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Description and Evaluation of the Hanford Personnel Dosimeter Program From 1944 Through 1989

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September 1990

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DESCRIPTION AND EVALUATION OF THE HANFORD
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Richland, Washington 99352



PREFACE

This report provides a historical review of the equipment, the dosimetry techniques, and the calibration protocols used at Hanford to measure and record personnel dose from the inception of Hanford operations in 1944 through 1989. An evaluation of the capability of each dosimeter to accurately estimate the dose to personnel is made, and includes comparison of the recorded dose to the 1-cm depth dose in tissue (i.e., deep dose) for six different facility types considered to represent Hanford operations. This evaluation is based on 1) review of extensive historical documentation, 2) results of a laboratory intercomparison of all Hanford film dosimeters during 1989, 3) results from performance testing of the Hanford thermoluminescent dosimeter during 1989, and 4) the professional judgment of the authors based on dosimetry experience during nearly 5 decades of Hanford Operations.

This report is addressed primarily to the dosimetrist of external sources of radiation. Evaluation of personnel dose from measured internal depositions of radioactivity is not included in this report. It is estimated that less than 1% of the Hanford worker population has received a dose from internal depositions that exceeds 10% of the recorded lifetime dose at Hanford. This report supplies the necessary background to allow for the development of recommendations, regarding adjustments that may be needed to convert recorded doses to the 1-cm depth dose and to doses to specific organs of the body. Organ doses are needed to allow for appropriate comparison of risk estimates based on worker data with risk estimates based on extrapolation from high-dose data.

Dose records for Hanford personnel are being used in the Hanford Health and Mortality Study, which is being conducted jointly by Pacific Northwest Laboratory and the Hanford Environmental Health Foundation. The objectives of this ongoing study are to determine 1) if cause-specific mortality is associated with cumulative radiation dose, and 2) to what extent direct data on a population exposed at low levels can confirm or reject risk estimates based on extrapolation from high-dose data.

To make the best use of available epidemiologic data in assessing risks from exposure to low-level radiation, it is important that the methods used to

assess and record personnel dose be understood. It is particularly important to evaluate comparability of recorded dose over time and among workers performing different types of work. In addition, recent efforts to combine data from several nuclear worker studies, both within the United States and internationally, make it necessary to evaluate the comparability of dose estimates across studies.

ABSTRACT

This report describes the evolution of personnel dosimeter technology at Hanford since the inception of Hanford operations in 1944. Each of the personnel dosimeter systems used by people working or visiting Hanford is described. In addition, the procedures used to calibrate and calculate dose for each of the dosimeter systems are described. The accuracy of the recorded dose, primarily whole body deep dose, for the different dosimeter systems is evaluated. The evaluation is based on an extensive review of historical literature, as well as a 1989 intercomparison study of all film dosimeters and performance testing of the thermoluminescent dosimeter, also conducted during 1989.



EXECUTIVE SUMMARY

External dose has been measured and recorded for Hanford personnel since the beginning of operations in 1944, and the technology for doing so has evolved throughout the nearly 5 decades of Hanford operations. This report was prepared to meet two primary objectives: 1) provide a historical overview of Hanford personnel dosimeter practices and, 2) evaluate the accuracy of recorded whole body doses in support of the Hanford Health and Mortality Study. Specifically, this report aims to describe dosimetry systems used to determine personnel dose and to evaluate the accuracy of the recorded dose for the different dosimeters and periods of use relative to a currently accepted national basis (i.e., deep dose). The evaluation is difficult because of the significant variation in beta, photon, and neutron radiation fields in the various Hanford facilities, as well as numerous technological and environmental aspects of the dosimeters used and the changing concepts in dose over the years.

Hanford was formed as a part of the Manhattan Project created in 1942 to develop atomic weapons. Hanford's role in this national effort was to produce plutonium. Early Hanford researchers recognized the significant uncertainties of measuring personnel dose from the complex beta, photon, and neutron radiation fields that would accompany the Hanford nuclear reactor, fuel reprocessing, plutonium separation, and waste handling tasks of the Manhattan Project. Large quantities of radioactive material would be produced, refined, and stored at Hanford. Accurate measurement of personnel dose for the large number of personnel involved in these tasks was of paramount importance. Initially, personnel dosimetry techniques were adopted from the medical community. This resulted in pioneering the science of measuring radiation for nuclear facilities and transferring this information into the technology to measure dose to personnel.

Technical interchange was common between different national laboratories. The original two-element film dosimeter implemented at both Hanford and Oak Ridge National Laboratory (ORNL, originally called Clinton Laboratory) was developed at the University of Chicago Metallurgical Laboratory. In 1945 the interpreted doses from film dosimeters used at Hanford, ORNL, and Los Alamos

National Laboratory (LANL, originally called Los Alamos Scientific Laboratory) were compared. During the years that followed, numerous intercomparisons were conducted between Hanford, ORNL, LANL, Rocky Flats Plant (RFP), and Savannah River Plant (SRP) dosimeters. In the 1960s Hanford was involved in a national intercomparison program to compare government and private film dosimeter processors. This program demonstrated that accurate measurement of dose from low-energy x-rays and neutrons was the most difficult, especially in mixed radiation fields. Additional dosimeter intercomparison studies were conducted during the 1970s and 1980s. The American National Standards Institute (ANSI) formally adopted a national standard for personnel dosimeter performance in 1983. This standard, ANSI N13.11, was used by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) as a basis for implementing national personnel dosimeter accreditation requirements for dosimetry programs in the late 1980s. It should be noted that significant improvement was observed for all laboratories in the measurement of personnel dose from 1) x-rays with the introduction of the multi-element film dosimeters and from 2) neutrons with the introduction of the thermoluminescent dosimeter (TLD).

This report describes the evolution in Hanford personnel dosimetry technology and associated practices. Numerous technical studies were conducted during the years and the most significant of these are described in this report. Topics include:

- a description of each dosimeter used since 1944
- technical details of dosimeter calibration and dose determination
- description of dosimeter quality control studies
- description of intercomparison programs
- methods used to calculate the recorded skin and whole body doses
- results of a laboratory intercomparison study conducted during 1989 of all Hanford film dosimeters
- performance of the Hanford TLDs during accreditation testing during 1989

- comparison of whole body dose with expected deep dose and the expected performance of Hanford personnel dosimeters used in typical radiation fields.

A bibliography is included for pertinent information not explicitly used in the report. Hanford facilities are categorized in this report into six general types in the evaluation of the recorded whole body dose compared with the actual tissue dose at a depth of 1-cm (i.e., deep dose). These categories included: 1) fuel fabrication, 2) reactor, 3) fuel reprocessing, 4) plutonium finishing, 5) waste, and 6) laboratory. Knowledge of radiation fields typical of these facility categories in conjunction with the dose response characteristics of the different dosimeters is used to assess the accuracy of calculated whole body dose at Hanford relative to the actual deep dose. The evaluation is based on information in this report as well as the professional experience of the authors extending throughout nearly all 5 decades of Hanford operations.

This evaluation concluded that the recorded whole body dose, on average, for the vast majority of Hanford personnel is estimated to be nearly equivalent to the actual deep dose. For higher energy (> 100 -keV) photon fields, which comprise the majority of personnel exposure in Hanford facilities, it is estimated that the difference between the recorded whole body dose and the actual deep dose for occupationally exposed personnel is about $\pm 50\%$, $\pm 30\%$, and $\pm 20\%$, respectively, for the two-element film dosimeter (used from 1944 to 1956), multi-element film dosimeters (used from 1957 to 1971), and TLD (used from 1972 to 1989). A greater difference between the recorded whole body dose and the actual deep dose occurs for facilities in which complex mixtures of beta and photon radiation or neutron radiation are present. Comparison of the recorded neutron dose with the actual dose equivalent with the TLD is estimated to be $\pm 50\%$. Greater uncertainty was evident with the DuPont Nuclear Track Emulsion film used from 1950 through 1972. These estimates are appropriate for personnel whose occupational radiation exposure is significantly greater than the natural environmental background radiation. It is important to note that the majority of Hanford workers received very little occupational exposure.

There were problems in the recorded whole body dose for plutonium facility personnel. There is little doubt that the recorded dose is underestimated

compared with the deep dose. This occurred because of the difficulties in measuring plutonium x-rays (16 keV to 17 keV) prior to the use of the multi-element film dosimeter in 1957 and because of the difficulty of measuring neutron dose prior to the use of the TLD in 1972. Methods that could be used to improve the recorded whole body dose for plutonium facilities personnel are presented in this report. It should be noted that these personnel comprised a small percentage of the total personnel employed at Hanford since 1944 and would not be expected to significantly impact the evaluation of radiation risk for Hanford personnel using recorded doses. However, determination of the source of exposure for more highly exposed personnel should be considered to ensure that no significant error in the analyses occurs.

ACKNOWLEDGMENTS

Since the inception of Hanford, numerous individuals have contributed to the science of measuring personnel exposure to radiation. The evolving nature of Hanford radiation protection technology and its implementation as routine practice is illustrated throughout this report. The report is a tribute to the dedication and talent of these many individuals. Interested readers are encouraged to consult the many documents cited in this report. The authors particularly acknowledge Ethel Gilbert, whose interest in documenting Hanford dosimetry practices in support of the Hanford Health and Mortality Study has made this report possible. She reviewed the report on several occasions providing detailed comments on content and presentation. Thanks also to Susan Ennor who edited the report and Marianna Cross who typed the final manuscript. We also wish to thank Bill Endres, Ron Kathren, and Leo Kocher for their technical review of this document and their many helpful suggestions to improve its validity.



ACRONYMS AND ABBREVIATIONS

ABS	acrylontrile-butadine-styrene
AEC	Atomic Energy Commission
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
BNL	Brookhaven National Laboratory
BNWL	Battelle Northwest Laboratories
CP	Cutie Pie (portable ionization chamber)
CSF	chip sensitivity factor
DOE	U.S. Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
ERDA	Energy Research and Development Administration
GE	General Electric Company
GM	Geiger-Mueller
HAPO	Hanford Atomic Products Operation
HBPD	Hanford beta/photon dosimeter
HEHF	Hanford Environmental Health Foundation
HEW	Hanford Engineer Works
HMPD	Hanford multipurpose dosimeter
HP	health physicist
IARC	International Agency for Research on Cancer (an agency of the World Health Organization)
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation and Measurements
LANL	Los Alamos National Laboratory (formerly Los Alamos Scientific Laboratory)

LASL	Los Alamos Scientific Laboratory
LET	Linear Energy Transfer
LLNL	Lawrence Livermore National Laboratory
NAS	National Academy of Sciences
NBS	Natural Bureau of Standards (now NIST)
NCRP	National Council on Radiation Protection and Measurements
NIST	National Institute of Standards and Technology (formerly NBS)
NRC	U.S. Nuclear Regulatory Commission
NTA	Nuclear Track Emulsion, Type A (film)
NVLAP	National Voluntary Laboratory Accreditation Program
OCR	optical character reader
ORNL	Oak Ridge National Laboratory
"p"	Production (department)
PNL	Pacific Northwest Laboratory
PSF	position sensitivity factor
PUREX	Plutonium Uranium Extraction (facility)
RBE	Relative Biological Effectiveness
RECUPLEX	Plutonium waste products recovery facility in the 234-5-Z Building
RFP	Rocky Flats Plant
RSF	reader sensitivity factor
"S"	Chemical Separation Department
SRP	Savannah River Plant
TEPC	tissue-equivalent proportional counter
TLD	thermoluminescent dosimeter
UST	United States Testing Company, Inc.

GLOSSARY

absorbed dose, D: the amount of energy imparted by radiation to unit mass of absorbing material (100 ergs per gram), including tissue. The unit used prior to the use of the International System of metric units (SI) is the rad; the SI unit is the gray.

accreditation: recognition that a dosimeter system has passed the performance criteria of ANSI N13.11 (ANSI 1983) or DOE Order 5480.15 (DOE 1987) in a specific irradiation category.

albedo dosimeter: a TLD device that measures the thermal and epithermal neutrons that are scattered and moderated by the body from an incident fast neutron flux.

algorithm: a computational procedure.

annual dose equivalent: the dose equivalent received in a year expressed in units of rem (sievert).

Atomic Energy Commission: original agency established for nuclear weapons and power production; a predecessor to the U.S. Department of Energy (DOE).

audit: an examination of records and procedures to check their accuracy.

BF₃ chamber or counter: proportional counter using gaseous BF₃ compound to detect slow neutrons through their interaction with boron.

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

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

bias, B: as used in dosimeter performance testing by the Department of Energy Laboratory Accreditation Program (DOELAP), the average of the performance quotients, P_i, for n dosimeters, for a specified irradiation category and depth.

$$B = \sum_{i=1}^n \frac{P_i}{n}$$

bremsstrahlung: secondary photon or x radiation produced by deceleration of charged particles passing through matter.

buildup: increase in flux or dose due to scattering in the medium.

calibration blank: a dosimeter that has not been exposed to a radiation source. The results from this dosimeter establish the dosimetry system base line or zero dose value.

collective dose equivalent: the sum of the dose equivalents of all individuals in an exposed population. Collective dose is expressed in units of person-rem (person-sievert).

control dosimeter: a dosimeter used to establish the dosimetry system response to radiation dose. The dosimeter is exposed to a known amount of radiation dose.

curie: a special unit of activity. One curie exactly equals 3.7×10^{10} nuclear transitions per second.

Cutie Pie (CP): a portable ion chamber survey meter with a pistol grip and a large cylindrical ionization chamber.

deep absorbed dose (D_d): the absorbed dose at the depth of 1.0 cm in a material of specified geometry and composition.

deep dose equivalent (H_d): the dose equivalent at the respective depth of 1.0 cm in tissue.

densitometer: instrument that has a photocell to determine the degree of darkening of developed photographic film.

density reading: see optical density.

detection level: the smallest amount of radiation or neutron flux that can be detected as being present.

dose equivalent (H): the product of the absorbed dose (D), the quality factor (Q), and any other modifying factors. The special unit is the rem. When D is expressed in Gy, H is in Sieverts (Sv). (1 Sv = 100 rem.)

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

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

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

DuPont 558: a film packet containing a 508 film with one side having a sensitive emulsion and the other side insensitive emulsion.

Eastman Kodak Nuclear Track Emulsion, Type A (NTA): a film that is sensitive to fast neutrons. The developed image has tracks caused by neutrons that can be seen by using oil immersion and 1000X power microscope.

error: a term used to express the difference between the estimated and "true" value. Error may also be used to refer to the estimated uncertainty.

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

exposure: as used in the technical sense, exposure refers to a measure expressed in roentgens of the ionization produced by gamma (or x) rays in air.

exposure-to-dose-equivalent conversion factor for photons (C_x): the ratio of exposure in air to the dose equivalent at a specified depth in a material of specified geometry and composition. The C_x factors are a function of photon energy, material geometry (e.g., sphere, slab, or torso), and material composition (e.g., tissue-equivalent plastic, soft tissue ignoring trace elements, or soft tissue including trace elements).

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

field calibration: dosimeter calibration based on radiation types, intensity and energies present in the work environment.

film: generally means a "film packet" that contains one or more pieces of film in a light-tight wrapping. The film when developed has an image caused by radiation that can be measured using an optical densitometer. (See Dupont 552, Dupont 558, Eastman Kodak, nuclear emulsions.)

film density: see optical density.

film dosimeter: a small packet of film within a holder that attaches to a wearer.

free-field dose equivalent: the dose equivalent assigned for neutron irradiation as if it were performed in free space with no background from air and room scattering and no source asymmetry (Schwartz and Eisenhauer 1982).

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

gamma ray interactions:

Photoelectric absorption - the process whereby a gamma-ray (or x-ray) photon, with energy somewhat greater than that of the binding energy of an electron in an atom, transfers all its energy to the electron, which is consequently removed from the atom.

Compton scattering - an attenuation process observed for x-ray or gamma radiation in which an incident photon interacts with an orbital electron of an atom to produce a recoil electron and a scattered photon of energy less than the incident photon.

Pair production - an absorption process for x-ray and gamma radiation in which the incident photon is annihilated in the vicinity of the nucleus of the absorbing atom, with subsequent production of an electron and positron pair. This reaction only occurs for incident photon energies that exceed 1.02 MeV.

Geiger-Mueller (GM) counter: a radiation measuring device used to detect beta and gamma radiation.

glove box: a device used in handling of quantities of radioactive isotopes to provide containment of the radioactivity and to avoid contamination of the hands.

gray (Gy): the SI unit of absorbed dose. (1 Gy = 100 rad)

half-life: the time required for the activity of a given radioactive species to decrease to half of its initial value due to radioactive decay.

induced radioactivity: radioactivity produced in certain materials as a result of nuclear reactions particularly the capture of neutrons.

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

irradiation category: the type and energy (or mixture) of radiation for which performance criteria are given in ANSI N13.11 (ANSI 1983) or DOE Order 5480.15 (DOE 1987).

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 (keV): an amount of energy equal to 1,000 electron volts.

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

net optical density: value obtained by subtracting background from measured optical density.

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

neutron film dosimeter: a film dosimeter that contains an Eastman-Kodak Neutron Track Emulsion, type A, film packet.

nuclear emulsion: is generally NTA film.

optical density: the quantitative measurement of photographic blackening the density defined as $D = \text{Log}_{10} (I_0/I)$.

"P" Department: Reactor Production Department.

PuF_4 source: a neutron source whose activating material is plutonium fluoride. The source was used to duplicate the neutron energies in Hanford's Z-Plant.

pencil dosimeters: a type of ionization chamber used by personnel to measure radiation dose. Other names: pencil, pocket dosimeter, pocket pencil, pocket ionization chamber.

performance quotient, P_i : the fractional difference between the reported and delivered absorbed dose or dose equivalent for the i th dosimeter,

$$P_i = \frac{[X_i (\text{reported}) - X_i (\text{delivered})]}{X_i (\text{delivered})}$$

where the absorbed dose (D) or dose equivalent (H) can be inserted for X.

photon: a unit or "particle" of electromagnetic radiation consisting of x- and/or gamma rays.

photon - x-ray: electromagnetic radiation of energies between 10 keV and 100 keV whose source can be x-ray machine or radioisotope.

protection dosimetry: routine measurements and the estimation of the dose equivalent for the purpose of determining and controlling the dose equivalent received by radiation workers.

quality factor, Q: a modifying factor used to derive dose equivalent from absorbed dose.

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

radiation: in this report, the term radiation is understood to include beta, neutron, and photon radiation from external sources.

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

RBE: relative biological effectiveness.

Recuplex: plutonium waste products recovery facility in the 234-5-Z Building.

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."

rep: Roentgen-equivalent-physical (mrep = millirep).

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

"S" Department: chemical separations operations (200 Areas).

scattering: the diversion of radiation from its original path as a result of interactions with atoms between the source of the radiations and a point at some distance away. Scattered radiations are typically changed in direction and of lower energy than the original radiation.

shallow absorbed dose (D_s): the absorbed dose at a depth of 0.007 cm in a material of specified geometry and composition.

shallow dose equivalent (H_s): dose equivalent at a depth of 0.007 cm in tissue.

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

sievert (Sv): the SI unit for dose equivalent. (1 Sv = 100 rem.)

sigma pile: a device used to obtain thermal neutrons for calibration purposes.

silver shield(s): the 1-mm- and 0.13- μ m-thick shields covering the film packet in the early personnel film dosimeters.

skin dose: absorbed dose at a tissue depth of 7 mg/cm².

Snoopy: portable neutron monitoring instrument with a moderated BF₃ detector.

standard deviation (S): as used in DOELAP dosimeter performance testing, the standard deviation of the performance quotients is calculated as follows:

$$S = \sum_i^n \left[\frac{(P_i - B)^2}{n - 1} \right]^{1/2}$$

where P_i is the performance quotient for each dosimeter i and B is the bias for the n dosimeters.

TLD chip: a small block or crystal made of LiF used in the TLD.

TLD-600 - A TLD chip made from Li-6 (>95%) used to detect neutrons.

TLD-700 - A TLD chip made from Li-7 (>99.9%) used to detect photon and beta radiation.

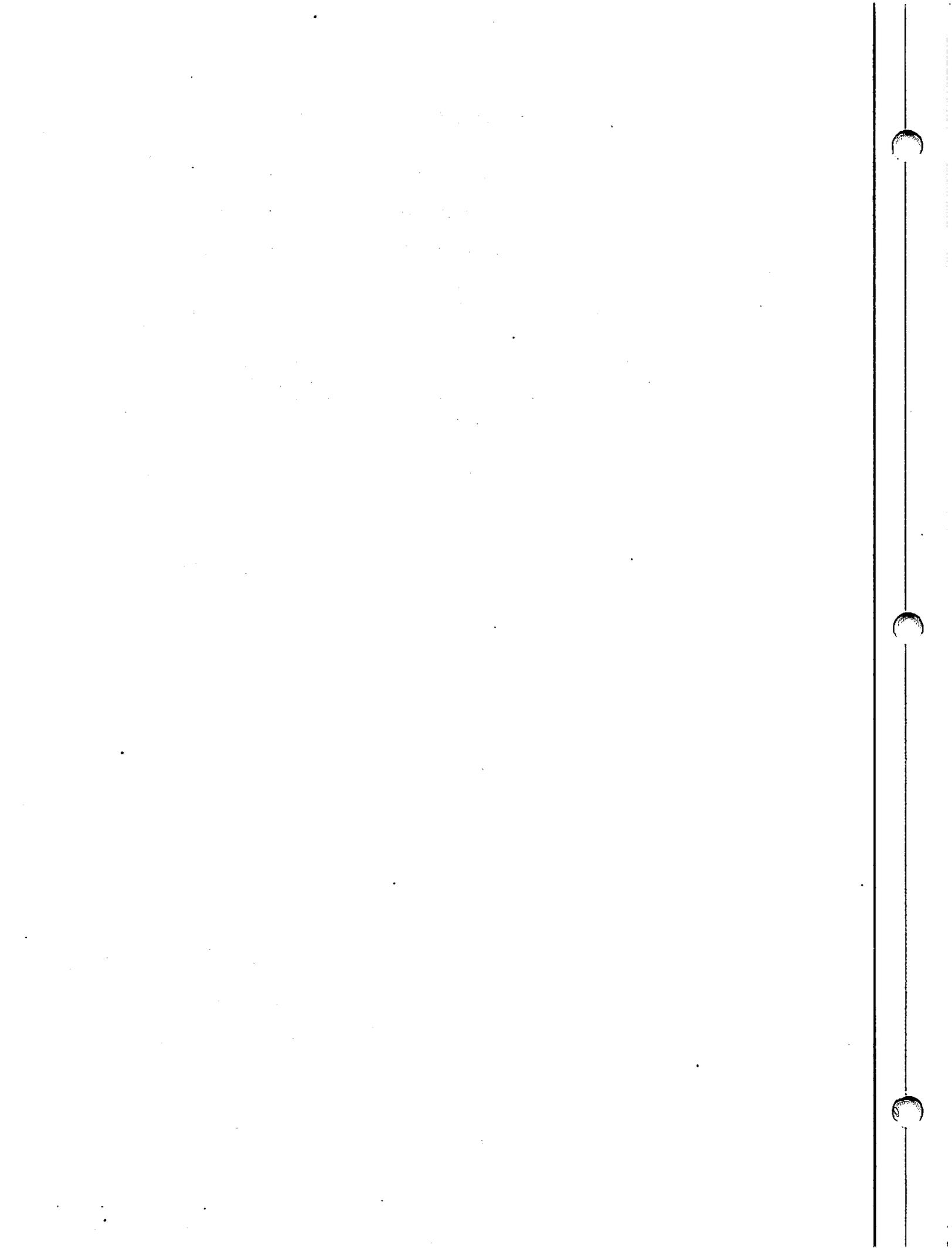
thermoluminescent: property of a material that causes it to emit light as a result of being excited by heat.

thermoluminescent dosimeter (TLD): a holder containing solid chips of material that when heated will release the stored energy as light. The measurement of this light provides a measurement of absorbed dose. The solid chips are sometimes called crystals.

whole body dose: commonly defined as the absorbed dose at a tissue depth of 1.0 cm (1000 mg/cm²); however, this term is also used to refer to the dose recorded.

x-ray: ionizing electromagnetic radiation of extranuclear origin.

Z-Plant: a Hanford facility, composed of several buildings, where plutonium is processed (also known as 234-5-Z Building).



CONTENTS

PREFACE	iii
ABSTRACT	v
EXECUTIVE SUMMARY	vii
ACKNOWLEDGMENTS	xi
ACRONYMS AND ABBREVIATIONS	xiii
GLOSSARY	xv
1.0 INTRODUCTION	1.1
1.1 REPORT PURPOSE AND CONTENTS	1.1
1.2 HISTORICAL OVERVIEW	1.3
1.3 RADIATION PROTECTION PHISOSOPHY	1.5
2.0 HANFORD PERSONNEL BETA/PHOTON DOSIMETERS	2.1
2.1 EARLY USE OF PERSONNEL DOSIMETERS AT HANFORD	2.2
2.1.1 Dosimeter Film, Design, and Assignment	2.4
2.1.2 Processing Film Dosimeters and Pencil Dosimeters	2.7
2.1.3 Film Dosimeter Calibration	2.11
2.2 BETA/PHOTON FILM DOSIMETER USED FROM 1944 TO 1957	2.11
2.3 BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962	2.14
2.4 BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972	2.19
2.5 THERMOLUMINESCENT DOSIMETER USED FROM 1972 TO THE PRESENT	2.24
2.6 PENCIL DOSIMETERS FOR BETA/PHOTON MEASUREMENTS	2.24
2.7 OTHER EXTREMITY DOSIMETERS	2.29
2.7.1 Finger Ring Dosimeters	2.29
2.7.2 Wrist and Flexible Dosimeters	2.30

3.0	HANFORD PERSONNEL NEUTRON DOSIMETERS	3.1
3.1	PENCIL DOSIMETERS USED FROM 1944 TO 1950	3.1
3.2	NEUTRON FILM DOSIMETER USED FROM 1950 TO 1957	3.1
3.3	NEUTRON FILM DOSIMETER USED FROM 1957 TO 1958	3.2
3.4	NEUTRON FILM DOSIMETER USED FROM 1958 TO 1972	3.2
	3.4.1 Design Characteristics	3.2
	3.4.2 Calibration of Nuclear Track Emulsions	3.4
	3.4.3 Cadmium-Clad Tin Shields	3.6
	3.4.4 Quality Factors	3.7
3.5	RHODIUM DOSIMETER	3.7
3.6	THERMOLUMINESCENT NEUTRON DOSIMETER USED FROM 1972 TO THE PRESENT	3.7
	3.6.1 Design Characteristics	3.8
	3.6.2 Calibration	3.9
3.7	ACCIDENT DOSIMETRY	3.9
4.0	DOSIMETER CALIBRATION AND DOSE DETERMINATION	4.1
4.1	TWO-ELEMENT BETA/PHOTON DOSIMETER USED FROM 1944 TO 1957	4.1
4.2	PERSONNEL NEUTRON FILM DOSIMETER USED FROM 1950 TO 1958.	4.7
4.3	MULTI-ELEMENT BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962.	4.8
4.4	MULTI-ELEMENT NEUTRON FILM DOSIMETER USED FROM 1958 TO 1972	4.10
4.5	MULTI-ELEMENT BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972	4.11
4.6	MULTI-ELEMENT THERMOLUMINESCENT DOSIMETER USED FROM 1972 TO THE PRESENT	4.13
4.7	BETA/GAMMA FILM DOSIMETER CALIBRATION	4.15
4.8	LOW-ENERGY GAMMA, PHOTON, AND X-RAY CALIBRATION	4.20

4.9	NTA FILM CALIBRATION PROCEDURE	4.22
5.0	DOSIMETER QUALITY CONTROL PROGRAMS	5.1
5.1	ROUTINE QUALITY CONTROL PROGRAMS	5.1
5.1.1	Early Reviews of Dosimeter Records	5.1
5.1.2	Film and Pencil Dosimeter Control	5.2
5.1.3	Audits of Nuclear Track Emulsion Film Dosimeter Density Readings	5.2
5.1.4	Early Evaluation of Dosimetry for Plutonium X-Rays	5.3
5.1.5	17-keV Deep-Dose Curve	5.5
5.1.6	Examination of Film for Reproducibility from 1944 to 1957	5.6
5.1.7	University of Pittsburgh Film Study	5.6
5.1.8	Personnel Film Dosimeter Audits During 1958 . . .	5.8
5.1.9	1960 Audit of Dosimeter Results	5.9
5.1.10	Routine Audit Dosimeter Program	5.10
5.1.11	Gamma Angular Dependence of the Hanford Atomic Products Operation Film Dosimeter During 1960	5.10
5.1.12	Personnel Exposure to Neutrons	5.13
5.1.13	Characterization of Calibration Sources	5.14
5.2	LABORATORY QUALITY ASSURANCE STUDIES	5.15
5.2.1	Study of DuPont 552 Film	5.15
5.2.2	Studies of Film Dosimeter Variables	5.16
5.2.3	Analysis of Detection Level During 1960	5.20
5.2.4	Security Credential Evaluation	5.21
5.2.5	Fading Effects in Eastman-Kodak NTA Film Emulsion	5.22
5.2.6	NTA Film Study	5.22

5.2.7	Study to Determine Effect of Security Credential Design Change	5.23
5.3	INTERCOMPARISON PROGRAMS	5.23
5.3.1	Intercomparison of Dosimeter Films Used at Hanford and at the Metallurgical and Clinton Laboratories	5.25
5.3.2	Intercomparison of Hanford, Savannah River Plant, Rocky Flats Plant, and Los Alamos National Laboratory Film Dosimeters	5.27
5.3.3	Hanford Dosimeters Exposed at Savannah River Plant in 1959	5.28
5.3.5	Hanford Dosimeters Exposed at Rocky Flats Plant in 1959	5.31
5.3.6	Hanford Dosimeters Exposed at Los Alamos National Laboratory in 1959	5.31
5.3.7	National Film Dosimeter Intercomparison Study . .	5.32
5.3.8	Comparison of Film and Thermoluminescent Dosimeters	5.35
5.3.9	Hanford Personnel Dosimeter Supporting Studies .	5.38
5.3.10	Personnel Dosimeter Accreditation	5.39
6.0	OFFICIAL RECORDED RADIATION DOSE FOR HANFORD PERSONNEL	6.1
6.1	METHODOLOGY FOR RECORDING RADIATION DOSE	6.1
6.2	RECORDS MAINTENANCE	6.4
7.0	PERFORMANCE OF HANFORD DOSIMETERS	7.1
7.1	EVALUATION OF DOSIMETER PERFORMANCE BASED ON HISTORICAL DOCUMENTATION	7.1
7.1.1	Radiation Response Characteristics	7.2
7.1.2	Thermoluminescent Dosimeter	7.5
7.1.3	Dosimeter Detection Levels	7.6
7.2	1989 INTERCOMPARISON STUDY	7.7
7.3	DOELAP ACCREDITATION	7.9

8.0	DEEP DOSE EVALUATION	8.1
8.1	HANFORD PERSONNEL DOSIMETRY PRACTICES AND SYSTEMS . . .	8.1
8.2	HANFORD FACILITIES	8.2
8.3	EVALUATION OF RECORDED DOSE	8.3
8.3.1	Dose from Beta and Photon Radiation	8.4
8.3.2	Dose from Neutron Radiation	8.7
8.3.3	Dosimetry for Personnel with Little or No Occupational Exposure	8.8
8.4	DOSIMETER RESPONSE IN HANFORD FACILITIES	8.9
8.4.1	Two-Element Film Dosimeter Used from 1944 to 1957	8.10
8.4.2	Multi-Element Film Dosimeter Used from 1957 to 1972	8.14
8.4.3	Multi-Element Thermoluminescent Dosimeter Used from 1972 to 1989	8.15
8.5	CONCLUSION	8.16
8.6	FUTURE WORK	8.17
	REFERENCES	Ref.1
	BIBLIOGRAPHYBiblio.1
	APPENDIX A - DOSE ALGORITHM FOR THE BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962	A.1
	APPENDIX B - DOSE ALGORITHM FOR THE BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972	B.1
	APPENDIX C - THERMOLUMINESCENT DOSIMETER ALGORITHMS	C.1
	APPENDIX D - DATA FOR BETA/PHOTON DOSIMETERS EVALUATED DURING THE 1989 INTERCOMPARISON STUDY	D.1
	APPENDIX E - ADDITIONAL LETTERS ON HISTORICAL RADIATION PROTECTION PRACTICES AT HANFORD	E.1

FIGURES

2.1	Reading Film from Film Dosimeters	2.3
2.2	Map of Hanford Site in Southeastern Washington State	2.6
2.3	Original Film Dosimeter Used at Hanford in 1944	2.7
2.4	Picking Up a Film Dosimeter at the Gatehouse When Entering the Process Area	2.8
2.5	The 300 Area Showing the 3701 Gatehouse, 3745 Calibrations Building, and the 3746 Health Instruments Headquarters Building (February 14, 1945)	2.9
2.6	Riveting and Unriveting Film Dosimeters to Recover the Film Packets for Processing	2.10
2.7	Original Modified Metal Hanford Beta/Photon Film Dosimeter Used from 1944 to 1959	2.12
2.8	Early Densitometer Used for Reading Personnel Film Dosimeters	2.13
2.9	Plastic Film Dosimeter Holder Introduced in 1957 and Old Metal Dosimeter Holder Used from 1944 to 1957	2.15
2.10	Design of the Plastic Film Dosimeter Holder Filter System	2.16
2.11	Ratio of Filtered Areas to Indicate Energy of Photon Radiation	2.18
2.12	Energy Response of Each Filter Region of the Beta/Photon Film Dosimeter Used from 1957 to 1962	2.18
2.13	First Hanford Automatic Film Dosimeter Processor (1957) . . .	2.19
2.14	Hanford Film Dosimeter Used from 1962 to 1972	2.20
2.15	Dosimeter Processing Machine Developed in 1962	2.21
2.16	Automatic Reading Densitometer for the Film Dosimeter Used from 1962 to 1972	2.22
2.17	Hanford Basic and Multipurpose Thermoluminescent Dosimeters	2.25
2.18	First Automatic TLD Reader Used at Hanford	2.26

2.19 Pencil Dosimeter Shown with Other Hanford Dosimeters Used from 1944 to 1957	2.28
3.1 Double-Packet Plastic Neutron Film Dosimeter Introduced in 1958	3.3
3.2 Counting Tracks on NTA Film with a Microscope	3.6
3.3 Rhodium Film Dosimeter	3.8
3.4 Hanford Area Criticality Dosimeter	3.11
4.1 Calibration Graph for the First Week of 1950	4.4
4.2 Film Calibration on the "Quija Board"	4.16
4.3 Improved Film Calibration Jig with Rotating Source	4.17
4.4 Uranium Calibration Jig	4.19
4.5 Jig for X-Ray (K-Sources) Calibration	4.21
4.6 Radiators for Various Low-Energy Calibrations	4.23
4.7 Sigma Pile	4.24
5.1 Reproducibility of the 1945 Film Density Readings	5.7
5.2 Net Optical Density of DuPont 552 Film	5.12
5.3 Results of the 1945 Intercomparison of Hanford, Metallurgical Laboratory, and Clinton Laboratory Film Exposed to Radium Gamma Radiation	5.26
5.4 Plywood Disc Used to Simultaneously Expose Hanford, SRP, RFP, and LANL Dosimeters to Plutonium for Intercomparison of Results	5.28
5.5 Comparison of Film Dosimeter and TLD Penetrating Dose Results	5.37
5.6 Comparison of Film Dosimeter and TLD Fast Neutron Dose Results	5.37
6.1 Early Records Maintenance At Hanford: Manual Handling and Storage of Employee Radiation Exposure Histories	6.4
7.1 Hanford Two-Element Dosimeter Response from 1944 to 1957	7.3

7.2 Hanford Multi-Element Film Dosimeter Response
from 1962 to 1972 7.3

7.3 Hanford Multi-Element Thermoluminescent Dosimeter
Response from 1972 to the Present 7.4

TABLES

2.1	Regular Pencil and Film Dosimeter Use at Hanford by Operating Area	2.4
2.2	Filtration Specifications for the Hanford Beta/Photon Personnel Film Dosimeter Holder Used from 1944 to 1957 . . .	2.12
2.3	Filtration Specifications for the Hanford Personnel Beta/Photon Film Dosimeter Holder Used from 1957 to 1962	2.17
2.4	Filtration Specifications for the Hanford Beta/Photon Film Dosimeter Holder Used from 1962 to 1972	2.23
2.5	Personnel Dosimeter Foil System Specifications for the Beta/Photon Film Dosimeter Used from 1962 to 1972	2.23
2.6	Filtration Specifications for the Hanford Personnel Thermoluminescent Dosimeter Holder Used from 1972 to the Present	2.27
3.1	Design Specifications for the Hanford Personnel Neutron Film Dosimeter Holder Used from 1958 to 1972	3.4
4.1	Historical Summary of Hanford Calibration and Dose Assessment Techniques	4.2
4.2	Calibration Data for the First Week of 1950	4.3
4.3	Standard Calibration Curve Developed in 1951	4.5
4.4	Standard Calibration Chart for DuPont 502 Film	4.6
4.5	Irradiations for Calibrated Film Sets from 1951 to 1957	4.9
5.1	Results of the 1951 Nuclear Track Film Processing Audit . . .	5.3
5.2	X-Ray Component of Total Dose	5.5
5.3	Results of Film Audit Dosimeters During 1958	5.8
5.4	Audit of Dosimeter Results During 1960	5.9
5.5	Radium Gamma Dosimeter Audit Results During 1966	5.11
5.6	Neutron Dosimeter Audit Results from 1965 to 1967	5.11
5.7	Optical Density Results for DuPont 508 Film	5.18

5.8	Absolute Error in Optical Density Units for DuPont 508 Film	5.18
5.9	Effect of Security Credential on Dose Assessment	5.24
5.10	Intercomparison of the Hanford, Metallurgical Laboratory, and Clinton Laboratory Film Dosimeters in 1945	5.25
5.11	Comparison of Total Dose for Hanford, Metallurgical Laboratory, and Clinton Laboratory Film Dosimeters in 1945	5.26
5.12	Hanford Film Dosimeter Results	5.29
5.13	Total Dose Comparison for all Laboratories	5.29
5.14	Comparison of Hanford and SRP Dosimeters	5.30
5.15	Hanford Dosimeters Exposed at Savannah River Plant	5.31
5.16	Hanford Dosimeters Exposed at Rocky Flats Plant	5.32
5.17	Hanford Dosimeters Exposed At Los Alamos National Laboratory	5.33
5.18	Hanford Intercomparison Study Results in 1967	5.34
5.19	Fast Neutron Dose Measurements	5.36
6.1	Terminology Used to Record Hanford Dosimeter Results	6.2
6.2	Methods of Determining Recorded Doses from Dosimeter Results	6.3
7.1	Hanford Dosimeter Holders Used in the 1989 Intercomparison Study	7.8
7.2	1989 Intercomparison Study Radiation Sources and Exposure Levels	7.8
7.3	Intercomparison of Deep Dose Determination for Hanford Film and Thermoluminescent Dosimeters	7.9
7.4	Intercomparison of Shallow Dose Determination for Hanford Film Dosimeters	7.10
7.5	Shallow and Deep Dose Performance Test Data	7.12
8.1	Dose Response of the Hanford Two-Element Film Dosimeter Used from 1944 to 1957	8.11

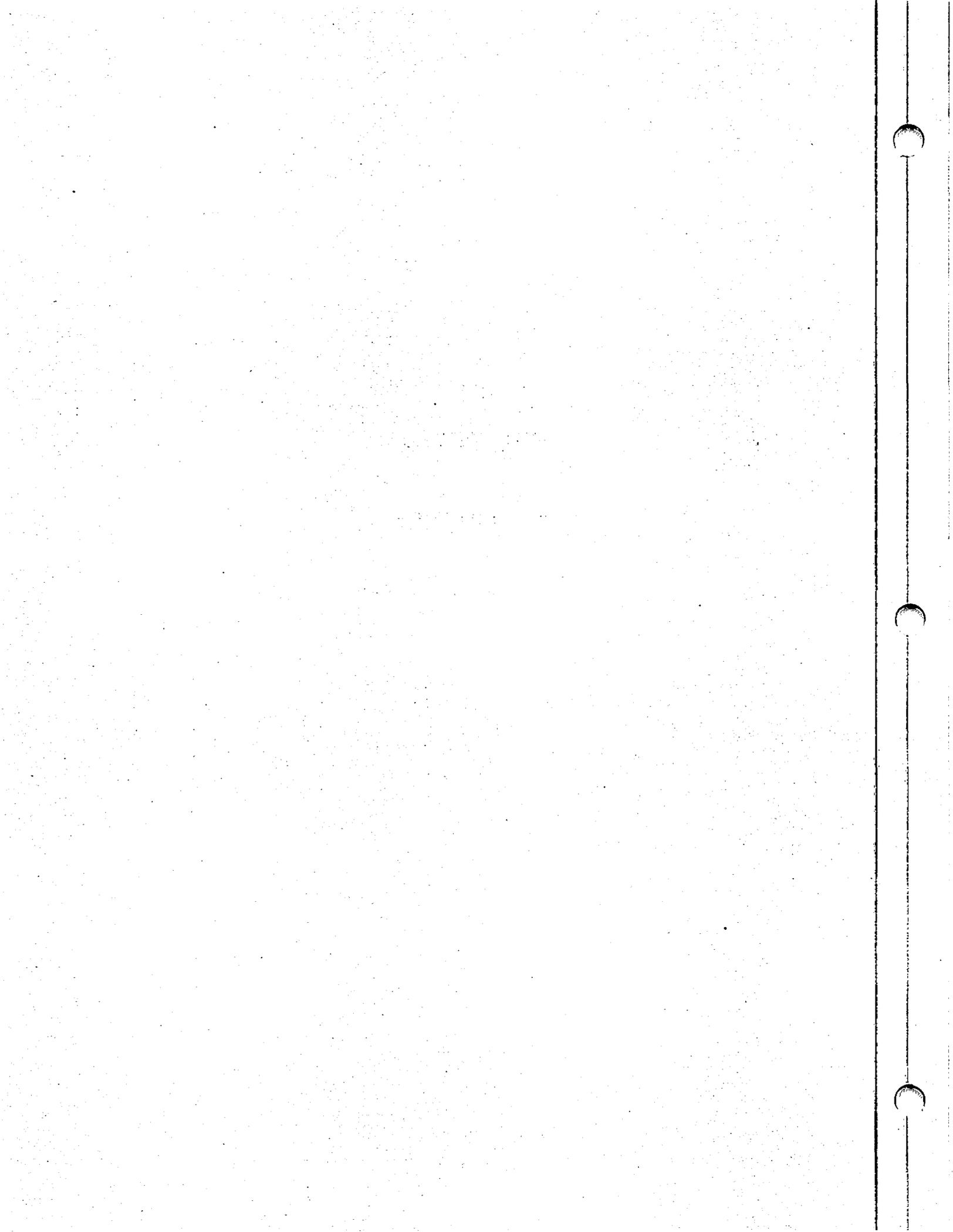
8.2 Dose Response of the Hanford Multi-Element Film
Dosimeter Used from 1957 to 1972 8.12

8.3 Dose Response of the Hanford Multi-Element
Thermoluminescent Dosimeter Used from 1972
to 1989 8.13



CHAPTER 1.0

INTRODUCTION



1.0 INTRODUCTION

External dose has been measured and recorded for Hanford personnel since the beginning of operations in 1944. The technology used to measure radiation dose has evolved throughout the nearly 5 decades of Hanford operations. This report aims to describe dosimetry systems used to determine personnel dose and to evaluate the accuracy of the recorded dose for the different dosimeters and periods of use relative to a currently accepted national basis (i.e., deep dose). The evaluation is difficult because of the significant variation in beta, photon, and neutron radiation fields in the various Hanford facilities, as well as numerous technological and environmental aspects of the dosimeters used and the changing concepts in dose over the years.

1.1 REPORT PURPOSE AND CONTENTS

This report was prepared by Pacific Northwest Laboratory (PNL)^(a) for the U.S. Department of Energy (DOE) to meet two primary objectives: 1) provide a historical overview of Hanford personnel dosimeter practices and, 2) evaluate the accuracy of recorded whole body doses in support of the Hanford Health and Mortality Study (Gilbert 1989).^(b) A current international effort to pool data from existing epidemiological studies is being undertaken to improve the assessment of risk from radiation exposure (IARC 1989). Documentation of past dosimetry practices as well as some assessment of accuracy are necessary to determine the consistency of dose estimates for these different studies. In this report, the recorded whole body dose is compared with the deep dose. The deep dose is used in current dosimeter performance studies (ANSI 1983; DOE 1987) and is defined as the dose at a depth of 1-cm (or 1000 mg/cm²) in tissue.

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- (a) Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.
- (b) The Hanford Health and Mortality Study is an ongoing study of Hanford workers by PNL and the Hanford Environmental Health Foundation to determine if cause-specific mortality is associated with cumulative radiation dose, and to what extent direct data on a population exposed at low levels can confirm or reject risk estimates based on extrapolation from high dose data.

Efforts have been underway for many years to better document Hanford dosimetry practices. An early summary was prepared by Heid and Allen in 1974 in support of the Hanford Health and Mortality Study.^(a) Wilson provided an overview in 1987 of radiation monitoring, portable instrument, radiological calibration, and internal and external dosimetry practices at Hanford (Wilson 1987). An overview of portable radiological instrumentation at Hanford was provided in 1989 (Howell et al. 1989).

This report goes beyond these earlier reports in providing considerably more detailed information on technical aspects of historical external dosimetry practices at Hanford. The remainder of this chapter provides a brief historical overview and a discussion of radiation protection philosophy. The evaluation of personnel dosimetry technology and associated practices and studies are described in the ensuing chapters of this report, which contain the following:

- the development of dosimetry technology at Hanford, including the specific dosimeters used since 1944 (Chapters 2.0 and 3.0)
- technical details of dosimeter calibration and dose determination (Chapter 4.0)
- dosimeter quality control and intercomparison programs and quality assurance studies that have been conducted at Hanford (Chapter 5.0)
- the methods used to calculate the recorded skin and whole body doses (Chapter 6.0)
- the results of a laboratory intercomparison study conducted during 1989 of all Hanford film dosimeters as well as the performance of the Hanford thermoluminescent dosimeters (TLDs) (Chapter 7.0)
- comparison of whole body dose with expected deep dose and the expected performance of Hanford personnel dosimeters used in typical radiation fields (Chapter 8.0).

In addition, five appendixes provide supplemental information. Appendixes A through C, respectively, contain the dose algorithm used for the beta/photon film dosimeters used from 1957 to 1962 and from 1962 to 1972 and for the TLD. Appendix D contains a description of the chronological history of major TLD

(a) Heid, K.R., and H.W. Allen. "Input Data to the AEC Health and Mortality Study, Radiation Exposure Experience of Employees 1944 Through 1974." Internal report, dated December 31, 1974, Pacific Northwest Laboratory, Richland, Washington.

system changes at Hanford. Appendix E contains a list of letters on historical radiation protection practices at Hanford. Chapter 8.0 integrates much of the more detailed information provided in earlier chapters, and provides an overall assessment of Hanford dosimetry practices. This assessment addresses the specific performance of dosimeters by time period and by facility. Readers may wish to obtain an overview by reading Chapter 8.0 prior to reading the detailed information presented in Chapters 2.0 through 7.0.

Please note that although radiation protection instruments, facilities, etc., have gone by different names historically, the most current terms are used in this report, i.e., film dosimeter, not film badge; pencil dosimeter, not pocket ionization chamber, Hanford or Hanford Plant, not Hanford Engineer Works, etc. Also, note that throughout this report, the "File" in footnote references, such as "Memorandum to the File," is a working file maintained by PNL's External Dosimetry group for their internal day-to-day use. Copies of such letters and memorandums to "the File," as well as other letters and documents footnoted herein, are also on file for wider access in the Hanford Radiation Protection Historical Files, maintained by PNL's Dosimetry Records group.

1.2 HISTORICAL OVERVIEW

Early in 1942, a metallurgical laboratory was established at the University of Chicago to develop methods of plutonium production and separation. In that same period of time, a highly secret atomic bomb project was assigned to the U.S. Army, and the associated Corp. of Engineers District was named the Manhattan District. Thus the "Manhattan Project" was created, and General Leslie R. Groves, then a Colonel in the Corp. of Engineers, was assigned overall responsibility for the project.

On December 2, 1942, the first successful nuclear chain reaction was achieved by Enrico Fermi at the University of Chicago's Metallurgical Laboratory, thereby providing the impetus for an all-out effort for production of plutonium. Immediately following the successful sustained nuclear reaction, U.S. Army Colonel Franklin T. Matthias was assigned to lead a search for a plutonium production site, and in late December the U.S. Government signed a contract with the E. I. DuPont de Nemours Company (DuPont Company) for

engineering, design, construction, and operation of the production plant. By December 31, 1942, the Hanford, Washington area was selected for development as a plutonium production site, which became known as the Hanford Engineer Works (HEW). Reactors for producing plutonium, chemical separations plants, fuels preparation plants, and a town for many thousands of people were built in a very short period of time. By September 1944, the first Hanford reactor began operation, and by February 1945 the first plutonium was delivered to Los Alamos, New Mexico, for use in the war effort.

In mid-1942, during the initial days of the Manhattan Project, Dr. Simeon T. Cantril, MD, a radiation therapist, was recruited from Swedish Hospital in Seattle, Washington, because of his work with radiation at the hospital's tumor institute. Later that year, Herbert M. Parker, a radiation physicist, was also recruited from Swedish Hospital because of his accomplishments in radiation physics. These recruitments marked the beginning of the development of large-scale radiation protection programs that evolved from the group of scientists assembled at the University of Chicago to work on developing the first sustained nuclear chain reaction and plutonium production. When the Medical Division was formed in August 1942 at the Metallurgical Laboratory in Chicago, radiation protection on the scale that would be developed had never before been envisioned. Parker headed the radiation control work at the Metallurgical Laboratory and Oak Ridge National Laboratory (ORNL; previously called Clinton Laboratory) in 1943 and 1944. From the developments at these locations, he envisioned that a much larger and more multi-talented staff than originally anticipated would be needed to support the work to be done at Hanford.

Parker transferred to Hanford in July 1944 when recommended by Dr. Robert S. Stone, Medical Director of the Manhattan Project, and Dr. Arthur H. Compton, Metallurgical Project Director, after they reviewed his outstanding work with the Manhattan Project. The position of Chief Supervisor was created for him in the Hanford Medical Department and he immediately initiated the necessary recruitment to form a radiation protection organization. This group, initially named the Health Instruments (HI) Section, developed throughout the years as an integral part of the organization necessary to safely operate such a large and complex nuclear facility.

Since Hanford startup, the responsibility for various Hanford operations has changed hands on several occasions and the radiation protection organization has evolved accordingly. In September 1946, DuPont Company relinquished operation of Hanford to General Electric Company (GE). During GE's management of the site, the Radiological Sciences Department, including its Radiation Protection subgroup, was created and later became integrated with the Hanford Laboratory Operation when the latter was created in 1956. In 1963, a multi-contractor approach to operating Hanford was initiated. By the end of 1964, United States Testing Company, Inc., (UST) was contracted to conduct the routine processing of Hanford personnel dosimeters, biological samples, and environmental samples. The Radiation Protection Department became part of Battelle Memorial Institute's Pacific Northwest Laboratory (PNL) organization on January 4, 1965, upon Battelle's assumption of the overall responsibility for the operation of the Hanford laboratory functions. Reactor operation, chemical separations functions, and other smaller functions necessary for the operation of the Hanford Plant were subsequently assumed by other contractors within the next year. In 1987 reactor and chemical separations functions were reconsolidated under the direction of the Westinghouse Hanford Company. In October 1988 PNL assumed responsibility for processing all personnel dosimeters.

1.3 RADIATION PROTECTION PHILOSOPHY

Radiation protection philosophy and capabilities have evolved at Hanford throughout the Manhattan Project. In the beginning, radiological instrumentation and dosimetry were based on techniques developed for use in the medical application of radiation measurement that involved only a few highly specialized persons. These techniques were the basis for the development of new techniques required to support the operation of the various Hanford facilities that housed reactor, fuel fabrication, fuel separation, and waste disposal functions. This pioneering effort at Hanford involved many uncertainties, because the safe handling of large quantities of radioactive material and the involvement of large numbers of people being exposed to many types of radiation had not been encountered before.

Technology developments at Hanford paralleled the radiation protection developments started at the University of Chicago Metallurgical Laboratory and

ORNL which had been primarily under the direction of Dr. Simeon T. Cantril and Herbert M. Parker since mid-1942. These laboratories were involved in the earliest development of nuclear weapons design and technology, while Hanford was primarily involved in the production of weapons-grade plutonium for use in weapons after the first successful nuclear chain reaction was achieved by Enrico Fermi at the Metallurgical Laboratory on December 2, 1942. The technology used to develop personnel dosimeters evolved with the increasing knowledge of radiation, radiological instrumentation, and radiation dosimetry, particularly with respect to radiation fields in Hanford facilities. Dosimeters and processing equipment to measure personnel exposure to radiation, as well as calibration techniques and radiation dose assessment methods, had to be developed. In compliance with applicable scientific and/or regulatory guidance, measurement results from these dosimeters were recorded to provide the official radiation dose record for Hanford employees.

From the very beginning the underlying philosophy instilled by early leaders, such as Parker and Cantril, was conservatism in the measurement and reporting of radiation exposure for workers. A policy of maintaining the workers' radiation exposure as low as practicable was quickly adopted for Hanford operations by Parker.^(a) There was also a strong desire from the onset to establish a permanent and official record of each employee's radiation exposure history, which included those occasions where exposure may not have been properly recorded by the person's radiation dosimeter. A policy for radiation safety was established and stated in a Hanford memorandum issued in 1945.^(b) Safety policies have been revised and upgraded continuously to reflect the growth in knowledge from experience and technical development and to be responsive to changes in regulations and directives from government agencies.

In 1954 the first 10 years of Hanford operations were assessed in an article that contained a discussion of several of the concerns about adapting techniques used in the medical community to anticipated problems at Hanford

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- (a) Parker, H. M. 1945. "Health Instruments Section-Exposure Standards, Reports, and Records." Memorandum to the File, dated September 7, 1945, DuPont Company, Richland, Washington.
- (b) Cantril, S. T. 1945. "Plant Medical Section Activities to August 1, 1945." Memorandum to the File, dated August 25, 1945, DuPont Company, Richland, Washington.

(Parker 1954). More recently, a comprehensive history of radiation protection practices used at Hanford was compiled (Wilson 1987). As of the last few years, data accumulated from personnel dosimeters are being used in epidemiological assessments to evaluate potential health effects from occupational radiation exposure at Hanford. With the additional radiation exposure data and evaluation of doses provided by this report, a more refined assessment of health effects can be made for Hanford radiation workers.



CHAPTER 2.0

HANFORD PERSONNEL BETA/PHOTON DOSIMETERS



2.0 HANFORD PERSONNEL BETA/PHOTON DOSIMETERS

Three primary personnel dosimeter techniques have been used at Hanford to measure beta, photon, and neutron radiation; these include the use of photographic emulsions on film, thermoluminescent materials in various configurations and types of dosimeters, and pencil dosimeters. The use of photographic emulsions to record radiation exposure began with the earliest history of radiation in the late 1800s. The sensitive material, or the emulsion, consists of small silver halide crystals in gelatin. The emulsion is used in the form of thin layers spread on film (cellulose acetate) or glass. The thickness of the emulsion varies from a few to several hundred microns, with the most common emulsions being between about 10 μm and 25 μm thick. The primary purpose of the gelatin is to permanently fix the silver halide crystals on the film (or glass), while also permitting the developing chemicals to come in contact with the crystals in order to develop an image. In the presence of radiation, electrons traversing the emulsion become trapped in the crystal lattice, thereby reducing the silver ions to atomic silver. These silver atoms, in turn, result in deeper traps that capture electrons, resulting in more silver atoms, and eventually forming microscopic aggregates of silver atoms, which constitute the latent image. When the film is developed, the latent images are reduced to metallic silver, which appears to the eye as the darkening of film or microscopic tracks in nuclear emulsions.

Thermoluminescent materials have been used widely in radiation detection since the 1960s. These materials characteristically store energy in the form of trapped electrons and luminesce when heated. The intensity of the luminescence is proportional to the energy absorbed from radiation. Many thermoluminescent materials are used. Since 1972, crystals of lithium fluoride (LiF) have been used in Hanford personnel dosimeters worn to record the radiation exposure of Hanford workers from beta, photon (i.e., gamma and x-ray radiation), and neutron radiations. These crystals have several desirable characteristics. The atomic number of LiF (8.14) is close to that of human tissue (7.4), so that the absorbed energy for photon radiation for LiF and human tissue is also similar. The crystals are available in a form that contains 99.999% pure ^7Li . In this form a crystal is responsive to beta and photon radiation, but has essentially no neutron response. However, another

crystal form contains 95% pure ^6Li , which is not only responsive to beta and photon radiation but also has a very high response to slow neutrons. Thus, by combining both forms of crystals in the design of a personnel dosimeter, the neutron radiation component can also be determined. Typically, the response is based on the reflected (i.e., "albedo") neutrons from the body. Dosimeters of this type are referred to as "albedo neutron dosimeters." (Hanford personnel neutron dosimeters are discussed in Chapter 3.0.)

A third type of dosimeter, adapted from medical and specialized research use prior to the Manhattan Project, is the condenser ionization chamber, commonly called the pencil dosimeter. These devices, which can easily be carried in the pocket or clipped to clothing, are designed to measure x-ray and gamma radiation. When using pencil dosimeters, auxiliary equipment is required to supply an initial voltage (or charge) and an electrometer is necessary to measure the residual voltage after the dosimeter has been exposed to radiation. The reduction in voltage is proportional to the radiation exposure. These devices have been improved and modified to provide the ability to directly read the radiation exposure from a scale located in one end of the dosimeter and to better withstand jolting, which tends to discharge the chamber and give a false exposure reading. Pencil dosimeters, however, have been used throughout Hanford operations to provide personnel with an immediate method of monitoring radiation exposure in their work environment. Because of limitations with pencil dosimeters, the official radiation dose of record for personnel has always been determined with film dosimeters and TLDs.

From 1944 to 1972, film in three distinct types of dosimeters was used to record the beta and photon radiation exposure of Hanford radiation workers. Each of these dosimeters, their periods of use, type of film, filtration specifications, evaluation methods, etc., are described in the following subsections.

2.1 EARLY USE OF PERSONNEL DOSIMETERS AT HANFORD

During the initial period of construction of the Hanford reactors and chemical separations plants, attempts were made to establish a system for monitoring personnel exposure to radiation. To this end, the first pencil dosimeter program was started in January 1944 in the 100 Areas (reactor operations) by the "P" Department, and subsequently in the 300 Area (fuels

preparation and laboratory functions). In July 1944, after the Health Instruments Section was formed as part of DuPont's Medical Department, responsibility for the 300 Area pencil dosimeter program was transferred to the Health Instruments Section. Soon the Health Instruments Section was also made responsible for plant-wide film dosimeter and pencil dosimeter programs that were to be activated as soon as equipment and personnel became available to administer these operations.

There are some indications that film was used in the latter part of July 1944, but it probably was used only on a trial basis with dosimeters from the Metallurgical Laboratory or Clinton Laboratory. The first film dosimeters used at Hanford to record radiation exposure were processed in October 1944. During this early period, film reportedly was spread out on a white table top and only the film with visible darkening was read on a densitometer (see Figure 2.1).



FIGURE 2.1. Reading Film from Film Dosimeters

A summary of the dates when regular film and pencil dosimeter coverage of selected personnel began in the plant operating areas is provided in Table 2.1. The Hanford Site map in Figure 2.2 shows the general layout of the operating areas and the distances between these areas and the surrounding communities. The 100 Areas along the river were the sites of Hanford's plutonium production reactors. Each of the nine plutonium production reactors was identified with a specific area such as 100-B Area (B Reactor), 100-D Area (D Reactor), etc. Fuel reprocessing and plutonium separation were conducted in the 200-East and 200-West Areas, where, over the years, several different facilities were used to conduct this effort. As mentioned previously, Hanford laboratory support was conducted in the 300 Area. The Fast Flux Test Facility (FFTF), involving a sodium-cooled test reactor, is located in the 400 Area.

A general overview of early dosimetry practices--the dosimeter design and film used, processing methods, and the use of calibration data--is provided in the following subsections.

2.1.1 Dosimeter Film, Design, and Assignment

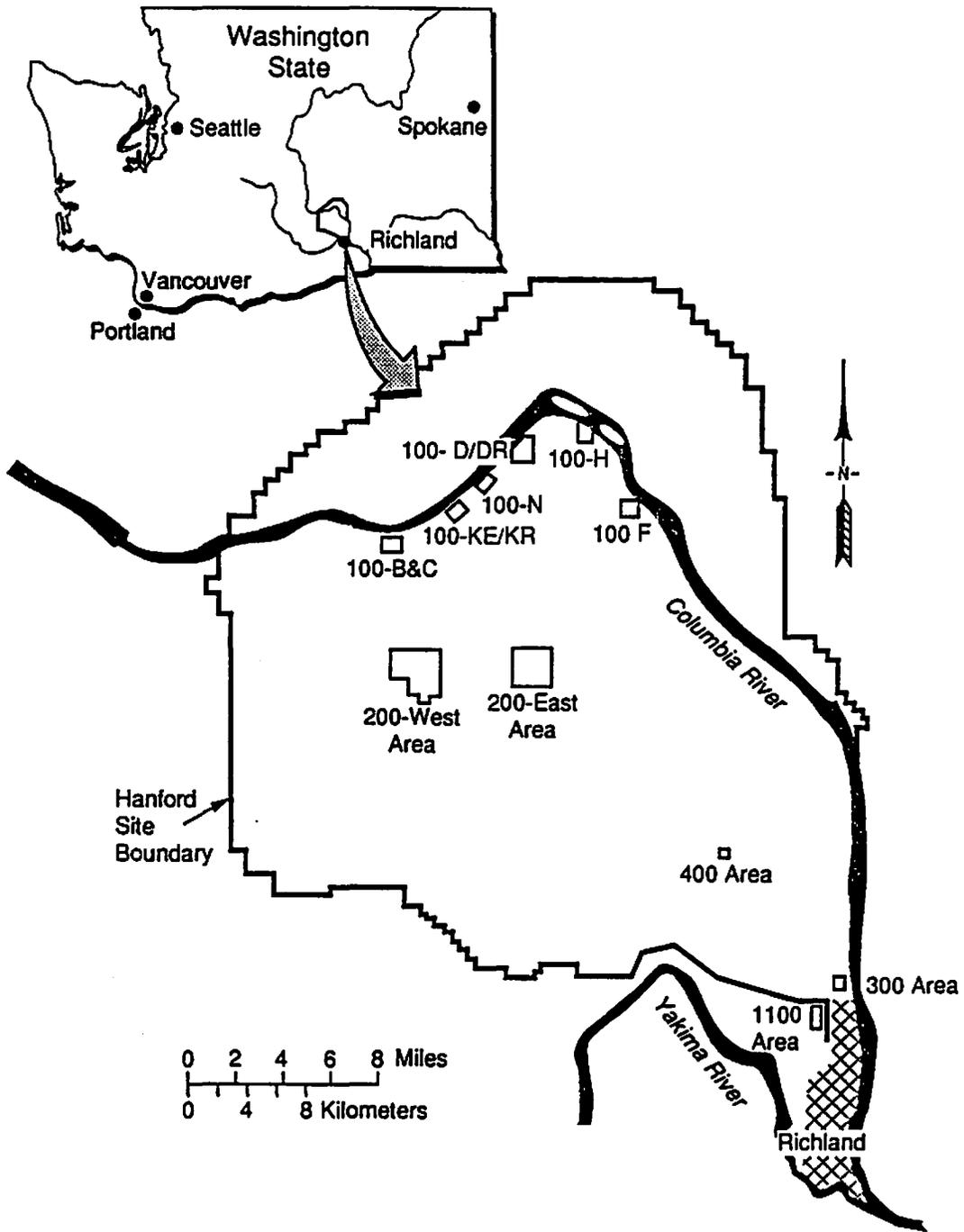
The original film used in beta/photon dosimeters (beginning in 1944) was the DuPont 552 film^(a) packet, which contained a sensitive film and an insensitive film packaged together in a lightweight, light-tight wrapper. The packet was housed in a holder totally shielded by silver that was 1 mm thick, with the exception of a 1.0-cm² hole, or open window, located symmetrically on the front and back of the badge. This system was developed by Wollan (Pardue, Goldstein, and Wollan 1944) at the University of Chicago Metallurgical Laboratory to balance film energy dependence.

Although the film dosimeter (see Figure 2.3) used at Hanford during the first few months of 1944 was identical in design to those used at the Metallurgical and Clinton Laboratories, it was soon modified to incorporate a security credential as an integral part of the dosimeter by enlarging the badge and was required to be worn in full view by all persons entering any of the Hanford operating areas. These dosimeters were not allowed to be taken from the area in which they were used; so it was necessary to pick them up

(a) The different types of DuPont film or film packets mentioned in this report (552, 520, and 502) are all products of E. I. DuPont de Nemours Company, Wilmington, Delaware.

**TABLE 2.1. Regular Pencil and Film Dosimeter Use at Hanford
by Operating Area**

<u>Area</u>	<u>Dosimeter Type</u>	<u>Date</u>	<u>Comments</u>
100-B	Pencil Film	September 11, 1944 September 13, 1944	B Reactor went critical on September 15, 1944
200-West	Pencil Film	November 7, 1944 November 7, 1944	T-Section of 200-West Area was accepted for use on October 9, 1944; the first tracer run of Clinton "slugs" started on December 6, 1944; 200-West Area was accepted for use on December 18, 1944
300 Area	Pencil Film	November 25, 1944 November 25, 1944	The 305 Test Pile went critical on February 23, 1944; production line canning of "slugs" started on May 11, 1944
100-D	Pencil Film	December 5, 1944 December 5, 1944	D Reactor went critical on December 6, 1944
100-F	Pencil Film	February 13, 1945 February 13, 1945	F Reactor went critical on February 15, 1945
200-East	Pencil Film	March 15, 1945 March 15, 1945	200-East Area was accepted for use on February 2, 1945



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FIGURE 2.2. Map of Hanford Site in Southeastern Washington State



FIGURE 2.3. Original Film Dosimeter Used at Hanford in 1944

from the Security Patrol (see Figure 2.4) upon entering an area and drop them off with a patrolman when leaving the area. Two pencil dosimeters were also given to each employee upon entering an operating area and then were turned in by the employee when leaving the area.

2.1.2 Processing Film Dosimeters and Pencil Dosimeters

The original dosimeter processing plan at Hanford located the laboratories for processing film dosimeters and pencil dosimeters in the gatehouse at the entrance to each operating area. However, when the personnel dosimeter program actually started all film dosimeters were processed and read in the 300 Area 3701 Gatehouse (see Figure 2.5). Pencil crews handled and serviced the pencil dosimeters in each area gatehouse for each shift. A traveling film dosimeter crew serviced the film dosimeters weekly. The film packets, after being identified with a portable x-ray unit, were brought to the 3701 Gatehouse for processing and reading. Processing and evaluating of personnel film packets were moved to the 3705 Building when it was completed in 1949 and until mechanized processing started in 1957.

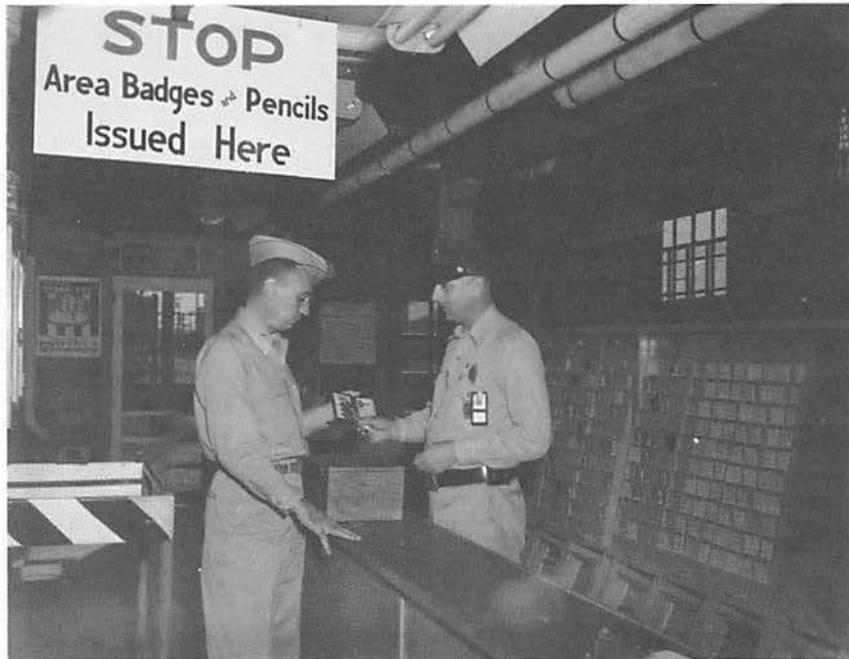


FIGURE 2.4. Picking Up a Film Dosimeter at the Gatehouse When Entering the Process Area

The film dosimeter was introduced for the first time for regular use in the 100-B Area on September 13, 1944, and plans called for the dosimeters to be processed weekly. However, these film dosimeters were not processed for the first time until October 18, 1944, because processing equipment was not ready to handle them. The 100-B Area film dosimeters were then processed at the end of November and 100-D and 200-W Area film dosimeters were processed in January 1945--all in the 300 Area. By February, 20,300 film dosimeters had been processed and because of the unriveting and riveting (see Figure 2.6) necessary to remove the film packet for each processing, the dosimeter holders started showing wear and the dosimeter components and equipment required increasingly more repair and replacement.

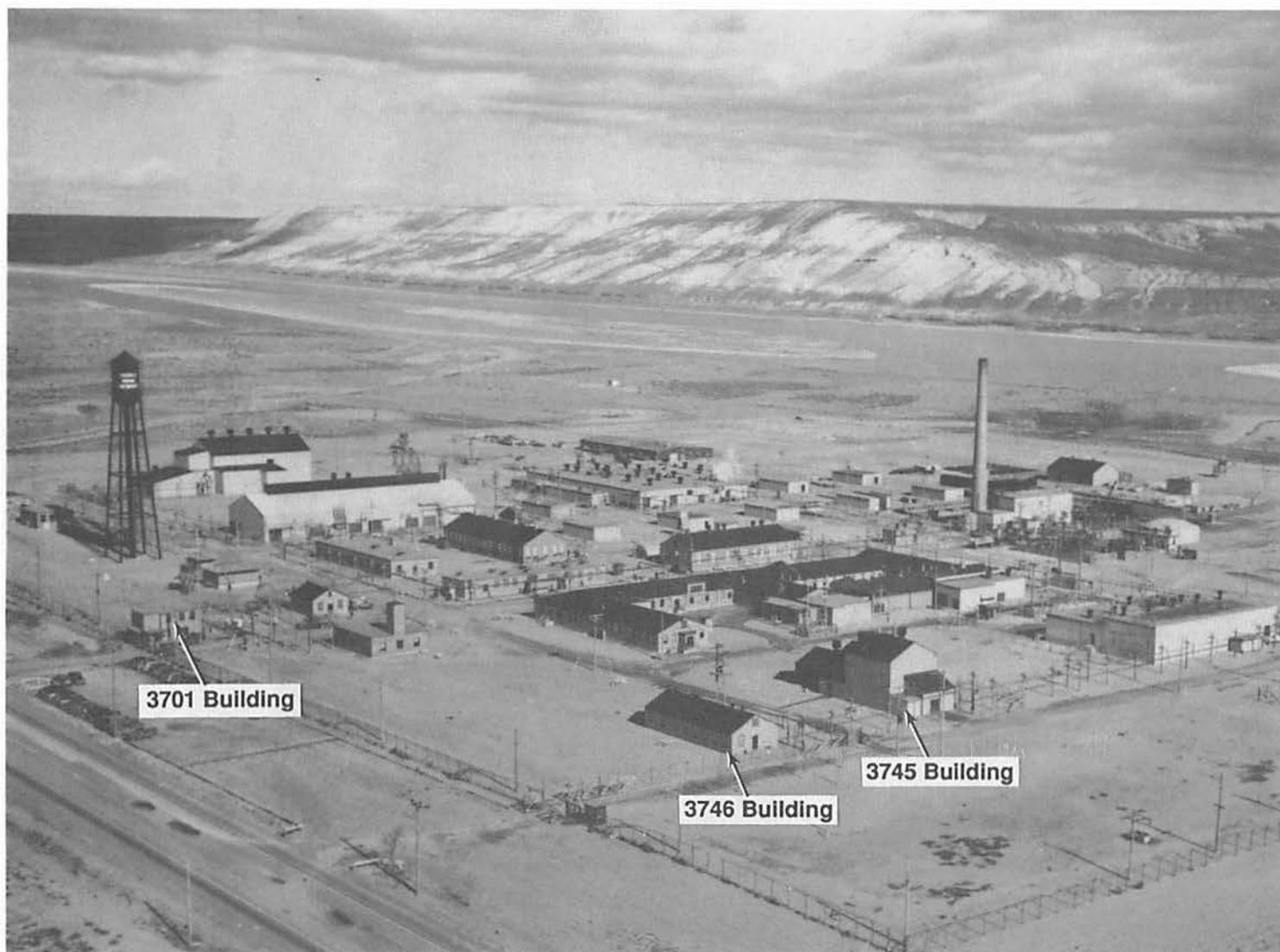


FIGURE 2.5. The 300 Area Showing the 3701 Gatehouse, 3745 Calibrations Building, and the 3746 Health Instruments Headquarters Building (February 14, 1945)



FIGURE 2.6. Riveting and Unriveting Film Dosimeters to Recover the Film Packets for Processing

2.1.3 Film Dosimeter Calibration

No evidence of calibration prior to 1945 has been found and it appears that values of exposure were assigned according to film density, i.e., .03, .05, and .06 represented 30 mR, 50 mR, and 60 mR. The first recorded calibration data used for reading personnel film apparently came in March 1945 (Wilson 1957). At that time, radium gamma data for a 10-day period were averaged and a curve for the shielded and open window portions was established. A radiation dose was assigned for both open window and shielded areas by reading directly from the calibration curve. This system was used through 1945 until a beta curve was established for the open window portion by exposing it to a slab of uranium. All open window density was considered beta exposure during the first 2 years of operation.

2.2 BETA/PHOTON FILM DOSIMETER USED FROM 1944 TO 1957

The film dosimeter used at Hanford from July 1944 through March 1957 consisted of a case fabricated from a machine-stamped metal plate and fitted with two silver filters, each 1 mm thick. A film packet was placed between the two filters. DuPont 552 film packets were used in the dosimeter throughout this time period. This packet was composed of a sensitive 502 film and an insensitive 510 film. The open window consisted of a 1-cm² hole symmetrically located in the two silver filters. The Hanford security credential was located on the front of the dosimeter along with a sheet of celluloid, which together measured about 95 mg/cm² and were an integral part of the dosimeter during this period of use. There was no additional material over the rear filter. The filtration specifications for this dosimeter holder are summarized in Table 2.2 and the dosimeter is illustrated in Figure 2.7.

All of the density of the film in the open window position was conservatively considered beta exposure during the first 2 years of operation. In the succeeding years the open window density was corrected for the contribution of penetrating exposure density from behind the shielded portion of the film dosimeter. A photograph of a densitometer used to read the film density during the early years of operation is shown in Figure 2.8.

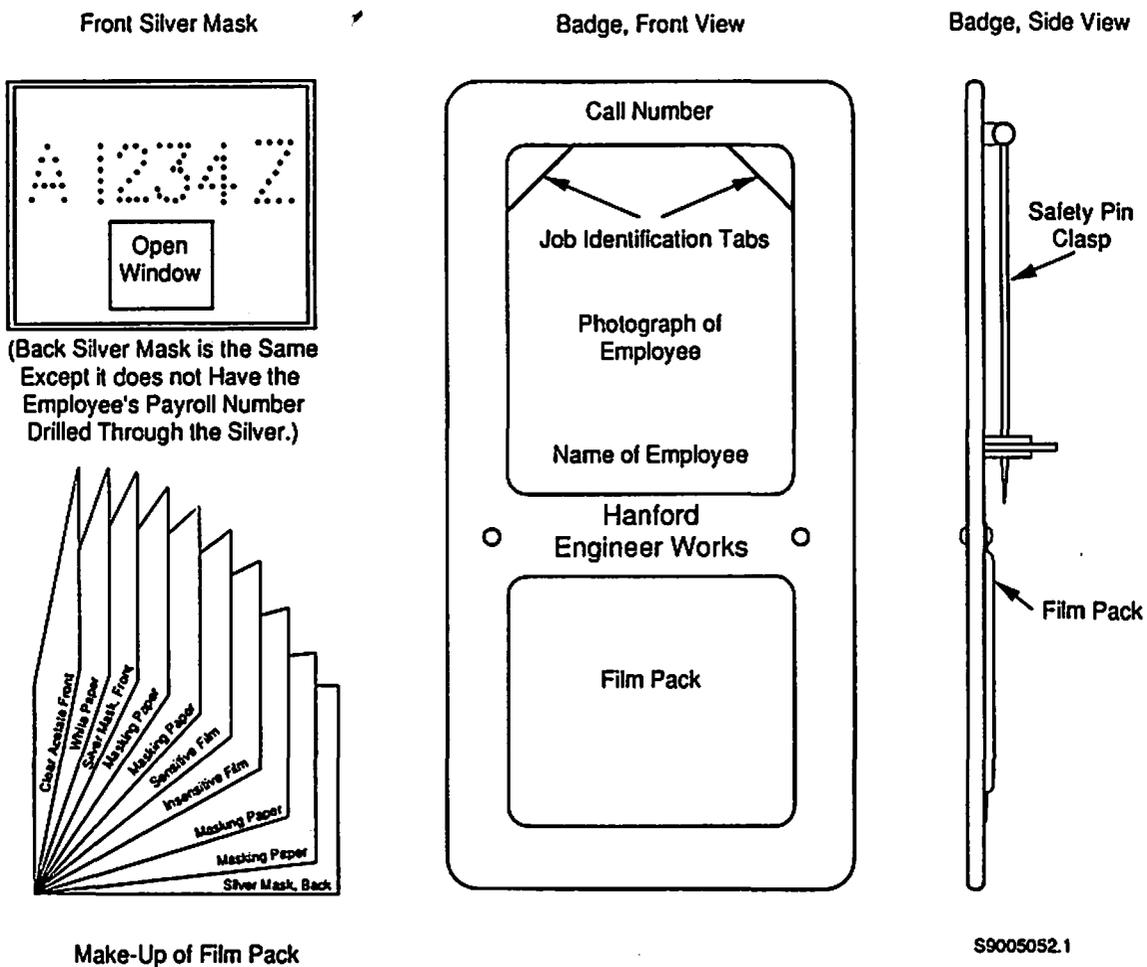


FIGURE 2.7. Original Modified Metal Hanford Beta/Photon Film Dosimeter Used from 1944 to 1957

TABLE 2.2. Filtration Specifications for the Hanford Beta/Photon Personnel Film Dosimeter Holder Used From 1944 to 1957

Dosimeter Position	Material	Holder	
		Thickness, cm	Mass Density, mg/cm ²
Open window	Security credential	0.06	60
	Cellulose	0.025	35
Silver	Security credential	0.06	60
	Cellulose	0.025	35
	Silver	0.1	1050

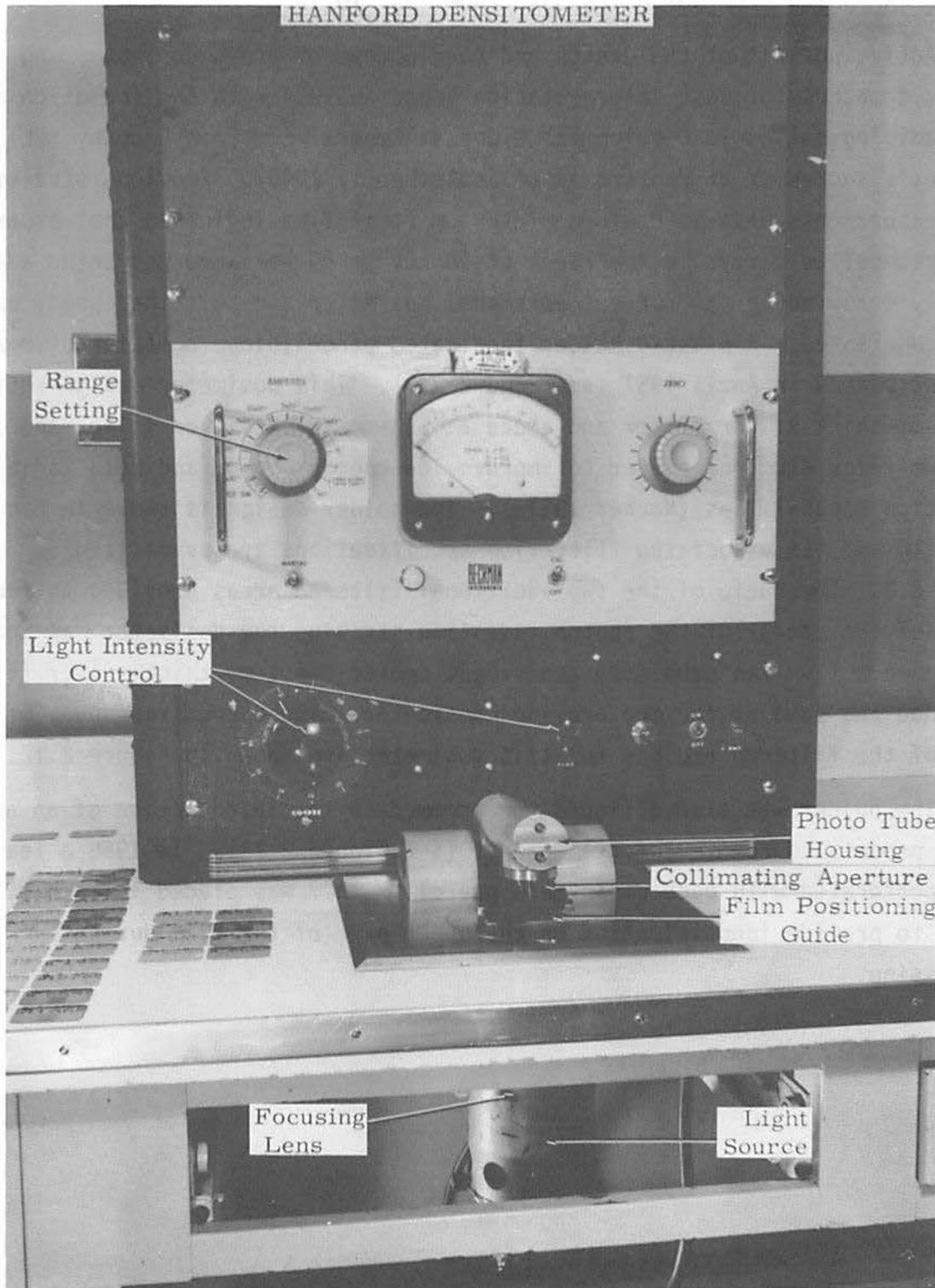


FIGURE 2.8. Early Densitometer Used for Reading Personnel Film Dosimeters

2.3 BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962

Active pursuit of the design and development of a new dosimeter and improved methods of dose interpretation began in 1954 with the formation of the Radiological Field Development Group at General Electric Company (GE) (DuPont's successor at Hanford as of September 1, 1946). Previous studies and measurements made in Hanford plutonium facilities indicated that exposure of personnel to x-rays in the range of 16 keV to 59 keV were not being adequately measured by the current personnel dosimeter and this inadequacy needed to be addressed. A plastic holder fabricated of cellulose acetate butyrate, was introduced in April 1957 (see Figure 2.9). This dosimeter design retained the 1-mm-thick silver filter and added a 0.13-mm-thick silver filter and a 0.49-mm-thick aluminum filter to improve low-energy photon and beta radiation detection capabilities (Kocher 1957a). The holder design is shown in Figure 2.10 and its associated filtration specifications are summarized in Table 2.3. The ratio of the two additional filtered areas provided an indication of the energy of the photon radiation striking the dosimeter, as shown in Figure 2.11. The deep dose assessment behind the 1-mm-thick silver filter remained the same as for the previous dosimeter. The energy responses of each of the filtered regions for this dosimeter are shown in Figure 2.12.

The holder was also designed to accommodate the introduction of an automatic process to remove the film packet (see Figure 2.13). In 1956 a lead tape perforated with each employee's payroll number was placed in each film badge to provide identification on the upper part of the film during processing.

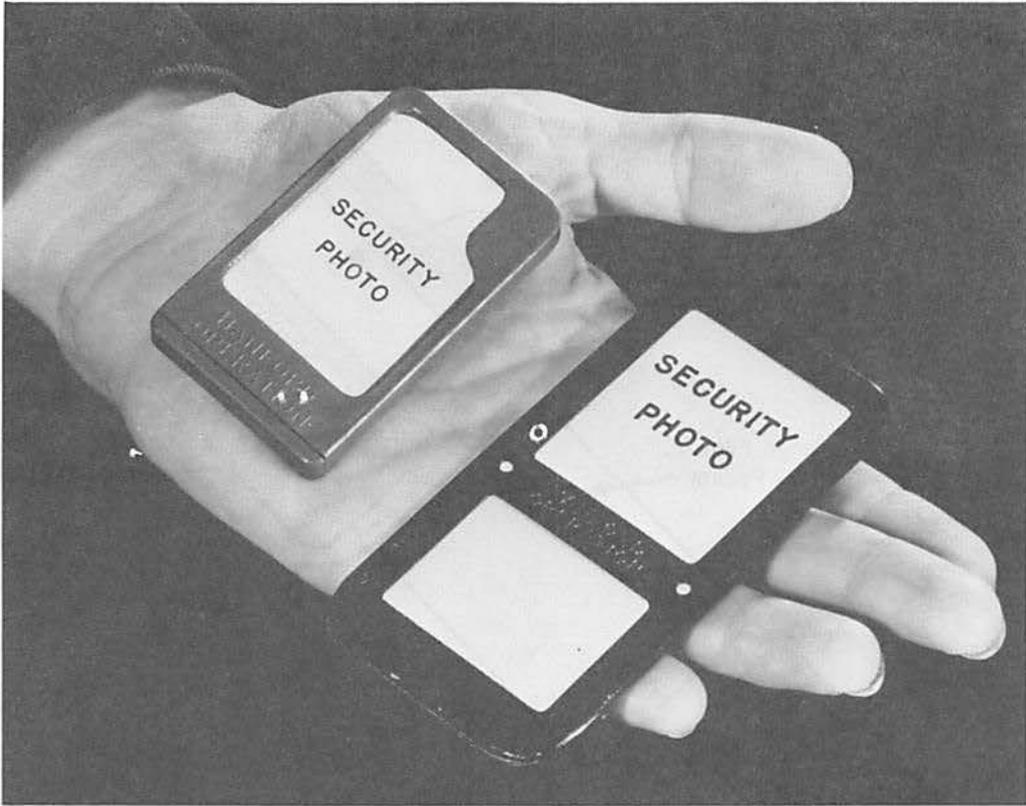
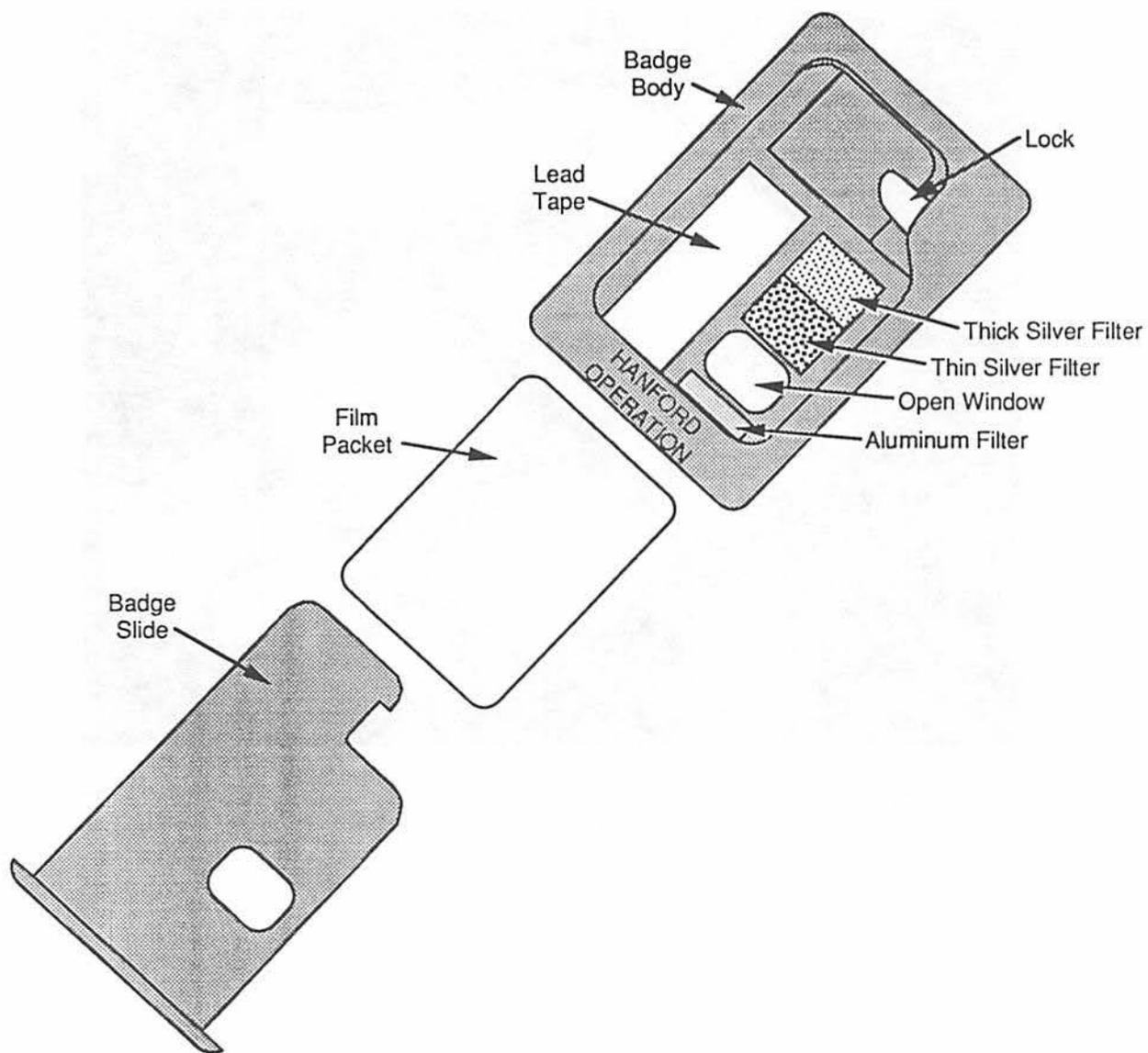


FIGURE 2.9. Plastic Film Dosimeter Holder Introduced in 1957 (left) and Old Metal Dosimeter Holder Used from 1944 to 1957 (right)



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FIGURE 2.10. Design of the Plastic Film Dosimeter Holder Filter System

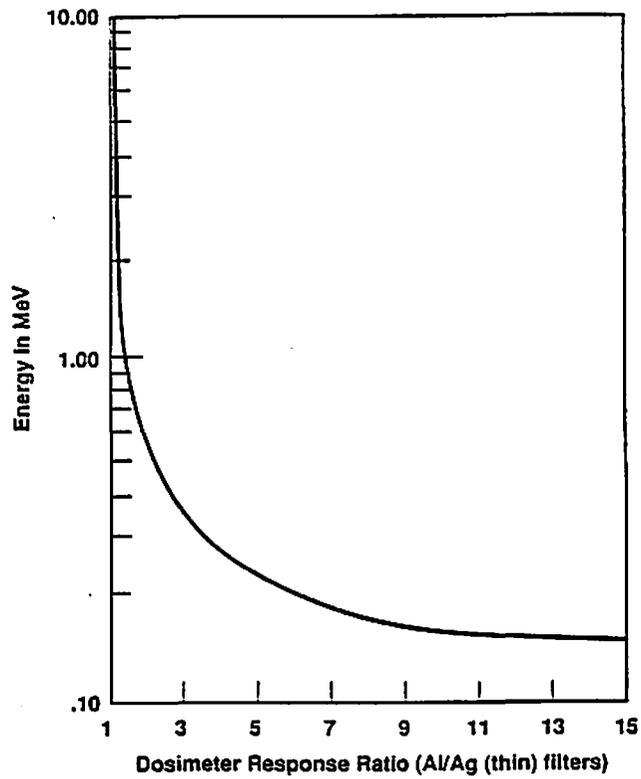
TABLE 2.3. Filtration Specifications for the Hanford Personnel Beta/Photon Film Dosimeter Holder Used from 1957 to 1962

Dosimeter Position	Holder		
	Material (a)	Thickness, cm	Mass Density, mg/cm ²
Open window	Security credential	0.05	50
	Cellulose	0.025	35
Aluminum	Security credential	0.13	130
	Cellulose	0.025	35
	Aluminum	0.049	132
Silver (Thin)	Security credential	0.13	130
	Cellulose	0.025	35
	Cellulose acetate	0.0762	81
	Silver	0.013	137
	Tenite II [⊗]	0.0508	62
Silver (Thick)	Security credential	0.13	130
	Cellulose	0.025	35
	Cyclac [⊗]	0.0711	75
	Silver	0.1	1050
	Tenite II	0.0508	62

(a) Assumed material densities:

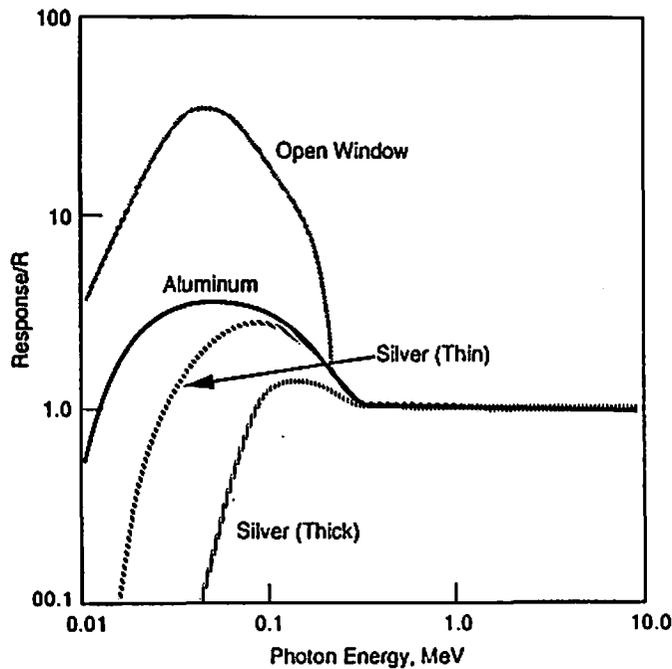
Plastic - Cyclac, 1.06 g/cm³
 Tenite II, 1.23 g/cm³
 Aluminum - 2.7 g/cm³
 Silver - 10.5 g/cm³

- ⊗ Tenite II is a registered trademark of Eastman Chemical Products, Inc., Rochester, New York.
- ⊗ Cyclac is a registered trademark of Borg-Warner Chemicals, Inc., Parkersburg, West Virginia.



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FIGURE 2.11. Ratio of Filtered Areas to Indicate Energy of Photon Radiations



S9005052.2

FIGURE 2.12. Energy Response for Each Filter Region of the Beta/Photon Film Dosimeter Used from 1957 to 1962

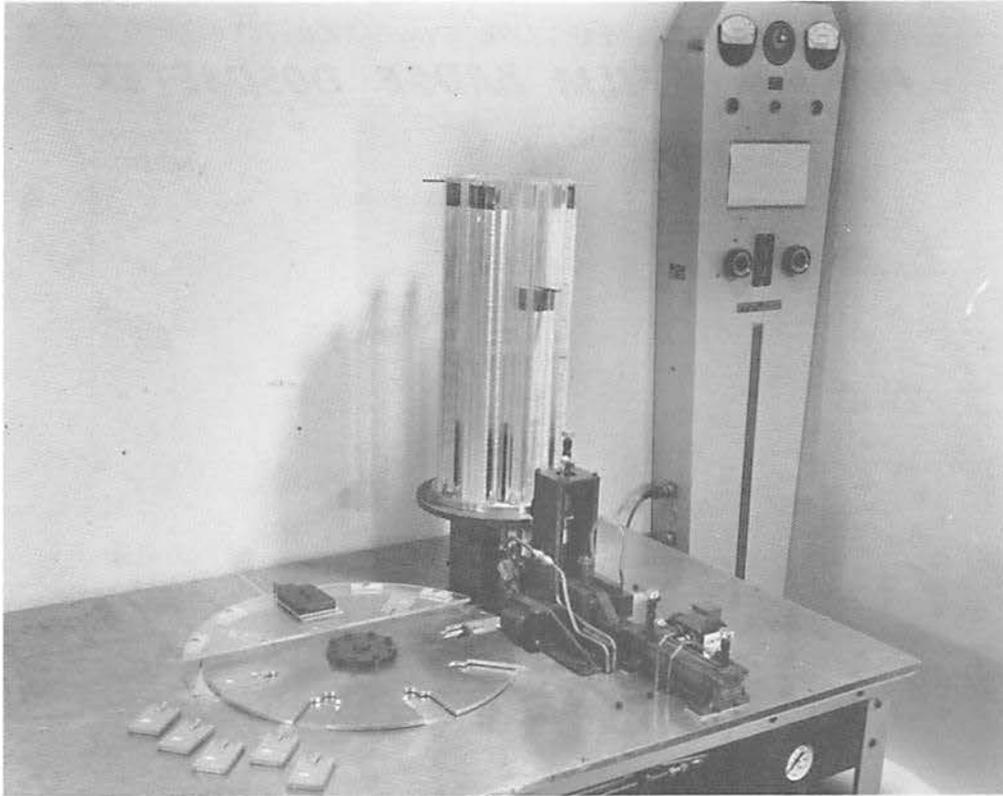
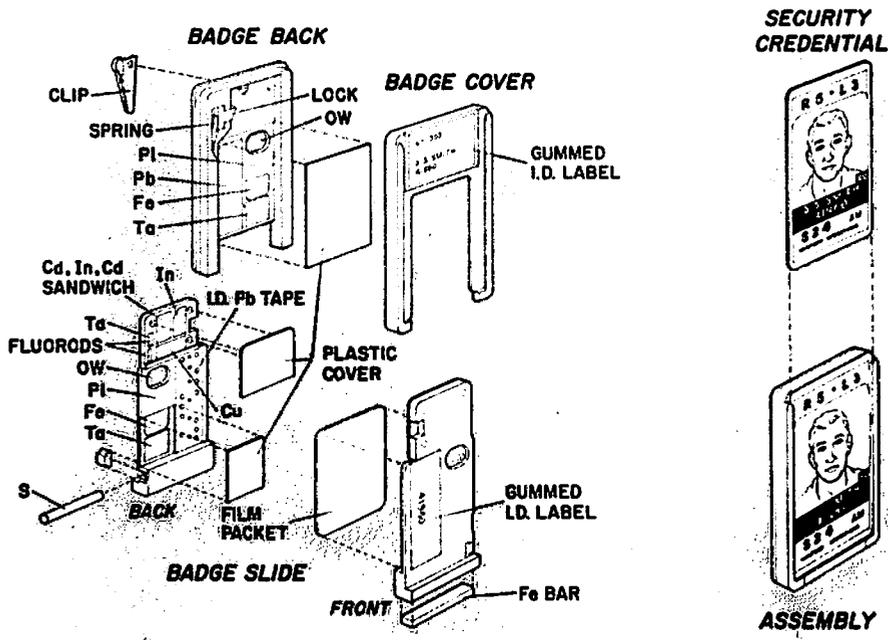


FIGURE 2.13. First Hanford Automatic Film Dosimeter Processor (1957)

2.4 BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972

An improved mixed-field film dosimeter (see Figure 2.14) was placed into routine service at Hanford on August 10, 1962. The mixed-film dosimeter partially solved the problems of measuring radiation dose in a field when several types of radiation were present (Kocher et al. 1962). The dosimeter holder was designed to take advantage of mechanized processing (see Figure 2.15). Each dosimeter contained a lead tape perforated with the employee's payroll number. A binary number code was used for the payroll number to facilitate machine reading. Prior to the removal of the film packet, the payroll number was x-rayed onto the upper part of the film to provide positive and permanent identification. (Film identification and film exchange are performed mechanically by a film dosimeter processing machine. The film slide, which is used to insert the film packet into the dosimeter holder, is held in the dosimeter holder by a concealed "T" lock, which is released magnetically for film exchange. Automatic reading densitometers

HANFORD EXPOSURE EVALUATION
HANFORD FILM BADGE DOSIMETER



RADIATION PROTECTION OPERATION
 AUGUST 10, 1962

FIGURE 2.14. Hanford Film Dosimeter Used from 1962 to 1972

were introduced during this period to further automate the handling of film from personnel dosimeters (see Figure 2.16). There were four different filtered areas on the film, similar to the previous dosimeter, but the dosimeter holder filtration specifications were changed as summarized in Table 2.4.

In the development of this dosimeter many different materials were investigated, such as solder, tin, aluminum, magnesium, cadmium, plastic, and silver, to determine their suitability for use in dosimeter designs (Kocher et al. 1963). Variations in filter thicknesses were also investigated to determine a suitable filtration system that would discriminate between mixtures of radiation types. As developed, this dosimeter also had the capability of measuring very high-level radiation exposures such as would occur during a nuclear criticality event. Glass fluorods extended the gamma dose range to about 10,000 rem and a system of foils provided an estimate of neutron flux

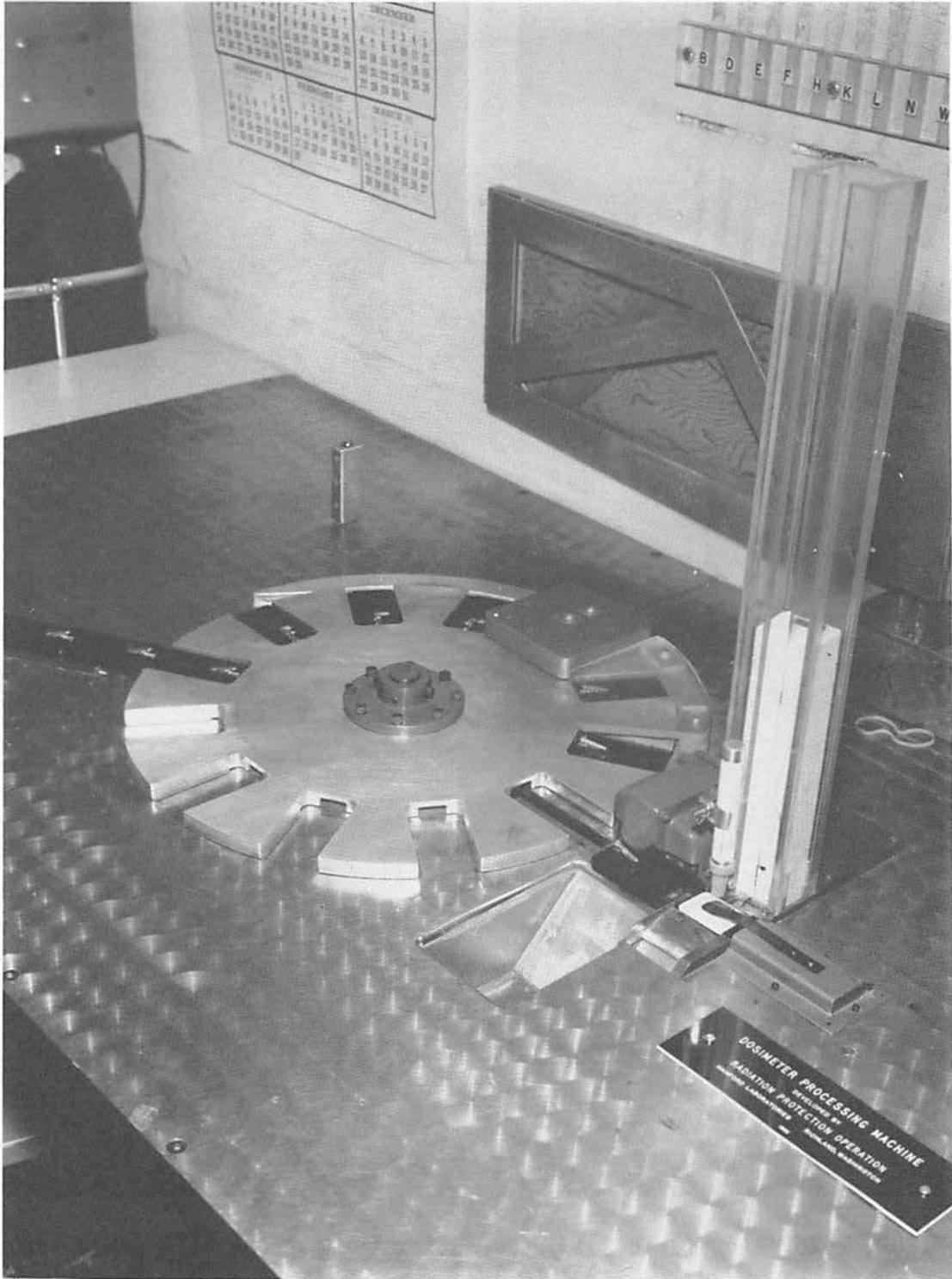


FIGURE 2.15. Dosimeter Processing Machine Developed in 1962

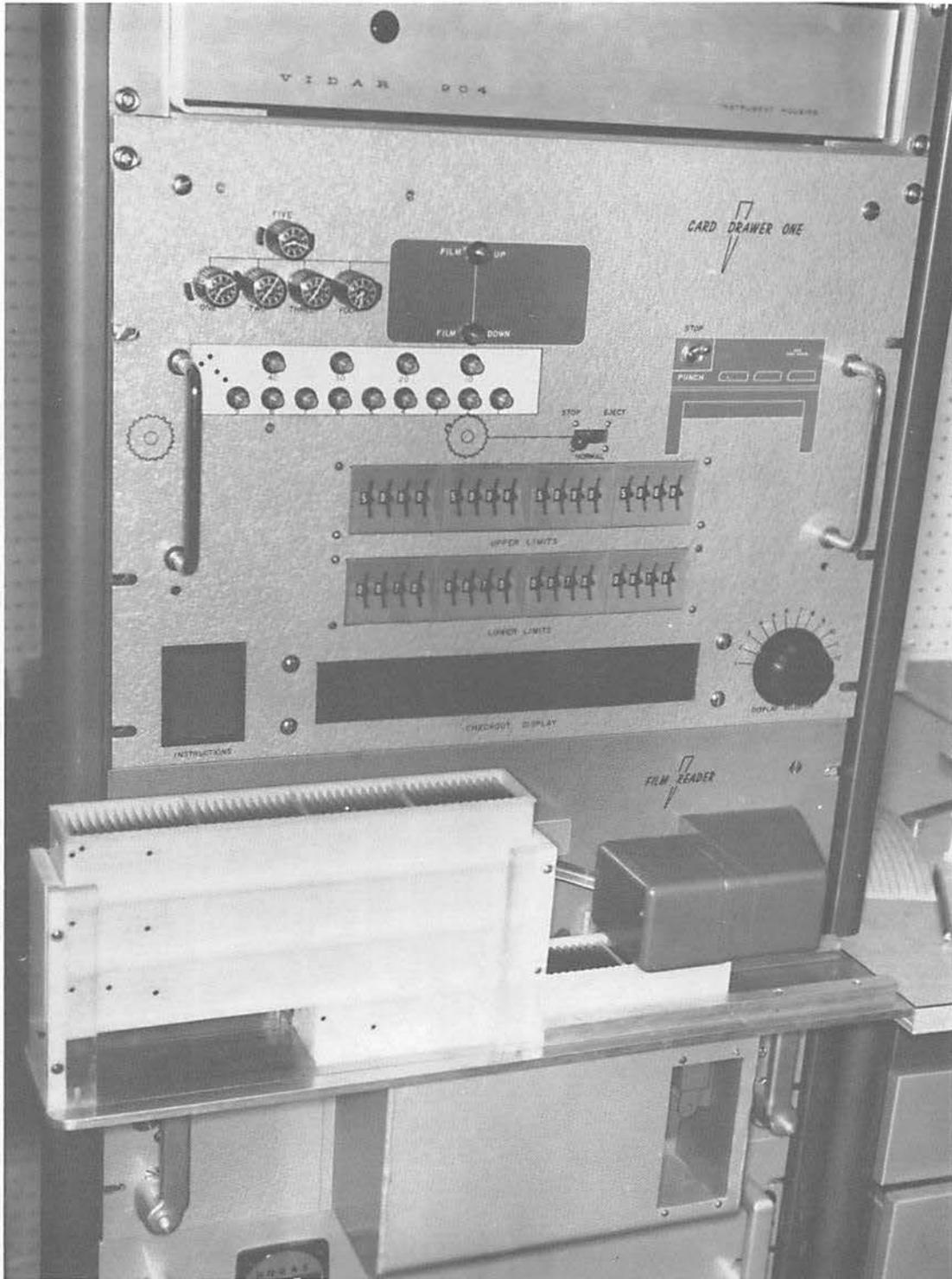


FIGURE 2.16. Automatic Reading Densitometer for the Film Dosimeter
Used from 1962 to 1972

TABLE 2.4. Filtration Specifications for the Hanford Beta/Photon Personnel Film Dosimeter Holder Used from 1962 to 1972

Dosimeter Position	Holder		
	Material(a)	Thickness, cm	Mass Density, mg/cm ²
Open window	Security credential	0.005	48
Plastic	Security credential	0.013	130
Iron	Security credential	0.013	130
	Cyclac	0.0762	81
	Iron	0.0025	20
	Tenite II	0.0508	62
Tantalum	Security credential	0.013	130
	Cyclac	0.0711	75
	Tantalum	0.0508	843
	Tenite II	0.0508	62

(a) Assumed material densities:
 Plastic - Cyclac, 1.06 g/cm³
 Tenite II, 1.23 g/cm³
 Tantalum - 16.6 g/cm³
 Iron - 7.86 g/cm³

and spectra following a nuclear excursion or other serious radiation event in the range of 1 rad to > 2000 rad. The foil system, whose specifications are listed in Table 2.5, was sensitive to a minimum of about 1 rad of fission spectrum neutrons.

The indium foil provided a "quick-sort" capability to identify personnel who might be seriously exposed following a nuclear criticality event. A few rad dose of fission spectrum neutrons could be detected easily by surveying the dosimeter with a conventional Geiger Mueller (GM) type meter. This

TABLE 2.5. Personnel Dosimeter Foil System Specifications for the Beta/Photon Film Dosimeter Used from 1962 to 1972

Foil Material	Size, in.	Neutron Energy Range
Indium	9/32 by 15/32 by 0.010	0.025 eV to 0.3 eV
Cadmium-indium-cadmium	9/32 by 15/32 by 0.010	0.3 eV to 2 eV
Copper	1/4 by 15/32 by 0.040	2.0 eV to 2.9 MeV
Sulfur cylinder	0.145 by 1.0 long	2.9 MeV and up

supplemented the procedures for measuring activated ^{24}Na in the body, which were developed in 1959 and in Hanford-wide use by 1959. Radiation monitoring personnel were trained for this type of action in the event of an nuclear criticality accident.

2.5 THERMOLUMINESCENT DOSIMETER USED FROM 1972 TO THE PRESENT

In January 1971 a basic (one-chip) TLD was introduced for use by all nonradiation workers. The basic TLD was followed, in January 1972, by the implementation of a multipurpose TLD for all radiation workers. The multipurpose TLD had the capability of measuring beta/photon and neutron exposure and contained many of the features of the film dosimeter. These dosimeter types are shown in Figure 2.17 and the first TLD automatic reader is shown in Figure 2.18. The filtration specifications for the dosimeter holder are listed in Table 2.6.

2.6 PENCIL DOSIMETERS FOR BETA/PHOTON MEASUREMENTS

In the beginning at the Metallurgical and Clinton Laboratories, pencil dosimeters (see Figure 2.19) were considered the primary personnel monitoring device, with a film dosimeter being only a valuable adjunct. With expanding experience at these laboratories and with the large-scale operations starting at Hanford in 1944, this practice was reversed: the film dosimeter provided the official dose of record, while the pencil became the day-to-day means for personnel to monitor their radiation exposure in the workplace. This also supported the establishment of an official radiation exposure record on a long-term and verifiable basis for each employee working at Hanford.

During the first few years of operation two pencil dosimeters were issued to personnel whenever they entered any of the controlled areas and were returned by the personnel whenever they left the areas. There were a few locations outside of the controlled areas where only designated personnel were issued pencil dosimeters. Each pencil was read daily. The results were recorded for the individual and then each pencil was returned to service after being recharged. The lowest reading was taken as the official result for the day (Parker 1946).



FIGURE 2.17. Hanford Basic (bottom) and Multipurpose (top) Thermoluminescent Dosimeters



FIGURE 2.18. First Automatic TLD Reader Used at Hanford

TABLE 2.6. Filtration Specifications for the Hanford Personnel Thermoluminescent Dosimeter Holder Used from 1972 to the Present

Dosimeter Position	Phosphor	Holder		
		Material	Thickness, cm	Mass Density, mg/cm ²
#1 (TLD-700)	TLD-700	Security credential	0.084	84
		Teflon	0.005	12
#2 (TLD-700)	TLD-700	Security credential	0.084	84
		Teflon	0.005	12
		ABS plastic(a)	0.105	111
		Aluminum	0.064	172
#3 (TLD-600)	TLD-600	Security credential	0.084	84
		Teflon	0.005	12
		ABS plastic	0.070	74
		Tin	0.102	742
#4 (TLD-600)	TLD-600	Security credential	0.084	84
		Teflon	0.005	12
		ABS plastic	0.070	74
		Tin	0.051	371
		Cadmium	0.051	439
#5 (TLD-700)	TLD-700	Security credential	0.084	84
		Teflon	0.005	12
		ABS plastic	0.070	74
		Tin	0.102	742

(a) ABS = acrylonitrile-butadiene-styrene.

As early as 1951 the accumulated Hanford experience indicated that it was not necessary to issue daily pencil dosimeters to many of the administrative personnel working in some of the controlled areas. Subsequently, this system was applied to other controlled areas throughout Hanford where only personnel with clearance to access the specified controlled areas routinely required pencils. This procedure was not initiated for the 300 Area until 1956 because of the diversity of activities within that area. At that time, 300 Area personnel film dosimeters were marked to indicate the requirement for pencil dosimeters. Further study in the 300 Area of pencil dosimeter use during 1957 indicated that it was technically feasible to wear pocket dosimeters for a week's duration and still achieve acceptable measurement accuracy.

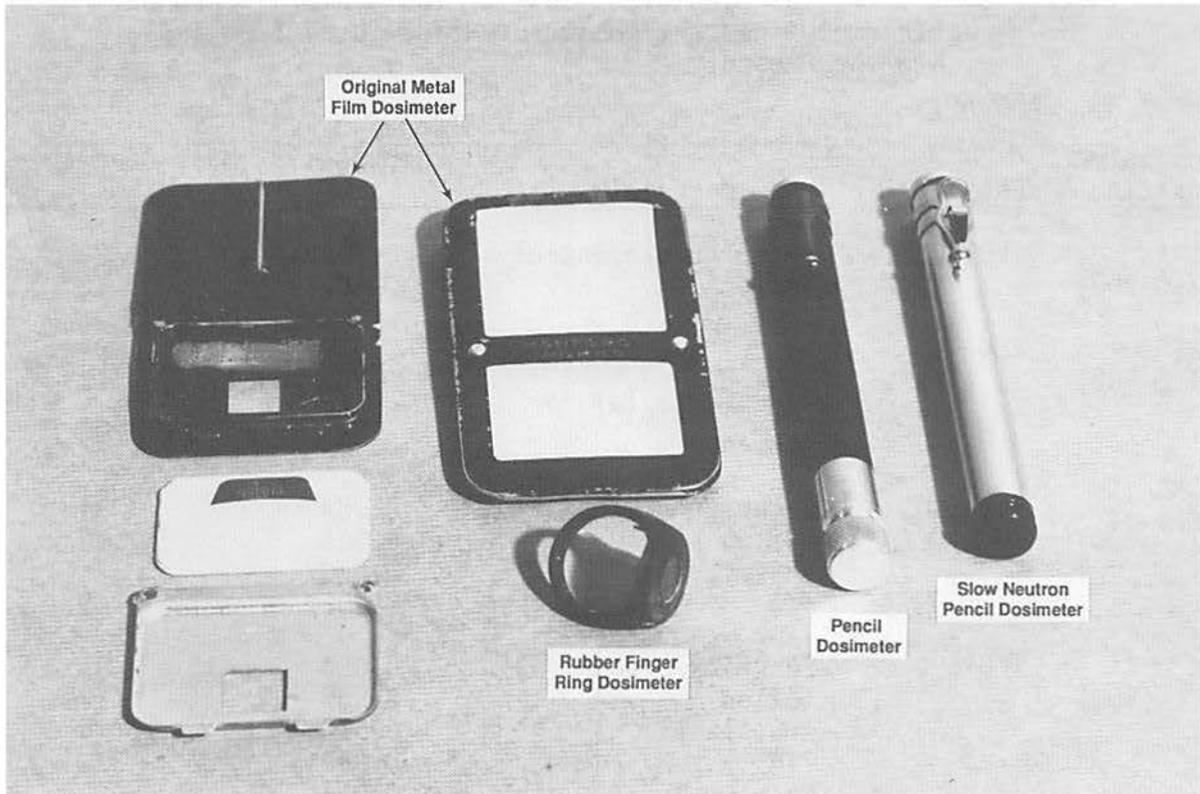


FIGURE 2.19. Pencil Dosimeter Shown with Other Hanford Dosimeters Used from 1944 to 1957

By the end of the year only those people expected to receive doses greater than 25 mR/wk were required to wear the pencil dosimeters.

Improvements in the pencil dosimeter and its reader justified major revisions in the requirements for its use. Statistical studies supported these changes and in 1962 the practice of wearing only one pencil dosimeter was initiated. Results obtained from these dosimeters were not considered a part of the official exposure record for an individual but were considered a control for daily operations. The revised philosophy on maximum permissible radiation exposures to man by the National Council on Radiation Protection and Measurements (NCRP) and International Commission on Radiological Protection (ICRP), which increased the time base for accumulation of radiation exposure, also supported the longer wearing period for pencil dosimeters.

2.7 OTHER EXTREMITY DOSIMETERS

Several adaptations were made to measure the exposure of various parts of the body during special work conditions and in special work locations. These dosimeters usually contained the conventional material and had shielding configurations similar to those for regular personnel dosimeters. The finger ring, wrist, and flexible dosimeters are three of the extremity dosimeters that have been used at Hanford. Extremity dosimeters are still being used routinely for special monitoring.

2.7.1 Finger Ring Dosimeters

From the beginning at the Metallurgical and Clinton Laboratories, researchers realized that exposure to the hands may be significantly higher than what is received by the body and measured by dosimeters worn on the body. Early attempts were made to develop a dosimeter that would monitor more closely the exposure received by the extremities (Healy 1944).

Aluminum rings with a thin silver shield covering part of the film were fashioned. The film discs were about 1/2 in. in diameter, cut from the DuPont 552 film packet using the DuPont 510 film. Later, the ring film was cut from large sheets of the 510 film. The film discs were packaged in various materials to provide a light-weight, light-tight cover and still be considered thin enough for most beta radiations. Some trial packages were even dipped in paraffin and taped directly to the worker's fingers. These early attempts were clumsy and tore the gloves occasionally, but did provide some measurement of hand exposure. The metal ring was soon followed by a rubber ring in which the film disc and black plastic cover were held in place with a flange.

By mid-1967 a flexible rubber thermoluminescent finger ring (Kathren, Kocher, and Endres 1970; Kathren, Kocher, and Endres 1971) using a rectangular wafer of LiF in a Teflon[®] matrix was available for routine hand dosimetry. The ring had a surface area of about 1.5 cm² that provided enough area for easy identification. The Teflon wafer and cover were easily inserted in the ring top to form a compact package that could be worn comfortably by workers.

⊗ Teflon is a registered trademark of E. I. DuPont de Nemours, Wilmington, Delaware.

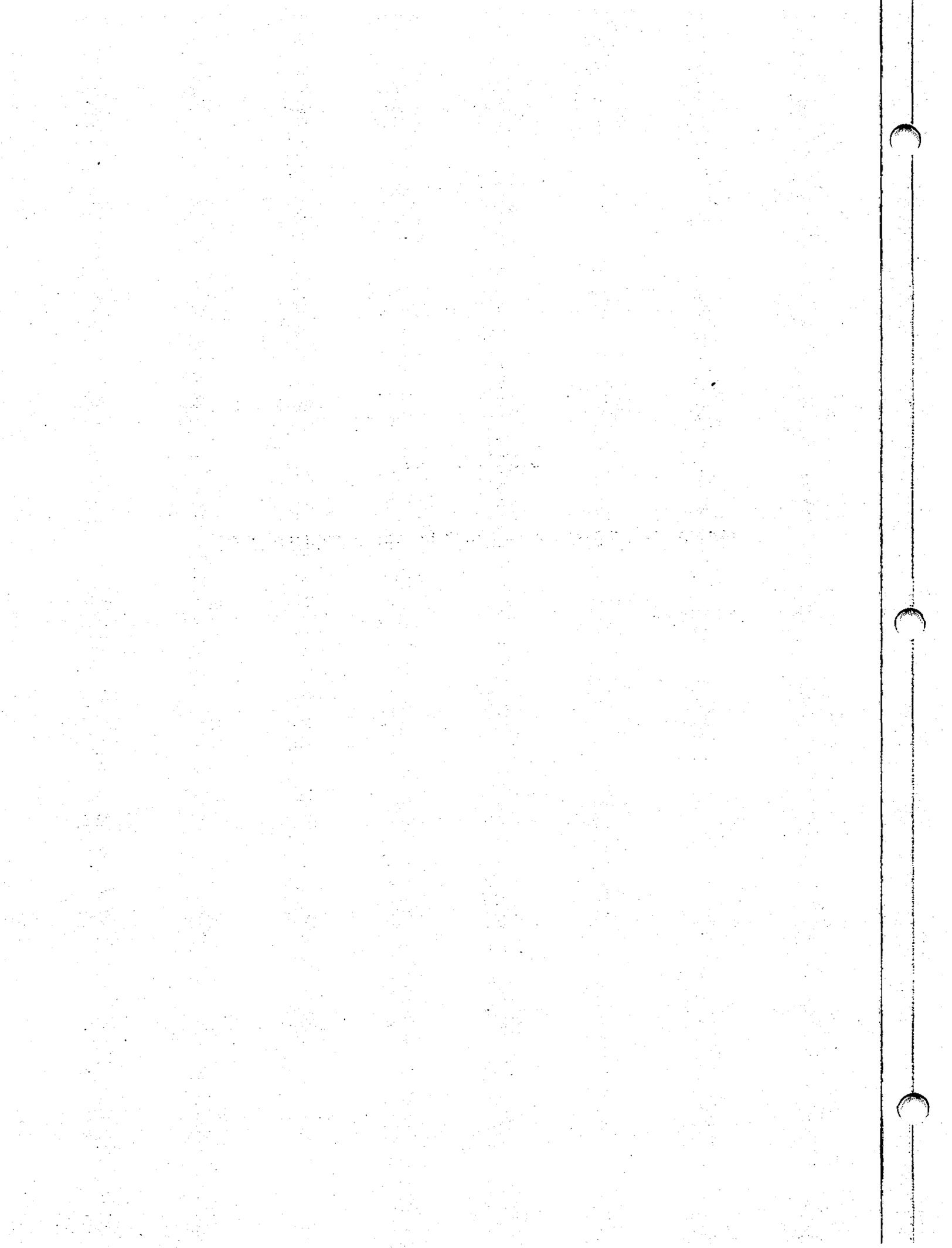
The wide range of response provided by the ring, $< 30 \text{ mR}$ to $> 1 \times 10^5 \text{ R}$, gave more than adequate coverage for all work situations. At the low exposures, the standard deviation was about $\pm 50\%$ and at higher exposures it was reduced to $\pm 10\%$. Another advantage was minimal energy dependence, allowing for its use for essentially any photon energy greater than 10 keV. At the 17-keV energy level most commonly associated with plutonium, the response per unit of exposure was virtually the same as for ^{60}Co . Beta response was only about half in terms of light output per rad but the ring was not usually used in mixed photon and beta fields. The ring has been used since January 1968 and has been well received by the workers. Blind audits indicate routine accuracy of $\pm 25\%$ at the 95% confidence level covering a range of 0.1 to 10 R, regardless of exposure conditions.

2.7.2 Wrist and Flexible Dosimeters

A wrist dosimeter, similar to a wrist watch, has also been used extensively in locations where exposure to the hands and forearms may be the limiting factor. Flexible dosimeters with appropriate shielding materials were used extensively by underwater divers when repairing the storage basins. These dosimeters could be affixed to almost any part of the body to determine the limiting exposure location where the source material could not be shielded or known with any certainty in remote locations of the basin. These dosimeters have also been used in work locations where the head and/or eyes may be the limiting exposure organ of the body.

CHAPTER 3.0

HANFORD PERSONNEL NEUTRON DOSIMETERS



3.0 HANFORD PERSONNEL NEUTRON DOSIMETERS

Five primary dosimeters have been used at Hanford to measure personnel exposure to neutrons. From 1944 to 1950, personnel exposure to neutrons was determined using a pencil dosimeter that had an enriched ^{10}B liner. In those early years, some attempts were made to measure fast neutrons using a fine-grain film to record tracks from recoil protons, but these attempts were unsuccessful. In 1950 the newly developed Eastman-Kodak[®] Nuclear Track Emulsion, Type A (NTA) film was placed in service using the regular beta/photon film holder and this holder was used until 1957. A special cellulose acetate butyrate holder (identical to the regular beta/gamma film holder) was introduced in 1957 and only used for about 1 year, because it was replaced with a dosimeter holder thick enough to enclose both the NTA and regular beta/photon film packets. The thick dosimeter holders were used from 1958 until 1972, at which time the multipurpose albedo TLD was implemented for measurement of neutron and beta/photon radiations. The neutron dosimetry systems used at Hanford since 1944 are discussed in the following subsections.

3.1 PENCIL DOSIMETERS USED FROM 1944 TO 1950

Hanford initially relied on pencil dosimeters with enriched ^{10}B liners to measure exposure to slow neutrons (see Figure 2.19). The pencil dosimeters were used almost exclusively for neutron measurements until the improved Eastman-Kodak NTA film was introduced in 1950. A fine-grain film was tried during the 1940s for measurement of fast neutrons, but the response of the film and the ability to adequately detect the tracks etched in the emulsion had not been developed to the level required for large-scale use.

3.2 NEUTRON FILM DOSIMETER USED FROM 1950 TO 1957

From 1950 to 1957, Eastman-Kodak NTA film was used in the regular metal beta/photon dosimeter holder (see Figure 2.7). The film had limited capability, measuring only fast neutrons with energies ≥ 0.8 MeV. The recoil proton

® Kodak is a registered trademark of Eastman-Kodak Company, Rochester, New York.

tracks on the NTA film were viewed microscopically at 970X magnification for 40 fields of view and compared with 40 fields on calibration and control film for an estimate of the neutron exposure. The neutron dosimeter was issued to selected employees working in reactor facilities where neutron exposure was possible and to employees working in the plutonium processing facilities.

3.3 NEUTRON FILM DOSIMETER USED FROM 1957 TO 1958

From April 1957 to July 1958, Eastman-Kodak NTA film was used in a separate cellulose acetate butyrate holder identical, except for color, to the one used for the beta/photon dosimeter. The method for interpretation of neutron dose was same as that used from 1950 to 1957.

3.4 NEUTRON FILM DOSIMETER USED FROM 1958 TO 1972

A separate neutron dosimeter (see Figure 3.1) was introduced in 1958. It differed from the Hanford beta/photon dosimeter only by an increase of 0.10 in. in thickness. This change was necessary to accommodate two film packets (one of NTA film and one of beta/photon film) and to reinforce the body of the dosimeter holder. The design characteristics, calibration technique and shield material of this neutron film dosimeter are discussed in the following subsections along with quality factors used to determine personnel dose.

3.4.1 Design Characteristics

The design of the neutron film dosimeter used from 1958 to 1972 was based on knowledge of materials available to separate slow and fast neutron radiation. Table 3.1 provides a summary of the holder design specifications.

The primary functional change in the Hanford beta/photon dosimeter that permitted its use as a neutron dosimeter was the incorporation of suitable shield materials. The selection of cadmium and tin in lieu of other metals was based upon their thermal neutron cross sections and x-ray and gamma ray mass absorption coefficients. Cadmium has a high thermal neutron cross section, and tin is relatively transparent with respect to neutrons. The prompt gamma coincident with a neutron capture in the cadmium is recorded as darkening of the film behind the cadmium shield. Because gamma rays

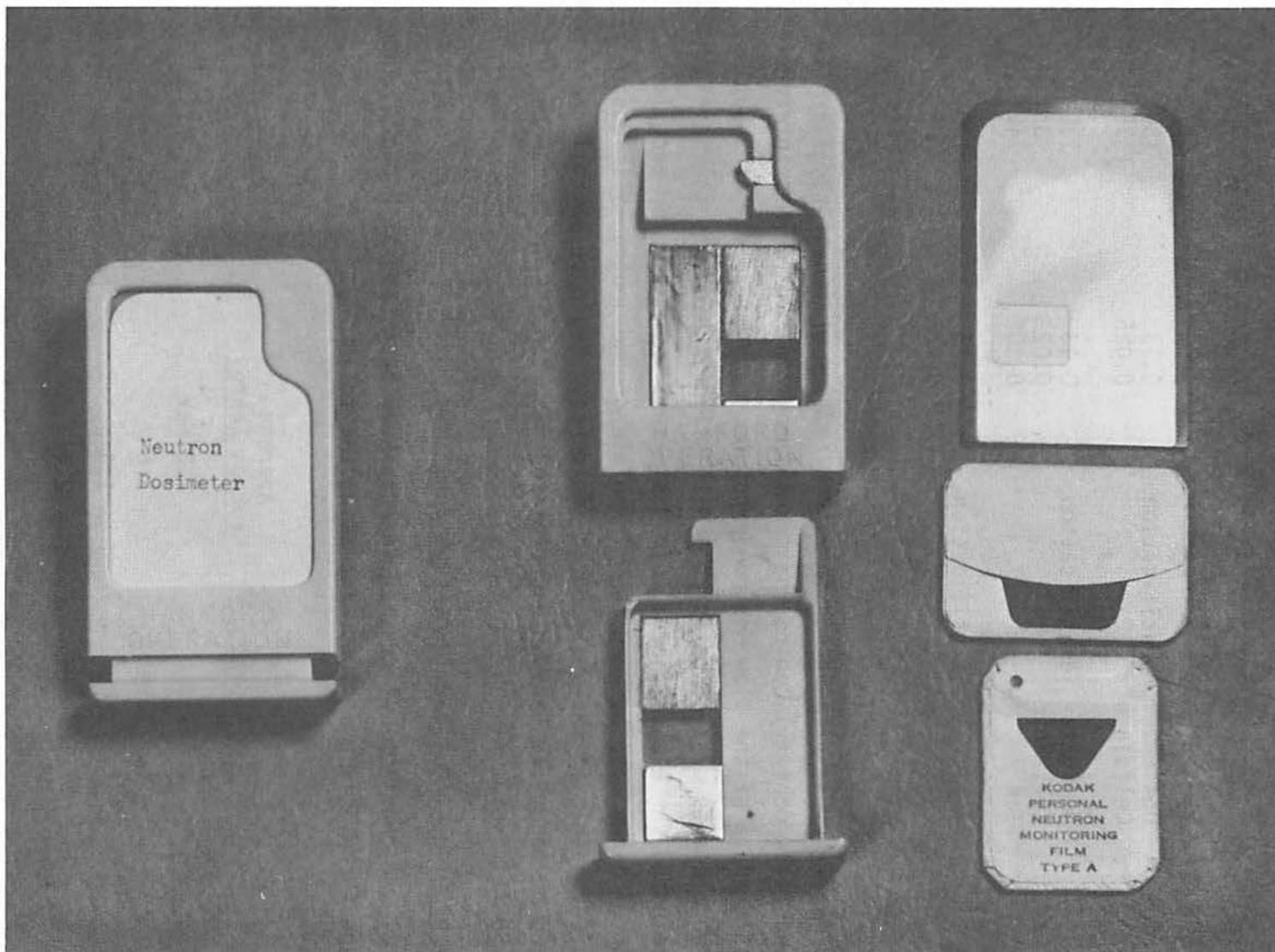


FIGURE 3.1. Double-Packet Plastic Neutron Film Dosimeter Introduced in 1958

TABLE 3.1. Design Specifications for the Hanford Personnel Neutron Film Dosimeter Holder Used from 1958 to 1972

<u>Dosimeter Position</u>	<u>Holder</u>		
	<u>Material</u>	<u>Thickness, cm</u>	<u>Mass Density, mg/cm²</u>
Open window	Dosimeter identification	0.13	130
	Cellulose	0.025	35
Tin	Dosimeter identification	0.13	130
	Cellulose	0.025	35
	Tin	0.102	742
Cadmium	Dosimeter identification	0.13	130
	Cellulose	0.025	35
	Cadmium	0.102	879

experience nearly equal attenuation in either cadmium or tin, the difference in darkening (film density) behind the cadmium and tin shields was interpreted as a direct measure of the slow neutron exposure. The gamma ray attenuation of these two elements also compares well with silver, which was the shielding material selected for a beta/photon film dosimeter; this made for excellent correlation of gamma dose between the tin shield of the neutron film dosimeter and the silver shield of the beta/photon dosimeter. Employee payroll numbers were x-rayed on each film through a perforated lead tape strip to identify each film by its user.

3.4.2 Calibration of Nuclear Track Emulsions

Several radionuclide calibration sources have been used at Hanford since implementing the NTA film in 1950, including the following:

<u>Source</u>	<u>Average Neutron Energy</u>
PoB	2.8 MeV
RaBe	3.6
PuF ₄	1.4
²⁵² Cf	2.4

The PoB source apparently provided the majority of the neutron calibrations from 1950 through 1956. During a period in 1957, the Van de Graaff positive ion accelerator was used to calibrate film using the reaction of deuteron on a ^9Be target. The energy of the neutrons produced varied from 1.0 MeV to 6.3 MeV with an average energy of 2.2 MeV. (a)

Roesch and DePangher provided an overview for converting neutron flux to dose for the early neutron sources used at Hanford. (b) The conversion factors used at Hanford for many years were $8 \text{ n/cm}^2\text{-sec}$ for fast neutrons, $48 \text{ n/cm}^2\text{-sec}$ for intermediate neutrons, and $120 \text{ n/cm}^2\text{-sec}$ for slow neutrons. The exact history of these numbers was not certain but was expected to have been calculated by Gamertsfelder et al. (1962). Slightly different numbers were used for the PoB calibrations, the Van de Graaff calibrations, and the plutonium fluoride calibrations to allow for the energy dependence.

Beginning in 1958, calibration was accomplished with the PuF_4 neutron source. The calibration films were exposed to a dose of 1.075 rem computed from first-collision theory. (The average film response yields 71.24 ± 13.51 tracks per 40 fields of view; this is equivalent to a 1075-mrem exposure with a 95% confidence interval.) 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 calibration regimen coincided with the introduction in 1958 of the new "double packet" dosimeter holder that accommodated two film packets.

Interpretation of NTA film after processing was accomplished by counting microscopically the tracks produced in the emulsion by recoil protons (see Figure 3.2). A $1/129\text{-cm}^2$ field of view was viewed under 970X magnification with oil immersion. Each of three observers counted the tracks occurring in 40 fields of view (a total of 120 fields). Films that indicated a significant increase in the number of tracks relative to background were viewed for a total of 400 fields. The number of tracks per 40 fields was determined at

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- (a) De Phanger, J. 1958. "Suggested Change in Procedure for Calibration of Neutron File." Letter to R. W. Meisinger, dated January 28, 1958.
(b) Roesch W. C. and J. De Pangher. "Neutron Flux-Dose Relations." Letter to A. R. Keene, dated September 9, 1958.



FIGURE 3.2. Counting Tracks on NTA Film with a Microscope

the 90% confidence level. The upper limit of the count was compared with the lower limit of the similar interval for tracks per 40 fields per 300 mrem on the calibration films. The ratio of the limits multiplied by 300 mrem was entered into the exposure record. The dosimeter also was capable of measuring slow neutrons with the cadmium (neutron, gamma) interaction.

3.4.3 Cadmium-Clad Tin Shields

For most purposes, the use of pure cadmium and pure tin as shield materials produced an excellent slow neutron dosimeter. In cases where the

neutron exposure was accompanied by very soft x-rays, the small difference in mass absorption coefficients between the two materials became a limiting factor for the measurement of slow neutron exposure. To make the two shields more similar with respect to x-ray attenuation, a number of tin shields were rolled to a thickness of 0.036 in. and plated with cadmium until the original 0.040-in. thickness was attained (Swanberg 1959).

3.4.4 Quality Factors

Recommendations included in National Bureau of Standards Handbooks 54, 59, and 63 were used during the earliest years (NBS 1954a; 1954b; 1957). Basically, quality factors of 10 and 3 were applied to convert the fast and slow neutron dose, respectively, from rad to rem. These factors for dose conversion has been used since the late 1940s to estimate the dose from neutrons.

3.5 RHODIUM DOSIMETER

In the early 1960s development work was started on a dosimeter that would provide photon measurement as well as neutron measurement for personnel (see Figure 3.3). The work done in developing this dosimeter lead to the development of the "albedo" type dosimeter that is currently used by personnel to measure neutron exposure. The rhodium dosimeter was never used routinely due to the administrative problems of introducing it into the system and because of efforts being concentrated on the development of a suitable TLD design that finally was chosen and put into service in 1972.

3.6 THERMOLUMINESCENT NEUTRON DOSIMETER USED FROM 1972 TO THE PRESENT

The Hanford "albedo" neutron dosimeter was introduced in 1972. This dosimeter had the capability to measure the fast and slow neutron dose received by personnel. The dosimeter dose response was dependent upon the reflection of neutrons from the body and, hence, was referred to as an albedo (i.e., reflected) neutron dosimeter.

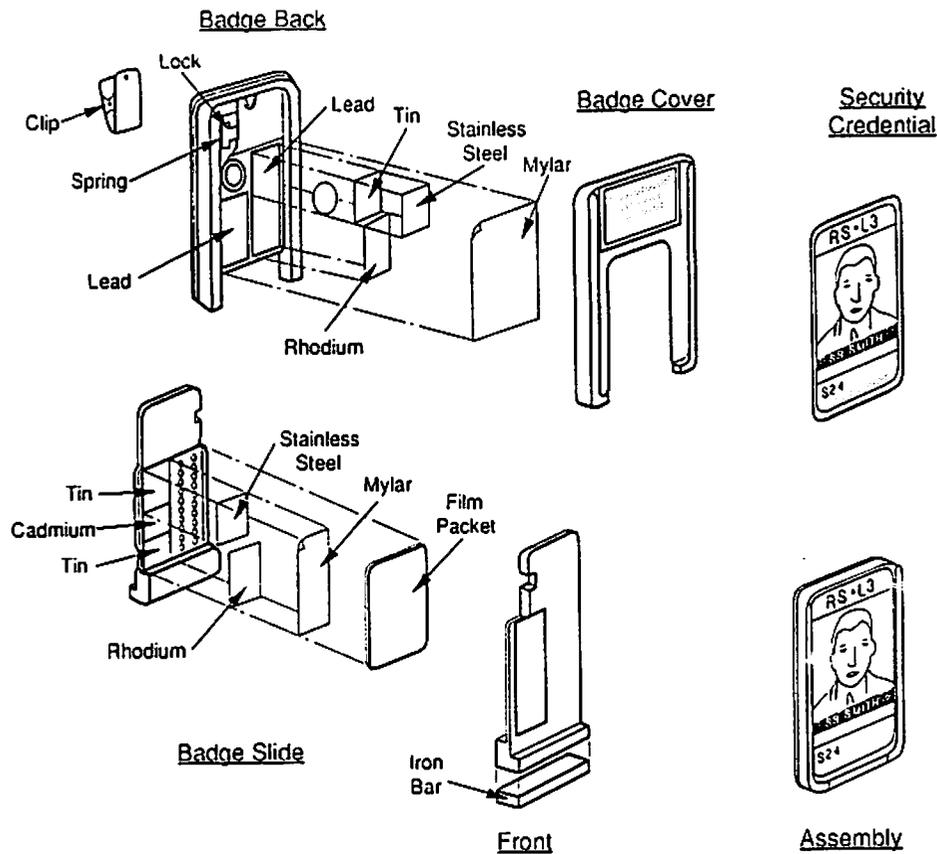


FIGURE 3.3. Rhodium Film Dosimeter

SS007018.1

3.6.1 Design Characteristics

The design of this dosimeter is discussed in Chapter 2.0. Dosimeter chip positions 3, 4, and 5 provided the albedo dosimeter capability. Thermoluminescent chips enriched in ${}^6\text{Li}$ (i.e., TLD-600) were placed in positions 3 and 4. A thermoluminescent chip with only the ${}^7\text{Li}$ isotope (i.e., TLD-700) was placed in position 5. A cadmium/tin filter was placed on the front side of the dosimeter holder 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 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.

3.6.2 Calibration

A field-specific neutron calibration was used with the albedo neutron dosimeter. This was determined by developing a calibration procedure with the PuF_4 source, which provided the same dosimeter response per dose as measured in the field with a tissue-equivalent proportional counter (TEPC). A sigma pile was used to determine the response of the dosimeter to slow neutrons. In 1981 the PuF_4 source was replaced with a ^{252}Cf source. To obtain the same dosimeter response per dose, the time of the exposure was increased by a factor of 1.73 (e.g., length of exposure time from a bare ^{252}Cf source increased by a factor of 1.73 to obtain the same dosimeter response as received from the PuF_4 source). This field-specific calibration has been confirmed several times during the years (Fix et al. 1981; 1982). The bare ^{252}Cf calibration is used in the DOE Laboratory Accreditation Program dosimeter performance testing.

3.7 ACCIDENT DOSIMETRY

During the early years of Hanford operation, no specific dosimetry was available to measure personnel exposure to the very high levels of radiation that may result from a criticality accident. To the extent possible, gamma radiation was measured with the low-sensitivity film in the personnel dosimeter. No measurement of high-level neutron exposure could be made with the available personnel dosimeters.

In the early 1950s, the possibility of nuclear accidents led to the development of a method of measuring the radiation levels that could occur in areas where personnel might be working if an accident occurred (Wilson and Larson 1961; Wilson 1962). An area type dosimeter (Hurst 1956) was used during the late 1950s in several plant locations, but it was replaced by the Hanford criticality dosimeter in 1962 (Bramson 1962). The use of alpha-emitting fission foils in the Hurst dosimeter was considered hazardous in case of fire at the location where it was placed. The Hanford criticality dosimeter not only eliminated this hazard, but could also give an immediate indication of the absorbed neutron dose (in rad) by measuring induced radioactivity in the moderated gold foil located in the center of the dosimeter package (see

Figure 3.4). Criticality dosimeters were placed throughout Hanford facilities where there was even the remotest possibility of a nuclear excursion. The Hanford design also gave short-term protection to some of the foils from fire or explosion. These dosimeters are currently used throughout the Hanford facilities where fissionable materials are handled. The only alteration to these dosimeters since their inception has been a minor change in the holder for the foils and the replacement of their glass rods with TLD chips.

A "quick sort" procedure was also developed in 1959 and immediately placed in service to provide an indication of high-level exposure to neutron radiation by direct survey of the individual (Wilson 1962). This capability was included in the design of the personnel film dosimeter (shown in Figure 2.14), which contained foils, sulfur, and glass fluorods for measurement of very high gamma exposures. With the implementation of the TLD, it became possible to measure employees' exposure to both gamma and neutron radiation.

The "quick sort" procedure was used following the 1962 Recuplex Plant (waste recovery section of 234-5-Z Building) criticality incident and immediately identified those personnel receiving high-level neutron exposure. Subsequent detailed dosimetry evaluation for these employees indicated that the "quick sort" estimates were very accurate estimates of the neutron dose received by these employees.



FIGURE 3.4. Hanford Area Criticality Dosimeter

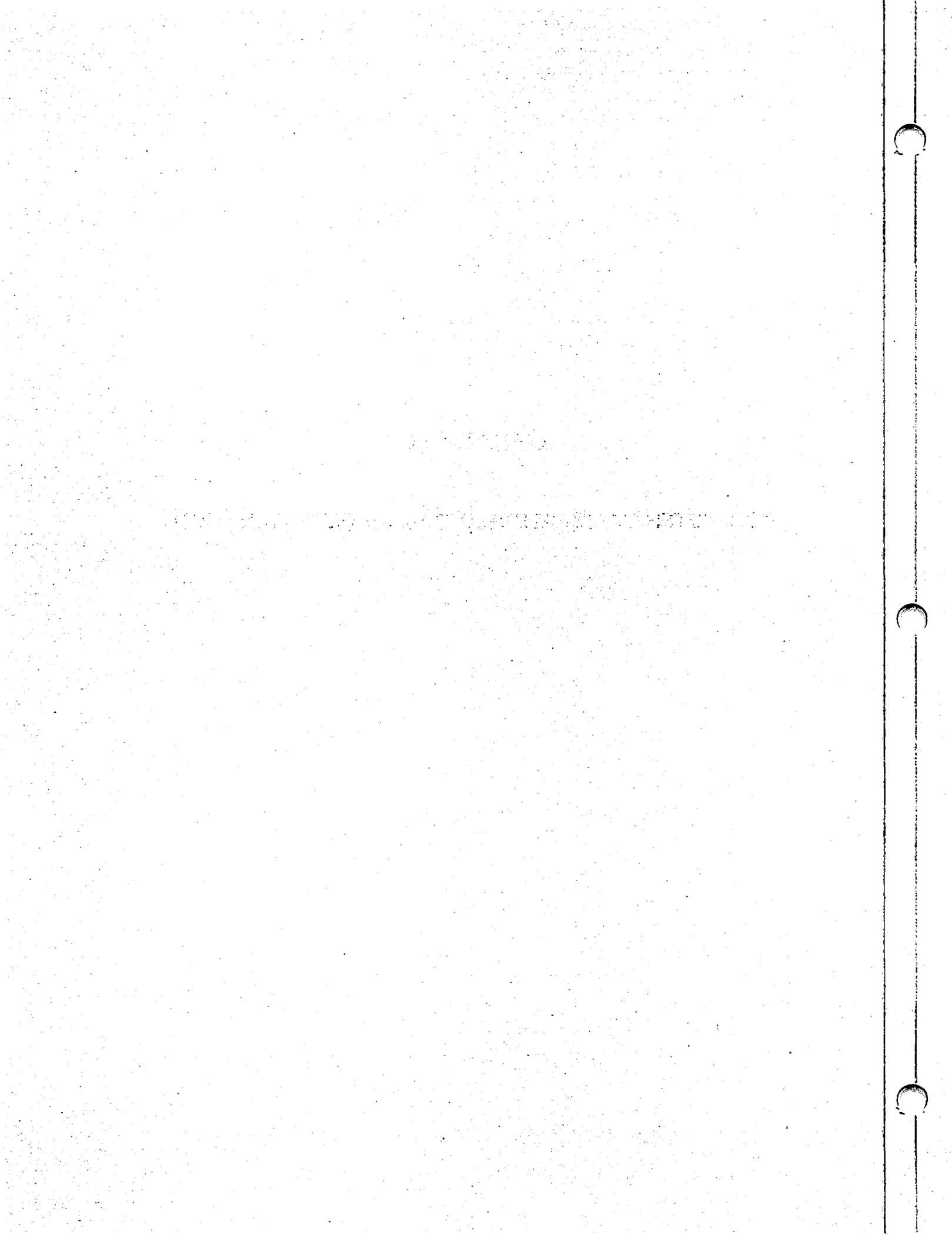
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CHAPTER 4.0

DOSIMETER CALIBRATION AND DOSE DETERMINATION



4.0 DOSIMETER CALIBRATION AND DOSE DETERMINATION

Consideration of the methods of calibrating, processing, and determining dose for the different dosimeter systems at Hanford is important to the evaluation of the recorded whole body dose relative to a consistent technical basis (i.e., deep dose) throughout the years. Hanford practices used to minimize known sources of error in dosimetry systems are important to estimating the potential uncertainties in the recorded dose. Since 1944 dosimetry technology has continued to evolve at Hanford with many changes in the methods of dosimeter calibration, processing, and dose determination. When Herbert M. Parker formed the Health Instruments (HI) Section at Hanford in July 1944, immediate attention was given to the calibration and performance capability of the available radiation monitoring devices to accurately measure radiation exposure. A summary of the major calibration and dose assessment techniques used at Hanford is provided in Table 4.1. The detailed formulas used to determine dose are provided in Appendixes A, B, and C for the multi-element film dosimeter used from 1957 to 1962, the multi-element film dosimeter used from 1962 to 1972, and the TLD introduced in 1972, respectively. A brief discussion of each significant change in the calibration and dose assessment practices for each dosimeter system is provided in the following subsections.

4.1. TWO-ELEMENT BETA/PHOTON DOSIMETER USED FROM 1944 TO 1957

Initial attempts to calibrate personnel beta/photon dosimeters were made shortly after some of the Hanford facilities were constructed in 1944 (Wilson 1987). From records of film densities and assigned radiation dose, it appears that a procedure of assigning values of 30, 50, and 60 mR to film densities of 0.03, 0.05, and 0.06 was initially used. No records of calibration film for 1944 have been located. This system was apparently used for only a few weeks because assigned doses for recorded film densities are different for the remaining part of 1944; however, no calibration data were located. The first evidence of calibration data used to determine dose for personnel film dates back to March 1945. At that time radium gamma calibration data for a 10-day period were averaged and a characteristic curve for the open window and shielded portion of the film was established. A radium source certified by the NBS was initially used as a reference source for these calibrations.

TABLE 4.1. Historical Summary of Hanford Calibration and Dose Assessment Techniques

- 1943 Pocket dosimeters were used to approximate radiation dose.
- 1944 DuPont 552 double film (502 sensitive side) packet was used. Deep dose was directly related to film density behind silver shield based on radium gamma calibration exposure.
- 1946 During the first few weeks of 1946, beta calibration curves, established by surface uranium exposure, were put in use for reading the open window portion of the film badge. The open window portion was read as all beta ray exposure and the shielded portion as gamma ray exposure.
- 1947 A 0.5-g radium capsule was introduced. A dose rate of 8.25 R/h at 1 cm from 1 mg ²²⁶Ra encapsulated in 0.5-mm platinum was considered the standard. A nonisotropic effect of about 5% at 10 cm was noted for this source. The effect decreased to about 1% at 100 cm.
- 1950 Eastman-Kodak Nuclear Track Emulsion (NTA) film was introduced. PoB was used as the calibration source.
- 1951 A standard calibration curve was developed using the 90% confidence levels for determining the limits at each calibration level. In November 1951, a correction factor of 1.5 times the shield density subtracted from the open window density was introduced to correct that part of the open window density caused by gamma radiation.
- 1955 Fast neutron calibration was based on the positive ion accelerator.
- 1957 Multi-element film dosimeter was implemented. IBM 702 computer was implemented for routine personnel dose determination. Automated film processing was implemented with controlled time and temperature tolerances for each film development step.
- 1958 In July 1958 the plutonium fluoride source was introduced. The dose factor was based on the single-collision neutron dose theory. A factor of 1.372 was multiplied by the single-collision calibration factor to obtain a calibration factor for multiple-collision neutron dose theory.
- 1980 DuPont 508 sensitive film was introduced.
- 1982 Improved multi-element film dosimeter was implemented. Improved densitometer was implemented and routine film calibration exposures were changed to lower doses (i.e., 30, 60, 90 mR) to improve accuracy for low doses.
- 1984 Dosimeter processing was subcontracted to United States Testing Company, Inc.
- 1985 NTA film dosimeters were calibrated on-phantom.
- 1971 Basic thermoluminescent dosimeter was introduced.
- 1972 Multipurpose thermoluminescent dosimeter was introduced. Penetrating dose was directly related to response on chip 2 of dosimeter. Neutron calibrations conducted on-phantom.
- 1977 Radium calibration source was replaced by a ¹³⁷Cs source
- 1981 Californium-252 source replaced the plutonium fluoride source. A factor of 1.73 was used to relate the Hanford albedo dosimeter response between the plutonium fluoride and ²⁵²Cf source to obtain a Hanford-specific neutron calibration for this dosimeter. Dosimeter exposures to a bare ²⁵²Cf source were increased a factor of 1.73 to obtain the expected dosimeter response for an equivalent delivered dose from a plutonium fluoride source.
- 1984 Calibration of thermoluminescent dosimeters was done on-phantom for beta/gamma dosimeters; use of barcodes to identify each insert and individual chip sensitivity factors were introduced.
- 1987 Use of the beta/photon dosimeter for mixed beta and photon radiation fields and a new dose algorithm for multipurpose dosimeter to meet DOE/LAP performance testing were introduced.
- 1988 Effective October 1, dosimeter processing was conducted by PNL.
- 1990 Hanford officially received DOE/LAP accreditation dated January 31, 1990.

Dose was determined for each film exchanged on a weekly frequency using characteristic calibration curves. Film was exposed separately to uranium and to radium gamma radiation. For example, calibration data derived via this process for the first week of 1950 are summarized in Table 4.2 and plotted in Figure 4.1. Film was exposed to several levels from uranium and radium, ranging from 100 to 5000 mrad and 100 mR to 10,000 mR, respectively. The film density resulting from these exposures was used to plot the open window and silver shield response. Similar calibration data and plots were prepared for each weekly processing of film dosimeters and each dose determination.

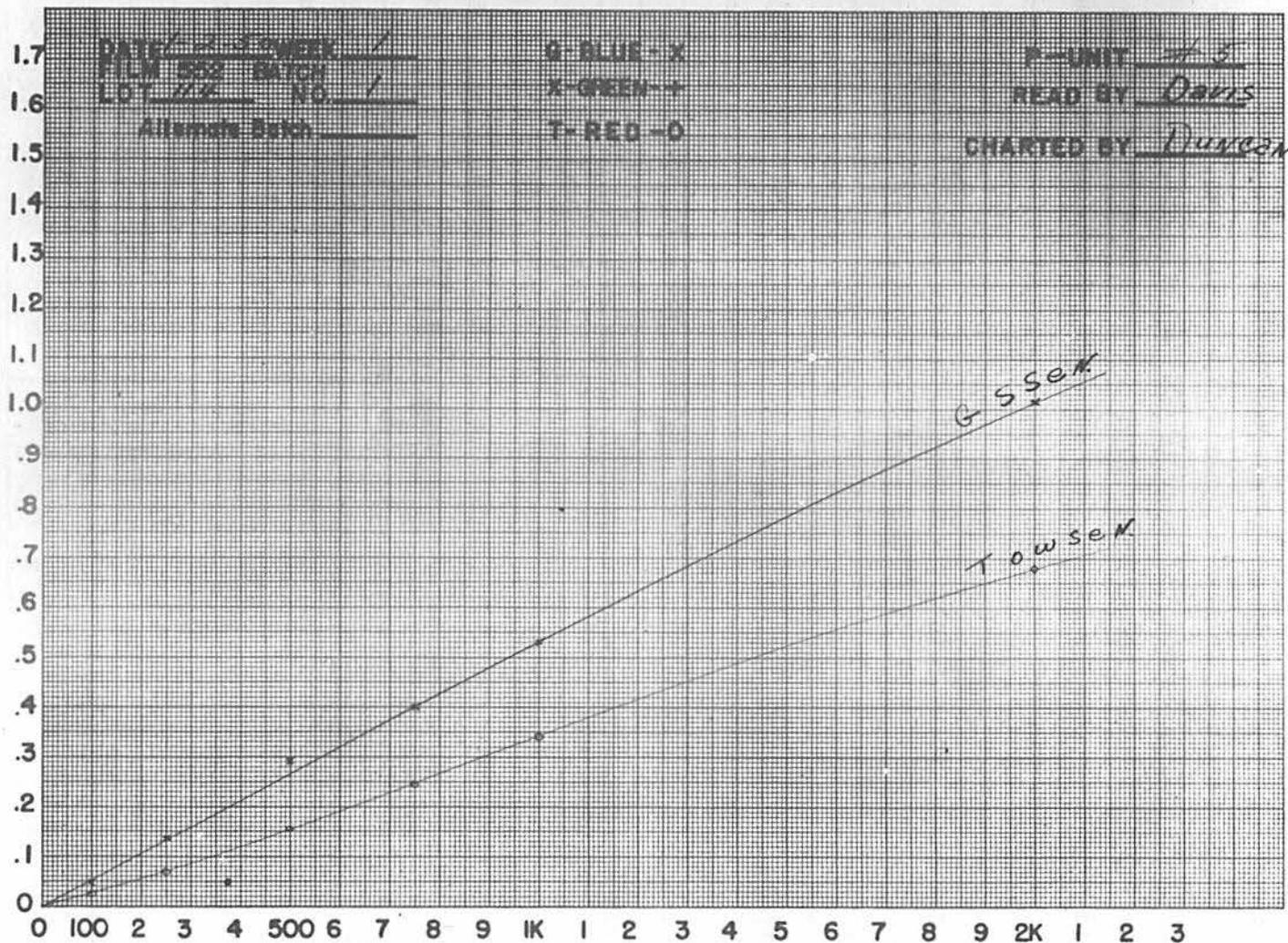
Radiation dose was assigned based on the response of the film behind the open window and silver shielded portions of the film compared with appropriate calibration curves. The open window portion was read as all beta radiation exposure and the shielded portion as gamma radiation exposure. By the latter part of 1951, a standard calibration curve was developed using the 90% confidence levels for determining the limits at each calibration

TABLE 4.2. Calibration Data for the First Week of 1950

Uranium		Radium		
Exposure mrad	Open Window, o.d. (a)	Exposure mR	Open Window, o.d.	Silver Shield, (thick) o.d.
100	0.03	100	0.065	0.04
250	0.08	250	0.25	0.155
500	0.155	500	0.42	0.28
750	0.255	750	0.6	0.41
1,000	0.35	1,000	0.8	0.57
2,000	0.69	2,000	1.48	1.15
5,000	1.5	5,000	2.46	2.06
		10,000	2.95	2.68

(a) o.d. = net optical density.

HW-3.48



4.4

FIGURE 4.1. Calibration Graph for the First Week of 1950. (The vertical axis is net optical density; horizontal axis is gamma radiation in milliroentgen.)

level. The calibration curve values are listed in Table 4.3. If three or more calibration points were within the values shown in Table 4.3, dose are determined from the data shown in Table 4.4. If fewer than three points were within these limits, a batch-specific calibration chart was prepared. In November 1951 a correction factor was also introduced to correct for the part of the open window film density caused by gamma radiation. This factor consisted of subtracting 1.5 times the film density behind the silver shield from the density behind the open window.

In February 1952 a system of reading calibration film density for only the 0.4 and 1.0 exposure levels was used. If these readings were within the limits, the film was considered to be within the limits at all levels and the dose was read from the standard dose chart (see Table 4.4). When deviations beyond the established limits were encountered, a special calibration curve was made from the set of calibration film processed for each batch of film. In February 1953 a revised calibration system was developed involving six exposure levels. If three or more of the six calibration levels were within the limits, the film was considered normal and read from a standard calibration curve. The corresponding radiation dose for densities of .005 to 0.26, as given in Table 4.4, continued to be used.

TABLE 4.3. Standard Calibration Curve Developed in 1951

Beta Radiation			Photon Radiation				
Exposure, mrad	Open Window, o.d.		Exposure, mR	Open Window, o.d.		Silver Shield, o.d.	
	Lower	Upper		Lower	Upper	Lower	Upper
100	0.025	0.035	100	0.040	0.070	0.025	0.050
200	0.050	0.075	200	0.090	0.145	0.065	0.100
300	0.080	0.115	300	0.150	0.225	0.105	0.160
400	0.115	0.145	400	0.230	0.275	0.165	0.200
500	0.145	0.175	500	0.280	0.335	0.205	0.235
600	0.180	0.225	600	0.340	0.405	0.240	0.300
800	0.245	0.305	800	0.440	0.535	0.325	0.400
1000	0.310	0.380	1000	0.565	0.650	0.405	0.490

TABLE 4.4. Standard Calibration Chart for DuPont 502 Film

<u>Net Optical Density</u>	<u>Open Window, mrad</u>	<u>Silver Shield, mR</u>	<u>Net Optical Density</u>	<u>Open Window, mrad</u>	<u>Silver Shield, mR</u>
0.005	15	10	0.135	410	320
0.010	35	25	0.140	420	330
0.015	50	35	0.145	440	340
0.020	70	55	0.150	455	355
0.025	85	70	0.155	470	365
0.030	100	85	0.160	485	375
0.035	115	100	0.165	500	385
0.040	130	110	0.170	515	400
0.045	145	120	0.175	525	410
0.050	160	130	0.180	540	420
0.055	175	140	0.185	555	430
0.060	185	150	0.190	570	445
0.065	205	165	0.195	585	455
0.070	220	175	0.200	600	465
0.075	235	185	0.205	615	475
0.080	250	195	0.210	630	485
0.085	265	210	0.215	645	500
0.090	280	220	0.220	660	510
0.095	295	230	0.225	675	520
0.100	310	240	0.230	690	530
0.105	325	255	0.235	705	540
0.110	335	265	0.240	720	555
0.115	350	275	0.245	735	565
0.120	365	285	0.250	745	575
0.125	380	300	0.255	760	585
0.130	400	310	0.260	775	600

Calibration curves were also available to determine dose from various qualities of x- and gamma rays and, to a certain extent, mixtures of these radiations. However, with the two-element dosimeter there was no method for distinguishing between mixtures of beta radiation and x-ray or gamma radiation for photon energies below 200 keV.

4.2 PERSONNEL NEUTRON FILM DOSIMETER USED FROM 1950 TO 1958

In the personnel neutron film dosimeter used from 1950 to 1958, Eastman-Kodak NTA film was enclosed in the two-element dosimeter holder along with the beta/photon film. The emulsion was approximately 25 μm thick. Dose evaluation was based upon a direct comparison of the number of tracks observed on the personnel film with a calibration curve showing track density as a function of neutron dose. Over the years, several different neutron-emitting sources were used to calibrate the film including RaBe (1944), PoB (1944), PoBe (1950), positive ion accelerator (1955), and PuF_4 (1958), where the year of first use is shown in parentheses. Watson (1951) provides an overview of several characteristics of NTA film, including energy dependence, number of tracks, track length, emulsion thickness, fading, and fields of view, which are important to the use of the NTA personnel neutron dosimeter at Hanford.

During the early years at Hanford, the personnel neutron film was routinely calibrated alternately with a RaBe or a PoB source. For example, the film was calibrated to a PoB source emitting on the order of 10^8 neutrons per second. The film was placed in the Hanford two-element dosimeter during exposure. The sensitivity of the NTA emulsion was approximately $6.86 \pm 0.53 \times 10^{-4}$ tracks/neutron- cm^2 . Measurement of the slow neutron sensitivity was made by exposing cadmium-wrapped and bare films to graphite-moderated neutrons from a PoB source. The sensitivity of the same emulsion was $2.29 \pm 0.19 \times 10^{-5}$ tracks/slow neutron- cm^2 .

Watson (1951) reported a precision of 30% for measuring 1.4×10^5 fast neutrons/ cm^2 using routine procedures, and also discussed certain aspects of the routine assessment of personnel neutron dose in a letter in 1956, (a) stating that Hanford routinely uses 120 fields to evaluate neutron dose.

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

Typically, if a larger-than-expected number of tracks was observed, 400 fields are viewed in order to more accurately determine the dose. The PoB source was used for routine calibration until the use of the positive ion accelerator was implemented. Neutron energies for both the PoB and positive ion accelerator are less than for PoBe. Apparently, it was also the practice to require a minimum number of observed tracks before dose was determined.

Watson also discussed aspects of neutron dose assessment in a letter in 1950.^(a) The standard practice apparently involved three independent observations of the total number of tracks for 40 fields. If the total observed tracks was less than 60, then no further assessment was conducted. Assuming 60 tracks or more were observed per 40 fields, then the results could be interpreted in terms of mrep (milliroentgen-equivalent-physical) of PoB equivalent.

4.3 MULTI-ELEMENT BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962

The first Hanford multi-element dosimeter incorporated a four-filter system to more accurately interpret exposure from various energy ranges of gamma radiation. The design of this dosimeter is described in Section 2.3. This dosimeter incorporated two additional filters, composed of silver and aluminum, in addition to the open window and 1-mm-thick silver filter used in the two-element dosimeter. The 0.13-mm thin silver and 0.49-mm aluminum shields were equal in mass per unit area for beta equivalency but were decidedly different in absorption qualities for x-ray or low-energy gamma radiation (Kocher 1957b). The evaluation (Wilson et al. 1960) of gamma dose could be made to a limited extent even in the presence of beta radiation. This capability to provide dose interpretation in mixed radiation fields was a major improvement in personnel dosimetry.

From 1951 to 1957 calibrated film sets were routinely prepared using the irradiations identified in Table 4.5. The film densities for these multi-element dosimeters were used to prepare calibration data for use in dose determination. A quick determination of the beta and gamma dose from the

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

multi-element dosimeter could be made as soon as film processing results were available from photometry using the following procedure:

1. Inspect the calibration data to determine whether or not the data fall within the limits of the standard curve.
 - a. If the data do not fall within the limits, batch-specific calibration will be necessary.
 - b. If the data fall within the limits, proceed with the following steps.
2. Determine the photon dose by comparing the dose-density relationships for the thick silver shield area from Table 4.3 and read directly.
3. Determine the beta dose by obtaining the equivalent density for the open window from the calibration curve for the photon dose previously determined.
4. Subtract the open window density obtained in Step 3 from the open window density determined for the personnel dosimeter.
5. Using the net density determined in Step 4, calculate the dose directly from the beta calibration table or curve.

TABLE 4.5. Irradiations for Calibrated Film Sets from 1951 to 1957

<u>Radium, mR</u>	<u>Uranium Slab, mrad</u>	<u>16 keV X-Ray, mR</u>	<u>59 keV X-Ray, mR</u>
30	30	20	10
60	60	40	20
90	90	60	30
120	120	80	40
180	180	100	50
240	240	120	60
300	300	140	70
500	500	160	80
750	750	--	--
1,000	1,000	--	--
2,000	2,000	--	--
5,000	5,000	--	--
10,000	--	--	--

The initial Hanford method for calibrating the multi-element film dosimeter involved each calibration set being fitted to a linear curve by the least-squares method using the IBM 702 computer that was introduced into routine use in 1957. This method was entirely adequate because the DuPont 502 emulsion response was essentially linear for the density values used in routine dose calculations. When the more sensitive DuPont 508 emulsion was introduced in 1960, the calibration data were fit to a cubic equation. Fitting the data to a cubic equation provided an "S" curve, which more closely simulated the actual DuPont 508 film response at low exposures to gamma radiation. The formula used in this calibration method, which is based on a system of simultaneous equations, is described in Appendix A.

4.4 MULTI-ELEMENT NEUTRON FILM 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 beta/photon film dosimeter. The thickness of the holder was increased 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 to be made by comparing densities 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. Gamma rays experience nearly equal attenuation in 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.

The film for fast neutrons was calibrated using the PuF_4 source as follows:

1. Film was exposed to a dose of 1.075 rem computed as the first-collision dose. The average film response yielded 71.24 ± 13.51

tracks per 40 fields of view--equivalent to a 1075-mrem exposure with a 95% confidence interval (Swanberg 1959).

2. Interpretation of personnel NTA film after processing was accomplished by counting microscopically the tracks produced in the emulsion by recoil protons. A field of view of $1/129 \text{ cm}^2$ was viewed under 970X magnification with oil immersion.
3. Each of three observers counted the tracks occurring in 40 fields of view (i.e., a total of 120 fields).
4. Films that indicated 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 upper limit of the count for personnel films was compared with the lower limit of the calibration films for similar intervals of tracks per 40 fields per 300 mrem. The ratio of the limits multiplied by 300 mrem was entered into the personnel exposure record.

In January 1965 NTA film was calibrated on-phantom.

Routine calibration of the neutron dosimeter response to slow neutron exposure required approximately 6 days (i.e., 40 hours) 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:

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 millirem behind the silver shield for the beta/photon dosimeter).
3. Divide the radium dose by a factor of 1.940 ± 0.056 to convert to the slow neutron exposure in millirem.

The slow-neutron dose was entered into the personnel exposure record.

4.5 MULTI-ELEMENT BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972

In 1962 an upgraded Hanford multi-element beta/photon film dosimeter was implemented. This dosimeter was designed to take full advantage of mechanized processing. Each dosimeter contained a lead tape perforated with the

employee's payroll number; prior to removal of the film packet, the payroll number was x-rayed onto part of the film to provide positive identification. Film identification and film packet exchange were performed mechanically by the dosimeter processing machine. The dosimeter was designed for use with the Hanford security credential in a neatly integrated badge assembly. The security credential could be removed from the holder by the wearer for easy exchange of only the dosimeter.

Both the iron and the tantalum filters were covered with 20-mil-thick Tenite II plastic to improve the energy response characteristics of the system. The filter system provided a linear density response within 10% for a given gamma radiation dose at any energy between 50 keV and 2 MeV (Kocher et al. 1971). For dose interpretation of a film dosimeter exposed to beta, gamma, and x-ray radiation, the density behind each of the four filters was measured. Dose components were determined for electromagnetic radiation between 50 keV and 2 MeV, electromagnetic radiation between 15 keV and 50 keV, and beta radiation (assuming a beta energy spectrum similar to that emitted by natural uranium). Dose interpretation methods for this dosimeter are described in Appendix B and are summarized as follows:

- Electromagnetic radiation from 50 keV to 2 MeV--The density behind the tantalum filter was caused by electromagnetic radiations with energies greater than 50 keV. This density could be directly related to the dose by use of an appropriate calibration curve.
- Electromagnetic radiation from about 15 keV to 50 keV--The densities behind the plastic filter and the iron filter resulted from electromagnetic radiation and beta radiation. The response characteristics of the filter system were chosen so that electromagnetic radiation energies greater than 50 keV and beta radiation produced equal densities behind each of these filters. For electromagnetic radiations with energies less than 50 keV, the iron filter had a significantly higher absorption coefficient than the plastic filter; consequently, the difference in density between the plastic and iron filters could be directly related to dose by using a calibration curve constructed for energies similar to those encountered by the dosimeter.
- Beta radiation--The densities behind the open-window and the plastic-filter areas resulted from electromagnetic radiation and beta radiation. Electromagnetic radiations with energies greater than 50 keV produced equal densities behind each of these filters. The difference in density between these two filters was a function of the low-energy (less than 50 keV) electromagnetic radiation dose

and the beta radiation dose. Because the low-energy electromagnetic radiation dose had been determined independently from the plastic and the iron-filter density difference, it was possible to correct the density difference observed between the open-window and the plastic-filter areas for the low-energy dose contributions by an appropriate calibration correction curve. After this correction was made, the remaining density difference between the open window and the plastic filter could be related to a beta calibration curve and the beta dose could be determined.

In addition to the normal range of dose evaluation, the new dosimeter had the capability of evaluating doses to an accuracy of within 10% from exposures to radium gamma radiations as well as plutonium and uranium metal radiations. These evaluation capability results were obtained by field testing (Kocher 1962). The dosimeter also contained foils and other dosimeter materials to measure the very high-level exposure from neutron and gamma radiations that may be encountered during a nuclear excursion. This dosimeter had the capability to measure gamma doses in the range of 15 mrem to 2000 rem with the sensitive and insensitive films (Baumgartner 1959a). Glass fluorods extended the gamma dose range to about 10,000 rem. An activation foil system using indium, cadmium-covered indium, copper, and sulfur provided an estimate of neutron flux and spectra in the event of a serious radiation event radiation dose in the range of 1 rad to > 2000 rad.

4.6 MULTI-ELEMENT THERMOLUMINESCENT DOSIMETER USED FROM 1972 TO THE PRESENT

Calibration and dose algorithms for the multi-element TLD are described by Kocher et al. (1971) and Fix.^(a) The use of this system for beta, gamma, and neutron dosimetry is described by Haverfield, Nichols, and Endres (1972). The sources used since the inception of the albedo TLD until 1984 for each dose component are as follows:

- Nonpenetrating--Several aged uranium disk sources are used, each equipped with a specially designed exposure jig. The response of the dosimeter to the uranium source is assumed to be equal to one-half the response to an aged ⁹⁰Sr source encapsulated in 10-mil aluminum (Fix et al. 1981). To calibrate the dosimeter readout, 10 dosimeters are exposed to 4 rad each on the uranium sources (equal to 2 rad of ⁹⁰Sr).

(a) Fix, J. J. Draft. Hanford External Dosimetry Program Manual. Pacific Northwest Laboratory, Richland, Washington).

- Penetrating--Since 1977 a ^{137}Cs source has been used predominantly, and a ^{60}Co source has been used occasionally. Originally, a radium source was used. Ten dosimeters are exposed in air to calibrate the readout of personnel dosimeters.
- Slow neutron--A graphite-moderated sigma pile is used. Six personnel dosimeters are simultaneously exposed in a reproducible geometry for calibration.
- Fast neutron--A PuF_4 source was used until 1981 when a ^{252}Cf source was used. A Hanford site-specific calibration was used based on field measurements as discussed in Chapter 3.0. Six dosimeters are exposed on a polyethylene phantom for calibration.

At the beginning of each routine processing of Hanford personnel dosimeters, a set of calibration dosimeters is read by the automated reader. The reader results for these calibration dosimeters are used to interpret the readout from the personnel dosimeters in terms of dose equivalent. The mathematical formulas used to calculate the calibration coefficients and the dose algorithms used to determine dose are summarized in Appendix C. A chronological history of major changes that have occurred in the Hanford thermoluminescent dosimetry system is also summarized in Appendix C.

The accuracy of the thermoluminescent dosimetry program relative to the evolving national performance standards of American National Standards Institute Standard N13.11 (ANSI 1983) was assessed during 1979 and 1980 (Fix et al. 1981; 1982). The following conclusions about dose components are from the 1982 report by Fix et al.

- Nonpenetrating dose--The dosimeter-determined dose for an actual ^{90}Sr exposure is 40% greater than the reported given calibration exposure based on a "strontium equivalent" uranium exposure (i.e., reported dosimeter results would be 40% too high for a sealed strontium source exposure).
- Penetrating dose--The dosimeter-determined dose for exposure on-phantom is 10% greater than the assumed in-air exposure for ^{137}Cs (i.e., reported results are 10% too high for the 1-cm deep dose from ^{137}Cs exposures).
- Fast neutron dose--The dosimeter-determined dose for a moderated ^{252}Cf exposure is a factor of 1.7 too high and for a bare ^{252}Cf exposure it is a factor of about 4 too low. The Hanford fast neutron calibration was based on the neutron spectra measured at the 234-5-Z Building, and as such, is expected to be an accurate calibration. Follow-up measurements have confirmed the accuracy of this calibration.

- Thermal neutron dose--No NBS-traceable source was available to compare the accuracy of this dose component. Also, ANSI N13.11 (ANSI 1983) does not include a thermal neutron exposure category. As such, the accuracy of this dose component was not evaluated.

Beginning in January 1984, several changes to the thermoluminescent dosimetry system were initiated. A chronological history of several of the changes is presented in Appendix C. Quality control was significantly enhanced by uniquely labeling each insert. Two inserts, one for even- and one for odd-exchange periods, were assigned to each permanent employee. The history of dose determinations for each dosimeter was tracked by computer. Individually determined sensitivity factors were introduced based on the response of the chip in each dosimeter position to an exposure from 1-R ^{137}Cs gamma radiation. The precision of dose determination was improved through the use of the chip sensitivity factors. Calibration exposures were made on-phantom instead of in-air.

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, 1987, the dose algorithm was changed to calculate shallow and deep dose components consistent with the recommendations of ANSI N13.11 (ANSI 1983). Calibration of the shallow dose component for the multipurpose dosimeter was changed to 16-keV fluorescent radiation. The shallow- and deep-dose components replaced the nonpenetrating and penetrating dose components used previously. With these changes the method of determining the recorded personnel doses was changed (as shown in Table 4.1). A more detailed description of changes to the thermoluminescent dosimetry system is included in Chapter 7.0, as well as in Appendix C.

4.7 BETA/GAMMA FILM DOSIMETER CALIBRATION

Since the beginning of Hanford operations, radium has been used to calibrate the film dosimeter and pencil dosimeters used to measure gamma exposure. Film dosimeter calibration was conducted on a "Ouija board" similar to pencil dosimeters and other wooden jigs that positioned the film dosimeter at various distances from a source (see Figure 4.2). The distances were carefully measured to provide the various levels of exposure to produce a calibration set.

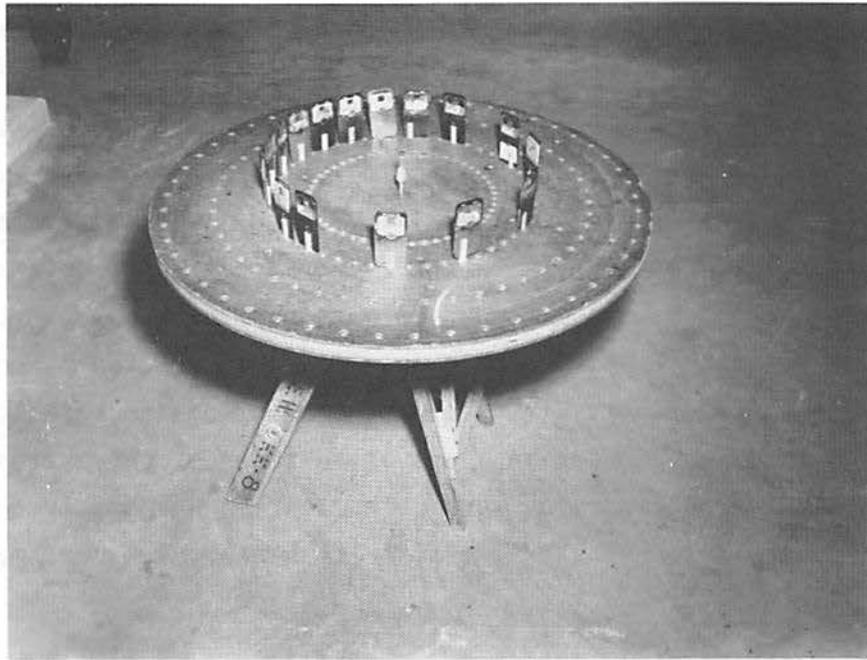


FIGURE 4.2. Film Calibration on the "Ouija Board"

In 1959 a calibration jig was placed in use to improve the accuracy of dose delivered to the film during calibration (Kocher 1959). During this period the first mechanization of source movement was also placed in service. The calibration source was a 0.5-g radium capsule prepared in 1947. Periodic checks of the source were made by the Radiological Physics group using calorimetric measurements and they found it to be 1.4% less than that calculated from the certified weight of the capsule. A dose rate of 8.25 R/hr at 1 cm from 1-mg ^{226}Ra encapsulated in 0.5-mm platinum was considered the standard. The jig (see Figure 4.3) held the film 4 feet above the concrete floor in a large open room to minimize scatter, and an automatic source positioning mechanism was used to position the source and control the time of exposure. The system uses a vacuum pump to lower pressure in the tube attached to the storage cask causing the source to rise into correct exposure position. Timing was regulated by controlling the operating time of the vacuum pump with an accuracy of ± 3 sec/hr, and during exposure the source rotated in the tube, which nullified any nonisotropic emission effects. Measurements on the

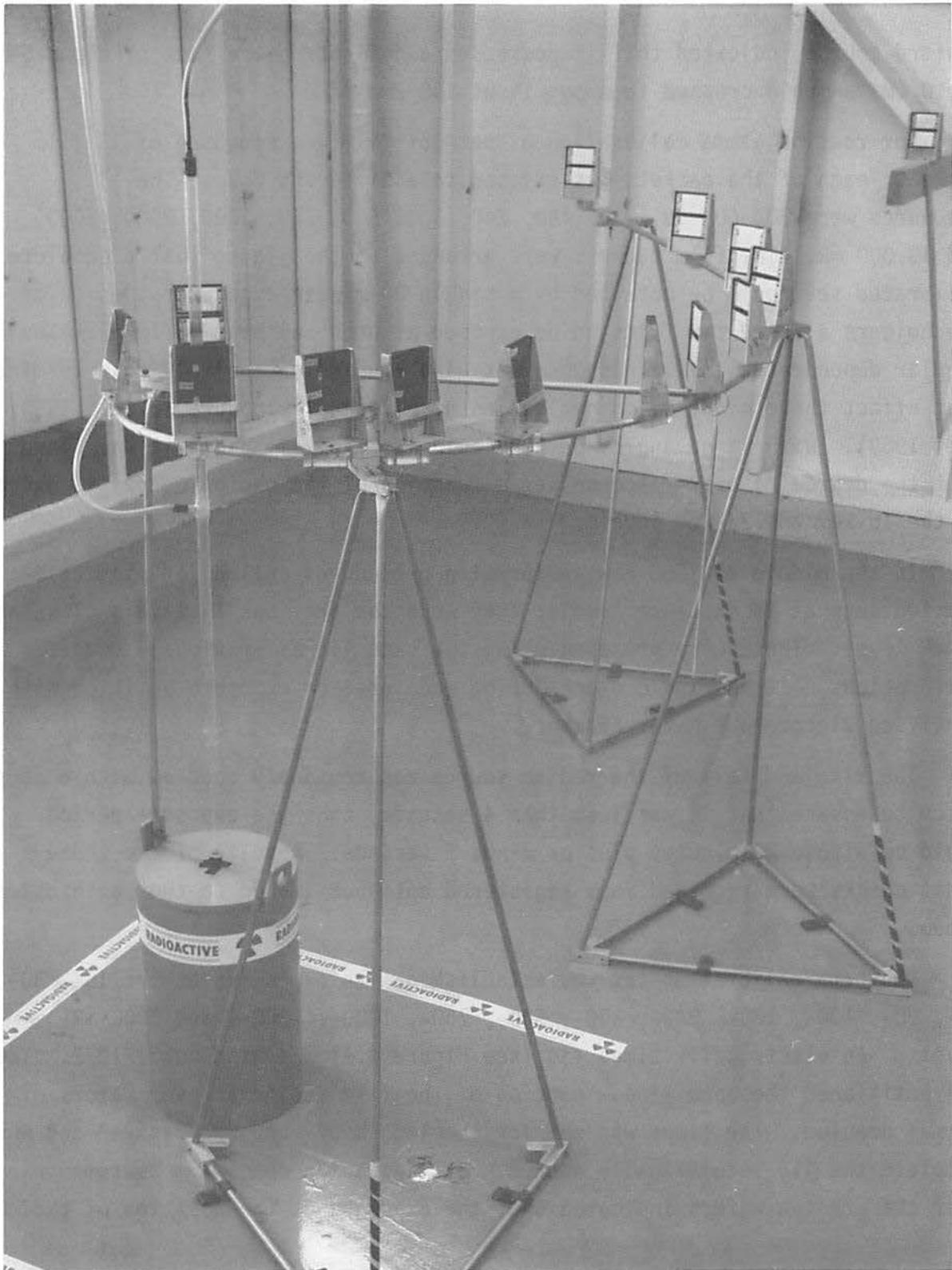


FIGURE 4.3. Improved Film Calibration Jig with Rotating Source

Hanford source indicated that it possessed a nonisotropic effect of about 5% at 10 cm, which decreased to about 1% at 100 cm. (a)

For routine gamma calibration a "set" of film was composed of 13 film packets; each of the packets was exposed to a different dose. The 13 exposures were 30, 60, 90, 120, 180, 240, 300, 500, 750, 1000, 2000, 5000, and 10,000 mR. The film packets were arranged on the jig so that a complete calibrated set could be obtained by a single 20-minute exposure. Design of the holders allowed two films to be exposed at each calibration level. The angular dependence of film response was also studied extensively to determine what effect there might be on evaluation of personnel exposure (Little 1960; Nees 1969). With large angles perpendicular to the film plane it was found that the degree of over-response was a function of the photon energies, except at the 16-keV and 23-keV levels.

In the middle of 1965 new calibration procedures called for film calibration sets at 14 exposure levels; they were the previous 13 levels plus the 15-mR level. These were prepared using the same jig as previously used for calibrations, with periodic checks being made at each exposure position with a certified Victoreen R-Meter chamber.

The rise and fall of the radium source was routinely checked with a stop watch to assure that it was less than 4 seconds, thus the exposure period would be within 20 minutes plus or minus 5 seconds. Results of the these audit checks were recorded in a registered notebook issued to the Calibrations group.

The beta calibration set was established with exposures at the 15-, 30-, 60-, 90-, 120-, 180-, 240-, 300-, 500-, 750-, 1000-, 1800-, and 5000-mR levels. An electrically timed jig (see Figure 4.4) was used until 1972. The jig positioned the open window portion of the film dosimeter over wafers of normal uranium. The timer was set for the length of exposure desired and when complete the jig automatically opened. Extrapolation chamber measurements over the uranium wafers indicated that the exposure at the position of the

(a) C. G. Hough, G. A. Little, and W. L. Nicholson. 1959. Radiation Protection Operation Precision and Accuracy Study; Non-Isotropic Effect in Radium Gamma Source. Internal report, General Electric Company, Richland, Washington.

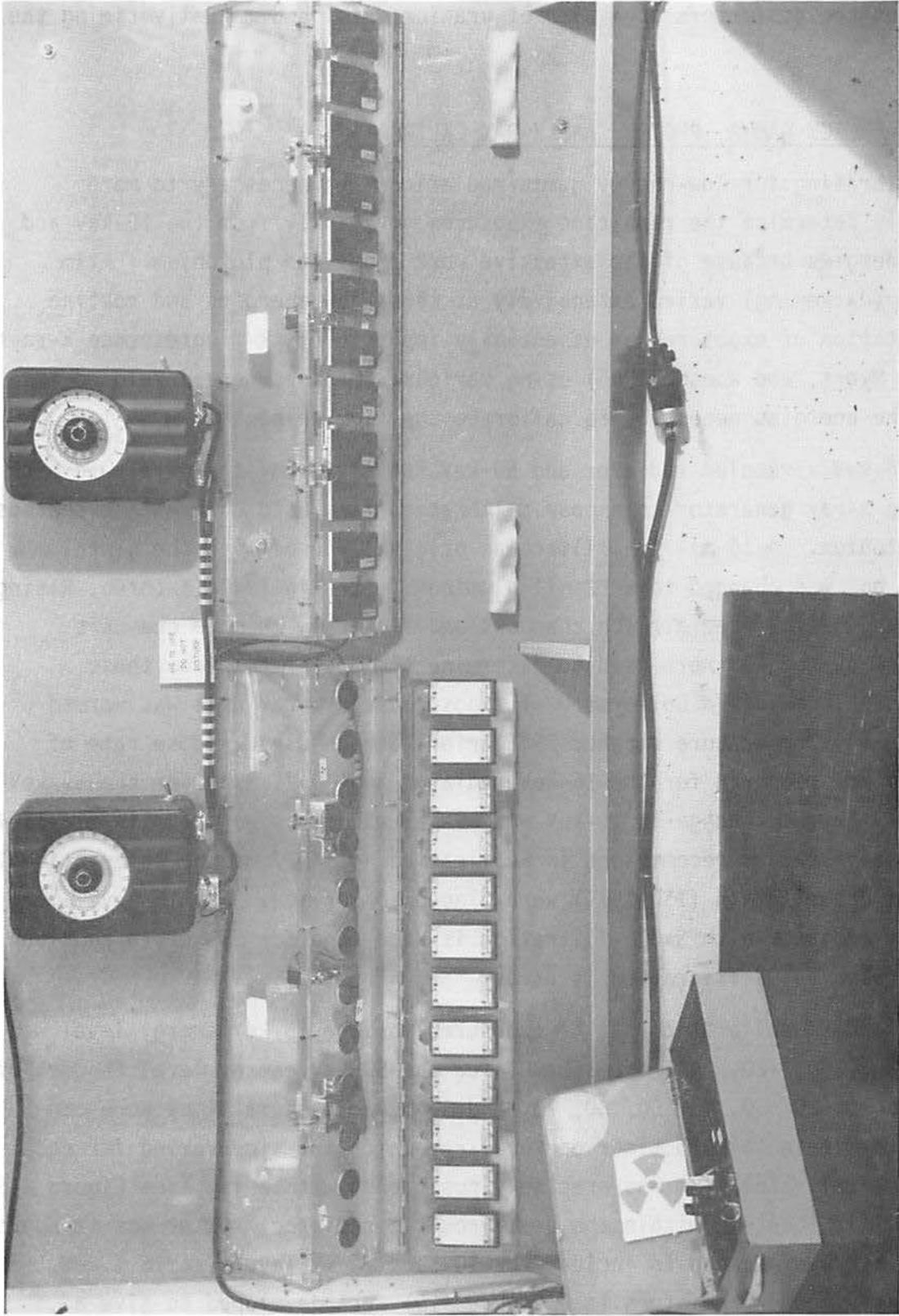


FIGURE 4.4. Uranium Calibration Jig

film was about 225 mrad/hr. Previously, beta calibrations had been performed by placing the dosimeters on a slab of uranium metal and manually timing the exposure.

4.8 LOW-ENERGY GAMMA, PHOTON, AND X-RAY CALIBRATION

Calibrating for low-energy gamma radiations was necessary to more accurately determine the resultant exposures, primarily from the 16-keV and 59-keV energies because of the extensive work done with plutonium. Film response (darkening) varied extensively at these low energies and routine interpretation of exposure was essentially impossible. K-fluorescence x-rays (Larson, Myers, and Roesch 1955) using various radiators were developed to obtain the energies necessary to calibrate the film response.

A 16-keV zirconium radiator and 59-keV tantalum radiator were used with a 220-Kvp x-ray generator to expose calibration film used to evaluate the dose from plutonium. A 16-mil tin filter was originally used with the tantalum radiator but was changed to a 32-mil aluminum filter in 1970 (Kathren, Rising, and Larson 1971). Free air ion chambers and Victoreen thimble chambers calibrated by the NBS were used to determine the dose rates from these radiators. To maintain uniformity of exposure, the x-ray unit was warmed until the oil temperature reached 75°F prior to each use. A dose rate of 4.79 R/hr was measured for the 16-keV radiator and 70.2 mR/hr for the 59-keV radiator. Another change in 16-keV and 59-keV radiators was made in mid-1984 when those radiators recommended in Publication No. 4037 of the International Standards Organization (ISO 1979) were placed in service. For 16 keV, a zirconium radiator with SrCO₃ filtration is used, and for 59 keV, a tungsten radiator with Yb₂O₃ filtration is used.

A standard calibration set of exposures for the 16-keV energy level was 40, 60, 80, 100, 120, 140, and 160 mR; for the 59-keV energy level the set of exposures was 20, 30, 40, 50, 60, 70, and 80 mR. Exposure times were controlled to within 1% by a timer on the x-ray unit; the time varied for each exposure level. The film was precisely positioned with a jig (see Figure 4.5) at a specific location within the beam from the radiator. Later the standard exposure set was changed to include the 10- and 20-mR levels at 16.1 keV. Subsequently, other radiators (see Figure 4.6) were developed to give a broader range of energies for calibrating dosimeters. The routine use of

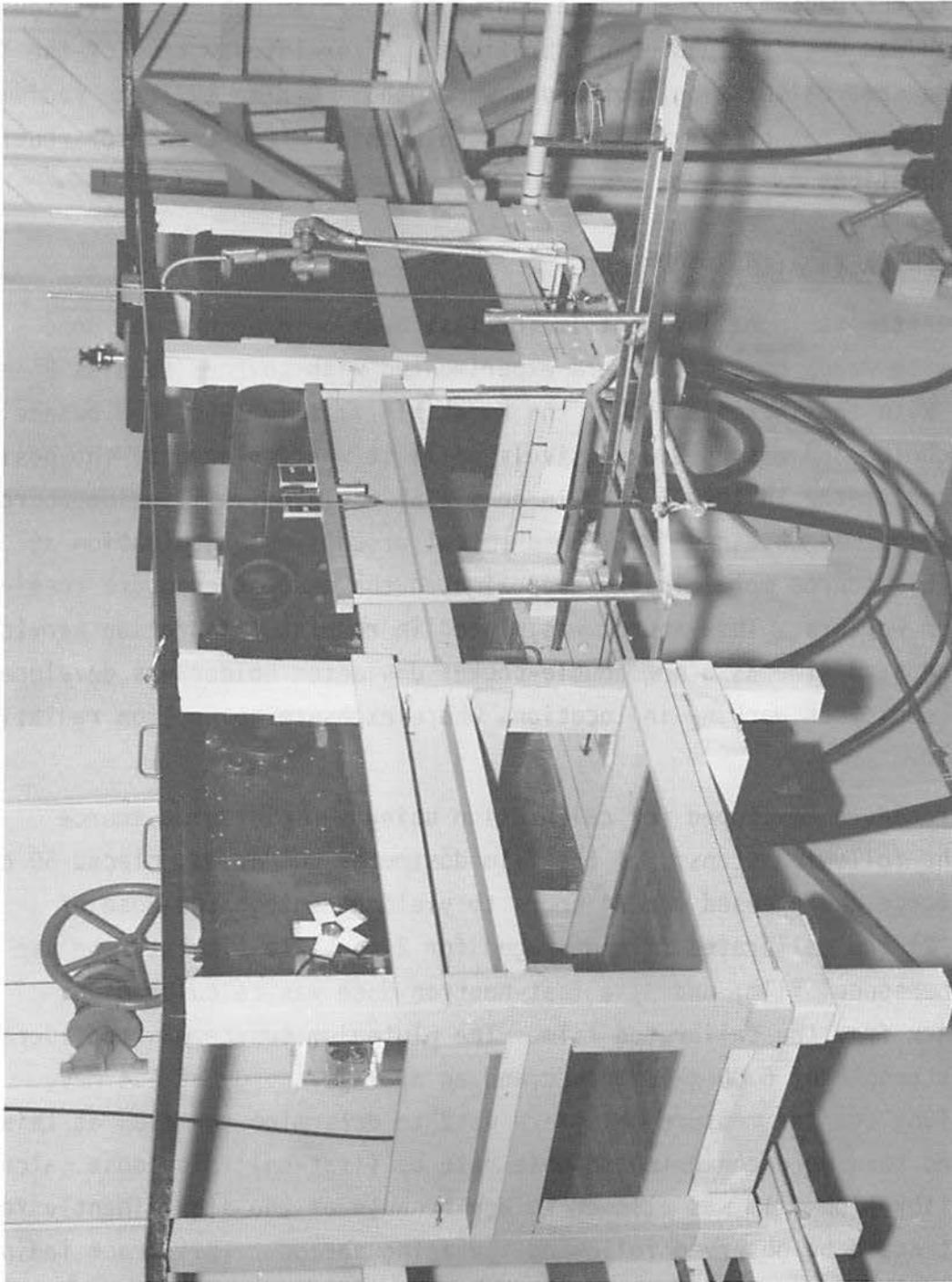


FIGURE 4.5. Jig for X-Ray (K-Sources) Calibration

radiators for personnel dosimeter calibration was phased out during the late 1960s and they were used only for occasional checking of dosimeter response and for special irradiations. The characteristic response of the film dosimeter to the radium source and darkening of the film behind the various shield areas was used for photon calibrations. After introduction of the TLD systems, the same calibration techniques were used. During 1977 the radium source was phased out of service and replaced with a ^{137}Cs source for routine photon calibrations.

4.9 NTA FILM CALIBRATION PROCEDURE

Early attempts to calibrate film for fast neutron exposure was done primarily with RaBe; however, others experimented with sources such as PoBe and PuBe. With the introduction of the Kodak NTA film in 1950, PoB became the source of choice and was used exclusively until it was replaced by the positive ion accelerator in late 1955. In July 1958 a plutonium fluoride source for calibration was obtained from the chemical processing organization at Z-Plant. This source more closely approximated the neutron exposure received by plutonium workers. This source was placed in routine calibration service at about the same time as a new double-pocket dosimeter holder was developed for use by employees working in locations where exposure to neutron radiation was possible.

The procedure developed for calibration using the plutonium source included the following steps: 1) the film dosimeter holder was placed 50 cm from the source and exposed for 64 hours to yield an integrated dose of 1050 mrem; 2) the calibrated film was aged for 2 weeks to simulate the use period of personnel film; and 3) a fast-neutron dose was calculated per neutron track from the calibrated film. The plutonium 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 this distance and then were 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 (see Figure 4.7), which had graphite stringers for positioning the neutron source and stringers for positioning the dosimeters for

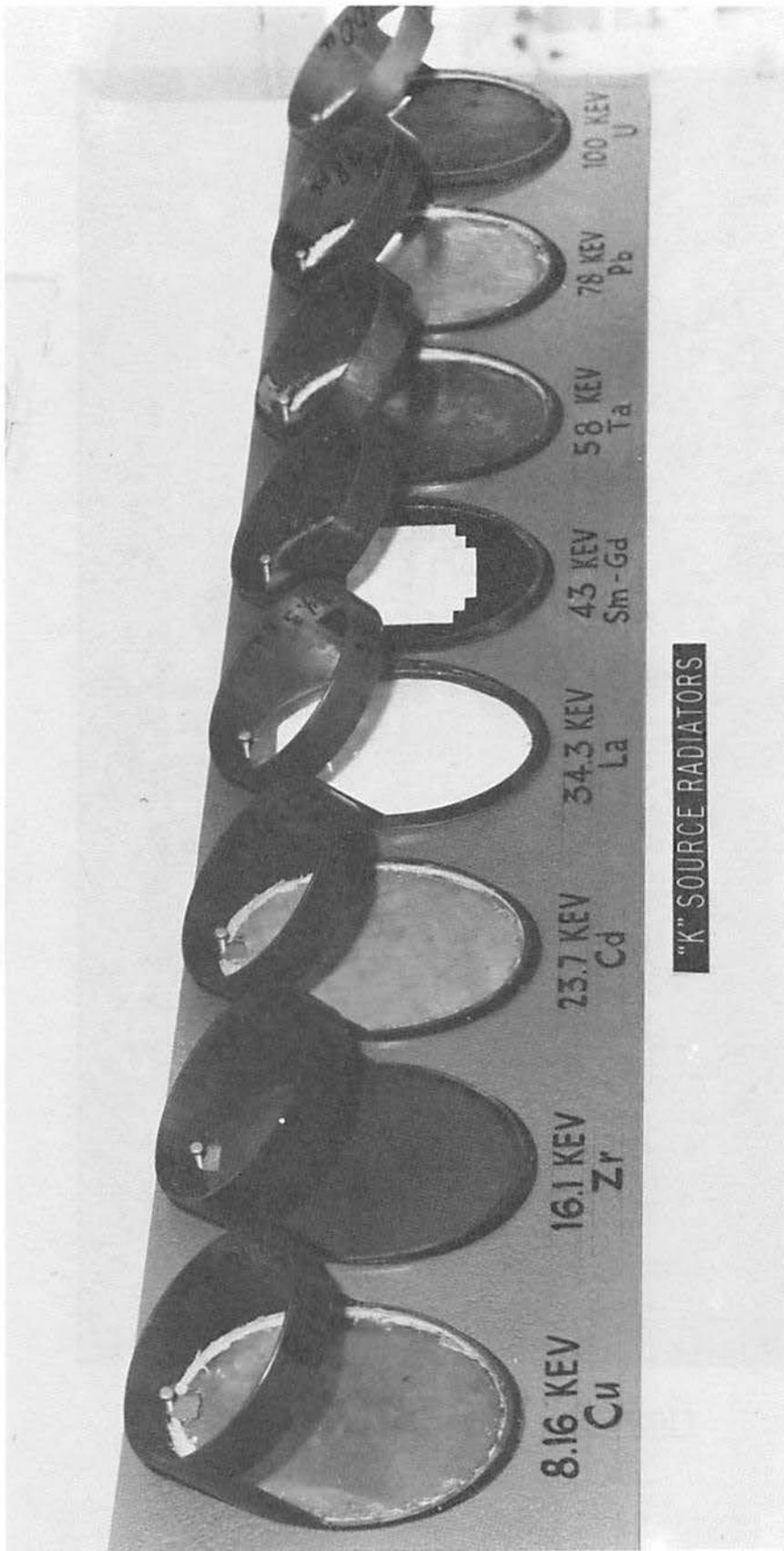


FIGURE 4.6. Radiators for Various Low-Energy Calibrations



FIGURE 4.7. Sigma Pile

calibration. Gold foils were used to calibrate the positions for dosimeter placement.

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 backscatter that affected the film and radiation dose received. When the TLD was introduced in 1972, it was calibrated in the same manner. In 1981 a ^{252}Cf source replaced plutonium fluoride for routine neutron calibration. This change eliminated the potential problems of handling and storing a large plutonium source.



CHAPTER 5.0

DOSIMETER QUALITY CONTROL PROGRAMS



5.0 DOSIMETER QUALITY CONTROL PROGRAMS

The accuracy and reliability of radiation exposure measurements and records have been important from the very beginning of the radiation protection program at Hanford. At the inception of the Manhattan Project, the limitations in knowledge and available capabilities in personnel dosimetry were well recognized. Dosimetry techniques were actively shared between U.S. laboratories. Many controls and checks were introduced immediately into the routine programs to provide assurance of the dosimeter capability to measure and record radiation exposure to personnel. A program was started almost immediately at Hanford for research and development within the Health Instruments (HI) Section that was formed in 1944 to improve radiation protection programs. Throughout the ensuing years, numerous quality control assessments, special evaluations, and laboratory intercomparisons were conducted to better determine and, if possible, upgrade the quality of personnel dose estimates. Program practices and improvements, although well-known to people intimately familiar with the program, were not always formally documented. The authors have summarized information in this chapter from many, but certainly not all, studies of program practices. Conclusions presented are those of the original authors. No attempt has been made in this chapter to evaluate these conclusions.

5.1 ROUTINE QUALITY CONTROL PROGRAMS

Quality control programs have been in place since the inception of Hanford operations. Over time, procedures have been adopted to better ensure the quality of dosimeter processing, dose assessment, and recording. Administrative reviews were conducted of elements of the dosimetry program. Dosimeter calibration was based on the exposure of dosimeters to known levels of radiation. Audit dosimeters, consisting of known levels of dose, were routinely processed along with personnel dosimeters.

5.1.1 Early Reviews of Dosimeter Records

Early audits (Parker 1945) of the film dosimeter records identified less than 1 error per 1000 entries, even with all of the manual handling and recording of these results. Most of these errors occurred in what was called the "Rover" series; these were dosimeters assigned to certain workers who

worked in as many as seven different work locations at one time. Such assignments resulted in seven dosimeters being processed each week for one person whether they were used or not.

5.1.2 Film and Pencil Dosimeter Control

Film packets used in the personnel film dosimeters were ordered in small lots of about 300 boxes. Specifications required that all of the film packets in each shipment be from the same emulsion lot. Each order usually covered about a 3-month operation (approximately 45,000 film packets). The film packets were kept in refrigerated storage until they were used. Each of the 300 boxes was sampled; one packet from the top, middle, and bottom was removed for immediate processing to determine background density. These control procedures were carefully followed during the period when film was used as the primary personnel dosimeter at Hanford.

Whenever film dosimeters were exchanged for processing by the dosimeter crews, they were routinely monitored for signs of external contamination or physical damage. Pencil dosimeters were routinely exposed to a given amount of radiation to verify that they were responding properly and they were also examined for physical damage. Any film or pencil dosimeter suspected of being damaged or not responding properly was removed from service for repair or replacement according to established personnel dosimeter procedures (Hart 1946; 1967).

In 1962 a system was initiated that would detect whether or not calibration film was exposed to any extraneous radiation during its storage and exposure in the 3745 Calibrations Building. Film packets called "calibration blanks" were used to measure the radiation background and extraneous exposure to calibration sources. The blanks were kept with the film sets at all times, except during exposure to a calibration source, and were processed at the same time as the calibration set to determine whether or not the film had received any measurable stray radiation. This control was temporarily dropped during the transition to thermoluminescent dosimetry, but was reinstated shortly thereafter to check for stray radiation effects.

5.1.3 Audits of Nuclear Track Emulsion Film Dosimeter Density Readings

In a 1951 report, Watson discussed the practice of training technicians and evaluating their performance in the determination of tracks for Eastman-

Kodak NTA film (Watson 1951). Watson also discussed the routine practice of processing film exposed to significant fractions of the permissible exposure with the personnel film. The results for processing 14 films are summarized in Table 5.1. Watson concluded that good precision between technicians is observed when they are properly trained and carrying a normal workload. Watson states that it is possible to measure 1.4×10^5 of fast neutrons/cm² within about $\pm 30\%$ error using routine procedures.

5.1.4 Early Evaluation of Dosimetry for Plutonium X-Rays

The two-element dosimeter holder that holds the film packet has a 1-mm silver shield and an open window area around the film packet. This holder design was adopted from the system originally developed for use at the Metallurgical and Clinton Laboratories and remained essentially unchanged until April 1957 when a new plastic film holder with multiple filters was introduced. The shortcomings of dose interpretation (particularly in mixed-radiation fields) were recognized very early, especially when large-scale processing of plutonium became routine in 1949 and mixtures of low-energy photons were present. Interpretation of dose as measured by the film dosimeter was studied extensively and methods of evaluating densities were determined to interpret dose contributions from low-energy photons (Larson and Roesch 1954; Larson, Myers, and Roesch 1955). These detailed methods did not lend themselves to routine processing of literally thousands of dosimeters

TABLE 5.1. Results of the 1951 Nuclear Track Film Processing Audit

<u>Permissible Exposure^(a)</u>	<u>Number of Films</u>	<u>Observed Number of Tracks/40 Fields</u>	<u>Standard Deviation of the Mean</u>	<u>Expected Number of Tracks/40 Fields</u>
0.1 (approximately)	6	8.6	± 24	7
0.2 (approximately)	3	15.0	± 24	15
0.4 (approximately)	2	39.4	± 22	30
0.8 (approximately)	3	56.0	± 18	60

(a) Based on 50 neutrons/cm²-s for 80 hours.

each week. If densities measured on the film indicated an unusual and/or high exposure, a detailed analysis would be made to provide the best estimate of exposure.

In 1957 Keene discussed the history of low-energy x-ray dosimetry problems at the plutonium finishing facility.^(a) Investigations had been initiated in 1949 to determine which radiations existed in this facility and to determine the accuracy of the film dose measurements. Early investigations focused on the effect of the low-energy x-rays on the open window and silver-shielded portions of film for the two-element dosimeter. Errors, particularly for the open window area, were estimated to be as much as a factor of 2 in extreme cases. Keene concluded that the present interpretation of the film dosimeter results was correct, assuming that no beta radiation was present.

Later, Watson provided an analysis of the low-energy x-ray dose history for approximately 20 selected employees who worked at the 234-5 Building from 1953 through 1956.^(b) This analysis indicated that the soft x-ray component of the annual dose for these individuals increased continuously during this time period. Watson's analysis of the low-energy x-ray component of the total dose is summarized in Table 5.2. While Watson did not provide any reasons for the increase, his analytical effort did underscore the continuing review of the two-element dosimeter to properly record x-ray exposures.

During 1957 the first multi-element beta/photon film dosimeter was introduced at Hanford. At the same time, the concept of treating the low-energy x-ray as a nonpenetrating radiation was introduced.^(c) The combination of these changes was estimated by Watson to result in a significant reduction in recorded nonpenetrating exposure. The effect of these changes was examined for selected personnel working in the 234-5-Z Building. Watson also discussed the improvements in 1958 with the introduction of the first multi-element neutron film dosimeter, which permitted measurement of slow and

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- (a) Keene, A. R. 1957. "Exposure Problem 234-5 Building." Letter to G. E. Backman, dated February 12, 1957.
 - (b) Watson, E. C. 1957a. "234-5 Exposure Histories." Letter to A. R. Keene, dated February 22, 1957.
 - (c) Watson, E. C. 1958. "CPD Measurements Data--1958." Letter to A. R. Keene, dated December 30, 1958.

TABLE 5.2. X-Ray Component of Total Dose

<u>Year</u>	<u>Number of People</u>	<u>Average Total Dose, R</u>	<u>X-Ray Dose Component, R</u>	<u>X-Ray/Total Dose Percent</u>
1953	23	1.3	0.6	46
1954	22	1.0	0.6	60
1955	23	1.5	0.9	60
1956	27	2.7	1.9	70

fast neutrons. Improvement in the calibration procedure for fast neutrons was greatly enhanced with the adoption of the PuF₄ source.

5.1.5 17-keV Deep-Dose Curve

Watson discussed personnel film dose measurements relative to the annual dose standards in 1957.^(a) Personnel exposures to photons at the 234-5-Z Building result primarily from three energy groups: 1) 17 keV, 2) 60 keV, and 3) higher energies. These components contribute 25%, 10%, and 65% of the total dose, respectively.

Watson described the measurement of the deep-dose curve for low-energy x-rays as summarized here. A water phantom was used with a condenser ion chamber. A deep-dose curve was generated for the observed ion chamber readings with increased depth. The 16.1-keV fluorescent x-ray source was used. As indicated by this curve, the dose at the depth of the blood-forming organs (i.e., 5 cm) was less than 1%. The dose at the depth of the gonads (i.e., 1 cm) was measured to be 35% of the surface dose. Watson stated that the penetrating dose plus 35% of the 17-keV dose should be compared with the dose limit of 3 R. This logic is extended by Vanderbeek to the permissible limits for exposure of personnel to metallic plutonium.^(b) Follow-up letters written by Watson^(c) and Backman^(d) indicate the position taken by management that

(a) Watson, E. C. 1957. "234-5 Gamma Exposure Limits." Letter to A. R. Keene, dated August 2, 1957.

(b) Vanderbeek, J. W. 1957. "Permissible Limits for Exposure to Metallic Plutonium." Letter to G. E. Backman and A. J. Stevens, dated August 28, 1957.

(c) Watson, E. C. 1957. Letter to A. J. Stevens, dated September 9, 1957.

(d) Backman, G. E. 1957. "Exposure of Operators." Letter to L. I. Brecke, dated November 6, 1957.

the total dose should be kept less than the 3-R/yr limit. This study apparently confirmed the Hanford practice of adding 35% of the x-ray dose to the penetrating dose to determine the whole body dose recorded for each employee.

5.1.6 Examination of Film for Reproducibility from 1944 to 1957

In 1957 Wilson analyzed the reproducibility of the density readings of personnel film dosimeters used from 1944 to 1957 and checked the condition of the film (Wilson 1957). For his study, personnel and calibration film from the years 1944, 1945, 1946, 1948, 1952, 1954, and 1956 were sampled and re-examined. The objectives of the study included the following:

1. Evaluate the evidence of density fading.
2. Observe the conditions of stored film.
3. Determine the reproducibility of film density readings.
4. Estimate the life expectancy of the stored film.
5. Determine the accessibility of film for specific individuals for specific time periods and availability of proper film calibration sets.

Wilson concluded that there was no problem with fading during the period observed and that the stored film was generally in good condition, having a life expectancy of up to 50 years. Existing methods provided complete information for evaluation of personnel film results. The reproducibility of the film density readings was considered to be generally within 10%, and occasionally within 30% to 40%; all obvious errors detected were prior to 1950. The accessibility of film for specific individuals was reasonably good except for the period from 1944 to 1945.

The measured density in 1957 and the recorded density in 1944 are plotted in Figure 5.1 to show the reproducibility of film density readings.

5.1.7 University of Pittsburgh Film Study

In 1965 an effort was undertaken by the Graduate School of Public Health at the University of Pittsburgh to re-evaluate the measurement results of Hanford film dosimeters (Mancuso et al. 1966).^(a) All film records for

(a) Brodsky, A. 1966. "Re-Evaluation of Hanford Film." Letter to J. M. Selby, dated December 14, 1966.

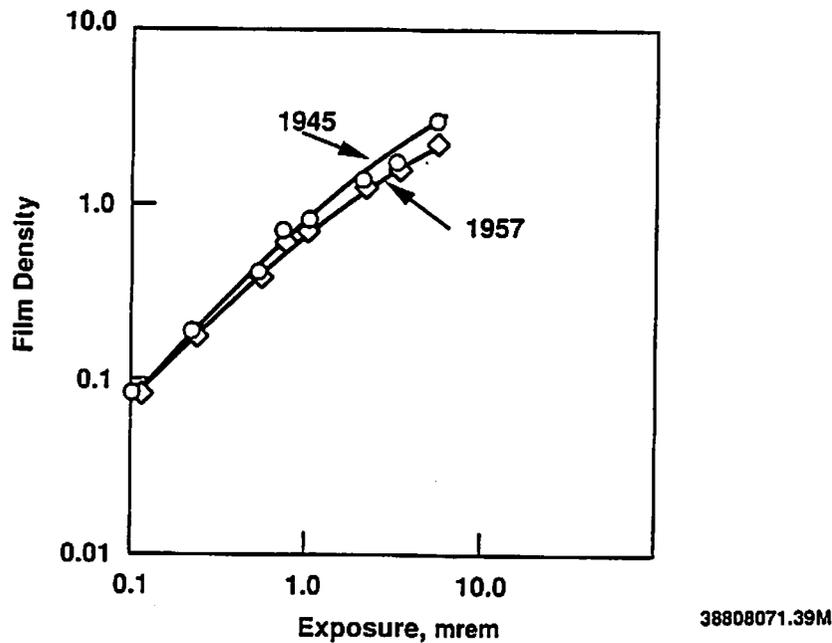


FIGURE 5.1. Reproducibility of the 1945 Film Density Readings

19 individuals were examined. Thirteen of the nineteen employees had work histories covering the entire period of Hanford operations since 1944. Film records for all of these individuals were shipped to the University of Pittsburgh for independent reading using their densitometer. Calibration film from each processing was also provided. This study resulted in the following conclusions:

- All calibration, control, and personnel monitoring films dating back to 1944 appeared to be in good condition and were still readable in 1966. The average quarterly calibration curves (presented in Figures 1 through 68 of the University of Pittsburgh report [Mansuco et al. 1966]) gave no evidence that the developed image, as produced by Hanford processing methods, had faded during the years.
- Considering that the calibration curves for the DuPont 502 films remained consistent in shape and in absolute magnitude of response from 1944 through 1960 and that, similarly, calibration curves for the DuPont 508 films introduced in 1960 were consistent, it was concluded that good quality control of the film dosimeter calibration and processing procedures was exercised at Hanford.
- The shapes of all calibration curves for both DuPont 502 and 508 films were consistent with the assumption of the dose-versus-density relationship of

$$d = d_s(1 - e^{-cd}) \tag{5.1}$$

where d = the net density above the unexposed control films
 d_s = the saturation density
 c = a constant for a particular film under fixed-exposure
and processing conditions
 D = the dose in millirem.

- Consideration of the soft x-ray component to the whole body exposure of personnel at Hanford cannot be neglected.
- It is feasible to reread the films processed and stored at Hanford over the years, but a reinterpretation of penetrating radiation exposure from the density readings requires consideration not only of the open-window and shield readings, but often of additional information from field surveys that identify the nature and intensities of the various components of the radiation field to which the individual employee is exposed.

5.1.8 Personnel Film Dosimeter Audits During 1958

Watson summarized the measurement results of film dosimeters assigned to four fictitious employees during 1958.^(a) According to the letter, these dosimeters were placed in service with the utmost discretion with only one other person aware of the fictitious payroll assignments. No one connected with the routine dosimeter program knew of the presence of these audit dosimeters in the system. Seventy-nine films from these dosimeters were processed during the year. Ten of the films were each exposed to 50 mR. The results for the exposed film are summarized in Table 5.3. A total gamma dose of 474 mrem was reported for a given exposure of 500 mR to the 20 dosimeters that were exposed. This represents a negative bias of approximately 5%.

TABLE 5.3. Results of Film Audit Dosimeters During 1958

Dosi- meter	Number of Exposed Film	Given Total Dose Gamma, mR	Reported Total Dose		Reported Dose for Unexposed Film Gamma, mrem
			Beta, mrad	Gamma, mrem	
A	6	300	0	266	0
B	1	50	0	30	0
C	0	0	0	0	0
D	<u>3</u>	<u>150</u>	<u>17</u>	<u>178</u>	<u>39</u>
Total	10	500	17	474	39

(a) Watson, E. C. 1959. "Film Audit-1958." Letter to H. A. Meloeny, dated January 23, 1959.

5.1.9 1960 Audit of Dosimeter Results

Wilson^(a) reported on the processing results for audit dosimeters during 1960. Fifty-two films were processed for four fictitious payroll numbers. Forty of these films were placed in the system throughout the year with no radiation exposure. Only one of these 40 films had a positive result, which was reported as 34 mrem during the early part of the year when the DuPont 502 film emulsion was still in use (Hanford changed to the 508 emulsion during 1960).

For the 12 dosimeters that received radiation exposure, gamma doses of 90, 180, and 300 mrem were used. A small amount of beta dose was placed on four films: two cases at the 90-mrem level and two at the 180-mrem level. The results are shown in Table 5.4. Considering the gamma dose only, approximately 95% of the given dose was reported in the routine dosimeter processing. For individual doses at the 90-, 180-, and 300-mrem levels, reported dose totals were 92%, 96%, and 95%, respectively, of the given dose. The data indicated that whenever a positive beta dose was reported, the gamma dose was correspondingly low. However, the total dose (gamma plus beta) was very close to the actual gamma dose delivered.

TABLE 5.4. Audit of Dosimeter Results During 1960

<u>Dosimeter</u>	<u>Given Gamma Dose</u>					
	<u>90 mR</u>		<u>180 mR</u>		<u>300 mR</u>	
	<u>Gamma</u>	<u>Beta</u>	<u>Gamma</u>	<u>Beta</u>	<u>Gamma</u>	<u>Beta</u>
Badge A	98	0	177	0	270	2
Badge B	88	0	163	15	280	0
Badge C	68	12	181	0	280	0
Badge D	<u>78</u>	<u>7</u>	<u>169</u>	<u>19</u>	<u>305</u>	<u>0</u>
Total reported	332	19	690	34	1135	2
Total given	360		720		1200	
Percent	92%		96%		95%	

(a) Wilson, R. H. 1961. "Audit of Film Badge System-1960." Letter to H. A. Meloeny, dated January 24, 1961.

5.1.10 Routine Audit Dosimeter Program

When dosimeter processing was performed by United States Testing Company, Inc. (UST), audit dosimeters were exposed to known levels of radiation by PNL and were routinely processed to determine the adequacy of the calculated doses. In three letters to the Hanford Radiation Protection Historical Files, Heid summarized audit dosimeter results for the years 1965 through 1967.^(a,b,c) The third letter provides an overview of the dosimeter results from 1965 through 1967. Performance charts are presented in the letters for the following:

- dosimeters exposed to radium gamma radiation between 100 mR and 299 mR, 300 mR and 499 mR, and 500 mR and 1000 mR
- dosimeters exposed to uranium beta radiation between 100 mrad and 299 mrad, 300 mrad and 499 mrad, and 500 mrad and 1000 mrad
- dosimeters exposed to 17-keV x-ray radiation between 10 mR and 99 mR and 100 mR and 160 mR
- dosimeters exposed to neutron radiation
- ring dosimeters exposed to radium gamma radiation.

Examples of the information provided are shown in Tables 5.5 and 5.6 for radium and neutron audit dosimeter results, respectively.

5.1.11 Gamma Angular Dependence of the Hanford Atomic Products Operation Film Dosimeter During 1960

Little (1960) described the results of a study of measured optical density units with angle of incidence for open window and 1-mm silver-shielded DuPont 552 film packets (containing 502 sensitive emulsion). The film was exposed in Hanford personnel dosimeters to approximately 800 mR of radium gamma radiation. The results of this study are shown in Figure 5.2, in which

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- (a) Heid, K. R. 1967. "Audit of USTC Performance-1966." Letter to the Radiation Exposure Record Historical File, dated January 26, 1967.
 - (b) Heid, K. R. 1968. "Audit of USTC Performance-1967." Letter to the Radiation Exposure Record Historical File, dated January 29, 1968.
 - (c) Heid, K. R. 1968. "Review of Quality Control Program-USTC Data 1965-67." Letter to the Radiation Exposure Record Historical File, dated February 6, 1968.

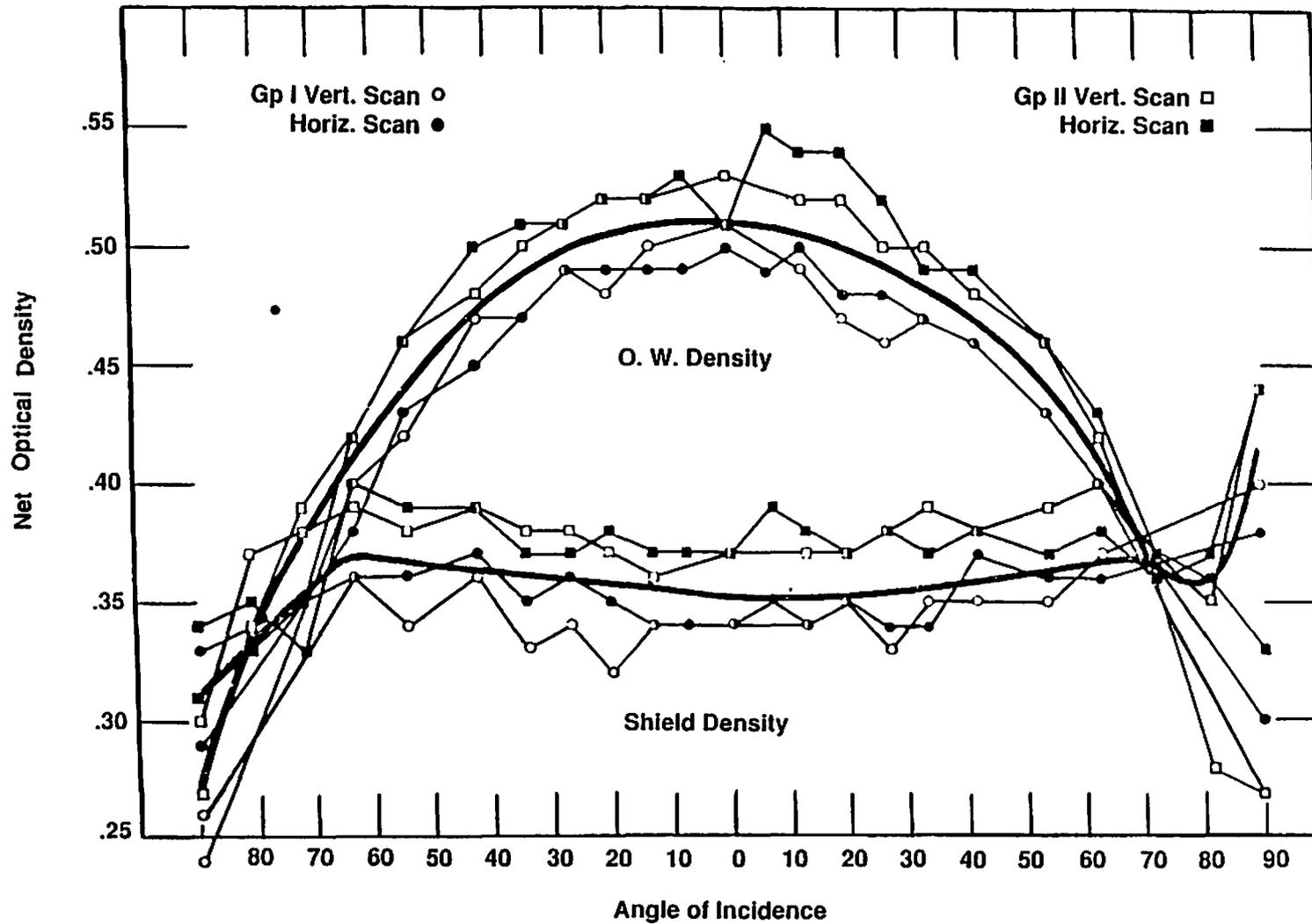
TABLE 5.5. Radium Gamma Dosimeter Audit Results During 1966

<u>Error E in Percent</u>	<u>Number of Results by Exposure Range, mR</u>				
	<u>20-99</u>	<u>100-299</u>	<u>300-499</u>	<u>500-1000</u>	<u>1000-5000</u>
-100 < E < - 50	20	1	0	0	0
- 50 < E < - 25	16	7	0	0	0
- 25 < E < - 10	6	17	9	10	10
- 10 < E < + 10	17	43	68	72	70
10 < E < 25	2	13	2		
25 < E < 50	9	10	10		
50 < E < 100	15	12	7		
100 < E < 200	0	4	3		
200 < E	0	5	0		

TABLE 5.6. Neutron Dosimeter Audit Results from 1965 to 1967

<u>Error E in Percent</u>	<u>Number of Results by Year</u>		
	<u>1965</u>	<u>1966</u>	<u>1967</u>
-100 < E < - 50	37	10	13
- 50 < E < - 25	18	9	19
- 25 < E < - 10	6	18	24
- 10 < E < + 10	13	19	22
10 < E < 25	2	13	2
25 < E < 50	9	10	10
50 < E < 100	15	12	7
100 < E < 500	0	4	3
500 < E	0	5	0

5.12



38910011.1

FIGURE 5.2. Net Optical Density of DuPont 552 Film (Zero [0] is perpendicular to the plane of film.)

the net optical density is plotted versus the angle of incidence. It is apparent from the figure that the response under the silver shield density is relatively flat for an angle of incidence between $\pm 75^\circ$.

5.1.12 Personnel Exposure to Neutrons

Studies of personnel exposure to neutrons were conducted at different times at Hanford (Watson 1951; DePhanger 1957, 1958; Endres 1964; Unruh et al. 1964; Unruh et al. 1966). In 1962 a series of measurements was conducted in operating areas of the plutonium finishing facilities^(a,b) to determine the need for additional radiation shielding along the plutonium finishing line, particularly around the fluorinator, as a means of further protecting personnel. 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.^(c,d)

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.^(e) The main objective of the study was to determine the proper calibration technique, considering the fact that the great majority of Hanford personnel are exposed to fast neutrons with effective energies at or below 1.2 MeV and realizing the poor response of NTA film to energies below 0.7 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

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- (a) Knight, L. M. 1962a. "Predicted 1962 Neutron Exposure." Letter to W. J. Gartin, dated February 16, 1962.
 - (b) Knight, L. M. 1962b. "Predicted Exposure to Neutrons-Button Line." Letter to J. J. Courtney, dated April 6, 1962.
 - (c) Bramson, P. E. 1962. "Neutron-Gamma Ratios in 234-5 Building." Letter to C. M. Unruh, dated October 19, 1962.
 - (d) Faust, L. G. 1964. "Neutron to Gamma Dose Rate Ratios of PuF₄." Letter to J. M. Selby, dated July 17, 1964.
 - (e) Budd, R. O. 1963. "Single Collision Versus Multiple Collision Fast Neutron Dose Calibration of the Hanford Neutron Film Badge Dosimeter." Letter to the File, dated July 2, 1963.

neutrons. Two fast neutron sources were used: $^{239}\text{PuBe}$ and $^{239}\text{PuF}_4$, 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 with 95% confidence 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/hr for 27 hours. These results were compared with measurements made using the new BF₃ counters.^(a,b) The total fast neutron dose was 222 mrem. Exposures were performed near the center of the front face at the 105-B Building. 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 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.

5.1.13 Characterization of Calibration Sources

In 1966 Beetle reported the results of several studies to measure the precision of several Hanford calibration sources used to expose Hanford dosimeters.^(c) These studies were conducted in preparation for a national intercomparison study of dosimeter performance to be conducted at Hanford. To meet the objectives of the intercomparison study it was important that sources of variability within the calibration sources and geometries be

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- (a) Unruh, C. M. 1962a. "Neutron-Gamma Ratios in 105 Buildings." Letter to L. A. Carter, H. V. Larson, F. L. Rising, and E. C. Watson, dated October 18, 1962.
 - (b) Unruh, C. M. 1962b. "Preliminary BF₃-Neutron Badge Comparison Data." Letter to A. R. Keene, dated October 18, 1962.
 - (c) Beetle, T. M. 1966. "Calibrations Equipment Experiments." Letter to C. M. Unruh, dated September 7, 1966.

understood. These studies involved repeated exposures of approximately 60 dosimeters to different sources and different geometries. Exposures generally were in the 200-to-300-mR range.

5.2 LABORATORY QUALITY ASSURANCE STUDIES

From 1954 to 1955 a Radiological Field Development Group was established at GE, primarily to improve the personnel dosimetry equipment used to measure and evaluate radiation doses received by plant workers. As a direct result of this group's efforts very significant improvements in personnel dosimetry were made. Some examples include the implementation of plastic dosimeter holders with multi-element dosimetry capabilities, improved neutron calibration sources, mechanized processors, automated readers, and computerized record-keeping with reports for field use in controlling exposure to workers.

Numerous variables of the personnel dosimetry system have been studied and evaluated since the inception of Hanford operations. These studies have addressed many issues, including the following:

- accuracy of calibration sources
- radiation sensitivity and precision of different types of film
- environmental dependency of film prior to, during, and after processing
- optimization of photometry variables
- design of different beta/photon and neutron dosimeters
- detection level of various film and personnel dosimeters
- mixed-field evaluation of dosimeter response
- angular response of dosimeters.

Several of these studies are discussed in the following subsections.

5.2.1 Study of DuPont 552 Film

Personnel film dosimeters at Hanford used DuPont film since the dosimetry program's inception in 1944. In 1945 DuPont 552 film with the 502 and 510 emulsions was introduced and used exclusively with some changes over the years. In 1958, studies of the DuPont film were conducted to update

information on the DuPont film and to determine how the film performance could be further improved (Baumgartner 1958). The objectives of the studies were to

- update information on the DuPont 552 film and standard darkroom procedures
- determine characteristics of film exposed to different types and amounts of radiation under various photographic processing procedures
- obtain the best estimate of the lowest detection levels.

Baumgartner concluded that the smallest dose of radiation that could be detected by the DuPont 552 film using standard photographic developing practices is 2 mR of 58-keV x-ray radiation or 25 mR of radium gamma radiation. Optimization of the developing procedures could reduce the detectable dose to about one-half of these values. The largest dose that could be interpreted using a Hanford type densitometer was about 50 R of radium gamma radiation using the DuPont 510 emulsion. Above 100 to 500 R, film reversal is observed on the DuPont 502 emulsion at the rate of about 0.04 optical density units per 100 R using standard photographic developing procedures.

In 1959 Baumgartner concluded that x-ray and gamma radiation with energies less than radium gamma radiation darken the film more per unit dose, with a maximum darkening being observed around 58 keV (Baumgartner 1959a). A unit dose of uranium beta radiation darkened the film about one-half as much as a unit dose of radium gamma radiation. The film exposed to radiation 3 months before being developed had about a 7% decrease in density over the film exposed to radiation on the day prior to being developed. There was no detectable decrease in density during the first month after exposure.

5.2.2 Studies of Film Dosimeter Variables

Results of studies of DuPont 508 and Eastman-Kodak type II films were reported by Baumgartner (1958; 1960). Although numerous studies were conducted of both DuPont and Eastman-Kodak films, only the DuPont films were used for beta/photon radiation at Hanford. The results for only the DuPont film are presented in this report. The studies were motivated by the desire to evaluate the potential error in the determination of the annual dose. The uncertainty of the annual dose was thought to be a function of the precision, detection limit, and the number of individual films. The most direct method

of reducing the error in the annual dose was simply to reduce the number of films assigned to each employee during the year. The study findings and results for DuPont 508 film were as follows:

- The latent image of DuPont film was found to fade about 1% per month for radium gamma doses between 1 to 5 R; no fading was detected for doses below about 1 R.
- Based on the small amount of fading of the latent image of DuPont film, the routine exchange frequency of film was changed from biweekly to monthly.
- The developer temperature, development time, and radiation dose were identified as significant variables. The non-significant variable was the depth of the film in the developer solution.
- The DuPont film density is a linear function of the radiation dose for radium gamma doses between 100 mR and 1000 mR.
- The temperature gradient is 0.10 ± 0.04 optical density units/ $^{\circ}$ F (95% confidence limit). The gradient is linear over the temperature range of 66° F to 74.2° F.
- The time gradient is 0.12 ± 0.06 optical density units/minute (95% confidence limit) and is linear during the time interval of 2 to 6 minutes.
- Time, dose, and temperature interact positively, such that the development of high-dose calibrated film is accelerated more than the low-dose calibrated film.
- Based on the foregoing results and other considerations, an automatic film processor was obtained to control the development time to within 1 second and the developer temperature to within 0.05° F. This processor was implemented in October 1959.

Greater detail on the precision, detection level, and conclusions are summarized by Baumgartner (1958; 1960). Fifty film packets of DuPont 508 film were exposed to radium gamma doses of 0, 35, 70, 100, and 200 mR. The optical density results of this study are shown in Table 5.7. The minimum interval for which the densitometer can be read is 0.005 optical density units. The information in Table 5.7 was used to prepare frequency tables of the error observed for each dose level, as summarized in Table 5.8 for DuPont film.

The standard deviation for each dose level in Table 5.8 was estimated by the proportion of the 50 films, which deviated by not more than 0.005 optical

TABLE 5.7. Optical Density Results for DuPont 508 Film^(a)

	Radium Gamma Dose									
	Zero		35 mR		70 mR		100 mR		200 mR	
	o.d.	Dose	o.d.	Dose	o.d.	Dose	o.d.	Dose	o.d.	Dose
	0.085	23	0.105	2	0.135	18	0.150	5	0.225	2
	0.090	26	0.110	39	0.140	30	0.155	24	0.230	17
	0.095	1	0.115	9	0.145	2	0.160	21	0.235	16
									0.240	13
									0.245	1
									<u>0.250</u>	<u>1</u>
Total	<u>4.390</u>	<u>50</u>	<u>5.535</u>	<u>50</u>	<u>6.920</u>	<u>50</u>	<u>7.830</u>	<u>50</u>	<u>11.736</u>	<u>50</u>
Average	0.088		0.111		0.138		0.157		0.235	

(a) From Baumgartner (1958).

TABLE 5.8. Absolute Error in Optical Density Units for DuPont 508 Film^(a)

Dose, mR	Absolute Error in Optical Density Units				Sigma ^(b)
	<0.005	0.005-0.010	0.010-0.015	>0.015	
0	49	1	0	0	0.002
35	48	2	0	0	0.002+
70	48	2	0	0	0.002+
100	45	5	0	0	0.003
200	33	15	1	1	0.005

(a) From Baumgartner (1958).

(b) Sigma = standard deviation

density units from the average value. For example, the distribution of errors for the DuPont film dose of 35 mR shows 48 films (96% of the 50 films) with an absolute error of not more than 0.005 optical density units. Ninety-six percent of the area under the normal curve lies between ± 2.06 standard deviation. Hence, the optical density standard deviation is $0.005/2.06$ or approximately 0.002+, as shown in Table 5.8. In the range of 0 mR to 100 mR, approximately 95% of the optical density data for DuPont film has an absolute error of not

more than 0.005 optical density units and 100% with an error of not more than 0.01 optical density units. Least-squares techniques were used to estimate a linear function between optical density data in the range of 0 and 10 mR, as measured by the average optical density for each frequency table and dose, with the following result:

$$\text{Optical Density Units} = 0.088 + 0.000697 * \text{Dose (DuPont)} \quad (5.2)$$

where Dose is measured in milliroentgen. Using these relationships, the optical density unit error can be translated to precision statements for estimating dose from optical density. For example, the statement that 95% of the optical density measurement errors for DuPont film are not more than 0.005 optical density units transforms to a precision statement, at the 95% confidence level, that the error in estimating the dose in the range of 0 to 100 mR is not more than $0.005/0.000697$, or about 8 mR. Similar calculations can be translated to precision statements for estimating dose and are as follows:

<u>Precision</u>	<u>DuPont 508 Film</u>
95%	± 8 mR
100%	± 15

With DuPont film in the range of 0 mR to 100 mR, the absolute upper bound on the error is about 15 mR.

The detection limit has been defined in this historical review document as a property for deciding when a particular film indicates a positive dose. The customary procedure is to define a critical point, a percentile point on the blank film (developed, unirradiated) distribution, and decide that the film was exposed to a positive dose if the optical density reading falls above the critical point. If the reading is less than the critical point, a decision of no dose (or undetectable dose) is made. The following analysis was presented for the detection limits for the DuPont film assuming a 95% critical point (i.e., the operational procedure such that on average 1 in 20 films that have received no dose will be flagged as a positively dosed film). Using the estimates of 0.088 for the mean of the blank film optical density

distribution of DuPont film (shown in Table 5.7) and assuming a normal distribution, the 95% critical point is 0.0925. Rounding this value to densitometer readings (i.e., multiples of 0.005) results in 0.095. The current operational procedures are actually better than 95% (i.e., the lowest reading is currently 0.005). The detection limit is defined as the minimum positive dose that is almost certain to be detected as positive using these operational procedures. It is important to note that the dose will be detected, not that it will be estimated correctly. Adding the error estimate of 0.01 to the DuPont critical point gives the detection limit in optical density units of 0.105. Transforming this value to dose units results in 17 mR for the DuPont film.

Baumgartner (1960) provides a comparison of the experimental results (described above) with routine production practices. At the time of the study, the routine program used a functional relationship estimate calculated from a least-squares fit to calibration net data (absolute optical density minus blank optical density) with one film exposed at 100, 200, 300, 400, 500, 600, 800, and 1000 mR. Thus, the precision with which the functional relationship is estimated in the range of 0 mR to 100 mR is determined by the precision with which the blank value is estimated and the precision with which the 100 mR value is estimated. An estimate of the increased uncertainty for non-laboratory conditions indicates that the sensitivity for the DuPont film during routine production must be relaxed from the experimental estimate obtained by a factor of about 2. Hence, the precision of estimating an unknown dose at the 95% and 100% confidence levels is not 8 mR and 15 mR, respectively, but probably closer to 16 mR and 30 mR, respectively. The optical density detection limit, instead of being 0.105, is probably closer to 0.021, or instead of being 25 mR, it is probably closer to 40 mR.

As a direct result of this experiment, the normal calibration doses were changed from 100, 200, 300, 400, 500, 600, 800, 1000, 5000, and 10,000 mR to 30, 60, 90, 120, 180, 240, 300, 500, 750, 1000, 2000, 5000, and 10,000 mR. Also, an improved densitometer was designed and built to be used for routine dosimetry evaluations, as well as for determining if there is a non-linear relationship between dose and optical density in the range from 0 mR to 100 mR. The new densitometer was subsequently implemented during 1962.

5.2.3 Analysis of Detection Level During 1960

During 1960 three changes were reported that contributed to significant reduction in the detection limit of the film dosimeter and the potential annual penetrating dose that could go undetected for an individual employee (Wilson 1960). These changes were

1. increased accuracy in the dose received by calibration film by eliminating the non-isotropic effect of the calibration source
2. reduction of routine processing variables by installing automatic equipment for precise temperature and time control
3. change to a more sensitive film (i.e., DuPont 508).

Wilson concluded that the largest contribution to improved performance was the capability of the DuPont 508 film to record measurable densities at lower dose levels. In the analysis, data for 30-mR calibration film were analyzed from 49 routine batches. The calculated mean value for this film was 0.028 optical density units with a standard deviation of 0.007. The detection level for the densitometer was considered to be 0.01 optical density units. Analysis of the zero-dosed control films indicated that about 8% fell above the 0.01 detection level and, as such, these control films were assigned a positive dose. Wilson concluded that the detection level of the system was approximately 15 mR at the 90% confidence level, assuming normal distribution of density/dose values for the 30-mR calibration level. Assuming 13 processings per year, Wilson concluded further that the annual detection level would be equivalent to 195 mR (i.e., 15 x 13). For comparison, the report states that the previous detection level for DuPont 502 film was 40 mR.

5.2.4 Security Credential Evaluation

A study^(a) was conducted to determine the quantitative effects of the security credential on dose evaluations as a result of changing to a thinner credential material. After evaluating the results of the study, the following recommendations were made:

(a) Baumgartner, W. V., G. W. R. Endres, and K. R. Heid. 1966. "A Study of Security Credential Effects on the Film Badge Dosimeter." Letter report dated November 28, 1966.

- The film dosimeter program should use calibrated film dosimeters with security credentials similar to those worn by employees. Dosimeters with old security credentials should be evaluated by calibration film exposed with old security credentials and vice versa.
- A thorough study to determine the actual energy of the 17-keV x-ray source should be made if this source is to be used in the film dosimetry program. From the absorption differences for the different types of security credentials, the average energy appears to be about 10 to 12 keV.
- The computer program for the routine personnel dosimetry program should be investigated to determine when the "rounding" of the values occurs. It appears that the rounding of the soft gamma values definitely influences the beta calculations.

5.2.5 Fading Effects in Eastman-Kodak NTA Film Emulsion

The fading effect of Eastman-Kodak NTA film emulsions used for monitoring personnel exposure to fast neutrons was studied by Watson in 1957, and it was concluded that the emulsions could be used for a period of 2 weeks without fading of proton tracks (Watson 1957). Recommendations resulting from this study are as follows:

- Neutron personnel monitoring films may be left in operation for a 2-week period.
- The time between calibration exposure and the last day of possible personnel exposure for the corresponding period should not exceed 21 days. It was found that for the energy spectrum used in calibration, a delay of 21 days in developing the film resulted in a loss of 25% of the tracks.

These recommendations were adopted into the routine program.

5.2.6 NTA Film Study

In 1959 the NTA (fast-neutron) program was studied to review the experience gained up to that point and to recommend further improvements in the program (Watson 1959). The recommendations resulting from this study were as follows:

- 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 HAPO. 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 4 weeks.

These study recommendations were implemented immediately. 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. Those workers not involved in plutonium work were read only when 100 mR or more of gamma exposure was indicated.

5.2.7 Study to Determine Effect of Security Credential Design Change

Kathren summarized the results of a study performed during 1968 to determine the effect of a change from a 14-mil-thick to a 20-mil-thick security credential.^(b) In this study, duplicate films (one with each security credential) were exposed to several sources of photon radiation as well as a few mixed (photon and beta) sources. The film was evaluated by UST the same as for all routine film dosimeter processing. Kathren's tabulated data were used by the authors to provide an estimate of the precision and accuracy of the reported dose relative to a 1-cm-deep dose using exposure to dose conversion factors from DOE/EH-0027 (DOE 1986). These data are summarized in Table 5.9.

5.3 INTERCOMPARISON PROGRAMS

Intercomparison of calibration and dosimetry data between laboratories has been conducted since 1945 at Hanford. Intercomparison studies continued over the years, with Hanford coordinating a national study in the mid-1960s.

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

(b) Kathren, R. L. 1968. "Effect of Security Credential on Dose Interpretation." Letter to K. R. Heid, dated October 23, 1968.

TABLE 5.9. Effect of Security Credential on Dose Assessment^(a,b)

Dosi- meter	Given Exposure			Given Deep Dose ^(c)	Reported Dose			Recorded Whole Body Dose ^(d)
	Source	Photon	Beta		Gamma	X-ray	Beta	
1	16.1 keV	200	0	76	0	120	0	42
2	16.1	200	0	76	20	120	0	62
3	23.7	200	0	148	40	120	0	82
4	23.7	200	0	148	30	110	0	69
5	34.3	200	0	198	90	40	0	104
6	34.3	200	0	198	80	40	0	94
7	43	200	0	260	130	40	0	144
8	43	200	0	260	130	40	0	144
9	58	200	0	344	250	40	0	264
10	58	200	0	344	250	30	0	261
11	100	200	0	348	170	0	0	170
12	100	200	0	348	180	0	0	180
13	120	208	0	~352	180	10	0	184
14	120	208	0	~352	190	10	0	194
15	170	200	0	~317	160	0	0	160
16	170	200	0	~317	170	0	0	170
17	58/U-nat	200	200	344	280	30	0	291
18	58/U-nat	200	200	344	290	30	0	301
19	Ra-γ	200	0	200	200	0	0	200
20	Ra-γ	200	0	200	190	0	0	190
21	Ra-γ/U-nat	200	200	200	170	0	50	170
22	Ra-γ/U-nat	200	200	200	170	0	50	170
23	0	0	0	0	20	0	60	20
24	0	0	0	0	0	0	80	0
25	0	0	0	0	0	0	70	0
26	0	0	0	0	0	0	80	0
27	⁶⁰ Co	200	0	200	170	0	0	170
28	⁶⁰ Co	200	0	200	170	0	0	170

- (a) Duplicate exposures of 14-mil-thick and 20-mil-thick security credentials.
- (b) Several units are used in this table as follows: given exposure, mR for photons and mrad for beta; given deep dose, reported dose, and recorded whole body dose in mrem.
- (c) Exposure to dose conversion factors taken from DOE/EH-0027 (DOE 1986). Factors for radium gamma radiation and ⁶⁰Co are assumed to be equal to 1.0.
- (d) Total dose is estimated from the algorithm: whole body dose = gamma + 35% * x-ray.

These efforts have assisted in the adoption of national dosimeter performance standards during the 1980s.

5.3.1 Intercomparison of Dosimeter Films Used at Hanford and at the Metallurgical and Clinton Laboratories

In December 1945 Parker summarized the results of an intercomparison study of dosimeter films used at Hanford and the Metallurgical and Clinton Laboratories (Parker 1945). The data for the individual dosimeter and total dose comparisons are shown in Tables 5.10 and 5.11, respectively. All dosimeters were exposed to radium gamma radiation (see Figure 5.3). Parker discussed several other tests conducted to observe the performance of the photometers used to measure film density. In particular, tests were conducted to observe the linearity of the photometer system at each of the laboratories. Photometry was evaluated for exposures of up to 1000 R. Tests were also done to determine the reproducibility of the photometer readings of film originally measured on August 11, 1945, and again on November 11, 1945. All of the tests

TABLE 5.10. Intercomparison of the Hanford, Metallurgical Laboratory, and Clinton Laboratory Film Dosimeters in 1945

<u>Exposure, mR</u>	<u>Reported Dose, mrem</u>		
	<u>Hanford</u>	<u>Metallurgical</u>	<u>Clinton</u>
200	200	230	230
	200	185	
	200	195	
	200		
300		355	
480			500
500	525	495	
	510	495	
	540		
600			620
1000	990	905	
	1005	955	

TABLE 5.11. Comparison of Total Dose for Hanford, Metallurgical Laboratory, and Clinton Laboratory Film Dosimeters in 1945

	<u>Given Total Exposure</u>	<u>Reported Total Exposure</u>
Hanford	4300 mR	4370 mR
Metallurgical Laboratory	3900	3815
Clinton Laboratory	1280	1350

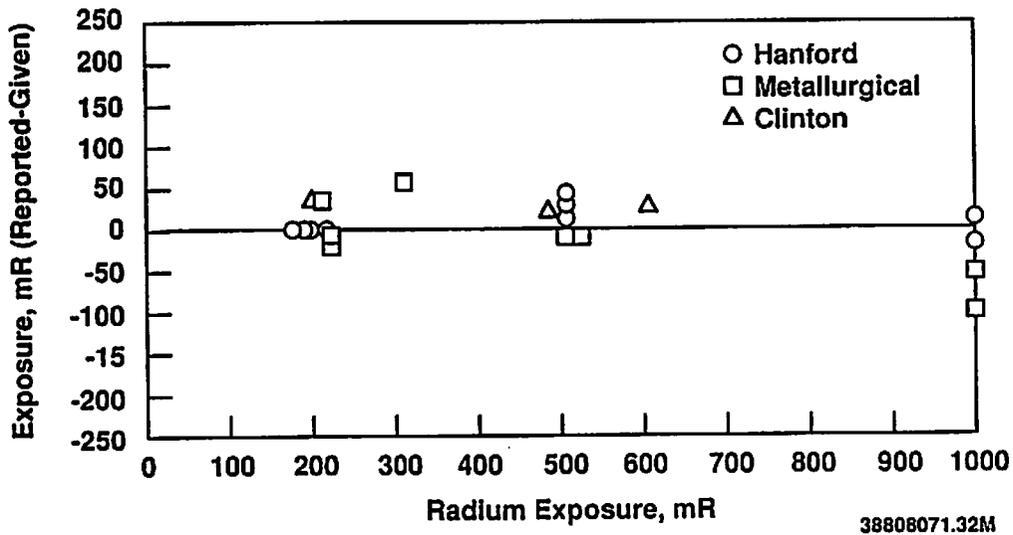


FIGURE 5.3. Results of the 1945 Intercomparison of Hanford, Metallurgical Laboratory, and Clinton Laboratory Dosimeter Films Exposed to Radium Gamma Radiation

confirmed the capability of film dosimeters to perform in a predictable manner. As a result of the intercomparison study it was concluded that:

- Determination of gamma radiation exposure was satisfactory.
- Beta or low-voltage x-ray calibration was needed.
- Attention would be given to photometer reproducibility.
- Neutron film was useful only in high-neutron exposures that were not normally expected to occur at Hanford.
- Intercomparisons should be conducted periodically.

This study led to the use of the uranium slab to calibrate film for exposure to beta radiation and the intercomparison of dose to the open window portion of the dosimeter in 1946.

5.3.2 Intercomparison of Hanford, Savannah River Plant, Rocky Flats Plant, and Los Alamos National Laboratory Film Dosimeters

Wilson described the results of an intercomparison of film dosimeter results from Hanford, Savannah River Plant (SRP), Rocky Flats Plant (RFP), and Los Alamos National Laboratory (LANL) conducted during 1959.^(a) This effort was undertaken because of the recognized dosimetry problems involving plutonium x-rays. The dosimeters were exposed at Hanford. A plywood disc about 30 in. in diameter was used to simultaneously expose 14 Hanford, 10 SRP, 9 RFP, and 11 LANL dosimeters. The apparatus is shown in Figure 5.4. The plywood disc was rotated at 5.8 rpm. The disc was placed approximately 5 ft from the front of a hood in the Recuplex Plant (waste recovery section of the 234-5-Z Building) where stable dose rates were expected with significant low-energy x-ray exposure. The bottom of the disc was approximately 2 ft above the concrete floor. The dose rate measured at the edge of the plywood disc with a CP ionization chamber was 10 mR/hr. The exposure continued for a period of 29.5 hours (estimated total exposure was 295 mR). Intermittent checks of the exposure rate did not show any measurable change. The results of the Hanford dosimeter measurements are summarized in Table 5.12. The results for the total dose for the dosimeters from all laboratories are summarized in Table 5.13.

The study concluded that evaluation of the diverse data collected during the study was not possible. However, general comparisons resulted in the following observations:

- Hanford radium gamma and SRP "hard" dose results were the only ones that compared favorably for penetrating dose categories.
- LANL and RFP penetrating doses were relatively low, compared with Hanford's, by factors of approximately 2 and 4, respectively.
- Combining Hanford's 16-keV and 58-keV dose categories was in reasonable agreement with LANL's dose assigned to the 20-keV component.
- Combining RFP's 17-keV and 60-keV dose categories appeared to agree with Hanford's 16-keV dose category.

(a) Wilson, R. H. 1960a. "Inter-Site Film Badge Exchange for Plutonium Exposure Comparison." Letter to the File, dated June 10, 1960.

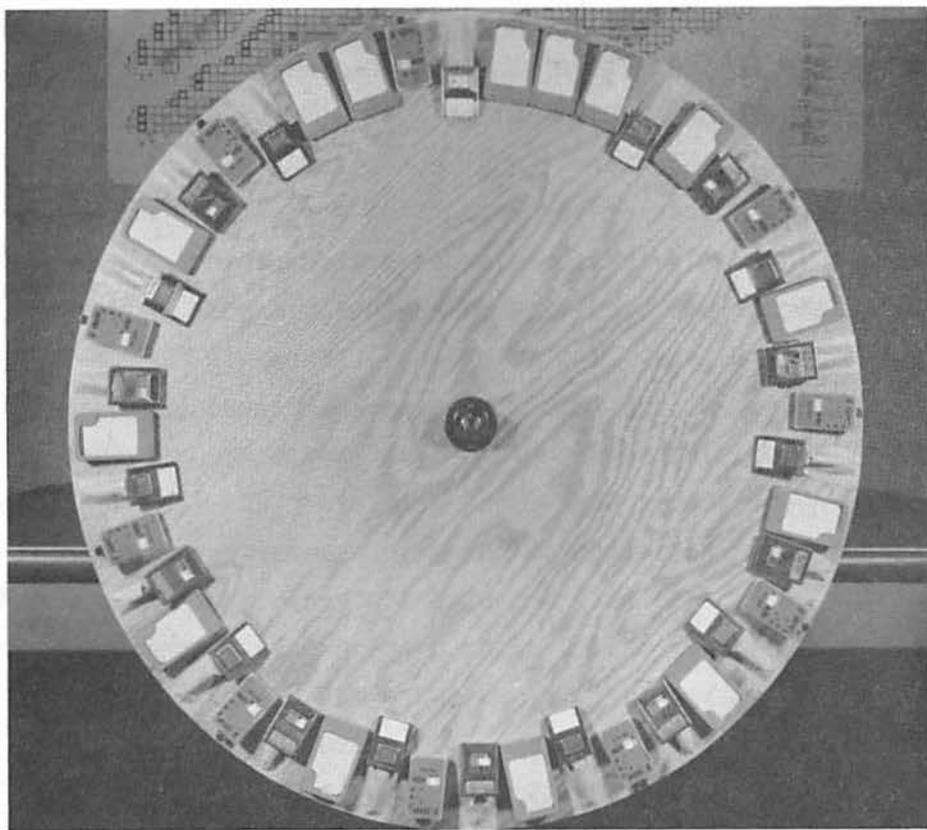


FIGURE 5.4. Plywood Disc Used to Simultaneously Expose Hanford, SRP, RFP, and LANL Dosimeters to Plutonium for Intercomparison of Results

A general conclusion of the study was that the total dose reported by the other laboratories was lower than the dose reported by Hanford.

5.3.3 Hanford Dosimeters Exposed at Savannah River Plant in 1959

A further comparison of Hanford and SRP dosimeter results was obtained through the simultaneous exposure of five Hanford dosimeters with SRP dosimeters at SRP.^(a) The exposure time for the dosimeters was 47.5 hours at various locations on the outside face of "cabinets" along the JB Line in the

(a) Wilson, R. H. 1960b. "Addendum, Inter-Site Film Badge Exchange for Plutonium Exposure Comparison." Letter to the File, dated June 10, 1960.

TABLE 5.12. Hanford Film Dosimeter Results, mR

<u>Dosimeter</u>	<u>16 keV</u>	<u>58 keV</u>	<u>Deep</u>	<u>Total</u>
1	94	21	200	315
2	94	21	200	315
3	90	23	190	303
4	92	21	210	323
5	88	22	210	331
6	92	19	220	331
7	82	21	200	303
8	92	21	210	323
9	90	21	200	311
10	92	21	210	323
11	90	21	200	311
12	90	21	210	321
13	92	22	200	314
14	<u>104</u>	<u>20</u>	<u>210</u>	<u>334</u>
Average	91.6	21.1	205.0	318
Standard deviation	4.7	0.9	7.6	9.8

TABLE 5.13. Total Dose Comparison for all Laboratories

<u>Laboratory</u>	<u>Number of Dosimeters</u>	<u>Total Reported Dose, mrem</u>
Hanford	14	318
RFP	9	149
SRP	10	185
LANL	11	210

plutonium facility. The results are summarized in an SRP letter^(a) and in Table 5.14. The pencil dosimeter results are based on the average of the lowest reading observed for each pair of Landsverk Model (L-65) pencil dosimeters used to measure the dose. Difficulties were experienced in determining an actual exposure because the dose rates were not constant and were very low, necessitating the long exposure time.

Another set of five Hanford film dosimeters was exposed at SRP in cooperation with a test of an exposure facility where x-ray and gamma doses from plutonium were measured with an extrapolation chamber. The dosimeters were exposed to a 0.67-g plutonium source deposited in a thin, uniform spot approximately 2.25 in. in diameter. The source was covered at all times by a 0.012-in.-thick plastic bag. In each case, the dose rate at the surface of the film dosimeter was determined by extrapolation chamber measurements. This

TABLE 5.14. Comparison of Hanford and SRP Dosimeters

Shielding Between Plutonium Source and Dosimeter	Dose, mrem						
	Hanford Dosimeter				Total Dose	SRP Total Dose	Pencil Results ^(a)
	Kerma	16 keV	58 keV	Ra Gamma			
0.5" Lucite [®] plus 0.25" safety glass 0.5" Lucite	0	0	21	140	161	130	180(360)
0.5" Lucite plus 0.25" safety glass 0.5" Lucite plus	49	76	23	200	299	160	195(390)
0.5" Lucite plus 0.25" safety glass 0.5" Lucite plus	138	212	29	275	516	175	260(520)
0.5" Lucite plus 0.25" safety glass	55	85	16	220	321	130	160(320)
0.5" Lucite plus 0.25" safety glass	45	70	20	190	280	100	140(280)

® Lucite is a registered trademark of E. I. DuPont Nemours and Company, Wilmington, Delaware.

(a) Dose determined by averaging the lowest reading observed for each pair of Landsverk Model 65 pencil dosimeters exposed simultaneously with film dosimeters.

(a) Wright, C. N. 1960. "Comparison Tests of SRP and HW Film Badge Response to Low Energy Radiations." Letter to the File, dated April 19, 1960.

information is summarized in Table 5.15. As shown in the table, the Hanford total dose is in close agreement with the measured dose. No information was received regarding SRP dosimeter results for these exposures.

TABLE 5.15. Hanford Dosimeters Exposed at Savannah River Plant

<u>Shielding Between Pu Source and Dosimeter</u>	<u>Dose, mrem</u>				<u>Actual Dose^(a)</u>
	<u>Hanford Dosimeter</u>				
	<u>16 keV</u>	<u>58 keV</u>	<u>Ra Photon</u>	<u>Total</u>	
0.012" plastic	175	18	25	218	300
0.5" Lucite	182	45	25	252	300
0.5" Lucite, 0.25 glass	0	89	70	159	200
0.25" Lucite	250	25	25	300	300
0.5" Lucite, 0.5 glass	0	175	110	285	300

(a) Measured with an extrapolation chamber.

5.3.5 Hanford Dosimeters Exposed at Rocky Flats Plant in 1959

A similar comparison of Hanford and RFP dosimeter results was obtained at RFP by simultaneously exposing nine Hanford dosimeters with RFP and LANL dosimeters.^(a,b) The exposure was made to plutonium metal through 0.5-in. plexiglass. Reference measurements were made with a CP portable ionization chamber and Beckman dosimeters. These data are summarized in Table 5.16. From data in Table 5.17, it is evident that the Hanford radium photon dose component is in better agreement with both the instrument measurements and the total dose reported by LANL and RFP than the Hanford total dose.

5.3.6 Hanford Dosimeters Exposed at Los Alamos National Laboratory in 1959

A similar comparison of Hanford and LANL dosimeter results was conducted by exposing 10 Hanford dosimeters at LANL.^(a) LANL plutonium sources were

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- (a) Wilson, R. H. 1960. "Inter-Site Film Badge Exchange for Plutonium Exposures Comparison." Letter to the File, dated June 10, 1960.
 (b) Littlejohn, G. J. 1960. "Film Badge Intercomparison." Letter to R. H., Wilson, dated June 8, 1960.

TABLE 5.16. Hanford Dosimeters Exposed at Rocky Flats Plant

Hanford Dosimeter				Site Doses		Measurement Device	
16 keV	58 keV	Ra Photon	Total	LANL	RFP	Cutie Pie	Beckman
108	52	275	435	295	257	230	172
50	60	255	365	320	281	246	190
102	42	255	399	240	240	244	200
151	58	255	464	335	326	264	175
92	47	255	394	270	273	203	188
116	50	315	481	285	295	241	195
77	62	255	394	260	231	244	200
75	60	230	365	255	221	235	200
58	50	210	318	230	160	235	175

used to expose dosimeters to known levels of radiation.^(a) Reference measurements were made with an extrapolation chamber. The data for the Hanford dosimeters are summarized in Table 5.17. Hanford total doses compare closely with the extrapolation chamber measurements for the dosimeters exposed to the nickel-coated plutonium source. For the dosimeters exposed to the uncoated plutonium source, the Hanford results are low.

5.3.7 National Film Dosimeter Intercomparison Study

During the early 1960s efforts were under way to develop a national performance standard for personnel dosimeters. Hanford personnel were intimately involved with these efforts and, in 1967, published the results of a national intercomparison study of commercial and government dosimeter processing (Unruh et al. 1967; Larson et al. 1967; Unruh, Larson, and Beetle 1968). The Hanford results included in these reports are listed in Table 5.18.

The concern for the need for a minimum performance standard developed fairly early in the nuclear field, as the number of commercial processors of personnel dosimeters multiplied, and as the number of Atomic Energy Commission (AEC), AEC prime contractors, and military installations operating their own film dosimeter facilities increased. In 1963 the AEC published in the

(a) Chapman, T. S. 1966. "Film Badge Exchange Results." Letter to A. R. Keene and D. Meyer, dated May 17, 1960.

TABLE 5.17. Hanford Dosimeters Exposed at Los Alamos National Laboratory

Dosimeter Number	Hanford Dosimeter Results, mR				Actual Dose ^(a)
	16 keV Dose	58 keV Dose	Ra Gamma Dose	Total Dose	
L-61	0	55	40	95	100
L-62	0	137	120	257	250
L-63	0	250	310	560	500
L-64	0	370	415	785	750
L-65	0	425	620	1045	1000
L-66	74	77	30	107	100
L-67	126	95	85	180	250
L-68	124	195	180	375	500
L-69	70	270	270	540	750
L-70	26	300	320	620	1000

(a) Dosimeters L-61 through L-65 were exposed to a plutonium source coated with nickel. Dosimeters L-66 through L-70 were exposed to an uncoated plutonium source encased in 0.020 in. polyvinylchloride. The dose was measured with an extrapolation chamber.

Federal Register a notice regarding the need for establishing a film dosimetry laboratory and the need for some interim film dosimeter performance criteria (28 FR 9411, cited in 52 FR 4601). No method of comparing the performance of these individual processors had ever been established, so the AEC asked PNL to conduct a study (Unruh et al. 1967) that would establish some expected film performance criteria and form the basis for establishing a film dosimetry calibration laboratory.

The study by Unruh et al. (1967) and intercomparisons of the performance of many processors around the country generated the following conclusions:

- Reasonable criteria to define acceptable levels of performance with respect to variance and bias can be established and administered.
- Excessive bias and variance exist among all groups participating in the test irradiation study (commercial firms, AEC laboratories, and military installations).
- A program that would provide an assessment of the quality of film processing services appears to be desirable.

TABLE 5.18. Hanford Intercomparison Study Results in 1967

<u>Exposure Category</u>	<u>Dose, mrem</u>	<u>Percent Bias</u>	<u>Relative Error</u>
Radium	60	-13	+17
	120	-4	10
	240	2	11
	500	8	11
	1,000	4	8
⁶⁰ Co	40,000	23	0
	100,000	10	0
	600,000	-9	1
170-keV filtered x-ray	60	-45	17
	120	-26	9
	240	-21	7
	500	-16	2
	1,000	-13	7
100-keV filtered x-ray	60	-47	17
	120	-25	0
	240	-15	5
	500	-18	2
	1,000	-11	1
17-keV K-fluorescent x-ray	60	0	0
	120	-8	0
	240	3	4
Beta radiation	120	0	0
	240	-2	4
	500	-8	4
Radium plus beta (gamma component)	120	1	4
	240	6	4
	500	15	2
Radium plus beta (beta component)	120	4	10
	240	20	34
	500	-1	4
Radium plus 17 keV x-ray (gamma component)	120	15	8
	240	13	4
	500	17	4
Radium plus 17 keV x-ray (17 keV x-ray component)	120	17	0
	240	-5	4
	500	-40	2
Thermal neutron	60	2	8
	120	-1	4
	382	-9	5

This study formed the basis of efforts to develop a national dosimetry performance testing standard.

5.3.8 Comparison of Film and Thermoluminescent Dosimeters

Hanford implemented the TLD in the early 1970s. The "basic" dosimeter, consisting of a single chip of LiF, was implemented on January 1, 1971, and the multi-element dosimeter, consisting of five chips, was implemented on January 1, 1972. The basic dosimeter was intended for use by personnel with the potential for little or no routine radiation exposure. The multi-element dosimeter was intended for use by personnel with the potential for exposure to radiation. The multi-element TLD was called the multipurpose dosimeter and replaced the multi-element beta/photon and neutron film dosimeters.

Several field studies were conducted to support the implementation of the new dosimeters. Kathren (1970) presented an evaluation of the basic dosimeter. 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 multipurpose TLD and multi-element film dosimeter (Nichols et al. 1972). The first type of study involved the simultaneous placement of two multipurpose TLDs along with two beta/photon and two neutron film dosimeters on 2-gal. 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 5.19. The data show wide variability between the results for the different measurement techniques. However, the data illustrate the general low bias of the film dosimeter results compared with the TEPC results. (Field studies were also conducted to determine the suitability of TLDs for monitoring extremities.

The second type of field measurement involved personnel wearing TLDs and film dosimeters simultaneously. Figure 5.5 illustrates the comparison of the penetrating dose component from both dosimeter types. Similarly, Figure 5.6 illustrates the comparison of the fast neutron dose component from both

TABLE 5.19. Fast Neutron Dose Measurements

<u>Location</u>	<u>Fast Neutron Dose, mrem</u>			
	<u>Snoopy</u>	<u>TEPC</u>	<u>Film</u>	<u>TLD</u>
105-KE				
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
308 Bldg.				
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
234-5 Bldg.				
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.

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.

5.3.9 Hanford Personnel Dosimeter Supporting Studies

During 1979 PNL began a 5-year upgrade of the Hanford Personnel Dosimeter System. Three reports of studies of existing dosimeter characteristics and evaluation of potential alternatives were published (Fix et al. 1981, 1982; Fix, Holbrook, and Soldat 1983). Several facets of the existing thermoluminescent dosimetry program are discussed in these reports, which also provide the following significant conclusions:

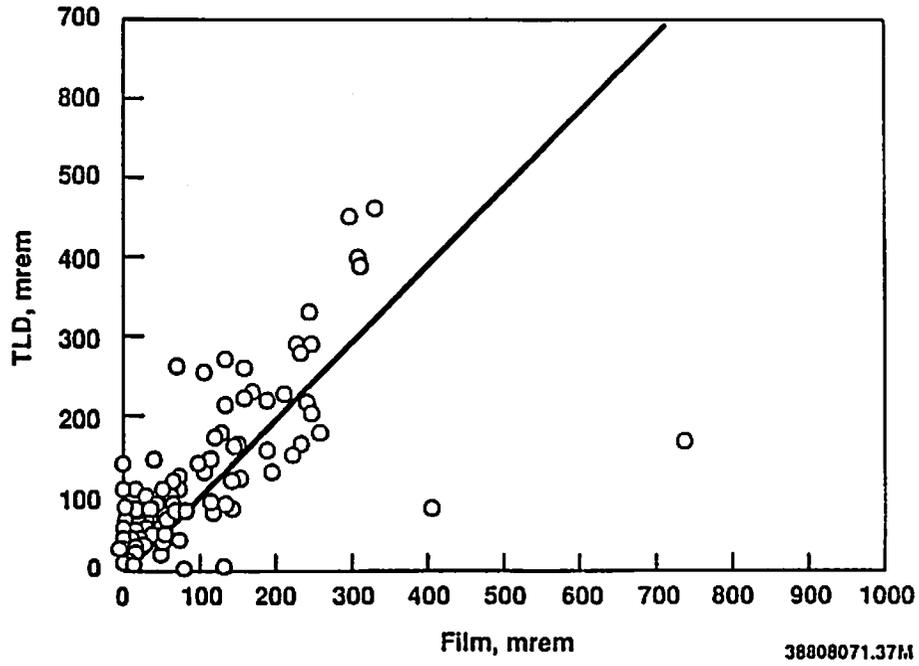


FIGURE 5.5. Comparison of Film Dosimeter and TLD Penetrating Dose Results

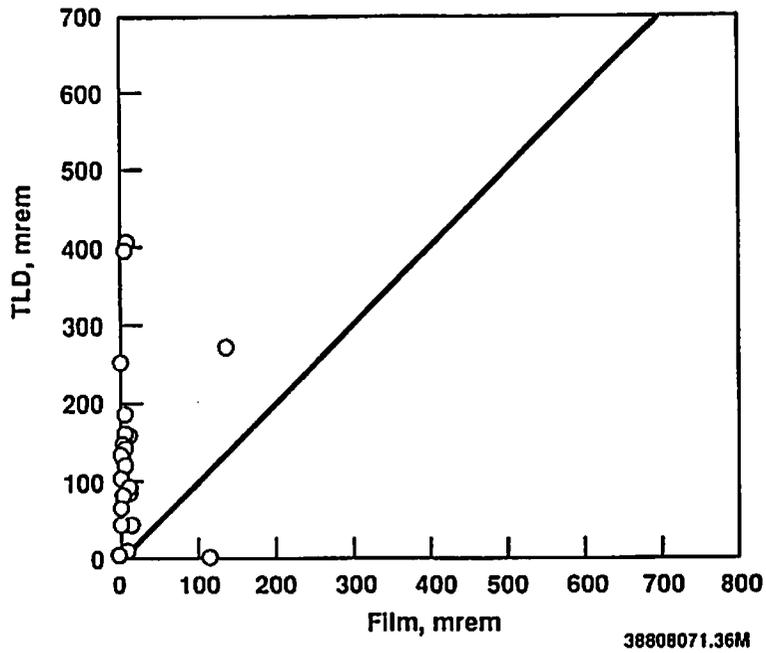


FIGURE 5.6. Comparison of Film Dosimeter and TLD Fast Neutron Dose Results

1. 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.
2. Based on the measured energy response of 10 Hanford dosimeters to selected radiation types, energies, and doses, the Hanford dosimeter response compared with the actual dose received from typical field exposures can be summarized as follows:
 - 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.
 - Existing dosimeter estimates of tissue dose at 1 cm from very high-energy photons (~7 MeV) are about 30% to 40% low. The shallow dose is overestimated by a factor of 2 or more. Differences in buildup between the two neutron-sensitive chips (positions 3 and 4) cause the algorithm to calculate false-positive fast-neutron doses. The use of chip 5 instead of chip 2 to calculate the 1-cm-depth dose results in good agreement. Measured dosimeter dose estimates from a ¹⁸N source were in good agreement because of the presence of significant lower-energy bremsstrahlung radiation from the accompanying high-energy beta decay.
 - Field measurements using several techniques, such as a TEPC, dosimeters, multispheres, Snoopy, etc., at several Hanford locations agreed fairly well. Differences were observed at some locations where the Hanford dosimeter over-responded relative to the results obtained with the tissue-equivalent instruments. The Snoopy was observed to also over-respond but at a level less than the Hanford dosimeter.

Many potential improvements to the overall dosimetry system are discussed in these reports, as well as the necessary steps to be taken to enable Hanford to participate in national dosimeter performance studies. In these studies performance criteria are based on overall performance. This implies that any deviation from the given dose is unacceptable. Because of these

studies, efforts were begun to reduce any significant under- or over-response of the Hanford dosimetry system to the performance categories included in ANSI N13.11 (ANSI 1983) and later the DOE performance standard (DOE 1986).

5.3.10 Personnel Dosimeter Accreditation

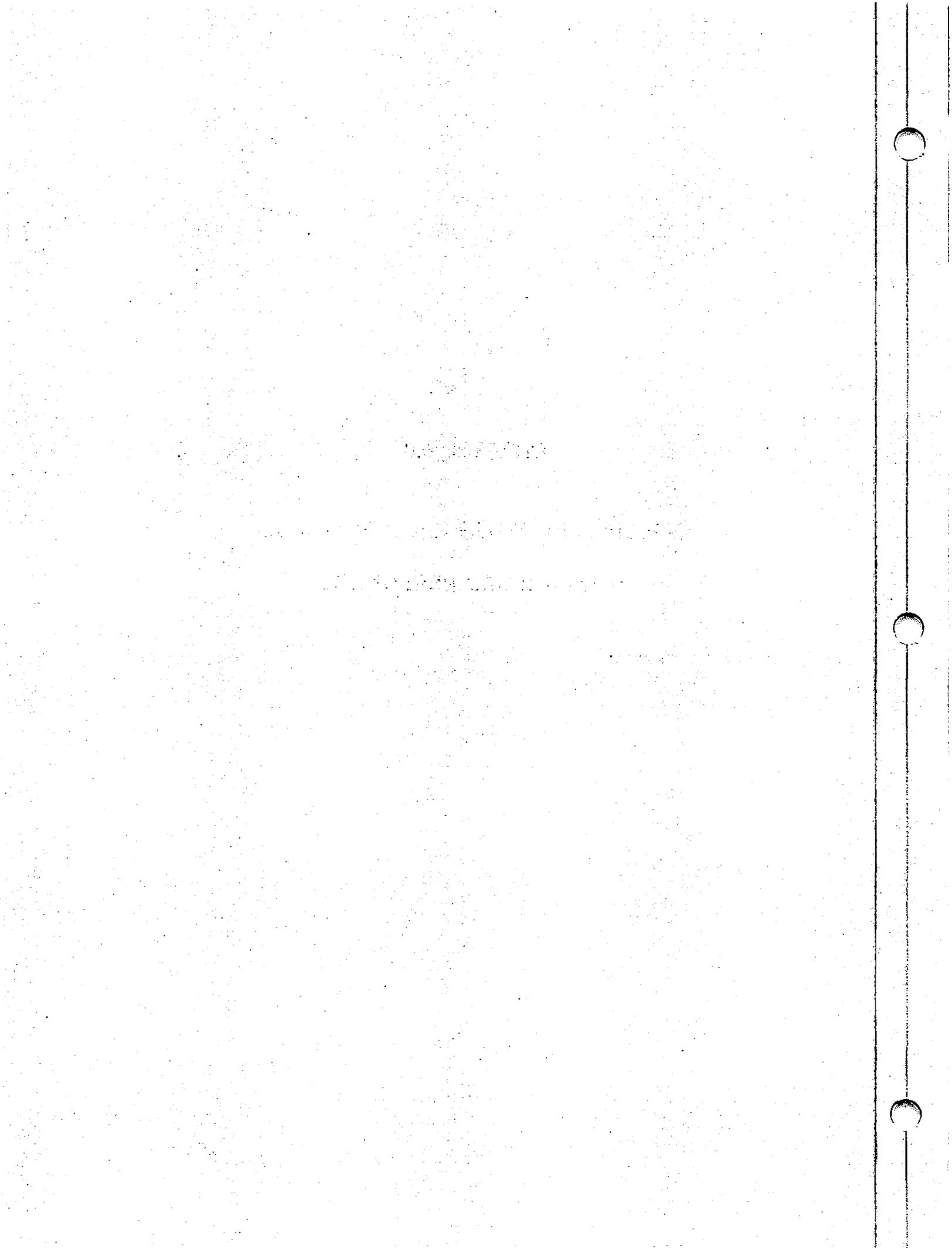
During the 1980s performance testing standards for personnel dosimeters were formally adopted (48 FR [146] 34316-34318). Participants that successfully met the various standards were accredited in one or more radiation exposure categories. The tests involved both personnel and accident level doses. Accreditation involves a two-step process: the laboratory must first pass a performance test, and then a technical program appraisal. Upon successful completion of both steps, the laboratory is accredited.

Hanford voluntarily participated in several of these tests during the early 1980s and received accreditation effective January 1, 1990, in all categories requested for testing.



CHAPTER 6.0

**OFFICIAL RECORDED RADIATION DOSE
FOR HANFORD PERSONNEL**



6.0 OFFICIAL RECORDED RADIATION DOSE FOR HANFORD PERSONNEL

An important consideration for each of the dosimeter systems used at Hanford is the methods used to determine the recorded dose assigned to each individual. The recorded dose is typically based on dose components calculated for each dosimeter system depending upon its design, calibration, and dose algorithm. Since the beginning of Hanford operations, various federal regulations have required that the dose to the skin, whole body, the extremities be recorded if the dose is expected to exceed specified levels. At Hanford, the practice has been to monitor essentially all permanent employees for radiation exposure. Doses have been recorded for each individual regardless of magnitudes, which are generally small for the majority of personnel. In general, administrative guidelines were in place to restrict exposure to the whole body, the skin of the whole body, and, for more highly exposed personnel, the extremities. The Hanford methods for calculating and recording the officially required whole body, skin, and extremity doses for personnel from dosimeter measurements of beta, photon, and neutron radiation dose are described in the following subsections.

6.1 METHODOLOGY FOR RECORDING RADIATION DOSE

A significant technical challenge of personnel dosimetry is relating the radiation dose measured by the dosimeter to a dose that can be used to assess health risk. Dosimeters provide a measurement of exposure to beta, x-ray, gamma, and neutron radiation of varying energies and intensities. Specific procedures are used to extrapolate from the dosimeter response to the radiation dose recorded for the whole body, skin, and extremities. A historical review of the recording format for Hanford dosimeters is included in a report by Gilbert (1989).

Over time, several technical notations have been used to record information from the dosimeter. Some of these notations are summarized in chronological order in Table 6.1. Beta and silver doses were recorded for the original two-element dosimeter and the first multi-element film dosimeter. Nonpenetrating and penetrating doses were recorded for multi-element film dosimeters and TLDs. X-ray dose for the multi-element film dosimeters typically refers

TABLE 6.1. Terminology Used to Record Hanford Dosimeter Results

<u>Term</u>	<u>Description</u>
'Beta' dose	Radiation dose determined from the film density behind the open window. Calibration was commonly based on uranium beta radiation and thus the interpreted dose was labeled as 'beta' dose.
'Silver' dose	Radiation dose determined from the film density behind the thick silver shield of the original and initial multi-element Hanford film dosimeters. Calibration was based on radium gamma radiation from 1944 to 1962. The interpreted dose was commonly labeled as 'silver' dose.
Nonpenetrating	Radiation component that is capable of penetrating only the thinner filters of a dosimeter is commonly referred to as 'nonpenetrating' radiation. For example, irradiation of a dosimeter with beta radiation will generally result in only a nonpenetrating dose because the radiation will be incapable of penetrating the thicker filters.
X-ray	Radiation component determined with intermediate filters used in multi-element film dosimeters between 1957 and 1972. Generally based on calibration to 18-keV k-fluorescent x-rays.
Penetrating	Term used for many years to refer to the penetrating component of the photon radiation that is capable of penetrating the thicker filters of the dosimeter. For example the radiation component that penetrates the 1-mm silver shield of the original two-element dosimeter is referred to as the 'penetrating' component.
Shallow	Term adopted in 1987 for the TLD and widely used to refer to the dose in tissue at a depth of 7 mg/cm ² .
Deep	Term adopted in 1987 for the TLD and widely used to refer to the dose in tissue at a depth of 1888 mg/cm ² or 1 cm.
Whole body	Officially recorded dose to the whole body. Dose was determined over the years using different dosimeter dose components depending upon the dosimeter design, calibration, and dose algorithm. Typically the whole body dose is equal to the sum of the penetrating silver dose, or deep dose components plus any dose received from neutron radiation. Beginning in the early 1980s the whole body dose includes any dose from tritium radiation.
Skin	Officially recorded dose to the skin. Dose was determined during the years using different dosimeter dose components depending upon the dosimeter design, calibration and dose algorithm. Typically the skin dose is equal to the whole body dose plus any additional nonpenetrating, beta, or shallow dose component.
Extremity	Officially recorded dose to the extremities. Dose was determined during the years using different procedures. Typically, the extremity dose is equal to the skin dose plus any dose recorded from extremity dosimeters.

to the dose based on a 16-keV calibration; however, determination of the x-ray dose for 16- and 59-keV x-rays was done for special evaluations. Shallow and deep doses were introduced in the 1980s with strict physical definitions. These terms are used in the Department of Energy Laboratory Accreditation Program (DOELAP) performance standards for dosimeters that are presently in use (DOE 1986; 1987).

The procedures followed at Hanford to determine the recorded whole body, skin, and extremity doses for personnel from the dose components recorded for the different dosimeter systems are described in Table 6.2 for the film dosimeters and TLDs used since 1944.

Hanford personnel visiting other nuclear sites or institutions were required to wear Hanford dosimeters along with those required by the location being visited. The other sites and institutions were required to cooperate in

TABLE 6.2. Methods of Determining Recorded Doses from Dosimeter Results

<u>Period</u>	<u>Whole Body</u>	<u>Skin</u>	<u>Extremity</u>
1944-1957	Sum of penetrating and neutron dose components	Sum of whole body dose and non-penetrating components	Sum of ring dosimeter results
1957-1972	Sum of gamma, 35% of x-ray, fast, and slow neutron dose components, as well as any tritium dose	Sum of whole body, beta, and 65% of x-ray dose	Sum of skin dose and ring dosimeter results
1972-1987	Sum of penetrating and fast and slow neutron dose components, as well as any tritium dose	Sum of whole body dose and non-penetrating components	Sum of skin dose and ring dosimeter results
1987-the present	Sum of deep and fast and slow neutron dose components, as well as any tritium dose	Sum of shallow and fast and slow neutron dose components	Sum of skin dose and ring dosimeter results

obtaining a record of their Hanford visitors' exposures and observing the permissible limits used at Hanford. If appropriate, bioassay sampling was included in the evaluation of offsite exposure to Hanford employees. These requirements were first published in the radiation protection standards that were issued August 1, 1952 (GE 1952). The reasons for the procedures adopted in Table 6.2 are evident from the discussion of the response characteristics of the respective dosimeters in Chapter 4.0.

6.2 RECORDS MAINTENANCE

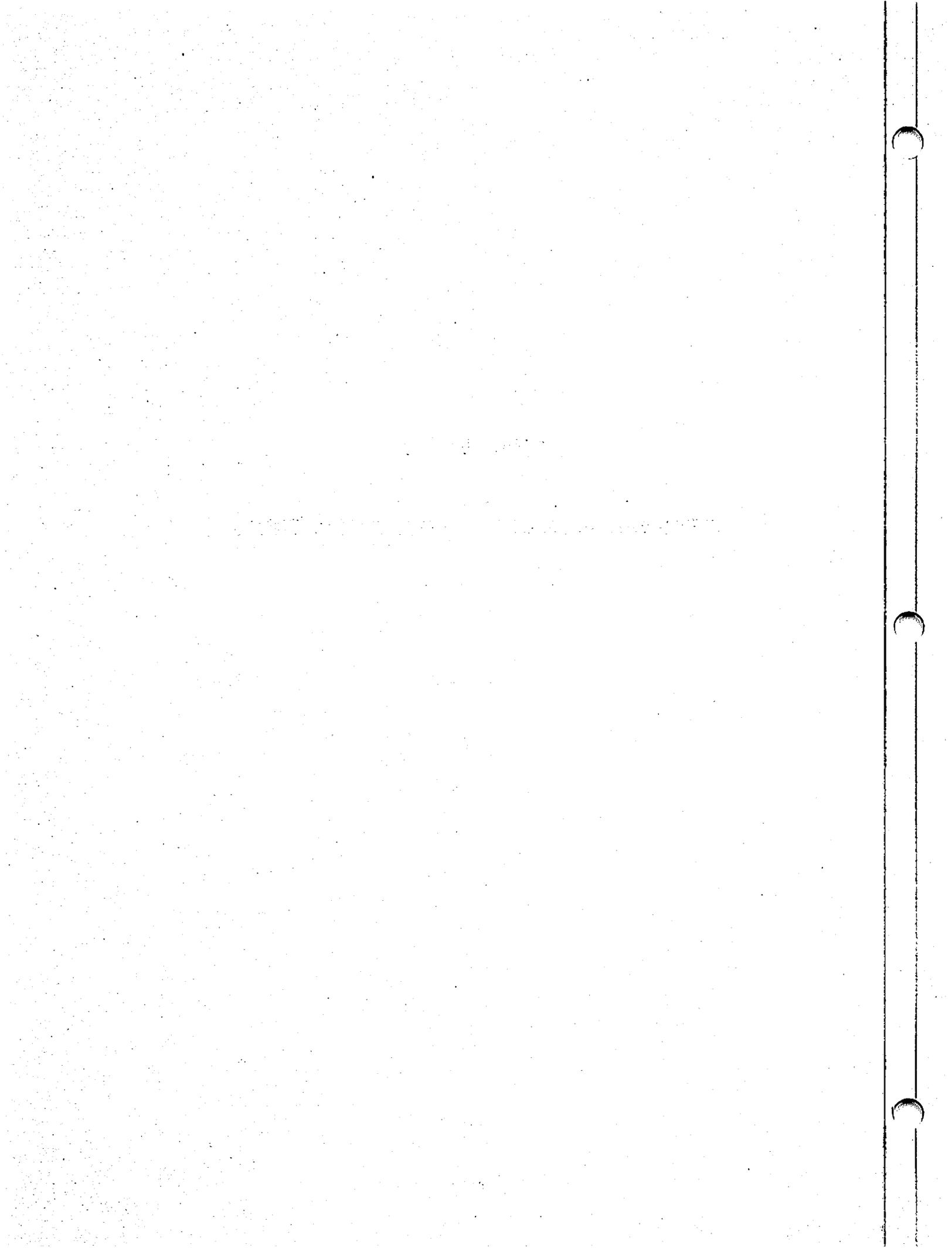
Maintaining the radiation exposure records for all personnel has always been an important function of the radiation protection programs at Hanford. Figure 6.1 is a photo of the records maintenance office where the data for each individual worker were manually recorded and filed during the early days at Hanford. The maintenance of the exposure history for each Hanford worker has been diligently maintained and is now computerized for easy access. Today a centralized database management system is used, enabling information to be entered daily into an individual's record and to be accessed immediately by authorized users via on-line data communication links.



FIGURE 6.1. Early Records Maintenance at Hanford: Manual Handling and Storage of Employee Radiation Exposure Histories

CHAPTER 7.0

PERFORMANCE OF HANFORD DOSIMETERS



7.0 PERFORMANCE OF HANFORD DOSIMETERS

Dosimeter design, radiation types, energies, intensities, etc., as well as the spatial relationship between the source of radiation and the dosimeter, affect the response of the dosimeter. In some cases the dosimeter response is dependent upon the intensity of scattered radiation, either from intervening material or through backscattered radiation. Processing, calibration, and dose calculation techniques have been developed to interpret personnel dose from the dosimeter response. Historically, these dosimetry techniques were chosen to provide the best measurement of personnel dose consistent with the scientific knowledge available at the time.

One objective of this report is to compare the recorded whole body dose with the dose at 1000 mg/cm^2 (commonly referred to as the deep dose) in tissue for the different Hanford dosimeters. The deep dose is an internationally recognized concept used in personnel dose evaluation.

Assessment of past Hanford dosimeter performance is difficult because of the many variables and changes in methodologies over the years. The analysis presented in the following subsections is based on 1) historical documentation of dosimeter studies and development throughout Hanford operations, 2) an intercomparison of the radiation response of all Hanford dosimeter designs during 1989, and 3) the results of performance testing of the TLD during 1989.

In comparing all historical Hanford film dosimeters, the calibration and dose interpretation practices used for the different dosimeters and periods of use were followed. Data obtained from the accreditation of the Hanford TLD during 1989 are included to demonstrate the dose response for this dosimeter. This information provides the laboratory dose response of the different dosimeters to selected sources of radiation.

7.1 EVALUATION OF DOSIMETER PERFORMANCE BASED ON HISTORICAL DOCUMENTATION

As discussed in Chapter 5.0, Hanford researchers have routinely evaluated many aspects of Hanford dosimeter performance since 1944. Evaluations have included a wide spectrum of issues, including the radiation response characteristics of dosimeters or instruments, processing variables, comparison of

Hanford's interpreted dose with that of other laboratories, and internal audits.

7.1.1 Radiation Response Characteristics

The design characteristics of the different Hanford dosimeters are presented in Chapters 2.0 and 3.0. The response of these dosimeters to beta, photon, and neutron radiation has been analyzed by various Hanford researchers. In particular, published studies by Roesch, Watson, Wilson, Larson, and Kocher (described in Chapter 5.0) focused on examining the response of Hanford film dosimeters to different types and energies of radiation. The average response of the original Hanford two-element dosimeter to photon radiation was documented in 1954 (Larson and Roesch 1954) and is illustrated in Figure 7.1. The deep dose as a function of photon energy is superimposed on the original information in Figure 7.1 for comparison.

Considering that the penetrating dose for the two-element dosimeter is based directly on the film response behind the silver shield, it is apparent that the penetrating dose estimate will be underestimated with this dosimeter for photons of energy less than approximately 100 keV. This was well recognized by researchers and was a principal reason for the development of the multi-element dosimeter that was implemented at Hanford in 1957. The response of all multi-element film dosimeters discussed in Chapter 2.0 is similar. The response of the 1962 dosimeter, as reported by Kocher, Bramson, and Unruh (1963), is illustrated in Figure 7.2, in which the deep dose as a function of photon energy is superimposed on the original information for comparison. Through the use of the different filtered regions of the film, the multi-element dosimeters were capable of assessing the dose to low-energy photon radiation.

In 1972 the Hanford multipurpose TLD was implemented. The crystals used in this dosimeter are significantly more "tissue-like" than film in their response to photon radiation, as illustrated in Figure 7.3. It is apparent that the response of the aluminum-filtered position of the dosimeter is very similar to the deep dose in tissue. A specific design objective in the development of this dosimeter was matching the plutonium x-ray response (i.e., 16 keV) to the deep dose in tissue.

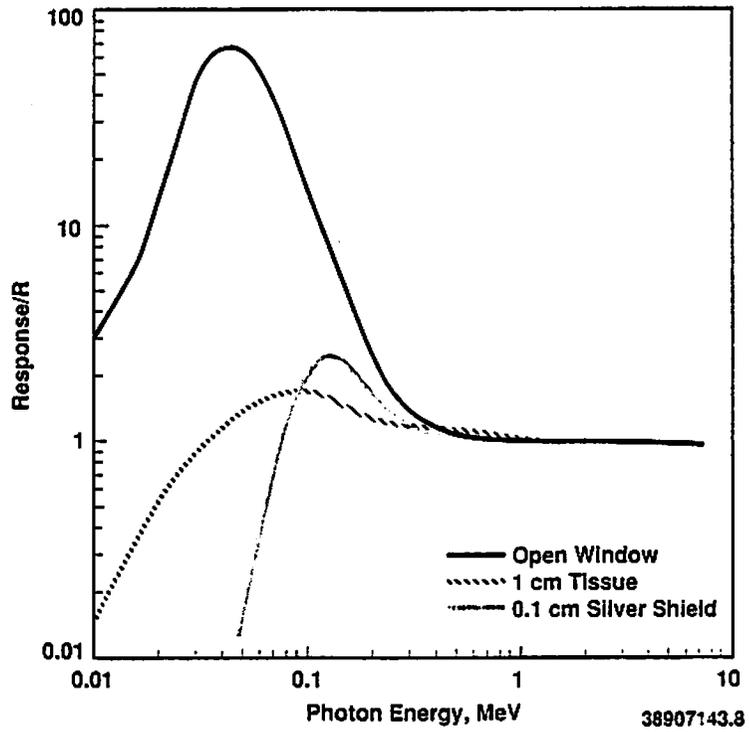


FIGURE 7.1. Hanford Two-Element Dosimeter Response from 1944 to 1957
(Source: Larson and Roesch 1954)

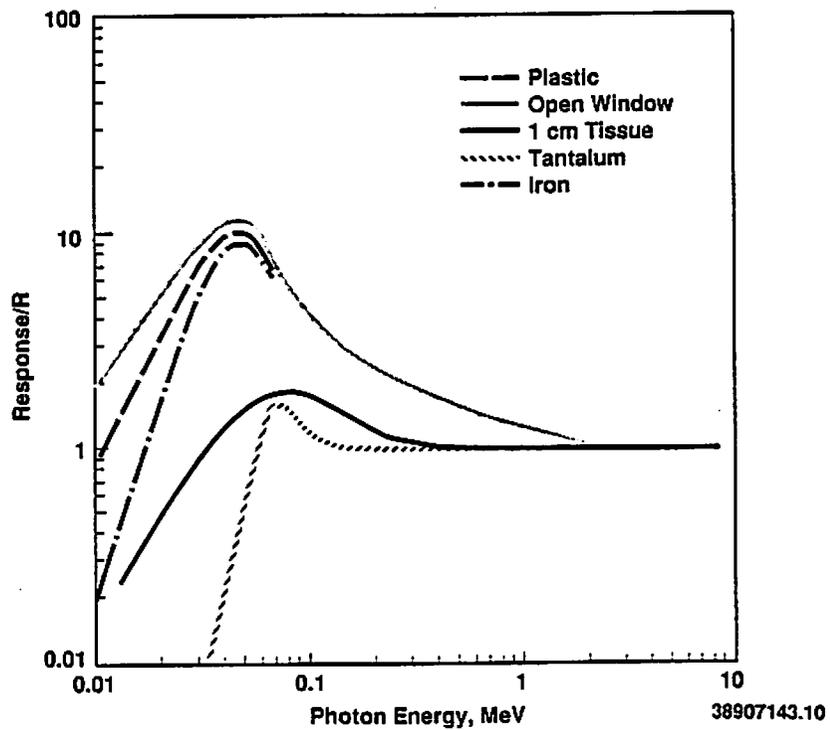


FIGURE 7.2. Hanford Multi-Element Film Dosimeter Response from 1962 to 1972
(Source: Kocher, Bramson, and Unruh 1963)

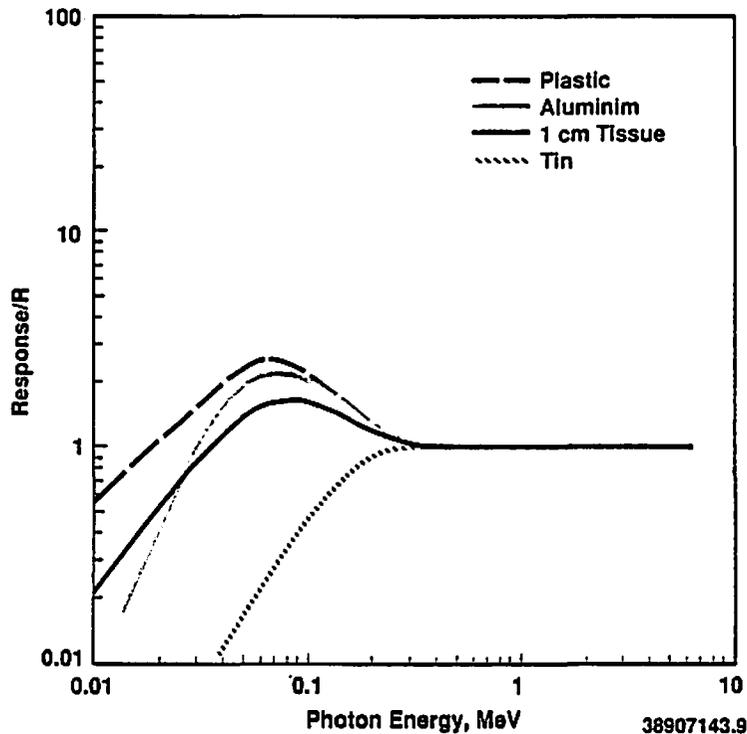


FIGURE 7.3. Hanford Multi-Element Thermoluminescent Dosimeter Response from 1972 to the Present

The response of both film dosimeters and TLD elements to beta radiation depends primarily on the material used in shielding the radiation-sensitive elements. Beta radiation is seldom an important consideration in the assessment of deep dose. However, for shallow dose, significant complexity arises from the response of film dosimeters exposed to mixed beta and low-energy photon radiation. As illustrated in Figures 7.1 and 7.2, the open window position in Hanford film dosimeters over-responds substantially to low-energy photon radiation.

The neutron response of different personnel neutron dosimeters has been studied extensively. A comprehensive study of personnel neutron dosimeters used in DOE facilities was published by Brackenbush et al. (1980). Achieving accurate dose estimates using the Hanford film dosimeters and albedo TLDs is principally dependent upon the ability to match the neutron energy fluence present in the work environment with that from the source used for calibration. A further complication for film dosimeters is the general inability of film to provide a reliable record for neutrons of energy less than about 800 keV.

The PuF₄ source was implemented at Hanford in 1958 and was used to calibrate film dosimeters through 1972. With the introduction of the TLD, a site-specific calibration was implemented, in which the dosimeter response in Hanford plutonium finishing facilities and in the laboratory exposed to the PuF₄ source was normalized to the dose measured with a TEPC. The similarity between dosimeter response to neutron radiation from this source and Hanford work environments has been verified on several occasions. Prior to 1958, PoB and PoBe sources, as well as the positive ion accelerator, were used to calibrate Hanford NTA film dosimeters. Each of these sources of neutron radiation have an effective energy greater than expected to be present in Hanford work environments; thus, it is likely that recorded neutron dose was underestimated. The inability of film to accurately measure neutron radiation was recognized by Hanford radiation protection personnel from the very beginning. This resulted in the administrative practice of maintaining personnel exposures to less than allowable limits.

7.1.2 Thermoluminescent Dosimeter

The history of performance for the Hanford TLD can be separated into three distinct periods during which different dose-determination methods were used and thus impacted the x-ray and gamma radiation dose response. The radiation response of the LiF crystals used in the Hanford dosimeter is shown in Figure 7.3. Calibration and dose algorithms are used to convert this response to estimates of radiation dose. These periods and the procedures used to determine dose from the TLD during these periods are described as follows:

- From 1972 to 1984--The penetrating dose from x-ray and gamma radiation was in direct proportion to the response of the aluminum-filtered LiF phosphor in position 2. Calibration was based on exposing dosimeters in-air to radium gamma radiation until 1977 when the calibration source was changed to ¹³⁷Cs.
- From 1984 to 1987--All aspects of the dosimeter and algorithm remained the same with the single exception that calibration was conducted on-phantom. A difference of about 10% is observed between in-air and on-phantom calibration. The in-air calibration results in the determination of higher personnel doses.
- From 1987 to the present--An energy-flattening algorithm was implemented to flatten the dose response of the dosimeter for all photon energies. This resulted in improved accuracy of the deep dose for all photon energies. In addition, a new beta/photon dosimeter was

introduced to improve the capability of Hanford dosimeters for mixtures of low-energy photons and beta radiation.

The changes beginning in 1984 were based on procedures being adopted in national personnel dosimeter performance testing standards, as discussed in more detail in Section 7.3.

The neutron response of the TLD is primarily the result of reflected (i.e., albedo) neutrons from the body. As such, the response of the dosimeter is highly dependent upon the energy of the incident neutrons. At Hanford, dosimeter calibration is based upon measurements at the plutonium finishing facility's glovebox operations. The TLD responds to essentially all neutron energies important to Hanford operations. For routine calibrations the dosimeter response to the Hanford field-specific calibration is simulated by extending the exposure time by a factor of 1.73 to the bare ^{252}Cf source in the low-scatter room of the Hanford Calibration Facility (318 Building). Consistency of the laboratory simulated and measured doses in the work environment was determined on several occasions. Doses measured with TEPCs were compared with doses measured with dosimeters at the same location (Fix et al. 1981; 1982). Because of the complexities of neutron dosimetry, the overall accuracy of personnel neutron recorded dose is estimated to be $\pm 50\%$.

7.1.3 Dosimeter Detection Levels

The detection level for film dosimeters was analyzed by Wilson (1960) and Baumgartner (1960). Based on their efforts, it is estimated that the detection level of the original DuPont 502 film was about 40 mR at the 95% confidence level for radium gamma radiation. The DuPont 508 film implemented during 1960 had a detection level of approximately 15 mR at the 95% confidence level for radium gamma radiation. Each of these films is significantly more sensitive to low-energy photons. The detection level of the thermoluminescent dosimetry system implemented in 1972 is estimated to be about 20 mR for radium gamma radiation.

The detection level for neutron radiation for film dosimeters is highly dependent upon the energy of the neutrons. Assuming comparability of current and historical work environments, the detection level for film would be expected to be from 50 mrem to several 100 mrem. The detection level for albedo TLDs to current work environments is likely to be about 50 mrem at the

95% confidence level. The detection level for film dosimeters or TLDs is significantly impacted by mixed neutron and photon exposures. There is little doubt that neutron dose was significantly underestimated with film dosimeters for a small group of personnel involved in plutonium glovebox operations.

7.2 1989 INTERCOMPARISON STUDY

In 1989 an intercomparison study of Hanford personnel film dosimeters was conducted. All types of personnel film dosimeters used at Hanford from 1944 to the present were exposed simultaneously to sources that were currently being used for calibration purposes. During the period from 1950 to 1958, neutron measurements with NTA film were made using the regular beta/photon film dosimeter in service at the time. A prototype neutron dosimeter holder was designed early in 1965 by Kocher for more accurate neutron evaluation; it had rhodium filtration and was also included for comparison purposes. This holder was never actually placed in routine service, but work done in its development provided a basis for the development of the albedo TLD that was implemented in 1972. Hanford film dosimeter holders and the selected radiation sources and doses levels to which they were simultaneously exposed are summarized in Tables 7.1 and 7.2, respectively. As much as possible, the original procedures for determining dose, as described in Chapter 4.0 and in Appendixes A and B of this report, were followed. Three to five dosimeters of each type were used for each radiation source. The measured response of these dosimeters was used to calculate the calibration coefficients. The results obtained are idealized, considering that variations in dosimeter response between dosimeters as well as from environmental or radiation field effects are minimized. However, the results illustrate the dose response of the different dosimeter types and algorithms.

The delivered deep dose for each radiation type and dose level was compared with the calculated whole body dose for each dosimeter type. The results of this comparison are shown in Table 7.3. All results are tabulated in Appendix D. It is apparent from the tabulated data that the deep dose response for all multi-element film dosimeters compares well with the delivered deep dose at all energies. For the original two-element dosimeters, a significant under-response to x-rays is apparent. There is little or no response to 16-keV x-rays and a response of about 30% to 59-keV x-rays.

TABLE 7.1. Hanford Dosimeter Holders Used in the 1989 Intercomparison Study

<u>Dosimeter Holder Type</u>	<u>Description</u>	<u>First Year of Use</u>
Original two-element	Half badge ^(a)	1944
Original two-element	Large badge ^(a)	1945
Multi-element	3 elements	1957
Multi-element	4 elements	1962
Multi-element neutron	3 elements	1958
Prototype rhodium neutron dosimeter	Testing	1965

(a) Metal holder for the film packet.

TABLE 7.2. 1989 Intercomparison Study Radiation Sources and Exposure Levels

<u>Radiation Source</u>	<u>Dose Level</u>
^{137}Cs	50, 240, 750 mR
^{90}Sr	50, 240, 750 mrad
16-keV x-ray	40, 80, 150 mR
59-keV x-ray	30, 50, 80 mR
Sigma pile	50 mrem
^{252}Cf	100 mrem (bare with Hanford field-specific calibration)

TABLE 7.3. Intercomparison of Deep Dose Determination for Hanford Film Dosimeters

Source	Given Exposure	Given Deep Dose (a)	Recorded Whole Body Dose, mrem			
			1944	1945	1957	1962
16 keV x-ray	40 mR	15 mrem	7	0	14	14
	80	30	7	0	27	28
	160	61	3	0	56	55
59 keV x-ray	30	44	17	7	46	49
	50	74	23	27	80	85
	80	118	27	33	126	137
¹³⁷ Cs	50	52	50	50	50	50
	240	247	247	227	240	240
	750	773	750	737	726	750
	1000	1030	1000	980	1002	1002
⁹⁰ Sr	50	3	0	0	0	
	240	0	3	0	10	0
	750	0	13	0	6	0
	1000	0	7	0	6	0
Uranium	50	0	0	0	0	0
	240	0	0	0	0	0
	750	0	20	30	20	0
	1000	0	23	30	20	0

(a) Exposure to dose conversion factors taken from DOE/EH-0027 (DOE 1986).

Comparison of the shallow dose determination for Hanford film dosimeters is shown in Table 7.4. Generally, the shallow dose is overestimated for all dosimeter systems. The comparison is within 5% for the 1962 multi-element film dosimeter for exposures to the uranium, 16-keV x-ray, 59-keV x-ray, and ¹³⁷Cs sources, which are used in the calibration of this dosimeter system. The shallow dose for ⁹⁰Sr is significantly overestimated. For the two-element dosimeter, it is apparent that the shallow dose is significantly overestimated for all sources except uranium and ¹³⁷Cs, which are used in the calibration of the dosimeter.

7.3 DOELAP ACCREDITATION

Development of national accreditation programs in personnel dosimetry was initiated in the 1960s. One of the earliest national intercomparison

TABLE 7.4. Intercomparison of Shallow Dose Determination for Hanford Film Dosimeters

Source	Given Exposure	Given Shallow Dose ^(a)	Recorded Skin Dose, mrem			
			1944	1945	1957	1962
⁹⁰ Sr	50 mrad	50 mrem	103	83	74	112
	240	240	353	360	286	410
	750	750	1370	1240	1016	2138
	1000	1000	2070	1790	1358	4990
Uranium	50	50	50	50	54	60
	240	240	250	237	230	252
	750	750	777	733	786	764
	1000	1000	1023	990	992	1016
16 keV x-ray	40 mR	43	353	397	40	40
	80	86	710	820	94	112
	160	173	2213	1997	266	194
59 keV x-ray	30	46	653	643	88	54
	50	77	1237	1213	162	94
	80	123	2553	2283	266	154
¹³⁷ Cs	50	52	57	50	50	50
	240	247	257	227	240	246
	750	773	773	763	726	750
	1000	1030	1047	1020	1002	1010

(a) Exposure to dose conversion factors taken from DOE/EH-0027 (DOE 1986).

programs was conducted at Hanford in the mid-1960s, as discussed in Section 5.3 of this report. Intercomparison studies of proposed national standards continued during the 1970s and 1980s. In 1983 ANSI formally adopted a national standard for personnel dosimeter performance (ANSI 1983). This standard was used by the U.S. Nuclear Regulatory Commission (NRC) and DOE (DOE 1986) as a technical basis for implementing national personnel dosimeter accreditation requirements for dosimetry programs in the late 1980s.

Hanford participated in DOELAP dosimeter performance testing in 1989 and successfully passed all requested categories for Hanford multipurpose, beta/photon, and basic thermoluminescent dosimeters. Performance testing covered a period of nearly 6 months and involved approximately 350 dose evaluations for a variety of single- and mixed-exposure conditions. Exposures

included personnel and accident level doses (the latter as high as 500 rem). The results of the performance testing are summarized in Table 7.4. The definition of the performance quotient, bias, and standard deviation used to determine the performance index of the dosimeters as used in the DOELAP standard are

$$P(i) = \frac{[X(i) \text{ (reported)} - Y(i) \text{ (delivered)}]}{Y(i) \text{ (delivered)}}$$

$$B = \Sigma P(i)/n$$

$$S.D. = \{[\Sigma(P(i) - B)^2]/(n-1)\}^{0.5}$$

$$P.I. = B + S.D.$$

where $P(i)$ = Performance quotient for each individual dosimeter

B = Bias for each exposure category

$S.D.$ = Standard deviation for each exposure category

$P.I.$ = Performance index for each exposure category.

For each exposure category, five dosimeters are irradiated each month for a period of 3 months for a total of 15 dosimeters in each category. There are six different exposure categories using exposures from a single radiation source, with a seventh category involving exposures from combinations of two different sources from categories three through six. This is illustrated in Table 7.5 for the categories in which Hanford dosimeters were tested.

Becoming accredited involves two distinct steps: 1) passing the performance test standard for each personnel dosimeter type, and 2) passing a technical program review for dosimetry adequacy relative to field conditions. The onsite technical program of the Hanford Program was conducted during December 1989, resulting in formal DOELAP accreditation of the Hanford program on January 31, 1990. Maintaining DOELAP accreditation requires re-accreditation every 2 years.

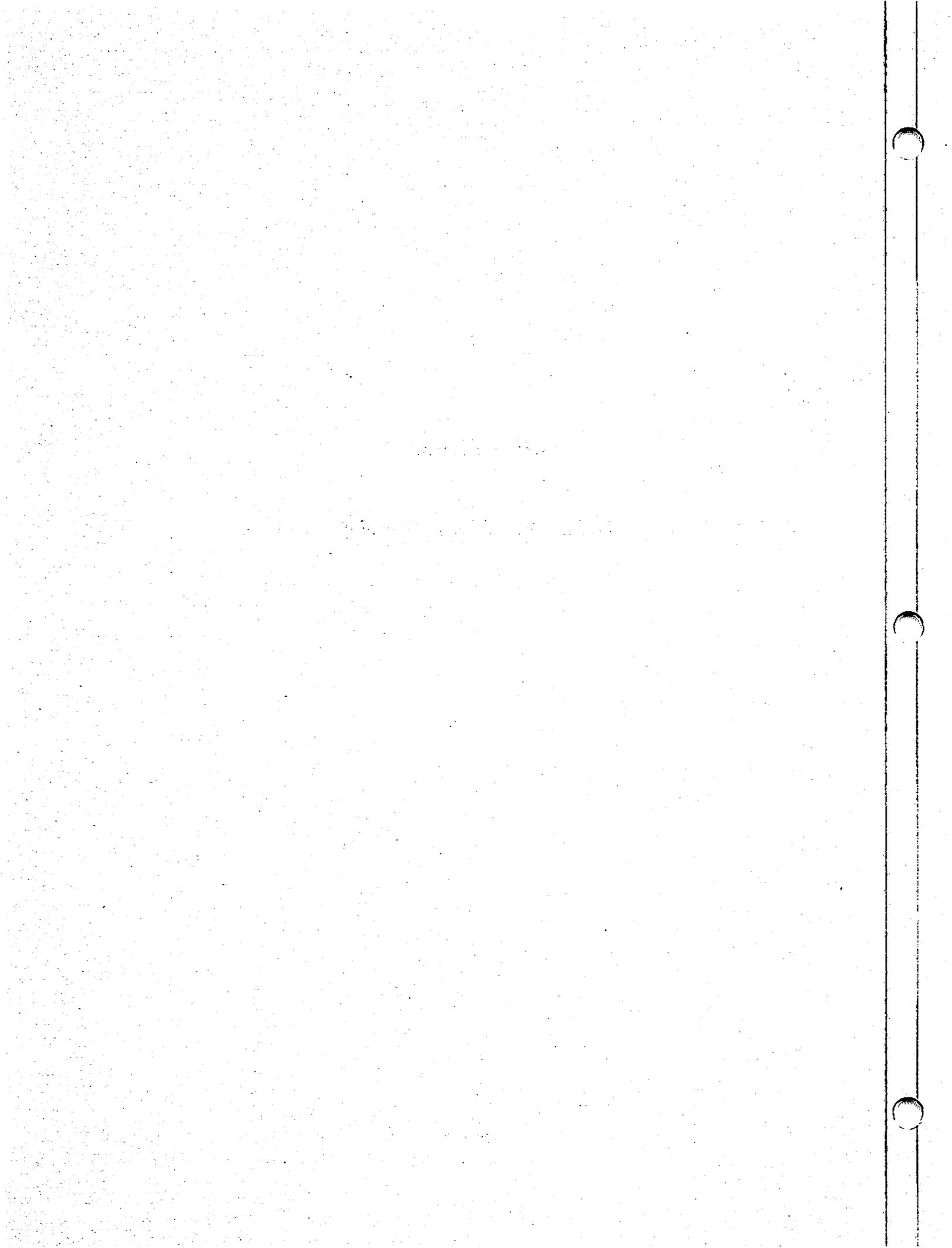
TABLE 7.5. Shallow and Deep Dose Performance Test Data

<u>DOELAP Category Description</u>	<u>DOELAP Criterion</u>	<u>Performance^(a)</u>		
		<u>Basic</u>	<u>HMPD</u>	<u>HBPD</u>
<u>Shallow-Dose Component</u>				
Low-energy photons, plutonium environments	0.3		0.09	0.20
High-energy photons, ¹³⁷ Cs	0.3		0.04	0.13
Beta particles, ⁹⁰ Sr	0.3			0.28
Mixtures:				
Low-energy photons + high-energy photons	0.4		0.08	0.21
Low-energy photons + beta particles	0.4			0.24
High-energy photons + beta particles	0.4			0.28
<u>Deep-Dose Component</u>				
Low-energy photons, accident levels	0.3		0.22	0.19
High-energy photons, accident levels	0.3	0.10	0.18	0.25
Low-energy photons, plutonium environments	0.3		0.16	0.22
High-energy photons, ¹³⁷ Cs	0.3	0.20	0.06	0.14
Neutrons, unmoderated ²⁵² Cf	0.3		0.10	
Mixtures:				
Low-energy photons + high-energy photons	0.4		0.12	0.23
Low-energy photons + beta particles	0.4			0.35
Low-energy photons + neutrons	0.4		0.12	
High-energy photons + beta particles	0.4			0.10
High-energy photons + neutrons	0.4		0.11	

(a) Performance results for the Hanford basic dosimeter, Hanford multipurpose dosimeter (HMPD), and Hanford beta/photon dosimeter (HBPD).

CHAPTER 8.0

DEEP DOSE EVALUATION



8.0 DEEP DOSE EVALUATION

In this chapter the response characteristics for Hanford film dosimeters and TLDs described in the previous chapters are used in conjunction with expected beta, photon, and neutron radiation fields present in Hanford facilities to compare the recorded whole body dose with the expected deep dose. It is important to note that the dose interpretation methods used are based on the professional knowledge of the authors through many years of experience in radiation dosimetry. The basis for each different dose assessments is described. In a few cases, conclusions provided by authors of earlier studies referenced in Chapter 5.0 may differ from conclusions presented in this chapter. This is to be expected, considering the information available at the time of the original studies, evolving dosimetry technology, and the scientific information currently available. Laboratory study reports, such as those presented in Chapter 7.0, are extremely useful, but they often do not include full descriptions of the performance of dosimeters in actual field conditions where the complex relationships of dose response with energy and fluence in mixed beta, photon, and neutron radiation fields must be considered. An attempt has been made in this chapter to estimate the expected performance of Hanford dosimeters used by personnel in typical field conditions.

8.1 HANFORD PERSONNEL DOSIMETRY PRACTICES AND SYSTEMS

Hanford personnel involved in radiation work have always been required to wear personnel dosimeters in a prescribed manner. Complete records of Hanford personnel radiation exposure have been maintained since 1944. If a dosimeter record for any individual was unavailable during a routine exchange period (i.e., weekly, monthly, etc.), an investigation was conducted to determine and record a dose. Recently, Gilbert (1990) compared the computerized dose estimates used in the Hanford Health and Mortality Study with the dose that would be calculated from the original microfilm and microfiche records of film dosimeter results for 139 employees. This study concluded that there were no discrepancies that would be likely to impact the conclusions of the Mortality Study. Generally, the larger discrepancies noted occurred in the earliest years of Hanford operations (i.e., from 1944 to 1946).

From 1944 through 1989 numerous changes have been made to the Hanford dosimetry program to adopt improved methodology and to better adjust the program to radiation fields present in Hanford facilities. Significant changes in Hanford dosimeters, calibration methods and sources, methods to interpret dose, and administration of the program during this 4-decade period are summarized in Table 4.1.

8.2 HANFORD FACILITIES

Six distinct facilities at Hanford have contributed the majority of radiation dose received by personnel since Hanford startup. These are the 1) reactor fuel fabrication facilities, 2) reactors, 3) irradiated fuel reprocessing facilities, 4) plutonium finishing facilities, 5) waste facilities, and 6) general laboratory facilities. The radiation fields typical of each of these types of facilities are described as follows:

1. Fuel Fabrication--Beginning in 1944 uranium metal was fabricated into fuel elements at Hanford. During the 1960s only encapsulated fuel elements were received at Hanford for use in fabricating fuel elements.) All fuel fabrication facilities were located in the 300 Area. Beta and photon radiation from uranium comprise the external radiation fields from fuel fabrication operations. Many Hanford personnel, particularly during the early years, were exposed to relatively low levels of occupational radiation from uranium in these facilities.
2. Reactors--Nine different production reactors were located in the 100 Areas of Hanford. Operations for the majority of the reactors were terminated in the late 1960s. The Fast Flux Test Reactor initiated operations in the late 1970s. Radiation to which personnel were exposed at the reactors was typically high-energy photon radiation greater than 100 keV, because extensive shielding removed low-energy photons from the field. Neutron radiation was present but personnel received low doses from neutron radiation compared with the dose from photon radiation. The majority of Hanford personnel exposure to beta and photon radiation occurred in the reactor facilities, primarily during maintenance operations.
3. Irradiated Fuel Reprocessing Facilities--Significant beta and photon radiation fields accompanied the reprocessing of irradiated fuel in several different facilities in the Hanford 200 Areas. Extensive shielding is used throughout these facility operations and thus personnel exposure is primarily due to photon radiation greater than 100 keV. Certain operations involving maintenance or decontamination involved exposure to beta and photon radiation typical of mixed fission products. Historically, these facilities provided the second largest contributor of external radiation exposure to Hanford personnel.

4. Plutonium Finishing Facilities--Plutonium finishing involves purifying plutonium and is conducted in facilities located in the Hanford 200-West Area. Most of this work is done by personnel in glovebox operations. Radiation fields are primarily from plutonium low-energy x-rays and spontaneous fission neutrons. During the early years of plutonium finishing operations, essentially all photon radiation resulted from plutonium x-rays. Later, 59-keV gamma radiation contributed significantly to the personnel exposure. The 59-keV gamma radiation was from ^{241}Am . Americium-241 (half-life, 458 years) ingrowth resulted from the ^{241}Pu (half-life, 14.4 years), which was present at about 1% by weight in the relatively low-exposure, "weapons-grade" plutonium produced at Hanford. Neutron radiation is substantially enhanced in part of the finishing operation when alpha radiation from plutonium interacts with fluorine. Although relatively few Hanford personnel were involved in plutonium finishing, these facilities provided the majority of personnel exposure to neutron radiation.
5. Waste Facilities--Personnel exposure at Hanford waste facilities, primarily in the 200 Areas, is typically from beta and photon radiation resulting from one or more mixed fission products. Many radionuclides are present in the waste streams with a broad spectrum of possible radiation energies. Extensive shielding is used in these facilities; thus the radiation fields encountered by personnel are similar to those present in the reprocessing facilities.
6. Laboratory Facilities--Personnel exposure at large laboratory facilities is typically from beta and photon radiation from uranium and/or plutonium as well as one or more mixed fission products. For some laboratory facilities, external radiation exposure to low-energy photons from x-rays and/or specific radionuclides is possible. Generally, personnel exposures are carefully considered and monitored because of the specific nature of the work. Overall, relatively few personnel were expected to be significantly exposed in these facilities. Laboratory facilities were located within all of the operating areas. However, the major laboratory facilities were located within the 200 and 300 Areas.

8.3 EVALUATION OF RECORDED DOSE

Complex interactions of radiation with matter and the comparison of dosimeter response with tissue dose result in uncertainty in the evaluation of recorded whole body dose compared with the deep dose for past Hanford dosimetry systems. Potential sources of uncertainty have been grouped for these systems, as follows:

1. Dosimeter design
 - Radiation response
 - Angular response
 - Energy threshold

2. Radiation fields
 - Geometry of exposure
 - Radiation types(s)
 - Energy
3. Dose interpretation
 - Calibration protocol and source(s)
 - Dose conversion factors
 - Dose algorithm.

Note that the evaluations to be presented in this report are primarily of the recorded whole body dose relative to the deep dose for beta and photon radiation. The shallow (i.e., skin) dose response of the dosimeters is more complicated due to the increased uncertainty of dosimeter response to beta and low-energy photons. However, there is little deep dose from beta radiation (i.e., energies greater than 2.0 MeV are necessary to penetrate 1 cm in tissue). Deep dose from low-energy photons is less than from higher-energy photons greater than 100 keV. An assessment of these sources of uncertainty in Hanford facilities is presented in the following subsections on doses received from beta and photon radiation and from neutron radiation. Dosimetry for personnel with little or no occupational exposure is also discussed.

8.3.1 Dose from Beta and Photon Radiation

Dosimeter design, radiation fields, and dose interpretation methods are critical elements of evaluating doses from beta and photon radiation.

Dosimeter Design

For Hanford film dosimeters, the mass density of the silver filter used from 1944 to 1961 or the tantalum filters used from 1962 to 1972 to cover the portion of film used to measure the whole body dose is approximately 1000 mg/cm². Recorded whole body dose for any beta radiation sufficiently energetic (i.e., > 2 MeV) to penetrate these filters would result in an estimate of the deep dose. For Hanford TLDs, the whole body dose from beta radiation would be overestimated. For example, a deep dose equal to approximately 30% of the shallow dose would be recorded for the encapsulated ⁹⁰Sr/⁹⁰Y source used in DOELAP performance testing when, in fact, no deep dose should be recorded. It should be noted that beta radiation contributed little to the recorded whole body dose in Hanford facilities.

The photon radiation response of Hanford film dosimeters and TLDs is presented in Chapter 7.0 relative to the deep dose. A study of the angular response of the Hanford film dosimeter is described in Chapter 5.0 (Little 1960). Little concluded that the film density was uniform between $\pm 75^\circ$ from normal. This response is expected to be representative of all Hanford film dosimeters. The angular response of Hanford TLDs has been measured for several photon energies, showing an increase in the uniform response from approximately $\pm 30^\circ$ from normal for 16-keV photons to $\pm 90^\circ$ from normal for ^{137}Cs . The photon angular energy response of Hanford dosimeters is summarized in Chapter 7.0. These data demonstrate that Hanford dosimeters respond without any significant bias for photons of energy greater than 100 keV. The dosimeter response is nearly identical for higher-energy photons even at large incident angles. The film density behind the silver filter for the original Hanford two-element film dosimeter did under-respond to low-energy photons (as discussed in Section 8.4.1 of this chapter).

Radiation Fields

Most Hanford personnel exposure to occupational sources of radiation is received to the front of the body. Typically workers are facing the work being done and, for routine radiation exposure over long time periods, the front of the torso can be reasonably expected to receive the largest cumulative exposure. Thus, Hanford dosimeters have always been worn on the front of the torso to maximize the recorded whole body dose. For certain work environments, such as glovebox and laboratory hoods, only the upper portion of the torso, along with the dosimeter, are directly exposed.

The majority of Hanford personnel exposure is from photons. Generally, photon radiation at Hanford was of energies greater than 100 keV from mixed fission and activation products. Radiation shielding used extensively in Hanford facilities to reduce the intensity of high-energy radiations effectively removed much of the lower-energy photon radiation. Neutron radiation was present in the reactor facilities, but contributed less than 5% to personnel exposure compared with the dose from photon radiation greater than 100 keV. Low-energy photons as well as neutrons were prevalent in the plutonium finishing facilities.

Dose Interpretation

Methods used to determine dose for the different Hanford dosimeters are discussed in Chapters 2.0 through 6.0. For each dosimeter type, dose components were determined based on comparison of the observed dosimeter response behind different areas of the dosimeter with a calibration response. Dose components are identified on historical records as beta, gamma, nonpenetrating, x-ray, penetrating, etc., depending upon the dosimeter design and the methods of calibration and dose interpretation. However for all Hanford film dosimeters, the whole body dose from photon radiation was determined fundamentally as the sum of the "penetrating" component resulting from the film response from photons that penetrate the thick silver (used from 1944 to 1962) or tantalum filters (used from 1962 to 1972), plus 35% of the "x-ray" component determined from the film response behind the other filters (used from 1957 to 1972). This relationship is shown as follows:

$$\text{Dose} = \text{Penetrating Component} + 35\% \text{ x-ray Component}$$

Hanford film dosimeters were calibrated in-air to radium gamma radiation until 1965 when the dosimeters were exposed on-phantom. This practice is estimated to result in a difference of about 10% in calculated dose. The deep dose was underestimated for photons of less than 100 keV for the two-element dosimeter used from 1944 to 1957 because of the use of the single film position shielded with 1 mm of silver. With the implementation of the multi-element film dosimeter in 1957, the exposure from lower-energy photons was interpreted based on a calibration exposure to 16 keV k-fluorescent radiation. In 1958 Hanford adopted the practice of adding 35% of the x-ray exposure determined with the multi-element film dosimeter to the whole body dose component. This is very close to the exposure to a deep dose conversion factor of 0.38 used in the current DOE Laboratory Performance Testing of personnel dosimeters for 16-keV photon radiation (DOE 1986).

From 1972 through 1986 the whole body dose for the multi-element TLD was based directly on the signal of the thermoluminescent chip in position 2. The signal in position 2, normalized to its response to ^{137}Cs , shows a relatively uniform response above 100 keV, an over-response at intermediate photon energies reaching a maximum of about 35% at 40 keV, and a declining response

for photons less than 40 keV. The response to 16-keV photons is nearly equivalent to the deep dose when the dosimeter is calibrated to ^{137}Cs gamma radiation. Procedures used to determine dose from TLDs can be divided into three distinct periods as follows:

- 1972-1984--Dosimeter was calibrated to ^{137}Cs gamma radiation in-air until 1984 when exposures were done on-phantom resulting in a difference of about 10% for all photon energies. For example, the dose response for ^{137}Cs -irradiated dosimeters on phantom is 10% higher than for similarly irradiated dosimeters in-air.
- 1985-1987--Dosimeters were calibrated on-phantom. The reported whole body dose for photons greater than about 100 keV was equal to the deep dose. For intermediate photon energies a maximum positive bias of about 35% for 40-keV photons is observed. No significant bias in reported whole body dose is observed for 16-keV photon radiation.
- 1988-1989--Dosimeter algorithm was improved. No significant deep dose bias is observed at any photon energies observed in Hanford work environs.

8.3.2 Dose from Neutron Radiation

The total whole body dose recorded at Hanford is equal to the sum of the whole body dose from photons and the whole body dose from neutrons. Dose for all Hanford neutron dosimeters was based on a direct comparison of the observed dosimeter signal during field use with the signal from a calibration exposure to a known radiation dose. Essentially four sources of neutron radiation have been used at Hanford for calibration: PoB (used from 1950 to 1957), positive ion accelerator (used from 1957 to 1958), PuF_4 (used from 1958 to 1981), and ^{252}Cf (used from 1982 to the present). For the ^{252}Cf source, a site-specific calibration was implemented, in which the dosimeter response in the field and in the laboratory was normalized to the dose measured with a TEPC. During the 1950s the dose recorded from neutrons was based on the first-collision dose from the different calibration sources used at that time. All calibration sources prior to the implementation of the PuF_4 source in 1958 have higher neutron energies than the energies of neutrons in work environments of Hanford reactor and plutonium finishing facilities. This situation resulted in an underestimate of the actual neutron dose.

It is known that, until the introduction of the TLD in 1972, the recorded whole body dose from neutron radiation in Hanford facilities was

underestimated. The boron-lined pencil dosimeter used from 1944 to 1949 responded to thermal neutron radiation only, whereas the majority of personnel exposure occurred from intermediate energy neutrons that were not measured. The NTA film introduced in 1950 had an energy threshold of approximately 800 keV. The majority of Hanford personnel exposure is expected to result from neutrons between 200 keV and 500 keV based on measurements conducted during the 1970s and 1980s. These energies are less than the energy threshold of the NTA film and, as such, were not measured.

Calibration of Hanford TLDs based on PuF_4 has been verified on several occasions during the 1970s and 1980s using parallel measurements between the dosimeter and neutron dose instruments, including Bonner spheres and TEPCs. The neutron spectrum was also determined.

The determination of dose from neutrons is complex. The dose from neutrons is currently based on the maximum dose equivalent in a 30-cm-diameter tissue-equivalent sphere as defined by the International Commission of Radiation and Measurements (ICRU 1988). This dose is not easily converted to a deep dose in tissue as is done for photons because of greater uncertainty in the dosimeter response and because of the energy fluence of neutrons in the workplace.

8.3.3 Dosimetry for Personnel with Little or No Occupational Exposure

It has been Hanford practice to monitor nearly all personnel for external radiation exposure. This includes personnel in facilities where no occupational radiation exposure is received and where the total radiation exposure is essentially equal to natural background radiation levels. The majority of Hanford personnel fall within this category. The relative uncertainty in the measurement of doses near background levels is very large. With film dosimeters this occurs because at low doses a small change in the net optical density (the quantity actually measured) results in a large change in the estimated exposure. For example, in an investigation of film dosimetry in atmospheric nuclear tests (NAS 1989), the uncertainties introduced in laboratory processing and calibration of film dosimeters for many of the test series evaluated were assessed by assigning a standard error that was 10% of the estimated exposure for exposures above 200 mR. However, this standard error was judged to be about 20%, 50%, and 100% for readings of 100 mR, 40 mR,

and 20 mR, respectively. This means that exposures below about 40 mR could not be statistically distinguished from zero. Similar results would be expected for the Hanford dosimetry system used from 1944 to 1957. Large relative errors at low doses would also be expected for the Hanford dosimetry system.

An additional problem occurs because the estimation of occupational dose requires adjustment for background exposure, which is accomplished by subtracting readings from control dosimeters. For personnel with little or no true occupational dose, this subtraction can yield negative estimates and these estimates are recorded as zeros. Because positive results for unexposed personnel are recorded and are not compensated by the subtraction of negative results, cumulative doses for personnel with little or no occupational exposure tend to be overestimated.

In addition, examination of data on the proportion of readings recorded as zero for various groups of Hanford personnel (Gilbert 1990) suggests that practices for handling very low recorded exposures may have varied from year to year. These procedures are not well documented and it is difficult to assess the bias that may have resulted. However, it should be noted that doses as low as 10 mR were recorded in all years.

The problems noted above were not of great concern for radiation protection purposes because the doses involved are much smaller than regulatory limits. The difficulties in measuring very low doses are not considered further in this report. However, it is emphasized that distinctions between very low doses or between small positive exposures and zero exposure are not likely to be meaningful.

8.4 DOSIMETER RESPONSE IN HANFORD FACILITIES

The dose response of past Hanford dosimeter systems can be estimated by considering the radiation fields in Hanford facilities (as discussed in Section 8.2) and the uncertainties in dosimeter response (as discussed in Section 8.3). The expected performance of the Hanford two-element film dosimeter, Hanford multi-element film dosimeter, and Hanford multi-element TLD are discussed in the following subsections. In the material that follows, bias correction factors are specified. These bias factors are intended to

reflect the average value of the ratio of deep dose to recorded dose, where the average is considered to be over all dosimeter readings in a specified facility and time period. Because there is uncertainty in our knowledge of this average ratio, ranges of bias correction factors are given for each situation. These ranges are generally greater for earlier years when dosimetry practices were not as well documented and standardized as in recent years. The ranges are not intended to reflect "random uncertainty" or the range of bias factors that might be found among individual readings in a specified population.

8.4.1 Two-Element Film Dosimeter Used from 1944 to 1957

As discussed in earlier chapters, the whole body dose recorded for the two-element dosimeter was based directly on the film density behind the silver shield. This dosimeter accurately estimated the deep dose for photon radiation greater than about 100 keV and beta radiation sufficiently energetic to penetrate the thickness (i.e., 1000 mg/cm²) of the silver filter. The whole body dose bias factors for each of the major facility types are summarized in Table 8.1. The majority of Hanford personnel working in fuel fabrication, reactor, irradiated fuel reprocessing, waste, and laboratory facilities were exposed to photon radiation of energy primarily greater than 100 keV. The estimated range of the bias factor for these facilities is 0.5 to 1.6 (i.e., about \pm 50%). The potential for under-response is estimated to be slightly greater than an over-response because of the under-response of the dosimeter to lower-energy photons. A relatively small amount of neutron dose was received by personnel in the reactor facilities. The neutron dose is estimated to comprise less than 5% of the cumulative personnel exposure with little likelihood of significant exposure of any individual to significant neutron radiation. The maximum for the range of the bias factor for the reactor facilities is increased to 1.7 because of the added possibility of under-recording the whole body dose from neutrons.

For plutonium finishing facility operations, this dosimeter under-estimates the deep dose for lower-energy photon radiation, such as plutonium x-rays (e.g., 16 keV to 17 keV) and 59-keV photons from ²⁴¹Am (ingrowth from ²⁴¹Pu). There is essentially no response to plutonium x-rays, whereas only about 30% of the deep dose from 59-keV photons would be determined. Thus, the potential bias in recorded whole body dose from photons in this facility is

TABLE 8.1. Dose Response of the Hanford Two-Element Film Dosimeter Used from 1944 to 1957

Facility Type	Field Description	Dosimeter Response	Whole Body Dose Bias Factor ^(a)		Comments
			Minimum	Maximum	
Fuel fabrication	Uranium beta and gamma radiation	Response within $\pm 50\%$ based on radium gamma calibration	0.5	1.6	Recorded whole body dose was predominantly from photon radiation of energy > 100 keV. Relatively low intensity of lower-energy photon radiation and uranium radiation.
Reactor	High-energy beta and photon radiation. Relatively low-level neutron radiation.	Response within $\pm 50\%$ to the generally high-energy photon radiation. Dose from neutron radiation was substantially underestimated.	0.5	1.7	Recorded whole body dose was predominantly from photon radiation of energy > 100 keV. Extensive shielding minimized intensity of lower-energy photon radiation. Relatively low dose, likely $< 5\%$, from neutrons in the reactor facilities was generally underestimated.
Fuel reprocessing	Generally mixed beta and photon radiation.	Response within $\pm 50\%$ to the generally high-energy beta and photon radiation. Underresponse to lower-energy photon radiation.	0.5	1.6	Recorded whole body dose was predominantly from photon radiation of energy > 100 keV. Extensive shielding minimized lower-energy radiation. Relatively little deep dose results from beta radiation.
Plutonium finishing	Neutron radiation generally between 200 and 500 keV. Plutonium x-rays and 59 keV photons from Am-241 ingrowth from 1% by weight Pu-241.	Dosimeter response to Am-241 59 keV photon radiation is about 30% of the radium response. May be no dosimeter response to plutonium photons or neutrons.	(See Comments in next column)		Recorded whole body dose is known to be greatly in error. It is possible, although unlikely, that no dose would be measured for either plutonium photons or neutrons. Maximum deep dose for these personnel could be crudely estimated by multiplying recorded beta dose by 20%. The basis for this factor is explained in Section 8.3.1. A 1:1 ratio between neutron dose and deep dose from plutonium x-rays is assumed. There were relatively few personnel involved in these operations.
Waste and laboratory	Generally mixed beta and photon radiation.	Response within $\pm 50\%$ for high-energy photon radiation. Underresponse for low-energy photons would occur.	0.5	1.6	Recorded whole body dose approximates the deep dose because of predominance of photons with energies > 100 keV.

(a) Bias factor is defined as the ratio of deep dose to recorded whole body dose.

TABLE 8.2. Dose Response of the Hanford Multi-Element Film Dosimeter Used from 1957 to 1972

Facility Type	Field Description	Dosimeter Response	Whole Body Dose Bias Factor ^(a)		Comments
			Minimum	Maximum	
Fuel fabrication	Uranium beta and gamma radiation	Response within $\pm 30\%$ for photons and beta radiation.	0.7	1.3	Recorded whole body doses closely approximates deep dose for all energies of photon radiation.
Reactor	High-energy beta and photon radiation. Relatively low-level neutron radiation.	Response within $\pm 30\%$ for beta and photon radiation. Relatively low neutron doses will be substantially underestimated.	0.7	1.4	Photon radiation will generally be > 100 keV because of substantial shielding. Relatively small neutron, $< 5\%$ on average, dose will be underestimated.
Fuel reprocessing	Generally mixed beta and photon radiation.	Response with $\pm 30\%$ for beta and photon radiation.	0.7	1.3	Extensive shielding reduces intensity of beta and low-energy photon radiation.
Plutonium finishing	Radiation consists of neutrons generally between 200 and 500 keV as well as plutonium and Am-241 (59 keV) photons. Am-241 results from ingrowth from Pu-241.	Dosimeter response very high plutonium x-rays. Significant underestimate for neutrons occurred.	1.0	2.0	Recorded whole body dose from photon radiation closely approximates deep dose based on the Hanford practice of adding 35% of the x-ray exposure to the deep dose from higher-energy photon radiation. Dose from neutrons is known to be underestimated. Crude estimates of the total deep dose could be determined by multiplying the recorded penetrating (deep) dose from photons by a factor of 2. This assumes 1:1 ratio between the neutron dose and the deep dose from plutonium photons. There were relatively few personnel involved in these operations.
Waste and laboratory	Generally mixed beta and photon radiation.	Response within $\pm 30\%$ for all beta and photon radiation.	0.7	1.3	Majority of recorded whole body dose likely the result of photon radiation > 100 keV. Relative intensity of low-energy photon and beta radiation is expected to be significantly less.

(a) The bias factor is defined as the ratio of deep dose to recorded whole body dose.

TABLE 8.3. Dose Response of the Hanford Multi-Element Thermoluminescent Dosimeter Used from 1972 to 1989

<u>Facility Type</u>	<u>Field Description</u>	<u>Dosimeter Response</u>	<u>Whole Body Dose Bias Factor^(a)</u>		<u>Comments</u>
			<u>Minimum</u>	<u>Maximum</u>	
Fuel fabrication	Uranium beta and gamma radiation	Dosimeter response within $\pm 20\%$ for photons. 15% of uranium beta shallow dose recorded as a deep dose.	0.8	1.2	Recorded whole body dose was predominantly from photon radiation > 100 keV high. Beta radiation over-response likely not significant because of shielding inherent to the encapsulated fuel elements received at Hanford.
Reactor	High-energy beta and photon radiation. Relatively low-level neutron radiation.	Dosimeter response within $\pm 20\%$ for photons. Neutron calibration to PuF ₄ will result in positive bias in neutron doses.	0.8	1.2	Recorded whole body dose was predominantly from photon radiation > 100 keV. Extensive shielding reduced intensity of lower-energy radiation. Relatively small neutron dose (<5% of recorded whole body dose) in these facilities, based on calibration to PuF ₄ , would be overestimated.
Fuel reprocessing	Generally mixed beta and photon radiation.	Dosimeter response to complex beta and photon fields within $\pm 30\%$. Sr/Y-90 beta radiation would contribute a deep dose equal to 30% of shallow dose.	0.7	1.3	Recorded whole body dose was predominantly from photon radiation > 100 keV. Extensive shielding reduced intensity of beta and lower-energy photon radiation.
Plutonium finishing	Neutron radiation generally between 200 and 600 keV. Plutonium x-rays and 59-keV photons from Am-241 ingrowth from 1% by weight Pu-241.	Dosimeter response within $\pm 10\%$ for plutonium 18 keV to 17 keV photons and over-responds by 30% to 40% for 59-keV photons. Neutron calibration was based on neutron fields in this facility.	0.6	1.4	Whole body dose generally estimated accurately. Dosimeter was designed and calibrated for radiation fields present in these facilities. Relative intensity of 59-keV photon radiation and plutonium x-rays is not easily estimated. Increase in range of the bias factor estimate is based on this as well as on the complexity of neutron dosimetry.
Waste and laboratory	Generally mixed beta and photon radiation.	Deep dose will be measured accurately.	0.8	1.2	Recorded whole body dose was predominantly from photon radiation > 100 keV. Relative intensity of low-energy photon and beta radiation is expected to be significantly less.

(a) The bias factor is defined as the ratio of deep dose to recorded whole body dose.

very large. The boron-lined pencil dosimeters used prior to 1950 to measure neutron dose in these facilities were generally poor. The NTA film implemented in 1950 was capable of reliably measuring dose from neutron radiation with energies of 800 keV or greater. Measurements in plutonium finishing facilities during the 1970s and 1980s have shown the average energy in the work environment to be between 200 keV and 500 keV because of scattering of the neutrons in the shielding. The problems of measuring neutron dose were well-known to early researchers at Hanford, but there was no available instrumentation to provide a better dose estimate.

It is possible to provide a crude estimate of dose from photons and neutrons for personnel in plutonium finishing facilities by extrapolating from the recorded beta and/or gamma dose. The film behind the open window of the dosimeter is very sensitive to low-energy photons (as shown in Section 7.3). Assuming that the film response was due to plutonium x-rays (i.e., 16 keV to 17 keV), a recorded beta dose of 1000 mrad would correspond to a deep dose of 115 mrem. To obtain an estimate of the maximum likely whole body dose for x-rays the recorded beta dose could be multiplied by a factor of 0.1 (i.e., estimated from 115 mrem/1000 mrad). The neutron dose received could be estimated by multiplying the estimated deep dose from x-rays by a factor of 2. This assumes a ratio 1:1 for the neutron dose to deep dose from plutonium x-rays. Hence, to estimate the total whole body dose from both x-rays and neutron radiation, the recorded beta dose would be multiplied by 20% (i.e., $2 * 0.1$). The whole body dose calculated in this manner would likely be within a factor of 2 of the deep dose because of uncertainty in the neutron to deep dose ratio. For example, if the ratio between the neutron dose and deep dose from plutonium x-rays was 3 to 1, the total dose would be calculated as 30% of the recorded beta dose.

8.4.2 Multi-Element Film Dosimeter Used from 1957 to 1972

Implementation of the multi-element dosimeter provided Hanford with the capability to distinguish between beta and low-energy photon radiation and hence to accurately estimate the deep dose from photons. Hanford adopted the practice of adding 35% of the x-ray exposure to the whole body dose (exposure) measured behind the thick silver shield. This practice provided an estimate of the deep dose (e.g., current DOELAP dose conversion factor for 16-keV photon radiation is 38%). The multi-element film dosimeters provided an

accurate dose estimate for all Hanford facilities with the exception of neutron radiation present primarily at plutonium finishing facilities. The estimated range of the bias factor is shown in Table 8.2. For fuel fabrication, reactor, fuel reprocessing, waste, and laboratory facilities, the range is estimated to be from 0.7 to 1.3 (i.e., $\pm 30\%$). The majority of the dose in these facilities resulted from photons of energy greater than about 100 keV.

The problems with neutron radiation were still present. The use of the PuF_4 calibration source beginning in 1958 provided a realistic calibration for the neutron energies in the work environment. However, significant problems with underestimation of neutron dose continued. The maximum for the range of the bias factor is increased for the reactor facilities to 1.4 because of the presence of neutron radiation. The neutron dose continued to be a small percentage, less than 5%, of the overall dose. For plutonium finishing facilities, the most likely range of the bias factor was estimated to be from 1.0 to 2.0. The minimum of 1.0 is based on the assumption that all dose was measured. The maximum of 2.0 for the range was determined based on the assumption that none of the neutron dose was measured. These estimates assume that the neutron dose could be equal in magnitude to the deep dose from plutonium x-rays that were accurately measured.

8.4.3 Multi-Element Thermoluminescent Dosimeter Used from 1972 to 1989

This dosimeter provided the first capability to accurately measure the dose from all significant beta, photon, and neutron radiation present in Hanford facilities. The dosimeter over-responded by as much as 35% to 40-keV photons. However, with the exception of plutonium finishing facilities, the average photon energy was greater than 100 keV in Hanford facilities. The dosimeter responded accurately to plutonium x-rays, and it was calibrated to the neutron energies present in the plutonium finishing facilities.

Estimates of the range for the whole body dose bias factor for the TLD used from 1972 to 1984 are shown in Table 8.3. The range for all facilities (except the plutonium finishing facilities) is estimated to be 0.8 to 1.2 (i.e., $\pm 20\%$). For the plutonium finishing facilities, the uncertainty in dosimeter response to plutonium x-rays and/or 59-keV ^{241}Am gamma radiation resulted in a best estimate of the range as 0.6 to 1.4 because of the complexity of neutron dosimetry, which is estimated to be about $\pm 50\%$. The

range for the different facilities for the whole body dose bias factor is shown in the Table 8.2. It should be noted that the deep dose for this dosimeter recorded a deep dose for beta radiation when, in fact, zero dose should have been determined. This over-response resulted in a deep dose contribution of about 15% and 30%, respectively, for uranium and ^{90}Sr radiation sources; but the relative significance of personnel deep dose from beta radiation is very low compared with the deep dose from photon radiation. However, because of the complexity of dose assessment for mixed fields of beta and photon radiation, the range for the fuel reprocessing facilities in Table 8.3 is increased from 0.7 to 1.3.

Over the years many changes in the TLD calibration and dose algorithm procedures have been made. Initially, the dosimeter was calibrated in-air; then, beginning in 1985, it was calibrated on-phantom. This practice results in a difference of about 10% for the calculated dose. The over-response of the dosimeter to low-energy photons was improved in 1987 with the implementation of an improved algorithm, and the TLD provided an accurate estimate of the neutron dose in the plutonium finishing facilities. However, the uncertainty in neutron dosimetry was the basis for increasing the range of the bias factor for the plutonium finishing facilities.

8.5 CONCLUSION

One of the goals of this report was to compare the recorded whole body dose with the actual tissue dose at 1000 mg/cm^2 and evaluate Hanford dosimeter performance over time. The evaluation was based on a review of the historical documentation, an intercomparison study of Hanford film dosimeters conducted during 1989, results of DOELAP performance testing of the TLD during 1989, as well as the professional experience of the authors extending throughout nearly 5 decades of Hanford personnel dosimetry.

As a result of the evaluation the recorded whole body dose, on average, for the vast majority of Hanford personnel is estimated to be nearly equivalent to the actual deep dose with the exception of plutonium facilities personnel, particularly prior to 1957. For higher-energy photon fields (greater than 100 keV), which comprise the majority of personnel exposure in Hanford facilities, it is estimated that the comparison between the recorded whole body dose and the actual deep dose for occupationally exposed personnel is

about $\pm 50\%$, $\pm 30\%$ and $\pm 20\%$, respectively, for the 1) two-element film dosimeter (1944-1956), 2) multi-element film dosimeters (1957-1971), and 3) TLD (1972-1989). Greater difference between the recorded whole body dose and the actual deep dose occurs in facilities where complex mixtures of beta and photon radiation or neutron radiation are present. Comparison of the recorded neutron dose with the actual dose equivalent with the TLD is estimated to be $\pm 50\%$. Greater uncertainty was evident with the NTA film used from 1950 through 1972. These estimates are appropriate for personnel whose occupational radiation exposure is significantly greater than the natural environmental background radiation. Dosimetry for the plutonium facilities personnel was particularly impacted because of the difficulties in measuring the deep dose from plutonium x-rays (16 keV to 17 keV) prior to the use of the multi-element film dosimeter in 1957 and because of the difficulty of measuring neutron dose prior to the use of the TLD in 1972.

Methods presented in the preceding sections could be used to improve the recorded whole body dose for plutonium facilities personnel. It should be noted that these personnel comprise a small percentage of the total personnel employed at Hanford since 1944 and would not be expected to significantly impact the evaluation of radiation risk for Hanford personnel using dose records. However, determination of the source of exposure for higher exposed personnel should be considered to ensure that no significant error in the analyses occurs.

8.6 FUTURE WORK

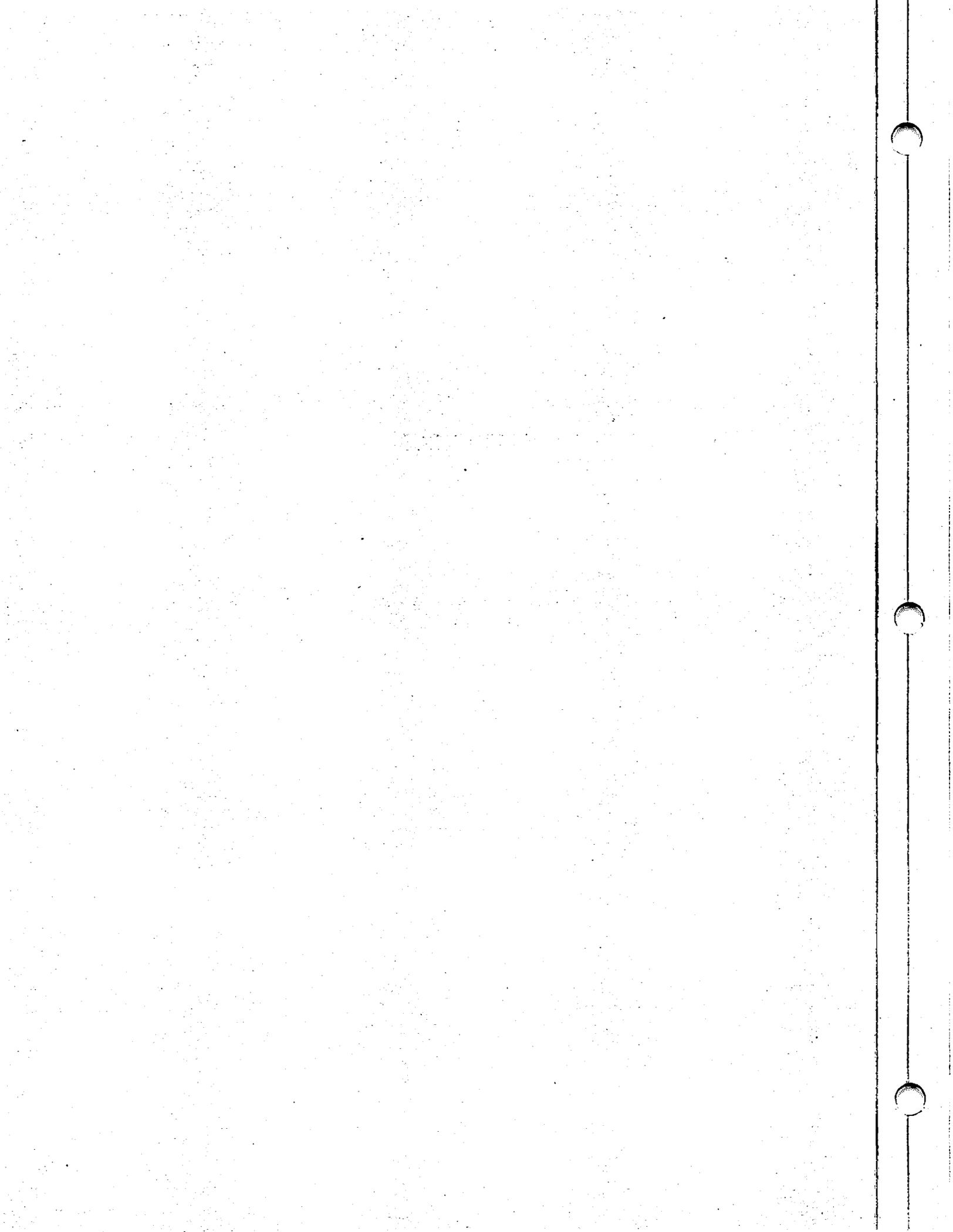
Efforts have been under way for many years to better document Hanford dosimetry practices in support of the Hanford Health and Mortality Study. An early summary was provided by Heid and Allen in 1974.^(a) Wilson provided an overview of radiation monitoring, portable instrument, radiological calibration, and internal and external dosimetry practices at Hanford (Wilson 1987). An overview of portable radiological instrumentation at Hanford was provided in 1989 (Howell et al. 1989).

(a) Heid, K. R., and H. W. Allen. "Input Data to the AEC Health and Mortality Study, Radiation Exposure Experience of Employees 1944 Through 1974." Internal report, dated December 31, 1974, Pacific Northwest Laboratory, Richland, Washington.

Recently, the National Academy of Sciences Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests developed methodology for assessing the overall bias and uncertainty in film dosimeter results, and applied this methodology to estimated doses for military and civilian personnel associated with atmospheric nuclear tests (NAS 1989). The approach required quantifying both the bias and uncertainty from each of several specified sources, and then combining the bias and uncertainty from the various sources to obtain an overall assessment. The NAS methodology uses a consistent analytical approach for evaluating each indentified source of bias and uncertainty as well as evaluating the combined effect of all sources.

There is interest in applying the NAS methodology to Hanford dosimetry in the future. However, there are several difficulties that will need to be addressed. One difficulty is that bias and uncertainty from many of the sources considered depend strongly on the energy and direction of the radiation. These have varied greatly in Hanford facilities over the years and are not specifically documented. Also, the NAS analysis did not address neutron radiation, which is significant for certain Hanford personnel. A possible approach is to restrict the NAS assessment to workers exposed primarily to high-energy photons, and to proceed by assessing each source for a range of energies and for two or three geometries. The overall assessment will require judgment regarding the actual distribution of energies and geometries that exist in various Hanford facilities.

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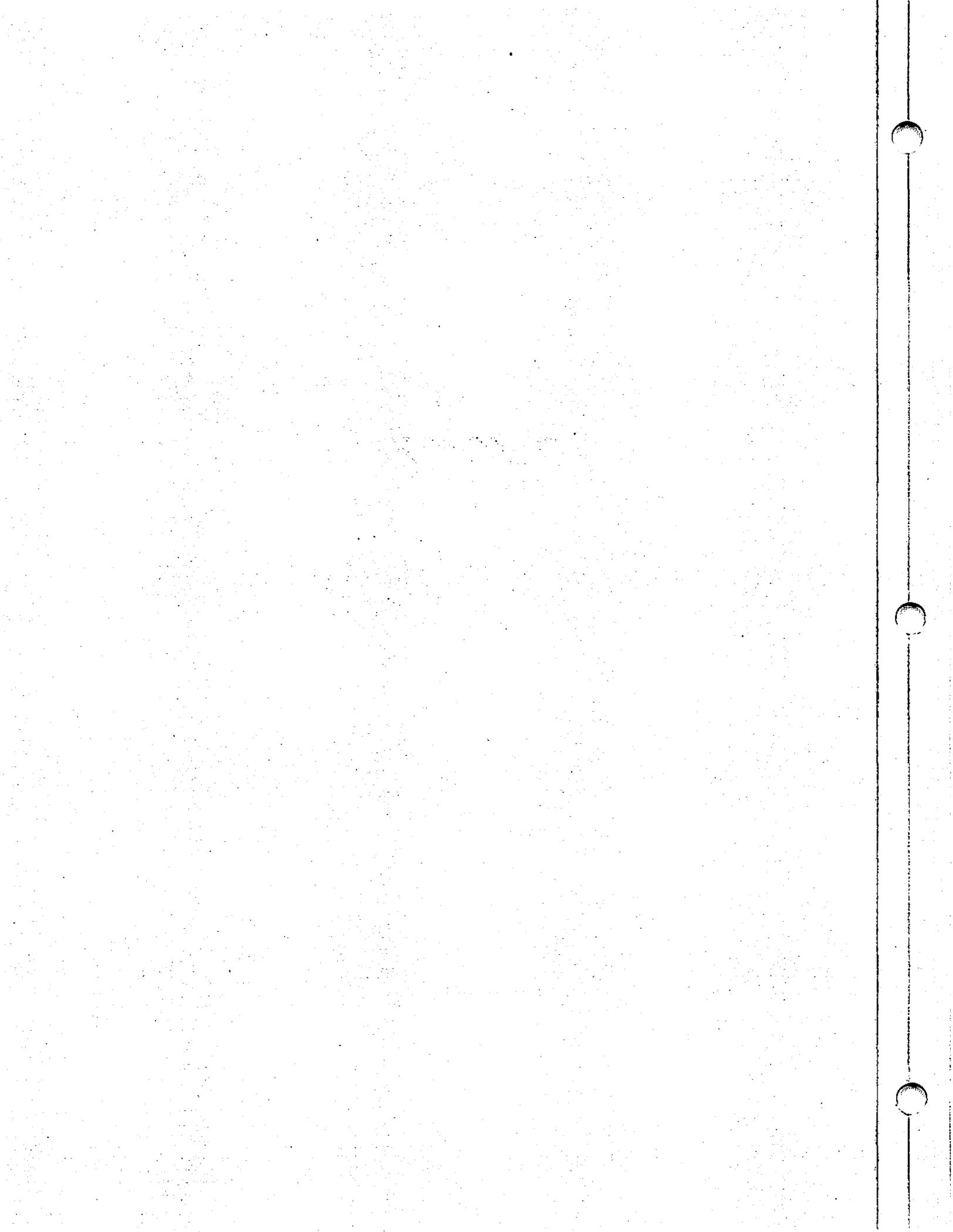
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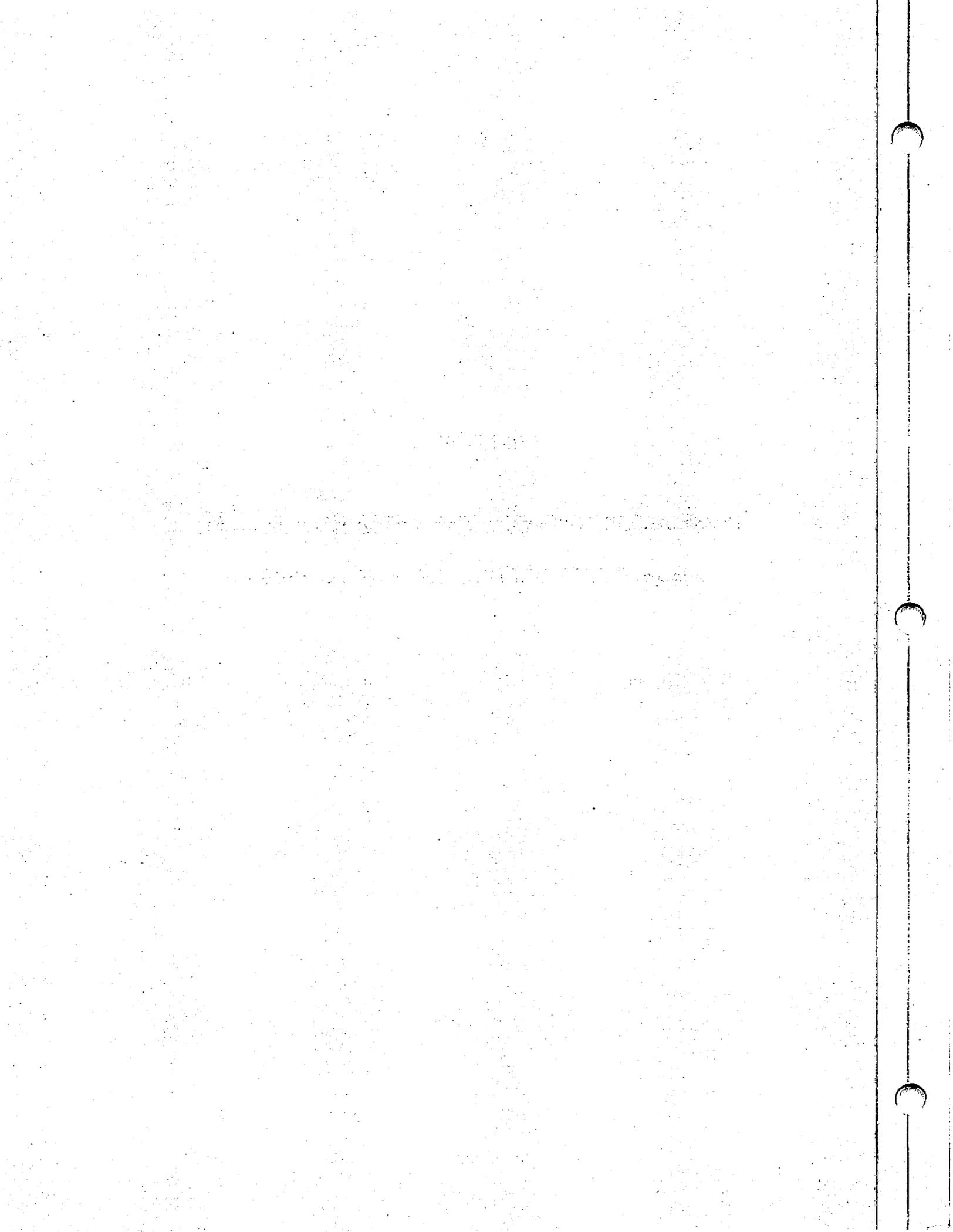
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APPENDIX A

DOSE ALGORITHM FOR THE BETA/PHOTON FILM

DOSIMETER USED FROM 1957 TO 1962



APPENDIX A

DOSE ALGORITHM FOR THE BETA/PHOTON FILM DOSIMETER USED FROM 1957 TO 1962

Wilson (1960) reported on a system for evaluating beta and gamma doses in mixed radiation fields. The dose algorithm for the beta/photon film dosimeter used from 1958 to 1962, as reported by Wilson, is described in this appendix.

GAMMA DOSE INTERPRETATION

Interpretation of gamma dose was accomplished by measuring the film density behind the thick silver shield and comparing it with a calibration curve. The calibration curve was established from a set of film exposed to 0-, 30-, 60-, 90-, 120-, 180-, 240-, 300-, 500-, 750-, and 1000-mrem doses and processed in the same batch as the unknown film for which dose interpretation was required. Additional calibration doses of 2000, 5000, and 10,000 mrem are included and processed with each set, but were not used in the routine program.

Immediate use of the calibrated film values was accomplished by plotting the dose-density relationships directly on graph paper and drawing the best fit by eye through the calibration levels from the zero intercept to 1000 mrem. Fast estimates of dose were made from this curve to determine the dose for any unusual film found in that particular batch. Hanford experience with the DuPont 502 emulsion showed very close agreement between estimates calculated manually and electronically.

All routine dose estimates were automatically calculated from parameters established for each calibration set by electronic data processing equipment. The dose for any density within the limits of the calibrations were calculated from the batch parameters.

The initial Hanford electronic computer program resulted in each calibration set being fitted to a linear curve by the least-squares method. This method was entirely adequate because the DuPont 502 emulsion response is essentially linear for the density values used in routine dose calculations.

When new computer equipment was installed at Hanford, that required reprogramming of the dose calculations, the program for electronic processing was developed to accept and fit net density values for each calibration dose fitted to a cubic equation. This change was made in anticipation of eventually using a more sensitive film emulsion where fitting to a cubic equation would give an "S" curve that more closely simulates the actual film response at low exposures for gamma radiation.

The basic cubic equation used for the calculation is:

$$\hat{\delta} = a_0 + a_1D + a_2D^2 + a_3D^3 \quad (\text{A.1})$$

where $\hat{\delta}$ is the best estimate of the density in optical density units for a given dose, D is the dose, and a_0, a_1, a_2, a_3 are the equation coefficients.

A calibration curve is established by fitting the raw data (measured densities for given doses) to the third-order equation where the sum of their differences about the calculated curve is a minimum. The function is minimized and the best values for the coefficients are calculated as follows:

$$G = \sum (\delta_i - \hat{\delta}_i)^2 \quad (\text{A.2})$$

and by setting partial derivatives to zero.

$$\frac{\partial G}{\partial a_j} = 0 \quad (\text{A.3})$$

from which four equations evolve that are used to determine the best values of the coefficients. The equations are as follows:

$$\sum a_0 + \sum a_1D + \sum a_2D^2 + \sum a_3D^3 = \sum \delta \quad (\text{A.4})$$

$$\sum a_0D + \sum a_1D^2 + \sum a_2D^3 + \sum a_3D^4 = \sum \delta D \quad (\text{A.5})$$

$$\sum a_0D^2 + \sum a_1D^3 + \sum a_2D^4 + \sum a_3D^5 = \sum \delta D^2 \quad (\text{A.6})$$

$$\sum a_0D^3 + \sum a_1D^4 + \sum a_2D^5 + \sum a_3D^6 = \sum \delta D^3 \quad (\text{A.7})$$

PLUTONIUM AND SOFT X-RAY DOSE EVALUATIONS

In addition to performing high-energy gamma dose evaluations, for certain work locations it was necessary to evaluate doses from low-energy x-rays. Specifically, radiations from plutonium are of greatest concern. Measurements through Hanford plutonium production hoods showed that a wide range of energies exists. These measurements indicated that it would be convenient to divide the radiation dose from plutonium into three effective energy groups of about 17 keV, 58 keV, and other radiations greater than approximately 200 keV.

By using the film densities found behind the open window, thick silver shields, and thin silver shields it is possible to determine the dose contribution from each of the three energy groups. This procedure is necessary because of the spectral response of the film. For energies of about 200 keV or greater, the ratio of true dose to dose obtained from the radium calibration curve is about 1. As the gamma energy decreases, the ratio decreases, reaching a minimum behind the thick silver shield at approximately 130 keV and at 45 keV for the open window area. The ratios for the open window are approximately 0.10 and 0.027 for the 17-keV and 58-keV energies, respectively. The true total dose is indeterminate when a mixture of these energies is present and only a single shield density measurement is available.

The density contribution of the three energy groups behind each of the shield areas can be represented by the following equations:

$$\delta_{ow} = a_{17}D_{17} + a_{60}D_{60} + a_{Ra}D_{Ra} \quad (A.8)$$

$$\delta_{t Ag} = b_{17}D_{17} + b_{60}D_{60} + b_{Ra}D_{Ra} \quad (A.9)$$

$$\delta_{Ag} = c_{17}D_{17} + c_{60}D_{60} + c_{Ra}D_{Ra} \quad (A.10)$$

where δ_{ow} = open window area density

$\delta_{t Ag}$ = thin silver shield density

δ_{Ag} = thick silver shield density

D_{17} = Dose ~17 keV group

D_{60} = Dose ~60 keV group

D_{Ra} = Dose equivalent to radium gamma

Coefficients a, b, and c are the slopes of density-dose curves for a given energy behind the three shields, i.e., b_{60} is the slope of the 60-keV group behind the thin silver shield. For these equations, it is assumed that the dose-density curves pass through the origin. Although this may not actually be the case each time, the average equation does make the intercept pass very nearly through zero.

There are several assumptions made in using these equations; first, the density for the high-energy radiations will be equal behind all shield areas. Error is introduced by this assumption, particularly in the open window, but on the conservative side. Because dose for high-energy radiations is based on the density behind the thick silver shield, any excess appearing in the open window will be included in the dose assigned to low-energy radiations. Second, it is assumed the 17-keV group x-rays will produce no density behind either silver shield and the 60-keV component will produce no density behind the thick silver shield. Error in this assumption appears only at the higher dose levels, 100 mR or more for the 60-keV component. Very few personnel exposures approach this dose for this energy component during the 4-week period of film use; therefore, coefficients $a_{Ra} = b_{Ra} = c_{Ra} = C$ and $b_{17} = c_{17} = c_{60} = \text{zero}$. Third, it is further assumed that no beta radiation is received by the dosimeters exposed to the lower energy radiations. Hanford's methods of operation tend to validate this third assumption.

Based on these assumptions, Equations (A.8), (A.9), and (A.10) can be modified as follows:

$$\delta_{ow} = a_{17}D_{17} + a_{60}D_{60} + CD_{Ra} \quad (\text{A.11})$$

$$\delta t \text{ Ag} = b_{60}D_{60} + CD_{Ra} \quad (\text{A.12})$$

$$\delta \text{Ag} = CD_{Ra} \quad (\text{A.13})$$

These equations are solved for the dose contributed by each of the three energy groups as follows:

$$D_{17} = \frac{1}{a_{17}} \left[\delta_{ow} - \delta \text{Ag} - \frac{a_{60}}{b_{60}} (\delta t \text{ Ag} - \delta \text{Ag}) \right] \quad (\text{A.14})$$

$$D_{60} = \frac{1}{b_{60}} (\delta t \text{ Ag} - \delta \text{ Ag}) \quad (\text{A.15})$$

$$D_{\text{Ra}} = \frac{1}{c} \delta \text{ Ag} \quad (\text{A.16})$$

The coefficients are quite variable depending upon the process parameters; however, the ratio of a_{60}/b_{60} is generally a constant that equals about 2.1. The values of these coefficients are obtained from calibrated film sets developed with each batch of personnel dosimeter film.

Experimental exposure studies have shown this method of dose evaluation to be reasonably reliable for variable percentages of each energy groups and for cases where the net density does not exceed 1.0. The evaluation can be made to within 15% of the known exposure.

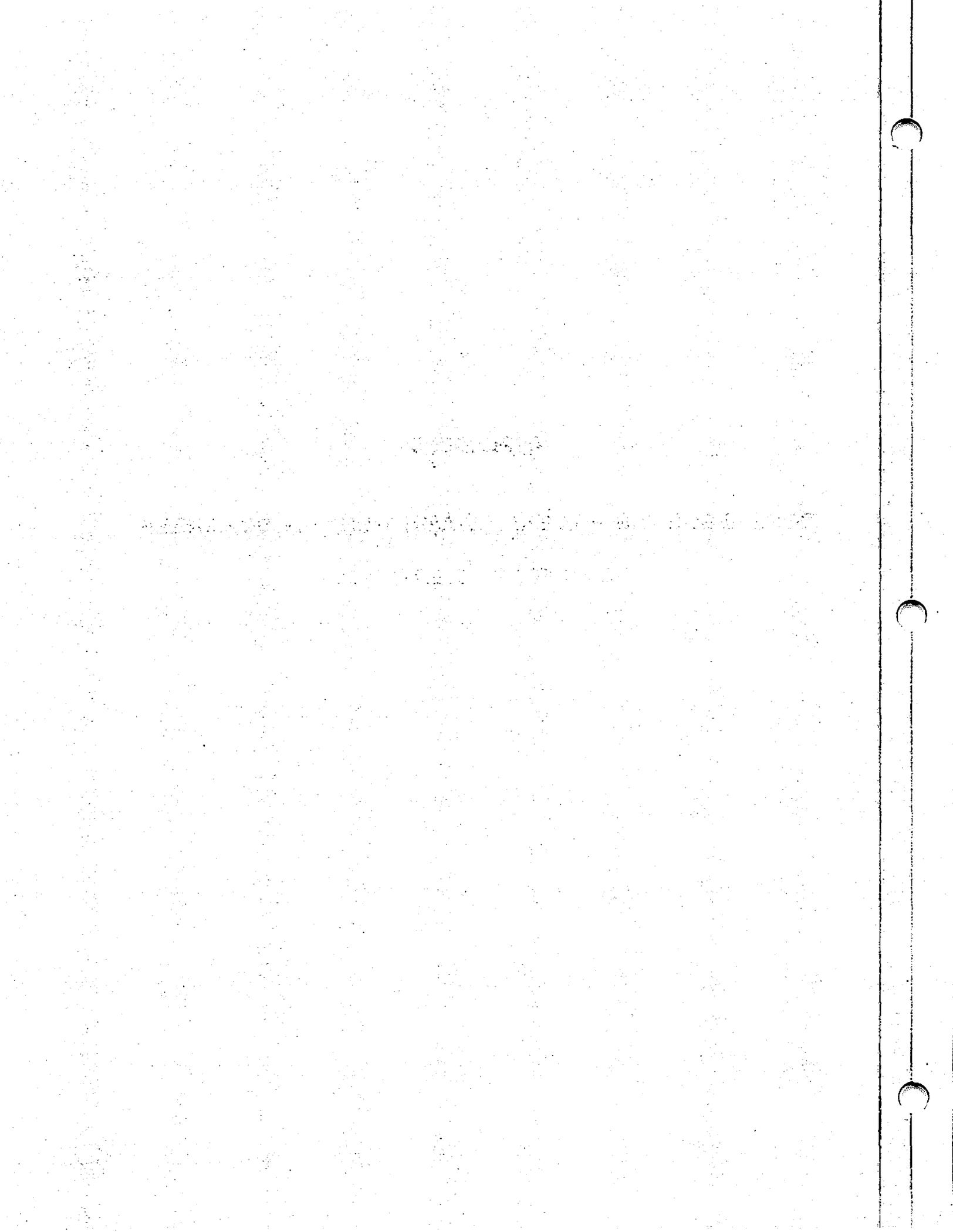
After determining the dose for each energy group, doses are assigned to each individual's exposure record. All dose contributed by the 60-keV group and higher-energy radiations is considered to be penetrating dose, but only 35% of the 17-keV component is considered to be penetrating dose. The total of all radiations is assigned as skin dose. Assignment of only 35% of the 17-keV group as penetrating dose is based on absorption studies and the assumption that the gonads are at a depth of 1 cm and are the critical organ.



APPENDIX B

DOSE ALGORITHM FOR THE BETA/PHOTON FILM DOSIMETER

USED FROM 1962 TO 1972



APPENDIX B

DOSE ALGORITHM FOR THE BETA/PHOTON FILM DOSIMETER USED FROM 1962 TO 1972

In 1962 Kocher reported on a system for measuring beta and gamma doses in mixed radiation fields (Kocher 1962). The dose algorithm for the beta/photon film dosimeter used from 1962 to 1972, as reported by Kocher, is described in this appendix.

For a radiation field consisting of beta particles of a single energy, photons of energies greater than 50 keV, and photons of a single energy less than 50 keV, the following set of equations defines the film density for each filter region:

$$D_{XTa} + D_{X'Ta} + D_{\beta Ta} = D_{Ta} \quad (B.1)$$

$$D_{XFe} + D_{X'Fe} + D_{\beta Fe} = D_{Fe} \quad (B.2)$$

$$D_{XP1} + D_{X'P1} + D_{\beta P1} = D_{P1} \quad (B.3)$$

$$D_{XOW} + D_{X'OW} + D_{\beta OW} = D_{OW} \quad (B.4)$$

where D_{XTa} = Density behind the tantalum filter due to photons of less than 50 keV

$D_{X'Ta}$ = Density behind the tantalum filter due to photons of greater than 50 keV

$D_{\beta Ta}$ = Density behind the tantalum filter due to beta radiation

D_{Ta} = Total density behind the tantalum filter.

As written Equations (B.1) through (B.4) have 12 unknowns, but, not all of these unknowns need to be defined to provide the desired dose interpretations.

The 980-mg/cm² tantalum filter is sufficient in density thickness to yield essentially zero density behind the tantalum filter for beta particles of energies less than about 3 MeV and for photon energies less than 50 keV, hence the following conditions:

$$D_{xTa} = 0 \quad (B.5)$$

$$D_{\beta Ta} = 0 \quad (B.6)$$

By experimental design, the density thickness of the iron and the plastic filters was chosen to provide equal film densities when the system was exposed to uranium-beta radiation under the following condition:

$$D_{\beta Fe} = D_{\beta P1} \quad (B.7)$$

Equal densities are produced behind the iron, plastic, and open window filters by photon radiation with energies greater than 50 keV by the following condition:

$$D_{xFe} = D_{xP1} = D_{OW} \quad (B.8)$$

Applying Conditions (B.5) and (B.6) to Equation (B.1) yields

$$D_{xTa} = D_{Ta} \quad (B.9)$$

Subtract Equations (B.2) and (B.3) and apply Conditions (B.7) and (B.8):

$$(D_{xP1} - D_{xFe}) = D_{P1} - D_{Fe} \quad (B.10)$$

Subtract Equations (B.3) and (B.4) and apply Condition (B.8):

$$(D_{\beta OW} - D_{\beta P1}) = D_{OW} - D_{P1} - (D_{OW} - D_{xP1}) \quad (B.11)$$

The absolute value of the terms in the parentheses in Equations (B.10) and (B.11) need not be determined. The difference between the terms is sufficient to define the dose values desired from this dosimetry system. For absolute accuracy in the use of Equations (B.10) and (B.11), calibrations should be performed with photon and beta radiations identical in energy spectra to those to be measured. As a practical dosimetry approach, the calibration at Hanford is carried out with uranium-beta radiations and with monoenergetic 17-keV x-rays from a K-fluorescent x-ray source. Such a

procedure introduces only nominal errors in the actual dose evaluations because the calibration sources used approximate the photon and beta spectra encountered at many work locations.

To interpret the dose from a film dosimeter that was exposed to beta, gamma, and x-ray radiations, the density behind each of the four filter areas is measured. At Hanford this density is measured and the identifying payroll number from the film is read with the Hanford mechanized densitometer that provides an electronic data processing machine card containing this information for machine processing. The machine processing, using appropriate calibration data, provided an evaluation of the radiation dose due to: 1) photons with energies between 50 keV and 2 MeV; 2) photons with energies between about 15 keV and 50 keV; 3) beta radiation assuming a beta energy spectrum similar to the beta spectrum emitted by natural uranium. The doses from the various radiations are interpreted as follows:

1. Photon Radiation Energies from About 50 keV to 2 MeV. The density behind the tantalum filter (D_{T_2}) is due primarily to the photon radiations with energies greater than 50 keV. This density can be directly related to the radiation dose by using an appropriate calibration curve and Equation (B.9).
2. Photon Radiation Energies from About 15 keV to 50 keV. The density behind the plastic filter (D_{P_1}) and the iron filter (D_{F_0}) areas results from photon radiation and beta radiation. The response characteristics of the filter system are chosen so that the photon radiation with energies greater than 50 keV and beta radiation produce equal densities behind each of these filters. For photons with energies less than 50 keV, the iron filter has a significantly higher absorption coefficient than the plastic filter; consequently, the difference in density between the plastic and iron filters ($D_{P_1} - D_{F_0}$) can be directly related to the low-energy photon dose by using a calibration curve constructed for photons with energies similar to those encountered by the dosimeter and Equation (B.10).
3. Beta Radiation. The density behind the open window (D_{OW}) and the plastic filter (D_{P_1}) areas results from photon and beta radiation. Photons with energies greater than 50 keV produced equal densities behind each of these filters. The difference in density between these two filters ($D_{OW} - D_{P_1}$) is a function of the low-energy photon dose (less than 50 keV) and the beta radiation (see Equation [B.11]). Because the low-energy photon dose is determined independently from the plastic and iron filter density difference, it is possible to correct the density difference observed between the open window and the plastic filter area for the low-energy

photon dose contributions by using an appropriate calibration correction curve. After this correction is made, the remaining density difference between the open window and the plastic filter may be calculated using a beta dose calibration curve and the beta dose may be determined using Equation (B.11).

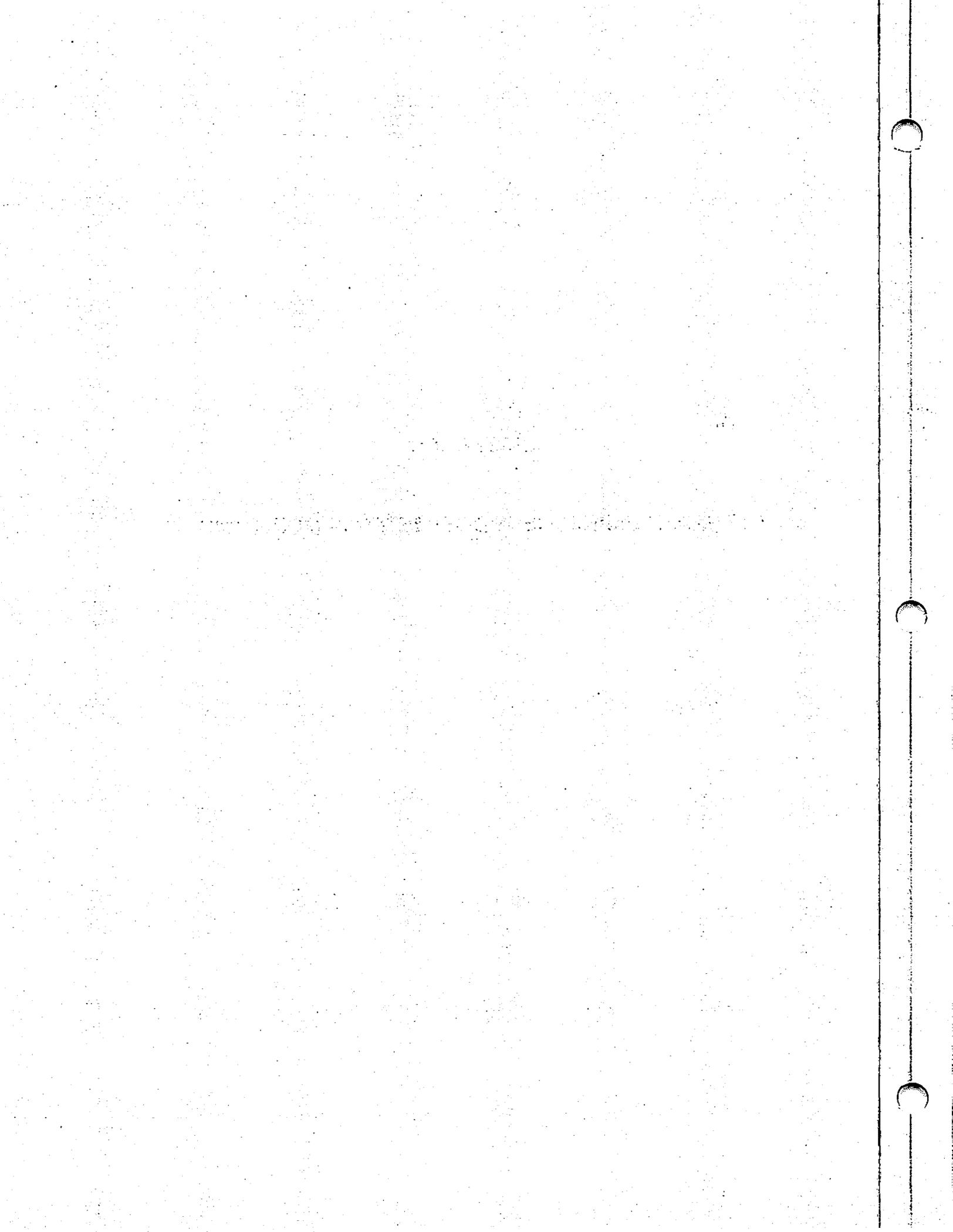
Field tests of the dosimeter filter system were conducted by exposing dosimeters to radium-gamma radiation, plutonium photon radiation, and uranium-beta radiation. Evaluation of the doses from the exposures yielded an accuracy of $\pm 10\%$ for each of the applied doses.

REFERENCE

Kocher, L. F. 1962. A Personnel Dosimeter Filter System for Measuring Beta and Gamma Doses in Mixed Radiation Fields. HW-71764, General Electric Company, Richland, Washington.

APPENDIX C

THERMOLUMINESCENT DOSIMETER ALGORITHMS



APPENDIX C

THERMOLUMINESCENT DOSIMETER ALGORITHMS

Thermoluminescent dosimeters were implemented at Hanford in 1971 with the basic dosimeter and in 1972 with the multipurpose dosimeter. The calibration sources, exposure geometry, and algorithm have been modified over the years. The procedures originally used with each dosimeter, the changes that involved both dosimeters, and the method of determining the recorded skin, whole body, and extremity dose components are discussed in this appendix.

BASIC DOSIMETER

A single calibration factor was determined for basic dosimeters using a radium source with exposures in-air. A set of 10 calibration and 10 blank (i.e., not exposed) dosimeters was used to determine the calibration constant. The calibration constant was termed C_0 and was calculated as follows:

$$C_0 = \frac{1000 \text{ mR}}{\text{Mean Value of Basic Calibration Dosimeters}} \quad (\text{C.1})$$

where 1000 represents the 1000 mR exposure in-air given to the basic calibration dosimeters. To calculate dose the observed chip count minus the average of the 10 blank dosimeters was multiplied by the calibration constant as follows:

$$\text{Penetrating Dose} = C_0(R(1) - B(1)) \quad (\text{C.2})$$

where C_0 is the calibration factor in millirem per chip signal described earlier for basic dosimeters, $R(1)$ is the response of the chip in position 1 $B(1)$ is the average of the basic blank dosimeters.

MULTIPURPOSE DOSIMETER

The multipurpose dosimeter had 5 chip positions that provided an estimate of the nonpenetrating, penetrating, fast neutron, and slow neutron dose components. A set of calibration dosimeters was used to determine the

calibration coefficients. Ten dosimeters were exposed in-air to ^{137}Cs and uranium, while six dosimeters were exposed to PuF_4 (on-phantom) and another six dosimeters were exposed in the middle stringer of the sigma pile. The mean response of these dosimeters, corrected for background determined from processing 10 blank dosimeters, was used to determine the calibration constants as follows:

- Non-Penetrating--Several aged uranium disk sources were used, each equipped with a specially designed exposure jig. The response of the dosimeter to the uranium source was assumed to be equal to one-half the response to an aged ^{90}Sr source encapsulated in 10-mil aluminum. To calibrate the dosimeter readout, 10 dosimeters were exposed to 4 rad each on the uranium sources (equal to 2 rad of ^{90}Sr).
- Penetrating--A radium source was used. Ten dosimeters were exposed in-air to calibrate the readout of personnel dosimeters.
- Slow Neutron--A graphite-moderated sigma pile was used. Six personnel dosimeters were simultaneously exposed in a reproducible geometry for calibration.
- Fast Neutron--A PuF_4 source was used. Six dosimeters were exposed on a polyethylene phantom for calibration.

At the beginning of each routine processing of Hanford personnel dosimeters, a set of calibration dosimeters was read through the automated reader. The results from the calibration dosimeters were used to interpret the readout from the actual personnel dosimeters in terms of dose equivalent.

The results of the calibration dosimeters were also used to determine several calibration constants (C1 through C7) as shown in Table C.1. These calibration constants were used to interpret the readout of each of the chips in terms of dose using the following dose algorithms are:

$$\frac{\text{Nonpenetrating (NP) Dose}}{\text{NP}} = (\text{R1} \cdot \text{C2}) - (\text{R2} \cdot \text{C3}) \text{ mrad} \quad (\text{C.3})$$

$$\frac{\text{Penetrating (P) Dose}}{\text{P}} = \text{R2} \cdot \text{C1} \text{ mrem} \quad (\text{C.4})$$

$$\frac{\text{Slow Neutron (SN) Dose}}{\text{SN}} = (\text{R3} - \text{R4}) \cdot \text{C4} \text{ mrem} \quad (\text{C.5})$$

$$\frac{\text{Fast Neutron (FN) (a) Dose}}{\text{FN}} = (\text{R4} \cdot \text{C5}) - (\text{R5} \cdot \text{C6}) - [(\text{R3} - \text{R4}) \cdot \text{C7}] \text{ mrem} \quad (\text{C.6})$$

TABLE C.1. Determination of Calibration Constants(a)

<u>Nonpenetrating Calibration</u>	<u>Penetrating Calibration</u>	<u>Slow Neutron Calibration</u>	<u>Fast Neutron Calibration</u>
R1 =	R1 =	R2 =	R2 =
R2 =	R2 =	R3 =	R3 =
	R4 =	R4 =	R4 =
$C2 = \frac{2000}{(R1-K2R2)}$	$C1 = \frac{1000}{R2}$	$C4 = \frac{50}{(R3-R4)}$ (b)	$K7 = \frac{R4-K6R5-K5 (R3-R4)}{1000}$ (c)
$C3 = C2 \times K2$	$K2 = \frac{R2}{R2}$	$K5 = \frac{R3-R4}{R3-R4}$	$C5 = \frac{1.0}{K7}$
	$K6 = \frac{R4}{R5}$ (c)		$C6 = K6 \times C5$
			$C6 =$
			$C7 = K5 \times C5$

(a) Ri where i = 1, 2, 3, 4, or 5 refers to chip position reading minus the respective background count for each position.

(b) Calibration exposures: Nonpenetrating = 2000 mrad (4000 mrad uranium)
 Penetrating = 1000 mrad
 Slow neutron = 50 mrem
 Fast neutron = 1000 mrem

(c) For 4-chip dosimeters, R2 would be used in place of R5.

CHANGES TO THE CALIBRATION SOURCES AND DOSE ALGORITHMS

Over the years the calibration sources, exposure geometry, and dose algorithms for both the basic and multipurpose dosimeters have been changed. A chronology of these changes is presented in Table C.2. The most significant changes are noted as follows:

- In 1977 a ¹³⁷Cs calibration source replaced the radium source.
- Beginning in 1978 a four-chip multipurpose dosimeter was implemented to allow for the use of a commercial reader system. This was done by eliminating position 5. Once the decision was made to return to the original Hanford automated reader systems, the original five-chip dosimeter design was reinstated. This process took several years to complete.
- In September 1984 all calibration exposures were changed to on-phantom.
- Beginning in September 1984 the average of all of the 1-R-dosed control dosimeters (i.e., 1T and 7T dosimeters) processed during a run was used to calculate calibration constants, instead of using a dedicated group of calibration dosimeters. In addition, the exposure in-air was transferred to a deep dose in tissue using a Roentgen-to-rem factor of 1.03. At this same time a backscatter

factor of 10% was used to extrapolate the exposure in-air to an expected response on-phantom.

PERSONNEL DOSE ASSESSMENT

Doses recorded in the official personnel files were assessed using the following formulation:

Whole Body Dose = Penetrating + Fast Neutron Dose + Slow Neutron Dose

Skin Dose = Nonpenetrating Dose + Whole Body Dose

Extremity Dose = Skin Dose + Finger Ring Dose

After January 1988 the following formulation was used:

Whole Body Dose = Deep Dose + Fast Neutron Dose + Slow Neutron Dose

Skin Dose = Shallow Dose + Fast Neutron Dose + Slow Neutron Dose

Extremity Dose = Skin Dose + Finger Ring Dose

TABLE C.2. Chronology of Hanford Thermoluminescent Dosimetry Changes

January 1971	Basic dosimeter use initiated.
January 1972	Multipurpose dosimeter use initiated.
January 1978	Five-chip multipurpose dosimeter changed to four-chip dosimeter to accommodate implementation of commercial reader system. Bar code label introduced at this time also.
January 1978	Commercial reader use initiated for routine processing for four-chip dosimeters.
March 1978	Commercial reader removed from service because heater was hitting plastic insert (instead of just the Teflon) occasionally. Pacific Northwest Laboratory (PNL) team formed to examine mechanical design of a commercial reader.
October 1978	Changed from 20-second readout to 12-second readout following evaluation to increase dosimeter throughput.
December 1978	Hanford Personnel Dosimetry Upgrade program presented to U.S. Department of Energy-Richland Operations Office. This program involved the building of new Hanford readers.

TABLE C.2. (contd)

July 1979	Implemented environmental subtraction of 0.18 mrem/day for penetrating dose component for basic and multipurpose dosimeters.
February 1980	New Hanford reader 2 used to process dosimeters.
November 1980	Original Hanford reader 1 retired from service.
January 1981	Changed from 12- to 20-second readout time to ensure complete readout of chip signal especially for TLD-600 chips.
March 1981	Large Hanford multipurpose dosimeter holder put into service. This was necessary to accommodate the new, larger security credential.
July 1981	New Hanford reader 3 put into service.
September 1981	Reader 2 taken out of service for upgrade.
October 1981	Reader 2 returned to service and renamed as reader 2A.
January 1983	Implemented use of glow curves as a routine diagnostic technique to determine "purity" of thermoluminescent signal and to use in subsequent enhancements to the dosimeter cleaning, annealing, and readout procedures.
March 1983	Adopted use of micro-probe digital temperature recorder to determine voltage settings for heater temperature. This replaced the use of the ice water and melting point of tin approach with associated extrapolation to 300°C.
March 1983	Installed silver-soldered thermocouple to heater on both readers. This improvement allows enhanced assurance of the control and monitoring of the actual temperature of the heater. The response time of the heater temperature control is much quicker because of the direct contact.
April 1983	Changed dosimeter chip readout order to positions 1, 2, 5, 4, and 3 from simply 1 through 5. This change minimizes "bleed over" of signal from one chip position to another by ordering the chip readout from the lowest to the highest potential signal.

TABLE C.2. (contd)

- May 1983 Implemented new readout times of 15 seconds for each TLD-700 chip position (i.e., 1, 2, and 5) and 27 seconds for each TLD-600 chip position (i.e., 3 and 4). This was done to reduce the significance of residual signals on TLD-600 chips and to reduce the number of rereads being conducted. Dosimeter rereads reduce the lifetime of the dosimeters as well as the readers and require greater processing cost by United States Testing Company, Inc.
- May 1983 Concluded tests of cleaning dosimeters with Freon®. Results of tests showed that this method would not clean the Hanford dosimeters as well as the existing acetic acid, water, and alcohol baths. Decided not to make any changes but to include a pre-read anneal to ensure that the chips were "dry" before readout. Any moisture remaining from the cleaning procedure could potentially act as a significant heat sink and result in inadequate heating of the chip(s).
- May 1983 Implemented use of pre-issue 16-hour and pre-read 30-minute anneal at 80°C for all multi-purpose dosimeters. This change was made to eliminate the presence of low-temperature traps that fade rapidly and, hopefully, to provide better long-term stability of the dosimeters. Los Alamos National Laboratory and Mound Laboratory employ a very similar pre-issue anneal, as did the Hanford system prior to 1978.
- July 1983 A routine quality control report to each contractor for each processing run was implemented.
- August 1983 Introduced concept of controlling reader sensitivities to plus or minus 5%, establishing chip sensitivity factors (CSFs), and matching the sensitivities of both readers.

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TABLE C.2. (contd)

August 1983 (contd)	Installed dedicated air-conditioning system for the automatic readers to better control the temperature of the electrical components and, hence, reduce the cause of reader variability. The internal light source was known to be associated with the temperature of the air circulated through readers and, as such, was not considered reliable enough to control the sensitivity of the readers.
November 1983	Introduced the changes to be made to adopt the new dosimetry changes involving the unique dosimeter identification, an improved environmental dose subtraction procedure using the actual dates of the previous and current dosimeter processing, contractor update of the dosimeter assignment changes using MAPPER, the cross-reference file at UST between dosimeter identification and assignment, etc.
November 1983	Installed oval-shaped bar code scanners on the Hanford readers. These scanners are much superior to the previous "dot" type scanners because they allow the scanners to see a larger area of the bar code and optical character labels. This modification reduced the error rate for bar code labels and allowed for implementation of the harder-to-read optical character reader (OCR) labels.
December 1983	Implemented use of a low-temperature anneal of Hanford dosimeters.
January 1984	Implemented dual label system involving a unique multipurpose dosimeter identification and assignment of dosimeters to specific individuals. Basic dosimeters were also uniquely identified, but not assigned to specific persons.
January 1984	Eliminated the use of the last of the four-chip dosimeters. Changed fast neutron criteria from: $(R4 - R2) > 0$ $\text{to } (R4 - R5) > 0$ to more correctly gamma compensate the neutron component of the dose.

TABLE C.2. (contd)

February 1984 Implemented changes to the integration of the internal light source involving a 2-second delay before data acquisition. This change eliminated the potential for an approximate 5% variability in the light source results because of timing differences between reader light integrations.

April 1984 Implemented CSFs into the routine assessment of dose, as follows:

$$R(i) = (R'(i) \times CSF(i)) - BK(i)$$
where $R'(i)$ refers to the raw count for each dosimeter position i , $CSF(i)$ is the chip sensitivity factor for position i of the dosimeter being processed, and $BK(i)$ is the average background count for each position determined from processing 10 basic and 10 multipurpose dosimeters. A different factor BK was used for basic and multipurpose dosimeters.

June 1984 Removed the backup Teflon wafer from new basic dosimeters following a review with Hanford contractors.

August 1984 Incorporated a change in the Hanford readers involving an increase in the operating voltage that minimized the dependence of the dosimeter results on variations in voltage. This change included a modification to the factor used to convert the reader output to the observed dosimeter reading. The factor was changed to provide the same dosimeter output as before the change.

September 1984 Implemented use of position sensitivity factor (PSF) for each dosimeter position based on relative count of average 1T control dosimeters to position 2. This is calculated as follows:

$$PSF(i) = \frac{(1TM(i) - OTM(i))}{(1TM(2) - TM(2))} \quad (C.8)$$

where 1TM and OTM are the adjusted chip counts.

TABLE C.2. (contd)

September 1984
(contd)

Implemented the determination of calibration coefficients for each run based on the average of control dosimeter results for each chip position using pre-established relationships. Calibration factors are determined based on the dosimeter response to ^{137}Cs gamma, ^{252}Cf fast neutron, and sigma pile slow neutron radiation. Several calibration factors are predicted from the 1T and 0T control dosimeters using the following formulation.

$$\begin{aligned} & \underline{1000 \text{ mrad } ^{90}\text{Sr (NBS Traceable)}} && \text{(C.9)} \\ & \text{NP1}' = 2.6 \times (1\text{TM}(1) - 0\text{TM}(1)) \\ & \text{NP2}' = 0.64 \times (1\text{TM}(2) - 0\text{TM}(2)) \end{aligned}$$

$$\begin{aligned} & \underline{2000 \text{ mrad U-nat (Hanford Site Specific)}} && \text{(C.10)} \\ & \text{NP1} = \text{NP1}' \times 0.53 \\ & \text{NP2} = \text{NP2}' \times 0.11 \end{aligned}$$

$$\begin{aligned} & \underline{1000 \text{ mR } ^{137}\text{Cs on Phantom}} && \text{(C.11)} \\ & \text{P1} = 1.10 \times (1\text{TM}(1) - 0\text{TM}(1)) \\ & \text{P2} = 1.10 \times (1\text{TM}(2) - 0\text{TM}(2)) \\ & \text{P4} = 1.10 \times (1\text{TM}(4) - 0\text{TM}(4)) \\ & \text{P5} = 1.10 \times (1\text{TM}(5) - 0\text{TM}(5)) \\ & \text{C}_1 = \frac{1000 \times 1.03}{\text{P2}} \text{ (mrem/reader count)} \\ & \text{K}_2 = \frac{\text{P1}}{\text{P2}}, \quad \text{K}_6 = \frac{\text{P4}}{\text{P5}} \end{aligned}$$

$$\begin{aligned} & \underline{50 \text{ mrem Sigma Pile}} && \text{(C.12)} \\ & \text{SN3} = 4.18 \times (1\text{TM}(3) - 0\text{TM}(3)) \\ & \text{SN4} = 2.16 \times (1\text{TM}(4) - 0\text{TM}(4)) \\ & \text{SN5} = 0.05 \times (1\text{TM}(5) - 0\text{TM}(5)) \\ & \text{C}_4 = \frac{50}{(\text{SN3} - \text{SN4})} \\ & \text{K}_5 = \frac{\text{SN4} - \text{K}_6 \text{SN5}}{(\text{SN3} - \text{SN4})} \end{aligned}$$

$$\begin{aligned} & \underline{1000 \text{ mrem } ^{252}\text{Cf Exposure On-Phantom (NBS Traceable)}} && \text{(C.13)} \\ & \text{FN3}' = 1.05 \times (1\text{TM}(3) - 0\text{TM}(3)) \\ & \text{FN4}' = 0.97 \times (1\text{TM}(4) - 0\text{TM}(4)) \\ & \text{FN5}' = 0.07 \times (1\text{TM}(5) - 0\text{TM}(5)) \end{aligned}$$

TABLE C.2. (contd)

September
(contd)

1000 mrem ²⁵²Cf Exposure On-Phantom (Hanford Site Specific) (C.14)

$$\begin{aligned} \text{FN3} &= 2.00 \times \text{FN3}' \\ \text{FN4} &= 1.87 \times \text{FN4}' \\ \text{FN5} &= 1.73 \times \text{FN5}' \end{aligned}$$

$$C_5 = \frac{1000}{(\text{FN4} - K_6 \text{FN5} - K_5 (\text{FN3} - \text{FN4}))}$$

$$\begin{aligned} C_6 &= K_6 C_5 \\ C_7 &= K_5 C_5 \end{aligned}$$

where, 1TM(i) and 0TM(i) represent the mean value of the adjusted chip counts for the multipurpose control dosimeters for the ith chip position, which numbers 1 through 5. The constants are based on predicting the respective chip signal that would be received from the calibration exposures on-phantom.

October 1985

Implemented procedure to subtract mean of basic (2T) and multipurpose (0T) control dosimeters from raw chip count prior to the use of any normalizing factors. This is illustrated as follows:

$$\text{Old} \quad R(i) = (R'(i) \times \text{CSF}(i) \times \text{PSF}(i) - \text{0T}(i)) \quad (\text{C.15})$$

$$\text{New} \quad R(i) = (R'(i) - \text{0T}(i)) \times \text{CSF}(i) \times \text{PSF}(i) \quad (\text{C.16})$$

where all variables are consistent with previous definitions.

January 1986

Implemented use of CSF for basic dosimeters. For new dosimeters, an individually determined factor was obtained by changing the acceptance procedure for basic dosimeters to 1000 mR of ¹³⁷Cs gamma radiation and 50 mrem of D₂O neutrons. The standard method was used to calculate a chip sensitivity factor based on the results of this single exposure. For the thousands of existing basic dosimeters, an average factor of 1.7 was assumed. This factor was determined by examining the ratio of the mean response of the 7T and 1T control dosimeters.

TABLE C.2. (contd)

January 1986
(contd)

Implementation of CSFs for basic dosimeters was necessary because the variability in the basic dosimeter chip population was continuing to increase with the introduction of any new dosimeters. The historical objective of tightly screening any new chips was impossible to maintain.

February 1986

Implemented use of reader sensitivity factor (RSF) by normalizing position 2 of the 1T control dosimeters to a reader count of 1500. This improved the consistency of calibration constants from processing to processing and is consistent with the concept of the CSFs. The factor is used in calculating the adjusted chip count, as follows:

$$R(i) = (R'(i) - OT(i)) \times CSF(i) \times PSF(i) \times RSF \quad (C.17)$$

where all variables are consistent with previous definitions.

January 1987

Initiated use of energy compensating algorithm for multipurpose dosimeters to participate in testing under the Department of Energy Laboratory Accreditation Program.

January 1987

Initiated use of new environmental correction formulation from naturally occurring environmental radiation as follows:

$$ENV_FAC = \frac{0.18 \times (1 - \exp^{-0.0008 \times Y1})}{0.0008} \quad (C.18)$$

where,

ENV_FAC = the dose in millirem contributed from background radiation.

0.18 = the expected dose in millirem per day expected from environmental radiation in the Hanford environs.

Y1 = is the number of days between the previous and current dosimeter processing.

0.0008 = is a factor to compensate for the fade of the thermoluminescent signal determined from a study to determine an appropriate formulation to be used to compensate for background radiation.

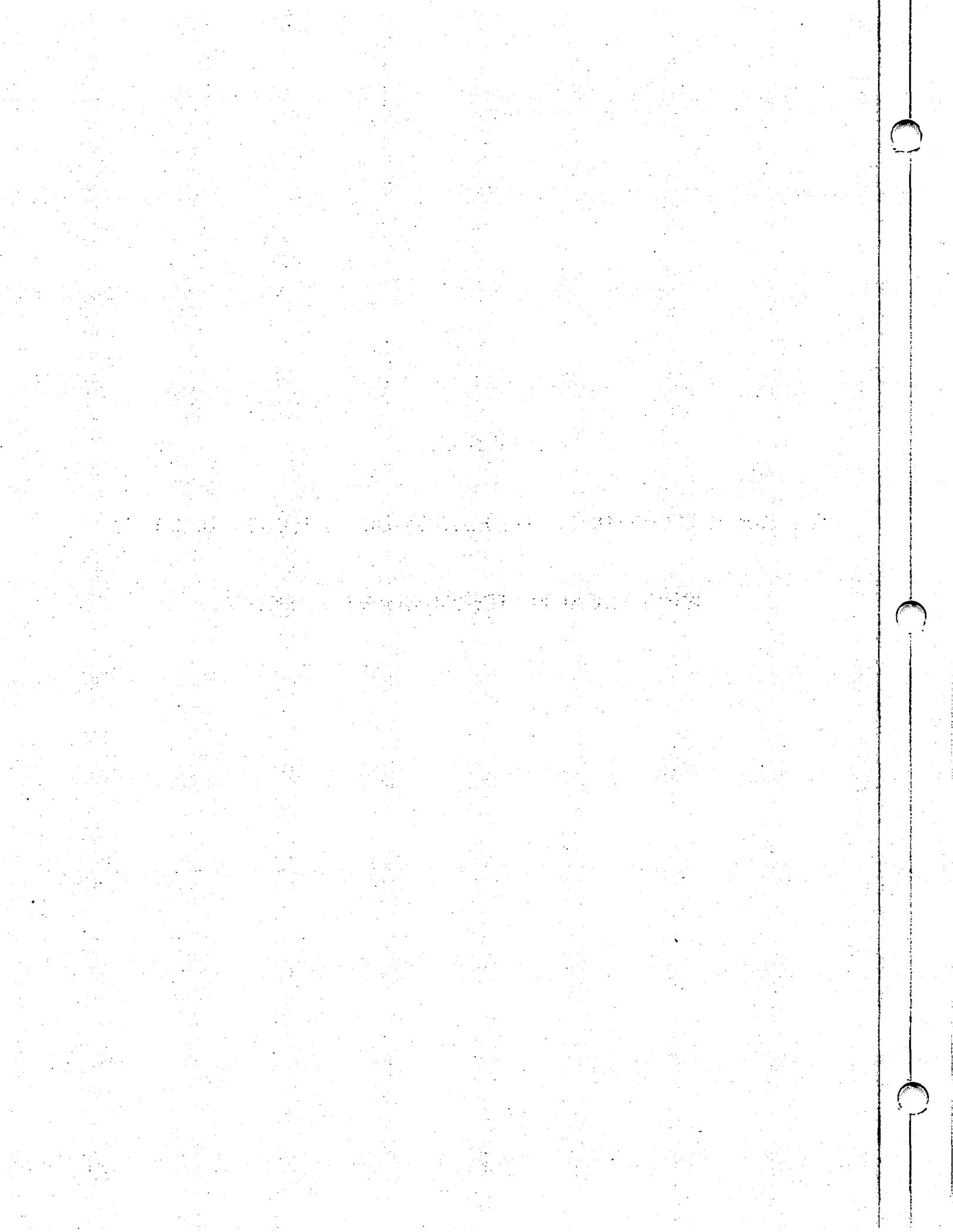
TABLE C.2. (contd)

June 1987	Initiated routine availability of area dosimeter to measure beta and gamma dose components in selected Hanford working environments.
October 1987	Initiated routine availability of beta/photon dosimeter for special field conditions.
January 1988	Initiated individually determined CSFs for basic dosimeters. Procedure identical for all new dosimeters.
October 1988	Site-wide dosimeter processing transferred to PNL. Upgraded Hanford readers were used to conduct the processing. These readers introduced electronic glow curve recording. These records were stored for 60 business days for use in resolving any questions regarding the processing.

APPENDIX D

DATA FOR BETA/PHOTON AND NEUTRON DOSIMETERS EVALUATED

DURING THE 1989 INTERCOMPARISON STUDY



APPENDIX D

DATA FOR BETA/PHOTON AND NEUTRON DOSIMETERS EVALUATED DURING THE 1989 INTERCOMPARISON STUDY

During 1989 an intercomparison study was conducted of all types of personnel film dosimeters used at Hanford from 1944 to the present. The data for beta/photon dosimeters is presented in Tables D.1 through D.4, which summarize dose evaluation data for the years 1944, 1945, 1957, and 1962, respectively. The data for film neutron dosimeters is presented in Tables D.5 and D.6.

TABLE D.1. 1944 Dose Evaluation

Dosimeter Number	Given ^(a) Exposure	Radiation Source	Film Density ^(b)			Dose		Whole Body Dose	Skin Dose
			Ag(1)	OW	Ag(2)	Gamma	Beta		
0	0	Control	240	239	238	0	0		
44001	40	18 keV	247	537	248	10	340		
44002	40	18 keV	246	532	248	10	330		
44003	40	18 keV	241	564	243	0	370	7	353
44004	80	18 keV	248	887	244	10	730		
44005	80	18 keV	243	871	245	0	710		
44006	80	18 keV	247	839	245	10	870	7	710
44007	180	18 keV	244	1580	245	0	2130		
44008	180	18 keV	243	1586	248	0	2130		
44009	180	18 keV	247	1702	250	10	2370	3	2213
44010	30	59 keV	250	820	252	10	850		
44011	30	59 keV	253	778	251	20	800		
44012	30	59 keV	280	842	280	20	880	17	853
44013	50	59 keV	253	1181	252	20	1170		
44014	50	59 keV	267	1240	258	30	1320		
44015	50	59 keV	253	1152	248	20	1150	23	1237
44016	80	59 keV	257	1787	256	20	2490		
44017	80	59 keV	278	1810	273	40	2540		
44018	80	59 keV	258	1792	255	20	2550	27	2553
44019	50	Sr-90	247	310	241	10	90		
44020	50	Sr-90	241	310	243	0	100		
44021	50	Sr-90	241	318	242	0	110	3	103
44022	240	Sr-90	250	583	250	10	380		
44023	240	Sr-90	243	530	241	0	340		
44024	240	Sr-90	241	544	241	0	350	3	353
44025	750	Sr-90	243	1243	245	0	1370		
44026	750	Sr-90	288	1280	283	30	1370		
44027	750	Sr-90	246	1220	241	10	1330	13	1370
44028	1000	Sr-90	246	1555	239	10	2040		
44029	1000	Sr-90	285	1810	246	10	2130		
44030	1000	Sr-90	243	1535	237	0	2020	7	2070
44031	50	Cs-137	287	309	279	50	0		
44032	50	Cs-137	286	305	282	50	0		
44033	50	Cs-137	284	313	282	50	20	50	57
44034	240	Cs-137	443	484	437	250	30		
44035	240	Cs-137	452	487	440	250	0		
44036	240	Cs-137	446	458	440	240	0	247	257
44037	750	Cs-137	889	920	882	750	20		
44038	750	Cs-137	893	936	888	750	30		
44039	750	Cs-137	899	934	871	750	20	750	773
44040	1000	Cs-137	1131	1210	1108	980	50		
44041	1000	Cs-137	1168	1230	1125	1010	40		
44042	1000	Cs-137	1164	1240	1130	1010	50	1000	1047
44043	50	Uranium	247	319	245	0	50		
44044	50	Uranium	244	322	247	0	50		
44045	50	Uranium	248	318	244	0	50	0	50
44046	240	Uranium	248	450	245	0	240		
44047	240	Uranium	246	485	245	0	260		
44048	240	Uranium	245	457	244	0	250	0	250
44049	750	Uranium	258	910	254	20	740		
44050	750	Uranium	275	915	258	40	730		
44051	750	Uranium	255	950	253	0	800	20	777
44052	1000	Uranium	288	1110	254	30	1020		
44053	1000	Uranium	258	1080	255	20	980		
44054	1000	Uranium	257	1100	255	20	1020	23	1023

(a) Exposure in mR for photon radiation and mrad for beta radiation sources.

(b) Ag refers to silver filtration; Ag(1) and Ag(2) refer to first and second readings, respectively; OW refers to readings behind the open window.

TABLE D.2. 1945 Dose Evaluation

Dosimeter Number	Given ^(a) Exposure	Radiation Source	Film Density ^(b)			Dose		Whole Body Dose	Skin Dose
			Ag(1)	OW	Ag(2)	Gamma	Beta		
0	0	Control	236	238	237	0	0		
45001	40	18 keV	244	587	248	0	430		
45002	40	18 keV	245	555	248	0	390		
45003	40	18 keV	250	542	248	0	370	0	397
45004	80	18 keV	250	859	247	0	750		
45005	80	18 keV	247	892	248	0	800		
45006	80	18 keV	247	959	247	0	910	0	820
45007	160	18 keV	248	1813	245	0	2200		
45008	160	18 keV	248	1639	244	0	1940		
45009	160	18 keV	244	1577	248	0	1850	0	1997
45010	30	59 keV	248	778	249	0	840		
45011	30	59 keV	248	781	252	0	850		
45012	30	59 keV	252	759	248	20	820	7	643
45013	50	59 keV	254	1151	250	20	1190		
45014	50	59 keV	258	1199	258	30	1250		
45015	50	59 keV	257	1136	254	30	1120	27	1213
45016	80	59 keV	259	1837	285	30	2220		
45017	80	59 keV	289	1893	284	40	2290		
45018	80	59 keV	284	1852	280	30	2240	33	2283
45019	50	Sr-90	244	308	248	0	80		
45020	50	Sr-90	247	311	244	0	90		
45021	50	Sr-90	244	308	240	0	80	0	83
45022	240	Sr-90	245	528	242	0	360		
45023	240	Sr-90	243	528	242	0	360		
45024	240	Sr-90	248	531	241	0	360	0	380
45025	750	Sr-90	242	1170	254	0	1230		
45026	750	Sr-90	243	1214	241	0	1300		
45027	750	Sr-90	248	1148	242	0	1190	0	1240
45028	1000	Sr-90	245	1531	243	0	1780		
45029	1000	Sr-90	245	1579	243	0	1850		
45030	1000	Sr-90	247	1510	239	0	1740	0	1790
45031	50	Cs-137	283	286	280	50	0		
45032	50	Cs-137	288	288	285	50	0		
45033	50	Cs-137	283	284	282	50	0	50	50
45034	240	Cs-137	457	458	437	230	0		
45035	240	Cs-137	457	459	452	230	0		
45036	240	Cs-137	453	481	452	220	0	227	227
45037	750	Cs-137	914	937	904	740	30		
45038	750	Cs-137	913	918	901	740	0		
45039	750	Cs-137	902	913	908	730	0	737	747
45040	1000	Cs-137	1155	1183	1119	970	40		
45041	1000	Cs-137	1185	1187	1150	990	30		
45042	1000	Cs-137	1158	1194	1188	980	50	980	1020
45043	50	Uranium	245	287	246	0	80		
45044	50	Uranium	245	278	241	0	40		
45045	50	Uranium	245	282	243	0	50	0	50
45046	240	Uranium	248	419	244	0	230		
45047	240	Uranium	243	410	244	0	220		
45048	240	Uranium	243	435	246	0	260	0	237
45049	750	Uranium	257	837	259	30	700		
45050	750	Uranium	257	840	257	30	700		
45051	750	Uranium	281	923	281	30	800	30	763
45052	1000	Uranium	280	1105	288	30	1110		
45053	1000	Uranium	259	991	280	30	880		
45054	1000	Uranium	259	1008	281	30	890	30	990

(a) Exposure in mR for photon radiation and mrad for beta radiation sources.

(b) Ag refers to silver filtration; Ag(1) and Ag(2) refer to first and second readings, respectively; OW refers to readings behind the open window.

TABLE D.3. 1957 Dose Evaluation

Dosimeter Number	Given Exposure	Radiation Source	Film Density ^(a)				Dose			Whole Body Dose	Skin Dose
			A _g	0W	Al	A _g	Gamma	Beta	X-ray		
0	0	Control	237	241	240	237	0	0	0		
57001	40	18 keV	243	548	257	387	0	0	40		
57002	40	18 keV	244	548	258	388	0	0	40		
57003	40	18 keV	248	559	258	379	0	0	40		
57004	40	18 keV	248	583	261	380	0	0	40		
57005	40	18 keV	241	554	258	388	0	0	40	14	40
57008	80	18 keV	242	832	270	483	0	80	70		
57007	80	18 keV	243	820	291	487	0	0	80		
57008	80	18 keV	244	857	270	507	0	0	80		
57009	80	18 keV	245	881	274	505	0	0	80		
57010	80	18 keV	244	893	276	517	0	0	80	27	94
57011	160	18 keV	243	1547	302	717	0	240	150		
57012	160	18 keV	244	1533	305	743	0	110	150		
57013	160	18 keV	242	1547	294	758	0	40	160		
57014	160	18 keV	248	1587	307	780	0	50	170		
57015	160	18 keV	247	1617	313	786	0	90	170	56	288
57016	30	59 keV	254	752	559	711	20	0	50		
57017	30	59 keV	253	753	573	766	20	0	70		
57018	30	59 keV	257	777	579	789	20	0	70		
57019	30	59 keV	259	798	604	781	30	0	80		
57020	30	59 keV	260	822	614	803	30	0	70	46	88
57021	50	59 keV	267	1198	816	1141	30	0	110		
57022	50	59 keV	263	1181	821	1167	30	0	120		
57023	50	59 keV	269	1231	840	1267	40	0	150		
57024	50	59 keV	270	1231	852	1196	40	0	120		
57025	50	59 keV	274	1277	864	1238	40	0	130	80	162
57026	80	59 keV	284	1863	1178	1602	50	0	150		
57027	80	59 keV	278	1799	1190	1808	50	0	220		
57028	80	59 keV	284	1842	1215	1939	50	0	250		
57029	80	59 keV	283	1884	1275	1920	50	0	230		
57030	80	59 keV	280	1883	1277	1932	50	0	230	126	268
57031	50	Sr-90	240	300	254	258	0	70	0		
57032	50	Sr-90	239	295	249	252	0	70	0		
57033	50	Sr-90	238	295	250	253	0	70	0		
57034	50	Sr-90	240	300	252	254	0	80	0		
57035	50	Sr-90	241	302	253	257	0	80	0	0	74
57036	240	Sr-90	240	518	294	310	0	170	10		
57037	240	Sr-90	240	494	287	301	0	330	0		
57038	240	Sr-90	240	507	292	309	0	270	10		
57039	240	Sr-90	239	528	300	311	0	360	0		
57040	240	Sr-90	242	537	297	310	0	380	0	1	308
57041	750	Sr-90	248	1153	408	449	0	1000	20		
57042	750	Sr-90	248	1112	397	438	0	970	10		
57043	750	Sr-90	243	1114	398	452	0	900	20		
57044	750	Sr-90	242	1200	433	487	0	1070	10		
57045	750	Sr-90	248	1221	419	488	0	1080	20	6	1028
57046	1000	Sr-90	243	1507	467	524	0	1400	20		
57047	1000	Sr-90	243	1414	448	504	0	1280	20		
57048	1000	Sr-90	241	1363	435	498	0	1210	20		
57049	1000	Sr-90	241	1487	477	518	0	1420	10		
57050	1000	Sr-90	243	1527	468	534	0	1390	20	6	1358

TABLE D.3. (contd)

Dosimeter Number	Given Exposure	Radiation Source	Film Density ^(a)				Dose			Whole Body Dose	Skin Dose
			Ag	OW	Al	Age	Gamma	Beta	X-ray		
57051	50	Cs-137	280	285	287	285	50	0	0		
57052	50	Cs-137	283	285	287	284	50	0	0		
57053	50	Cs-137	284	286	286	283	50	0	0		
57054	50	Cs-137	282	285	287	285	50	0	0		
57055	50	Cs-137	280	280	285	282	50	0	0	50	50
57056	240	Cs-137	443	461	457	448	240	0	0		
57057	240	Cs-137	446	454	461	442	240	0	0		
57058	240	Cs-137	443	455	458	447	240	0	0		
57059	240	Cs-137	447	455	458	444	240	0	0		
57060	240	Cs-137	444	455	461	445	240	0	0	240	240
57061	750	Cs-137	898	923	939	902	760	0	0		
57062	750	Cs-137	867	902	932	898	720	0	0		
57063	750	Cs-137	882	902	930	901	720	0	0		
57064	750	Cs-137	859	877	898	864	710	0	0		
57065	750	Cs-137	881	893	911	883	720	0	0	726	726
57066	1000	Cs-137	1114	1138	1160	1084	1010	0	0		
57067	1000	Cs-137	1084	1123	1170	1130	970	0	0		
57068	1000	Cs-137	1109	1148	1192	1155	1000	0	0		

(a) Ag refers to film readings behind thick silver filter; OW to readings behind the open window; Al to readings behind the aluminum filter; Age to readings behind the thin silver filter.

TABLE D.4. 1962 Dose Evaluation

Dosimeter Number	Given Exposure	Radiation Source	Film Density ^(a)				Dose			Whole Body Dose	Skin Dose
			OV	PI	Fa	Ta	Gamma	X-Ray	Beta		
00000	0	Control	235	239	242	238	0	0	0		
82001	40	18 keV	537	507	398	241	0	40	0		
82002	40	18 keV	544	509	377	242	0	40	0		
82003	40	18 keV	552	518	384	242	0	40	0		
82004	40	18 keV	554	524	403	242	0	40	0		
82005	40	18 keV	558	524	401	241	0	40	0	14	40
82006	80	18 keV	828	780	532	240	0	70	0		
82007	80	18 keV	841	782	489	241	0	90	0		
82008	80	18 keV	877	788	508	241	0	90	0		
82009	80	18 keV	882	759	540	242	0	70	180		
82010	80	18 keV	892	821	557	243	0	80	0	38	80
82011	180	18 keV	1585	1415	858	247	0	150	0		
82012	180	18 keV	1555	1370	760	248	0	180	70		
82013	180	18 keV	1641	1448	800	249	0	180	110		
82014	180	18 keV	1658	1518	900	262	0	180	0		
82015	180	18 keV	1680	1524	918	264	0	180	0	55	194
82016	30	59 keV	784	795	778	289	50	10	0		
82017	30	59 keV	795	794	784	283	40	10	0		
82018	30	59 keV	815	811	790	284	40	10	0		
82019	30	59 keV	810	819	804	293	50	0	0		
82020	30	59 keV	825	824	808	290	50	10	0	48	52
82021	50	59 keV	1184	1191	1155	314	80	10	0		
82022	50	59 keV	1201	1199	1144	307	70	20	0		
82023	50	59 keV	1208	1199	1180	310	70	10	0		
82024	50	59 keV	1241	1255	1228	328	90	10	0		
82025	50	59 keV	1282	1287	1238	328	90	20	0	85	94
82026	80	59 keV	1888	1888	1815	367	130	20	0		
82027	80	59 keV	1905	1879	1789	350	110	30	0		
82028	80	59 keV	1984	1973	1858	354	120	40	0		
82029	80	59 keV	1988	2007	1948	382	150	20	0		
82030	80	59 keV	2008	2020	1960	371	130	20	0	137	154
82031	50	Sr-90	293	288	273	239	0	0	100		
82032	50	Sr-90	294	282	289	239	0	0	120		
82033	50	Sr-90	294	284	289	239	0	0	110		
82034	50	Sr-90	287	259	287	236	0	0	110		
82035	50	Sr-90	290	259	287	236	0	0	120	0	112
82036	240	Sr-90	485	343	373	241	0	0	380		
82037	240	Sr-90	475	331	353	237	0	0	430		
82038	240	Sr-90	489	329	348	239	0	0	420		
82039	240	Sr-90	483	341	368	237	0	0	380		
82040	240	Sr-90	492	345	378	237	0	0	440	0	410
82041	750	Sr-90	1020	570	654	241	0	0	1710		
82042	750	Sr-90	1082	548	618	244	0	0	2380		
82043	750	Sr-90	1051	547	593	242	0	0	2230		
82044	750	Sr-90	1078	594	670	245	0	0	2020		
82045	750	Sr-90	1101	584	674	245	0	0	2370	0	2138
82046	1000	Sr-90	1283	681	825	244	0	0	3540		
82047	1000	Sr-90	1348	851	748	246	0	0	5400		
82048	1000	Sr-90	1323	844	725	244	0	0	5000		
82049	1000	Sr-90	1338	888	792	240	0	0	4440		
82050	1000	Sr-90	1451	707	824	240	0	0	6570	0	4990

TABLE D.4. (contd)

Dosimeter Number	Given Exposure	Radiation Source	Film Density ^(a)				Dose			Whole Body Dose	Skin Dose
			OW	PI	Fe	Ta	Gamma	X-Ray	Beta		
82061	50	Cs-137	284	286	286	288	50	0	0		
82062	50	Cs-137	281	283	285	288	50	0	0		
82063	50	Cs-137	282	285	291	290	50	0	0		
82064	50	Cs-137	281	285	290	292	50	0	0		
82065	50	Cs-137	283	285	289	293	50	0	0	50	50
82066	240	Cs-137	444	440	448	472	240	0	0		
82067	240	Cs-137	449	442	442	487	230	0	30		
82068	240	Cs-137	455	458	457	481	250	0	0		
82069	240	Cs-137	445	448	443	470	240	0	0		
82080	240	Cs-137	445	445	449	471	240	0	0	242	248
82081	750	Cs-137	878	879	890	974	760	0	0		
82082	750	Cs-137	858	860	874	940	730	0	0		
82083	750	Cs-137	882	870	868	950	740	0	0		
82084	750	Cs-137	870	870	873	973	760	0	0		
82085	750	Cs-137	880	882	878	971	760	0	0	7 50	7 50
82086	1000	Cs-137	1086	1098	1103	1235	1000	0	0		
82087	1000	Cs-137	1100	1090	1094	1203	970	0	40		
82088	1000	Cs-137	1084	1092	1095	1224	990	0	0		
82089	1000	Cs-137	1098	1103	1104	1259	1020	0	0		
82070	1000	Cs-137	1102	1113	1114	1270	1030	0	0	1005	1010
82071	50	Uranium	284	248	251	238	0	0	80		
82072	50	Uranium	288	248	250	238	0	0	80		
82073	50	Uranium	289	252	258	239	0	0	80		
82074	50	Uranium	273	255	258	241	0	0	80		
82075	50	Uranium	287	250	254	238	0	0	80	0	80
82076	240	Uranium	384	288	297	239	0	0	280		
82077	240	Uranium	358	285	297	243	0	0	240		
82078	240	Uranium	360	280	298	241	0	0	280		
82079	240	Uranium	382	285	298	239	0	0	250		
82080	240	Uranium	380	283	297	240	0	0	250	0	252
82081	750	Uranium	685	388	421	251	0	0	770		
82082	750	Uranium	688	391	423	252	0	0	820		
82083	750	Uranium	642	383	425	254	0	0	710		
82084	750	Uranium	675	390	431	253	0	0	790		
82085	750	Uranium	657	390	427	250	0	0	730	0	784
82086	1000	Uranium	722	420	480	255	0	0	850		
82087	1000	Uranium	783	418	459	251	0	0	1030		
82088	1000	Uranium	784	409	482	252	0	0	1070		
82089	1000	Uranium	784	425	470	253	0	0	1000		
82090	1000	Uranium	798	430	484	257	0	0	1130	0	1018

(a) OW refers to readings behind the open window; PI to readings behind the plastic filter; Fe to readings behind the iron filter; Ta to readings behind the tantalum filter.

TABLE D.6. Prototype Rhodium Film Dosimeter Neutron Response

Dosimeter Number	Given (a) Dose	Radiation (b) Source	Film Density (c)		
			Rh+Cd	Rh+Sn	Sn+SS
00000	0	0	236	235	233
00001	1.07	Cf252U	281	283	280
00002	1.07	Cf252U	281	281	274
00003	1.07	Cf252U	278	276	275
00004	1.07	Cf252U	279	279	277
00005	1.18	CF252M	493	493	388
00006	1.18	Cf252M	506	504	387
00007	1.18	Cf252M	504	501	392
00008	1.18	Cf252M	496	496	388
00013	1.18	Cf252M	518	515	400
00014	1.18	Cf252M	520	513	397
00009	0.051	Sigma	513	453	258
00010	0.051	Sigma	525	460	258
00011	0.050	Sigma	522	464	263
00012	0.050	Sigma	533	463	263

- (a) Given dose in rem.
 (b) Cf252U = a bare Cf252 source exposure;
 Cf252M = a Cf252 source moderated with D₂O in a cadmium shield;
 sigma pile = the middle stringers of the sigma pile.
 (c) Rh+Cd = combination rhodium and cadmium filter;
 Rh+Sn = combination rhodium and tin filter;
 Sn+SS = combination tin and stainless steel filter.

TABLE D.5. Hanford Nuclear Track Emulsion Neutron Response

<u>Dosimeter Number</u>	<u>Given^(a) Dose</u>	<u>Radiation^(b) Source</u>	<u>T/25^(c)</u>	<u>Mean</u>	<u>Standard Deviation</u>
00000	0	0	1		
58001	1.07	Cf252U	60		
58002	1.07	Cf252U	45		
58003	1.07	Cf252U	58		
58004	1.07	Cf252U	65		
58013	1.07	Cf252U	71		
58014	1.07	Cf252U	70		
58015	1.07	Cf252U	45		
58016	1.07	Cf252U	59	58.375	9.13
58005	1.18	Cf252M	71		
58006	1.18	Cf252M	80		
58007	1.18	Cf252M	52		
58008	1.18	Cf252M	54		
58017	1.18	Cf252M	66		
58018	1.18	Cf252M	57		
58019	1.18	Cf252M	61		
58020	1.18	Cf252M	66	63.375	9.35
58009	0.051	Sigma	3		
58010	0.051	Sigma	1		
58011	0.051	Sigma	2		
58012	0.051	Sigma	2		
58021	0.051	Sigma	1		
58022	0.051	Sigma	1		
58023	0.051	Sigma	2		
58024	0.051	Sigma	3	1.875	0.835

(a) Given dose in rem.

(b) Cf252U = a bare Cf252 source exposure;
 Cf252M = a Cf252 source moderated with D₂O in a cadmium shield;
 sigma pile = the middle strings of the sigma pile.

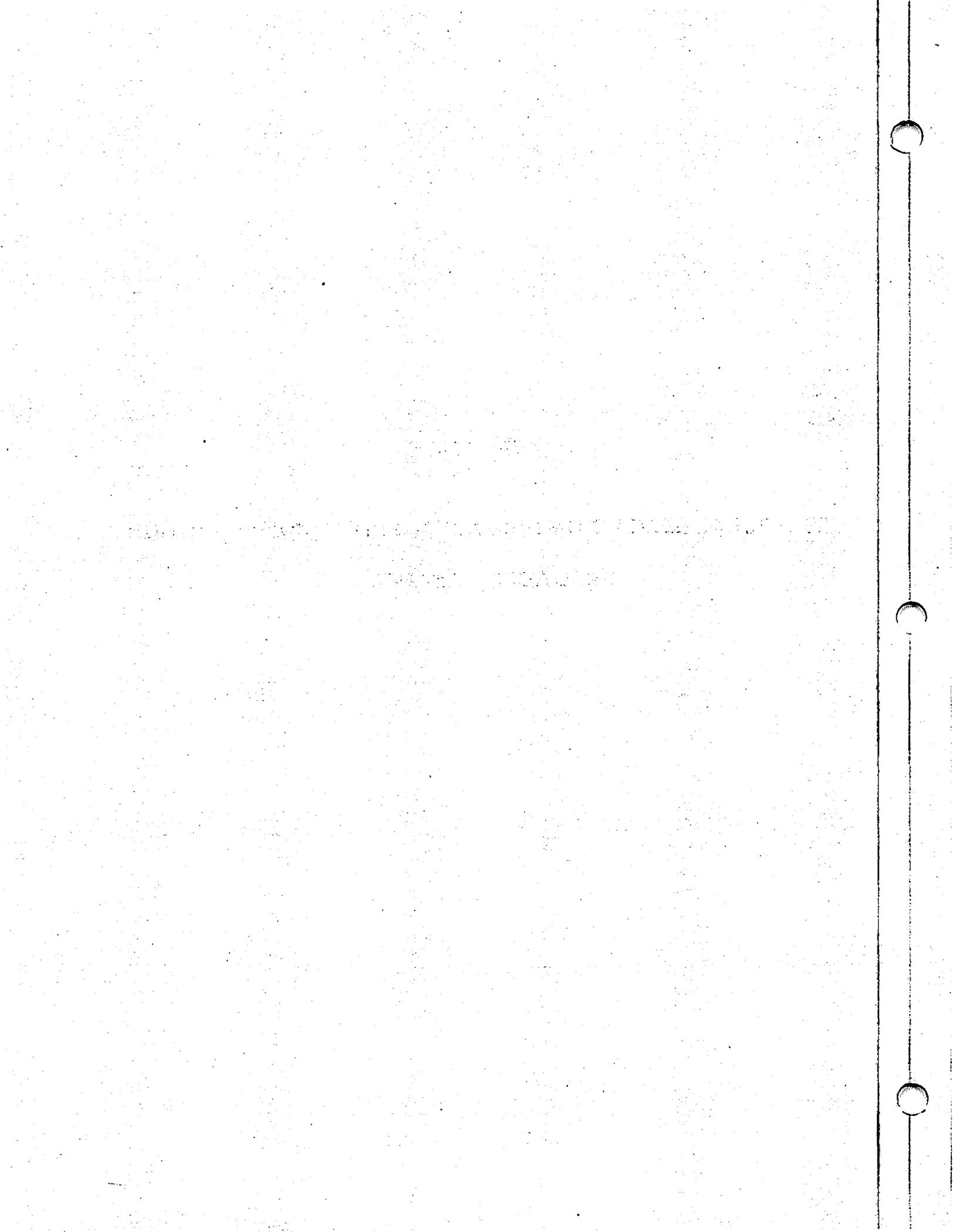
(c) Tracks per 25 fields.



APPENDIX E

ADDITIONAL LETTERS ON HISTORICAL RADIATION PROTECTION

PRACTICES AT HANFORD



APPENDIX E

ADDITIONAL LETTERS ON HISTORICAL RADIATION PROTECTION PRACTICES AT HANFORD

Numerous letters, in addition to the letters footnoted in the main text of this report, document the evolution of radiation protection practices at Hanford since the 1940s. Some of the letters most pertinent to the subject matter of this report are listed in this appendix. Each of these letters is on file in the Hanford Radiation Protection Historical Files, which are maintained by Pacific Northwest Laboratory's Radiological Records group for the U.S. Department of Energy-Richland Operations Office.

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