., a total of 120 fields) at a minimum.
4. Films showing a significant increase in the number of tracks relative to background were viewed for a total of 400 fields. A 90% confidence interval of the tracks per 40 fields was constructed.
5. The average and standard deviations were calculated for both the personnel and calibration films. The upper statistical limit (average plus one standard deviation) of the personnel films was compared with the lower statistical limit (average minus one standard deviation) of the calibration films for similar intervals of tracks per 40 fields per 300 mrem.
6. The fast neutron dose was calculated as the ratio of the respective personnel and calibration film limits, from step 5, multiplied by 300 mrem. This dose was entered into the personnel exposure record.

Calculation of the slow neutron dose involved similar steps. Routine calibration of the neutron dosimeter response to slow neutrons required approximately several days using the sigma pile with a PuBe source traceable to NBS. To alleviate this time-consuming process, measurements were conducted to relate film darkening from radium to an equivalent darkening from the sigma pile exposures. Interpretation of slow-neutron dose involved three steps, as follows:

(a) Watson, E. C. "Suggested Revisions of Neutron Metering Program." Letter to H. A. Meloeny dated September 1, 1950.

1. Obtain the net difference in optical density behind the cadmium (thermal and fast-neutron response) and tin filters (fast-neutron response).
2. Obtain a radium equivalent dose from the calibration curve (e.g., radium gamma exposure in mrem behind the silver shield for the beta/photon dosimeter).
3. Divide the radium equivalent dose by a factor of 1.940 ± 0.056 to convert to the slow neutron dose in mrem. The slow-neutron dose was entered into the personnel exposure record.

3.2.5 Dose Reporting Threshold

Dose reporting thresholds are very important to the cumulative worker dose. Two Hanford practices are of particular interest for the question of unrecorded neutron dose.

As described in Section 3.2.4.1, Hanford practice was to record any dose less than about 50 mrem as essentially zero, depending upon the counting statistics for each batch of films. The NTA film was exchanged bi-weekly. This value can be used to calculate a maximum missed annual dose of about 1.0 rem for the bi-weekly exchange periods. This type of analysis must have been the motivation, as reported by Watson (1959), to identify a design basis goal of 0.5 rem per year for an improved neutron dosimeter.

Another perspective on this issue is whether every NTA film was evaluated. Visual counting of the tracks by microscope for many NTA emulsions conducted field by field is a tedious endeavor. The practice used at Hanford, based on oil immersion and a magnification of 970, was done to enhance the contrast between tracks and general fogging of the film by background or photon radiation. Typically, staff could do this work no more than four hours per day without undue eye strain or increasing the likelihood of overlooked information (Watson 1951). Screening practices were employed to improve the overall efficiency of this operation and to ensure that the more highly exposed NTA films were examined. It appears from the historical record that some discussion of screening the NTA film to be evaluated by microscope was considered during the late 1950s. Watson (1959) reports on the recommendations of a study which states that NTA film should be processed only if significant photon dose had been received as measured by the neutron dosimeter. This recommendation was based on the observation that neutron dose occurred only in combination with photon dose. In 1960, Wilson^(a) describes a practice in which tracks on NTA film were counted only if a minimum photon dose of 100 mR had been observed on the accompanying beta/photon film or the neutron emulsion showed a large thermal neutron dose, which was determined by comparing the film density behind the cadmium and tin shields. This memo recommended that all NTA film assigned to PFP workers be routinely analyzed because this group showed the highest level of routine neutron exposure. This recommendation was adopted into the routine program.

(a) Wilson, R. H. "Evaluation of Fast Neutron Dose." Letter to H. A. Meloeny dated July 28, 1960.

3.2.6 Neutron Dose Response

The NTA film response (i.e., the number of tracks per unit area) depends on the incident neutron energy. Above a threshold neutron energy of about 1 MeV, the number of recoil proton tracks increases with energy up to about 10 MeV, as shown in Figure 3.2. There exists a threshold for the detection of lower energy recoil protons. It is commonly assumed that protons of 0.5 MeV lead to tracks of not more than three to four grains, which can easily be missed because of background grains and/or fading effects. The standard procedure at Hanford was to consider that a track had at least 4 grains, an assumption which increases the energy threshold somewhat. Noting the curve in Figure 3.2 and considering the degradation in neutron energy in Hanford plutonium facilities compared to the calibration spectra, it is expected that the neutron dose would be under-reported. In fact, the current recommendation is not to use NTA film in neutron fields with energies lower than about 1 MeV (Alberts et al. 1996).

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Figure 3.2. Dose Equivalent Response of NTA Film (Bartlett et al. 1980)

3.3 Thermoluminescent Dosimetry

Thermoluminescent phosphors have the property of emitting light upon heating. For thermoluminescent dosimeters (TLDs) used in personnel dosimetry, the amount of luminescence is proportional to the amount of radiation energy deposited in the phosphor. Thermoluminescent dosimetry is currently the most widely used technology among DOE facilities. The Hanford "albedo" personnel neutron TLD was introduced in 1972 (Kocher et al. 1971). The introduction of this technology followed several years of

research and development (Unruh 1964 and Unruh et al. 1966, Endres et al. 1966, Endres and Kocher 1968a, 1968b) at Hanford and paralleled the use of this technology at other laboratories. The Hanford dosimeter was capable of measuring both the fast and slow neutron dose received by personnel. The dosimeter response is dependent upon the reflection of neutrons from the body and, hence, was referred to as an albedo (i.e., reflected) neutron dosimeter.

Hanford TLDs utilize lithium fluoride (LiF) phosphors obtained from Harshaw (i.e., currently manufactured by Bicron/Harshaw).^(a) The LiF has many characteristics which make it attractive for personnel dosimetry applications:

- near-tissue-equivalent response for photons
- unaffected (relatively) by environmental conditions (i.e., humidity, normal working temperatures, etc.)
- linear dose response at occupational dose levels
- availability in two forms: 1) TLD-700 (approximately 99.99% ^7Li and approximately 0.01% ^6Li), which is primarily responsive to beta and photon radiation and 2) TLD-600 (approximately 95.6% ^6Li and 4.4% ^7Li), which is responsive to beta, photon and neutron radiation
- relatively easy automation of dosimeter processing.

The nearly identical response of TLD-600 and TLD-700 phosphors to beta and photon radiation allows the neutron signal to be measured by subtracting the Li-700 response from the Li-600. The isotope ^6Li has a relatively large capture cross-section (approximately 953 barns) for thermal neutrons. Since this isotope is present in natural lithium (i.e., approximately 7%), lithium fluoride (available as TLD-100) makes an excellent detector of thermal neutrons. In contrast, ^7Li has an extremely small capture cross-section (approximately 0.037 barns). Natural lithium can be made more sensitive by enriching it in the isotope ^6Li (i.e., TLD-600 phosphor). Likewise, it can be made almost insensitive to thermal neutrons by depleting the natural lithium of the ^6Li (i.e., TLD-700 phosphor). The TLD-600 and TLD-700 phosphors contained in Hanford dosimeters are 3.2-mm (1/8-in.) squares in the form of extruded ribbon. Three different thicknesses of LiF phosphors have been used: 0.15 mm (0.006 in.), 0.38 mm (0.015 in.), and 0.89 mm (0.035 in.). Prior to 1995, only the 0.89-mm-thick phosphors were used.

Lithium fluoride has some undesirable performance characteristics such as supra-linearity at higher dose levels (> 100 rad), complicated annealing behavior, and response to light (Horowitz 1984). To compensate for these characteristics, rigid quality control is necessary in the preparation, packaging, and processing of the dosimeters. In addition, sophisticated evaluation of the dosimeter processing data is necessary to determine personnel dose.

(a) Bicron, Saint-Gobain/Norton Industrial Ceramics Corporation, Solon, Ohio.

The Hanford TLD program continued to evolve after 1972 with several notable technical improvements, which are shown in Table 3.3. Several important improvements include the following:

- Beginning in January 1984, each dosimeter card was uniquely labeled and the processing history of each card was tracked by computer.

Table 3.3. Hanford Personnel Neutron Dosimetry Practices, 1972-Present

Year	Practice	Description
January 1972	Implemented five-element Hanford albedo TLD	Multipurpose TLD implemented to measure beta, photon, and neutron dose for selected Hanford employees. Neutron dose calibration procedure based on field-specific measurements using a tissue equivalent proportional counter (TEPC).
July 1979	Environmental dose subtraction	Implemented environmental dose background compensation to deep dose of 0.18 mrem/day.
January 1980	Four-element dosimeter	Five-chip dosimeter changed to four-chip dosimeter to accommodate planned implementation of commercial reader system, which was not successful.
February 1980	New Hanford reader system	First of two Hanford-built replacement reader systems was introduced into routine processing.
January 1981	Calibration source ^{252}Cf	Introduced ^{252}Cf source for routine calibrations but time of exposure was increased by a factor of 1.73 to provide a dosimeter response similar to that observed with the PuF_4 source.
May 1983	Low temperature annealing	Implemented routine use of 16-hour 80°C low temperature annealing of all Hanford TLDs prior to issue.
January 1984	Five-element dosimeter	Eliminated last of four-chip dosimeters and changed fast neutron dose algorithm to five-chip design.
April 1984	Chip sensitivity factors	Implemented use of individual chip sensitivity factors in the routine calculation of dose.
1989	Accredited system	Received accreditations for Hanford dosimetry system under new DOE Laboratory Accreditation Program (DOELAP).
1995	Combination TLD/track-etch dosimeter	Commercial TLD system and PNNL-developed track-etch dosimetry system implemented.

- Beginning in April 1984, individual phosphor sensitivity factors were used to normalize the response of all phosphors based on exposure from 1-R ^{137}Cs gamma radiation.
- Effective September 1984, calibration coefficients were calculated based on the mean response of processed control dosimeters exposed to 1 R of ^{137}Cs gamma radiation as well as the mean response of unexposed background control dosimeters.
- Effective January 1, 1990, the Hanford External Dosimetry Project (HEDP) was accredited under the new DOE Laboratory Accreditation Program (DOE 1986).
- Effective January 1995, the Hanford Combination Neutron Dosimetry System was implemented.

3.3.1 Hanford Dosimeters

Three Hanford TLD designs have been used to date. All of these designs use the TLD-600 and TLD-700 phosphors in combination with selected metallic filters which modify the response of the respective phosphors.

Dosimeter used from 1972 to 1977 and 1980 to 1984. Detailed considerations in the design of this dosimeter are provided by Kocher et al. (1971) and by Fix et al. (1981, 1982). In the original five-chip design used from 1972 to 1977 and again from 1984 to 1994, dosimeter positions 3, 4, and 5 provided the albedo dosimeter capability. The TLD-600 chips were placed in positions 3 and 4. A TLD-700 chip was placed in position 5. A cadmium/tin filter was placed on the front side of the chip in position 4, whereas tin was used for the front side of the other two positions and the back side of all three dosimeter positions. All three chips had the same response to beta and photon radiation. Chip 4 responds only to the albedo signal from the body due to fast and slow neutrons, whereas chip 3 responds to incident thermal neutrons in addition to the albedo neutrons. The combination of information from all five chips (positions 1 and 2 had TLD-700 phosphors for measuring shallow and deep dose from beta and photon radiation) allows calibration of the shallow and deep dose from beta and photon radiation and determination of the dosimeter thermal and fast neutron dose from the incident neutron spectra.

Dosimeter used from 1978 to 1983. This dosimeter was identical to the five chip design except for the elimination of chip 5, located in the center of the dosimeter card. This modification was made with the goal of using a commercially provided dosimeter reader system which required rotation of the dosimeter card around the center (i.e., chip 5) position. The response of the TLD-700 chip in position 2 was used to compensate for the beta/photon signal from neutron-sensitive chips in positions 3 and 4. This dosimeter design required some modifications to assure continued accuracy in mixed neutron and photon fields since filtration over position 2 (i.e., aluminum) was not the same as the cadmium/tin or tin only over positions 3 and 4. The relative response of the TLD-700 phosphors in positions 5 and 2 was well characterized; however, this was not used in the routine calculation of neutron dose.

Dosimeter used from 1995 to 1996. Effective January 1, 1995, Hanford implemented a new TLD system supplied by Harshaw. The neutron component of this system involves a four-chip dosimeter with three TLD-600 chips and one TLD-700 chip. All chips are 0.38 mm thick. The addition of a third

TLD-600 chip provides improved dosimetry capabilities, as described in the report by Endres et al. (1996). This dosimeter also includes a track-etch neutron dosimeter, which provides an energy-independent dose response for neutron energies greater than 100 keV.

3.3.2 Processing Methodology

Automated reader systems have been used to process Hanford TLDs. A photograph of the original reader system is shown in Figure 3.3. All of these systems had the characteristic of heating each of the -600 and TLD-700 phosphors contained within the respective dosimeter cards inside the light-opaque interior of the reader system under controlled conditions. The light emitted by the phosphor was recorded using a photomultiplier tube assembly and associated electronics. Several parameters were available to ensure proper operation of the respective reader systems, as described by Baumgartner et al. (1992).

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Figure 3.3. Original Hanford Automated Thermoluminescent Dosimeter Reader System

Characteristics of the light emitted by the respective chips (the "glow curve") were examined in setting up the reader system so that adequate heating of the chips ensured measurement of at least 99% of the radiation-induced signal. The relative light output from the respective chips for undosed and dosed control cards was examined by the reader system to ensure that results were within stated tolerance limits and that control dosimeters were processed within a set number of personnel dosimeters, typically 50. In addition, reader data for the magnitude of the dark current (i.e., phototube reading with no dosimeter) and sensitivity to an internal light source were compared to stated tolerance limits. In essentially all cases, any processing parameters which exceeded defined tolerance limits resulted in the reader system stopping dosimeter processing and emitting an audible alarm. To restart dosimeter processing, the cause of the alarm had to be resolved. Each of these reader systems provided a detailed processing log of all dosimeter and quality control data.

3.3.3 Calibration Methodology

The calibration methodology for TLDs is similar to film. Calibration and control TLDs are exposed to known levels of radiation and processed with the personnel-assigned dosimeters. The data from the calibration TLDs are used to calculate calibration constants that are, in turn, used to calculate dose. Calibration dosimeters are exposed to beta, photon, and neutron sources of radiation. Shallow and deep doses were calculated directly from the calibration data with the exception of the neutron dose. Fast and slow neutron doses were calculated with the Hanford TLD albedo dosimeter. The Hanford site-specific calibration protocol was used. For the fast neutron dose, the calibration was determined by developing a calibration configuration with the PuF_4 source, which provided the same dosimeter response per unit dose as measured in the field with a TEPC. For the slow neutron dose, calibration was determined by measuring the dosimeter response in a sigma pile. The sigma pile consisted of a large graphite assembly with a PuBe neutron source. This system is shown in Figure 3.4. At the location of the dosimeters, the spectra was highly thermalized. The calibration and dose algorithms used with the original Hanford TLD are described by Kocher et al. (1971). Haverfield et al. (1972) describe the use of this system for beta, gamma, and neutron dosimetry.

In 1981, the PuF_4 source was replaced with a ^{252}Cf source. The time of irradiation with the ^{252}Cf source was increased by a factor of 1.73 to obtain the same dosimeter response as obtained with the PuF_4 irradiation (i.e., ^{252}Cf has a higher energy neutron radiation, compared to PuF_4 , with a corresponding lower dosimeter response. As such, it was necessary to increase the irradiation time by a factor of 1.73 to obtain the same dosimeter response)^(a) This was necessary because there is a lower dosimeter response to the higher energy neutrons from a same ^{252}Cf source compared to the dosimeter response from the lower energy neutrons from a PuF_4 source. This field specific calibration has been confirmed on several occasions during the years (Fix et al. 1981, 1982). The bare ^{252}Cf calibration is used in the DOE Laboratory Accreditation Program dosimeter performance testing (DOE 1986).

(a) Roberson, P. L. "3745A/318 Transfer Dosimetry of the Fast Neutron Calibration of the HMPD." Memo to D. M. Fleming dated March 12, 1984.

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Figure 3.4. Hanford Sigma Pile

3.3.4 Dose Interpretation

Dose interpretation from Hanford albedo TLDs involves exposing calibration dosimeters to known doses of photon and neutron radiation. Calibration and personnel-assigned dosimeters are processed on the same reader system. Calibration coefficients are determined from the calibration dosimeters. Very similar approaches have been used with all of the Hanford albedo TLD systems as follows:

- Photon radiation response of TLD-600 chips is compensated for by subtracting the TLD-700 chip signal. Typically, the TLD-600 and TLD-700 chips are enclosed behind nearly identical filtration.
- Slow neutron dose is calculated by subtracting the signal on the TLD-600 chip, which is responsive primarily to reflected neutron radiation, from the signal on the TLD-600 chip, which is responsive to all incident and reflected neutron radiation (i.e., surrounded by tin shielding). A calibration factor is used to calculate the actual thermal neutron dose.

- Fast neutron radiation dose is calculated from the TLD-600 chip, which is responsive primarily to reflected neutron radiation which is compensated for any contribution from photon and slow neutron radiation.

Various chip response factors, such as the contribution of slow and/or fast neutron radiation to the respective TLD-600 chips, are used in the calculation based on the calibration exposures. The dose calculation procedure is discussed in detail in Kocher et al. (1971), Fix et al. (1982), Wilson et al. (1990), and Endres et al. (1996).

3.3.5 Dose Reporting Thresholds

Kocher et al. (1971) reported that the dose threshold for the TLD, based on statistical analysis of mixed field data, was 0.5 mrad (i.e., 1.5 mrem with a quality factor of 3) for thermal neutrons and 5 mrad (i.e., 50 mrem with a quality factor of 10) for fast neutrons under ideal conditions. For laboratory exposures to a neutron source, the detection level is less than these values. The dose reporting threshold in the Hanford radiological records system for thermal or fast neutron dose was 10 mrem. Since the dose reporting threshold of 10 mrem is less than the statistically calculated detection level, there is really no effect on the cumulative personnel dose from the administratively determined dose reporting threshold. However, questions of low dose variability resulting in either false positive or missed neutron dose are important to the cumulative dose.

The statistically calculated neutron detection level of importance to Hanford workers is primarily a function of variability, particularly at no or low dose levels in mixed neutron and photon fields. The near tissue equivalent response of the thermoluminescent phosphors and the design of the TLDs for separation of the neutron and photon radiation-induced signals are significant improvements compared to film. Since implementation of the TLD system in 1972, several improvements have been made in the Hanford TLD system over the years.^(a) Perhaps the most significant improvement in low dose, including neutron, capabilities was the incorporation of chip-specific radiation sensitivity factors beginning in April 1984. Prior to this time, all TLD chips were screened to have nearly the same radiation sensitivity to within about $\pm 20\%$. Using chip-specific sensitivity factors and routine processing procedures, precision among the chips exposed to 1 R of ^{137}Cs gamma radiation is easily less than 5% at the 95% confidence level.

3.3.6 Neutron Energy Response

The dose response of TLD albedo dosimeters is highly dependent upon the energy of the incident neutron spectra, as shown in Figure 3.5. For the Hanford site-specific calibration used with the original five-chip albedo TLD, the dosimeter-determined dose for a moderated ^{252}Cf exposure is a factor of 1.7 too high. For a bare ^{252}Cf exposure, the calculated dose is a factor of about 4 too low (Fix et al. 1982). Detailed field measurements have been used to determine the Hanford site-specific calibration, which was used essentially without change from implementation of the TLD system in 1972 through implementation

(a) Fix, J. J. "Close-out of 5-year Hanford Dosimeter Upgrade Program." Letter to D. Elle dated November 25, 1984.

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Figure 3.5. Relative Neutron Energy Response of Hanford Dosimeter Exposed on a Water Phantom (Fix et al. 1982)

of the new combination neutron dosimeter system in 1995. The new system utilizes a more complicated field-based calibration procedure (Endres et al. 1996). Field studies of the neutron dose have been conducted on several occasions^(a) (Fix et al. 1981, Brackenbush et al. 1991).

3.3.7 Accreditation

Beginning in the late 1980s, all personnel dosimeter systems were required to satisfy national performance testing criteria. The ANSI N13.11 (1993) standard involves accident- and protection-level dose categories, categories where only one type of radiation is used (i.e., beta, photon, or neutron) and mixed exposure categories. The Hanford dosimetry system has been formally accredited by DOE on several occasions beginning in 1989. Re-accreditation is required every two years.

(a) Roberson, P. L., F. M. Cummings, and J. J. Fix. 1995. "Neutron and Gamma Field Measurements at the 234-5 Facility." Hanford External Dosimetry Project File.

3.3.8 Neutron Albedo Response

Neutron response characteristics of TLDs are also dependent upon the distance of the dosimeter from the surface of the body. Kocher et al. (1971) describes the results of studies made to evaluate this dependence. Sets of badges were positioned in front of a phantom at selected distances and irradiated to a known dose of PuF_4 neutrons. Irradiations were also conducted with selected accelerator sources of neutrons. The results of these studies are shown in Figure 3.6. At a distance of about 5 cm between the back of the dosimeter and the surface of the phantom, the dosimeter response is about 50% of the response observed when the dosimeter is located at the surface of the phantom.

Figure 3.6. Dosimeter Response as a Function of Distance Between the Dosimeter and The Surface of the Phantom (Kocher et al. 1971)

3.4 Sources of Uncertainty

Accounting for sources of uncertainty in calculating neutron dose involves considerations of the capability of the neutron dosimeter to accurately compensate for effects on dosimeter neutron radiation response from a variety of circumstances: from photon radiation in typical mixed neutron and photon fields; from environmental conditions involving heat, humidity, and/or light; and from different neutron energies and directions typical of the work environment. For both film and thermoluminescent dosimeters, the confounding effects of thermal neutrons, which typically contribute little to personnel neutron dose, can be very important. Dosimeter response characteristics involving dosimeter orientation and geometry relative to the source of neutron radiation are also important. Kocher et al. (1971) describes evaluations of

some of these parameters associated with the implementation of the Hanford TLD. In some of these evaluations, film and TLD comparative studies were conducted. Selected parameters important to neutron dose interpretation are presented in the following sections.

3.4.1 Mixed Neutron/Photon Radiation Fields

With the exception of the original Hanford two-element film dosimeter used prior to 1957 and the four-element TLD used between 1978 and 1983, all Hanford neutron dosimeters were designed to compensate for dosimeter response to beta/photon radiation. Considerations of beta and photon radiation in the design of these dosimeters are described by Wilson et al. (1990). With respect to neutron dose interpretation, NTA film enclosed in the original two-element Hanford dosimeter film holder showed acceptable performance because of the presence of the 1-mm silver shield over much of the film. The silver minimized the film response to lower-energy photon radiation. For the four-chip TLD, photon compensation based on chip 2, as opposed to chip 5, had the effect of subtracting too much thermoluminescent signal. This occurred because of reduced shielding for the number 2 position.

3.4.2 Neutron Energy Dependence

Hanford NTA and TLDs have very different neutron energy response characteristics. In general, the Hanford NTA film dosimeters, based on recording track(s) at least 4 grains, respond only to higher energy neutrons greater than about 1 MeV. The TLDs, on the other hand, have a very energy-dependent response. For either dosimetry system, proper calibration of the dosimeter response to the neutron energy fluence in the work environment is critical to its overall performance. Both the NTA film and TL dosimeters have design features to compensate for the effects of thermal or slow neutrons on the dosimeter response. However, the TLD is extremely sensitive to slow neutron radiation (Brackenbush et al. 1980). The Hanford NTA film dosimeters have essentially no response to neutrons having energies less than about 1 MeV. Sensitivity of the TLD to slow neutrons in the work environment represents one of the more difficult challenges in calibrating a TLD system. Shielding installed in the work environment to minimize employee dose often results in substantial scattered neutron radiation of lower energies, which greatly complicates the determination of personnel dose.

3.4.3 Environmental Effects

The NTA film is subject to fading. The fading is more pronounced for lower energy neutron radiation. The TLD is relatively insensitive to environmental effects if properly administered. At Hanford, the use of low temperature dosimeter annealing (i.e., 60°C for 24 hours or 80°C for 16 hours) and rigorous processing quality control are expected to minimize any environmental effects on TLD results.

3.4.4 Lower Dose Threshold

As dose results over nearly five decades show, lower dose thresholds are important, particularly with respect to Hanford practices used to record low doses. The uncertainty of practices in earlier years, when there were higher dose limits and less precise technology, is much greater than during more recent years.

Hanford routinely recorded personnel dose as low as 10 mrem; however, the uncertainty of these doses is anticipated to be very high. The reporting dose threshold for NTA film during 1950 to 1957 is expected to be about 65 mrem. This reporting threshold is expected to be less when the PuF_4 calibration source was introduced in 1958. The reporting dose threshold for TLDs beginning in 1972 is expected to be about 50 mrem exposed to the PuF_4 .

3.4.5 Dosimeter Wearing Practices

The NTA film dosimeter had a direct response to neutron radiation and was not dependent upon the presence of a reflecting body, as was the case with the TLD. Kocher et al. (1971) document the differences in dosimeter response with increasing distance between the TLD and the surface of the body. For the TLD dosimeter to perform properly, it must be worn next to the body. Hanford NTA film and TLDs provide the correct dose, based on the calibration energy and protocol, only when the dosimeter is oriented perpendicular to the source of neutron radiation. The TLD generally has a better angular response; however, the response of both dosimeters decreases as the angle of incidence increases. The overall situation is complicated because of 1) the energy threshold of the NTA film, and 2) the significant change in TLD response with neutron energy.

4.0 Evaluation of NTA Film Dosimetry

Original processing data sheets for the Kodak Nuclear Track type "A" (NTA) films worn by all Hanford neutron radiation workers, and the associated calibration results for each batch of film, were retrieved from the Federal repository in Seattle, Washington. These data reflect the original recorded results for all Hanford personnel neutron monitoring during the period 1950-1961. These results were computerized to allow analysis. Recorded dose information for a sample of 14 workers was analyzed in detail. Workers in this sample were all on the work force in 1961 and typically had many years of employment. Nine of the 14 workers began Hanford employment during the 1940s. In addition, the neutron dose for these workers was retrospectively calculated from the original processing data using several assumptions. The results of this evaluation were compared to the recorded dose of record.

4.1 NTA Processing Records

Dosimetry technicians maintained detailed data sheets for all personnel and calibration NTA films processed. These data sheets are categorized according to the exchange period of the dosimeter (i.e., third week, January monthly, year, etc.) and the facility, organization, and/or work location. Processing results for all workers within a specific facility or work group and exchange period are listed sequentially on these data sheets. Each data sheet indicates the specific batch of film used for calibration (i.e., indicated by calibration sheet number). For the calibration data, results are provided for both dosed and undosed (i.e., background) films. By use of the original field and calibration data, the dose of record can be recalculated using various criteria. It is also possible to examine the magnitude and variability of the calibration data to observe trends in reproducibility and sensitivity of the respective batches of film used over the years. It is important to recognize the effort made by Hanford dosimetry staff to associate field and calibration film for each batch of film. During the period of 1950-1961, there were 529 distinct batches of film, beginning with batch number 1 in January 1950. Calibration and field results were specifically identified according to a batch of film. This was done because of the known variation in response characteristics for each batch of film.

Four boxes of original handwritten processing records were retrieved from the Federal records center in Seattle, Washington.^(a) These boxes contained records of all personnel and calibration NTA processing for the time period of 1950 through 1961. Information on these records was entered into computerized files for analysis. Files were prepared of the personnel and calibration processing data. These files resulted in a database containing over 85,000 entries.

(a) Boxes are identified as: G-64003, "1950-1952 Neutron Film Processing Sheets," G-64004, "1953-1955 Neutron Film Processing Sheets," G-64005, "1956-1959 Neutron Film Processing Sheets," and G-71422, "1960-1961 Neutron Film Processing Sheets."

4.2 NTA Calibration Records

From each batch, films were selected for use as calibration films. These consisted of films which were exposed to a known source of neutron radiation at the beginning of the dosimeter exchange cycle and other films which were kept as background controls. Upon return of the worker-assigned dosimeters, all film was processed as a group. A batch-specific calibration factor was determined, based on the results of the calibration film. This factor was applied to the processing results (i.e., number of tracks) of the personnel-assigned dosimeter film to calculate dose.

All processing records analyzed included specification of the calibration films used in dose assessment. For the data analyzed from 1950 through 1961, there were 529 calibrations determined for the respective batches of film. Appendix A is a summary of this information. For each calibration, several processing parameters were identified, including the date, number of technicians reading the calibration and blank film, the mean number of counts and standard deviation for both calibration and blank film, the calibration source, the neutron fluence or the delivered dose, and the calibration constant (i.e., in neutrons or dose per track). The standard deviation of the calibration and blank film, indicating variability in counting tracks among the technicians, was used as one means of quality control. If the standard deviation was unacceptable, typically indicating one technician's results varied significantly from the others, then the film had to be reanalyzed.

In the original calibration data, the neutron fluence is given for all PoB irradiations. A factor of 3.5×10^{-5} mrem/neutron-cm² was used to convert the fluence data to dose equivalent.^(a) A dose of 150 mrad is shown in the original calibration data for all positive ion accelerator irradiations. These numbers were converted to dose equivalent by multiplying by a factor of 8. For all PuF₄ irradiations, a delivered dose of 1075 mrem is shown in the original calibration data. The original and adjusted calibration data are shown in Appendix A. Figure 4.1 is a plot of the adjusted calibration factor in terms of mrem/track. The respective periods of PoB, positive ion accelerator, and PuF₄ NTA film calibration are illustrated in the figure.

(a) Brackenbush, L. W. "Dose Equivalent Conversion Coefficient for Polonium-Boron Sources." Memo to W. V. Baumgartner dated July 14, 1994.

Figure 4.1. Plot of NTA Adjusted Calibration Factor, 1950-1961

4.3 Recorded Dose for Selected Sample

Characteristics of the recorded dose of record were analyzed for the 14 workers selected for detailed study. Three distinct periods of dose recording, during 1944-1961, were identified as follows:

Period	Description
<u>1944 - 1949</u>	Predated the use of NTA film. Shallow and deep dose were determined from Hanford two-element dosimeter. Neutron dose was determined from boron-lined pocket ionization chamber.
<u>1950 - 1957</u>	Included use of the NTA film and determination of shallow (nonpenetrating) and deep (penetrating) dose using the Hanford two-element film dosimeter.
<u>1958 - 1961</u>	Included use of the Hanford multi-element film dosimeters for beta, photon, and neutron radiation. The end of this period was chosen to coincide with the end of the processing database data in 1961 selected for analysis.

Dose of record data for each of the selected workers within each of these selected recording periods is summarized in Table 4.1. The year of first recorded radiation exposure is shown in the first column of this table for each worker. All workers had recorded dose in 1961 and in the inclusive years between the year of first recorded radiation dose and 1961. An attempt was made to identify the primary work area for each of the workers, as shown in the second column of Table 4.1. It is interesting to examine trends in these data.

Table 4.1. Internal Dose for Selected Recording Periods for Selected Sample of 14 Workers^(a)

Year ^(b)	Work Area	Recording Period, Dose in mrem									
		1944 - 1949			1950 - 1956			1957 - 1961			
		Sh	Dp	Nt	Sh	Dp	Nt	Sh	Dp	X	Nt
1945	200 W	1270	510	0	5450	4180	0	9740	9700	3090	0
1950	100 A				11410	8130	0	6350	5970	0	40
1951	100 A				19540	11950	0	14220	13010	0	80
1947	200 W	420	130	0	8180	3520	130	10340	10060	2080	870
1945	200 W	790	230	0	11260	9490	280	9080	9080	1840	1570
1945	100 A	530	130	0	12720	3750	0	1290	1140	10	730
1951	100 A				10970	9440	0	8150	8090	0	220
1945	?	1430	440	0	8450	3650	1360	8800	3650	20	0
1945	200 W	1400	380	0	11720	10360	0	11730	11670	2630	4150
1944	200 W	1030	320	0	10300	7070	800	6710	6710	3220	120
1952	100 A				17430	12950	110	15530	13280	0	20
1952	100 A				3090	2670	0	1330	1310	0	50
1945	200 W	1830	410	0	11180	4970	1180	9280	9090	1090	1570
1948	?	680	60	0	7010	5980	0	1020	830	0	0
Totals		9380	2610	0	148710	98110	3990	113570	103590	13980	9420

(a) Sh - shallow dose; Dp - deep dose; Nt - total neutron dose; X - x-ray dose

Whole body dose = deep + 35% x-ray + total neutron

Whole body skin dose = shallow + 65% x-ray + total neutron

(b) First year of recorded Hanford dose.

The ratios of the shallow to deep dose and neutron to deep dose for the respective recording periods are summarized in Table 4.2. The trend toward a lower shallow-to-deep-dose ratio is evident in Table 4.2 for succeeding monitoring periods. This is not surprising because of the significant over-response of film to the relatively low-energy photon radiation characteristic of plutonium work environments. Prior to 1958, the Hanford beta/photon dosimeter was incapable of distinguishing the x-ray component of the dose (Wilson 1987). Any response on the film behind the 1-mm silver filter is included in the estimated deep (i.e., penetrating) dose. Likewise, there was no method available, based only on the dosimeter data, to accurately calculate the shallow dose. Rather, interpretation of the shallow dose required knowledge of where the person was working. This situation did not affect all of the workers, as illustrated in Table 4.1, but only those workers with positive x-ray dose during the 1957-1961 monitoring period.

Another characteristic of the data is the increase in the ratio of the recorded neutron to deep dose between the 1950-1956 and 1957-1961 monitoring periods. One reason for this change is anticipated to be the implementation of the PuF₄ calibration source beginning during 1958.

4.4 Retrospective Calculation of Neutron Dose

The neutron dose component retrospectively calculated for each of the 14 workers, was determined using one of five methods. Assuming that A is the measured track count for the personnel film, B is the measured track count on the blank film, and C is the calibration constant calculated from the calibration film, the respective methods are described as follows:

Method 1 - $\text{Dose} = C * A$

Neutron dose calculated from the database using the number of tracks for each worker for each processed film multiplied by the calculated number of millirem per track from the calibration data, as shown in Appendix A. This method, which uses the gross track count, does not compensate for the observed background counts on the blank film. As such, this method is classified as representing the **maximum** dose possibly calculated from the processing data.

Table 4.2. Ratio of Recorded Dose Components

Recording Period	Ratio	
	Shallow/Deep	Neutron/Deep
1944 - 1949	3.6	0.0
1950 - 1956	1.5	0.04
1957 - 1961	1.1	0.09

Method 2 - If $(A - B) > 0$, then $\text{Dose} = C * (A - B)$, else $\text{Dose} = 0$

Neutron dose calculated from the number of tracks minus the background multiplied by the number of millirem per track. In the event the calculated dose is a negative number for any record, the dose is recorded as zero. This method is termed **historical** because it best represents the dose calculation followed historically.

Method 3 - If $(A - B) > 1$, then $\text{Dose} = C * (A - B)$, else $\text{Dose} = 0$

Neutron dose calculated from the number of tracks minus the background, when the value is greater than or equal to one, multiplied by the number of millirem per track.

Method 4 - If $(A - B) > 2$, then $\text{Dose} = C * (A - B)$, else $\text{Dose} = 0$

Neutron dose calculated from the number of tracks minus the background, when the value is greater than or equal to 2, multiplied by the number of millirem per track.

Method 5 - If $(A - B) > 0$, then $\text{Dose} = C * [A - (B + 0.7)]$, else $\text{Dose} = 0$

Neutron dose calculated from the number of tracks minus the background plus 0.70 multiplied by the number of millirem per track. The background count was increased by the value of 0.7 (i.e., the standard deviation of all blank control films was equal to 0.35 tracks), based on statistical analysis of the two-sigma variation of the background control film. This method is termed the **best estimate** based on current acceptable procedures.

Table 4.3 summarizes the results of the foregoing compared to the recorded dose of record (i.e., 1944-1961) for each of the workers. Certainly, in all of the methods evaluated, a higher neutron dose would be estimated than originally recorded. However, even in the extreme case of Method 1, where no background is subtracted, the recalculated neutron dose is substantially less than the recorded photon shallow or photon deep dose. Results for plutonium workers can be identified in this table by significant positive x-ray dose.

To calculate the official whole body and skin dose of record, 35% and 65% of the x-ray component was assigned to the deep and shallow dose components, respectively (Wilson 1987).

Interestingly, significant differences are observed between the original and recalculated neutron dose in Table 4.3, depending upon whether the worker had recorded x-ray dose. Workers with recorded x-ray dose compared to the deep dose, as shown in Table 4.3 during 1958-1961, are likely associated with plutonium-handling operations. Workers without significant recorded x-ray dose are likely associated with the 100 Area reactor facilities. For example, workers 1, 4, 5, 9, 10, and 13 had significant recorded x-ray dose, indicating that they were plutonium workers, or were at least after 1958. For these workers, the ratio between the "best estimate" method 5 neutron dose and the recorded neutron dose ranges from 0.73 (worker 9) to 4.15 (worker 1). With the exception of worker 1, all ratios are less than 2. This can be

Table 4.3. Comparison of Integrated Neutron Dose Component, 1950 - 1961

Worker	Recorded Dose ^(a)				Method Used to Recalculate Neutron Dose				
	Shallow	Deep	X-ray	Neutron	1	2	3	4	5
1	15,190	13,880	3,090	130	2,900	1,018	846	494	540
2	17,760	14,100	0	40	5,531	1,937	1,547	778	914
3	33,760	24,960	0	80	3,420	1,457	1,172	823	868
4	18,520	13,580	2,080	1,000	4,974	2,228	1,826	1,212	1,210
5	20,340	18,570	1,840	1,850	8,023	3,987	3,528	2,482	2,669
6	14,010	4,890	10	730	3,149	1,684	1,524	1,179	1,170
7	19,120	17,530	0	220	4,300	1,667	1,340	616	763
8	17,250	7,300	20	1,360	1,873	1,186	1,162	1,081	943
9	23,450	22,030	2,630	4,150	7,932	4,356	4,038	3,259	3,026
10	17,010	13,780	3,220	920	5,381	2,341	2,063	1,173	1,329
11	32,960	26,230	0	130	3,456	1,150	771	376	472
12	4,420	3,980	0	50	2,994	1,151	825	418	496
13	20,460	14,060	1,090	2,750	4,699	2,647	2,505	2,129	1,937
14	8,030	6,810	0	0	4,882	1,798	1,373	729	839

(a) Whole body skin dose = Shallow + 65% of x-ray + neutron

Whole body deep dose = Deep + 35% of x-ray + neutron

contrasted with the generally much higher ratio observed for workers with no recorded x-ray dose: between 3.47 (worker 7) and 22.85 (worker 2). This general pattern is expected to result from the significant difference in neutron energy observed in the plutonium facilities (i.e., positive x-ray dose recorded) and in the 100 Area reactor facilities (i.e., no significant x-ray dose recorded). In the plutonium facility, the neutron spectra was substantially lower in energy. Also, with few exceptions, relatively little neutron dose was recorded in the highly shielded and controlled reactor facilities even though the neutron energies were much higher. It is important that there is essentially no neutron radiation when the reactor is not operating, such as during refueling or maintenance, whereas there is significant photon radiation from activation and fission radionuclides. Method 5 was primarily used in the analysis because it is expected to provide the most technically defensible approach to estimate neutron dose from the measured tracks on NTA film.

Another method which can be used to estimate the neutron dose is based on the ratio of the neutron to shallow or deep photon dose. Watson (1959) reported a very definite correlation between neutron and gamma doses for the limited group of workers at the 234-5 Facility. The measured deep photon dose would be preferred in this method because it is much less susceptible to dosimeter response uncertainties associated with low-energy photon or beta radiation. However, the two-element dosimeter used from 1950-1956 had a relatively poor response to plutonium x-rays (Wilson et al. 1990). A conservative approach, assuming a suitable neutron-to-deep photon dose could be determined from the multi-element film or thermoluminescent dosimeter data would be the use of the shallow dose to calculate the neutron

dose. In the plutonium facilities, the open window response of the Hanford two-element dosimeter (1944-1956) was reduced by a factor of 5 (i.e., response divided by a factor of 5) to compensate for the severe over-response of the dosimeter to plutonium x-rays.

4.5 Whole Body Dose

The change in the whole body dose (photon plus neutron) during the period 1950-1961 was found using the neutron doses calculated with Method 5, which is considered to represent the currently preferred analytical approach, and Method 1, which represents a substantial overestimate of the actual dose based on the NTA processing data. The results are shown in Table 4.4. Method 5 shows both increases and decreases in the revised whole body dose for the individuals within the analyzed sample. The re-evaluation showed changes in revised whole body dose ranging -4.8% to +12.3%. In general, little effect on the revised whole body dose occurred because of the substantially greater dose from photon radiation compared to neutron radiation. Using Method 1 to estimate the revised whole body dose resulted in increases ranging from approximately 6% to 73%, as shown in Table 4.4.

Table 4.4. Re-Evaluation of Whole Body Dose for Selected Sample of 14 Workers, 1950 - 1961

Worker	Work Location	Whole Body Dose, mrem				
		Recorded	Revised Method 5	Percent Change	Revised Method 1	Percent Change
1	200 W	15,092	15,502	2.7	17,862	18.4
2	100 A	14,140	15,014	6.2	19,631	38.8
3	100 A	25,040	25,828	3.1	28,380	13.3
4	200 W	15,308	15,518	1.4	19,282	26.0
5	200 W	21,064	21,883	3.9	27,237	29.3
6	100 A	5,624	6,064	7.8	8,043	43.0
7	100 A	17,750	18,293	3.1	21,830	23.0
8	100 A	8,667	8,250	-4.8	9,180	5.9
9	200 W	27,101	25,977	-4.1	30,883	14.0
10	200 W	15,827	16,236	2.6	20,288	28.2
11	100 A	26,360	26,702	1.3	29,686	12.6
12	100 A	4,030	4,476	11.1	6,974	73.1
13	200 W	17,192	16,379	-4.7	19,141	11.3
14	100 A	6,810	7,649	12.3	11,692	71.7

4.6 Comparison of Recorded and Calculated Neutron Dose

Relatively few Hanford workers had recorded neutron dose prior to 1958. To evaluate methods used to calculate and record neutron dose, NTA processing data were analyzed for three long-term Hanford workers who had recorded neutron dose in 1950. The results are shown in Table 4.5. The dose equivalent (rem) calibration for the PoB neutron source tabulated in Appendix A and shown in Figure 4.1 was used to retrospectively calculate the neutron dose, based on the following equation:

$$\text{Neutron dose} = (\text{Number of tracks} - \text{Blank}) * \text{Calibration factor} \quad (4.1)$$

The neutron dose calculated using Equation 4.1 is shown in Table 4.5 for each NTA film processed during 1950. The annual dose calculated as the summation of all of the individual results is shown on the bottom of Table 4.5 and compared with the official neutron dose of record for 1950 in Table 4.6. It is interesting that the retrospectively calculated annual neutron dose is less than the recorded neutron dose for each of these individuals. This is shown in Table 4.6, which shows more dose recorded by differences of 210, 273, and 31 mrem, respectively, than recorded in 1950 from the NTA processing data. This information generally validates the historical methods being used to calculate neutron dose from the measured tracks on NTA emulsion.

However, the issue of whether the NTA emulsion was responsive to all of the neutron spectra in the work environment which contributed dose cannot be answered from examining the historical processing data. Validation studies of dosimeter and instrument-measured dose have been performed for Hanford work environments. The results of these studies are discussed in Section 5.0.

Table 4.5. Retrospective Calculation of Dose for Three Cases During 1950

Date	Calibration Data			Processing Data ^(a)			Calculated Dose ^(b)		
	Sheet No.	Factor	Control	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
05/08-21/50	9	8.83	0	NE	8	NE	-	71	-
07/06-12/50	16	7.95	0	NE	2	3	-	16	24
07/13-19/50	17	8.04	0	NE	11	6	-	88	48
07/20-26/50	18	6.03	0	NE	6	1	-	36	6
07/27-08/02/50	19	6.1	0	NE	NE	2	-	-	12
08/03-09/50	20	7.38	0	8	NE	NE	59	-	-
08/10-16/50	21	6.07	0	2	NE	8	12	-	49
08/17-23/50	22	7.96	2	5	NE	5	24	-	24
08/24-30/50	23	5.64	2	5	NE	3	17	-	6
08/31-09/06/50	24	6.69	2	5	NE	4	20	-	13
09/07-13/50	25	7.25	2.4	12	5	8	70	19	41
09/14-20/50	26	7.52	0	8	3	3	60	23	23
09/21-27/50	27	5.78	2	5	7	4	17	29	12
09/28-10/04/50	28	6.58	2.17	5	2	2	19	0	0
10/05-11/50	29	5.74	2.5	5	3	4	14	3	9
10/12-18/50	30	7.07	2.6	7	10	4	31	52	10
10/19-25/50	31	5.7	2	9	8	4	40	34	11
10/25-11/01/50	32	7	2.33	4	5.3	4.7	12	21	17
11/02-08/50	33	5.89	2.33	8	7.8	7.3	33	32	29
11/09-16/50	34	7.95	2.17	3.3	NE	2.3	9	-	1
11/17-22/50	35	5.27	0	9.7	7.6	4.7	51	40	25
11/23-29/50	36	7.22	2.33	4.7	6.6	3	17	31	5
11/30-12/06/50	37	5.94	3.17	4.3	3	4	7	0	5
12/07-13/50	38	7.9	2	7.2	8.6	10.3	41	52	66
12/14-20/50	39	6.13	2.4	6.6	7.6	4.3	26	32	12
12/21-27/50	40	7.2	3.5	6.4	7.4	5.5	21	28	14
Totals							600	607	459

(a) All NTA processing data, number of tracks, during 1950 are shown. NE = No entry

(b) Dose, in mrem, calculated using dose conversion factors shown in Appendix A.

- No processing data

Table 4.6. Comparison of Recorded and Retrospective Calculation of Dose

Worker No. ^(a)	Retrospective Calculation of Neutron Dose, mrem ^(b)	Recorded Neutron Dose, mrep ^(c)	Difference, mrem
1	600	810	210
2	607	880	273
3	459	490	31

(a) Worker identifications (1-3) are not the same as shown in tables previous to Table 4.5.

(b) Dose calculation from Table 4.5.

(c) Dose shown as mrep on official tabulation but anticipated to have actually been recorded in mrem based on a quality factor of 10.

5.0 Workplace Validation

Validation of dosimeter performance to the neutron dose and spectra in the work environment is complex. Work environment fields involve both primary (i.e., from the radioactive source) and scattered radiation, mixed types of radiation (typically neutron and photon), and complicated exposure geometries (i.e., radiation exposure from many directions). Measurements conducted to validate the actual dose involve numerous technical issues. Response characteristics of the instruments, such as radiation type, energy, geometry, and dose, which are used to measure or calculate the dose, are very important. At the beginning of Hanford operations in 1944, air ionization chamber instruments were available to measure the photon dose in the work environment relatively accurately. However, similar instrument capabilities for neutron radiation evolved over many years. Validation measurements of personnel neutron dose typically involve comparing the dosimeter and instrument interpreted dose in the work environment. Locations are generally chosen which contribute the majority of the personnel dose. Dosimeters used in these measurements typically must remain for many hours of exposure to obtain a statistically meaningful value.

5.1 Portable Neutron Radiological Instruments

Howell et al. (1989) describe the history of portable radiological instrumentation at Hanford. The neutron responsive instruments described in that report are typically capable of indicating only the relative magnitude of the neutron dose rate and do not provide an accurate measurement of dose.

5.1.1 BFP Counters

The boron trifluoride (BF_3) proportional (BFP) counter detector was introduced at Hanford during 1948. The BFP had a paraffin moderator, and with BF_3 gas, was very sensitive to slow neutrons. Scattering of higher energy neutrons in the paraffin moderator provided an instrument response to neutron energies present in the work environment. There was no attempt to provide a dose rate calibration with this instrument.

5.1.2 NEUT

A second instrument, called the "Neut," was used to measure fast neutron radiation. This instrument was also introduced during 1948 and consisted of two detector chambers which were interchangeably mounted. One chamber was filled with CO_2 gas and would respond only to gamma radiation. A second chamber was filled with methane gas and would respond to both gamma and neutron radiation. Any observed increase in count rate obtained with the methane chamber relative to the CO_2 chamber was attributed to neutron radiation.

5.1.3 Modified BFP

In 1958, a modified BFP was introduced with a larger BF_3 detector. It had a large double cylindrical moderator weighing about 30 pounds. The theory of this instrument is described in detail by De Pangher

(1957a). The instrument was developed for measuring fast neutron dose, flux, and average energy primarily in the laboratory. This instrument could also be used for measuring dose in the work environment in spite of its directional cylindrical geometry. The instrument was very sensitive to neutron radiation and quite insensitive to photon radiation. This instrument measured neutron flux and dose in the energy range of 0.1 to 5 MeV and with an average neutron energy of less than 1.5 MeV. The core of this instrument, which consisted of a BF_3 tube at the center of a paraffin cylinder, is called the "fluxmeter," and the assembly, consisting of the core and an outer removable shell of paraffin, was called the "dose meter."

5.1.4 BFQ

The boron trifluoride quality (BFQ) proportional counter detector was introduced during 1963. It was essentially a transistorized version of the BFP, with some modifications. The BF_3 detector was smaller than the BFP, making the instrument less sensitive. The unit had three counting ranges and a double scale: one for slow neutrons and one for fast neutrons.

5.2 Neutron Spectra and Dose Instrument Capabilities

Neutron instrumentation evolved to provide capabilities to measure the spectra and dose in the work environment. These instruments have been used to conduct validation studies of the performance of personnel dosimeters in Hanford work environments. However, significant complexity is involved in comparing the dosimeter and instrument information, particularly in the earlier years. It was not unusual to observe large differences in response in the work environment, which required substantial technical analysis and knowledge to understand. The "field of view" of the respective devices is quite different. Radiation exposures in the laboratory were typically from a specific source of known radiation type and energy. However, in the work environment irradiations may occur from many directions, be of unknown energy because of scattering, and be of mixed radiation types (i.e., photon and neutron). The response of each device is a complex combination of the geometry, energy, and radiation type.

5.2.1 Long Counter

The "long counter" of Hanson and McKibben (1947) was a widely used instrument for measuring fast neutron flux. The instrument had nearly uniform sensitivity to neutrons of all energies and had excellent gamma ray discrimination (NBS 1960). The principle of operation of the long counter may be understood by considering the range of neutrons incident normally to the surface of a semi-infinite slab of paraffin. Neutrons of low energy will penetrate a short distance and be captured, whereas neutrons of higher energy will penetrate further before capture. If a boron counter is placed in the paraffin parallel to the incident neutrons, to a first approximation the neutron energy will determine the effective center of the counter at which the neutrons are detected. De Pangher (1957b) reported that the long counter was the standard instrument for measuring fast neutron flux at Hanford. Later, the paraffin was replaced by polyethylene to provide a more uniform moderator. The long counter was particularly used for comparing neutron sources of different energies.

5.2.2 Double Moderator Neutron Detector

De Pangher and Roesch (1955) described a paraffin moderator and BF_3 counter configured in such a way that count rate is approximately proportional to first-collision dose rate over a range of neutron energies from 0.1 to 5.1 MeV (NBS 1961). This instrument consisted of two coaxial cylindrical paraffin shells surrounding a sensitive BF_3 proportional counter (De Pangher 1957a). The full assembly is a dose meter, but removal of the outer paraffin shell converts the instrument into a fluxmeter.

5.2.3 Snoopy

The "Snoopy" was introduced during 1969. It consists of a BF_3 proportional counter mounted along the central axis of a relatively large cylindrical moderator. Through the use of internal filters in the moderator, this instrument was used to provide a single neutron dose rate. The choice of the calibration source significantly affects the instrument response. For example, a factor of 2 difference in dose equivalent response is observed between laboratory sources of PuBe and ^{252}Cf .

5.2.4 Multi-Sphere Spectrometer

The multisphere spectrometer provides an approximate measurement of the neutron energy spectrum from thermal energies to 20 MeV, so that neutron dose equivalent can be calculated from the energy spectrum using published fluence-to-dose equivalent conversion coefficients (NCRP 1971). The multi-sphere spectrometer consists of a ^6LiI scintillator neutron detector that is inserted into polyethylene spheres of various sizes. Using the computer code SPUNIT (Brackenbush and Scherpelz 1983), it is possible to unfold an approximate neutron energy spectrum from count rates using the different sphere sizes. The unfolded spectra have low energy resolution but are still very useful in analyzing fast neutron exposures. In recent years, the accuracy of the technique has been verified by performing spectral measurements with a NIST-traceable ^{252}Cf source and the fluence-to-dose equivalent conversion coefficient given in the National Bureau of Standards (NBS) Special Publication 633 for calibrating neutron dosimeters (Schwartz and Eisenhower 1982).

5.2.5 Tissue Equivalent Proportional Counter

The tissue equivalent proportional counter (TEPC) consists of a hollow sphere of tissue equivalent plastic filled with tissue equivalent gas. It measures the energy deposition in a known mass of tissue equivalent gas and thus provides a direct measure of absorbed neutron dose. Using appropriate algorithms (Brackenbush et al. 1985), it is possible to determine the distribution of absorbed dose as a function of linear energy transfer (LET). Because quality factors are defined as a function of LET, it is possible to determine average neutron quality factors, and hence dose equivalent, directly from a single TEPC measurement.

5.3 Early Hanford Validation Studies

Studies of personnel exposure to neutrons have been conducted at different times at Hanford (Watson 1951; De Pangher 1957b; Endres 1964; Unruh 1964; Unruh et al. 1966). Validation studies were made on the general use of NTA film, on the capabilities of the film dosimeter in the PFP, and on the proper technique for calibration.

5.3.1 NTA Film Study

In 1959, the Hanford NTA dosimetry system was studied to review the experience gained up to that point and to recommend further improvements in the program (Watson 1959). Recommendations resulting from this study included the following:

- NTA films should be evaluated only for fast neutron exposure when there is a significant gamma exposure as measured by the neutron film dosimeter.
- Records of the gamma dose as measured with the neutron dosimeter should be maintained for future analysis.
- The sequential analysis developed in this report should be adopted for the NTA films that will be evaluated for fast neutron exposure only when significant gamma exposure is indicated.
- A research program to investigate improved personnel neutron monitoring devices is required. Such a personnel monitoring device should be capable of measuring the full spectrum of neutron energies encountered at Hanford. It should be sensitive enough to measure an annual exposure dose of 0.5 rem and permit reporting exposure information at frequent intervals, preferably every four weeks.

These recommendations were immediately implemented. An important consideration in the forgoing sequential evaluation involved the presence of significant photon dose whenever there was a potential for neutron dose. The results of adopting the recommended practices and conducting the recommended studies were observed closely during the next year. Based on these observations and Wilson's recommendations,^(a) the routine reading of all neutron dosimeters of workers involved with plutonium work was instituted. The dosimeters of those workers not involved in plutonium work were read only when 100 mR or more of gamma exposure was indicated.

5.3.2 Plutonium Finishing Plant Facilities

In 1962, a series of measurements was conducted in operating areas of the Plutonium Finishing Plant (PFP) facilities to determine the need for additional radiation shielding along the plutonium finishing line,

(a) Wilson, R. H. "Evaluation of Fast Neutron Dose." Letter to H. A. Meloeny dated July 28, 1960.

particularly around the fluorinator, as a means of further protecting personnel.^(a) Field measurements of neutron dose rates were conducted with a double moderated BF₃ neutron counter. The inability of the personnel film dosimeter to fully estimate the neutron dose was recognized by the investigators. The use of neutron-to-gamma ratios to administratively limit total dose to personnel was considered; however, the wide range of observed ratios deterred investigators from using this option.^(b)

5.3.3 Dose Calibration

In 1963, Budd discussed a study conducted to resolve questions concerning the validity of using a single-collision dose calibration of the NTA film in the Hanford personnel neutron dosimeter.^(c) The main objective of this study was to determine the proper calibration technique, considering the fact that Hanford personnel are typically exposed to neutron radiation with effective energies at or below 1.2 MeV and realizing the poor response of NTA film to energies below about 0.8 MeV. Standard Hanford personnel neutron dosimeters were exposed in air and with the dosimeters backed with a BF₃ double moderator to determine the increase in tracks, if any, produced by reflected neutrons. Two fast neutron sources were used: ²³⁹PuBe and ²³⁹PuF₄, with mean energies of about 4.5 MeV and 1.3 MeV, respectively. With the PuBe source, an increase of about 15% in track density was observed for the dosimeters backed with the moderator. No difference was observed for the PuF₄-irradiated dosimeters. Statistical analysis of the data showed that at the 95% confidence level the maximum difference in track density between backed and unbacked dosimeters would not exceed 6%.

Previously, Unruh described a study involving the comparison of 24 neutron dosimeters exposed in a fast neutron field of about 8.2 mrem/h for 27 hours (e.g., 221 mrem). These results were compared with measurements made using the new BF₃ counters.^(d) Exposures were performed near the center of the B-Reactor front face. Upon routine processing at the 3705 Building, only three neutron dosimeters yielded positive readings of 100, 150, and 200 mrem. Further investigation showed that 10 of the neutron dosimeters indicated positive dose readings between 11 mrem and 22 mrem. A total slow neutron dose of 4.1 mrem was accumulated during the 27-hour exposure. Cutie Pie (CP) gamma measurements estimated

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- (a) Knight, L. M. "Predicted 1962 Neutron Exposure." Letter to W. J. Gerten dated February 16, 1962.
Knight, L. M. "Predicted Exposure to Neutrons—Buttonline." Letter to J. J. Courtney dated April 6, 1962.
 - (b) Bramson, P. E. "Neutron-Gamma ratios in 234-5 Building." Letter to C. M. Unruh dated October 19, 1962.
Faust, L. F. "Neutron to Gamma Ratios of PuF₄," Letter to J. M. Selby dated July 17, 1964.
 - (c) Budd, R. O. "Single Collision Versus Multiple Collision Fast Neutron Dose Calibration of the Hanford Neutron Film Badge Dosimetry." Letter to File dated July 2, 1963.
 - (d) Unruh, C. M. "Neutron-Gamma Ratios in 105 Buildings." Letter to L. A. Carter, H. V. Larson, F. L. Rising, and E. E. Watson dated October 18, 1962.
Unruh, C. M. "Preliminary BF₃-Neutron Badge Comparison Data." Letter to A. R. Keene dated October 18, 1962.

the total integrated gamma dose to be between 350 mR and 370 mR. The gamma dose interpreted from the neutron dosimeters ranged from 320 mR to 385 mR.

5.4 Hanford TLD Albedo Dosimeter

Implementation of the new Hanford TLD involved many issues. Notably, several years of research and development had been devoted to developing Hanford capabilities to utilize this technology. Field studies had been performed to characterize the dosimeter performance in Hanford radiation fields. However, with the introduction of this new dosimetry system, significant increases in recorded neutron dose were observed. This resulted in a national technical review of the Hanford personnel dosimetry system. This is discussed in the following sections.

5.4.1 Field Measurements

Using improved neutron instrumentation and recognizing the energy-dependent characteristics of the new Hanford multipurpose albedo TLD, staff conducted detailed field measurements during the early 1970s to base the calibration of this dosimeter on the neutron energy spectra in the work environment. Several characteristics of the multipurpose dosimeter are described in a report by Kocher et al. (1971). Two major types of field studies were conducted to compare the response of the new multi-purpose TLD and multi-element film dosimeter used at Hanford since 1962 (Nichols et al. 1972). The first type of study involved the simultaneous placement of two multi-purpose TLDs along with two beta/photon and two neutron film dosimeters on 2-gallon polyethylene jugs filled with water. The jugs were placed at 49 work locations in the Plutonium-Uranium Extraction Facility (PUREX), B-Plant, Z-Plant, 105-KE Building (reactor operating), 100-N (reactor not operating), and the 325-B, 325, and 327 Buildings. Instrument readings with a CP and a Snoopy were taken at the beginning of each measurement. A similar experiment was done in which a TEPC was used to measure the dose from fast neutrons. These data are summarized in Table 5.1. The data show wide variability between the results for the different measurement techniques. However, the data illustrate the general under-response of the film dosimeter results compared with the TEPC results.

The second type of field measurement involved personnel wearing TLDs and film dosimeters simultaneously. Figure 5.1 illustrates the comparison of the penetrating dose component from both dosimeter types. Similarly, Figure 5.2 illustrates the comparison of the fast neutron dose component from both dosimeter types. It is apparent in these figures that the penetrating doses compare reasonably well, whereas there is a significant under-response of the film for the fast neutron dose.

5.4.2 National Review of Hanford Recorded Neutron Dose

After the implementation of the Hanford TLD on January 1, 1972, Atomic Energy Commission headquarters staff conducted a detailed review of recorded neutron dose for Hanford personnel using a

Table 5.1. Fast Neutron Dose Measurements (Nichols et al. 1972)

Location	Snoopy	Fast Neutron Dose, mrem		
		TEPC	Film	TLD
<u>105-KE</u>				
X-1	60	270	0	530
Top #23	1,400	1,700	470	4,100
Mon	0	0	0	60
Front face	50	900	0	250
<u>308 Bldg.</u>				
Rm 208	2,000	2,700	270	3,700
Corr #7	4,200	14,100	1,270	11,100
Vent rm	30	30	0	0
Rm C	700	730	70	870
<u>234-5 Bldg.</u>				
17 DC	340	NM ^(a)	0	100
HC-11	280	NM	0	180
9B top stairs	410	NM	100	440
9B under stairs	280	NM	60	450
Rm 221	410	790	170	460
Rm 192	510	620	950	490
Rm 192-C	150	230	310	240
Rm 193	380	500	770	600
2731-Z	200	NM	60	50

(a) NM = not measured.

committee of technical experts from Hanford and other AEC facilities.^(a) Central to this investigation was the selection of 18 long-term workers for detailed evaluation. The evaluation conducted at that time showed an average increase in the cumulative dose for these workers, to account for the unrecorded neutron dose, by a factor of 2.2 times the recorded dose. The maximum increase was a factor of 2.8 times the recorded cumulative dose. An updated analysis of this information was conducted for this report based on information obtained since 1972. Three distinct periods of dose recording from 1950 through the present have been identified as follows:

(a) Biles, M. B. "Ad Hoc Technical Committee Findings." Letter to T. A. Nemzak dated November 23, 1972.

RG96060215.14

Figure 5.1. Comparison of Film Dosimeter and TLD Penetrating Dose Results (Nichols et al. 1972)

RG96060215.13

Figure 5.2. Comparison of Film Dosimeter and TLD Fast Neutron Dose Results (Nichols et al. 1972)

Period	Description
1950 - 1956	This period of record included use of the NTA film and determination of shallow (nonpenetrating) and deep (penetrating) dose using the original Hanford two-element dosimeter.
1957 - 1971	This period of record involved use of the Hanford multi-element film dosimeter for beta, photon, and neutron radiation.
1972 - 1995	This period of record involved use of the Hanford TLD for beta, photon, and neutron radiation.

Dose-of-record data for each of the selected workers within each of these selected recording periods are summarized in Table 5.2. The year of first recorded radiation exposure is shown in the first column of this table for each worker (1950 is shown for any worker whose first recorded radiation exposure occurred during or prior to 1950). All of these workers had the Hanford PFP facility as the primary work area at least during the 1970s. It is interesting to examine trends in this data. For example, the ratios of the shallow to deep dose and neutron to deep dose for the respective recording periods are summarized in Table 5.3. These ratios exhibit response characteristics of the respective dosimeters observed during laboratory studies.

The shallow dose response for the two-element film dosimeter used prior to 1957 is expected to be too high because of the significant over-response of this dosimeter to the low-energy photons prevalent in the PFP (Wilson et al. 1990). These data also show increasing levels of recorded neutron dose, relative to the deep dose, for each succeeding dosimeter design. Moreover, it is possible to observe changes in relative dose components 1) during the 1957 period when the multi-element film dosimeter was introduced along with the PuF_4 neutron source calibration (calibration in rem) and 2) during the 1972 period when the multi-element TLD was introduced. Nine of the 18 workers have dose histories which extend from 1950 or earlier through 1980 or later.

Characteristics of the recorded dose for these workers are illustrated in Figures 5.3 and 5.4. In Figure 5.3, the cumulative whole body and neutron dose is plotted from 1950 through 1980. Beginning in about 1962, the pattern of the two curves was closely associated. Certainly, the significant peak in recorded whole body dose in 1972 is attributable to the large increase in recorded neutron dose with the new TLD which responded to the full neutron spectrum. Dramatic increases in recorded neutron dose in 1958 resulting from implementation of the new multi-element NTA dosimeter holder and the use of the PuF_4 calibration source are not readily apparent from this data. The ratios of the shallow to deep and neutron to deep dose components are illustrated in Figure 5.4. The most noticeable features of this figure involve the dramatic increase in neutron to deep dose observed in 1972, and the general consistency in the shallow to deep dose ratio beginning in about 1957 with the implementation of the multi-element film dosimeter. Prior to 1957, the two-element dosimeter was incapable of distinguishing between beta and photon radiation. Shallow dose interpretation depended upon knowing where the person was working and using an appropriate calibration. The large shallow dose components in the early years are likely associated with not using an appropriate low-energy photon source for plutonium finishing workers (i.e., shallow dose interpretation based on uranium beta calibration would be highly over-estimated).

Table 5.2. Integrated Recorded Dose for Selected Sample of 18 Workers, mrem^(a)

Year ^(b)	1950 - 1956			1957 - 1971				1972 - 1995		
	Sh	Dp	Nt	Sh	Dp	X	Nt	Sh	Dp	Nt
1950	6140	2610	160	26810	24970	6420	11140	1090	1010	720
1950	10060	7550	0	25590	23610	6340	12220	1120	830	1350
1950	9310	7690	0	26910	25240	6470	8500	22850	17420	10140
1950	15920	6650	0	22650	21110	5370	4430	12760	9410	3860
1950	9090	6660	0	23700	21770	5570	12350	14120	12060	8640
1950	5960	4400	0	31230	29620	7760	8350	11200	8680	9170
1950	10200	8950	0	27000	25980	5790	8620	6490	5220	3600
1962	-	-	-	15980	14710	3910	3010	23110	16790	4660
1950	14670	10400	0	29400	27690	5800	10680	12890	10120	7938
1950	6650	2390	0	17860	13260	3150	7950	340	260	510
1950	10450	4990	0	25390	23480	5220	11480	1490	1360	1040
1961	-	-	-	13000	7480	1430	880	14460	12260	1330
1962	-	-	-	12920	10520	3310	2050	13424	9661	10787
1960	-	-	-	11680	8520	1610	1070	17140	13430	2710
1963	-	-	-	15920	13980	4350	2470	2230	1840	2820
1950	14350	12670	100	25900	24830	5070	17140	13950	9050	5760
1950	19070	5180	0	25440	23580	6810	13920	13760	10270	5360
1950	11190	8000	0	29430	26860	6180	7050	15730	14200	8920
Sum	143060	88140	260	406810	367210	90560	143310	198154	153871	89315

(a) Sh = Shallow dose, Dp = Deep Dose, Nt = Neutron Dose, X = x-ray Dose

(b) Year of first recorded radiation exposure. For years equal to or prior to 1950, 1950 is entered.

Table 5.3. Ratio of Recorded Dose Components

Recording Period	Ratio (Range)	
	Shallow/Deep	Neutron/Deep
1950 - 56	1.6 (1.1 - 3.7)	0.003 (0 - 0.06)
1957 - 71	1.2 (1.1 - 1.7)	0.4 (0.1 - 0.7)
1972 - 95	1.3 (1.1 - 1.5)	0.6 (0.1 - 1.6)

Figure 5.3. Plot of Cumulative Dose for Selected Worker Sample

Figure 5.4. Plot of Ratio of Shallow to Deep Photon and Neutron to Deep Photon Dose Components

5.5 Hanford Personnel TLD Supporting Studies

During 1979, PNL began a five-year evaluation of the Hanford Personnel Dosimeter System. Three reports of studies of existing TLD characteristics and evaluation of potential alternatives were published (Fix et al. 1981, 1982; Fix, Holbrook, and Soldat 1983). Several facets of the existing TLD program are discussed in these reports, which also provide the following significant conclusions:

- The blind audit acceptance procedure used to determine the validity of processing runs for each dose category (i.e., nonpenetrating, penetrating, fast neutron, and slow neutron) confirms the observed accuracy of the Hanford dosimeter to estimate dose, on the average, received from the laboratory calibration sources used to irradiate the dosimeters.
- The dosimeter overestimates the actual dose at all energies to filtered x-ray techniques using existing calibration procedures. Observed bias for deep and shallow doses ranged from 17% to 75% with the maximum response at an effective energy of 32 keV.
- The dosimeter response to a National Institute of Standards and Technology (NIST) D₂O-moderated ²⁵²Cf source was a factor of 7 higher than the response to the routine calibration exposure.
- The present dosimeter algorithm may calculate significant false-positive fast-neutron doses when exposed to thermal neutrons or penetrating photon radiation. Dose equivalents equal to about 30% of the delivered photon dose and as high as a factor of 6 times the delivered thermal neutron dose equivalent were observed.

Based on these studies, the recorded dose was considered relatively accurate with the noted exception of potentially large over-estimates to thermal neutrons.

5.6 Hanford Combination Neutron Dosimeter Field Measurements

During the 1990s, field measurements were performed with a new Hanford prototype personnel neutron dosimeter design (Brackenbush et al. 1991) and, subsequently, with the commercially procured Hanford Combination Neutron Dosimeter (HCND) (Endres et al. 1996), which was implemented on January 1, 1995. Plutonium tetrafluoride (PuF₄), plutonium oxide (PuO₂), and plutonium metal sources were used at the Hanford PFP facility to characterize the response of Hanford dosimeters in several exposure configurations involving bare and moderated sources. TEPCs and multi-spheres were used to determine the neutron dose and spectra. For some of these measurements, the Hanford Nuclear Track Emulsion (NTA) film dosimeter, used from 1962-1971, was included.

In these measurements, the accuracy of the TEPC was verified by measurements on a ²⁵²Cf source in the Pacific Northwest National Laboratory (PNNL) 318 Calibration Laboratory with calibrations directly traceable to NIST. The TEPC data were expected to measure the dose equivalent within ±15% (Endres et al. 1996). An internal alpha source was used to check for gain shifts before and after each TEPC measurement was completed.

Each group of NTA film exposed to a particular neutron source was developed as a single group using the same equipment and procedures as used at Hanford from 1962 to 1971. These film groups came from the same film emulsion lot. Although the performance of the NTA film was not the focus of these studies, these measurements showed the same results as discussed in Section 5.4, i.e., the NTA film showed a significant dose under-response. The dose under-response was particularly evident as the neutron energy spectra was degraded using increasing thicknesses of Lucite shielding between the source and the dosimeters.

6.0 Retrospective Evaluation of Neutron Dose

This report was prepared to describe an investigation into the historical pattern, described in Section 1.0, of recorded neutron and deep dose. Epidemiologic studies of Hanford workers include the annual dose for each person as well as the lifetime dose. Consistency of the recorded dose is very important to these studies (Gilbert and Fix 1995; Fix and Gilbert 1991). Combined epidemiological studies conducted by the International Agency for Research on Cancer (IARC), which includes the Hanford cohort, have identified concerns regarding the accuracy of worker dose to low-energy photon and neutron radiation (Cardis et al. 1995a, 1995b).

6.1 Hanford Dosimeter Assignment, Processing, and Recorded Dose

Hanford practices to measure and record personnel dose have been previously described (Wilson 1987, Wilson et al. 1990, Gilbert 1990). Dosimeter assignment and processing records clearly illustrate Hanford practices to assign dosimeters to all personnel and, for this report, neutron dosimeters to all personnel with any potential of neutron dose. For most years, as shown in Section 1.0, many workers have measured deep dose from photon radiation. Although there is no recorded neutron dose prior to 1950 and relatively little recorded neutron dose prior to about 1958, compared to the recorded photon deep dose, this appears to be directly attributable to the level of neutron radiation in the work environment and to the dosimetry technology. Prior to operation of the PFP in 1949, no significant Hanford worker exposure to neutron radiation is expected. As described in this report, major changes in Hanford dosimetry technology occurred during 1950, 1957, and 1972.

6.2 Neutron Radiation

Hanford health physics staff were aware of the neutron radiation hazards in Hanford reactor and plutonium facilities seemingly from nearly the very beginning of operations. Representatives from Hanford were involved in formulating both national and international radiation protection guidelines. For example, at least two representatives from Hanford, H. M. Parker and G. H. Whipple, were involved in the joint meeting of Canadian, British, and U.S. (Tripartite) radiation protection committees held in Chalk River, Canada, on September 29-30, 1949. At this meeting, relative biological effectiveness (RBE) factors were adopted for application to various types of radiation, among other technical issues (e.g., factors of 5 and 10, respectively, were adopted for slow and fast neutrons). These factors were used at Hanford to multiply the measured neutron dose, originally in units of rep, to record an RBE effective dose, or what is now referred to as the dose equivalent in mrem.

6.3 Recorded Dose

The recorded dose involves issues regarding the statistical minimum detection level of the dosimetry system, dose recording thresholds, and the potential annual dose missed.

6.3.1 Minimum Detection Level

The minimum detection level (MDL) can be calculated for Hanford beta/photon film, NTA film, and TLD systems for shallow, deep, and neutron dose. The analysis is more complicated for the NTA film dosimeters because the area counted on each film varied according to the magnitude of the dose, whereas for the other dosimetry systems only one number was obtained for each radiation-responsive region of the processed dosimeter. Using techniques described in ANSI N13.30 (ANSI 1996), the minimum detection level for NTA film dosimeters can be calculated as follows:

$$\text{MDL} = \text{CF}' \frac{4.65 s_b + 3}{\text{Area}} \quad (6.1)$$

where CF' is the calibration factor, normalized to a counting area of 1 mm², in mrem/track/mm², s_b is the standard deviation of the blank NTA film (obtained, like the calibration factor, from Appendix A), and Area is the counting area in mm² of the NTA film. For each 40 fields of view, an area of 0.78 mm² is counted. Hanford practice was to count each film at least three times. For example, for sheet number 1 in Appendix A, the detection level is calculated as follows:

$$\text{MDL} = 9.74 \frac{4.65 * 0.58 + 3}{3 * 0.78} \quad (6.2)$$

$$\text{MDL} = 23.7 \text{ mrem/track} \quad (6.3)$$

where CF' is the calibration factor, normalized to a counting area of 1 mm². This represents the case where each NTA film is read three times. The MDL is strongly dependent upon the counting area and the standard deviation. The NTA film was always read at least three times. If the standard deviation increased much above 0.5, the film was read additional times.

For the beta/photon film dosimetry system, Wilson (1960) reported the detection level to be 30 mrem. For the TLD system, reports by Kocher et al. (1971) and Fix et al. (1981, 1982) evaluated many aspects of the Hanford TLD system. Based on information in these reports, the detection level of this dosimetry system was between 10 and 20 mrem for photon radiation. The lowest level of significant detection (dose equal to standard deviation) was about 10 mrem for a pure fast neutron exposure as received in a calibration laboratory. The level of detection for fast neutron dose is highly dependent upon dosimeter response to thermal neutron radiation. In mixed radiation fields, typical of Hanford plutonium-handling operations, a detection level for fast neutron radiation of approximately 30 mrem was estimated for the TLD system, with the understanding there is substantial likelihood of over-estimating any dose from highly scattered lower-energy neutron radiation. The most recent workplace validation studies illustrate the complexity of measuring neutron dose in the work environment (Endres et al. 1996, Brackenbush et al. 1991).

From the foregoing, it is evident that the minimum detection level and accuracy for the respective dosimetry systems are significantly improved for photon radiation as compared to neutron radiation.

6.3.2 Dose Recording Threshold

Hanford used the total track count in the calculation of the dose to be recorded for the NTA film. The exact process was complicated and varied over the years. In the early 1950s, a sequential analysis procedure was used involving a total of at least 60 tracks counted in 10 readings (i.e., an average of six tracks per reading) for a positive dose to be recorded. If the average number of tracks counted exceeded six tracks per reading, then additional readings were conducted to a maximum of 10 readings. If the average was equal to or less than an average of six tracks per reading, the dose was recorded as zero. Based on the calibration factor in Appendix A, this corresponds to a dose recording threshold of about 46 mrem (6×7.6 for calibration sheet #1).

For the TLD system, the practice was to report any dose calculated to be 5 mrem or greater as a positive dose. A protocol was adopted to round doses to the nearest multiple of 10 mrem (i.e., doses between 5.0 and 14.9 were recorded as 10, doses between 15.0 and 24.9 as 20, etc.).

6.3.3 Potential Annual Missed Dose

Hanford researchers provided estimates of the potentially missed annual dose, particularly with the NTA film dosimeter (Watson 1959). These analyses were done to evaluate the best alternative for dosimeter exchange periods. The magnitude of the potential missed dose with the NTA film dosimeter was a primary basis for research into improved neutron dosimetry systems in the 1960s. Assuming a dose recording threshold of 46 mrem and an exchange period of every two weeks, this corresponds to a maximum potential missed dose of about 1196 mrem, assuming that the dose results on each NTA film were slightly less than the dose reporting threshold.

For the TLD system, a monthly exchange period was adopted. Assuming a detection level of 30 mrem per dosimeter processing, this corresponds to a potential maximum missed dose of 360 mrem per year.

6.4 Neutron to Photon Dose Ratio

As described in Section 1.0 of this report, no neutron dose was recorded prior to implementation of the NTA film in 1950. Relatively little neutron dose is recorded from 1950 until 1956. Beginning in about 1956, significantly greater neutron dose is observed, in comparison to the recorded deep photon dose. In 1972, upon implementation of the Hanford TLD system, substantially greater neutron dose was measured. This increase was the subject of DOE/HQ expert committee review.^(a) The committee report included a review of neutron to photon dose ratios measured for several work assignments during the first six months of using the new Hanford TLD system. At that time, the decision was made not to estimate dose

(a) Biles, M. B., Director, Division of Operational Safety. "Ad Hoc Technical Committee Findings." Letter to T. A. Nemzak, Manager, Richland Operations Office dated November 23, 1972.

retrospectively for specific individuals, based on the understanding that previous estimates were made with the best available technology, and understanding the uncertainty associated with a retrospective assessment of individual dose because of changes in isotopic ratios, changes in work assignments, changes in shielding, etc. This report clearly states the committee's opinion that under-recorded neutron dose occurred and provides methods to retrospectively assess the total dose. A sample of 18 workers, the same sample evaluated in Section 5.0 of this report, was selected for study. For these workers, estimated total doses (neutron plus photon) were calculated. Neutron-to-photon ratios used in this analysis are shown in Table 6.1. At that time, substantial effort was made to retroactively calculate dose to this sample of workers. The estimated total dose, using the foregoing neutron-to-photon dose ratios, were compared to the lifetime limit of 5(N-18), with the judgment that no workers exceeded this dose limit.

Table 6.1. Ratio of Neutron Dose to Deep Photon Dose

	1961 to Present	1956 - 1960	1948 - 1955
Plutonium workers	2.01	1.36	1.23
Maintenance workers	1.60	1.09	1.00

In Section 5.0, dosimeter data for this sample of 18 workers were analyzed. The years chosen for analysis in Section 5.0 coincided with the use of the respective dosimetry systems; the basis for the time periods shown in Table 6.1, as used in the 1972 analysis, is expected to be a combination of changes in the dosimetry system and in plutonium-handling practices. As described in Section 5.0, nearly the same shallow to deep dose ratio is observed between the Hanford multi-element beta/photon film dosimeter used from 1957 to 1971, and the TLD used from 1972 to 1995 (see Table 5.3, ratio of 1.2 versus 1.3). However, the ratio of recorded neutron dose compared to recorded deep dose for the TLD system was only 0.6. This represented an average increase of about 50% (see Table 5.3, ratio of neutron dose to photon dose of 0.4 for the film dosimetry system versus 0.6 for the TLD system). However, this ratio, which is equivalent to a neutron dose to photon dose ratio of about 1.0, is much less than the values shown in Table 6.1. The analysis in Section 5.0 showed that essentially no neutron dose was recorded, compared to the deep dose, for the sample of 18 plutonium workers with the two-element film dosimeter used before 1957 (see Table 5.3, neutron dose to deep photon dose ratio of 0.003 from 1950 to 1956).

An explanation for the significant difference in the ratio of neutron to deep photon dose in the current investigation and in the 1972 review may be ascertained from the trend in the ratio of neutron to photon deep dose plotted in Figure 5.4. The substantial increase in neutron dose is apparent by the peak shown in 1972. This peak is attributed to implementation of the TLD system and its responsiveness to the full energy spectra of neutrons in the work environment. Because of the significant increase in measured neutron dose, practices were quickly adopted to minimize personnel neutron dose involving rotating job assignments, installing additional shielding, minimizing occupancy in neutron fields, etc. The rapid decrease in the ratio of neutron to deep photon dose with the TLD system beginning in 1973, as shown in Figure 5.4, can be attributed to these changes. The neutron to deep photon ratios used in the 1972 committee review was based on the first six months of experience with the new TLD system. As illustrated in Figure 5.4, this ratio was significantly elevated compared to the long-term average (1972-1995)

used in the analyses in this report. However, the TLD dose data in 1972 likely best illustrate employee dose with the NTA film prior to implementation of the TLD system. Based on this observation, the neutron to deep photon (i.e., gamma) dose ratios presented in the 1972 committee review are considered to be the best available for use in any retrospective analysis.

6.5 Retrospective Evaluation of Neutron Dose

Plutonium-handling facilities represent the only Hanford work environment with the potential for significant under-recording of neutron dose. This work environment is further complicated because of low-energy photon radiation, which was also difficult to measure accurately before the use of the Hanford multi-element beta/photon dosimeter beginning in 1956 (Wilson et al. 1990). Based on information presented in this report, four distinct periods have been identified when retrospective evaluation of recorded neutron dose should be considered:

- 1944-1949, before implementation of the NTA film dosimeter
- 1950-56, before implementation of the multi-element NTA film dosimeter
- 1957-71, before implementation of the multi-element TLD
- 1978-83, during the period of 4-chip TLD use.

The following approach is recommended in conducting a retrospective evaluation of whole body dose:

1. For the multi-element film and TLDs, the recorded deep dose is considered accurate.
2. For the two-element film dosimeter, and specifically for the plutonium-handling facility, the deep dose is likely inaccurate. As such, the only alternative is to use the recorded shallow dose. Based on the analyses of the selected worker samples of 14 and 18 workers analyzed, respectively, in Sections 4.0 and 5.0 of this report, the recorded shallow and deep doses are highly correlated.
3. The ratio of neutron dose to shallow photon dose for the two-element dosimeter and neutron dose to deep photon dose for the multi-element film dosimeter results should be used to retroactively estimate the neutron dose.
4. The recorded neutron dose based on TLDs is expected to provide the best estimate of the actual neutron dose from field validation measurements.
5. For the film dosimeter data, the whole body dose (neutron plus photon deep dose) should be estimated and compared to the original recorded dose.

For the period when the four-element TLD was used, a committee was formed to evaluate this situation. It was concluded that the five-chip dosimeter would undoubtedly calculate higher fast-neutron

dose. Based on this study,^(a) a factor could be calculated from the known response of this dosimeter to 16-keV and 60-keV photon fields. The study involved examination of detailed dose records for a selected sample of plutonium facility workers. An increase in the recorded whole body dose of 25% was estimated for these workers. This analysis undoubtedly was an important factor in the decision to return to the five-chip dosimeter design.

An advantage of using the ratio of neutron to photon doses is minimization of the potential for significant missed neutron dose based on the relatively high detection level of neutron dosimeters, particularly for the NTA film dosimeter (see Section 6.4). It should be stated that there is substantial controversy regarding the use of the neutron to photon dose ratio. Considering that photon and neutron radiation interact with matter very differently, there are good reasons to expect the photon dose to be an inaccurate predictor of the neutron dose. Certainly, there is little correlation when many different work environments are considered. However, for specific application to the plutonium-handling environment, this is considered to represent the best alternative. Certainly, the photon dose has been measured accurately with all of the Hanford personnel dosimeters within reasonable tolerances. The primary difficulty is with the precise value of the neutron to photon dose ratio. However, ranges of values could be used to evaluate the approximate magnitude of the missed dose.

(a) Fix, J. J. "234-5 Dose Evaluation." Letter to External Dosimetry Committee dated August 31, 1983.

7.0 Conclusion

Based on information contained in this report and references, several statements regarding Hanford recorded dose can be made as follows:

1. The recorded whole body deep dose is calculated as the sum of the photon deep dose and the neutron dose.
2. From the historical record, all Hanford workers and visitors were assigned personnel beta/photon dosimeters when there was any significant potential for radiation exposure.
3. The deep dose from photon radiation is expected to be measured accurately for all Hanford facilities beginning with the use of the multi-element beta/photon film dosimeter in 1957. For the original two-element beta/photon dosimeter used at Hanford and elsewhere, serious under-reporting of the deep dose may occur in low energy photon fields, such as would be expected in the plutonium facilities (Wilson et al. 1990). In these cases, as described in this report, the shallow dose can be used to conservatively estimate the deep dose. As originally recorded, the shallow dose from low energy plutonium x-rays is approximately a factor of 5 too high. This was recognized by Hanford dosimetrists with the result that the recorded shallow dose was reduced by a factor of 5 (multiplicative factor noted as 0.2 in the historical documentation) based on the knowledge of the work location (Wilson et al. 1990).
4. From the historical dosimeter processing records, it appears that Hanford workers with any significant potential for neutron dose were assigned NTA film (1950-71) and albedo thermoluminescent (1972-present) dosimeters. These dosimeters were processed and results recorded. Prior to the operation of PFP beginning in July 1949, no significant neutron exposure of Hanford workers is expected.
5. Validation of the originally recorded dose from NTA film processing was done in this report. Comparisons between the official dose of record and as calculated from the processing data between 1950 and 1961 showed good comparisons. In particular, neutron dose recorded in 1950 for three long-term Hanford workers was validated from the raw processing data using current dose conversion factors.
6. Based on current knowledge, there is under-recorded neutron dose, primarily prior to the use of the Hanford TLD in 1972, and specifically for the relatively few Hanford workers involved with plutonium-handling operations. This occurred because of significant neutron radiation in the workplace less than the energy threshold of about 1 MeV (based on a minimum of 4 grains to be counted as a track) for the Hanford NTA film dosimetry system.
7. It is evident that substantial effort was made by Hanford health physics organizations to conduct neutron dosimetry using NTA film. Personnel, calibration, and control dosimeters were administered in batches, as procured from the supplier. For example, as examined in this report, Hanford dosimetry

staff processed and analyzed 85,000 NTA film emulsions, separated into 529 separate lots of procured film during the period of 1950-1961, and recorded the data. These practices continued through 1971 when the TLD system was implemented. However, it is evident that the NTA film dosimeter was technologically incapable of accurate neutron dosimetry in Hanford plutonium facilities.

8. The neutron dose was under-recorded during January 1980 through January 1984 when the four-element Hanford TLD was used. A study conducted at that time showed an under-recorded whole body dose of about 25%.
9. The ratio of recorded neutron to deep photon dose would be expected to vary significantly throughout Hanford facilities. However, the ratio for specific work environments and groups of workers is expected to be highly correlated, as shown in this report, as reported in 1972^(a) in a national technical committee review, and as shown by Watson (1959). The 1972 national review includes tabulation of neutron-to-gamma (photon deep dose) ratios for several plutonium-handling operations, as described in Section 6.0.
10. Relatively little personnel neutron dose is expected from the Hanford production reactor facilities. Personnel neutron dose was limited by the large quantities of shielding, high temperatures near the reactor core, and the general practice to limit personnel access to areas near the core during reactor operation. Neutrons were observed in selected reactor areas such as control rod drive rooms and areas near the core where special tests were being performed. However, in general, neutrons in these areas would be expected to be of much higher energy than observed in plutonium-handling facilities and to be accompanied by high energy gamma radiation. There is essentially no neutron radiation while the reactor is not in operation.
11. Because of the concern for unrecorded neutron dose, Hanford used internal controls (such as 3 rem/year beginning around 1958) to limit whole body dose to personnel.

Accuracy of the recorded dose is important to the validity of Hanford exposure records and to the conduct of epidemiologic studies which utilize these records. The general quality of Hanford radiation exposure records appears to be excellent. Under-reporting of neutron dose described in this report is limited to the relatively few hundred Hanford personnel, collectively to date, working in the plutonium-handling facilities, compared to the many tens thousands of Hanford personnel working in many different radiation environments involving reactor, processing, waste, and research facilities. Retrospective estimates of corrected dose for these plutonium workers are recommended because of the relatively few Hanford workers affected, the availability of dosimeter assignment and processing records which identify the affected individuals, and the availability of computerized records to conduct the necessary calculations.

A retrospective analysis of the magnitude of the unrecorded neutron dose and the change in whole body dose (i.e., photon and neutron dose) could be done. However, tremendous effort would be necessary

(a) Biles, M. B., "Ad Hoc Technical Committee Findings." Letter to T. A. Nemzak dated November 23, 1972.

to determine the best estimate of dose for all workers based on analysis of the type and location of work performed by each worker. If a retrospective analysis were performed for an individual worker, recommended steps in this analysis would include:

1. Determine if the worker was potentially affected by unrecorded neutron dose based on a review of the person's work history and exposure history file, and if necessary, from the dosimeter processing database prior to 1957 and from recorded dose characteristics (x-ray, deep, neutron) from 1957-1971.
2. Determine the range in neutron to gamma ratios from the 1972 report, or other reference, applicable for selected time periods.
3. Calculate the neutron dose from the computerized dose record using the neutron to deep dose ratios from step 2.
4. Compare the calculated dose in step 3 with the recorded neutron dose for the same period of time.
5. Document cases where the maximum of the calculated neutron dose exceeds the recorded neutron dose.

A small refinement in the foregoing is to base the calculation of neutron dose during the period of use of the Hanford two-element dosimeter or neutron dose to shallow dose ratios. For this period of time, the shallow dose is considered to be a more reliable indicator of the potential dose received than the deep dose. An estimate of the range in under-recorded neutron dose associated with use of the 4-chip TLD during January 1980 to January 1984 is less significant. However, it is possible to include these years as well in any effort to calculate the range in unrecorded neutron dose for an individual worker based on existing documentation referenced in this report.

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10.0 Glossary^(a)

Absorbed Dose. The amount of energy imparted by radiation to a unit mass of absorbing material (100 ergs per gram), including tissue. The unit prior to the SI is the rad; the SI unit is the gray (Gy).
1 Gy = 100 rad.

Accreditation. The process of evaluating a program which uses personnel dosimeters to measure, report, and record dose equivalents received by radiation workers.

Alpha Particle. A particle emitted spontaneously from the nuclei of some radioactive elements. It is identical with a helium nucleus, having a mass of four units and an electric charge of two positive units.

Angular Dependence. The response of a dosimeter as a function of angle of incidence of the radiation detected compared to its response at normal incidence (non-perpendicular incidence).

Atomic Number. The number of protons in the nucleus of each chemical element.

Backscatter. The deflection of radiation by scattering processes through angles greater than 90 degrees, with respect to the original direction of motion.

Barn. A unit of area used in expressing a nuclear cross-section. 1 barn = 10^{-24} cm². Cross-sections per atom are customarily measured in barns.

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 beta particles. Physically, the beta particle is identical with an electron moving at high velocity.

Bias (B). The average of the performance quotients, P_i for n dosimeters, for a specified irradiation category and depth,

Calibration Specific to Work Environment. The dosimeter calibration applicable only to a particular occupational work environment. These calibrations are determined by comparing reference instrument measurements to dosimeter response measurements. Both measurements are performed in the workplace.

Capture. A process in which a neutron becomes part of the nucleus with which it collides without release of another heavy particle.

(a) This section was adopted and expanded from the National Research Council report on "Film Badge Dosimetry in Atmospheric Nuclear Tests," (1989).

Cross Section. Effective target area for specified nuclear interaction. The cross-section is a measure of the probability for the interaction. It is expressed in barns.

Density Thickness (mg/cm^2). Product of the density (g/cm^3) times the thickness (cm) of a material. Term is used in radiation dosimetry to describe penetration of radiation in various materials.

Detection Threshold. The minimum evaluated dose equivalent for which the readout value of a dosimeter is significantly different (at the 95% confidence level) from the mean readout value of unirradiated dosimeters.

Dose. As used in the general sense, dose denotes absorption of a quantity of ionizing radiation. See Absorbed Dose, Dose Equivalent.

Dose Equivalent (H). A quantity used in radiation protection to normalize the biological effectiveness of the absorption of different radiations. It is defined as the product of the absorbed dose (D), the quality factor (Q), and any other modifying factors. The unit of dose equivalent prior to the SI is the rem. The SI unit is the Sievert (Sv). When D is expressed in Gy, H is in Sieverts (Sv). $1 \text{ Sv} = 100 \text{ rem}$.

Dosimeter. An instrument for measuring and registering the total accumulated dose of ionizing radiations. A dosimeter consists of a combination of absorber(s) and radiation-sensitive element(s) that is used to provide a cumulative record of absorbed dose or dose equivalent received when worn by an individual.

Deep Dose Equivalent. Dose equivalent from penetrating radiation to soft tissue located at a depth of 10 mm in the body. Symbolized as $H_p(10)$. See also Absorbed Dose and Dose Equivalent.

Dose Conversion Factors. The numerical quantity that relates dosimeter response characteristics or exposure in air to the dose equivalent at a specified depth in a material of specified geometry and composition.

Electron. A subatomic particle of very small mass, carrying a unit charge. Electrons, surrounding the nucleus, are present in all uncharged atoms; their number is equal to the number of protons in the nucleus.

Estimates of Uncertainty. The estimated uncertainty of the dose or dose equivalent. The value of the uncertainty is dependent upon the number of sources of error included in the analysis.

Fast Neutron. Neutron of energy between 10 keV and 10 MeV.

Film Dosimeter. A type of dosimeter in which a dental-sized packet of photographic film is used to measure radiation. Often the dosimeter contains films of differing sensitivities and filters, located in the film dosimeter holder, to shield parts of the film.

First-Collision Dose. The "first-collision dose" can be determined for either photons or neutrons. For neutron radiation, perhaps the simplest calculation that can be made is one relating dose to flux through a thin layer of tissue. The resulting graph, sometimes referred to as the first-collision curve, is derived from

the assumption that the probability of two or more interactions per neutron is negligible. Because of the short range of the charged secondary radiation from fast neutrons, the first collision dose in irradiated material is practically the same as the absorbed dose.

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. Often referred to as "bare" source exposure.

Gamma (γ) 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 with x-rays of high energy, the only essential difference being that x-rays do not originate in the nucleus.

Gray. The SI unit of absorbed dose, abbreviated Gy. $1 \text{ Gy} = 1 \text{ joule/kilogram} = 100 \text{ rad}$.

Ionization. The separation of a normally electrically neutral atom or molecule into electrically charged components.

Ionizing Radiation. Refers to electromagnetic radiation (consisting of photons) or particulate radiation (consisting of electrons, neutrons, protons, etc.) usually of high energy, but in any case capable of ionizing air, directly or indirectly.

Intermediate Energy Neutron. Neutron of energy between 0.5 eV and 10 keV.

Isotopes. Forms of the same element having identical chemical properties but differing in their atomic masses. Isotopes of a given element all have the same number of protons in the nucleus but different numbers of neutrons. Some isotopes of an element may be radioactive.

Kilo-Electron Volt (or keV). An amount of energy equal to 1,000 electron volts.

Linear Energy Transfer (LET). Radiation transferring matter loses energy at a rate which depends upon both the nature of the radiation and its energy. The lineal rate of local energy absorption is known as the "linear energy transfer" (LET).

Neutron Capture. Radioactivity produced in certain materials as a result of the capture of neutrons.

Mega-Electron Volt (or MeV). An amount of energy equal to 1,000,000 electron volts.

Minimum Detectable Level (MDL). The minimum dose that can be distinguished from zero.

Neutron. A neutral particle (i.e., with no electrical charge) of approximately unit atomic mass, present in all atomic nuclei, with the notable exception of the common isotope of hydrogen with an atomic mass of 1 (i.e., contains only a single proton).

Nucleus (or Atomic Nucleus). The small, central, positively charged region of an atom which carries essentially all of the mass. Except for the isotope of hydrogen with an atomic mass of 1 (i.e., a single proton), all atomic nuclei contain both protons and neutrons.

Personnel Monitoring. The practice of assigning dosimeters to personnel for the purpose of measuring occupational radiation dose.

Photon. A unit or "particle" of electromagnetic radiation, carrying a specific quantum (particular level) of energy.

Proton. A particle of approximately unit atomic mass, present in all atomic nuclei, with the notable exception of the common isotope of hydrogen with an atomic mass of 1 (i.e., contains only a single proton).

Quality Factor. The factor by which absorbed dose is multiplied to obtain (for radiation protection purposes) a quantity that expresses, on a common scale for all ionizing radiations, the biological effectiveness of absorbed dose. Historically, the quality factor replaced the earlier use of the relative biological effectiveness factor (see Relative Biological Effectiveness).

Rad. An unit of absorbed dose of radiation. One rad represents the absorption of 100 ergs per gram of absorbing material, such as body tissue. The unit has been replaced by the SI unit of gray (see Gray).

Relative Biological Effectiveness (RBE). This concept is used to refer to scientific measurements of the RBE for a specified experimental study or, historically, to the product of the dose in rads and an agreed conventional value of the RBE with respect to a particular form of radiation effect. The historical standard of comparison is x- or gamma-radiation.

RBE Dose. Historically, the product of absorbed dose (as measured in rad) and RBE. The RBE Dose is measured in rem. This unit was replaced with the Dose Equivalent.

Rep. Historically the rep (roentgen-equivalent-physical) has been used extensively for the specification of permissible doses of ionizing radiations other than 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/g.

Rem. The rem is a unit of dose equivalent which is equal to the product of the number of rads absorbed and the "quality factor" (see Dose Equivalent).

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

Scattering. Refers to either elastic, in which kinetic energy of neutron plus nucleus is unchanged by the collision, or inelastic, in which kinetic energy is lost to target nucleus, and subsequent release of secondary radiation.

Shallow Dose Equivalent. Dose equivalent from penetrating radiation to soft tissue located at a depth of 0.7 mm in the body. Symbolized as $H_s(0.7)$. See also Absorbed Dose and Dose Equivalent.

Slow Neutron. See definition for thermal neutron.

Thermal Neutron. Strictly, neutrons in thermal equilibrium with surroundings. Generally, refers to neutrons of energy less-than 0.5 eV.

Tissue Equivalent. This term is used to imply that the radiation response characteristics of the material being irradiated are equivalent to tissue. Achieving a tissue equivalent response is typically an important consideration in the design and fabrication of radiation-measuring instruments and dosimeters.

Tissue Equivalent Proportional Counter (TEPC). This device is used to measure the absorbed dose from neutron radiation in near tissue-equivalent materials and, through analysis of the counter data, determination of the effective quality factor and the dose equivalent.

Appendix A

Hanford Nuclear Track Emulsion Calibration Data

Table A.1.

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
1	03/10/50	3	239	79.67	9.87	5	1.67	0.58	107PoB	0.17E+08	605.50	7.60
2	03/18/50	3	215	71.67	1.15	3	1.00	0.00	107PoB	0.17E+08	584.50	8.16
3	03/24/50	3	133	66.50	3.54	4	1.33	0.58	107PoB	0.16E+08	563.50	8.47
4	04/01/50	2	135	67.50	2.12	3	1.50	0.71	107PoB	0.16E+08	546.00	8.09
5	04/09/50	3	186	62.00	2.00	1	0.33	0.58	107PoB	0.15E+08	525.00	8.47
6	04/16/50	3	337	112.33	4.04	0	0.00	0.00	106PoB	0.22E+08	770.00	6.85
7	04/23/50	3	186	62.00	3.46	0	0.00	0.00	107PoB	0.14E+08	490.00	7.90
8	04/30/50	2	113	56.50	2.12	0	0.00	0.00	107PoB	0.14E+08	476.00	8.42
9	05/07/50	3	157	52.33	1.15	0	0.00	0.00	107PoB	0.13E+08	462.00	8.83
10	05/14/50	2	93	46.50	4.95	0	0.00	0.00	107PoB	0.13E+08	444.50	9.56
11	05/21/50	4	206	51.50	5.45	0	0.00	0.00	107PoB	0.12E+08	430.50	8.36
12	05/28/50	2	90	45.00	8.49	0	0.00	0.00	107PoB	0.12E+08	413.00	9.18
13	06/04/50	3	142	47.33	1.53	0	0.00	0.00	107PoB	0.11E+08	399.00	8.43
14	06/11/50	3	140	46.67	1.53	0	0.00	0.00	107PoB	0.11E+08	385.00	8.25
15	06/25/50	2	84	42.00	1.41	0	0.00	0.00	107PoB	0.10E+08	357.00	8.50
16	07/02/50	5	218	43.60	2.07	0	0.00	0.00	107PoB	0.99E+07	346.50	7.95
17	07/09/50	5	209	41.80	1.92	0	0.00	0.00	107PoB	0.96E+07	336.00	8.04
18	07/16/50	4	295	73.75	3.50	0	0.00	0.00	106PoB	0.13E+08	444.50	6.03
19	07/23/50	5	353	70.60	2.97	0	0.00	0.00	106PoB	0.12E+08	430.50	6.10
20	07/30/50	5	205	41.00	2.92	0	0.00	0.00	107PoB	0.87E+07	302.75	7.38
21	08/06/50	5	326	65.20	4.09	0	0.00	0.00	106PoB	0.11E+08	395.50	6.07
22	08/13/50	5	177	35.40	2.79	10	2.00	0.71	107PoB	0.81E+07	281.75	7.96
23	08/20/50	4	258	64.50	1.73	8	2.00	0.00	106PoB	0.10E+08	364.00	5.64
24	08/27/50	4	157	39.25	7.93	8	2.00	0.82	107PoB	0.75E+07	262.50	6.69
25	09/03/50	5	175	35.00	3.67	12	2.40	0.55	107PoB	0.73E+07	253.75	7.25
26	09/10/50	5	163	32.60	3.13	0	0.00	0.00	107PoB	0.70E+07	245.00	7.52
27	09/17/50	5	283	56.60	3.05	10	2.00	0.71	106PoB	0.94E+07	327.25	5.78
28	09/24/50	6	209	34.83	3.43	13	2.17	0.98	107PoB	0.66E+07	229.25	6.58
29	10/01/50	6	320	53.33	2.07	15	2.50	0.84	107PoB	0.88E+07	306.25	5.74
30	10/08/50	5	151	30.20	4.15	13	2.60	0.55	107PoB	0.61E+07	213.50	7.07
31	10/15/50	5	247	49.40	4.04	10	2.00	0.00	107PoB	0.80E+07	281.40	5.70
32	10/22/50	6	171	28.50	3.21	14	2.33	1.51	107PoB	0.57E+07	199.50	7.00
33	10/29/50	6	265	44.17	1.60	14	2.33	0.52	106PoB	0.74E+07	260.05	5.89

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Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
34	11/05/50	6	140	23.33	1.97	13	2.17	0.41	107PoB	0.53E+07	185.50	7.95
35	11/12/50	6	280	46.67	2.58	0	0.00	0.00	106PoB	0.70E+07	246.05	5.27
36	11/19/50	6	144	24.00	2.83	14	2.33	0.52	107PoB	0.50E+07	173.25	7.22
37	11/26/50	6	231	38.50	2.26	19	3.17	0.75	106PoB	0.65E+07	228.55	5.94
38	12/03/50	3	41	20.50	3.54	4	2.00	0.00	107PoB	0.46E+07	162.05	7.90
39	12/10/50	5	172	34.40	1.52	12	2.40	0.89	106PoB	0.60E+07	210.70	6.13
40	12/17/50	2	42	21.00	2.83	7	3.50	0.71	107PoB	0.43E+07	151.20	7.20
41	12/25/51	4	112	28.00	1.83	12	3.00	0.82	107PoB	0.55E+07	193.90	6.93
42	12/31/50	3	48	24.00	1.44	7	3.50	0.71	107PoB	0.52E+07	180.60	7.53
43	01/07/51	4	73	18.25	0.96	13	3.25	0.50	107PoB	0.39E+07	136.50	7.48
44	01/14/51	2	36	18.00	1.41	6	3.00	0.00	107PoB	0.38E+07	131.25	7.29
45	01/21/51	5	91	18.20	1.10	17	3.40	1.67	107PoB	0.37E+07	127.75	7.02
46	01/28/51	2	60	30.00	0.00	4	2.00	0.00	106PoB	0.48E+07	166.95	5.57
47	02/11/51	1	17	17.00	0.00	2	2.00	0.00	107PoB	0.33E+07	114.45	6.73
48	02/26/51	5	965	193.00	9.62	10	2.00	0.71	182PoB	0.52E+08	1802.50	9.34
49	03/01/51	6	1076	179.33	3.27	6	1.00	0.00	182PoB	0.51E+08	1771.00	9.88
50	03/08/51	6	1119	186.50	10.60	6	1.00	0.00	182PoB	0.48E+08	1690.50	9.06
51	03/15/51	6	1079	179.83	8.33	7	1.17	0.41	182PoB	0.47E+08	1645.00	9.15
52	03/22/51	6	974	162.33	7.28	6	1.00	0.63	182PoB	0.46E+08	1592.50	9.81
53	03/29/51	6	962	160.33	7.89	9	1.50	0.55	182PoB	0.44E+08	1540.00	9.60
54	04/05/51	6	959	159.83	5.34	7	1.17	0.41	182PoB	0.43E+08	1487.50	9.31
55	04/12/51	6	918	153.00	5.62	5	0.83	0.75	182PoB	0.41E+08	1435.00	9.38
56	04/19/51	6	956	159.33	2.94	10	1.67	0.82	182PoB	0.40E+08	1382.50	8.68
57	04/26/51	6	851	141.83	7.99	10	1.67	0.82	182PoB	0.38E+08	1330.00	9.38
58	05/03/51	6	836	139.33	5.68	6	1.00	0.00	182PoB	0.37E+08	1295.00	9.29
59	05/10/51	6	784	130.67	5.57	5	0.83	0.41	182PoB	0.36E+08	1260.00	9.64
60	05/19/51	0	0	0.00	0.00	0	0.00	0.00	Failure	0.00E+00	0.00	9.21
61	05/24/51	6	801	133.50	9.61	8	1.33	0.52	182PoB	0.34E+08	1172.50	8.78
62	05/31/51	6	760	126.67	3.14	8	1.33	0.82	182PoB	0.33E+08	1137.50	8.98
63	06/07/51	6	604	120.80	4.49	8	1.33	0.52	182PoB	0.32E+08	1102.50	9.13
64	06/14/51	6	728	121.33	4.41	15	2.50	0.55	182PoB	0.31E+08	1067.50	8.80
65	06/21/51	6	720	120.00	6.20	8	1.33	1.03	182PoB	0.30E+08	1032.50	8.60
66	06/28/51	6	545	90.83	8.04	5	0.83	0.75	182PoB	0.28E+08	983.50	10.83
67	07/05/51	5	536	107.20	4.87	6	1.20	0.84	182PoB	0.27E+08	952.00	8.88
68	07/12/51	6	600	100.00	4.65	8	1.33	0.52	182PoB	0.26E+08	917.00	9.17
69	07/19/51	6	557	92.83	2.86	10	1.67	0.52	182PoB	0.26E+08	892.50	9.61
70	07/26/51	6	568	94.67	3.08	12	2.00	0.63	182PoB	0.25E+08	857.50	9.06

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
71	08/02/51	5	419	83.80	3.96	9	1.80	0.45	182PoB	0.24E+08	833.00	9.94
72	08/09/51	6	527	87.83	6.88	10	1.67	0.52	182PoB	0.23E+08	805.00	9.17
73	08/16/51	6	536	89.33	5.92	9	1.50	0.55	182PoB	0.22E+08	770.00	8.62
74	08/23/51	5	406	81.20	3.90	11	2.20	0.45	182PoB	0.22E+08	752.50	9.27
75	08/30/51	6	481	80.17	5.53	14	2.33	1.03	182PoB	0.21E+08	721.00	8.99
76	09/06/51	6	465	77.50	5.21	14	2.33	0.52	182PoB	0.20E+08	700.00	9.03
77	09/13/51	6	426	71.00	3.16	11	1.83	0.41	182PoB	0.19E+08	675.50	9.51
78	09/20/51	6	393	65.50	4.37	7	1.17	0.41	182PoB	0.19E+08	654.50	9.99
79	09/27/51	6	424	70.67	3.50	12	2.00	0.00	182PoB	0.18E+08	630.00	8.92
80	10/04/51	6	380	63.33	3.67	8	1.33	0.52	182PoB	0.17E+08	609.00	9.62
81	10/11/51	6	403	67.17	4.75	8	1.33	0.52	182PoB	0.17E+08	588.00	8.75
82	10/18/51	5	290	58.00	3.16	6	1.20	0.45	182PoB	0.16E+08	567.00	9.78
83	10/25/51	5	603	120.60	4.16	8	1.60	0.55	182PoB	0.31E+08	1067.50	8.85
84	11/01/51	5	537	107.40	1.95	7	1.40	0.55	182PoB	0.40E+08	1393.00	12.97
85	11/07/51	5	515	103.00	3.94	12	2.40	0.89	182PoB	0.29E+08	997.50	9.68
86	11/14/51	6	627	104.50	7.48	11	1.83	0.98	182PoB	0.28E+08	976.50	9.34
87	11/21/51	6	572	95.33	2.88	15	2.50	1.38	182PoB	0.27E+08	938.00	9.84
88	11/28/51	6	538	89.67	9.97	14	2.33	0.52	182PoB	0.26E+08	906.50	10.11
89	12/06/51	6	503	83.83	2.71	9	1.50	0.84	182PoB	0.25E+08	875.00	10.44
90	12/12/51	5	404	80.80	2.95	11	2.20	0.45	182PoB	0.24E+08	840.00	10.40
91	12/19/51	5	405	81.00	5.66	11	2.20	0.84	182PoB	0.23E+08	805.00	9.94
92	12/27/51	6	477	79.50	4.68	11	1.83	0.75	182PoB	0.23E+08	787.50	9.91
93	01/02/52	6	445	74.17	3.76	9	1.50	0.55	182PoB	0.22E+08	752.50	10.15
94	01/09/52	6	456	76.00	6.84	10	1.67	0.52	182PoB	0.21E+08	735.00	9.67
95	01/16/52	5	376	75.20	3.27	11	2.20	0.84	182PoB	0.20E+08	700.00	9.31
96	01/23/52	6	383	63.83	5.15	9	1.50	0.55	182PoB	0.19E+08	665.00	10.42
97	01/30/52	6	383	63.83	2.64	10	1.67	0.52	182PoB	0.19E+08	658.00	10.31
98	02/06/52	5	337	67.40	2.70	7	1.40	0.55	182PoB	0.18E+08	633.50	9.40
99	02/13/52	6	343	57.17	4.58	12	2.00	1.10	182PoB	0.18E+08	612.50	10.71
100	02/20/52	6	343	57.17	2.64	13	2.17	0.75	182PoB	0.17E+08	595.00	10.41
101	02/29/52	5	497	99.40	4.72	9	1.80	0.84	182PoB	0.33E+08	1158.50	11.65
102	03/06/52	6	600	100.00	1.67	13	2.17	0.75	182PoB	0.32E+08	1120.00	11.20
103	03/13/52	6	561	93.50	5.68	11	1.83	0.41	182PoB	0.30E+08	1050.00	11.23
104	03/20/52	6	611	101.83	7.19	12	2.00	0.63	182PoB	0.31E+08	1085.00	10.65
105	03/27/52	6	581	96.83	3.60	12	2.00	0.63	182PoB	0.29E+08	1015.00	10.48
106	04/03/52	6	519	86.50	3.99	13	2.17	0.41	182PoB	0.28E+08	980.00	11.33
107	04/10/52	5	395	79.00	2.00	6	1.20	0.45	182PoB	0.27E+08	945.00	11.96

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
108	04/18/52	6	472	78.67	2.50	9	1.50	0.55	182PoB	0.26E+08	910.00	11.57
109	04/24/52	6	519	86.50	4.37	15	2.50	0.55	182PoB	0.25E+08	875.00	10.12
110	05/01/52	4	305	76.25	2.22	9	2.25	0.50	182PoB	0.24E+08	840.00	11.02
111	05/08/52	5	382	76.40	5.18	13	2.60	0.55	182PoB	0.23E+08	805.00	10.54
112	05/15/52	6	436	72.67	2.16	10	1.67	1.21	182PoB	0.23E+08	787.50	10.84
113	05/22/52	5	334	66.80	2.77	13	2.60	0.55	182PoB	0.22E+08	770.00	11.53
114	05/29/52	6	381	63.50	3.27	10	1.67	0.52	182PoB	0.21E+08	735.00	11.57
115	06/05/52	6	424	70.67	5.85	8	1.33	0.82	182PoB	0.21E+08	717.50	10.15
116	06/12/52	6	354	59.00	5.69	13	2.17	0.75	182PoB	0.20E+08	682.50	11.57
117	06/20/52	5	308	61.60	3.05	7	1.40	0.55	182PoB	0.19E+08	665.00	10.80
118	06/26/52	6	357	59.50	2.74	12	2.00	0.63	182PoB	0.19E+08	647.50	10.88
119	07/03/52	4	234	58.50	3.00	6	1.50	1.00	182PoB	0.18E+08	630.00	10.77
120	07/10/52	6	327	54.50	9.79	4	0.67	0.52	182PoB	0.17E+08	595.00	10.92
121	07/17/52	6	211	35.17	4.83	2	0.33	0.52	182PoB	0.17E+08	577.50	16.42
122	07/24/52	6	219	36.50	4.37	3	0.50	0.55	182PoB	0.16E+08	560.00	15.34
123	07/31/52	6	234	39.00	2.19	3	0.50	0.55	182PoB	0.16E+08	542.50	13.91
124	08/07/52	6	479	79.83	4.02	3	0.50	0.55	182PoB	0.30E+08	1050.00	13.15
125	08/14/52	6	472	78.67	8.55	18	3.00	0.63	182PoB	0.29E+08	1015.00	12.90
126	08/21/52	6	536	89.33	2.58	11	1.83	0.75	182PoB	0.28E+08	980.00	10.97
127	08/28/52	6	525	87.50	2.81	11	1.83	0.75	182PoB	0.28E+08	980.00	11.20
128	09/04/52	5	410	82.00	6.67	11	2.20	0.45	183PoB	0.26E+08	910.00	11.10
129	09/11/52	6	396	66.00	4.69	9	1.50	1.05	182PoB	0.25E+08	875.00	13.26
130	09/18/52	6	409	68.17	3.43	0	0.00	0.00	182PoB	0.25E+08	857.00	12.58
131	09/25/52	6	371	61.83	4.07	3	0.50	0.55	182PoB	0.24E+08	822.50	13.30
132	10/02/52	6	280	56.00	2.45	1	0.17	0.41	182PoB	0.23E+08	805.00	14.38
133	10/09/52	6	332	55.33	5.28	5	0.83	0.41	182PoB	0.22E+08	770.00	13.92
134	10/16/52	6	338	56.33	3.50	5	0.83	0.41	182PoB	0.21E+08	735.00	13.05
135	10/23/52	5	290	58.00	3.32	5	1.00	0.71	182PoB	0.21E+08	717.50	12.37
136	10/30/52	5	280	56.00	3.54	3	0.60	0.55	182PoB	0.20E+08	682.50	12.19
137	11/03/52	7	585	83.57	8.34	2	0.29	0.49	182PoB	0.37E+08	1295.00	15.50
138	11/13/52	6	496	82.67	8.43	4	0.67	0.52	182PoB	0.36E+08	1260.00	15.24
139	11/19/52	6	500	83.33	8.04	2	0.33	0.52	182PoB	0.30E+08	1050.00	12.60
140	11/28/52	6	444	74.00	8.17	3	0.50	0.55	182PoB	0.34E+08	1172.50	15.84
141	12/05/52	6	504	84.00	14.72	1	0.17	0.41	182PoB	0.33E+08	1137.50	13.54
142	12/11/52	6	448	74.67	7.00	1	0.17	0.41	182PoB	0.31E+08	1085.00	14.53
143	12/18/52	6	405	67.50	4.18	2	0.33	0.52	182PoB	0.31E+08	1067.50	15.81
144	12/29/52	7	714	102.00	5.94	7	1.00	0.00	180PoB	0.40E+08	1414.00	13.86

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
145	01/02/53	6	395	65.83	3.92	1	0.17	0.41	182PoB	0.28E+08	980.00	14.89
146	01/08/53	6	427	71.17	5.91	6	1.00	0.00	182PoB	0.28E+08	962.50	13.52
147	01/15/53	6	455	75.83	5.34	7	1.17	0.41	182PoB	0.27E+08	927.50	12.23
148	01/22/53	7	546	78.00	22.95	4	0.57	0.53	182PoB	0.26E+08	892.50	11.44
149	01/29/53	7	473	67.57	6.85	3	0.43	0.53	182PoB	0.25E+08	875.00	12.95
150	02/05/53	6	453	75.50	8.14	5	0.83	0.75	182PoB	0.24E+08	840.00	11.13
151	02/12/53	6	393	65.50	9.57	5	0.83	0.41	182PoB	0.23E+08	805.00	12.29
152	02/19/53	8	515	64.38	5.93	7	0.88	0.64	182PoB	0.23E+08	787.50	12.23
153	02/26/53	5	353	70.60	2.51	4	0.80	0.45	182PoB	0.22E+08	752.50	10.66
154	03/05/53	7	484	69.14	4.06	3	0.43	0.53	182PoB	0.21E+08	717.50	10.38
155	03/12/53	7	455	65.00	2.24	4	0.57	0.53	182PoB	0.20E+08	700.00	10.77
156	03/17/53	7	443	63.29	4.19	6	0.86	0.69	182PoB	0.20E+08	682.50	10.78
157	03/25/53	7	1233	176.14	4.18	7	1.00	1.00	304PoB	0.51E+08	1785.00	10.13
158	04/01/53	7	1130	161.43	7.96	4	0.57	0.79	304PoB	0.50E+08	1750.00	10.84
159	04/08/53	7	1146	163.71	4.27	3	0.43	0.53	304PoB	0.48E+08	1680.00	10.26
160	04/15/53	7	1028	146.86	14.30	7	1.00	0.58	304PoB	0.47E+08	1627.50	11.08
161	04/22/53	7	1073	153.29	4.39	4	0.57	0.53	304PoB	0.45E+08	1575.00	10.27
162	04/29/53	8	1117	139.63	8.68	8	1.00	0.00	304PoB	0.44E+08	1522.50	10.90
163	05/06/53	8	989	123.63	9.01	10	1.25	0.71	304PoB	0.42E+08	1470.00	11.89
164	05/13/53	7	921	131.57	8.04	6	0.86	0.38	304PoB	0.41E+08	1435.00	10.91
165	05/20/53	7	921	131.57	7.07	7	1.00	0.00	304PoB	0.39E+08	1365.00	10.37
166	05/28/53	8	895	111.88	9.36	5	0.63	0.74	304PoB	0.38E+08	1330.00	11.89
167	06/03/53	7	784	112.00	5.92	4	0.57	0.53	304PoB	0.37E+08	1295.00	11.56
168	06/11/53	8	949	118.63	5.29	5	0.63	0.74	304PoB	0.36E+08	1242.50	10.47
169	06/17/53	8	863	107.88	5.03	2	0.25	0.46	304PoB	0.35E+08	1207.50	11.19
170	06/25/53	8	932	116.50	6.78	3	0.38	0.52	304PoB	0.33E+08	1155.00	9.91
171	06/30/53	8	812	101.50	7.86	6	0.75	0.71	304PoB	0.32E+08	1120.00	11.03
172	07/08/53	8	891	111.38	6.65	4	0.50	0.53	304PoB	0.31E+08	1085.00	9.74
173	07/15/53	8	828	103.50	6.99	5	0.63	0.52	304PoB	0.30E+08	1050.00	10.14
174	07/21/53	8	742	92.75	4.03	2	0.25	0.71	304PoB	0.29E+08	1015.00	10.94
175	07/31/53	8	788	98.50	5.42	4	0.50	0.76	304PoB	0.28E+08	962.50	9.77
176	08/06/53	8	764	95.50	9.06	6	0.75	0.46	304PoB	0.26E+08	910.00	9.53
178	08/13/53	8	960	120.00	11.35	8	1.00	0.93	304PoB	0.39E+08	1347.50	11.23
180	08/20/53	8	752	94.00	5.35	5	0.63	0.52	304PoB	0.25E+08	857.50	9.12
181	08/24/53	7	625	89.29	4.23	1	0.14	0.38	304PoB	0.24E+08	840.00	9.41
182	09/04/53	8	731	91.38	3.34	12	1.50	1.20	304PoB	0.23E+08	805.00	8.81
183	09/10/53	8	612	76.50	4.04	3	0.38	0.52	304PoB	0.22E+08	770.00	10.07

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
189	09/16/53	8	670	83.75	4.59	7	0.88	0.35	304PoB	0.21E+08	735.00	8.78
190	09/23/53	7	512	73.14	4.38	3	0.43	0.53	304PoB	0.21E+08	735.00	10.05
191	10/01/53	7	1038	148.29	4.61	3	0.43	0.53	304PoB	0.42E+08	1470.00	9.91
192	10/08/53	8	1041	130.13	5.22	8	1.00	0.93	304PoB	0.41E+08	1435.00	11.03
195	10/15/53	8	1096	137.00	7.09	6	0.75	0.46	304PoB	0.39E+08	1347.50	9.84
196	10/20/53	8	1004	125.50	5.68	6	0.75	0.71	304PoB	0.39E+08	1347.50	10.74
197	10/28/53	8	968	121.00	7.15	6	0.75	0.46	304PoB	0.37E+08	1295.00	10.70
198	11/05/53	8	919	114.88	3.87	8	1.00	0.76	304PoB	0.36E+08	1260.00	10.97
199	11/12/53	8	921	115.13	5.36	5	0.63	0.52	304PoB	0.35E+08	1207.50	10.49
200	11/19/53	8	882	110.25	5.28	4	0.50	0.53	304PoB	0.34E+08	1172.50	10.63
201	11/25/53	8	923	115.38	5.40	10	1.25	0.46	304PoB	0.32E+08	1120.00	9.71
202	12/02/53	8	889	111.13	7.26	9	1.13	0.35	304PoB	0.31E+08	1085.00	9.76
203	12/09/53	8	823	102.88	5.82	7	0.88	0.64	304PoB	0.30E+08	1050.00	10.21
204	12/16/53	8	777	97.13	5.44	7	0.88	0.35	304PoB	0.29E+08	1015.00	10.45
205	12/21/53	8	853	106.63	4.75	7	0.88	0.64	304PoB	0.28E+08	980.00	9.19
206	12/29/53	8	767	95.88	3.09	9	1.13	0.35	304PoB	0.27E+08	945.00	9.86
207	01/06/54	8	767	95.88	3.72	8	1.00	0.53	304PoB	0.26E+08	910.00	9.49
208	01/14/54	8	723	90.38	4.90	6	0.75	0.46	304PoB	0.25E+08	875.00	9.68
209	01/21/54	8	628	78.50	2.62	7	0.88	0.64	304PoB	0.24E+08	840.00	10.70
210	01/27/54	8	660	82.50	5.55	8	1.00	0.53	304PoB	0.24E+08	840.00	10.18
211	02/03/54	9	1523	169.22	4.44	8	0.89	0.33	304PoB	0.56E+08	1960.00	11.58
212	02/10/54	9	1527	169.67	7.76	10	1.11	0.60	304PoB	0.55E+08	1907.50	11.24
213	02/18/54	8	1371	171.38	6.50	9	1.13	0.35	304PoB	0.52E+08	1820.00	10.62
214	02/25/54	9	1529	169.89	8.72	14	1.56	0.53	304PoB	0.51E+08	1785.00	10.51
215	03/05/54	9	1512	168.00	8.40	13	1.44	0.73	304PoB	0.49E+08	1715.00	10.21
216	03/11/54	7	1201	171.57	9.69	8	1.14	0.38	304PoB	0.48E+08	1662.50	9.69
217	03/18/54	8	1244	155.50	4.99	11	1.38	0.74	304PoB	0.46E+08	1592.50	10.24
218	04/01/54	9	1217	135.22	5.17	9	1.00	0.50	304PoB	0.44E+08	1540.00	11.39
219	04/06/54	8	1274	159.25	2.71	12	1.50	0.53	304PoB	0.43E+08	1487.50	9.34
220	04/08/54	9	1177	130.78	4.76	8	0.89	0.60	304PoB	0.41E+08	1435.00	10.97
221	04/15/54	10	1061	106.10	4.75	9	0.90	0.74	304PoB	0.40E+08	1400.00	13.20
222	04/22/54	10	1110	111.00	3.68	4	0.40	0.52	304PoB	0.38E+08	1330.00	11.98
223	04/29/54	10	1197	119.70	5.76	20	2.00	0.47	304PoB	0.37E+08	1295.00	10.82
224	05/10/54	10	779	77.90	5.70	5	0.50	0.53	304PoB	0.36E+08	1260.00	16.17
225	05/17/54	9	1004	111.56	6.00	16	1.78	0.83	304PoB	0.35E+08	1225.00	10.98
226	05/24/54	10	756	75.60	11.98	5	0.50	0.53	304PoB	0.34E+08	1190.00	15.74
227	06/01/54	10	695	69.50	8.17	5	0.50	0.53	304PoB	0.32E+08	1120.00	16.12

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
228	07/14/54	9	850	94.44	4.77	17	1.89	0.78	304PoB	0.31E+08	1085.00	11.49
229	06/10/54	10	984	98.40	4.72	16	1.60	0.52	304PoB	0.30E+08	1050.00	10.67
230	06/17/54	10	551	55.10	4.91	8	0.80	1.03	304PoB	0.29E+08	1015.00	18.42
231	06/28/54	10	773	77.30	2.71	11	1.10	0.57	304PoB	0.28E+08	980.00	12.68
232	07/01/54	11	807	73.36	7.55	15	1.36	0.67	304PoB	0.27E+08	945.00	12.88
233	07/07/54	10	722	72.20	3.43	12	1.20	0.42	304PoB	0.26E+08	910.00	12.60
234	07/19/54	11	941	85.55	10.11	17	1.55	0.52	304PoB	0.25E+08	875.00	10.23
235	07/26/54	11	1285	116.82	13.86	25	2.27	1.27	304PoB	0.35E+08	1225.00	10.49
236	07/29/54	11	1264	114.91	3.53	19	1.73	0.65	304PoB	0.34E+08	1172.50	10.20
237	08/04/54	11	1257	114.27	5.44	20	1.82	0.98	304PoB	0.33E+08	1137.50	9.95
238	08/11/54	11	1302	118.36	2.11	14	1.27	0.47	304PoB	0.31E+08	1085.00	9.17
239	08/18/54	10	1181	118.10	4.28	12	1.20	1.14	304PoB	0.30E+08	1050.00	8.89
240	08/25/54	9	932	103.56	4.56	10	1.11	0.60	304PoB	0.29E+08	1015.00	9.80
241	09/01/54	10	1047	104.70	5.77	15	1.50	0.53	304PoB	0.28E+08	980.00	9.36
242	09/08/54	10	1017	101.70	6.95	17	1.70	0.48	304PoB	0.27E+08	945.00	9.29
243	09/15/54	10	1015	101.50	3.72	17	1.70	0.82	304PoB	0.26E+08	910.00	8.97
244	09/22/54	10	998	99.80	3.05	18	1.80	0.63	304PoB	0.25E+08	875.00	8.77
245	10/01/54	9	801	89.00	4.56	19	2.11	0.33	304PoB	0.22E+08	780.50	8.77
246	10/08/54	8	698	87.25	4.65	16	2.00	0.76	304PoB	0.22E+08	777.00	8.91
247	10/15/54	10	849	84.90	5.86	23	2.30	0.82	304PoB	0.22E+08	777.00	9.15
248	10/20/54	10	810	81.00	3.46	20	2.00	1.05	304PoB	0.22E+08	777.00	9.59
249	10/27/54	10	751	75.10	5.55	21	2.10	0.74	304PoB	0.22E+08	773.50	10.30
250	11/02/54	10	745	74.50	2.80	18	1.80	0.79	304PoB	0.21E+08	717.50	9.63
251	11/10/54	9	918	102.00	4.06	15	1.67	0.50	304PoB	0.30E+08	1050.00	10.29
252	11/18/54	10	992	99.20	2.97	24	2.40	0.52	304PoB	0.29E+08	1015.00	10.23
253	11/24/54	10	1016	101.60	4.60	15	1.50	0.53	304PoB	0.28E+08	980.00	9.65
254	12/01/54	9	846	94.00	3.81	15	1.67	0.71	304PoB	0.27E+08	945.00	10.05
255	12/10/54	11	1012	92.00	3.95	21	1.91	0.54	304PoB	0.26E+08	910.00	9.89
256	12/16/54	10	896	89.60	3.41	21	2.10	0.74	304PoB	0.25E+08	882.00	9.84
257	12/22/54	10	875	87.50	2.32	15	1.50	0.71	304PoB	0.25E+08	857.50	9.80
258	12/30/54	11	937	85.18	4.40	16	1.45	0.52	304PoB	0.24E+08	822.50	9.66
259	01/06/55	9	744	82.67	3.08	18	2.00	0.71	304PoB	0.23E+08	805.00	9.74
260	01/12/55	10	827	82.70	4.69	22	2.20	0.42	304PoB	0.22E+08	770.00	9.31
261	01/20/55	10	766	76.60	4.12	21	2.10	0.74	304PoB	0.22E+08	752.50	9.82
262	01/27/55	10	809	80.90	5.38	25	2.50	0.71	304PoB	0.21E+08	717.50	8.87
263	02/03/55	9	669	74.33	3.91	19	2.11	0.33	304PoB	0.20E+08	700.00	9.42
264	02/10/55	8	590	73.75	4.03	23	2.88	0.83	304PoB	0.19E+08	665.00	9.02

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
265	02/16/55	9	634	70.44	1.59	17	1.89	0.78	304PoB	0.19E+08	647.50	9.19
266	02/24/55	9	584	64.89	3.26	15	1.67	0.50	304PoB	0.17E+08	595.00	9.17
267	03/04/55	9	584	64.89	3.26	16	1.78	0.44	304PoB	0.17E+08	595.00	9.17
268	03/09/55	11	658	59.82	3.52	22	2.00	0.89	304PoB	0.17E+08	577.50	9.65
269	03/14/55	11	658	59.82	3.09	24	2.18	0.75	304PoB	0.16E+08	560.00	9.36
270	03/21/55	10	1238	123.80	6.09	14	1.40	0.52	304PoB	0.37E+08	1295.00	10.46
271	03/28/55	10	1229	122.90	3.93	18	1.80	0.63	304PoB	0.35E+08	1225.00	9.97
272	04/02/55	10	1177	117.70	5.25	16	1.60	0.52	304PoB	0.35E+08	1207.50	10.26
273	04/09/55	11	1220	110.91	5.86	16	1.45	0.52	304PoB	0.33E+08	1155.00	10.41
274	04/16/55	8	906	113.25	5.55	15	1.88	0.83	304PoB	0.32E+08	1120.00	9.89
275	04/23/55	11	1217	110.64	4.34	16	1.45	0.69	304PoB	0.31E+08	1085.00	9.81
276	04/30/55	12	1299	108.25	4.54	15	1.25	0.45	304PoB	0.30E+08	1050.00	9.70
277	05/09/55	12	1178	98.17	4.51	10	0.83	0.39	304PoB	0.29E+08	1015.00	10.34
278	05/16/55	12	1075	89.58	5.16	12	1.00	0.43	304PoB	0.28E+08	980.00	10.94
279	05/23/55	11	1012	92.00	6.94	19	1.73	0.65	304PoB	0.27E+08	945.00	10.27
280	06/02/55	11	836	76.00	6.62	9	0.82	0.60	304PoB	0.37E+08	1302.00	17.13
281	06/11/55	9	847	94.11	5.49	10	1.11	0.60	304PoB	0.25E+08	875.00	9.30
282	06/13/55	12	923	76.92	4.46	18	1.50	0.67	304PoB	0.25E+08	875.00	11.38
283	06/19/55	11	814	74.00	5.95	14	1.27	0.47	304PoB	0.26E+08	910.00	12.30
284	06/25/55	10	612	61.20	4.54	10	1.00	0.00	304PoB	0.23E+08	794.50	12.98
285	07/05/55	10	935	93.50	8.90	11	1.10	0.32	304PoB	0.31E+08	1092.00	11.68
286	07/12/55	11	1024	93.09	7.83	9	0.82	0.40	304PoB	0.35E+08	1225.00	13.16
287	07/19/55	12	1121	93.42	4.56	12	1.00	0.60	304PoB	0.30E+08	1032.50	11.05
288	07/25/55	10	946	94.60	5.06	13	1.30	0.48	304PoB	0.28E+08	980.00	10.36
289	08/01/55	12	1142	95.17	4.24	17	1.42	0.51	304PoB	0.28E+08	962.50	10.11
290	08/08/55	11	987	89.73	6.13	15	1.36	0.67	304PoB	0.27E+08	927.50	10.34
291	08/15/55	11	965	87.73	3.61	16	1.45	0.69	304PoB	0.26E+08	892.50	10.17
292	08/22/55	11	923	83.91	4.68	15	1.36	0.50	304PoB	0.25E+08	857.50	10.22
293	08/29/55	11	938	85.27	4.71	12	1.09	0.54	304PoB	0.24E+08	840.00	9.85
294	09/05/55	12	1025	85.42	5.09	17	1.42	0.51	304PoB	0.23E+08	805.00	9.42
295	09/09/55	11	1430	130.00	5.08	17	1.55	0.52	Ion Acc	150	1200.00	9.23
296	09/16/55	12	1565	130.42	6.23	13	1.08	0.90	Ion Acc	150	1200.00	9.20
297	09/23/55	10	1330	133.00	8.22	17	1.70	0.67	Ion Acc	150	1200.00	9.02
298	09/30/55	9	1123	124.78	5.78	13	1.44	0.53	Ion Acc	150	1200.00	9.62
299	10/07/55	9	1087	120.78	8.41	15	1.67	0.71	Ion Acc	150	1200.00	9.94
300	10/14/55	9	1054	117.11	6.90	10	1.11	0.33	Ion Acc	150	1200.00	10.25
301	10/21/55	6	700	116.67	17.65	10	1.67	0.52	Ion Acc	150	1200.00	10.29

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
302	10/28/55	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.84
303	11/04/55	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.84
304	11/11/55	9	948	105.33	6.52	11	1.22	0.44	Ion Acc	150	1200.00	11.39
305	12/02/55	10	1112	111.20	6.16	17	1.70	0.82	Ion Acc	150	1200.00	10.79
306	12/10/55	9	965	107.22	2.33	13	1.44	0.53	Ion Acc	150	1200.00	11.19
307	12/28/55	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.01
308	12/29/55	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.01
309	01/01/56	10	1360	136.00	6.24	18	1.80	0.63	Ion Acc	150	1200.00	8.82
310	01/08/56	9	1214	134.89	14.37	19	2.11	0.78	Ion Acc	150	1200.00	8.90
311	01/15/56	10	1246	124.60	6.40	21	2.10	0.57	Ion Acc	150	1200.00	9.63
312	01/22/56	10	1271	127.10	5.11	26	2.60	0.97	Ion Acc	150	1200.00	9.44
313	01/28/56	8	985	123.13	6.58	18	2.25	0.71	Ion Acc	150	1200.00	9.75
314	02/08/56	9	1165	129.44	4.13	21	2.33	0.50	Ion Acc	150	1200.00	9.27
315	03/09/56	9	1104	122.67	5.12	21	2.33	0.50	Ion Acc	150	1200.00	9.78
316	03/21/56	10	1421	142.10	9.49	23	2.30	0.67	Ion Acc	150	1200.00	8.44
317	03/23/56	10	1090	109.00	3.89	28	2.80	0.63	Ion Acc	150	1200.00	11.01
318	03/27/56	10	1180	118.00	5.56	30	3.00	0.67	Ion Acc	150	1200.00	10.17
319	03/30/56	10	1249	124.90	3.81	27	2.70	1.06	Ion Acc	150	1200.00	9.61
320	04/05/56	10	1148	114.80	6.18	28	2.80	0.63	Ion Acc	150	1200.00	10.45
321	04/12/56	10	1087	108.70	3.47	32	3.20	1.23	Ion Acc	150	1200.00	11.04
322	04/20/56	10	1103	110.30	4.27	22	2.20	0.63	Ion Acc	150	1200.00	10.88
323	04/28/56	10	1040	104.00	2.71	22	2.20	1.14	Ion Acc	150	1200.00	11.54
324	05/05/56	10	1129	112.90	4.58	25	2.50	0.53	Ion Acc	150	1200.00	10.63
325	05/12/56	10	1088	108.80	6.12	25	2.50	0.97	Ion Acc	150	1200.00	11.03
326	05/20/56	10	1075	107.50	6.65	22	2.20	0.42	Ion Acc	150	1200.00	11.16
327	05/28/56	10	967	96.70	4.72	23	2.30	0.48	Ion Acc	150	1200.00	12.41
328	06/05/56	10	1052	105.20	2.53	19	1.90	0.57	Ion Acc	150	1200.00	11.41
329	06/12/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.99
330	06/20/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.99
331	06/28/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.99
332	07/05/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.99
333	07/12/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	10.99
334	07/20/56	9	1022	113.56	5.00	12	1.33	1.00	Ion Acc	150	1200.00	10.57
335	07/28/56	9	887	98.56	4.10	11	1.22	0.44	Ion Acc	150	1200.00	12.18
336	08/05/56	10	1016	101.60	8.96	10	1.00	0.00	Ion Acc	150	1200.00	11.81
337	08/12/56	10	971	97.10	7.67	9	0.90	0.32	Ion Acc	150	1200.00	12.36
338	08/20/56	9	815	90.56	16.99	7	0.78	0.67	Ion Acc	150	1200.00	13.25

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
339	08/28/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	13.05
340	09/05/56	9	841	93.44	5.59	8	0.89	0.93	Ion Acc	150	1200.00	12.84
341	09/12/56	10	1215	121.50	5.21	9	0.90	0.57	Ion Acc	150	1200.00	9.88
342	09/20/56	10	1067	106.70	5.31	8	0.80	0.42	Ion Acc	150	1200.00	11.25
343	09/28/56	10	1055	105.50	5.64	12	1.20	0.63	Ion Acc	150	1200.00	11.37
344	10/05/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	12.45
345	10/15/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	12.45
346	10/20/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	12.45
347	10/28/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	12.45
348	11/14/56	9	799	88.78	6.82	12	1.33	0.50	Ion Acc	150	1200.00	13.52
349	11/16/56	9	824	91.56	4.82	7	0.78	0.44	Ion Acc	150	1200.00	13.11
350	11/17/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	13.27
351	11/18/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	13.27
352	11/19/56	9	805	89.44	5.70	8	0.89	0.33	Ion Acc	150	1200.00	13.42
353	11/20/56	9	785	87.22	3.35	5	0.56	0.53	Ion Acc	150	1200.00	13.76
354	11/22/56	9	894	99.33	5.83	10	1.11	0.60	Ion Acc	150	1200.00	12.08
355	11/25/56	8	807	100.88	4.67	10	1.25	0.71	Ion Acc	150	1200.00	11.90
356	11/28/56	9	917	101.89	4.04	9	1.00	0.00	Ion Acc	150	1200.00	11.78
357	12/05/56	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	11.91
358	12/10/56	10	997	99.70	5.93	14	1.40	0.52	Ion Acc	150	1200.00	12.04
359	12/13/56	10	888	88.80	5.90	14	1.40	0.84	Ion Acc	150	1200.00	13.51
360	12/20/56	10	926	92.60	4.67	12	1.20	0.42	Ion Acc	150	1200.00	12.96
361	12/26/56	9	920	102.22	4.68	9	1.00	0.50	Ion Acc	150	1200.00	11.74
362	01/02/57	10	976	97.60	4.58	9	0.90	0.57	Ion Acc	150	1200.00	12.30
363	01/08/57	8	835	104.38	5.80	10	1.25	0.46	Ion Acc	150	1200.00	11.50
364	01/15/57	9	1010	112.22	10.63	12	1.33	0.50	Ion Acc	150	1200.00	10.69
365	01/22/57	8	948	118.50	6.52	11	1.38	0.74	Ion Acc	150	1200.00	10.13
366	01/29/57	9	1003	111.44	13.82	12	1.33	0.71	Ion Acc	150	1200.00	10.77
367	02/05/57	8	1069	133.63	5.63	10	1.25	0.71	Ion Acc	150	1200.00	8.98
368	02/11/57	8	966	120.75	7.15	11	1.38	1.06	Ion Acc	150	1200.00	9.94
369	02/18/57	8	993	124.13	14.49	7	0.88	0.35	Ion Acc	150	1200.00	9.67
370	02/20/57	9	1161	129.00	10.98	11	1.22	0.97	Ion Acc	150	1200.00	9.30
371	03/04/57	8	1074	134.25	6.58	12	1.50	0.53	Ion Acc	150	1200.00	8.94
372	03/06/57	9	1266	140.67	10.40	13	1.44	0.53	Ion Acc	150	1200.00	8.53
373	03/18/57	8	1091	136.38	4.17	12	1.50	0.53	Ion Acc	150	1200.00	8.80
374	03/20/57	9	1209	134.33	6.40	16	1.78	1.09	Ion Acc	150	1200.00	8.93
375	04/01/57	8	1006	125.75	9.07	13	1.63	0.52	Ion Acc	150	1200.00	9.54

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
376	04/03/57	9	1226	136.22	8.97	17	1.89	0.78	Ion Acc	150	1200.00	8.81
377	04/15/57	8	996	124.50	7.43	16	2.00	0.53	Ion Acc	150	1200.00	9.64
378	04/17/57	4	463	115.75	4.57	6	1.50	1.00	Ion Acc	150	1200.00	10.37
379	04/23/57	5	628	125.60	15.66	9	1.80	0.84	Ion Acc	150	1200.00	9.55
380	04/29/57	4	362	90.50	17.21	9	2.25	0.50	Ion Acc	150	1200.00	13.26
381	05/07/57	6	620	103.33	7.89	12	2.00	0.63	Ion Acc	150	1200.00	11.61
382	05/13/57	4	392	98.00	3.74	9	2.25	0.50	Ion Acc	150	1200.00	12.24
383	05/20/57	5	577	115.40	5.94	11	2.20	0.84	Ion Acc	150	1200.00	10.40
384	05/27/57	4	468	117.00	10.95	5	1.25	0.50	Ion Acc	150	1200.00	10.26
385	06/03/57	5	547	136.75	12.74	8	1.60	0.55	Ion Acc	150	1200.00	10.97
386	06/10/57	4	569	142.25	7.85	6	1.50	0.58	Ion Acc	150	1200.00	8.44
387	06/17/57	5	677	135.40	6.84	7	1.40	0.55	Ion Acc	150	1200.00	8.86
388	06/24/57	4	612	153.00	10.42	5	1.25	0.50	Ion Acc	150	1200.00	7.84
389	07/01/57	6	813	135.50	8.07	9	1.50	0.55	Ion Acc	150	1200.00	8.86
390	07/08/57	4	530	132.50	13.30	5	1.25	0.50	Ion Acc	150	1200.00	9.06
391	07/15/57	6	713	118.83	8.89	6	1.00	0.00	Ion Acc	150	1200.00	10.10
392	07/22/57	4	518	129.50	12.77	4	1.00	0.00	Ion Acc	150	1200.00	9.27
393	08/06/57	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	9.10
394	08/07/57	4	538	134.50	5.92	2	0.50	0.58	Ion Acc	150	1200.00	8.92
395	08/12/57	6	822	137.00	5.90	11	1.83	0.41	Ion Acc	150	1200.00	8.76
396	08/19/57	4	518	129.50	7.42	4	1.00	0.00	Ion Acc	150	1200.00	9.27
397	08/26/57	6	817	136.17	3.66	6	1.00	0.00	Ion Acc	150	1200.00	8.81
398	09/03/57	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	8.47
399	09/09/57	6	886	147.67	7.71	11	1.83	0.75	Ion Acc	150	1200.00	8.13
400	09/16/57	4	568	142.00	9.63	5	1.25	0.50	Ion Acc	150	1200.00	8.45
401	09/23/57	6	868	144.67	6.06	12	2.00	0.63	Ion Acc	150	1200.00	8.29
402	09/30/57	4	566	141.50	15.09	9	2.25	1.89	Ion Acc	150	1200.00	8.48
403	10/07/57	6	899	149.83	6.01	12	2.00	0.63	Ion Acc	150	1200.00	8.01
404	10/14/57	4	448	112.00	13.09	10	2.50	1.91	Ion Acc	150	1200.00	10.71
405	10/21/57	6	727	121.17	5.56	8	1.33	0.52	Ion Acc	150	1200.00	9.90
406	10/28/57	4	502	125.50	27.45	11	2.75	1.71	Ion Acc	150	1200.00	9.56
407	11/04/57	6	757	126.17	11.20	12	2.00	0.63	Ion Acc	150	1200.00	9.51
408	11/11/57	4	501	125.25	18.91	11	2.75	1.50	Ion Acc	150	1200.00	9.58
409	11/18/57	6	792	132.00	1.26	12	2.00	0.63	Ion Acc	150	1200.00	9.09
410	11/25/57	4	516	129.00	6.16	17	4.25	2.63	Ion Acc	150	1200.00	9.30
411	12/02/57	6	758	126.33	8.64	10	1.67	0.52	Ion Acc	150	1200.00	9.50
412	12/09/57	4	745	186.25	6.55	9	2.25	0.50	Ion Acc	150	1200.00	6.44

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
413	12/13/57	6	760	126.67	4.46	11	1.83	0.41	Ion Acc	150	1200.00	9.47
414	12/20/57	4	551	137.75	6.65	9	2.25	0.96	Ion Acc	150	1200.00	8.71
415	12/27/57	6	800	133.33	7.47	7	1.17	0.41	Ion Acc	150	1200.00	9.00
416	01/06/58	4	485	121.25	27.75	9	2.25	0.96	Ion Acc	150	1200.00	9.90
417	01/10/58	6	672	112.00	6.54	9	1.50	0.55	Ion Acc	150	1200.00	10.71
418	01/17/58	4	482	120.50	4.65	4	1.00	0.00	Ion Acc	150	1200.00	9.96
419	01/24/58	6	602	100.33	9.20	6	1.00	0.89	Ion Acc	150	1200.00	11.96
420	01/31/58	4	505	126.25	12.34	6	1.50	1.00	Ion Acc	150	1200.00	9.50
421	02/07/58	6	614	102.33	23.90	6	1.00	0.00	Ion Acc	150	1200.00	11.73
422	02/14/58	4	431	107.75	23.92	5	1.25	0.50	Ion Acc	150	1200.00	11.14
423	02/21/58	6	826	137.67	7.58	5	0.83	0.41	Ion Acc	150	1200.00	8.72
424	02/28/58	4	546	136.50	5.07	4	1.00	0.82	Ion Acc	150	1200.00	8.79
425	03/07/58	6	698	116.33	18.97	4	0.67	0.52	Ion Acc	150	1200.00	10.32
426	03/14/58	4	488	122.00	12.73	5	1.25	0.50	Ion Acc	150	1200.00	9.84
427	03/21/58	6	782	130.33	5.72	5	0.83	0.41	Ion Acc	150	1200.00	9.21
428	03/28/58	3	384	128.00	12.77	6	2.00	0.00	Ion Acc	150	1200.00	9.38
429	04/04/58	6	831	138.50	7.64	4	0.67	0.52	Ion Acc	150	1200.00	8.66
430	04/11/58	3	363	121.00	9.54	4	1.33	0.58	Ion Acc	150	1200.00	9.92
431	04/18/58	6	601	100.17	16.55	3	0.50	0.55	Ion Acc	150	1200.00	11.98
432	04/25/58	4	426	106.50	6.81	9	2.25	2.50	Ion Acc	150	1200.00	11.27
433	05/02/58	6	493	82.17	16.17	5	0.83	0.41	Ion Acc	150	1200.00	14.60
434	05/09/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	15.06
435	05/16/58	3	232	77.33	8.02	2	0.67	1.15	Ion Acc	150	1200.00	15.52
436	05/23/58	4	335	83.75	13.28	1	0.25	0.50	Ion Acc	150	1200.00	14.33
437	06/03/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.96
438	06/09/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.96
439	06/17/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.96
440	06/20/58	4	308	77.00	7.75	5	1.25	0.50	Ion Acc	150	1200.00	15.58
441	06/30/58	4	305	76.25	30.70	2	0.50	0.50	Ion Acc	150	1200.00	15.74
442	07/15/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.84
443	07/25/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.84
444	08/10/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.84
445	08/25/58	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	14.84
446	09/10/58	10	861	86.10	8.77	11	1.10	0.32	Ion Acc	150	1200.00	13.94
447	09/22/58	8	571	71.38	8.45	11	1.38	0.52	Ion Acc	150	1200.00	16.81
448	10/05/58	10	885	88.50	12.57	0	0.00	0.00	Ion Acc	150	1200.00	13.56
449	10/22/58	10	836	83.60	6.33	0	0.00	0.00	Ion Acc	150	1200.00	14.35

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
450	11/05/58	10	705	70.50	8.20	10	1.00	0.47	PuF ₄	1075	1075.00	15.25
451	11/18/58	9	680	75.56	10.03	8	0.89	0.33	PuF ₄	1075	1075.00	14.23
452	12/01/58	10	872	87.20	9.82	14	1.40	0.84	PuF ₄	1075	1075.00	12.33
453	12/15/58	10	761	76.10	6.67	14	1.40	0.52	PuF ₄	1075	1075.00	14.13
454	12/28/58	9	710	78.89	6.29	16	1.78	0.44	PuF ₄	1075	1075.00	13.63
455	01/12/59	10	730	73.00	6.09	21	2.10	1.20	PuF ₄	1075	1075.00	14.73
456	01/25/59	10	743	74.30	14.41	27	2.70	1.34	PuF ₄	1075	1075.00	14.47
457	02/10/59	10	709	70.90	11.09	20	2.00	0.82	PuF ₄	1075	1075.00	15.16
458	02/25/59	10	757	75.70	9.07	19	1.90	0.74	PuF ₄	1075	1075.00	14.20
459	03/10/59	10	953	95.30	10.48	14	1.40	0.52	PuF ₄	1075	1075.00	11.28
460	03/25/59	10	910	91.00	7.57	31	3.10	0.88	PuF ₄	1075	1075.00	11.81
461	04/08/59	10	971	97.10	10.25	17	1.70	0.82	PuF ₄	1075	1075.00	11.07
462	04/20/59	10	876	87.60	10.19	11	1.10	0.32	PuF ₄	1075	1075.00	12.27
463	05/05/59	10	739	73.90	16.24	20	2.00	0.47	PuF ₄	1075	1075.00	14.55
464	05/20/59	10	459	45.90	6.17	13	1.30	0.48	PuF ₄	1075	1075.00	23.42
465	06/08/59	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	16.68
466	06/22/59	9	973	108.11	11.87	18	2.00	1.12	PuF ₄	1075	1075.00	9.94
467	07/08/59	9	752	83.56	3.64	8	0.89	0.78	PuF ₄	1075	1075.00	12.87
468	07/22/59	9	773	85.89	9.27	11	1.22	0.83	PuF ₄	1075	1075.00	12.52
469	08/04/59	9	812	90.22	8.03	9	1.00	0.00	PuF ₄	1075	1075.00	11.92
470	08/17/59	9	754	83.78	6.12	8	0.89	0.33	PuF ₄	1075	1075.00	12.83
471	09/01/59	9	881	97.89	6.01	7	0.78	0.67	PuF ₄	1075	1075.00	10.98
472	09/15/59	10	965	96.50	8.98	17	1.70	0.48	PuF ₄	1075	1075.00	11.14
473	09/30/59	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	12.38
474	10/12/59	10	789	78.90	7.29	13	1.30	0.67	PuF ₄	1075	1075.00	13.62
475	10/25/59	9	825	91.67	9.75	11	1.22	0.67	PuF ₄	1075	1075.00	11.73
476	11/10/59	10	908	90.80	6.80	17	1.70	1.16	PuF ₄	1075	1075.00	11.84
477	11/25/59	10	977	97.70	6.33	23	2.30	0.95	PuF ₄	1075	1075.00	11.00
478	12/07/59	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	11.24
479	12/20/59	8	750	93.75	4.86	14	1.75	0.71	PuF ₄	1075	1075.00	11.47
480	02/15/60	8	573	71.63	6.28	10	1.25	0.46	PuF ₄	1075	1075.00	15.01
481	03/01/60	9	730	81.11	3.62	15	1.67	0.71	PuF ₄	1075	1075.00	13.25
482	03/15/60	9	672	74.67	7.50	16	1.78	0.67	PuF ₄	1075	1075.00	14.40
483	03/28/60	9	627	69.67	6.61	18	2.00	1.12	PuF ₄	1075	1075.00	15.43
484	04/12/60	9	616	68.44	12.15	13	1.44	0.73	PuF ₄	1075	1075.00	15.71
485	04/26/60	9	566	62.89	7.75	15	1.67	1.00	PuF ₄	1075	1075.00	17.09
486	05/10/60	9	626	69.56	25.77	16	1.78	0.83	PuF ₄	1075	1075.00	15.46

Table A.1. (contd)

Sheet Number	Date	No. of Readers	No. of Tracks	Tracks/ Readers	Standard Deviation	No. of Blanks	Blanks/ Readers	Standard Deviation	Calibration Source	Fluence or Dose	Adjusted Dose	Dose/ Track
487	05/25/60	9	694	77.11	6.83	26	2.89	0.60	PuF ₄	1075	1075.00	13.94
488	06/07/60	9	648	72.00	27.48	15	1.67	1.12	PuF ₄	1075	1075.00	14.93
489	06/25/60	9	630	70.00	0.00	9	1.00	0.00	PuF ₄	1075	1075.00	15.36
490	07/05/60	0	0	0.00	0.00	0	0.00	0.00	No Calib	0	0.00	19.45
491	07/20/60	9	411	45.67	9.38	17	1.89	0.78	PuF ₄	1075	1075.00	23.54
492	08/03/60	9	471	52.33	11.75	9	1.00	0.71	PuF ₄	1075	1075.00	20.54
493	08/16/60	9	516	57.33	8.47	9	1.00	0.71	PuF ₄	1075	1075.00	18.75
494	09/01/60	9	345	38.33	5.39	9	1.00	0.50	PuF ₄	1075	1075.00	28.04
495	09/14/60	9	534	59.33	6.40	11	1.22	1.30	PuF ₄	1075	1075.00	18.12
496	09/25/60	9	621	69.00	0.00	0	0.00	0.00	PuF ₄	1075	1075.00	15.58
497	10/10/60	9	372	41.33	12.59	10	1.11	0.78	PuF ₄	1075	1075.00	26.01
498	11/07/60	9	618	68.67	6.04	12	1.33	0.50	PuF ₄	1075	1075.00	15.66
499	11/20/60	10	704	70.40	8.21	14	1.40	0.84	PuF ₄	1075	1075.00	15.27
500	12/05/60	10	718	71.80	13.33	24	2.40	1.17	PuF ₄	1075	1075.00	14.97
501	12/13/60	1	68	68.00	0.00	3	3.00	0.00	PuF ₄	1075	1075.00	15.81
502	12/20/60	9	533	59.22	11.32	14	1.56	1.33	PuF ₄	1075	1075.00	18.15
503	01/01/61	11	833	75.73	14.68	27	2.45	1.04	PuF ₄	1075	1075.00	14.20
504	01/15/61	11	837	76.09	9.33	20	1.82	0.98	PuF ₄	1075	1075.00	14.13
505	02/01/61	11	724	65.82	13.80	17	1.55	0.69	PuF ₄	1075	1075.00	16.33
506	02/17/61	11	652	59.27	9.11	20	1.82	0.75	PuF ₄	1075	1075.00	18.14
507	03/01/61	10	653	65.30	10.77	22	2.20	1.03	PuF ₄	1075	1075.00	16.46
508	03/14/61	10	783	78.30	10.33	19	1.90	0.57	PuF ₄	1075	1075.00	13.73
509	03/28/61	10	727	72.70	6.78	27	2.70	0.67	PuF ₄	1075	1075.00	14.79
510	04/12/61	9	560	62.22	7.92	20	2.22	1.39	PuF ₄	1075	1075.00	17.28
511	04/28/61	11	569	51.73	4.05	22	2.00	0.63	PuF ₄	1075	1075.00	20.78
512	05/05/61	2	128	64.00	5.66	4	2.00	0.00	PuF ₄	1075	1075.00	16.80
513	05/10/61	10	517	51.70	9.58	14	1.40	0.84	PuF ₄	1075	1075.00	20.79
514	05/23/61	11	597	54.27	6.34	21	1.91	0.94	PuF ₄	1075	1075.00	19.81
515	06/05/61	10	575	57.50	5.60	21	2.10	1.29	PuF ₄	1075	1075.00	18.70
516	06/20/61	10	613	61.30	9.26	15	1.50	0.71	PuF ₄	1075	1075.00	17.54
517	07/02/61	10	475	47.50	10.47	9	0.90	0.74	PuF ₄	1075	1075.00	22.63
518	07/20/61	11	587	53.36	6.38	17	1.55	1.57	PuF ₄	1075	1075.00	20.14
519	08/01/61	10	496	49.60	5.06	16	1.60	0.84	PuF ₄	1075	1075.00	21.67
520	08/15/61	11	602	54.73	3.77	14	1.27	1.10	PuF ₄	1075	1075.00	19.64
521	08/27/61	11	591	53.73	8.20	24	2.18	1.72	PuF ₄	1075	1075.00	20.01
522	09/12/61	11	600	54.55	5.45	17	1.55	0.69	PuF ₄	1075	1075.00	19.71
523	09/25/61	10	646	64.60	8.78	13	1.30	0.95	PuF ₄	1075	1075.00	16.64

Table A.1. (contd)

<u>Sheet Number</u>	<u>Date</u>	<u>No. of Readers</u>	<u>No. of Tracks</u>	<u>Tracks/ Readers</u>	<u>Standard Deviation</u>	<u>No. of Blanks</u>	<u>Blanks/ Readers</u>	<u>Standard Deviation</u>	<u>Calibration Source</u>	<u>Fluence or Dose</u>	<u>Adjusted Dose</u>	<u>Dose/ Track</u>
524	10/10/61	10	658	65.80	3.49	17	1.70	1.34	PuF ₄	1075	1075.00	16.34
525	10/25/61	11	774	70.36	6.83	16	1.45	1.37	PuF ₄	1075	1075.00	15.28
526	11/10/61	10	722	72.20	4.85	18	1.80	1.32	PuF ₄	1075	1075.00	14.89
527	11/21/61	2	155	77.50	2.12	6	3.00	0.00	PuF ₄	1075	1075.00	13.87
528	12/05/61	2	148	74.00	12.73	6	3.00	2.83	PuF ₄	1075	1075.00	14.53
529	12/20/61	1	78	78.00	0.00	5	5.00	0.00	PuF ₄	1075	1075.00	13.79

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