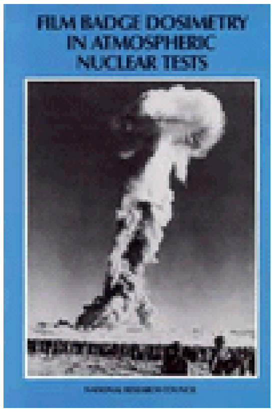

Film Badge Dosimetry in Atmospheric Nuclear Tests

Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests, National Research Council

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Film Badge Dosimetry in Atmospheric Nuclear Tests

Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

Francis X. Masse, Chairman

George Lalos, Editor

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S003

Photo caption-

Shot DOG was detonated over the Nevada Proving Ground at 0730 hours on 1 November 1951 during Operation BUSTER-JANGLE. The nuclear device was dropped from an aircraft and detonated 1,417 feet above Yucca Flat with a yield of 21 kilotons. The mushroom cloud top reached an altitude of 46,000 feet (MSL). Soldiers in the foreground were part of 3,700 observers and troops taking part in military exercises.

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COMMITTEE ON FILM BADGE DOSIMETRY IN ATMOSPHERIC NUCLEAR TESTS

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WALTER L. BROWN, (*Vice-Chairman*), AT&T Bell Laboratories, Murray Hill, New Jersey
JUDITH AREEN, Georgetown University Law Center, Washington, D.C.
WILLIAM J. BRADY, Reynolds Electrical & Engineering Company, Inc., Las Vegas, Nevada
JOHN R. FRAZIER, International Technology Corporation, Knoxville, Tennessee
ETHEL S. GILBERT, Pacific Northwest Laboratories, Richland, Washington
ROBERT O. GORSON, Thomas Jefferson University, Philadelphia, Pennsylvania
NATHANIEL A. GREENHOUSE, Lawrence Berkeley Laboratory, Berkeley, California (12/1/87 to 6/24/88)
RONALD L. KATHREN, Hanford Environmental Health Foundation, Richland, Washington
NORMAN C. RASMUSSEN, Massachusetts Institute of Technology, Cambridge, Massachusetts
R. CRAIG YODER, Tech/Ops Landauer, Inc., Glenwood, Illinois

Liaison with Energy Engineering Board

ADEL F. SAROFIM, Massachusetts Institute of Technology, Cambridge, Massachusetts

Committee Staff

GEORGE LALOS, Study Director
DOROTHY R. MAJEWSKI, Study Assistant
ANN M. STARK,* Study Assistant

* Until February, 1989

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* Until February, 1989

Preface

During the 18-year period when the U.S. government tested nuclear weapons in the atmosphere, radiation exposure monitoring of military and civilian personnel associated with that testing was performed primarily with film badges. The accuracy and reliability of the film badge for monitoring radiation exposures during those early days of weapons testing and the availability and accuracy of the data have been questioned in recent years as veterans seek to gain compensation for health effects that might have been related to their radiation exposure during these tests.

To provide an independent assessment of this issue, the Defense Nuclear Agency (DNA) commissioned the National Research Council (NRC) on September 28, 1987, to organize a Committee on Film Badge Dosimetry in Atmospheric Nuclear Tests. The basic mandate of the Committee was to make an in depth, detailed evaluation of film badge practices used during the period, the recording and record-keeping processes utilized to maintain exposure data, and the overall uncertainties in recorded radiation exposure of participants based on film badge dosimeter results.

Members appointed to the Committee include recognized experts in photographic film processing, development, and interpretation, film badge dosimetry and applications, statistical treatment of uncertainties, radiation characteristics of nuclear weapons, and legal implications of study results. One member of the Committee was present at many weapons tests and has had continuous involvement in the nuclear weapons testing program since the early test series.

The Committee held a series of 10 two-day meetings over 18 months to address this issue. In addition, individual members took on specific study assignments. Two meetings were held in Nevada to access the extensive film badge dosimetry files maintained for the Department of Energy (DOE) by the Reynolds Electrical & Engineering Company (REECo). The study was facilitated by the extent and quality of data available as long as four decades after the initial tests.

Briefings were presented to the Committee by the DNA, the General Accounting Office, the Senate Veterans' Affairs Committee, the Federation of American Scientists, Science Applications International Corporation, JAYCOR, and REECo personnel. The REECo briefing included a detailed introduction to the above mentioned DOE files on the weapons test participants. That briefing was conducted by health physicists Cathryn Teasdale and Martha DeMarre, who have been extensively involved in the management and analysis of these records for many years. In addition, the Committee was briefed on study-related subjects by Dr. Edward Webster, Dr. Ralph E. Lapp, Dr. C. Dennis Robinette, and Dr. Barton C. Hacker. Finally, individual members held informal discussions with key personnel directly involved with the nuclear weapons testing program. The Committee acknowledges the cooperation and assistance it received from all parties.

Arrangements to conduct the study were facilitated by Dennis F. Miller, director of the Energy Engineering Board until November 1987. He was succeeded by Archie L. Wood in December 1987. George Lalos served as study director 3 and as editor of this report.

FRANCIS X. MASSE,

CHAIRMAN,

COMMITTEE ON FILM BADGE DOSIMETRY IN ATMOSPHERIC NUCLEAR TESTS

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Executive Summary

The Committee's mandate was: to evaluate the reliability of film badge results for personnel exposed to radiation during the atmospheric testing of nuclear weapons between 1945 and 1962; to recommend optimum procedures for deriving best estimates of doses received by persons wearing them; and to quantify the uncertainty associated with these estimates.

To accomplish these objectives the Committee reviewed volumes of reference reports and archival data for each of the nineteen test series, including examination of a representative number of original films. The Committee identified, categorized, and quantified sources of uncertainty and developed a method for combining them into overall estimates of series-specific bias and uncertainty. The method allows uncertainty to be expressed as a continuous function of *exposure*.[1] Bias and uncertainty parameters for this function were determined for each test series.

Even for early and less completely documented test series, the Committee found that estimates of *exposure* can be established within 95% confidence limits that rarely exceed a factor of 2 (i.e., from two times the *exposure* at the upper limit, to one-half the *exposure* at the lower limit) of the best *exposure* estimate. Usually this factor is less than 1.5. At very low *exposures*, relative uncertainties in film badge readings are largest, but these low *exposures* contribute very little to the accumulation of a substantial total *exposure*.

[1] When the term "exposure" is italicized it refers to the intensity of x or gamma rays at the point in question. See Section 4.H for a more detailed definition.

The Committee applied methodology developed by the International Commission on Radiation Units and Measurements to convert *exposure* measured by film badges (expressed in R) to dose equivalent (expressed in rem). The quantitative value of the deep-dose equivalent is 70 to 80% of the value of the *exposure*. Thus a best estimate of an *exposure* of 1 R converts to a best estimate of a deep-dose equivalent of 0.7 to 0.8 rem. Thus all previously reported values based on 1 rem/R were overestimated.

The Committee had great difficulty in devising an optimal method for dealing with *exposures* reported as zero or less than the minimum detectable level (MDL) established for a particular film badge emulsion during a particular test series. The second recommendation that follows addresses this situation. The Committee notes that the film badge readings reported as less than the MDL rarely can be realistically construed to contribute a total deep-dose equivalent of more than a few hundred millirem when the maximum number of reports at less than the MDL in any one individual's record are considered.

The following paragraphs contain abbreviated summaries of the conclusions and recommendations of the Committee as a result of this study. The complete version of the conclusions and recommendations are presented at the end of this report. The text of the report develops the rationale relevant to each and should be referred to for a better understanding of the intent of the Committee in making these conclusions and recommendations.

CONCLUSIONS

Tractability of the Problem: Although not complete, extensive documentation is available. Despite deficiencies, it is possible to estimate dose equivalents for participants with reasonable certainty. A method is presented for doing so.

Gamma Radiation from Fission Products and Activation Products: Exposure of participants was due primarily to x and gamma radiation; beta radiation and neutrons were not significant in terms of deep-dose equivalent.

Capabilities and Limitations of Film Badge Dosimeters: While film badges improved throughout the period, they were adequate and reliable from the beginning of testing, particularly for measurement of *exposures* above 0.1 R. The reliability and precision generally improved throughout the period of testing.

Bias and Uncertainty: Various sources of bias and uncertainty were identified, evaluated, and quantified on a series-specific basis. While the uncertainty increases with lower *exposures*, the overall uncertainty was small enough to make the data useful for consideration of potential biological effects in an individual participant.

Methodology for Assessing Bias and Uncertainty: A method is presented for assessing bias and uncertainty in film badge *exposure* readings and for converting them to deep-dose equivalent values. This method is reasonable and of potentially broader application.

Minimum Detectable *Exposure* Level: The minimum detectable level of radiation *exposure* can be established by a procedure presented in this report. For most test series, the minimum detectable level was determined to be approximately 40 mR.

Conversion from *Exposure* to Deep-dose Equivalent: Deep-dose equivalent is the quantity of interest in evaluating the potential for biological effects from the radiation received by an individual involved in the weapons test series. Conversion from film badge readings to deep-dose equivalent is a necessary element in the evaluation of a participant's radiation exposure history. Hence the conversion method is included in this report.

RECOMMENDATIONS

The Committee recommends that the bias (B) and the uncertainty (K) be established for each reported *exposure* that is under investigation. The method for determining the bias and uncertainty is thoroughly discussed and tabulations of bias and uncertainty are included for each test series. Final evaluation of a participant's *exposure* should include the reporting of the B and K values and the conversion to deep-dose equivalent.

The recommendation of the Committee is to allot one-half of the MDL for each zero appearing in the record when attempting to determine the total deep-dose equivalent. This will overestimate the true deep-dose equivalent and may not be appropriate under special circumstances as described in the body of the report.

The recommended procedure for summing multiple film badge readings is included in the report. The total deep-dose equivalent can be represented as the sum of the individual deep-dose equivalents obtained from individual readings, estimating the upper and lower bounds of the range of uncertainty by summing the upper and lower confidence limits of the individual assessments.

1

Introduction

In 1977, the Center for Disease Control (later named Centers for Disease Control) reported that a larger than expected number of leukemia cases had occurred among Camp Desert Rock soldiers present at the Nevada Test Site during Shot SMOKY, a nuclear test event which included military maneuvers during Operation PLUMBBOB in 1957. Meetings were held between Department of Energy (DOE) and Defense Nuclear Agency (DNA) representatives and their contractors to determine if radiation exposure records for military participants in atmospheric nuclear tests were available for epidemiological studies. In December 1977 and January 1978, the Department of Defense (DOD) named DNA as the executive agency to conduct a Nuclear Test Personnel Review (NTPR), and DOE established an exposure records centralization project which later was named the Dosimetry Research Project (DRP).

Hearings on Health Effects of Ionizing Radiation were held by the House of Representatives Rodgers Subcommittee in January and February 1978. DNA and DOE representatives testified on radiation exposures of test participants and on efforts to identify military participants. Veterans who participated in PLUMBBOB and who later became ill with leukemia testified on their requests to the Veterans Administration (VA) for medical treatment and compensation for their illnesses. Veterans Administration representatives testified on claims of these and other "atomic veterans." A Center for Disease Control representative asked DNA for assistance in identifying all military SMOKY participants.

With this stimulus, the NTPR program increased its efforts to identify all DOD-affiliated participants in atmospheric nuclear tests and determine their radiation exposure. DOE's DRP increased its activities to locate missing exposure records, develop a nuclear testing radiation exposure data base, and provide assistance to the NTPR program. Reynolds Electrical & Engineering Company, Inc., (REECo), DOE's prime operating and support contractor at the, Nevada Test Site (NTS), had carried out the NTS radiological safety program since 1955 and also conducted the DRP.

Hearings were conducted by the U.S. Senate Committee on Veterans' Affairs in June 1979. Representatives of both DNA and DOE were required to testify on NTPR and on past nuclear testing activities. The VA and Veterans' groups also testified (U.S. Senate 1979).

In 1978, DNA and DOE commissioned the National Research Council (NRC) to conduct an epidemiological study on military participants in atmospheric nuclear testing (NAS 1985a). In studying some 46,000 of an estimated 205,000 military participants, the report concluded that there was no general increase in the incidence of cancer in test participants. Only the incidence of leukemias in military participants at NTS during SMOKY was higher than expected, with the exception of a slight increase in prostate cancers for Operation REDWING participants. Critics pointed out, however, that selection of cancer incidence in the population at large for comparison biased the results because health screening before entering military service assured that soldiers were healthier on average than the population at large.

Upon request of DNA, the NRC in 1984 appointed a Committee on Dose Assignment and Reconstruction for Service Personnel at Nuclear Weapons Tests to review methods used by NTPR in determining radiation doses. That committee's purpose was to advise DNA on whether or not the methods used by NTPR to assign doses of radiation were comprehensive and scientifically sound and to recommend improvements if needed. The charge to that committee did not require it to make judgements about the biological significance of the radiation exposures of participants at the atmospheric weapons tests, nor did it direct that committee to conduct audits of dose assignments or reconstructions of specific individuals.

The committee, which was chaired by Merril Eisenbud of the Institute of Environmental Medicine of the New York University Medical Center, reported on its study in a 1985 NAS publication (NAS 1985b). The Eisenbud committee found that the principal sources of information on external radiation exposure are film badge records that were compiled into a master file by REECo. This file contains more than 485,000 entries on both military and civilian participants in the atmospheric test series and includes records of about 143,000 of the estimated 205,000 military-affiliated participants in atmospheric testing.

The Eisenbud committee found that the design of film badges, methods of film processing, and densitometric techniques and calibration were relatively crude during World War II, but improved substantially during the 18-year period during which atmospheric weapons tests were conducted. The committee estimated that film badge data on gamma radiation exposure have a positive bias of about 45 percent and a random uncertainty of about ± 100 percent between minimum detection levels and 100 mR and about ± 40 percent above 100 mR. The committee reported that film badge measurement of beta radiation exposure were nonexistent or of uncertain quality during the period. The committee concluded that the methods used by the NTPR teams to assign external gamma doses were generally reasonable and made appropriate use of available data. Committee members further concluded that the methods employed provide a data base and a system of dose assignment for estimating the external doses received by persons who participated in atmospheric tests of nuclear weapons.

NTPR efforts and the above referenced NRC committee review were followed by two General Accounting Office (GAO) investigations and reports on specific segments of the atmospheric weapons testing program.

The first was entitled "Operation CROSSROADS-Personnel Radiation Exposure Estimates Should Be Improved" (GAO 1985). Regarding CROSSROADS film badges only, this report concluded in part that they were not reliable for measuring external gamma or beta radiation and measured only a limited *exposure* range. This report recommended that DNA assign some gamma *exposure* to each zero film badge result reported, develop an error range recognizing film and processing inaccuracies for each film badge reading, and reassess the accuracy of film badge beta readings. Also recommended was providing the Veterans Administration (VA) with error ranges associated with all individual film badge readings reported to the VA (all atmospheric test series).

The second report was titled "Nuclear Health and Safety-Radiation Exposures for Some Cloud-Sampling Personnel Need to be Reexamined" (GAO 1987). This report covered investigation of film badge dosimetry for cloud-sampling, cloud-penetrating, and cloud-tracking air crews, in addition to supporting ground crews, who participated in Operations TUMBLER-SNAPPER, REDWING, and DOMINIC 1. Report conclusions regarding film badges were that badge readings for pilots were sometimes half the readings indicated by radiation monitoring instruments installed in cockpits, inaccuracies resulted because measurement ranges of two films in the badges did not sufficiently overlap, and records of film badge exposures and cumulative exposures contained recording mistakes or omissions.

Recommendations of this second GAO report were that records of each Air Force participant in any atmospheric nuclear weapons test should be reviewed for similar errors, and cockpit-installed instruments should be used in conjunction with film badge readings to better define *exposures* received by aircraft crews during all atmospheric tests.

As a result of these GAO conclusions and recommendations, DNA commis sioned the National Research Council to organize a committee on Film Badge Dosimetry in Atmospheric Nuclear Tests. The basic charge of the committee was to make an in-depth, detailed evaluation of uncertainties in the determination of radiation doses with personnel film badge dosimeters. In addition to its basic charge, the committee made an attempt to address each of the GAO conclusions and recommendations relative to personnel film badge dosimetry. As a useful product of its study, the committee produced most probable doses and dose ranges for use by DNA in interpreting film badge *exposures* for each test series. It is pointed out that the results of the study are applicable to both military and civilian participants. The following "Statement of Task" was assigned to this project from its inception.

STATEMENT OF TASK

The Committee's task is to evaluate uncertainties in the determination of radiation doses with personnel film badge dosimeters. This study shall focus, as follows, on methodology for dose determination with specific types of film badges employed at different times and in different environments during atmospheric testing of nuclear weapons, based on published data and documentation that are available for analysis:

1. *Review kinds of radiation and their energies that personnel film badges were used to monitor during the different testing series.*
2. *Characterize capabilities and limitations of film badge dosimeters used during the 18-year period of testing (1945–1962) in terms of evolving designs, films, and responses to relevant radiations and energies.*
3. *Categorize uncertainties in personnel film badge dosimetry, as introduced during calibration, storage, and processing of films in the laboratory, and in the use of film badges in the field. Evaluate ranges of uncertainty for specific dosimeter designs, environmental conditions, and procedures employed.*
4. *Define reasonable and optimum procedures for reporting radiation doses from film badge data, including uncertainty levels, for the various parameters encountered, e.g., for Pacific and continental environments, and for major differences in film badge construction and components.*
5. *Develop reasonable and prudent methods for analyzing and reporting radiation doses that may have been experienced during the various series of atmospheric tests but that may have fallen below minimum detectable levels.*

This Committee's charge does not extend to attempts at dose reconstruction for persons with only partial film badge records, nor does it include internal dose assessments. Results of this study should not be used to infer doses received by individuals to whom film badges were not issued.

The legal recourse of veterans who suspect that their health has been adversely affected by radiation exposure received as a result of their involvement in the weapons tests has undergone significant change in recent years. A brief overview of the relevant law follows.

Since 1950, when the Supreme Court decided *Feres v. United States* (340 U.S. 135, 1950), military personnel (including veterans) have been barred from seeking compensation from the federal government for injuries "aris[ing] out of or... in the course of activity incident to service." Instead, veterans have been authorized to seek compensation for disabilities connected to their service pursuant to a comprehensive claims system operated by the Veterans Administration (See 38 United States Code Sections 310–314).

In 1988, Congress adopted and President Reagan signed into law the Radiation-Exposed Veterans Compensation Act of 1988 (Pub. Law 100–321). The law amends Section 312 of Title 38 of the United States Code by establishing that veterans who, while serving on active duty, participated onsite in a test involving the atmospheric detonation of a nuclear device (or in the occupation of Hiroshima or Nagasaki, Japan, between August 6, 1945, and July 1, 1946, or were interred as prisoners of war in Japan) and who develop within forty years[1] any of a specific list of radiogenic cancers, will be presumptively entitled to disability compensation from the Department of Veterans Affairs. The Act thus enables veterans who manifest one of the listed diseases within the requisite time period to obtain compensation without proving that radiation exposure caused the cancer in question. In proposing this legislation to the Senate, Senator Cranston, its sponsor, noted that compensation had been awarded in less than 40 of the over 6,000 radiation claims filed with the VA (Cong. Rec. S4638, April 25, 1988).

Veterans who develop a cancer not on the list set forth in the Radiation-Exposed Veterans Compensation Act of 1988 must still prove that their cancer was caused by exposure to ionizing radiation from atmospheric tests if they are to win disability benefits.

Civilians exposed to radiation from atmospheric tests have recourse only through the Federal Tort Claims Act.[2] Such claims were upheld at the trial court level in *Allen v. United States* (588 F. Supp. 247, D.Utah 1984), where Judge

[1] In the case of leukemia, the cancer must manifest within a thirty yen period from the last date of exposure.

[2] Civilian employees of the United States generally may not obtain compensation for work-related injuries pursuant to the Federal Tort Claims Act. Instead, they may seek compensation pursuant to the Federal Employees Compensation Act (FECA), 5 U.S.C. 8101–8193, which authorizes recovery of lost wages and medical costs for "personal injury sustained while in the performance of...duty."

Bruce Jenkins ruled in favor of nine plaintiffs alleging injury or death from fallout from atmospheric tests in Nevada in the 1950s and 1960s. On April 20, 1987, however, the United States Court of Appeals for the Tenth Circuit reversed the lower court decision in *Allen v. United States* on the grounds that the Atomic Energy Commission (AEC) in planning and conducting its monitoring and information programs concerning the testing was making the kind of policy judgements which are immune from liability under the Federal Tort Claims Act (816 F.2d 1417, 10th Cir. 1987). The Supreme Court in January of 1988 declined to hear an appeal in the case (108 S.Ct 694), thereby letting stand the ruling of the Tenth Circuit Court. Civilians are thus unlikely to succeed in suits brought against the government for exposure to radiation from atmospheric tests unless Congress changes the relevant law.

In 1988, Congress adopted legislation that turned the Veterans Administration into the fourteenth Cabinet department of the United States in March, 1989 (Department of Veterans Affairs Act, Pub. Law 100–527). Of more significance for those seeking disability claims, Congress also authorized veterans to appeal denials of benefits to a new United States Court of Veterans Appeals, and from there to the United States Court of Appeals for the Federal Circuit (Veterans Judicial Review Action, Pub. Law 100–687). Previously, benefit denials were not appealable beyond the Veterans Administration.

2

Basic Principles of Film Badge Dosimetry

For those readers who are familiar with the use of the film badge as a device for the measurement of radiation in potentially exposed workers, this chapter may be superfluous. For others, it will provide background material helpful in understanding the rest of the report.

A. HISTORICAL INTRODUCTION

Photographic emulsions have long been used for detection and measurement of ionizing radiations. Even before Roentgen's discovery of x-rays in 1895, fogging of unknown origin was observed in photographic emulsions by researchers who were unknowingly producing x-rays during their research with evacuated discharge tubes. Among the first to apply photographic emulsions to radiation protection was William H. Rollins, a Boston dentist and x-ray protection pioneer who in 1902 described a protective housing for x-ray tubes (Rollins 1902). As a test of the efficacy of the shielding, Rollins recommended placing an unexposed photographic plate against the exterior of the housing, noting that the housing was satisfactory if the plate was not fogged by an exposure of seven minutes duration.

Perhaps the first application of photographic film, rather than plates, to radiaton protection came the following year when an American dermatologist, S. Stern, proposed its use to quantify the dose received by patients undergoing radiologic procedures (Stern 1903). Fundamental work carried out a decade later established the suitability of photographic emulsions for dose measurements. In Germany, Kronke (1914), Friedrich and Koch (1914) and Glocker and Traub

(1921), along with Allen and Lafy (1919) and Bloch and Renwick (1920) in Britain, demonstrated that for a given x-ray spectrum, the blackening or density of the film could be correlated with the exposure, producing a characteristic dose-response curve.

Routine monitoring of personnel exposures to x-rays and radium with photographic films for protection purposes was first suggested in 1922 by Pfahler, a prominent American radiologist. Pfahler recommended that x-ray and radium workers routinely carry an unexposed dental radiographic film packet in their breast pocket. After two weeks, this film was to be developed and die degree of blackening correlated with radiation exposure in terms of skin erythema dose (Pfahler 1922). Four years later, Edith Quimby, a New York medical physicist, proposed the first true film badge, incorporating a system of metallic filters to compensate for the energy dependence of the film sensitivity (Quimby 1926) i.e., the propensity of the photographic emulsion to over-respond or produce excessive darkening to certain energies of x radiation. A few months later, Robert S. Landauer Sr., a physicist at Cook County Hospital in Chicago, suggested the use of easily obtained and reasonably constant quality dental x-ray film packets (Landauer 1927).

In 1928, the roentgen unit for radiation exposure was formally adopted by the Second International Congress on Radiology. This unit, which was defined in terms of air ionization, thus became the primary standard for radiological measurements, replacing other units based on biological effects (such as the skin erythema dose) or induced colorimetric change in chemicals. The degree of film blackening or optical density, essentially a chemical effect, was correlated with the *exposure* measured in roentgens (R), a physical effect, by Franke (1928) in Germany. In Holland, Bouwers and van der Tuuk (1930) extended the work of Franke to a lower level of detection, below the then-current daily exposure limit of 0.2 R, and described a sophisticated film badge for personnel monitoring that utilized multiple metallic filters.

Despite the correlations established under laboratory conditions, and the film badge of Quimby, practical difficulties were encountered with dose determinations in the field because the response of photographic film was dependent on photon energy. Photographic films were accordingly considered unreliable and hence not always used for monitoring exposure of x-ray workers, although they were considered satisfactory for monitoring exposure of radium workers (Hamann 1932; Holthausen and Hamann 1932).

The work of the Manhattan District in the early 1940's created a need for a reliable and sufficiently sensitive personnel monitoring device capable of application to the protection program for a large and diverse work force. Commercially available x ray films were tried and found to be well suited to this task if used with filtration to compensate for energy dependence. The standard holder or badge contained two pieces of dental x ray film—one low range (20 mR – 20 R) and one high-range (1 R – 400 R) in a holder made of silver or cadmium, 1 mm thick, with a window to admit beta radiation (Figure 2-1)(Morgan 1947; Pardue et al. 1944; Parker 1980). The metal filter provided compensation, albeit imperfect, for the over-response of film to photons with energies between about 25 and 100 keV. It was also in the Manhattan District that the basic techniques for large scale personnel monitoring with films evolved, including quantity purchasing (arid hence uniformity of large batches), storage under controlled conditions to enhance shelf life, batch calibration and development techniques with suitable controls, improved densitometry, and controlled distribution, recovery, and development (Auxier 1980; Pardue et al. 1944).

B. PERSONNEL DOSIMETRY FILMS

Films used for personnel dosimetry are basically the same as ordinary black and white photographic film or x-ray films, consisting of a layer of gelatin emulsion containing a specified quantity of silver halide laid on top of a sheet of supporting structure known as the film base (Figure 2-2).

The film base is typically made from a nonflammable inert material such as cellulose acetate, and is relatively thick, usually on the order of 100–200 micrometers (μm). The base serves both to prow and to support the emulsion.

The response of a photographic emulsion to a given exposure to radiation is dependent on a number of factors, including the presence or absence of various chemicals which may act as sensitizers or retardants, and grain size. Generally, the larger the grain size, the more sensitive the film is to a given exposure to radiation. Thus, the so-called fine-grain films typically will have less radiation

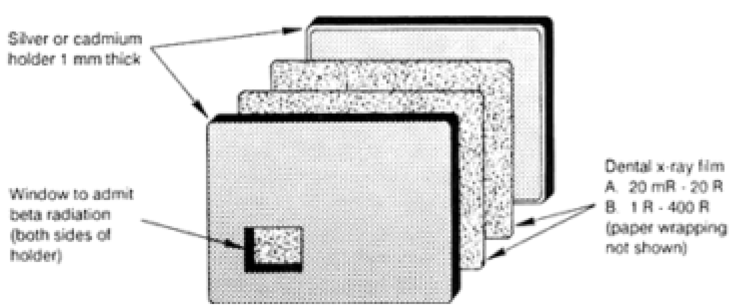

Figure 2-1
Standard Film Badge with Silver or Cadmium Holder.

sensitivity than those with coarser grains. Depending on the intended use of the film, the emulsion thickness may range from a few to several hundred μm. In films used for personnel monitoring of beta and photon radiations, the emulsion is typically a few tens of μm in thickness. Grains of silver bromide (AgBr) typically ranging from 0.1 to 10 μm in diameter are distributed more or less uniformly throughout the emulsion. These constitute the sensitive portion of the film; exposure to ionizing radiation, light or other forms of electromagnetic energy, such as infrared, induce a physico-chemical change which is a function of the exposure.

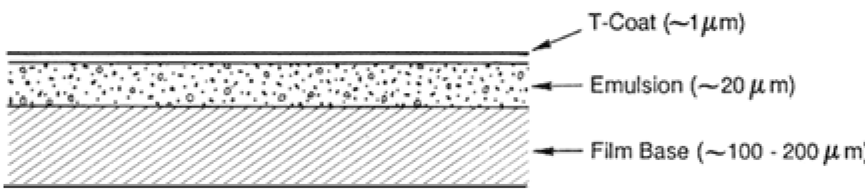

Figure 2-2
Cross-section of a Typical Photographic Film (not to scale).

Photographic emulsions are produced by a complex series of well controlled manufacturing operations. The first step is the precipitation of silver halide in a gelatin solution. This is accomplished by addition of an aqueous solution of silver salts, primarily silver nitrate, to a gelatin solution containing an excess of alkali halide under controlled conditions. Grain size is increased by subsequent heating to 50–70°C for up to an hour. The grains are not uniform in size and shape but do have a reasonably consistent distribution. The emulsion is then washed with water to remove the remaining soluble salt, and heated to the melting point. Additional gelatin and various sensitizers and stabilizers are added, and the emulsion is held at temperature for a suitable time to produce the desired sensitivity characteristics and to minimize background darkening (fog). It is then spread in a uniform layer on the film base and allowed to cool and dry. It may be coated with a thin protective layer about a micrometer in thickness known as the T-coat (Figure 2-2).

A dosimeter film may be single-coated (i.e., the base has the emulsion on one side only) or double-coated. If double-coated, the same emulsion may be on each side of the base, or two different emulsions may be used. Dual coating with the same emulsion was originally used primarily to enhance sensitivity. Dual coating with emulsions of different sensitivity is now used to enhance the overall range of the film. A typical photographic emulsion for personnel dosimetry purposes contains about 50% by weight of AgBr (including a few per cent of silver iodide) and 50% gelatin. The thickness of AgBr in the emulsion layer is a few mg/cm^2, and the grain density of AgBr is in the range 10^9 –10^{12} $grains/cm^2$.

Manufacture of photographic film is carried out in darkness, as visible light will expose the film. It is fabricated in large sheets which are cut into the desired size and packaged in light-tight paper or plastic wrappings. Dosimeter films have traditionally been sized and wrapped like dental x-ray films, although smaller sizes have been produced.

C. PHYSICAL AND CHEMICAL BASIS OF FILM DOSIMETRY

When a film is exposed to radiation, a complex series of interactions takes place. The basic theory of the photographic process was described a half century ago by Gurney and Mott (1938) and can be expressed in terms of solid state quantum theory (Mees 1967). Basically, the Gurney-Mott theory proposes that all or a portion of the incident energy of a photon or charged particle is transferred to one or more valence band electrons in the silver halide crystal, raising them into the conduction band, where they are free to migrate through the crystal. These electrons will either recombine with positive holes (i.e., a deficiency of electrons) within the valence band or will be captured by electron traps (also known as sensitivity centers) elsewhere within the crystal. Deep electron traps result from lattice imperfections within the crystal due to structural defects or to the inclusion of certain impurities such as ions with a greater net positive charge than the silver. Once captured, electrons in these traps have little chance of escape.

The negatively charged electrons are attracted to the positively charged traps. As electrons accumulate in traps, a region of slight negative charge is produced, which serves to attract a small mobile fraction of the interstitial silver ions, reducing them to metallic silver according to the relationship $Ag^{+} + e^{-} = Ag$ °. The reduced silver atoms constitute the latent image which serves as the focal point for the development process. Only a few of the very large number of silver atoms in a single grain of AgBr are directly reduced to atomic silver by the radiation exposure.

D. THE DEVELOPMENT PROCESS

Film development is a multi-stage process that may be thought of as a chemical amplification process. In a darkroom, the film is removed from its wrappings and dipped into a solution containing a reducing agent such as methyl p-amino phenol sulfate, hydroxyquinone, 1-phenyl, 3-pyrazolidone, or other para-substituted benzene derivatives, which reduces the silver halide in the emulsion to metallic silver. The developer also contains alkali buffers to maintain constant pH (because the rate of development is pH-dependent) and sulfites to retard oxidation by air. The development process occurs very rapidly in those grains in which there is a latent image, being initiated at the point of the latent image. These grains are fully developed long before the unexposed grains—i.e., those with no latent image. The film is thus held in the developing solution only long enough to develop those grains in which a latent image has been formed, typically on the order of 3–5 minutes.

The degree of blackening or response of a film is dependent upon the fraction of grains in a film that is developed, which in turn is dependent upon the number of grains in which a suitable latent image has been formed. A minimum of about four silver atoms is required to render a grain developable, which is equivalent to an energy deposition of about 10 electron volts (eV). The number of silver ions reduced to metallic silver in the development process is on the order of 10^{12} times greater than that in the latent image.

The development process is a chemical reaction and as such is affected by the amount of reducing agent present. The developer needs to be replenished or replaced from time to time, as the reducing agent is consumed by the development process or is oxidized by dissolved oxygen or by contact with the air. As is true of most chemical reactions, the reaction rate is temperature-dependent, and development is normally carried out at a constant controlled temperature of 68 $\pm$ 0.5°F (20 $\pm$ 0.3°C). To ensure continued contact of the film with fresh developer, the developer is agitated mechanically during the development process. This can be done by stirring or by bubbling an inert gas such as nitrogen through the developer solution.

After chemical development, the film is washed in water or in a suitable chemical "stop bath", such as a weak solution of acetic acid, which serves to halt the action of the developer by physically removing the residual developer from the film or by lowering the pH. This stage is brief, usually lasting only a minute or so. The film is then transferred to a chemical bath containing sodium thiosulfate, sodium metabisulfite, or similar materials which dissolve the undeveloped silver halide grains, leaving behind the developed grains. This is the fixing procedure, and typically requires 15–20 minutes for completion. After final washing and drying, the film is ready for readout and interpretation. The final washing is usually carried out for an hour in running water, perhaps containing a wetting agent, to ensure complete removal of chemical residues. The wetting agent helps prevent the occurrence of water marks which may affect subsequent optical density measurement.

E. DENSITOMETRY

Transmission of light through the developed film is largely a function of the amount of elemental silver remaining on the developed film base. The process by which transmission of light through the developed film is measured is known as densitometry (or, alternatively, sensitometry) and is accomplished with a device known as a densitometer. Light transmission is measured in terms of the optical density (OD) which is defined as the logarithm of the intensity of the light incident on the film (I0) divided by the intensity of the light passing through the film (I), or

$$OD = \log(I_o/I). \qquad \text{2-1}$$

The light absorption attributable to background fog (I_{bkd}), determined from measurement of control films processed simultaneously with the exposed group, is subtracted from the OD to obtain the net optical density (NOD). Thus,

$$\begin{aligned} NOD &= \log(I_o/I) - \log(I_o/I_{bkd}) \\ &= \log(I_{bkd}/I). \end{aligned} \qquad \text{2-2}$$

From Equation 2-2 it is clear that only the optical density of the control film and the exposed film need be measured. In actual practice, only a single measurement is required, as many densitometers are equipped with a potentiometric adjustment to zero out the contribution from background.

F. RESPONSE CHARACTERISTICS OF FILM

The optical density of an exposed film is usually plotted as a semilogarithmic function of the radiation exposure and is characterized by a curve of the form shown in Figure 2-3. This characteristic response curve is known as a Hurter and Driffield (H and D) curve, and has five distinct identifiable regions, but with no sharp boundaries.

Region I is the toe of the curve in which the density does not increase appreciably with exposure; this so-called base density and background fog define the lower limit of detectability of the film. In Region II, the response as determined by the OD is approximately proportional to *exposure*, and film becomes useful for dosimetry. In Region III the film response is proportional to the logarithm of the exposure; hence this region is most useful for dosimetry. Region IV is the shoulder of the curve, and the film response or increase in density per unit exposure declines with increasing exposure until some maximum OD value is reached. The final portion of the curve, Region V, shows a decline in density with increasing dose. This is the region of reversal, technically known as solarization, a phenomenon attributable to a reduction in the number of sensitivity centers in the AgBr caused by the escape of bromine from the surface of the AgBr grains. For any given film emulsion, the onset of solarization is controlled by a complex combination of many factors, including the exposure rate, development conditions, and the energy and type of the exposing radiation. However, in personnel monitoring films, solarization does not occur except at doses well beyond the defined usable range of the film.

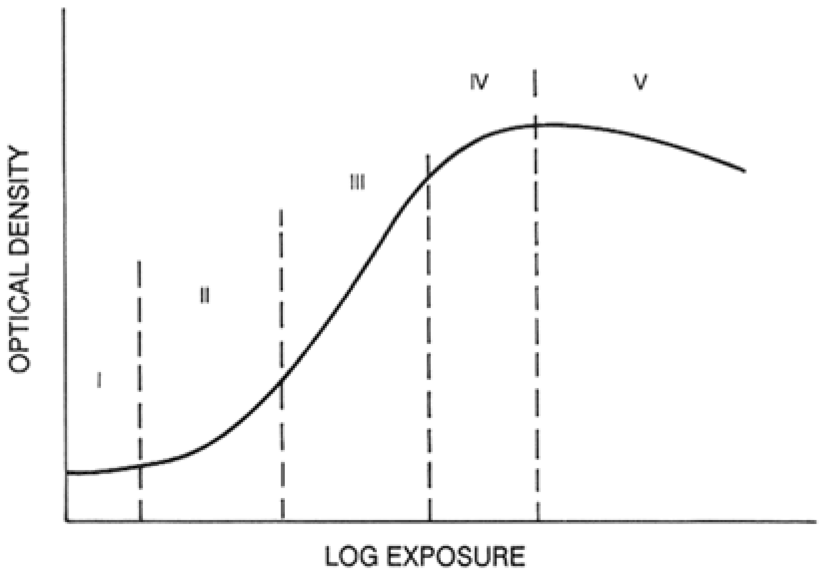

Figure 2-3
Characteristic Response Curve (H & D) for a Photographic Emulsion Exposed to Ionizing Radiation.

In general, film response depends on the total exposure (Ehrlich 1956; Herz 1969). In other words, the response of a film to a given exposure level is independent of the rate of exposure. However, at extremely high exposure rates (10^{10} R/s), a diminution in the response per unit exposure—i.e., a reduction in the sensitivity of the film—has been observed (Dudley 1966). This is known as the Schwartzchild effect, or reciprocity failure.

The response or degree of blackening per unit exposure is a measure of the sensitivity of the film and is analogous to film speed as used in the context of photography. More rigorously, film sensitivity is defined as the reciprocal of the dose required to produce a specified NOD. For photographic emulsions used for personnel dosimetry in the normally expected occupational exposure range, a typical film sensitivity is 0.5 NOD units per 400 mR exposure. For films with this sensitivity, the lower limit of detection is about 10–20 mR for photon energies above a few hundred keV.

This type of film sensitivity is determined by a number of factors, including the energy and type of exposing radiation, inclusion of impurities or sensitizers in the emulsion, the development process, quantity of silver halide in the emulsion, and grain size and density. In general, the greater the grain density (i.e., the number of grains per unit area), the greater the sensitivity. Similarly, sensitivity is a function of grain size; as only about four reduced silver atoms in a grain will result in development of the entire grain, the larger the grain, the greater the sensitivity.

G. ENERGY DEPENDENCE AND FILM BADGE DESIGN

Because the atomic numbers (Z) of both silver (Z = 48) and bromine (Z = 35), which constitute the sensitive portion of the film, are significantly greater than the atoms in air or soft tissue, film sensitivity to photons relative to that of air (Z = 7.78) and tissue (Z = 7.64) is strongly energy dependent. This follows because the probability of photoelectric interactions (and hence energy absorption) is a function of both photon energy and the atomic number of the absorbing medium. Simply stated, the response of film relative to the dose received by tissue is not constant, but rather varies with photon energy. In Figure 2-4, the energy dependence relative to *exposure* in air is shown; this is similar to the soft tissue response curve. In other words, the sensitivity of the film is highly dependent on the energy of the exposing photons. The effect is most pronounced in the photon energy region below a few hundred kilovolts, peaking as shown in Figure 2-4.

A reasonable solution to the problem of photon energy dependence is to use filters to obtain a response for the film that is reasonably independent of photon energy and approximates that of soft tissue. A photon filter is simply an appropriate thickness of a suitable material (usually a metallic element) placed over the film to selectively absorb a greater proportion of the lower-energy photons and thus compensate for the over-response at these energies. No single filter will provide a perfectly flat response, and typically several filters are used.

Reasonably good results for both beta and photon radiations can be obtained with a film badge having three filters—a high-Z, a medium-Z and a low-Z—in addition to an unshielded or "open window" portion. The low-Z filter is selected to absorb all or most of the beta radiation, but a minimal amount of photons. A low-Z material such as polyethylene or other plastic with an a real density of 1 gcm^{-2} is sufficient to attenuate beta particles with energies < 2 MeV, and has little effect on photon transmission. Thus, the photon response under the low-Z shield and on the unshielded portion of the film will be essentially the same. However, only the open window portion will be affected by the beta radiation. Hence, by subtracting the response under the low-Z portion from that of the open window portion, the, response attributable to beta radiation will be obtained, and the beta dose can be evaluated. The NOD under each filter must be converted to a common calibration exposure before subtraction to assure linear relations among the values.

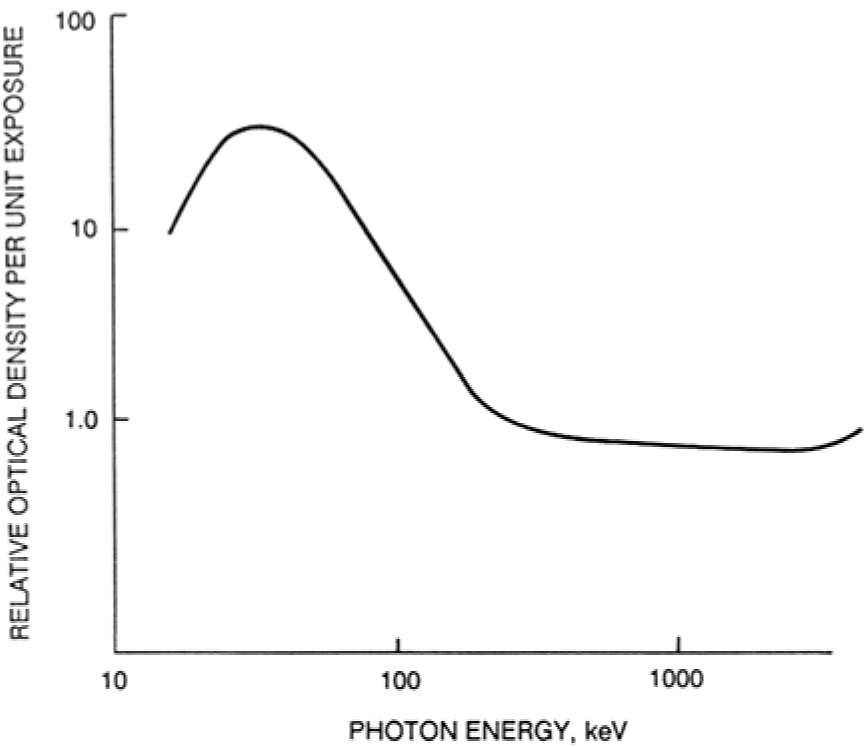

Figure 2-4
Energy Dependence Curve for Unshielded Personnel Monitoring Film.

The measured and converted NOD values under each of the three filters can be used to determine the dose from photons over a wide energy range. If the filters are judiciously selected, the combination of responses under the three filters will uniquely correspond to an effective energy and thus the sensitivity of the film to the unknown exposing spectrum can be determined and the appropriate exposure/ density relationship obtained. This may be done by computerized techniques or manually.

On a practical level, the high-Z filter is selected to provide an essentially flat response over the widest possible energy range. An appropriate thickness, e.g., 0.5 mm (0.020 inch) of tantalum (Z = 83), will provide an essentially flat or constant sensitivity to photons with energies in the range of approximately 50 keV to about 2 Mev (Figure 2-5), and if the exposure is wholly due to photons in this energy region, only a single NOD is needed to determine the dose. Similar results can be obtained with other high-Z materials. If the exposure includes photons below the effective energy cutoff range of the high-Z filter (e.g., 50 keV in the case of the tantalum filter mentioned), the NOD values under the other two filters will be greater than the NOD under the tantalum, and the interpretation of the low-energy component must be made using the densities under the other filters.

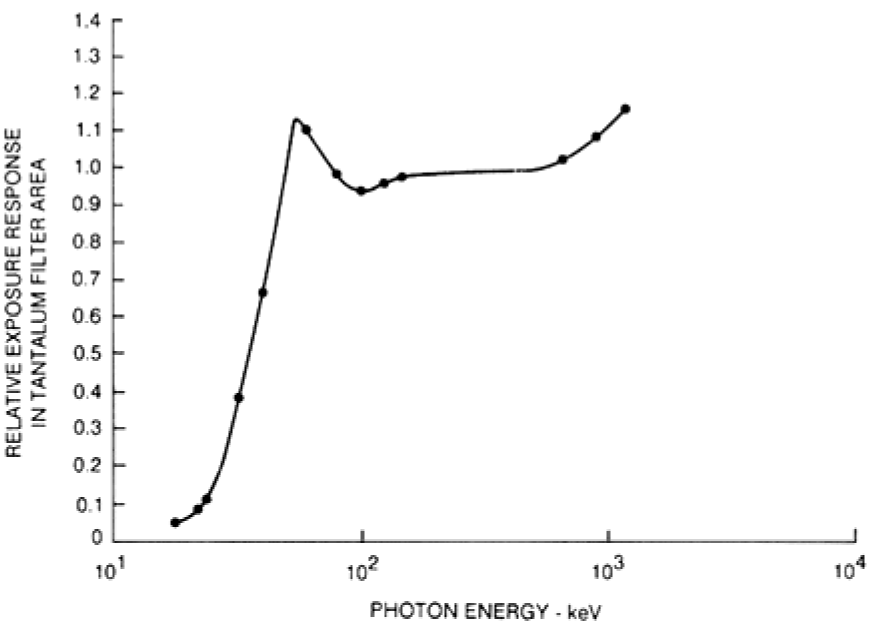

Figure 2-5
Film Response With 0.020-inch Tantalum Filter (adapted from Brady and Iverson, 1968).

At high photon energies, dose interpretation is complicated by the lack of charged particle equilibrium. Exposure to photons with quantum energies above 2 MeV may result in a situation in which the density under the filters is greater than the density in the open window area, with the greatest density occurring under the high-Z filter. Additional filters may be required to facilitate interpretation of doses in mixed radiation fields involving high-energy photons. Note that there is no theoretical limit on the number of filters that can be used; in fact, the greater the number and sophistication of filters, the more quantitative the evaluation (Storm and Shlaer 1965).

H. OTHER SOURCES OF ERROR IN FILM BADGE DOSIMETRY

Although the intrinsic accuracy of personnel dosimetry films to suitable reference levels of radiation is quite good (Brodsky 1963; Brodsky and Kathren 1963;

Brodsky et al. 1965; Herz 1969), films are subject to a variety of influences which may adversely affect subsequent dose interpretation. Because the planar geometry of film and badge-filter combination cause angular dependence, the angle of incidence of the exposing radiation will affect the response. Photons or beta particles incident at oblique angles will pass through a proportionately larger thickness of overlying filter. This produces a variable response, an effect particularly pronounced for the lower-energy photons and beta particles (Ehrlich 1954, 1962; Heard et al. 1960).

Environmental conditions may affect film response in a variety of ways. Numerous studies have documented the complex effects of temperature and humidity on personnel dosimetry films and have been summarized in the literature (Becker 1966, 1973; Kathren 1987). The numerous and varied effects noted also may be time dependent and reversal of the effect may occur with time. Latent image fading will result from high humidity, but condensation of water on the film emulsion may cause fogging. Heat-induced fogging may occur, and is most pronounced in the relative humidity range 40–60%. Chemicals such as mercury or sulfur present in the atmosphere can act as either sensitizers or inhibitors of the photographic response. Protective packaging in polyethylene or other hermetically sealed pouches has been recommended to minimize or obviate effects induced by humidity or chemicals (Kathren et al. 1966).

Static charge will produce characteristic discharge "trees" on the developed film. These are usually insufficient to interfere with sensitometry and dose interpretation. Pressure may result in increased density, as may exposure of the film to light. Light-struck films are characterized by areas of high density at the points of light exposure. These latter effects are readily recognizable to the experienced observer, although they may produce spurious results in automated readout systems.

I. CALIBRATION AND STANDARDIZATION

Film calibration procedure involves the exposure of a number of film badges to suitable levels of reference radiation. For a typical sensitive personnel dosimeter film, ten to fifteen points over an exposure range of three to four decades is adequate. It is important to determine the specific energy and angular dependence characteristics of the particular film and film badge-filter combination. Sources providing specific photon energies and spectra suitable for calibration have been described in the literature (IAEA 1971; ISO 1983; Kathren et al. 1965). Because these characteristics are constant, it usually is unnecessary to repeat the determination unless the film or film badge-filter combination has been altered. Once the specific energy and directional dependence have been determined, it is possible to obtain adequate calibration with a single or a few specific calibrated sources; a high-energy photon source, such as Cs 137, is well suited to this purpose (IAEA 1971).

Suitable film badge calibrations can be obtained by exposure in free air, without a backing phantom, and this is the traditional calibration procedure. In some instances, use of a phantom may be necessary to determine the backscatter contribution (Figure 2-5) (IAEA 1970). Calibrations are specific for each unique combination of source, badge, and geometry conditions. In all cases, the source output at the specific locations at which the calibration is performed should be determined and should be relatable to one at the National Institute of Standards and Technology, or similar recognized primary standards laboratory.

Calibration films and controls should be developed along with each processing batch as a quality-control measure and to compensate for variations associated with the processing. Slight changes in the temperature and strength of processing solutions or temporal factors may introduce a shift in the dose response curve which will be detectable by calibration films processed with each batch of dosimeters. The number of calibration films developed with each batch will depend on the specific dosimetry operation. Usually, a few percent of the processing batch should be unexposed controls to establish the background fog level for that particular processing batch; similarly, each batch should contain one or more films exposed to a predetermined level in the usable portion of the H and D curve (e.g., 100 mR to 1 R referenced to air for a typical personnel dosimetry film).

Although film manufacture is well controlled, variations in response and background fog may occur from batch to batch, necessitating individual calibration of each manufacturing batch. Energy and directional dependence should remain constant from batch to batch, unless there have been changes in the composition or geometry of the emulsion or film base. An American Standards Association report (ASA 1956) gives procedures for evaluating films for monitoring x rays and gamma rays with energies up to 2 MeV.

J. NEUTRON DOSIMETRY

Photographic emulsions also have been applied to personnel dosimetry of both thermal and fast neutrons, although they were not often used for this purpose during atmospheric testing. Thermal neutrons may be measured with the aid of a filter made from a material with a high thermal-neutron capture cross-section, such as cadmium or rhodium. When exposed to neutrons, these elements will be activated, and the film will be exposed from both the beta and gamma rays produced in the reaction or by the activated material. The NOD attributable to the neutron activation is determined by subtracting the NOD produced by photon radiation. This is accomplished by use of a filter with a very small thermal neutron cross-section but with similar photon absorption properties. Two ele ments with nearly equal atomic numbers are suitable; tin and cadmium or tin and rhodium have been used successfully (Kocher et al. 1963). Again, subtraction must be after conversion of NOD to a calibration exposure.

Thick emulsions—so-called nuclear track emulsions—are used for fast neutron dosimetry. Such emulsions are 100 to several hundred micrometers in thickness. The most common track inducing process is from proton recoils produced by the (n,p) reaction in the emulsion, film base, and low-Z material (e.g., paper wrappings) around the film (Cheka 1954). There is also the potentially significant 14N(n,p)14C reaction with thermal neutrons (Lehman 1961). Quantification is accomplished by direct counting of proton recoil tracks.

Nuclear emulsions have a fairly limited dynamic range and are subject to large errors from statistical uncertainties associated with counting. Different persons counting tracks on the same film will come up with widely divergent results. Tracks may be lost through latent image fading, which is more pronounced in nuclear-track emulsions, and may be obscured by concomitant exposure to photons which produce a general darkening of the film. Nuclear-track emulsions are also sensitive to all the environmental effects associated with films used for beta and photon monitoring.

3

Radiation Source Terms in Atmospheric Testing

A. INTRODUCTION

Ionizing radiation emitted as a consequence of a nuclear explosion includes photons, neutrons, beta particles, and alpha particles. (Photons refer to high-energy electromagnetic radiation that includes both x and gamma rays, which physically are the same kind of radiation. Historically, the term x ray was given to those high energy photons originating from energy transitions in the orbital electrons outside of the atomic nucleus and the term gamma ray was given to those high-energy photons originating from energy transitions occurring within the atomic nucleus. Photons with the same energy, however, are indistinguishable regardless of their origin).

Of these, most of the neutrons and a portion of the gamma rays are emitted simultaneously with the explosion. During subsequent nuclear processes, beta particles and other gamma and x rays are emitted. Alpha particles are emitted by unfissioned uranium or plutonium, by certain activation products produced during the explosion, and directly by fusion reactions (Glasstone and Dolan 1977). In addition, x rays are emitted both as a direct result of the fission process as well as from the various radioactive species associated with a nuclear explosion.

Initial radiation will be defined as ionizing radiation emitted within the first minute after the detonation. The selection of this demarcation is somewhat arbitrary, and was originally based on the approximately one minute required for the radioactive cloud to rise to a height of two miles following the explosion. This appeared to be independent of the yield of the explosion (Glasstone and Dolan

1977). Ionizing radiation emitted after the first minute following the detonation isclassified as residual radiation.

B. INITIAL RADIATION

Initial radiation includes neutrons, gamma and x rays, alpha particles and beta particles which are emitted almost instantaneously with the explosion, and gamma rays emitted by fission products and activation products present in the rising cloud. Both neutrons and gamma rays, as well as x-rays, can travel considerable distances in air due to their low probabilities of interaction. Alpha particles and beta particles, on the other hand, have very short ranges in air, typically a few centimeters to a few meters, respectively. Therefore, of the initial radiation, only neutrons, gamma rays, and x rays can travel far enough from a detonation to present a significant hazard to living organisms surviving other weapons effects (e.g., heat and blast).

Although the total energy of initial neutrons, gamma rays and x rays is only a few percent of the total energy released during detonation of a fission device, greater penetrating ability and the nature of interactions with matter by these radiations makes them a significant aspect of a nuclear explosion (Glasstone and Dolan 1977). Although only a small fraction of initial neutrons, gamma rays, and x rays emitted during a weapon detonation escapes from the explosion region, these radiations present a significant hazard even at large distances from the explosion.

Most of the neutrons from a nuclear explosion are emitted within a fraction of a second and are released in either the fission or fusion process. Both prompt and delayed neutrons are emitted as initial radiation, with delayed neutrons being emitted throughout the initial time period. Although high-energy neutrons are emitted during the explosion, their interactions as they emerge from the region of the explosion create a spectrum of neutron energies. This energy spectrum continues to decrease in mean energy within the first few hundred meters from the point of detonation as the neutrons pass through air, after which an equilibrium neutron spectrum is achieved (Glasstone and Dolan 1977). At greater distances from the explosion, the neutron energy spectrum does not change appreciably, although there is a rapid reduction in neutron dose rate with distance due to geometric effects and neutron absorption.

Gamma rays which are present in the initial radiation are from several distinct sources. These include:

a. gamma rays accompanying fission,
b. gamma rays emitted as a consequence of capture of fission neutrons by nonfissionable nuclei (both weapons components and surrounding materials),

c. gamma rays emitted following inelastic scattering of fission neutrons, and
d. gamma rays emitted from decay of short-lived radionuclides formed in the explosion.

The calculated time dependence of the gamma-ray energy output from a hypothetical explosion is shown in Figure 3-1. Variations in this relationship occur as a consequence of differences in weapons type, type of burst, and a number of other factors. X rays are also present in initial radiation as a consequence of fission processes and decay of isomers formed in the explosion. Initial radiation from fusion devices also includes x rays from several sources.

Further details of the initial nuclear radiation are found in *The Effects of Nuclear Weapons* by Glasstone and Dolan (1977).

C. RESIDUAL RADIATION

Ionizing radiation emitted after the first minute of a nuclear explosion is referred to as residual radiation. Residual radiation is emitted from the fallout following the detonation and from radioactivity induced in nearby materials by neutrons emitted during the detonation. Both of these sources of radiation may continue to emit radiation for many years. The induced radiation field decreases more rapidly with time than the fallout radiation field. Alpha particles, beta particles, and gamma rays are the principal components of residual radiation, because neutrons are emitted primarily as initial radiation during the explosion.

Of the components of the residual radiation, only ionizing electromagnetic radiation is penetrating radiation. These include gamma rays and other electromagnetic radiations present after the initial explosion, such as x rays from fission products and activation products, photons from positron annihilation, and bremsstrahlung from interactions of beta particles.

Weakly penetrating radiations include alpha particles, beta particles, conversion electrons, and Auger electrons, and are generally termed non-penetrating radiations. Because nearly all radioactive decay of fission products and activation products includes beta-particle emission, residual radiation fields include a significant beta-particle component. The spectral nature of beta particle fields, the short range of beta particles in matter, and unpredictable field exposure conditions cause the calculation and measurement of beta-radiation doses to be highly unreliable. Beta radiation dose is of concern for skin and eye irradiation, but external exposure to beta particles does not contribute to the radiation dose to deeper radiosensitive organs in the body.

Neutron activation can occur in virtually any material. The soil, building materials, steel, and other materials in naval vessels or other transportation vehicles, and sea water are but a few examples (Hashizume et al. 1969). Although

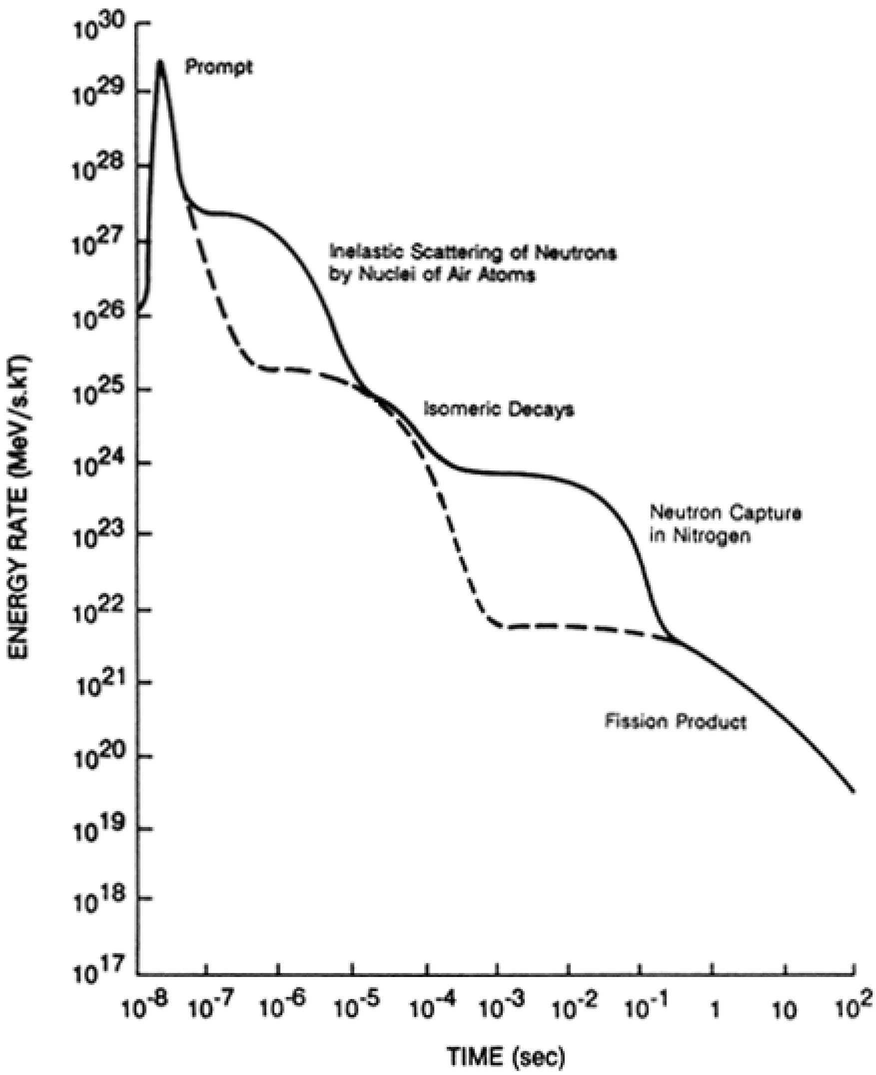

Figure 3-1
Calculated Time Dependence of Gamma-ray Energy Output Per Kiloton Energy Yield from a Hypothetical Nuclear Explosion (the dashed line refers to an explosion at very high attitude).

the elemental content of these materials varies greatly, all contain trace amounts or more of elements which have a high probability for neutron activation, such as iron, manganese, silicon, aluminum, sodium, chlorine, and cobalt. The radioactive isotopes of these elements present as induced residual activity are relatively few. The most important among these radionuclides are aluminum 28, manganese 56, sodium 24, chlorine 38, scandium 46, cobalt 60, and cesium 134. Induced activity can be present in fallout and in materials exposed to the initial radiation and not entrained into the radioactive debris cloud. Selected properties of these radionuclides are presented in the next section.

As is well known, there are significant differences in initial radiation produced in fusion and fission device detonations. However, these detonations resulted in residual radiation fields that were quite similar. With a few exceptions, as discussed in subsequent sections, the residual radiation field following detonation of either fusion or fission weapons is due to the same radionuclides, with differing relative abundances.

Fallout

Radioactive materials that appear in fallout include fission products, unfissioned uranium or plutonium, and activation products. (Cook 1957; Cook 1959; Glasstone and Dolan 1977). More than 200 radionuclides are produced in the detonation of a fission or fusion weapon. Nearly all emit beta particles, and many also emit gamma rays and x rays as they decay.

The total initial activity of fission products is extremely large but decreases rapidly because half-lives of most of the radionuclides are very short. There is more than a 2000-fold decrease in residual radiation due to fission products from the one-minute point to the end of the first 24 hours after detonation. Despite such a rapid decrease, the very large quantities of fission products that may be contained in fallout can produce a considerable amount of fission-product fallout activity after the first day following the explosion (Glasstone and Dolan 1977).

Activation products produced by neutron interactions with weapon components during and after the detonation include quantities of radioactive isotopes of iron, chromium, manganese, nickel, molybdenum, copper, cobalt, and vanadium from the weapon components. Although many of the radionuclides produced in this way have very short half-lives, there are several with half-lives exceeding several weeks. An important activation product present in fallout is cobalt 60 with a half-life of 5.3 years.

Other activation products include uranium 237, uranium 239, neptunium 239, neptunium 240, plutonium 239, and plutonium 240. Of these, the most prominent is neptunium 239 which is produced by beta decay of uranium 239 following radiative capture of neutrons by uranium 238. With a half-life of approximately 2.4 days, measurable levels of neptunium 239 are present in fallout for several weeks following a nuclear explosion (Cook 1960).

Materials (other than weapons components) in the vicinity of a nuclear detonation may become activated by neutrons from the explosion and subsequently entrained in the radioactive debris cloud. These materials include soil and other small particulates, vaporized structures, vaporized metallic objects, and water vapor. Elements in these materials which undergo neutron activation include sodium, manganese, silicon, iron, aluminum, chlorine, and potassium.

Induced Activity Other Than Fallout

Activity can be induced in materials in the vicinity of a nuclear explosion and not become entrained in the radioactive debris cloud. For a low-altitude detonation of a nuclear weapon, this activity can be significant. It includes many of the same induced radionuclides found in fallout. The location and concentrations of induced activity depend on several factors, including:

a. type of weapon
b. weapon yield
c. type of burst
d. distance from point of detonation
e. environmental conditions
f. elemental composition of materials in the vicinity of the detonation
g. time since detonation

These factors will determine the relative contributions that fallout and non-fallout induced activity make to the overall residual radiation. When there is little or no local fission-product fallout, neutron-induced activity is of primary concern for external dosimetry purposes.

D. PHOTON FIELDS FROM RESIDUAL RADIOACTIVITY

As discussed in the preceding section, the residual radiation following a nuclear explosion arises from fallout and induced radioactivity. The photon field from these radiation sources consists of bremsstrahlung, other x rays, and gamma rays. The field from gamma rays is composed of direct, unscattered photons as well as photons which have undergone one or more scattering interactions with surrounding materials.

Bremsstrahlung

As stated earlier, beta radiation from fallout is of concern for protection of personnel from exposures to the skin and the lenses of the eyes. Because beta particles have a short range in matter, external exposure to beta particles does not contribute to radiation doses to deeper radiosensitive organs. On the other hand, as beta particles are stopped in matter, bremsstrahlung is produced and subsequently contributes to the photon field. The energy distribution and intensity of bremsstrahlung depend primarily on the maximum energy of the beta particles and on the properties of the material with which beta particles interact. The intensity of bremsstrahlung produced has been shown to be proportional to the energy of the beta particle and the atomic number of the material. Low-energy beta particles interacting with low atomic-number atoms do not produce appreciable levels of bremsstrahlung.

For fission products and activation products produced as a consequence of the detonation of a fission or fusion device, the overall beta-particle spectrum is composed of numerous individual beta spectra of each radionuclide. The overall spectrum is dominated by beta particles with energies less than 1 MeV.

In general, materials with which fallout beta particles can interact have low atomic numbers. These include nitrogen, oxygen, carbon, sodium, hydrogen, silicon, etc., which are components of air, water and soil. Thus bremsstrahlung production in the vicinity of residual radioactivity does not contribute significantly to the photon field. This is confirmed by photon-spectrum measurements of the residual radiation fields.

X Rays

Characteristic x rays are emitted as a consequence of radioactive decay of many fission products and activation products. Few of these x rays have energies exceeding 100 keV and emission intensities (x ray per decay) are much lower than gamma-ray emission intensities.

Gamma Rays

A summary of gamma-ray energies for the selected radionuclides described previously is given in Table 3-1. Although many more radionuclides constituting residual radioactivity have been investigated in both theoretical and experimental studies (Cook 1959; Hashizume et al. 1969; Sandmeier and Battat 1982; NCRP 1982), the list of principal gamma-ray emitters producing the residual radiation field after a few hours can be reduced to the activation products neptunium 239, sodium 24, manganese 56, and fission products with half-lives exceeding approximately one minute.

TABLE 3-1 Significant Contributors to Residual Photon Field*

Production	Radionuclide	Half-Life	Gamma-Ray** Energy (KeV)	Intensity (%)
Activation Products	Np 239	2.36 days	100	61
			117	11
			210	3
			228	11
			278	14
	Na 24	15.0 hr.	1369	100
			2754	100
	Mn 56	2.58 hr.	847	99
			1811	27
			2113	14
	Cl 38	37.2 min.	1642	33
			2168	44
	Al 28	2.24 min.	1779	100
	Sc 46	83.8 days	889	100
			1121	100
	Cs 134	2.06 yr	569	15
			605	98
			796	85
	Co 60	5.27 yr.	1173	100
			1332	100
Fission Products	Numerous	—	Range of Energies	

* (Kocher 1981)
** Principal emissions

Photon energies listed in Table 3-1 range from 100 keV to 2.754 MeV. The photon energy spectra for radionuclides listed in Table 3-1 are time-dependent. Because half-lives of the individual radionuclides are different and because quantities that are produced during the explosion are related, the short-lived radionuclides dominate the photon energy spectra in the first few hours after detonation.

Because there are a large number of fission products in fallout which emit gamma rays with a wide range of energies, it is not practical to list every gamma-ray emitter produced as a fission product. The range of half-lives of these fission products is also very great (ranging over several orders of magnitude). The tabulation of photon emitters is further complicated by the chain of decay of initial fission fragments.

The photon spectrum due to fission-product activity has been reported for selected times following detonation (Nelms and Cooper 1959). The photon intensity as a function of energy, taken from the referenced report, is shown in Figure 3-2. In this energy spectrum, the dominance of gamma rays between 100 keV and 2 MeV is apparent.

Photon energy spectra for fallout have been measured for times ranging from two hours to 3000 hours following detonation (Cook 1960). Measured spectra indicate that between 65 and 85 percent of the photon intensity is from photons with energies between 100 keV and 1600 keV. Gamma rays with energies above 1600 keV contribute approximately 15 percent of the total photon intensity at three hours following detonation (Cook 1960). The contribution of lower-energy photons to the photon intensity from direct radiation is a few percent. The overall photon intensity from fallout includes a contribution from scattered photons which can be significant for selected exposure geometries.

The mean energy per photon in the fallout field has been shown to vary with time after detonation. This energy has been determined by calculation and measurement to decrease from approximately 1 MeV/photon at 2 hours following detonation to approximately 0.7 MeV/photon between 10 and 3000 hours after detonation. The concept of the mean photon energy is presented with the important caveat that it should not be used for shielding calculations or other physical processes (Cook 1960).

Although the mean photon energy is as stated above, there is a significant photon intensity for energies below 300 keV until several days following detonation. This low-energy contribution is probably from the presence of large quantities of neptunium 239 for the first few days after detonation (Cook 1960). Measurement results reported by other authors are in good agreement with these data (DeVries 1964; Sondhaus and Bond 1955; Ferguson et al. 1958; Webb et al. 1956; Thompson 1957).

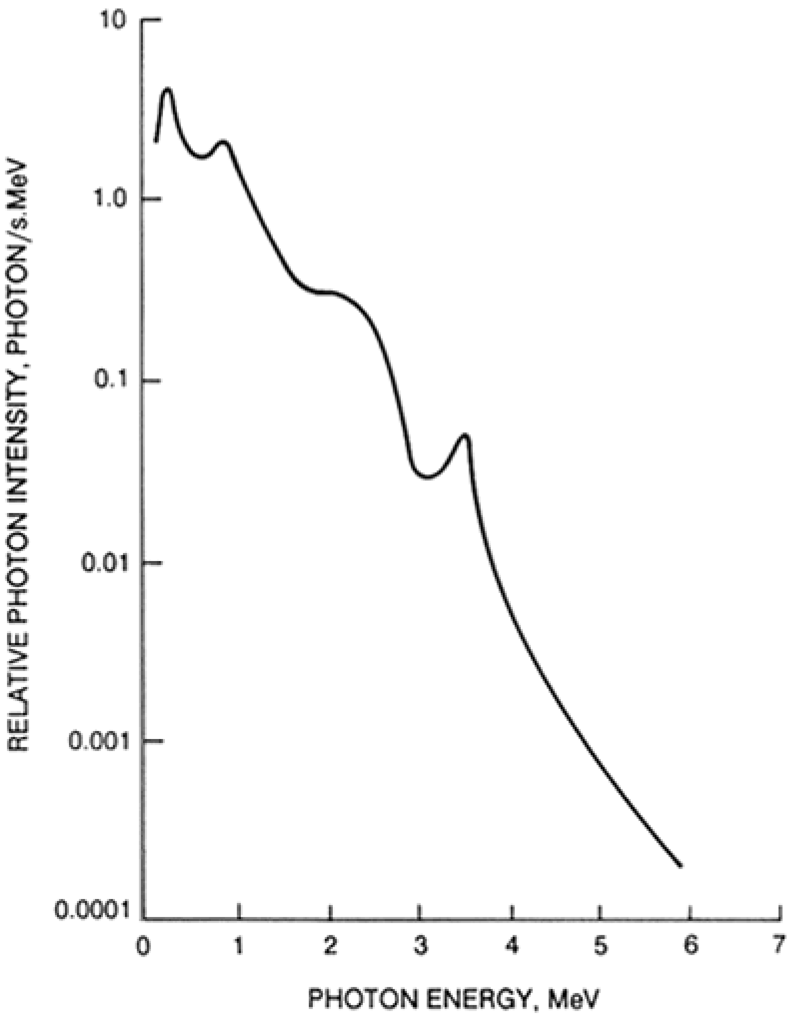

Figure 3-2
Experimental Photon Spectrum (t = 25.8 min.) (Nelms and Cooper 1959).

E. CONCLUSION

The residual radiation field following detonation of nuclear weapons consists of radiations from fission products, activation products, and unfissioned uranium or plutonium. During atmospheric testing of fission devices and fusion devices, differences in residual photon fields of residual radioactivity from detonations were observed. The nature of these differences has been determined to be caused by the relative abundance of a few radionuclides which were produced in each atmospheric test. For example, a low-altitude detonation of a fusion weapon induces large quantities of activation products emitting high-energy gamma rays which dominate the residual radiation spectrum for the first few days following the detonation. Conversely, a low-altitude detonation of a fission weapon produces large quantities of fission products which emit a very wide range of photon energies. In either type of weapon, depending on the design of the device, there can be a large amount of activity from the neptunium 239 produced, which can dominate the spectrum for several days.

Although the residual radiation intensity depends on a number of factors which may vary from shot to shot, there are relatively few radionuclides, common to all shots, which contribute to the major part of the photon spectrum. The relative abundance of each of these radionuclides determines the photon energy spectrum. In all cases, the photon field is from photons with energies between approximately 100 keV and 2 MeV. There is very little contribution from photons with energies less than 100 keV except for scattering from large area sources. In those cases, this scattered radiation was determined to have an energy of approximately 75 keV and to have contributed up to 10 percent of the overall photon spectrum.

In conclusion, atmospheric nuclear testing which included underwater, surface, and atmospheric shots at the Pacific Proving Ground and surface and atmospheric shots on the continent produced residual radiation which had photon fields with energies from approximately 100 keV to 2 MeV. Although photon spectra varied considerably from shot to shot, the range of photon energies was relatively constant.

4

Use of Film Badges in Atmospheric Nuclear Testing

A. FISSION AND ACTIVATION-PRODUCT MONITORING WITH FILM BADGES

Radiation produced by fission and activation products contain mixtures of beta particles, gamma rays, and x rays. The relative proportion and energies of these radiations will change with time and location. Such changes pose special problems for film badge dosimetry. These problems include:

- The need to compensate for rapidly changing sensitivity of film to photons with energies less than 100 keV (see Section 2.G).
- The selection of an appropriate calibration source, representing field exposure conditions, with which to produce the characteristic response curve relating density and *exposure.*
- The need to distinguish beta from photon exposures.

The prime radiological concern is exposure from photons with energies ranging from several hundred keV to a few MeV. These photons are the most significant radiation emitted by fission and activation products because of their abundance per disintegration range in air, and their ability to irradiate the deeper radiosensitive organs of the body.

As described in Section 2.G, the response of film per roentgen of *exposure* to these energies of photons is relatively uniform. This allows the same characteristic response curve to be used over a wide range of photon energies and also allows any one of several radionuclides that emit photons in the higher portion of this energy range to be used as a calibration source. These features allow film badges to be used to reliably monitor the most important radiations contributing to exposure from weapons-test-related photon fields.

The accuracy of monitoring exposure from photons with film badges is adversely affected by the presence of photons with energies less than 250 keV. These lower-energy photons cause a disproportionate amount of film darkening relative to their contribution to exposure. A lead filter, covering part of the film, was generally used during the atmospheric testing period to minimize the effect of the lower-energy photons. Use of filters to flatten the energy response of film was discussed in Section 2.G. When *exposure* was assessed from the optical density of the film underneath the filter, the same characteristic curve developed for high energies could be used for mixtures of low-and high-energy photons encountered by test participants.

A 0.020-inch-thick lead filter was used during operations CROSSROADS through IVY. This was not totally effective in correcting the over-response caused by photons of lower energy (Storm and Bemis 1950; Storm 1951). As a result of research performed at the National Bureau of Standards (NBS), beginning with the TUMBLER-SNAPPER operation and continuing throughout the atmospheric testing program, a 0.028-inch-thick lead filter was used. With this filter, the response to photons above 120 keV varied by 6%. The maximum sensitivity of this film badge occurred at 70 keV and was only 20% higher than the response at 1 MeV (AEC 1952). Because the experts in film monitoring at that time believed that the predominant energy of the troublesome low-energy photons was 100 keV, the 0.028-inch-thick lead filter was felt to be the most appropriate.

Small changes in lead thickness can alter the film badge response to low-energy photons. A 10% change in the thickness of the 0.028-inch-lead filter caused a 20% change in the response to 120 and 70 keV photons (Servis 1954). This variability was considered acceptable. Variations in lead thickness had little influence on film response at higher energies. Because the abundance of low-energy photons was small and variable, the true effect of changing lead thicknesses should be negligible in the presence of all the other factors known to influence film response.

As implied above, determination of the characteristic curve of *exposure* versus film density underneath the photon filter can be accomplished with any radionuclide that emits high-energy photons. Radium 226 in equilibrium with its daughters and cobalt 60 were used during the nuclear testing period. Radium 226 (1600-year half-life) and its daughters emit photons of many energies and best approximate the primary distribution of energies that led to exposures of test participants. Radium 226 was a principal standard in radiation measurements and was a useful laboratory source.

Another calibration source was cobalt 60 (5.3-year half-life) which emits two high-energy photons that represent higher photon energies in the test environment. A disadvantage is the relatively short half-life that limits the useful time for using the source to several years.

The effects of low-energy photons and beta particles present in the radiological field are not properly addressed by radium or cobalt sources used in the laboratory. The film response to unfiltered radiation cannot be evaluated because the composition of the radiation causing the density is unknown. For the open-window portion of the film it is not possible to duplicate field radiation conditions in the laboratory. The film in the open window area responds to all radiations penetrating the wrapper and any other overlying material. When low-energy photons are present, beta-particle exposures cannot be assessed because the increased sensitivity of film to low-energy photons masks response to beta particles (see Section 4.B for further discussion).

More than one film emulsion is normally required to measure the range of *exposures* sometimes encountered in atmospheric testing. Early test operations employed Kodak Type K film to measure lower *exposures* and Kodak Type A to measure *exposures* of several roentgens or more. Later operations used Du Pont Type 502 or 508 film for lower *exposures* and Du Pont Types 606, 1290, or 834 for higher ranges. All emulsions had similar energy-response curves, with the maximum sensitivity occurring for photons of about 40 to 50 keV (Storm 1951; Storm and Bemis 1950; Storm and Shlaer 1965).

The shape of the characteristic curve was similar for all of the emulsions. The Du Pont emulsions exhibited an effect in which the slope of the curve depended on the ionization density of the radiation. The slope of the curve for photons decreased with decreasing energy at optical densities less than 2.0. No effect was observed for densities greater than 2.0. Neither Kodak emulsion demonstrated this phenomenon (Golden and Tochilin 1959). For weapons testing dosimetry this effect is not likely to be of any consequence.

The use of the optical density under the filter assumes that a single characteristic curve is applicable for all energies. For the Du Pont emulsions, the *exposure* from low-energy photons evaluated with a characteristic curve for cobalt 60 could be underestimated by 10% to 20%. Because the 0.028 inch lead filter was not totally effective in reducing the over-response to these energies, the effect of an energy-dependent characteristic curve appeared minimal as no compensating corrections were proposed.

B. BETA PARTICLE MONITORING

Personnel film badge dosimeters were used for beta radiation monitoring during underground nuclear testing operations at the NTS from 1966 until 1987

(Brady and Iverson 1968). Film badges used for monitoring beta radiation at NTS and other locations where mixtures of beta and photon radiations were encountered, had at least three unfiltered and filtered film packet areas. As discussed in Section 2.B, unfiltered film responds to a given *exposure* from low-energy photons by more than 20 times the response to the same exposure from high-energy photons (Hine and Brownell 1956). For example, the NOD of films exposed to one roentgen of 40 keV x rays will be more than 20 times the NOD of films exposed to one roentgen of cobalt 60, an emitter of high-energy photons. The unfiltered or unshielded area of a film packet is referred to as the "open area" or "open window."

As also discussed in Section 2.B, a metallic filter with a high atomic number is used to provide a relatively uniform film response under this filter to photons from low to high energies. Thus, even if exposure is to low-energy photons, the amount of darkening under an optimum photon filter is not greatly different from the darkening which will result after the same amount of exposure to high-energy photons.

A third film area employs a filter either to attenuate beta radiation preferentially or to provide a different photon response. By discriminating against beta radiation, the photon contribution to the open area NOD can be determined. Photon-energy information can be obtained with a second photon filter response as a ratio with the primary photon filter response plotted against effective photon energy. Both methods can be used to subtract the NOD caused by photons in the open area.

The subtraction must be performed, however, in terms of *exposure*, not NOD, because the function of NOD versus *exposure* is not linear, i.e., an increment of NOD represents a different amount of *exposure* at different locations on a calibration curve. After subtraction, the remaining open-area NOD can be used to evaluate beta dose, provided that qualification is made and uncertainties provided regarding the film response variations at different beta-particle energies.

The response of Du Pont 502 double-coated emulsion in a paper wrapper (a typical low-range film component used during atmospheric testing) changes for maximum beta-particle energies between 0.5 and 3 MeV by almost a factor of ten (Hine and Brownell 1956). The energy distribution of beta particles from fission products changes with time. Uncertainties introduced by the film response to different beta-particle energies can be large when monitoring fission products with unknown beta-particle energies.

Optimum materials for a beta-discriminating filter are those with a suitably high mass density to maximize the attenuation of beta particles and a low atomic number to minimize photon attenuation (Brady and Iverson 1968; NAS 1986). One of the earliest beta-discriminating filters used was aluminum (atomic number 13 and density 2.7 g-cm^{-3}). For comparison, the most recent NTS film dosimeter utilized Teflon (TFE) (effective atomic number 8, density 2.15 g-cm^{-3}). The most recent beta-discriminating filter developed is tetraboron carbide (effective atomic number 5.45, density 2.5 g-cm^{-3}) (NAS 1986).

The filter system used in most atmospheric testing operations included a lead (atomic number 82, density 11.34 g-cm^{-3}) filter and open areas (wrapped with paper and plastic). Only very high energy beta particles could penetrate the lead filter. As a result, contribution of beta particles to the NOD under the lead filter was small, and had little effect on the evaluation of photon exposures. NODs in open areas, however, were affected by high-energy photons, low-energy photons to a much greater degree, and beta particles, to an extent dependent on beta-particle energy.

When a film badge with only a lead filter and an open area is exposed to unknown mixtures of beta and photon energies, it is not possible to determine contributions from each component to NOD in the film open area. At one extreme, an excess NOD in the open window area may be the result of only photons. At the other extreme, it may be the result of only beta radiation.

The first attempt to monitor beta exposures with personnel film badges during atmospheric nuclear testing was at Operation CROSSROADS in 1946 at Bikini Atoll in the Pacific. Double emulsion Eastman Kodak Type K film was used with a 0.020-inch-thick lead cross on one side of the packet; the tips of each cross leg bent around the four edges of the packet about 0.25 inch (see Figure 4-1).

All of the NOD in the open areas (the four corners of the packet) was assumed to be caused by beta radiation exposure. This assumption did not allow for exposure to high and, particularly, low-energy photons contributing to the NOD in the open areas. It is likely that the NOD of some films attributed to beta exposure was in fact caused entirely by photon exposure. For these reasons, beta exposure results determined with film badges at Operation CROSSROADS are unreliable.

The next test operation with reported beta exposures was RANGER which took place at NTS during January and February 1951. The film badge used was a Los Alamos badge with brass and cadmium filters. Both the brass and cadmium filters were 0.020 inches thick. Ratios of the responses under these filters were used to determine photon energies and photon-caused NOD in the open area. The same film badge design was used in the BUSTER-JANGLE test operation during October and November of 1951 in Nevada, but beta dosimetry was not attempted. Communication with the person responsible for dosimetry at Los Alamos and at Nevada during this time period established that the methodology used to determine beta exposure with the brass-cadmium badge was successful with laboratory calibration sources, but was not successful in the field (Littlejohn 1988a).

Operation WIGWAM was a single nuclear detonation deep in the Pacific Ocean about 500 miles from San Diego, California, and contamination which reached the surface rapidly dispersed. The WIGWAM radiation safety report stated that a cadmium filter and a vinyl filter "intended to facilitate the measurement of beta radiation" were used (Baietti 1957). There is no evidence in the records that beta dosimetry was performed during WIGWAM.

The final attempt to evaluate and report beta exposure with film badges during atmospheric testing was at Camp Desert Rock, outside NTS, during Operation PLUMBBOB in 1957. The U.S. Army Lexington Bluegrass Signal Depot provided film badges which were processed at Desert Rock by Signal Corps personnel. Most military personnel entering NTS in convoy for maneuvers during tests wore these badges. Other military personnel wore the standard NTS film badge with a lead filter.

This badge had four filter areas: lead-tin laminate, open window, copper, and aluminum. This combination was thought to be capable of providing beta exposure, but the analytical procedures used were faulty. The NOD measurements were improperly incorporated into certain equations, when converted exposure data should have been used instead. As stated previously, the function of NOD versus *exposure* is not linear, and NODs from a film must be converted to *exposure* with a common calibration curve because an increment of NOD can represent a different amount of *exposure* at different locations on a calibration curve.

Each of the film badge types used to monitor beta dose at the three test operations discussed could have been used to adequately monitor exposure to

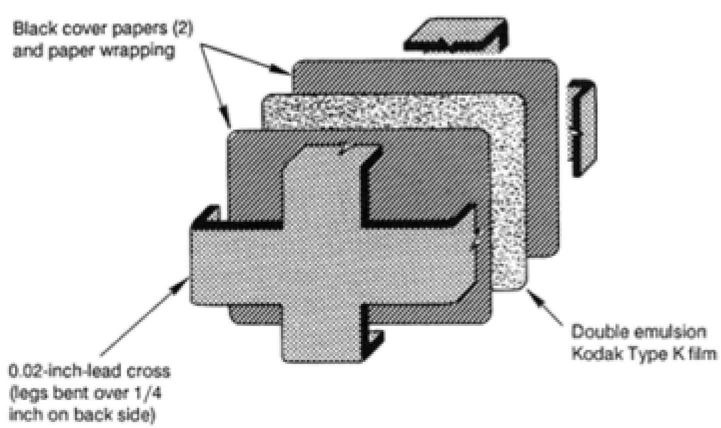

Figure 4-1
Film Badge Used in Operation CROSSROADS (first attempt to monitor beta exposure).

photons. Use of these badges to monitor beta dose, however, was unsuccessful. Either the film badge used did not have the capabilities for monitoring beta dose, or procedures used for evaluating beta exposures were incorrect. Thus, beta-particle monitoring with personnel film badges was not successful during atmospheric nuclear testing series.

C. CALIBRATION

The response of a film badge emulsion to ionizing radiation is measured by the darkening of the film that results after chemical processing (development) of the exposed film. This darkening is sensitive to the specific batch of emulsion from which the films were prepared by the manufacturer, conditions and length of storage before use, and conditions during the development process. To minimize uncertainties from all of these contributing factors during the nuclear test series, calibrations of films were made using gamma-ray sources, usually radium 226 in equilibrium with daughters, or cobalt 60, to establish the NOD versus log-*exposure* relationship for a film-development combination. Either of two calibration procedures was used: the gamma source was used to expose a number of different films simultaneously at different well-defined distances from the source for a well defined single time, or at a number of individual films for a well defined single distance for a set of well-defined times. Using the inverse-square-law dependence of gamma-ray intensity on distance from a physically small source, and a knowledge of source strength (relatable to an NBS calibration), the *exposures* of the calibration films were calculated. The NOD's of films thus exposed were measured after development and plotted as a function of log-*exposure* to produce a continuous calibration curve. Comparison of film darkening for a film badge exposed while worn in the field with this curve enabled the unknown film to be assigned a value indicating its *exposure*.

In most of the test series, one or a few films that had been exposed as calibration films to a radioactive source in a standard way we processed with each batch of films from the field. This provided an additional internal check on the reproducibility of the chemical processing. It was the practice during some early test series to calibrate each new batch of film from the manufacturer and to use the calibration thus derived to interpret all field-exposed films from that batch. These calibrations were carried out only every other day and resulted in some loss of accuracy in the calibration. This was not severe if processing conditions were carefully controlled.

D. FILM BADGE RANGE AND THE PROBLEM OF OVERLAP

Films of the types used for personnel dosimetry during the atmospheric tests had limited *exposure* ranges over which their responses changed in a useful way.

From the least *exposure* at which a reliably measurable NOD is produced to the highest measurable exposure is a factor of only a few hundred. Furthermore, the change in NOD per unit exposure, and hence the accuracy of dose determination, is much greater in the middle of the range than at either end. For different types of films, the most useful middle portion of the exposure range occurs at different exposures (see Section 2.F). The film badge used at CROSSROADS had a Type K film component for which the useful exposure range was small, only from 0.04 to 2 R with the densitometer used.

One way of extending the useful measurement range of a film badge is to include more than one type of film in the packet. After CROSSROADS, multiple films were used in all film badges. The choice of films had an important impact on the accuracy of the *exposure* determination in the *exposure* regions where responses overlapped. During the test series in 1951, a Du Pont 553 packet containing Type 502 (0.02–10 R), Type 510 (5–50 R) and Type 606 (10–300 R) components was used. This combination was adequate to determine exposures from 0.02 R to as much as 300 R for the photon energy spectra encountered in the tests.

During 1952, however, the Du Pont 558 packet with Type 508 and Type 1290 components was used. Figure 4-2 shows typical calibration curves for the upper range of the 508 component and the lower range of the 1290 component. Calibration data show that the useful upper limit of the Type 508 *exposure* range was 10 R, and there is little change in the NOD from 10 to 20 R. Similarly, the NOD of the Type 1290 component changes very little in the *exposure* range between 10 and 20 R. For this combination of film components there is inadequate overlap in the 10–20 R range, because the NOD changes are small and the calibration curves are relatively flat.

The Du Pont 559 packet with Type 502 low-range (0.02–10 R) and Type 606 high-range (10–300 R) components was used in each test series from 1953 until 1958. Figure 4-3 shows that this packet can achieve better results in the 10–20 R range than the 558 packet used in 1952, because NOD changes are greater and the curves accordingly are steeper. For test operations from 1958 through the end of atmospheric tests in 1962, a modified Du Pont 559 packet (later called a 556 packet) with Type 502 and Type 834 components was used. Figure 4-4 shows the overlap region of this packet and illustrates that the *exposure* uncertainty in the overlap region was also reduced considerably compared to Figure 4-2.

E. EFFECTS OF SOLARIZATION ON FILM BADGE MONITORING

Solarization is the reduction of film OD with increasing exposures. As related to film badge dosimetry, reduction (known as reversal) of OD may occur when a film component is exposed well beyond its useful or saturation range (see Section 2.E). Definitive research in this area of film dosimetry has been done by Ehrlich and McLaughlin (1961).

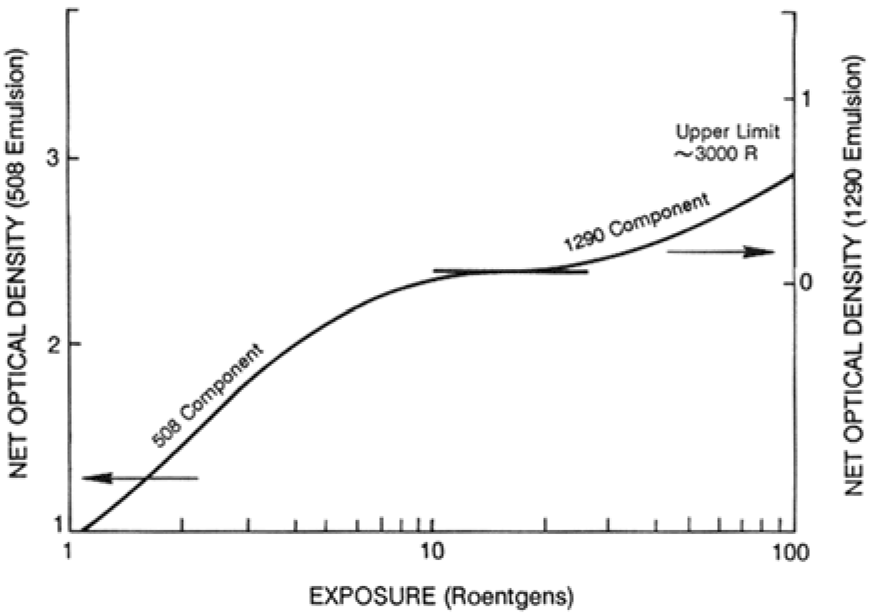

Figure 4-2
Overlap of Types 508 and 1290 Film Components.

A typical low-range film component used for film badging during atmospheric test series was the Du Pont Type 502, which had a maximum useful exposure range of about 10 R. At *exposures* to ionizing radiation between 100 and 300 R, the 502 film characteristic curve of NOD versus log-exposure reached its peak and descended, under certain exposure rate and film-development conditions.

This reversal of NOD with increasing *exposure* could have caused serious underestimates of exposure to the wearer of a reversed film component were it not for other compensating factors. First, the film badge, a passive integrating device, was used to determine an *exposure* of record, and could not serve as an indication of how long a person should stay in a radiation area or how much *exposure* was being accumulated before leaving. Radiation monitoring instruments were used to determine *exposure* rates and to estimate how long to remain in a radiation area. Self-reading pocket dosimeters were used to approximate how much *exposure* was being received while in a radiation area. Because film badge results were not available until after an individual left a radiation area, film badges were not used to control time spent in a radiation area, i.e., to control *exposure* being received during that time.

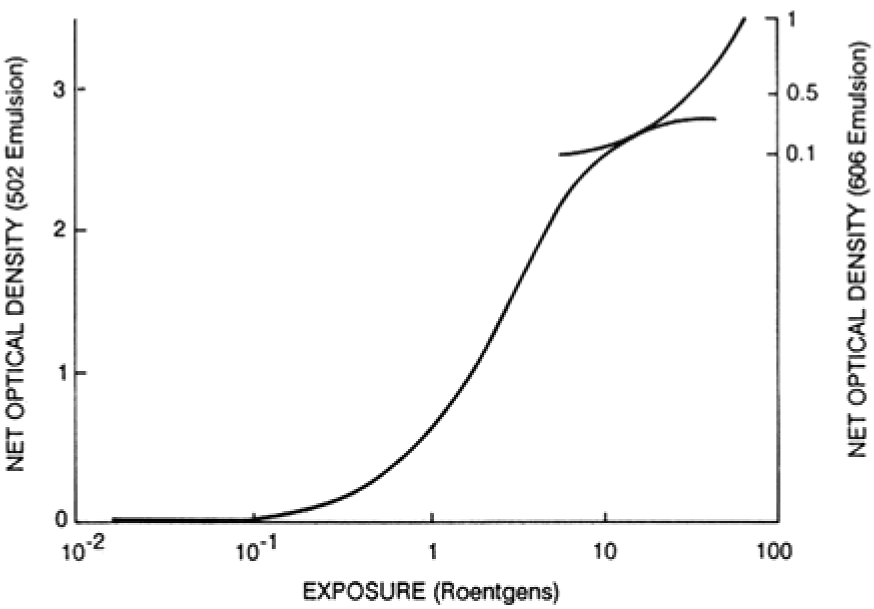

Figure 4-3
Overlap of Types 502 and 606 Film Components.

Secondly, at least one additional higher range film component was included with the Type 502 in the film packet during each test series when the Type 502 was used. The additional film usually had a useful *exposure* range that began at about the maximum *exposure* measurable with the more sensitive film component (see Section 4.D). If the Type-502 component indicated an *exposure* approaching its limit of 10 R, then *exposure* evaluation was performed with results from the high-range film.

As previously stated, reversal of the Type 502 begins at 100 to 300 R, but reversal to a density indicating 10 R or less would require an exposure of more than 600 R. An acute personnel exposure of this magnitude is considered lethal, and radiation-sickness symptoms would be obvious if a person received such an exposure over a few days or weeks.

When high-range film component *exposures* of several hundred R are applied to film packets to establish calibration curves, or for testing purposes, developing the low-range film components sometimes shows that reversal has occurred. Film-packet numbers were stamped (embossed) with impression dots on film packets used in most atmospheric test series. The colored dots were readable on the outside paper wrapping and, because film emulsions are sensitive to pressure, the dots of developed films were usually much darker than the remaining film areas.

If a film was very dark, the dots could still be read as numbers because the impression dies caused indentations on one side of the film and raised portions on the other. If a film was exposed beyond its range, the first indication of reversal would be the dots, which had a greater optical density to begin with. Thus, impression dots lighter than the remaining film indicated an *exposure* between the maximum usable range of the film component and the minimum required for reversal.

Another useful characteristic of reversal is as an indication and verification of light damage. As discussed in the next section, several types of environmental damage affect film, and knowing the cause or causes of emulsion damage is an aid to evaluating a film. Type 502 film OD does not reverse completely to the density of an unexposed film after cobalt 60 exposures up to 10,000 R or more.

Light leaks occur in film packets after damage to the wrapping causes a pinhole or tear. Typical light leaks show dark streaks radiating from the damage point (typically the edge or corner) on the developed films. More extensive light leaks may cause the entire film to be dark, but NOD measurements will show a

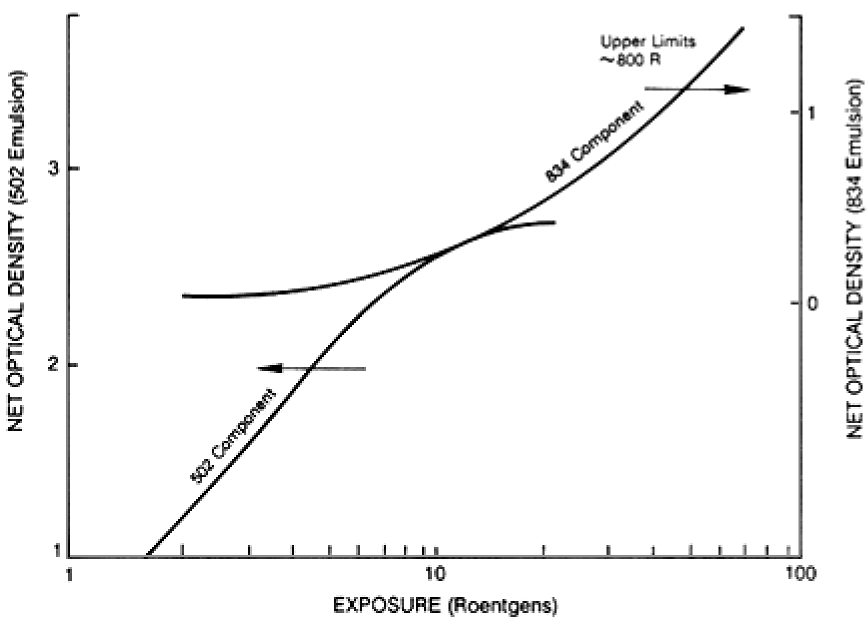

Figure 4-4
Overlap of Types 502 and 834 Film Components.

decreasing NOD gradient away from the damaged area. If a light leak is sufficient to darken the entire film, the light exposure may be sufficient to cause a small area of the film adjacent to the leak to reverse. Thus, a small, clear area is an immediate visual indication to the dosimetry technician that a light leak has occurred and that a careful evaluation of density gradient and minimum measurable density is necessary before any exposure assignment is made or investigation is conducted.

In summary, use of portable radiation-detection instruments and self-reading pocket dosimeters can usually avoid film badge *exposures* in the range that will result in solarization. A high-range film component, used in all atmospheric test series except one, could be evaluated to determine *exposures* above the range of the low-range component. If personnel *exposures* of the magnitude necessary to reverse a typical low-range film occurred, acute radiation syndrome symptoms most certainly would have been exhibited by the exposed person. The dosimetry technician was alerted to the approach to or the actual solarization by reversal of impression dots or other usually higher-density film areas. Finally, reversal is an aid to recognizing extensively light-damaged films.

F. RADIOLOGICAL AND OPERATIONAL EFFECTS

Interpretation of film badges is based on performance of the badges under controlled laboratory conditions, which are chosen to reveal the variations and uncertainties that can occur under various field situations. It is assumed that the film badges used in the laboratory are no different than those used in the field. This way, laboratory experiences can be transferred to evaluation and understanding of films used in the field.

This assumption must be seriously examined for film badge evaluations made during the weapons testing series. The conditions of radiation exposure of a film badge will be different between the field and the laboratory. This section identifies those differences between field and laboratory conditions which may require consideration of additional uncertainties in interpreting exposures of film badges worn in the field.

Conversion of the OD of an exposed film to *exposure* is accomplished by comparison with ODs of films exposed to known amounts of radiation. These latter films provide a calibration of film response to *exposure* . Different radiation sources were used to deliver the known *exposures* to calibration films during various test series. References have been made for radium 226 in equilibrium with daughters, for radium-beryllium and and cobalt 60 (see 5.D).

Calibrations were performed in air without any deliberate attempt to provide a backscatter contribution (not truly representative of the real situation in which photons are backscattered to a film badge by the wearer's body). Variations in calibration conditions occurred among the test series with regard to the control of other sources of scattered radiation (e.g., from nearby walls, bulkheads of ships, etc.).

Films exposed in the field differ from calibrated films in the following ways with regard to exposure conditions:

1. Personnel film badges were worn on a person, not freely suspended in air.
2. Sources described for the weapons tests are better characterized as area or volume sources as compared to the calibration sources which are considered to be point sources.
3. Scattered radiation was present in uncontrolled ways based on the objects that were present to generate the scatter.

The body can be effective in scattering radiation into the rear or sides of a film badge worn on a person. This backscatter contribution can range from 10 to 50 percent of the response from unscattered radiation, resulting in more darkening per unit of *exposure* for film worn on the body compared to film freely suspended in air. Based on calibration techniques used during atmospheric weapons tests, results in terms of exposure to personnel film badges worn by individuals might be overstated. No evidence exists that corrections for backscatter were made.

Film badge dosimeters with different filtration on front and back may be affected more by backscatter than those with equal filtration on both faces. Interpretation of film results using calibration data assumes that the radiation is normally incident on the film and has passed through the expected filtration. The film may have a different response to unfiltered radiation passing under the filter and affecting the accuracy of the evaluation. This problem can be very severe when low-energy photons are present. The purpose of filtration is to compensate for film response to such photons and to prevent significant overstatement of exposure.

Wide-area distribution of radiation sources and the presence of large objects which create scatter cause a film badge to be exposed from many angles. For the same level of *exposure*, film badges may exhibit large differences in response for different angles of irradiation. This angular dependence also changes with radiation energy, which may vary over space and time. The actual response of films worn in the field is the cumulative response to all the different combinations of *exposures* and angles at which radiation entered the badge.

Under field conditions, the angular distribution of radiation entering the badge is unknown and largely uncontrolled. Angular dependence is one of the most important contributors to uncertainty in the evaluation of dosimeters in the field.

Residual radionuclides associated with atmospheric weapons tests generally emit photons with energies from a few hundred keV to a few MeV. At these energies, the calibration sources used could have been adequate representations for the field environment. However, the interaction of radiation fields with various objects (e.g., ships and machinery) could alter the photon energy spectrum. The resulting spectrum could have a larger low-energy component than would be expected based on the original energy spectrum after a nuclear test. Film badge response could be changed, most likely resulting in an overestimate of *exposure*.

Radioactive contamination of a film badge is another problem. Fallout in areas around a detonation could have been directly deposited, resuspended, or otherwise transferred to the surface of a badge. Contaminated badges result in exposure of the films that are not characteristic of those received by the individual; solarization may occur in the center. Such contamination is rarely deposited. Results of contamination normally appear as spots or blotches of intense blackness. In addition, the exposure rate close to a speck of contamination changes very rapidly over fractions of an inch. These variations make it possible to identify most contaminated film.

If the contamination is localized to a small area of the badge, an estimate of the radiation from other sources could be attempted, using the unaffected regions. This is not advisable if the contamination affected a significant part of the film, as an erroneously high value is likely to result. In such cases it may be advisable to disregard the film data, considering the potential for error.

The pressures of developing and analyzing large numbers of films in short time frames can increase the likelihood of human error. Processing was often performed at night. Results were needed by morning so that those personnel approaching or exceeding *exposure* limits could be identified and work reassignments implemented.

Films were developed in batches. Variations in darkening of similarly exposed films among processed batches should be expected from differences in solution temperatures, developing time, and developer concentration. Standard operating procedures required that these factors be controlled to minimize these variations.

The effect of batch-to-batch developing variations can be minimized if one or more films exposed to a known level are developed in each batch; in effect, this enables each batch to be separately calibrated. This technique was used in most of the later test series. Gross variations between batches could be identified in these earlier tests through the use of unexposed control films; however, unexposed films are not as sensitive as calibrated film for indicating changes during developing.

Clerical errors can become more frequent under the stress of large-volume processing. Clerical mistakes are unpredictable, isolated, and usually noticed if inconsistent with expectations.

The large numbers of films necessitated manual readout by several persons using a number of densitometers. This required the densitometers to be intercom-pared to assure that each film would indicate the same density irrespective of which densitometer was used. This was accomplished by cross-calibration of the densitometers with films of different densities to assure appropriate agreement across the range of densities to be measured. The extent to which this procedure was performed is unknown.

G. ENVIRONMENTAL EFFECTS IN FIELD USE

Extreme or harsh environmental conditions may alter the response or affect the dose interpretation of film dosimeters. A variety of such environments was encountered during atmospheric testing. High temperatures and humidities along with salt water spray characterized the Pacific tests, while very dry, hot, and physically abusive conditions were found in the Nevada desert.

The potential effects can be conveniently grouped into five categories:

1. *Heat-Induced Fog*. Film is susceptible to fogging from exposure to heat and humidity. The film darkening due to such fogging can result in erroneously high estimates of radiation exposure if undetected. Even when detected, subjective judgment is required to assess whether any darkening might be due to radiation. When radiation is suspected, conservatism often results in a higher-than-actual exposure estimate.

   There appears to be a temperature threshold of about 130°F (50°C) below which fogging does not occur (Kathren et al. 1966). Several days at this temperature are required to induce measurable density, even in the more sensitive emulsions. At higher temperatures, shorter times are needed —as little as several hours at temperatures above 150°F (70°C).

   Several factors minimized the effects of heat fogging during atmospheric testing. Prior to use, films were stored in controlled environments where the effects of heat or humidity are not a concern. Secondly, the times to which film might be subjected to high heat were restricted by the short wearing intervals and the limits of human physical endurance at the temperatures necessary for rapid fogging. Therefore, it is unlikely that heat fogging is an important source of error, except in an extraordinary situation in which a film was placed near an infrared radiation source such as a hot metal bulkhead or engine. The non-uniform densities across a film and the inconsistent density relations among different emulsions make such cases identifiable. For example, radiation would not be indicated by a slight darkening of the sensitive Type 502 emulsion when accompanied by a darkened, less-sensitive Type 606.
2. *Latent-Image Instability*. Latent-image instability refers to the fading of the latent image and the resultant decrease in the expected density of exposed film.

Also dependent on temperature and humidity, fading results in underestimates of radiation dose.

High relative humidities have been shown in numerous studies to cause fading, with the greatest effect occurring when humidities approach 100%. Minimal effects are observed at relative humidities below 75% (Kathren et al. 1966). In the low-humidity desert climate of Nevada, latent-image fading can be eliminated as a contributor to uncertainties in radiation-dose estimates.

If unprotected, paper-wrapped films must be subjected to high humidities for one or (more likely) two weeks after exposure before fading becomes measurable. At the Pacific Proving Ground, where high relative humidities were the norm, the short times during which films were worn greatly lessened if not totally eliminated humidity-induced fading. Further protection from potential high-humidity effects was realized when film packets were sealed with wax or in plastic cases. Such efforts could extend the usable wearing interval to 2–3 months (Kathren 1987). These protective actions also reduced the damaging effects of water dampened film packets which increased film density, a much more prevalent problem than either latent-image fading or heat fogging.

For unprotected film badges worn for intervals greater than a week in relative humidities exceeding 70%, some fading can be postulated. The amount of fading depends on the time between radiation exposure and development. The amount of fading exponentially declines with time in reaching a maximum loss of 50% of the expected net optical density after six weeks. This represents an upper boundary to the error in the dose estimate. It is unreasonable to expect this amount of error as all of the radiation exposure would need to have occurred on the first day of use, followed by six weeks of constant high humidity. More realistically, exposures would have occurred at various times during the wearing interval, and the necessary humidity to produce fading would not always exist. Therefore, a suggested correction might be to increase the net optical density by one-third for films with positive readings and with documented potential for fading. This approach would result in an underestimate of 25% for the unrealistic upper boundary condition and an overestimate of about 30% for film that suffered no fading.

Another problem related to heat and humidity is the degradation of the film-packet integrity. During Operation REDWING, operation or series badges were initially issued for 4-to 6-week intervals. When unprotected, those badges used for longer periods showed frequent evidence of light leaks and water damage. Failure of adhesives holding the packet together is suspected to have resulted from the prolonged exposure to the weakening effects of heat and humidity. Fortunately, light leaks can be visually detected.

3. *Water Damage*. Water-damaged films were frequently encountered during the atmospheric tests. Decontamination activities, salt water sea spray, and

clothing wet with perspiration offered ample opportunities for damaging films. Early efforts to protect the film with plastic pouches were sometimes ineffective because water vapor would condense inside the pouch. Better protection was afforded by coating the badges in ceresin wax or encasing them in sealed plastic cases. The latter technique, while successful in one test series, required a saw to open the case, and this led to light leaks in another test series.

Water-damaged film usually can be visually identified. The damaged area appears as an irregularly shaped, unevenly darkened image, sometimes resembling a dried water drop. Often having a mottled appearance, the damage can be localized or involve most of the film. When localized, radiation *exposure* can be estimated by evaluating the undamaged area. Damage to radiation-exposed film may not be visually recognized when the *exposure* results in densities exceeding 2.5 or so. If the range of densities evaluated across the film is greater than expected, damage might be indicated.

No one limit can be established for the amount of uncertainty or error introduced by water damage. Subjectivity is almost always involved in deciding whether to attribute darkening to radiation or to water. Radiological safety reports and film reexaminations suggest that conservative decisions were made which resulted in overestimates of radiation exposure (Cooney 1951).

4. *Exposure to Light*. Exposure to visible light manifests itself as an area of intense darkening. Small breaches in the light-tight packaging will produce streaked areas or dark lines, usually radiating outward. Large openings can cause the entire film to become black with some areas possibly exhibiting density reversal from solarization (Section 4.E).

   Light-struck films were experienced during many of the tests. Physical abuse was not the only reason for cracks or tears in the film packet. Embossing identifying numbers as dots on packets sometimes resulted in small holes through which light could strike the film. A source of damage in one series was the sawing open of protective plastic cases. The saw blade sometimes would nick the corner of the packet, producing a light leak.

   The influence of fight damage on *exposure* estimates cannot be predicted. If localized, the damage may have no adverse effect, and the *exposure* can be determined from an undamaged area. Uncertainty occurs when deciding how much damage can be tolerated before a significant assessment error results. Extensive damage can preclude any meaningful dose assessment.

   Light-damaged film can mask darkening due to radiation. In those badges containing more than one emulsion, the possibility exists that the emulsions were not equally affected. The less-affected emulsion might have been used to establish boundaries on the amount of radiation that had been received.

5. *Other factors*. Other environmental factors with the potential for affecting the response or interpretation of a film include pressure and other mechanical

effects, chemical sensitization, static electricity, and radioactive contamination. With the exception of chemical sensitization, each of the effects listed produces a clearly identifiable anomaly. Pressure effects were noted in some of the earlier test-series badges which used the metal cross-shaped filter; these, however, were minor and should not have interfered significantly with densitometry or subsequent exposure interpretation. Static electricity can produce a characteristic treelike pattern on the developed film. The effect is usually associated with clothing made from nylon or other synthetic fabrics and is unlikely in humid environments. If severe, the effect can result in increased density readings. However, static discharge effects were rare and could easily be identified so that an undamaged film area could be used for evaluation.

Certain chemicals (such as mercury vapor in air) may cause a chemical sensitization or desensitization which produces a generalized increase or decrease in film density. However, there is no reason to suspect that films were exposed to sensitizing chemicals, and corrections are therefore not indicated.

Radioactive contamination in the form of particulates on the exterior of the film badge will produce what is basically an autoradiograph on the developed film, and has been discussed in Section 5.F.

H. FILM BADGE EXPOSURE VERSUS DOSE

This section presents a brief summary of the basic quantities used in the measurement of ionizing radiation and the units in which these quantities were expressed throughout the atmospheric test series period.

The concepts of primary importance are (1) "*exposure*" or "*exposure* dose", (2) "absorbed dose" or simply "dose", and (3) "dose equivalent". These concepts and their units are discussed below. The traditional "special units" (the roentgen, the rad and the rem) were used exclusively during the subject period. The new International System of Units (SI) was not adopted until 1975, and is now in common use outside the United States. For the precise technical definitions of radiation quantities and units, see ICRU Report 33 (ICRU 1980).

The term "exposure" has several meanings which depend upon the context in which it is used. In the generic sense it frequently means the condition of being exposed to something such as the elements, or light, or radiation. It also has a specific technical definition as a measure of the amount of x-rays and/or gamma rays at some point, as described below. When used in this latter sense in this report, it will be italicized.

Exposure , E, is a measure of the intensity of x or gamma rays reflecting the amount of ionization such radiation produces in air under standard conditions of temperature and pressure. When the air molecules (mostly oxygen and nitrogen) are ionized by radiation, some of the radiation energy is absorbed, releasing electrons. The original unit of *exposure* was the *roentgen* named after the discoverer of x rays. The roentgen, with the symbol "R", was defined as the quantity of radiation which would release sufficient electrons to produce at a specified point in air one electrostatic unit of electric charge per cubic centimeter under standard conditions. Thus the *exposure* is an indirect measure of the *intensity* of x or gamma rays.

It should be stressed that *exposure* refers only to x or gamma rays in air. Thus, strictly speaking, one cannot refer to the dose to a person in units or in terms of the roentgen. Its value in R units is determined not only by the number of x or gamma rays incident per unit area but also by the energy of the x or gamma rays. The SI unit of *exposure* is coulomb per kilogram (of air) and is equal to 3876 R. This conversion factor takes into account the mass of one cm3 of air under standard conditions.

Because absorption of photons is a complex function of the atomic number of the absorber and the photon energy, the measurement of *exposure* or *exposure* rate at a given point in air provides only the first step in the determination of how much radiation energy would be absorbed by an object placed at that point in the radiation field. The absorbed dose, D, is the amount of energy absorbed from any kind of ionizing radiation per unit mass of absorbing material at a specified point. The previous special unit of absorbed dose was the *rad* which was defined as 100 ergs of radiation energy absorbed per gram of material. The SI unit for absorbed dose is joule per kilogram and its special name is the *gray* (Gy). One gray is equal to 100 rad. One millirad is 0.001 rad and 0.00001 Gy.

Note that the concept of absorbed dose applies to all kinds of ionizing radiation, not only to x and gamma rays. It also applies to any kind of absorbing material and is not limited to air as is *exposure*. Absorbed dose is the most commonly used concept in radiation dosimetry. However, absorbed dose is difficult to measure in practice, whereas *exposure* is relatively easily measured by the use of air ionization chambers. Therefore absorbed dose at a given point in a specified material was often calculated from a measurement of *exposure* in air at or near the point of interest. Such calculations require knowledge of other dose-dependent factors such as the energy spectrum of the radiation field, density and effective atomic number of the absorbing material, attenuation of the incident radiation, and geometric orientation of the absorber relative to the radiation field. Radiation-measuring devices such as films (film badges) and thermoluminescent dosimeters in the past have been calibrated in terms of *exposure* (i.e. roentgen) for a given energy spectrum. Conversion of this calibration to dose has special limitations which are dependent on the instrument used, the characteristics of the radiation, and the conditions of exposure.

Equal absorbed doses of different radiations and energies may produce biological effects that differ in severity or frequency of occurrence if the doses are high enough for such effects to be observed. For radiation-protection purposes, where absorbed doses are usually very low, presumed differences in biological effectiveness has led to the development of the concept of *dose equivalent*, H, which is the absorbed dose modified by a "quality factor", Q.

The dose equivalent at a specified point in tissue is defined as: H=DQ, where D is the absorbed dose at the point and Q is the "*quality factor*" which takes into account differences in biological effectiveness. In the SI, the unit of dose equivalent is given the special name *sievert* (Sv). The traditional special unit used throughout this report is the rem. One sievert is equal to 100 rem. For a more comprehensive discussion on dose equivalent and quality factor, see ICRU (1980). Note that for x rays, gamma rays, and electrons (the so called low-LET radiations) the Q factor is 1.0. Therefore for these radiations the dose equivalent is numerically the same as the absorbed dose. In this report, the traditional units are used throughout because the SI units were not in use during the time period of atmospheric testing.

If the *exposure*, E, at a specified point is known or can be calculated from a knowledge of the relevant parameters, then the absorbed dose, D, also can be calculated by taking into account differences in the *absorption coefficients* for air and the medium at the point of interest and in the energy required to produce ionization in air. These parameters can be combined into one factor called the "f factor." The f factor for air itself is about 0.88. Hence for air, D = 0.88E. Thus an *exposure* of one R produces in air an absorbed dose of 0.88 rad (8.8 mGy) (ICRU 1973).

It should be noted that radiation dosimetry concepts are widely misunderstood by the public and radiation units are often used incorrectly even by the experts in radiation protection. For example, the traditional units "roentgen, rad, and rem" are often used interchangeably. In the case of x and gamma rays, the three units are numerically about the same (within 13%) for an accurately identified point in soft tissue and, because the uncertainties in absorbed dose measurements are often very much larger at very low levels (less than 1 rad), many experts ignore the distinction. In addition, the point or points where the absorbed dose is measured or calculated often is not accurately identified, even though the absorbed dose can and usually does vary widely from point to point throughout the body. If the dose to any point is below a level that can be considered biologically significant, then the failure to be specific about the dosimetry points of interest is of no practical consequence. This is usually the case in personnel dosimetry.

A simple statement of *exposure* in roentgen provides only very limited information about the absorbed dose to organs at risk. Such is the case when no information is given about the location where the measurement was made, or specifying the orientation of the person with respect to the measurement point, or the type of radiation and its energy, or the uniformity and extent of the radiation field. The organ of biological significance, the so-called "critical organ", also is usually not specified. Finally, a simple statement of the *exposure* gives no information about the reliability of the exposure measurement itself nor the time period over which the *exposure* (and hence the dose) was delivered. Nevertheless, when the reported *exposure* is low, an estimate of the upper limit of the absorbed dose to critical organs of interest may be sufficient, and certain plausible conclusions are possible.

When the entire body is in a penetrating x or gamma radiation field (such as during weapons testing), the critical organ is usually the bone marrow, which is relatively sensitive to ionizing radiation and is the source of radiogenic leukemia. If a dosimeter, such as a film badge, on or near an exposed person produces a response consistent with an *exposure* of one R, then it is likely that the biologically significant dose, (i.e., the mean dose to the bone marrow, is less than one rad (0.01 Gy), perhaps around 0.7 rad. If any part of the body was shielded, the mean bone marrow dose could be considerably less. In any case, when the absorbed dose is low (less than 1 rad to any critical organ), the lifetime risk for future cancer induction is also very low so that efforts to carry out further refinements in dose reconstruction are usually not justified. Such refinements, if made, are likely to reduce the estimated dose even further. Thus the error made by using *exposure* as a substitute for absorbed dose to a critical organ is of little consequence when the *exposure* values are low (less than the allowable *exposure* limits).

I. TEST SERIES EXPOSURE LIMITS

Recommended *exposure* (dose) limits for individuals who are exposed to ionizing radiations in the course of their work (radiation workers) have been reduced over the years from about 30 R per year in the 1930s and 1940s to 5 rem per year in recent years. Dose limits recommended by the National Council on Radiation Protection and Measurements (NCRP) in the United States generally have been adopted by various governmental agencies from time to time with only minor modifications. In addition to these limits, there is now a general policy that all doses should be kept as low as is reasonably achievable (the ALARA principle).

The prospective *exposure* limits adopted for the various U.S. nuclear test series were generally consistent with NCRP (and/or ICRP) standards for occupational exposure at the time. These are summarized in Table 4-1.

There were several reasons for wearing personnel dosimeters (such as film badges). The first was to monitor the radiation environment to provide reasonable assurance that *exposures* to individuals would remain below the applicable limits and to take corrective action if those limits were approached. The second purpose was to make possible rough estimates of absorbed doses to critical organs of any individuals who might be inadvertently subjected to *exposures* considerably greater than the prescribed limits.

TABLE 4-1 Radiation *Exposure* Standards for U.S. Nuclear Test Series

	Recommended Dose Limits By Agency						
OPERATION	NCRP	ICRP	ROUTINE MPE*	CLOUD SAMPLERS	DESERT ROCK	SPECIAL GROUPS	REMARKS
TRINITY (Alamogordo, NM) 7/16/45	0.1 R/day; 0.5 R/wk	0.2 R/day; 1.0 R/wk	5 R/2-month period				Personnel were to evacuate before 30 minutes if gamma readings outside shelter reached 1 R/h.
CROSSROADS (Bikini) 7/1/46-7/25/46			0.1 R/day, not to exceed 50-60 R in 2 wks. If individual received 10 R in one day or 60 R in 2 wks he was withdrawn from operation				Cloud trackers adhered to same standards as other units at CROSSROADS
SANDSTONE (Enewetak) 4/14/48-5/15/48			0.1 R/day, not to exceed 3 R per approved reentry for data	Cloud samplers were Drone B-17s			Exposures above 0.1 R/day required no exposure at 0.1 R/day until compensated for.
RANGER (NTS) 1/27/51-2/6/51	0.3 R/wk	0.3 R/wk	3 R/operation: 2 R for personnel participating in GREEN-HOUSE: AEC	Manned sampler aircraft first used at RANGER		Public could receive up to 25 R without danger	Cloud sampling aircraft in Nevada operated out of Indian Springs AFB.

GREENHOUSE (Enewetak) 4/8/51-5/25/51	3.9 R/13 wks; 0.1 R/day, not to exceed 0.7 R/week	Drone B-17s used as Cloud Samplers			
BUSTER-JANGLE (NTS) 10/22/51-11/29/51	3 R/operation	1.9 R for 13 week operation; cloud sampling aircraft were B-29s	1 R total (DR I), 3 R (DR II &III)	All observers wore film badges (DR II, III)	3 R MPE could be exceeded if test director approved
TUMBLER-SNAPPER (NTS) 4/1/52-6/5/52	3 R/operation	Cloud samplers: B-29s, T-33s, F-84s; cloud trackers: B-29s, B-25s	DR 3 R/operation recommended exposure level be raised above 3 R	When transporting radioactive samples, aircrew members were limited to 10 mR/h	
IVY (Enewetak) 11/1/51-11/16/52	3.9 R/operation gamma only	Crews on sampling aircraft: total MPE of 20 R for operation		AEC approved emergency exposure of 25 R total	
UPSHOT-KNOTHOLE (NTS) 3/17/53-6/4/53	3.9 R/operation gamma only	Cloud samplers F-84s, Cloud trackers B-29s & B-25s	6 R for operation		

*MPE = Maximum Permissible *Exposure*.

	Recommended Dose Limits By Agency						
OPERATION	NCRP	ICRP	ROUTINE MPE*	CLOUD SAMPLERS	DESERT ROCK	SPECIAL GROUPS	REMARKS
CASTLE (Bikini, Enewetak) 3/1/54-5/14/54	3.0 R/13 wk 0.3 R/wk (max) 15 rem/yr	3.9 R/13 weeks;	augmented by 0.3 R/wk after that	Special MPE of 20 R (gamma only)		MPE waiver to 7.8 R approved by Dir., DBM, Surgeon General's Office	
TEAPOT (NTS) 2/18/55-3/15/55			3.9 R/operation	Cloud samplers: F-84s; Cloud trackers: B-25s, B-50s, B-29s	DR VI 6 R total: no more than 3 R prompt for test; 6 R in six months	DR VI: Volunteers: 10 R total w/5 R prompt; not more than 25 R/operation	Exposure of personnel above 3.9 R was authorized in advance by the test manager upon recommendation of the test director based on operational necessity
WIGWAM (Pacific) 5/14/55			3.5 R/operation; hands and feet 20 R/operation	Only Cloud trackers, no Samplers at WIGWAM		Approx. 10 water-sample collectors were authorized 20 R/operation	
REDWING (Bikini, Enewetak) 5/5/56-7/22/56			3.9 R/13 weeks	20 R (gamma only) authorized for operational period	Emergency MPE:	600 persons exceeded 7 R/operation; Authorization to exceed MPE limits granted by CJTF-7	3.9 R exposure limit

PLUMBBOB (NTS) 4/27/57-10/7/57	5 rem/yr (avg.); 12 rem/yr (max)		3 R/13 weeks, 5 R/yr	7.5 R B-57s used for cloud sampling	5 R/6 months: rate of accumulation no more than 2 R prompt		MPE limits recommended by DBM
HARDTACK I (Bikini, Enewetak, Johnston Islands) 4/25/58-8/18/58	0.5 rem/wk (max); 3.0 rem/13 wk; 12 rem/yr (max.); 5(N-18) rem/yr**	0.5 rem wk/; 3.0 rem/13 wk; 5(N-18) rem/yr**	3.75 R/13 wks; 5 R for operation	B-57s used for cloud sampling		TG7.7 (H&N) requested that 3.75 R be increased (unspec.) & that 5 R be increased to 10 R for 35 H&N employees	25 individuals exceeded the 5 R limit
ARGUS (South Atlantic) 8/27/58-9/6/58							
HARDTACK II (NTS) 9/10/58-10/30/58			3 rem/quarter, 5 rem/year	10-15 rem for those also participating HARDTACK I		12 personnel: (AFSWP) authorized by test manager to receive 25 R	Provisions of Handbook 59 (NBS 1954) prevailed in case of accidental or emergency exposure

*MPE = Maximum Permissible *Exposure*.

**N is age in years at last birthday.

OPERATION	Recommended Dose Limits By Agency NCRP	ICRP	ROUTINE MPE*	CLOUD SAMPLERS	DESERT ROCK	SPECIAL GROUPS	REMARKS
DOMINIC I (Christmas & Johnston Islands, Eastern Pacific) 4/25/62-11/4/62			3 rem/13 weeks & 5(N-18) rem/yr**	None	25 R	Emergency MPE: MPE 50 R.	Grave emergency Personnel under age 18 had to evacuate if cumulative dose reached 1 R
DOMINIC II (NTS) 7/7/62-7/17/62			3 rem/quarter, 5 rem/yr.				

*MPE = Maximum Permissible *Exposure*.
**N is age in years at last birthday.

Selected abbreviations used in this radiological matrix are:

AEC	Atomic Energy Commission
AFB	Air Force Base
AFSWP	Armed Forces Special Weapons Project
CJTF	Commander Joint Task Force
DBM	Division of Biology and Medicine, AEC
DR	Desert Rock
FC	Field Command
H&N	Holmes and Narver, Inc.

5

Quantification of Personnel Film Badge Uncertainties

A. DEVELOPMENT AND APPLICATION OF MEASURES OF TOTAL UNCERTAINTY

In Chapter 4, several sources of uncertainty in film badge dosimetry were identified. This chapter quantifies those uncertainties, and assesses their effect, acting jointly, on estimates of *exposure* and of deep-dose equivalent obtained from personnel film badges (see Section 5.E). The assessment is made specific to each test series, to the magnitude of the estimated *exposure*, and to other relevant conditions surrounding the film badge reading.

The uncertainty assessment is accomplished by developing an approach for calculating upper and lower limits for the *exposure* and deep-dose equivalent based on any film badge reading obtained during atmospheric nuclear tests. The method of calculation is intended to assure that there is a high probability that the limits include the actual *exposure* and deep-dose equivalent received by the individual. The intervals may be calculated for any specified probability level, with 95% being a common choice.

Because the available data are inadequate to quantify all sources uncertainty in a rigorous statistical manner, expert opinion must often be relied on for this assessment. For this reason, the limits are not "confidence intervals" in the classical statistical sense, and are sometimes referred to as "subjective confidence intervals." The appropriate interpretation of 95% intervals presented in this report is that, based on a careful assessment by experts of many individual sources of uncertainty, there is a 95% probability that the interval includes the true value. It is also appropriate to interpret the intervals as indicating that there is only a 2.5% chance that the true value exceeds the upper limit, and only a 2.5% chance that the true value is less than the lower limit.

Evaluating Individual Sources of Uncertainty

To evaluate overall uncertainty, it is first necessary to specify probability distributions for each uncertainty source; this is accomplished by specifying the probability that the estimated value falls within any specified range. The distributions for individual uncertainty sources are then used to evaluate the probability distribution for all uncertainty sources acting jointly. This process may require complex calculations and possibly computer simulations. A discussion of approaches to uncertainty analyses is provided in a report of the National Council on Radiation Protection and Measurements (NCRP 1984).

The assessment in this report is based on the use of lognormal distributions for describing uncertainties from individual sources. The lognormal distribution is one in which the logarithms of the estimated values follow symmetric normal distributions, and is symmetric on a multiplicative scale; that is, the probability that an estimated value exceeds F times the median value, is the same as the probability that a value is less than 1/F times the median value. A major advantage of the use of lognormal distributions is that uncertainties from different sources can be easily combined without the need for extensive computations. The use of the lognormal distribution for uncertainty analyses is described by the NCRP (1984) and is illustrated by the National Institutes of Health Ad Hoc Working Group to Develop Radioepidemiological Tables (1985). The general properties of the lognormal distributions are described in detail by Johnson and Kotz (1970) and by Aitchison and Brown (1969).

If the logarithm of an estimate follows a normal distribution with mean, m, and standard deviation, s, then the estimated value follows a lognormal distribution characterized by its median $M = e^m$, and by its geometric standard deviation (GSD), $S = e^s$. It is useful to express M as a factor B times the true value, and refer to B as the bias. If B >> 1, the true value on average has been overestimated; while if B < 1, the true value on average has been underestimated. (It should be noted that the mean of the lognormal distribution is a factor $e^{s^2/2}$ higher than the median; however, this source of bias is negligible relative to the overall uncertainty, and can be safely ignored for most purposes). The GSD has the property that two-thirds of the estimated values fall between (1/S)M and SM.

If adequate data are available, B and S can be estimated using standard statistical procedures. In the absence of such data, B and S must be estimated, based on judgments of scientists with relevant expertise. One approach is first to provide a subjective assessment of B and then to provide a factor K such that the interval obtained by multiplying the true value by (1/K)B and KB is thought to cover 95% of the estimated values. The GSD and s can then be determined by the relationships K = S1.96, and s = log(S). The values of K satisfying this relationship are referred to as 95% uncertainty factors. Once the parameters of the lognormal uncertainty distribution have been specified, the P% subjective confidence intervals can be determined as

$$(E/B)\, e^{\pm Z_p \cdot s} \qquad 5\text{-}1$$

where E is the *exposure* as determined from the film badge reading, and Zp is an appropriate factor determined from tables of the normal distribution. The values of Zp are 1.960, 1.645 and 1.00, respectively, for 95%, 90%, and 66.7% subjective confidence intervals.

Figure 5-1 shows a plot of two lognormal distributions with M = 1. The probability that an estimated value falls between two specified values is represented by the fraction of the total area under these curves falling in the specified region. The plot with K = 1.5 (S = 1.23) represents a modest amount of uncertainty with 95% probability that the estimated value falls between 0.67 and 1.5. The plot for K = 4 (S = 2.03) represents a much greater amount of uncertainty; the range 0.25 to 4 is now required to cover 95% of the probability.

Combining Several Sources of Uncertainty in One Badge Reading

The approach used to combine uncertainties is based on the assumption that the uncertainties from specific sources follow independent lognormal distributions. This assumption of independence requires that the direction and magnitude of the error from one source have no influence on the direction and magnitude of error from any other source. This assumption appears reasonable for combining uncertainties from most of the sources considered in this report. For example, it is unlikely that uncertainties resulting from the way a film badge is used in the field would be related to uncertainties resulting from laboratory processing. Where uncertainties from different sources were judged to be interdependent, they have been assessed in combination rather than individually.

It is assumed that the film badge reading, E, can be written as the product of the true *exposure* (or deep-dose equivalent) and several factors Ei, i = 1, 2, ... N. It is further assumed that the Ei follow independent lognormal distributions, that B_i and S_i represent the bias and the standard deviation on a logarithmic scale,

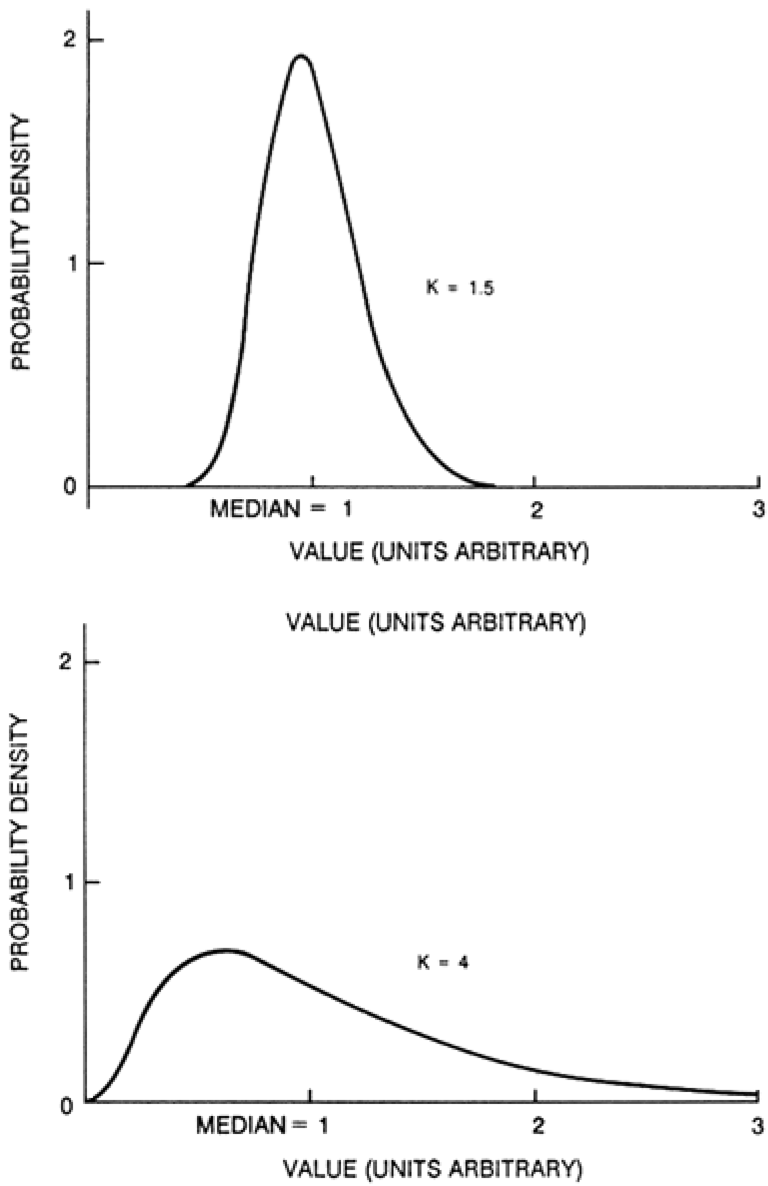

Figure 5-1
Lognormal Distributions.

respectively, for distribution i. It then follows that E will also follow a lognormal distribution with bias given by B = ΠiBi, with a logarithmic standard deviation, s, defined by

$$s^2 = s_1^2 + s_2^2 + \ldots + s_N^2, \qquad 5\text{-}2$$

and with a P% confidence interval given by

$$(E/B)\, e^{\pm Z_p s}. \qquad 5\text{-}3$$

This is the same expression as Equation 5-1, but now s and B include uncertainties from several sources. It is useful to define the GSD and 95% uncertainty factor from source i as Si and Ki respectively, where Si = es i, Ki = Si 1.96 and to define the overall GSD and 95% uncertainty factor by S = es and K = S1.96, respectively. *Example*: A film badge reading, obtained in test A, provides an *exposure* estimate of 0.8 R. In Section 5.B, three major categories of uncertainty in *exposure* will be identified: laboratory, radiological, and environmental. The following values for Bi, Ki, and Si are typical and illustrate the combining of uncertainty sources.

Uncertainty source	B_i	K_i	S_i
Laboratory	1.0	1.2	0.093
Radiological	1.0	1.3	0.133
Environmental	1.2	1.1	0.049

In this case, B = 1.0 x 1.0 x 1.2 = 1.2

$$s^2 = 0.093^2 + 0.133^2 + 0.049^2 = 0.0287$$

$$s = 0.170, K = 1.39$$

The 95% interval is given by $(0.8/1.2)^{e\ \pm 1.96\ \times\ 0.170}$ or as (0.48, 0.93). Without the bias factor of 1.2, the interval would have been (0.57, 1.12), based on an overall 95% uncertainty factor of 1.39. This factor is not as large as the product of the individual K_i, which is 1.72. Because they are uncorrelated, uncertainties from different sources tend to cancel each other out. However, the overall uncertainty factor can never be smaller than the maximum K_i.

In the sections that follow, the estimates of the parameters Bi and si, as well as Si and Ki, are determined for each of several uncertainty sources. These estimates are specific to each test series, and in some cases to the magnitude of the estimated *exposure*. In addition, the calculations necessary to combine uncertainties have been performed for the reader. In Chapter 6 tables are provided giving 95% subjective confidence limits for each test series as a function of *exposure*.

Special Problems in the Application of Uncertainty Analyses to Film Badge Dosimetry

Because uncertainties in film badge readings are often expressed in a form that is symmetric on an additive scale (e.g., ± 50%), the use of the lognormal distribution in this report merits comment. In general, the lognormal distribution, with symmetry on a multiplicative scale, is more appropriate for measures that cannot be less than zero, but with no clear upper bounds. For small uncertainties (K. ≤ 5, or 50% error), the lognormal distribution is very close to a symmetric normal distribution (see Figure 5-1) and thus the two distributions yield similar confidence limits. For large uncertainties, the symmetric normal distribution may permit negative estimates with high probability; this would be inappropriate for many film badge uncertainty sources.

Nevertheless, certain sources may be more appropriately described on a symmetric scale. In these cases, emphasis has been put on determining the correct upper bound; the effect of using a lognormal instead of a normal distribution in such cases will be a lower limit that is too high. For example, if the correct 95% limits for an estimate are $M \pm 1.96\ \sigma$, K is taken to be $1 + 1.96\ \sigma/M$. The upper limit of KM would be correct, but the lower limit (1/K)M is larger than the correct lower limit of $M-1.96\ \sigma$. (This result can be shown algebraically, or a few trial values for M and σ should assure the reader of its validity.)

Since laboratory uncertainties at low *exposures* are likely to be better described by the symmetric normal distribution than by the lognormal distribution, a special procedure has been used to treat such uncertainties. Note that at low *exposures*, negative estimates are possible because adjustment for background fog of a film is needed (although such estimates are generally recorded as zero). This special procedure is described in Section 5.B, and provides lower confidence limits of zero for very small estimated exposures.

Uncertainty in Estimates of Total Dose Based on the Sum of Several Film Badge Readings

Although the scope of this report has been defined to include only the assessment of uncertainty in single film badge readings, uncertainties in the estimates of the total *exposure* for individual test participants, which are based on the sum of several film badge readings, are naturally of interest. Because the sum of several lognormally distributed variables does not follow a lognormal distribution, and because uncertainties from some sources may not be independent for different readings from the same subject, the assessment of uncertainty of the estimated total *exposure* is complex.

The following recommendations are made for assessing uncertainty in the total *exposure* derived from the sum of several film badge readings. First, it is noted that the interval obtained from the sums of the upper (lower) P% limits for the individual film badge readings may in many cases provide useful limits, especially if the number of readings is small and/or the estimated *exposures* are small. The confidence level associated with such an interval will be ≥ P%, and, because intervals obtained in this manner do not account for possible cancelling of uncertainties as *exposures* are summed, they will generally be wider than necessary. However, if the limits obtained from this approach provide sufficient information for the application of interest, it may not be necessary to proceed further.

When the problem of lognormal summation is encountered, it is often solved by using a Monte Carlo simulation method (Lee and Salem 1977). In the case of film badge readings, it is possible to take advantage of a reasonable approximation that greatly simplifies the calculation. Note in Figure 5-1 that when the uncertainty is relatively small (i.e., the 95% uncertainty factor is 1.5), the lognormal distribution approaches a normal distribution. In this case the mean and median are nearly equal. Thus to a reasonable approximation the mean of the sum is just the sum of the medians. For example, even when the 95% uncertainty factor is 2, the largest value encountered in this study, the mean is only 6% larger than the median.

If uncertainties in readings from different badges for the same individual are independent, this approach also suggests that to a reasonable approximation, the variance, V, of the sum of M readings is given by

$$V = \left\{ 1/(1.96)^2 \right\} \sum_j (K_j - 1)^2 (E_j/B_j)^2, \qquad \text{5-4}$$

where Kj, Ej, and Bj are respectively the 95% uncertainty factor, the film badge reading, and the bias for the jth reading. Approximate 95% confidence intervals for the total are then obtained as

$$E_j/B_j \pm 1.96\sqrt{V} = E_j/B_j \pm \sqrt{\sum_j (K_j-1)^2 (E_j/B_j)^2} \qquad 5\text{-}5$$

Thus, for example, if an individual's record consisted of the following readings, the total *exposure* and its 95% confidence interval could be calculated as follows.

Reading(j)	E_j	B_j	K_j	E_j/B_j	$(K_j-1)^2(E_j/B_j)^2$	95% confidence limits for single readings
1	0.1	1.0	2.0	0.10	0.0100	(0.05, 0.20)
2	0.4	1.2	1.2	0.33	0.0044	(0.28, 0.40)
3	0.6	1.0	1.2	0.60	0.0144	(0.50, 0.72)
Total				1.03	0.0288	(0.83, 1.32)

The resulting confidence limits for the total, based on the assumption of independence of uncertainties in the three readings, are $1.03 \pm \sqrt{0.0288}$ or (0.86, 1.20). These limits are narrower than the more conservative limits (0.83, 1.32) obtained by summing the lower and upper limits from the three readings.

B. CATEGORIES OF UNCERTAINTY

The sources of uncertainty in radiation exposure determined from film badge dosimetry have been grouped into three categories: laboratory, radiological, and environmental. Uncertainties associated with each of these will be combined as described in Section 5.A. The three categories are interpreted as follows:

Laboratory Uncertainties

This category includes all the uncertainties introduced in film calibration, chemical processing of films, reading their optical densities, comparing these densities with the densities of unexposed and calibration films, and in interpreting the measured densities in terms of *exposure*.

Even under the best controlled laboratory conditions, laboratory uncertainties are a strong function of exposure level, particularly at low exposure levels. This behavior is evident from the general mathematical form of the variation of film optical density, D, with *exposure*:

$$D = D_\infty (1-e^{-\gamma E}), \qquad 5\text{-}6$$

where D∞ is the saturation density of the film at high *exposures*, E, and γ is the sensitivity of the film. For the Du Pont Type 502 film illustrated in Figure 4-3, D∞ = 2.8. and γ= 0.25 with *exposure* expressed in R; other films of comparable sensitivity to that of the Type 502 film should yield similar values.

If it is assumed that the standard deviation of the measured optical density does not depend on *exposure*, and is given by a constant σ*, the standard deviation of the measured *exposure*, σ (E), can be shown to be approximately equal to

$$\{\sigma^*/(D_\infty \gamma)\}\, e^{\gamma E}. \qquad 5\text{-}7$$

If it is further assumed that measured *exposures* are approximately normally distributed, the upper confidence limit (for two-sided 95% limits) are given by E + 1.96 σ (E). The 95% uncertainty factor (the factor needed to multiply the measured *exposure*, E, to obtain this upper limit) is then given by

$$K(E) = 1 + 1.96\, \sigma (E)/E. \qquad 5\text{-}8$$

Because replicate density readings at the same *exposure* generally yield values within ± 0.03 density units, it is reasonable to take σ* = 0.015. With the values of D∞ and γ given above, we have

$$K(E) = 1 + 0.042\, e^{0.25E}/E. \qquad 5\text{-}9$$

In Figure 5-2 this K(E) is plotted (solid line) as a function of *exposure*. The 95% uncertainty factors K(E) for *exposures* between 0.5 R and 14 R are less than 1.1, with a minimum value of 1.03 at 4 R. However, below 0.2 R and above 14 R the uncertainty rises rapidly. In general, the *exposure* levels that delineate the useful range of the film, (small K(E)) depend on the sensitivity of the film.

If a badge contains more than one film component, the overall *exposure* uncertainty using both film components may have a peak in the region of overlap (see section 4.1)) of the different components. The low sensitivity Du Pont Type 606 film, part of whose *exposure* curve is shown in Figure 4-3, has a D ∞ = 3.0 and a γ = .006. The uncertainty, K(E), vs *exposure*, E(R), for this film (from Equation 5-8 with σ * = 0.015) is shown by the dashed line in Figure 5-2. For the two film components shown in Figure 5-2, the overlap between the two films is sufficiently good that there is only a small rise in K (to K = 1.2) at the high-*exposure* end of the 502 film and the low-*exposure* end of the 606 film. If the

508–1290 film combination shown in Figure 4-2 had been used, there would have been a much larger peak in K in the region of overlap.

The intrinsic uncertainties in determining *exposure* discussed above are increased by uncertainties in the radiation field and in the time used in calibration, by variations in film processing conditions if calibration and unexposed films are not processed with each batch of field exposed film badges, and by possible inaccuracies in reading a calibration curve. For these reasons, the minimum laboratory uncertainty is never estimated to be as low as 1.03. Under controlled laboratory conditions it is conservatively estimated to be at least 1.2. Under less favorable conditions in some test series the minimum K is even larger. In almost all cases, the intrinsic uncertainty dominates at low *exposures*. The value of K for laboratory uncertainty is deduced as the appropriate combination (see Section 5.A) of the intrinsic uncertainty and estimated uncertainties in processing, calibration and interpretation. Unless stated otherwise, uncertainties for *exposures* in the overlap region of two different films were based on a K of 1.5 for laboratory uncertainty.

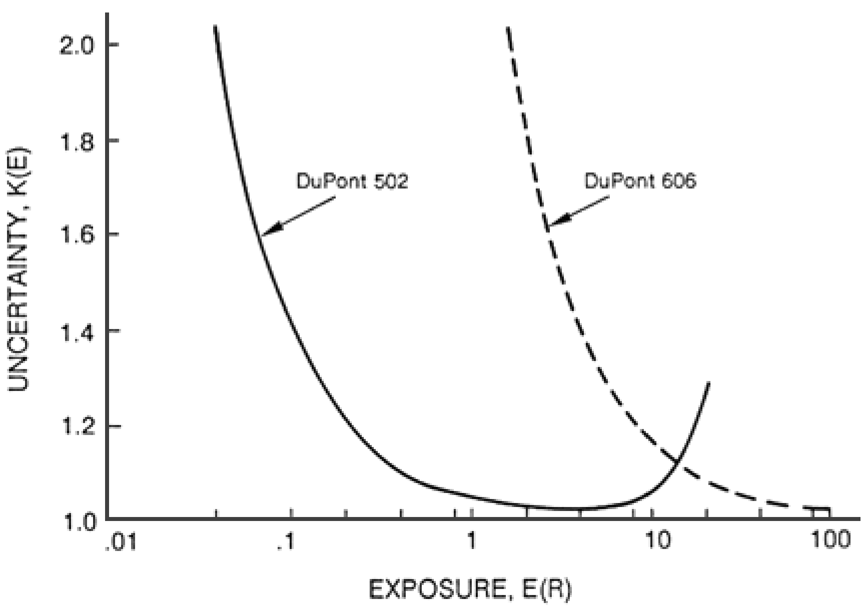

Figure 5-2
Plot of Uncestainty, K(E) vs Exposure, E(R) for Du Pont 502 and 606 Film Components.

In Chapter 6, value for laboratory uncertainty are presented for each test series and are intended to be applied for *exposures* over 0.2 R with special consideration of larger *exposures* as indicated. As noted above, these laboratory uncertainties are never less than K= 1.2. The 95% uncertainty factor for the *additional* uncertainty for *exposures* below 0.2 R is obtained as

$$K^*(E) = e^{\sqrt{(\ln^2 K(E) - \ln^2 1.2)}} , \qquad 5\text{-}10$$

where $K(E) = 1 + 0.042\ e^{0.25E}/E$ for Du Pont 502 film. Values of K*(E) are given in Table 5-1.

TABLE 5-1 Additional Uncertainty Factors for Film Badge Readings Below 0.2 R

E(R)	K(E)	K*(E)
0.02	3.11	3.07
0.04	2.06	2.01
0.06	1.71	1.66
0.09	1.54	1.47
0.10	1.43	1.36
0.12	1.36	1.28
0.14	1.31	1.22
0.16	1.27	1.17
0.18	1.24	1.13

These factors are to be combined with uncertainties from other sources as usual, including the "standard" laboratory uncertainty factor, which is 1.2 or 1.3 for most test series.

Special treatment is required below the minimum detectable level (MDL). The MDL is the minimum *exposure* that can be statistically distinguished from zero in the laboratory. It is usually established at the point where the laboratory uncertainty is ± 100% at the 95% confidence level (see Section 5.C). It should be noted that the expression "minimum detectable level" is often used in a less precise sense; thus the MDL values indicated in various documents describing test series may not satisfy the above definition exactly.

For Du Pont 502 film, the MDL must satisfy

$$MDL = 0.042\, e^{0.25 MDL} \qquad 5\text{-}11$$

implying that the MDL is approximately 0.04 R. In obtaining 95% confidence limits for recorded *exposures* below the MDL, the lower limit should be taken to be zero. To avoid problems of applying multiplicative factors to *exposure* estimates of zero it is recommended that *exposures* recorded as less than the MDL be considered as half the MDL, for purposes of defining the additional laboratory uncertainty factor K*(E) and for calculating the upper subjective confidence limit, including all uncertainty sources. Note that this treatment of laboratory uncertainties at low doses is a departure from the use of the lognormal distribution in that it allows for the inclusion of zero in the confidence limits. Laboratory uncertainties may be better described by the symmetric normal distribution than by the lognormal distribution.

To illustrate the above procedure, suppose that the worker in the example given in Section 5.A had a film badge *exposure* of 0.1 R instead of 0.8 R. For this exposure $K = 1 + 0.042\ e^{(0.25 \times 0.1)}/0.1 = 1.43$, and $K^*(E) = e^{\sqrt{(\ln^2 1.43 - \ln^2 1.2)}} = 1.36$, with corresponding s*(E) = (In 1.36)/1.96 = 0.157. If this additional uncertainty is added to that in the example, the overall s^2 is $0.170^2 + 0.157^2 = 0.0535$, and s = 0.231, K = 1.57. The 95% subjective confidence limits for *exposure* are (0.05, 0.13).

Radiological Uncertainties

Three sources of uncertainty have been identified in the radiological category: photon energy spectrum, body wearing position and radiation backscatter.

The influence of the low energy part of a photon energy spectrum on film badge *exposure* has been discussed in Section 4.A, particularly with regard to the thickness and material of the filter used to attenuate the lowest-energy photons. A 0.028 inch thick lead filter was found to minimize the uncertainty in the *exposure* caused by uncertainties in the energy spectrum (see Section 4.A), but even at this thickness there is a residual bias B that is estimated to be 1.1 and an uncertainty in the consequences of the spectrum on the measured *exposure* which is estimated to give a K of no less than 1.2. For thinner and lower-atomic-number filters such as used in early test series, both the B and K values are estimated to be larger.

A film badge is normally expected to be worn on the chest. At such a position it is not experiencing the same radiation field as if it were freely exposed in air because the body attenuates radiation from the back. The magnitude of the bias in the measured *exposure* clearly depends on the energy spectrum of the photon radiation, the spatial distribution of the radiation field and on the size of the wearer. It is estimated to have a typical value of B = 0.8 and an uncertainty associated with this effect for which a typical value of K = 1.1 is estimated. This uncertainty includes allowance for improper wearing, e.g., attached to the belt or carried in a pants pocket.

The presence of the body on which a badge is worn increases the radiation field (as well as decreasing it due to attenuation, as discussed above) because the body backscatters photons. This is estimated to contribute a typical B of 1.1 and to have an uncertainty of at least K = 1.1 as well. Notice that the net effect of the wearing and backscatter contributions to the radiological effect with the above values of B tend to compensate in bias (1.1 x 0.8) but their K uncertainties are cumulative (not compensating).

The radiological situation for pilots and other crew members exposed to radiation in aircraft is different from that for personnel exposed on the ground or on ships. The structure of an airplane provides substantial shielding to persons within and preferentially removes low-energy photons from the spectrum and thus reduces the bias due to the low-energy spectrum (toward 1.0). The shielding is greater from behind and below as a result of the seat. This increases the value of B attributed to body shielding, "wearing", toward 1.0. The reduction in the low-energy part of the photon spectrum also reduces the B due to backscatter (toward 1.0). The net effect of the three radiological contributions on the overall radiological B is not very different from those for ground personnel.

Because aircraft personnel have relatively little mobility within an airplane, there is less uncertainty associated with the radiological effects than for typical ground personnel. Therefore, film badge readings for aircraft personnel are more reproducible measures of *exposure* than for ground personnel, and perhaps more accurate as well. Nevertheless, in order to provide a conservative estimate of uncertainty, the same values of K are adopted as for ground personnel in most test series. Exceptions are IVY and TUMBLER-SNAPPER where special conditions warranted special treatment.

Environmental

The final category of uncertainty combines all those uncertainties related to the field environment in which film badges are exposed. Section 4.G discusses the consequences of exposure to moisture, light, high temperatures, and radioactive contamination. As noted in that section, with expert examination of processed films, these effects can often be recognized and even taken into account. However, in some of the test series in this report where environmental effects were known to be present, it is not reasonable to conclude that such expert ex aminations were made and reinterpretation is not feasible nor even possible because many of the original films are no longer available. The environmental bias and uncertainty are estimated from a knowledge of the environmental conditions of each test series. In general, these were quite different for test series conducted in the Pacific, where conditions of high humidity prevailed, than for test series conducted at the NTS. These differences are reflected in the estimates of uncertainty in individual test series.

For GREENHOUSE and TUMBLER-SNAPPER, fallout contamination increased the uncertainty in estimates of low-dose *exposures*. These effects are included under the environmental contributions to uncertainty and are discussed for those test series.

Environmental conditions for personnel exposed to radiation while in aircraft was different from that for ground personnel in several respects. Badges usually were issued and collected on a daily basis, so no long-term environmental effects took place. There was no effect attributable to high humidity or temperature and there was no fallout on the badge of a wearer. As a result, environmental uncertainty in determining the *exposure* of pilots and other crew members is lower than for ground personnel. Consequently, uncertainties estimated for the latter provide a conservative estimate for the former. Exceptions occur in the cases of the IVY and TUMBLER-SNAPPER tests. Aircraft ground crews who often encountered radiation as they cleaned aircraft flown in proximity to nuclear tests, or as they removed air filters used to collect radioactive debris from detonation clouds, are estimated to have bias and uncertainty values associated with their dosimetry readings that are similar to those of other ground personnel.

C. MINIMUM DETECTABLE LEVEL OF RADIATION EXPOSURE MEASURABLE WITH A FILM BADGE

As described in Section 5.3, the laboratory uncertainty factor increases as film badge *exposure* readings approach zero, and this results in a level below which readings are not statistically distinguishable from zero. This minimum detectable level (MDL) is usually established at the point where the laboratory uncertainty of the reading at the 95% confidence level is $\pm$ 100% in normal distribution terms. A series of *exposures* at the MDL should yield film badge readings, 95% of which would fall between 0 and twice the MDL, and which follow a symmetric normal distribution. Because the uncertainty of readings below the MDL is greater than the reading such readings are indistinguishable from zero or the MDL itself.

Exposures midway between zero and the MDL are as likely to be interpreted as zero as they are to be read at the MDL. Similarly, as *exposures* increase to the MDL, they are more likely to fall into the readable range just as those ap proaching zero are more likely to be interpreted as zero. The general practice in film badge dosimetry is therefore to make the best possible interpretation of the *exposures* in this region, reporting zero for those that favor that end of the range and a positive reading for those approaching the MDL, bearing in mind that there is no statistical difference between the two.

In Section 5.B, the Committee suggested using one-half the MDL for determining the upper limits in a consistent manner for exposures reported below the MDL. It should be noted that this does not imply a recommendation to modify the existing records of exposures recorded below the MDL.

D. COMMONALITY AMONG THE TEST SERIES

The particular personnel film badge selected for one multiple-detonation test series or single-detonation testing operation was not always the same as the next. Film badge use, however, included identical film badges or film packets for some series, the same containers for film packets during several series, and the same metallic filter during most series. After the third test operation, SANDSTONE, only single film packets containing two or three film types, or components, were used in personnel film badges.

Environmental conditions during the use of film badges in atmospheric testing were similar within each of two categories, continental and oceanic testing locations. Except for the first nuclear detonation, TRINITY, in an arid New Mexico location, the remaining continental atmospheric test series were conducted in Nevada at either Frenchman Flat or nearby Yucca Flat in a semi-desert environment. Oceanic test operations were an at Pacific locations, except for ARGUS detonations which occurred outside the atmosphere above the Atlantic. Environmental effects on personnel film badges, therefore, were comparable during operations on the continent and similar during oceanic operations, where different protective measures against environment film damage were employed.

Film badge calibration and processing techniques during the test operations were similar and became more uniform as testing continued. Radium 226 calibration sources were common in early test operations. These generally were replaced by cobalt 60 sources later, but techniques for film badge calibration in air were similar. Radium exposure rates were calculated during early series, and both radium and cobalt exposure rates in later operations were related to NBS calibrations either by direct NBS-calibrations or by use of NBS-calibrated "R-meters".

Processing became fairly uniform after the first few series. An important change was maintaining developing solutions within ± 0.5°F rather than within ± 1°F, as during CROSSROADS. Another important evolution was developing standard calibration films with known *exposures* for each developed batch of personnel films, in addition to unexposed control films, to monitor and adjust for variations in the developing solutions and processing.

Perhaps the most important common factor in personnel film badge use is the characteristic shape of the H & D curve for any personnel dosimeter film type (see Figure 2-3). This leads to a uniform variation of laboratory uncertainty versus *exposure* for each film type (see Section 5.B).

As previously mentioned, the ARGUS I, II, and III events were detonations outside the atmosphere, high above the earth. Detonation yields were between one and two kilotons for each test, and no fallout was detected at the earth's surface. Film badges were worn during Operation ARGUS, but no personnel doses were recorded from ARGUS fallout. Thus, any discussion of *exposure* assignment accuracy during ARGUS is moot.

Personnel-dosimetry accuracy during the Plowshare program tests (GNOME, SEDAN) is not discussed separately because these detonations were not part of the atmospheric test series, but were underground tests between atmospheric test series. The film badge used and the associated processing program during both Plowshare tests were the same as were used in DOMINIC II, and the same uncertainty considerations apply.

E. CONVERSION FROM EXPOSURE TO DEEP-DOSE EQUIVALENT

During the period of atmospheric nuclear testing, film badge results were customarily expressed in roentgen, R, the unit of the radiological quantity, *exposure*. This approach proved useful as a quantitative means to control and limit the radiation *exposure* received by test participants. However, *exposure* is a measure of the electrical charge created by ionization of air by x or gamma radiation, and as such only indirectly reflects the amount of radiation energy absorbed within the body, or the risk of an adverse biological effect. The Committee therefore related film badge readings to deep-dose equivalents that are more relevant to health effects. By converting film badge *exposure* to deep-dose equivalent, the film badge readings from atmospheric nuclear tests are easily compared to current results for other activities, including underground weapons testing, nuclear power plant operation, diagnostic radiology, and nuclear medicine.

Procedures have been developed for conversion among the various radiological quantities defined for external radiation. Use is made of extensive computer calculations because some of the quantities cannot be directly measured. Where measurements have been made, there is good agreement with calculations. Publication 51 of the International Commission on Radiological Protection (ICRP 1987) is the most recent compilation of relevant data.

Several factors must be considered when making conversions among the various quantities. Among these are:

- type and energy of radiation
- exposure geometry
- dose equivalent of interest

The type and energy of radiation were established by radiation conditions at nuclear tests and have been described in Chapter 3.

Undoubtedly many exposure geometries were encountered, but an area (extended plane) source of photons from the radioactive products of a nuclear detonation seems to be most representative. (Beta-particle exposures were not adequately monitored and are excluded in the dose assessments). ICRP Publication 51 presents conversion factors for different geometries. Geometries that are most frequently evaluated are:

- *Anterior-posterior* (front to back irradiation)
- *Posterior-anterior* (back to front irradiation)
- *Lateral* (irradiation from the side)
- *Rotational* (uniform irradiation from front, back and sides as would occur if one stood in a cylinder made of radioactive material or if a vertical line source was rotated about oneself)
- *Isotropic* (uniform irradiation from the front, back, sides, top and bottom as would occur if one was suspended in a uniformly radioactive cloud)

None of the above is truly representative of the area source most commonly encountered in atmospheric weapons testing.

The rotational geometry was selected as the best approximation to the area-source geometry, although the first three geometries are inappropriate because the radiation is too directional, i.e. personnel entering a contaminated area would not be irradiated from one side only. Compared to the isotropic geometry, the other reasonable alternative, the dose to various body organs per unit *exposure* is greater for the rotational geometry. Furthermore, the isotropic condition was rejected because uniform exposure from the top and bottom at the same time was not likely, even for pilots submerged in a radioactive cloud. The rotational condition appears to offer the best compromise between conservatism and applicability.

The Individual Dose Equivalent, Penetrating, Hp, (as defined in ICRU 1985) was selected as the endpoint dose equivalent quantity for this study. This is the *operational quantity* for personnel monitoring. Hp(10) is the dose equivalent from penetrating radiation to soft tissue located at a depth of 10 mm in the body.

Also called the deep-dose equivalent, $H_p(10)$ can be evaluated with film badges or other types of personnel dosimeters. Such devices are normally calibrated using body phantoms to simulate backscatter conditions. A 30-em-diameter sphere or a 30 cm x 30 cm x 15 cm slab of tissue-equivalent material is commonly used. The deep-dose equivalent is also the quantity specified for performance testing of personnel dosimetry systems by the American National Standards Institute (ANSI 1983) and the Department of Energy (DOE 1986).

The Effective Dose Equivalent, H_e, and the dose equivalent to specific organs (e.g., the red bone marrow) were considered by the Committee but not selected for conversion. The effective dose equivalent is a conceptual quantity established by the ICRP. It cannot be measured, only calculated (ICRP 1977). It is defined as the sum of the weighted dose equivalents for the major radiosensitive organs that exhibit stochastic (carcinogenic or genetic) effects. Weighting is based on the relative risk of a stochastic death per unit dose equivalent to the various tissues or organs. The effective dose equivalent is thus the quantity that most closely associates exposure to radiation with the risk of an adverse biological effect. Its advantage is that it provides a mechanism for combining dose equivalents from uniform and non-uniform body irradiation from either external or internal sources, to arrive at a single risk estimate. The deep-dose equivalent, however, is more practical, has been in use for several years, and is implicit in current regulations.

The relation between effective dose equivalent and deep-dose equivalent for anterior-posterior and rotational exposure geometries is presented in Table 5-2. For the rotational geometry, the deep-dose equivalent and the effective dose equivalent are nearly identical for photon energies above 0.08 MeV. The deep-dose equivalent overestimates the effective dose equivalent by 10% to 15% for anterior-posterior irradiation.

Table 5-3 relates the deep-dose equivalent to the quantity *exposure* for rotational irradiation. The quantitative value of the deep-dose equivalent (in rem) is 70 – 80% of the value of the *exposure* (in R) for the photon energies associated with nuclear weapons tests. Consequently, the Committee selected a bias of B = 1.3 for converting film badge *exposure* data to deep-dose equivalent. A value of 1.2 was selected as the uncertainty factor (K) at the 95% confidence level to account for possible dissimilarities of irradiation geometries actually encountered and those assumed for the conversion, as well as variations in the shapes and sizes of people.

Deep-dose equivalent does not indicate dose equivalent to specific organs. To assess the risk of a clinically detectable effect (e.g., cancer) to a specific organ, it necessary to estimate the dose equivalent to that organ. Calculations may be performed to estimate an organ-dose equivalent from deep-dose equivalent. Tables 5-4 and 5-5 are examples for red bone marrow and lung, respectively, for rotational irradiation.

Table 5-2 The Ratios of Effective Dose Equivalent H_e to the Deep-Dose Equivalent, $H_p(10)$[a]

Photon Energy (Mev)	Posterior Irradiation	Anterior-Rotational Irradiation
0.05	0.73	0.87
0.08	0.85	1.06
0.10	0.87	1.09
0.20	0.87	1.06
0.40	0.87	1.03
0.60	0.88	1.03
0.80	0.89	1.02
1.00	0.90	1.02
2.00	0.90	0.99

[a]Calculated from data presented in ICRP Publication 51 (ICRP 87).

Table 5-3 The Ratio of the Deep-Dose Equivalent $H_p(10)$ to *Exposure*[a]

Photon Energy (MeV)	Ratio for Rotational Irradiation, (rem/R)
0.05	0.69
0.08	0.78
0.10	0.77
0.20	0.71
0.40	0.70
0.60	0.70
0.80	0.71
1.00	0.72
2.00	0.77

[a]Calculated from data presented in ICRP Publication 51 (ICRP 1987).

Table 5-4 The Ratio of the Red Bone Marrow-Dose Equivalent to the Deep-Dose Equivalent, $H_p(10)$[a]

Photon Energy (MeV)	Ratio for Rotational Irradiation
0.05	0.69
0.08	0.92
0.10	0.99
0.20	1.04
0.50	1.00
1.00	1.00

[a]Calculated from data presented in ICRP Publication 51 (ICRP 1987).

Table 5-5 The Ratio of the Lung-Dose Equivalent to the Deep-Dose Equivalent, $H_p(10)$[a]

Photon Energy (MeV)	Ratio for Rotational Irradiation
0.05	0.93
0.08	1.12
0.10	1.14
0.20	1.12
0.50	1.08
1.00	1.07

[a]Calculated from data presented in ICRP Publication 51 (ICRP 1987).

6

Uncertainty Analysis by Individual Test Series

The United States conducted 19 atmospheric nuclear weapons test operations spanning the period from July 1945 to November 1962 (Table 6-1). Each test operation was different in some aspect of personnel film badge dosimetry. The type and number of nuclear test detonations varied, environmental conditions were not the same in the Pacific as at Nevada Test Site, type of film badge used changed, dosimeter film components used also changed, and film calibration and processing procedures differed for some operations. To assure that all these different factors affecting film dosimetry programs were considered, the film dosimetry bias and uncertainty for each test operation were analyzed separately. A full analytical discussion for each test operation follows in this chapter.

Each of the individual discussions include consideration of personnel exposed; technical factors such as type of film badge, issue, processing and calibration procedures; availability of records; tabulation of bias and uncertainty values established; and tables showing deep-dose equivalent and 95% confidence limits of these values as functions of *exposure*.

For some test operations, significant differences were found in uncertainties associated with results from badges worn by flight personnel, i.e., those who flew cloud sampling or similar missions in aircraft, and those worn by ground personnel, including those aboard ships. In these cases, separate tabulations are provided for flight and ground personnel. Relatively large radiological-spectrum bias and uncertainty values resulted when film badges used during some test operations were analyzed. These badges generally had an insufficient thickness of filter material and were used during the earlier operations. Another factor affecting dosimetry in early test operations was inadequate *exposure*-range cover

Table 6-1 U.S. Aunospheric Nuclear Weapon Test Operations

Test Operation	Date(s)	Location	Tests	Comments
TRINITY	7/45	Alamogordo, NM	1	First atomic test
CROSSROADS	7/46	PFG[1] (Bikini Atoll)	2	Effects an ships
SANDSTONE	4-5/48	PPG (Enewetak Atoll)	3	AEC scientific tests
RANGER	1–2/51	NTS[2]	5	First tests at NTS
GREENHOUSE	4–5/51	PPG (Enewetak Atoll)	4	Thermonuclear weapon development
BUSTER-JANGLE	10–11/51	NTS	7	Included Desert Rock I, II, III
TUMBLER-SNAPPER	4–5/52	NTS	8	Included Desert Rock IV
IVY	8/52	PPG (Enewetak Atoll)	2	First thermonuclear test (MIKE)
UPSHOT-KNOTHOLE	3–6/53	NTS	11	First atomic artillery test. Desert Rock V
CASTLE	3–5/54	PPG, (Bikini/Enewetak)	6	Included largest U.S. test (15 MT)
TEAPOT	2–5/55	NTS	14	Included Desert Rock VI
WIGWAM	5/55	500 ml SW San Diego	1	Deep (2000 ft) underwater test
REDWING	5–7/56	PPG (Bikini Enewetak)	17	High-yield thermonuclear tests
PLUMBBOB	5–10/57	NTS	24	Included largest NTS test and Desert Rock VII, VIII
HARDTACK I	4–8/58	PPG (Bikini/Enewetak)	35	First high-yield rocket tests
ARGUS	8–9/58	Atlantic Ocean	3	Tests in upper regions of atmosphere
HARDTACK II	9–10/58	NTS	37	Last test series before moratorium
DOMINIC I	4–11/62	PPG (Christmas/Johnston Is.)	36	Last test series in Pacific
DOMINIC II	7/62	NTS	31	Last continental atmospheric tests

[1] Pacific Proving Grounds
[2] Nevsda Test Site

age of the dosimeter film or films used. Uncertainties in this regard are not listed in particular test operation bias and uncertainty tables, but are presented, where appropriate, in narrative form after tables which convert from film badge *exposure* to deep-dose equivalent. Bias and uncertainty tables conclude with overall values for converting film badge *exposures* of 0.2 R or more to deep-dose equivalents.

PROJECT TRINITY

Background

Project TRINITY was the first test of a nuclear explosive device. The detonation occurred atop a tower at the Alamogordo Bombing Range in New Mexico on July 16, 1945. The device was identical to the one in the weapon dropped on Nagasaki, Japan, a few weeks later. The yield (tons of TNT explosive that would release an equivalent energy) of both detonations was 21 kilotons (kt).

The test was the culmination of the "Manhattan Project", the code name given to the atomic bomb development program directed by the Manhattan Engineer District of the Army Corps of Engineers. Scientists from the Los Alamos Scientific Laboratory (LASL), part of the Manhattan Engineer District, developed, constructed, and detonated the device. LASL personnel also provided radiation protection and film badge monitoring.

Personnel Exposed

Only a few hundred people observed the detonation near the test location (Maag and Rohrer 1982), but the total number of observers, experimenters, and workers who had visited the site by the end of 1946 was about 1000.

The highest recorded cumulative *exposure* was 15 R and was received by an individual who made several entries to "Ground Zero" shortly after the detonation. Most exposures occurred at or near "Ground Zero" but several people were exposed off-site while tracking the fallout cloud.

Type of Film Badge

A special film badge was used at Project TRINITY and was not used in any subsequent operations. The badge, contained two film packets that were placed side by side in a brass holder. The brass was 0.020 inches (0.508 millimeters) thick and acted as a filter which reduced the characteristic over-response of film to low-energy photons.

One film packet was manufactured by the Eastman Kodak Company and contained a single Type K film. The other packet was manufactured by Du Pont and was a special Type 552 packet. It contained three films; a Type D-1 and two Type D-2 films (Reinert 1946; Littlejohn 1946; LASL 1945). The Type D-1 and D-2 films are believed to correspond with Du Pont Type 502 and 510 films, respectively, manufactured later.

The measurement range of the Type K film was generally considered to be 0.05 R to 5 R (Buckland 1945; Dessauer 1947). *Exposures* as low as 0.01 R were reported for people who visited the site many months after the test (Reinert 1946).

The Type D-1 film had a range from 0.1 R to 10 R (Storm 1951; Ehrlich and Fitch 1951). The Type D-2 film was less sensitive and measured *exposures* between 5 R and 40 R (Storm 1951; Ehrlich and Fitch 1951).

Conceptually, no problems should have been caused by overlap of the measurement, ranges of the films. For unknown reasons, data for each of the films were not always recorded nor used in *exposure* evaluation. Some exposures were assessed using the Type K and the two D-2 films, some with the Type K and the D-1 films, and some with Type K alone. The first case produced overlap problems. The poor agreement that often occurred between the two D-2 films aggravated the problem.

Badge Issue and Exchange

Badges were generally issued at the test site. For the first few days after the detonation, entries were controlled by a "Going-In Board." This procedure assured that all personnel entering radiation areas were properly badged. The primary source of information concerning badge issuance is that presented in a report on safety and monitoring of personnel (Aebersold 1947). There is no evidence that cohort badging was used (see Operation CROSSROADS).

Calibrations, Processing, and Interpretation

Calibrations were performed with a radium-beryllium source. The source activity was approximately 1000 millicuries (mCi) (LASL 1945). All films were exposed at a distance of 49.5 cm from the source with the time varied to achieve different levels of exposure. Seven *exposure* levels were used ranging from 0.19 R to 10.29 R (LASL 1945). Calibrations were infrequent and the same characteristic curve was used for many developing batches. Developed films were evaluated with a Marshal densitometer (LASL 1945; Littlejohn 1946; Reinert 1946). An unexposed film was developed with each group of personnel film to account for base fog (LASL 1945).

The *exposure* reported for individuals was obtained by averaging the *exposure* determined from the separate films. As indicated, the number of films used to calculate the *exposure* varied because some films were not always evaluated. Of the 51 readings above 1 R, 19 were calculated from the K and both D-2 films. The rest used the K and D-1 films or the K by itself (Buckland 1945).

Current Availability of Records

No personnel dosimeter films are available for review from the TRINITY event. Density and *exposure* data for personnel films and films sent to various post offices in New Mexico are listed in LA Notebook 1144 (LASL 1945). Data for two calibrations are available also. A summary of personnel *exposures* was reported by Buckland (1945) for those people exposed during the first few days after the detonation. Exposures occurring later were reported in Los Alamos Scientific Laboratory memoranda (Littlejohn 1946; Reinert 1946).

Estimated Bias and Uncertainty

The following table presents bias and uncertainties that result from different influences on film badge performance. These values are appropriate for *exposures* ranging from approximately 0.2 R to 3 R.

The brass filter created a positive bias, as it was unable to fully compensate for

Bias (B) and Uncertainty (K) For Project TRINITY

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.6		1.4	
Wearing	0.8		1.1	
Backscatter	1.1		1.1	
Total Radiological		1.4		1.5
Environmental		1.0		1.1
Overall (*Exposure*)		1.0		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.8		1.6

the over-response of the films to low-energy photons. For 100 keV photons, Type K film filtered with 0.020 inches (0.508 mm) of brass over-responded by a factor of 10 (Storm and Bemis 1950). Allowing for other low energy photons that do not produce such a large over-response, the estimated bias is 1.6 for spectral dependence.

Larger uncertainties are associated with laboratory bias estimates at lower and higher exposures. For the lower exposures, the increase is attributed to the imprecision that occurs when films are used at their lower ranges of detection. Some additional uncertainty is introduced by the varying number of films used to determine *exposure.*

For *exposures* over 3.0 R, the assignment procedure introduces even more uncertainty because of the disagreements between the two D-2 films. For example, the readings of the D-2 films in one badge were 8.4 R and 11.8 R while the Type K film in the badge indicated an *exposure* of 5.4 R. The *exposure* assigned from these readings was 8.5 R, but it is obvious that a large uncertainty exists. At the highest doses, when both D-2 films and the X film were averaged, a positive bias was created by the unequal weight applied by using both D-2 films. More confidence can be placed on the K film based on the available calibration data, but it represents only one third of the average value.

The small numbers of high readings allowed each high *exposure* to be reviewed. The overall effect of the film capabilities and assignment procedures is to create a laboratory bias of about 1.3. For the reasons presented above and the fact that the D-2 films were not always used, the uncertainty of the bias estimate is larger than that for lower *exposures*.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the TRINITY series. Film badge readings between 0.2 R and 3.0 R may be converted by multiplying by the factors in the next-to-the-last line of the table, which were obtained from the overall bias and uncertainty factors for TRINITY given above. Readings between 3 and 15 R may be converted by multiplying by the factors in the last line of the table; no *exposures* above 15 R were recorded. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings as described in Section 5.B under *Laboratory Uncertainties.*

Deep-Dose Equivalent and 95% Confidence Limits for Project TRINITY

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.02	(0.00,0.05)
0.05	0.03	(0.01, 0.06)
0.06	0.03	(0.02, 0.07)
0.07	0.04	(0.02, 0.07)
0.08	0.04	(0.02, 0.08)
0.09	0.05	(0.03, 0.09)
0.10	0.06	(0.03, 0.10)
0.12	0.07	(0.04, 0.11)
0.14	0.08	(0.05, 0.13)
0.16	0.09	(0.05, 0.15)
0.18	0.10	(0.06, 0.16)
0.20	0.11	(0.07, 0.18)
0.20<*Exp*<3.0	0.56 E	(0.35 E, 0.89 E)
3.0-15	0.43 E	(0.22 E,0.86 E)

where E is the film badge *exposure* (R)
Discontinuity attributable to use of Type D-2 film for *exposures* above 3 R.

OPERATION CROSSROADS

Background

Operation CROSSROADS was held in July 1946 at Bikini Atoll in the central Pacific. Its primary purpose was to determine the effect of atomic bombs on naval vessels. The operation consisted of two tests (DOE 1988; Berkhouse et al. 1984):

Personnel Exposed

About 42,000 personnel, 251 ships and 156 aircraft were involved in the tests. Ninety of the vessels were target ships in the Bikini lagoon. No personnel were on the target ships at the time of the detonations. Most personnel were on the remaining (support) ships of the fleet. Personnel were primarily exposed to radiation during the period when they entered the lagoon after shot BAKER and boarded the target vessels that had been engulfed in a water plume, surface wave and spray resulting from the underwater explosion, during efforts to decontaminate the ships, beginning ten days after shot BAKER, and during ammunition offloading of target ships that had been towed or sailed to Kwajalein.

Operation CROSSROADS Events

Name	Date	Type	Yield (kt)
ABLE	07/01/46	Airdrop, detonated at 520-foot altitude	21
BAKER	07/25/46	Underwater, in lagoon, detonated at 90-foot depth	21

Because the ABLE detonation was 520 feet above the ocean and 1500 to 2000 feet from the target ships, residual radioactivity in the target array was mostly from neutron activation and it decreased rapidly. Accordingly, the number of film badges issued for ABLE decreased from 1,627 on 1 July to none on 7 July, with a total during this time interval of 2, 132 (Berkhouse et al. 1984). Only 71 badges were issued from 7 July until 24 July, the day before test BAKER. Badges issued from 24 July until 31 August, when most support ships had left Bikini, totaled 8101 (REECo 1982). This time period included both recoveries after BAKER and attempts to decontaminate target vessels. More than 8000 film badges were issued on a daily basis to about 700 personnel unloading ammunition from target vessels at Kwajalein, beginning about 30 August and continuing until the end of the year (Berkhouse et al. 1984).

The test series was designed with the objective of keeping the daily *exposure* below 0.1 R, and badges were used to measure the daily *exposure* in order to limit work activities if a greater *exposure* was experienced on a single day.

Type of Film Badge

The film badge contained a single component type K double-emulsion dental film pack. It was covered by a 0.020-inch-thick lead cross filter, the arms of which were bent over the edges of the pack about 1/4 inch. The badge was in a plastic envelope to minimize damage to the film by exposure to moisture. The badge was intended to cover the exposure range 0–2 R with a minimum detectable *exposure* of approximately 0.05 R. The lead filter thickness (0.020 inches) was thinner than was later found to be optimum (0.028 inches) for minimizing the excess response of the film emulsion to low energy components of the gamma and x-ray spectrum.

Badge Issue and Exchange

Badges were intended to be issued on a daily basis. That was the typical experience although a few badges were retained for 2 or 3 days and as long as 9 days. Badges were not issued to all personnel working or living in radiation areas. They were typically issued only to one or a few Rad-Safe monitors in a group. The film badge *exposure* of the Rad-Safe monitor was intended to be representative of the *exposure* of all members of the group, a concept called cohort badging. During the major ship decontamination effort between August 4 and 10 there were typically two monitors per 100 personnel. All personnel in aircraft that were within 20 miles of the explosions were badged at the time of the test detonations. About 15% of the Navy personnel in the task force were issued at least one badge sometime during the test series. The largest number of badges issued to one person (a Rad-Safe monitor) was 19.

Calibration, Processing, and Interpretation

Calibration, processing, and interpretation took place aboard the *USS Haven*. Calibrations were performed with a radium source at constant distance with variable time to produce *exposures* varying by approximate factors of 2 between 0.05 R and 2 R. Calibration films were not processed with each batch of films that was developed. The calibrations were assumed to be valid over a series of successive development batches. New calibration curves were made at least for each new emulsion batch from the film badge manufacturer. An unexposed control badge was included in each development batch to determine the base fog of the film. The development temperature was controlled at 68°F but only to ± 1°F accuracy (rather than ± 0.5°F called for in later test series). Each developed film was read in four positions corresponding to locations under the arms of the lead cross and close enough to the edge to also be under the bent-over ends of the arms. The film density was read to a maximum optical density of 3, corresponding to an *exposure* of about 2 R. The average of the four optical-density readings on one film, minus the density of the unexposed film developed in the same batch, was used with the density versus *exposure* calibration curve to interpret the *exposure* to an individual badge. Optical-density readings also were taken in the unshielded four comers of each film for beta-exposure determination. As previously discussed in Section 4.B, however, beta-dosimetry results in Operation CROSSROADS were not reliable.

Film badges worn at Operation CROSSROADS were subject to the high temperature and humidity of the Pacific test site and were not free of environmental damage in spite of the plastic "tropical" envelope. Recent evaluation of available film badges from that test series indicates substantial film darkening due to environmental damage. This darkening may have been difficult to separate from the density produced by radiation at the low densities typical of most of the films in the archives.

Current Availability of Records

Only a part of the more than 18,000 films from badges worn at Operation CROSSROADS is currently available. The films from the ammunition unloading operation at Kwajalein, more than 8000 films, are all that are in REECo archives at Las Vegas, Nevada. The film badge records that were made at the time of the tests are generally available. Even though the record keeping at the time of the tests was not uniformly done and penmanship was sometimes poor, 85 90% of the Navy badge records have been matched to individuals. The method of record keeping evolved during the test series. Because of the unexpected level of contamination of the ships following test BAKER, the large number of badges issued led to establishing a card file on each Rad-Safe monitor to record his daily *exposures*. At the time ammunition was unloaded from the target vessels at Kwajalein, the record keeping was greatly improved, so that each person had his daily and cumulative *exposure* record kept on a single 5x8 inch card.

Estimated Bias and Uncertainty

The following table presents bias and uncertainties that result from different sources. These values are appropriate for *exposures* greater than 2 R.

The laboratory procedures seem to have been well established and free of bias. The broader range within which the temperature was controlled leads to the greater-than-normal value for the laboratory K. The thinner-than-optimum lead filter biases the results to overestimate the *exposure* and also increases the uncertainty in the effect of the filter. Film badge location and backscatter contributions to the *exposure* bias and uncertainty are similar to those in other test series. The uncertainty in the environmental effects of heat and water are reflected in the K value of 1.3. The bias and uncertainty in conversion of *exposure* to dose are assigned the values used throughout this report.

The lack of a second film component to evaluate *exposures* greater than approximately 2 R was rarely significant because the individual daily *exposures* were not this large. Cumulative *exposures* to a few test participants exceeded 2 R, but the lack of a second film component is only significant on an individual film badge, not on the cumulative *exposure* derived from several badges.

Bias (B) and Uncertainty (K) for Operation CROSSROADS

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.3		1.3	
Wearing	0.8		1.3	
Backscatter	1.1		1.1	
Total Radiological		1.1		1.5
Environmental		1.0		1.3
Overall (*Exposure*)		1.1		1.7
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.8

The minimum detectable *exposure* of 0.05 R is in some places stated as 0.04 R. At this level of *exposure*, the uncertainty in the *exposure* deduced from the net film density is larger than this apparent inconsistency.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and range of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the CROSSROADS series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for CROSSROADS given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation CROSSROADS

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.03	(0.01, 0.08)
0.06	0.04	(0.02, 0.09)
0.07	0.05	(0.02, 0.10)
0.08	0.05	(0.03, 0.11)
0.09	0.06	(0.03, 0.12)
0.10	0.07	(0.03, 0.13)
0.12	0.08	(0.04, 0.15)
0.14	0.09	(0.05, 0.17)
0.16	0.11	(0.06, 0.20)
0.18	0.12	(0.07, 0.22)
0.20	0.13	(0.07, 0.24)
>>0.20	0.67 E	(0.37 E, 1.20 E)

where E is the film badge *exposure* (R)

Because only one film component was used during CROSSROADS, there were no overlap problems.

OPERATION SANDSTONE

Background

Operation SANDSTONE was held in April and May 1948 at Enewetak Atoll in the Central Pacific. Its primary purpose was to proof-test improved design atomic weapons. The operation consisted of three tests:

Operation SANDSTONE Events			
Event	Date	Type	Yield (kt)
X RAY	04/15/48	Tower	37
YOKE	05/01/48	Tower	49
ZEBRA	05/15/48	Tower	18

Personnel Exposed

Approximately 10,000 personnel participated in the test series. The majority of them were at Kwajalein, 400 nautical miles southeast of the test site or on board ship more than 10 nautical miles from the test site. A minority were on Enewetak Island, a distance of approximately 10 nautical miles from test ZEBRA, and further away from tests X RAY and YOKE, and on a few ships of the task force that held positions close to Enewetak Island. One of these ships was the *USS Bairoko*, on which the photodosimetry section was based that had responsibility for film badge processing and interpretation throughout the test series. About 2800 persons were badged (REECo 1988). The standard maximum radiation *exposure* for personnel was set at 0.1 R/day and at 3 R for specific missions. Radiation exposure was primarily experienced by work teams that visited the test sites after the detonations. Although fallout was produced in all three test shots, only following YOKE was there measurable fallout where personnel were stationed. Measurable radiation was recorded on the *USS Bairoko* and at Kwajalein two and three days following detonation.

Type of Film Badge

The film badge packet consisted of two film components, Eastman type K to cover the *exposure* range from 0.06 to 2 R and Eastman type A primarily intended to cover the range between 1 and 10 R. The type A film had radiation sensitivity of much less than 1 R, however, and was typically calibrated at levels of 0.1 R and even lower. The minimum detectable dose of 0.06 R stated for the type K film was slightly different from the 0.04 R or 0.05 R stated for the same type of film in Operation CROSSROADS. The packet was covered with a 0.020-inch lead cross, and was enclosed in a waterproof plastic cover.

Badge Issue and Exchange

Badges were issued for single-day use to all personnel expected to be exposed to radioactivity. For example, on April 24, 9 days after test X RAY, monitors were instructed to issue badges to anyone who was expected to come closer than 530 yards from ground zero. When work was completed in a radioactive area, film badges were returned to the monitor for processing. A film badge also was issued to each crew member of aircraft flying into radioactive areas. These badges were returned by air from Kwajalein, where the aircraft were stationed to the *USS Bairoko* at Enewetak, where processing was done. A total of approximately 6,000 badges was used in the test series.

Calibration, Processing, and Interpretation

All calibrations, processing and interpretation were carried out on the *USS Bairoko*. Calibrations were made with radium sources at known distances for fixed times of typically 25 and 144 minutes. During the series, two different sources of 48.7 mg and 231.7 mg were used. The calibration badges were attached to a wooden rack to assure their positions. Twenty-five calibration series were carried out over the time of the operation. From the existing calibration records, the identification, data plotting, and curve drawing do not appear to have been carefully done so that these records do not permit detailed confirmation of the reproducibility of the calibrations, nor assurance that they were precisely used. New processing solutions were made up daily from pre-packaged chemicals to assure reproducibility of the processing. The processing and interpretation were carried out on a daily basis. Originally, the densitometry of the films was determined in serial number order. On days during which a large number of badges were issued, this took many hours for the small number of personnel doing this work. As the test series progressed, in order to quantify significant *exposures* so that changes in job assignments for a following day could be made earlier, a new procedure was instituted. A general screening of the processed films selected those with highest density which were then read first. The procedures for identifying film badges with individuals to whom they were issued were careful and thorough, though the personnel in charge recommended that future film badges receive identification numbers readable both on the developed film and on the outside of the packet to further simplify the record-keeping process.

Current Availability of Records

A number of the detailed calibration records are still available for both the type K and type A films. Some films from badges are also available. The detailed personnel-*exposure* records are available. They indicate not only the readings of the densities of the two film components and their interpretation in *exposure* but also the *exposure* as recorded by a pocket dosimeter which was typically also worn by a participant in a radiation area. In some cases it appears that the dosimeter reading was used as well as (or even instead of) the film badge readings to assign a final *exposure* to an individual for a particular day.

Estimated Bias and Uncertainty

The following table presents bias and uncertainties that result from different sources. These values are appropriate for *exposures* greater than 2 R.

Bias (B) and Uncertainty (K) for Operation SANDSTONE

Source		B		K
Laboratory		1.0		1.5
Radiological				
Spectrum	1.3		1.3	
Wearing	0.8		1.3	
Backscatter	1.1		1.1	
Total Radiological		1.1		1.5
Environmental		1.0		1.1
Overall (*Exposure*)		1.1		1.8
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.8

The laboratory procedures seem to have been very well established and free of bias, with calibrations made on almost a daily basis. However, the inaccurate plotting and drawing of calibration curves have led to assignment of a large uncertainty (K = 1.5) to the overall laboratory operations. The thinner-than-optimum lead filter biases the results to overestimate the *exposure* and also increases the uncertainty in the effect of the filter. The other radiological contributions and the environmental effects are similar to those in other well controlled test series. The bias and uncertainty in conversion of *exposure* to dose are assigned the values used throughout this report.

The presence of a second film component (type A) to cover the range higher than 2 R was important in a few cases, although cumulative *exposures* (not single-badge exposures) in excess of the mission maximum of 3 R were reported for only 11 individuals.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the SANDSTONE series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for SANDSTONE given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation SANDSTONE

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.03	(0.01, 0.08)
0.06	0.04	(0.02, 0.09)
0.07	0.05	(0.02, 0.10)
0.08	0.05	(0.03, 0.11)
0.09	0.06	(0.03, 0.12)
0.10	0.07	(0.03, 0.13)
0.12	0.08	(0.04, 0.15)
0.14	0.09	(0.05, 0.17)
0.16	0.11	(0.06, 0.20)
0.18	0.12	(0.07, 0.22)
0.20	0.13	(0.07, 0.24)
>0.20	0.67 E	(0.37 E, 1.20 E)

where E is the film badge *exposure* (R)

Exposure ranges for the two film components used in SANDSTONE overlap sufficiently that no overlap problems existed. In addition, no *exposures* above the range of the insensitive film component occurred.

OPERATION RANGER

Background

RANGER was the first test series at the Nevada Test site (NTS). Five nuclear-detonation tests were conducted for weapons development purposes; the first on January 27, 1951. and the last on February 6, 1951. All were airdrops, with four burst heights between 1,000 and 1,100 feet above Frenchman Flat and the largest-yield test at more than 1,400 feet. The detonations included two yields of 1 kt, two of 8 kt, and one of 22 kt (DOE 1988). The summary of RANGER detonations is as follows:

Operation RANGER Events

Event	Date	Type	Yield (kt)
ABLE	01/27/51	Airdrop	1
BAKER	01/28/51	Airdrop	8
EASY	02/01/51	Airdrop	1
BAKER-2	02/02/51	Airdrop	8
FOX	02/06/51	Airdrop	22

None of the tests resulted in local fallout. Thus, participants entering the surface ground-zero areas were exposed to radiation only from neutron activation products.

Personnel Exposed

According to the RANGER Security Group Report, 570 operation security badges were issued and 156 visitors were escorted to observer areas (Tyler 1951). The Rad-Safe group report stated "all persons entering the contaminated areas wore film badges which had to be returned to Los Alamos for processing" (Shipman 1952). Reportedly, exposure records were kept for a total of 182 personnel who entered the "hot" area. Existing records, however, show only 180 personnel. The highest radiation intensity monitored was 16 R/h at 100 yards from ground zero for the 8 kt detonation on January 28, 1951 (Buckland 1951). Five participants accumulated more *exposure* than the 3-roentgen *exposure* limit for the test series. The highest *exposure* was 4.4 roentgens, and the rest were less than 4. The five included three construction workers, one Rad-Safe monitor, and one project participant, a Navy Commander assigned to the Armed Forces Special Weapons Project.

Type of Film Badge

The personnel film badge used during RANGER included the Du Pont 552 packet with a Type 502 sensitive component (0.05 to 10 R) and Type 510 insensitive component (5 to 50 R). The packet was contained in a prototype Los Alamos brass-cadmium badge with 0.020-inch-thick brass and cadmium filter clips (Shipman et al. 1951) that symmetrically covered both sides of the filter, and an open-window (unfiltered) area. This was the first use of a Los Alamos brass-cadmium type badge, and the production-model badges were issued to all personnel at Los Alamos later in the year (Littlejohn 1988b). Because the production model of this badge was used later in 1951 during Operation BUSTER-JANGLE at the same Nevada location, limitations, bias, and uncertainties during RANGER are assumed to be the same as discussed in the section on BUSTER-JANGLE.

Badge Issue and Exchange

Film badges were issued to all participants who entered radiation areas and to Air Force personnel at Nellis Air Force Base (AFB), at Las Vegas, Nevada, and Kirtland AFB, at Albuquerque, New Mexico. NTS film-badge issue and collection was at the combination control point and Rad-Safe building some eight miles south of the surface ground-zero area. Collected badges were sent by plane to New Mexico for processing at LASL, an unwieldy procedure because the test series lasted only 11 days, and exposure results were not received in time to be useful for participants who entered radiation areas each day. As a consequence, self-reading pocket dosimeter results were relied upon as indicating cumulative exposure. These measurements sometimes were lower than film badge exposures, and overexposure of a few participants resulted. Preliminary typed reports were prepared from film badge processing results (REECo 1988). On March 1 and March 6, memos listing *exposures* were sent from the Monitoring Section to the LASL H-Division Leader (Starner 1951).

Calibration, Processing, and Interpretation

Los Alamos film badge processing procedures included developing control and standard calibration films with each batch. An NBS-calibrated radium source, LASL No. 231, about 51 millicuries, was used to expose calibration films for preparation of calibration curves and use as batch standards (Littlejohn 1988b). According to the supervisor of dosimetry at LASL during RANGER, a Weston densitometer was used for measuring optical densities up to 3, and an Ansco densitometer was used as backup to density 6 (Littlejohn 1988b). Los Alamos procedures included measuring densities in three film areas, under a 0.020-inch-thick brass filter, under a 0.020 inch-thick cadmium filter, and in an open-window area. The open window area density was used to assign beta exposure, but, as previously indicated in Section 4.B, beta dosimetry during RANGER was unreliable.

Current Availability or Records

Exposure records that exist in the Master File source documents on file at Reynolds Electrical & Engineering Company, Inc., in Las Vegas, Nevada, include two typewritten lists of exposures and a computer listing containing the same information. Both of these lists apparently were derived from two Los Alamos Scientific Laboratory "Inter-Office Memorandum" listings tided "Exposures of Personnel Film Badges from the Nevada Tests" from Martha L. Starner, H-I Monitoring Section, to Thomas L. Shipman, M.D., H-Division Leader, dated 1 March and 6 March, 1951 (Starner 1951). These memos list "Badge Number", "Name", "Gamma", and "Beta." The gamma *exposures* appear to be in roentgens. RANGER films and calibration data currently are in storage at Los Alamos National Laboratory.

Estimated Bias and Uncertainty

Bias and uncertainties for RANGER film badge *exposures* greater than 200 mR are listed in the following table.

The use of 0.020 inch-thick brass and cadmium filters resulted in an over-response of the film emulsion to photon energies less than 100 keV of about a factor of 10. Optical density readings for RANGER films have not been located, but log sheets for BUSTER-JANGLE films, when the same filters were employed, show that only cadmium densities were recorded and used to determine *exposures*, even though columns existed for brass-filter and open window densi ties and ratios for determining other information. Thus, spectral response in the above table reflects greater bias, 1.3, and uncertainty, 1.3, than the usual 1.1 and 1.2, respectively. Otherwise, good procedures employed by well-trained LASL personnel and short exposure periods in a relatively dry environment result in minimal bias and uncertainties for other sources of these values.

Bias (B) and Uncertainty (K) for Operation RANGER

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.3		1.3	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.1		1.4
Environmental		1.0		1.1
Overall (*Exposure*)		1.1		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.5

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the RANGER series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for RANGER given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation RANGER

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.06)
0.05	0.03	(0.02, 0.07)
0.06	0.04	(0.02, 0.08)
0.07	0.05	(0.03, 0.08)
0.08	0.05	(0.03, 0.09)
0.09	0.06	(0.04, 0.10)
0.10	0.07	(0.04, 0.11)
0.12	0.08	(0.05, 0.13)
0.14	0.09	(0.06, 0.15)
0.16	0.11	(0.07, 0.16)
0.18	0.12	(0.08, 0.18)
0.20	0.13	(0.09, 0.20)
>>0.20	0.67 E	(0.44 E, 1.00 E)

where E is the film badge *exposure* (R)

Exposure ranges for the two film components used in RANGER overlap sufficiently that no overlap problems existed. In addition, no *exposures* above the range of the sensitive film component occurred.

OPERATION GREENHOUSE

Background

Operation GREENHOUSE was the fifth atomic weapon test series and the third to be conducted in the Pacific. It was the second operation occurring in the Enewetak Atoll area, following Operation SANDSTONE by three years.

The following table lists the test events for Operation GREENHOUSE. The tests were part of the thermonuclear or fusion weapons development program.

Operation GREENHOUSE Events

Event	Date	Type	Yield (kt)
DOG	4/08/51	Tower	*
EASY	4/21/51	Tower	41
GEORGE	5/09/51	Tower	*
ITEM	5/25/51	Tower	*

* Unannounced yields

Joint Task Force 3, created by the Atomic Energy Commission and the Joint Chiefs of Staff, directed the Operation. Task Unit 3.1.5 provided technical Rad-Safe support and film badge monitoring service, assisted by health physicists from the national nuclear weapons laboratories.

Personnel Exposed

Approximately 9,350 people participated in the operation and film badges were issued to 3,335 people (Cooney 1951). After some of the tests, fallout was deposited unexpectedly on Enewetak, Parry and Japtan islands where housing, recreation, and laboratory facilities were located. Film badges were not required for most people on these islands because they were planned to be radiation-free areas, and film badge supplies were insufficient to begin monitoring, once the problem occurred. Uneven deposition of fallout and variations in the time people spent on the island necessitated individual reconstructions of fallout *exposures*. Film badges were analyzed to exclude the effects of fallout; thus doubling of the fallout contribution in *exposure* records (Cooney 1951) was avoided.

The highest film badge reading was 8.8 R (Berkhouse et al. 1983a). The average *exposure* to individuals who were issued film badges was 0.51 R (Cooney 1951). Excluding 913 people receiving less than 0.1 R, the average film badge-determined *exposure* was 0.71 R.

Type of Film Badge

The film badge used during Operation GREENHOUSE consisted of a Du Pont

Type 553 film packet partially wrapped with 0.020 inch-thick (0.508 mm) lead strip (Cooney 1951; Littlejohn 1951). Inside the packet were three films, Type 502, Type 510 and Type 606. The measurement range for high-energy photons for the Type 502 was 0.05 R to 10 R (Ehrlich 1951). Ranges for the Type 510 and Type 606 were 1 R to 50 R and 10 R to 300 R, respectively.

The Type 606 films were seldom evaluated because *exposures* were too low (Cooney 1951). Examination of the highest exposed films reveal no measurable density above background on the Type 606 component. No overlap problems appeared between the other two film types.

The lead strip acted as a filter for low-energy photons but it was poorly designed and did not adequately cover both sides of the packet. Only a quarter inch of the strip extended over the edge of the packet to cover the rear. Littlejohn (1951) believed the area of the film covered on both sides did not allow for an appropriate density measurement. Considering the aperture of the densitometer and the penumbra region seen along the edge of the filtered area, Littlejohn's concern was valid.

The possibility exists that density measurements were made in the film area that was only filtered from the front. If so, overestimates of *exposure* would occur. Without filtration on both sides, errors would be introduced by backscattered low-energy photons and incorrect wearing of the badge.

An identification number was embossed onto each packet. Some films became exposed by light because the embosser occasionally perforated the paper wrapping of the packet. This problem was discovered early in the operation and the numbers of film affected were minimized by wrapping packets in black electrical tape (Cooney 1951).

Badge Issue and Exchange

Film badges were issued from the Rad-Safe building on Parry Island. A few badges were issued on Kwajalein to Air Force cloud-sampling pilots and ground crews servicing contaminated aircraft.

Most badges were issued for specific missions and were to be returned by the end of the day. Littlejohn (1951) noted that some badges were not returned on time and were used for more than a month. Announcements were made at the theater to remind people to return their badges. Retrieval of unreturned badges was inhibited by the failure to note an individual's base organization on the issue record (Cooney 1951).

Cohort film badging was performed on several naval vessels that were not expected to enter radiation areas but several were caught in unexpected fallout. Procedures for assigning exposures from badged cohorts were not located.

Calibration, Processing, and Interpretation

Films were calibrated by exposure to a 948 milligram radium source. Distances ranged from 12 cm to several meters. Eighteen *exposure* levels were used, ranging from 0.05 R to 50 R. Fixtures did not permit exact repositioning of the source or films. Errors that may have been introduced at the shorter distances (i.e. higher exposure levels) were not of significance, as personnel exposures were not experienced at exposure levels corresponding to these distances. Often, films were exposed at a nonperpendicular angle to the radiation beam (Littlejohn 1951). The uncertainty from this contributing factor is reflected in the increased values of K for this test series.

Sets of calibrated film were developed daily but not necessarily together with the personnel film. An unexposed control badge did accompany the personnel films through the development process. Careless drawing of the daily calibration curves was noted in a review of the film badge program (Littlejohn 1951). Discrepancies between film badges and pocket ionization chambers were ascribed to this carelessness or to poor technician training.

A Weston model 877 densitometer was used to evaluate the films (Cooney 1951). Its useful measurement range was from 0 to 3.0 optical density units (Littlejohn 1952).

Unspecified measures were taken to compensate for or to remove the contribution from fallout to the film badge reading. The cumulative *exposure* from fallout prior to test ITEM was about 2 R and increased to about 5 R afterwards. Allowing for the shielding effects of buildings and storage boxes, unexposed stored film could have received several hundred mR, causing problems. The existence of a problem was revealed in Cooney's report (1951) where little confidence was placed on film readings less than 0.4 R.

During review of the data from the Operation, some films were retrieved and analyzed in an attempt to deduce the method used to adjust film readings for fallout. Calibration and unexposed control films as well as all density data no longer exist. Comparisons of the reported exposure and new density measurement did not reveal consistent patterns. A film reported with an *exposure* of 0.04 R on April 9, 1951, had a gross density of 0.87. A film reported with 0.4 R three days later had a density over 3.0. The densities are too high for the reported *exposures* unless a large control density for background and fallout was subtracted during the original analysis.

Current Availability of Records

A summary of personnel exposures exists at the REECo repository in Las

Vegas. Also available are many of the films and copies of individual 5 x 8-inch *exposure*-history cards.

Annex 9.3 of the Scientific Director's Report for Operation Greenhouse contains much information about the film badge program and the unexpected fallout problem (Cooney 1951).

Estimated Bias and Uncertainty

The following table lists biases and uncertainties for *exposures* greater than 0.4 R. No bias appears to have been introduced, but the uncertainties in the estimates are much higher than other test series.

Estimated Bias (B) and Uncertainty (K) for Operation GREENHOUSE

Source			B	K
Laboratory			1.0	1.3
Radiological				
Spectrum	1.1	1.2		
Wearing	0.9	1.3		
Backscatter	1.1	1.2		
Combined Radiological			1.1	1.4
Environmental			1.0	1.6
Overall (*Exposure*)			1.1	1.9
Conversion to Deep-Dose Equivalent			1.3	1.2
Overall (Deep-Dose Equivalent)			1.4	2.0

The laboratory uncertainty reflects the imprecision of the calibration routines and technician performance. The poor lead filter design and resulting decrease in filtered area for the rear of the packet significantly increase the uncertainty estimate compared to other film badge designs.

The effects of fallout contribute the most to the uncertainties of the estimates. Treated as an environmental factor, the accumulation of exposure from fallout introduces a time consideration. The values in the table are for exposures received prior to shot ITEM, the detonation that produced the most fallout. After ITEM the uncertainty in the environmental factors is increased from 1.6 to 1.8.

The exposure from fallout causes the most uncertainty in lower film badge readings where the amount of fallout is comparable to the person's mission exposure. Without information on the approach used to exclude the effects of fallout, and with the report comments that *exposures* less than 0.4 R had questionable accuracies, a large uncertainty in the estimate at low exposures is created.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the GREENHOUSE series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for GREENHOUSE given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation GREENHOUSE

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00,0.08)
0.05	0.04	(0.01,0.09)
0.06	0.04	(0.02,0.10)
0.07	0.05	(0.02,0.11)
0.08	0.06	(0.03,0.13)
0.09	0.06	(0.03,0.14)
0.10	0.07	(0.03,0.15)
0.12	0.09	(0.04,0.18)
0.14	0.10	(0.05,0.21)
0.16	0.11	(0.06,0.23)
0.18	0.13	(0.06,0.26)
0.20	0.14	(0.07,0.29)
>0.20–10	0.71 E	(0.36 E, 1.43 E)

where E is the film badge *exposure* (R)

No overlap problems were experienced with the 3-component film packets used in GREENHOUSE.

OPERATION BUSTER-JANGLE

Background

BUSTER-JANGLE was the second test series at the Nevada Proving Ground (NPG; referred to as Nevada Test Site, NTS, during RANGER, January and February 1951, and renamed NTS December 31, 1954) (Ponton et al. 1982d). Seven nuclear detonation tests were conducted from October 22 to November 29, 1951, the first five for weapons development purposes and the last two for determining weapons effects. Desert Rock Troop maneuvers were conducted after some of the tests. The first test device was on a 100-foot tower, and the resulting yield was less than 0.1 kt. The next four development tests were airdrops at altitudes of from 1,100 to 1,400 feet for the highest yield test. Both effects tests had yields of 1.2 kt. One effects test device was detonated on the surface, and the other was buried 17 feet below the surface (DOE 1988; Hawthorne 1979). The following table is a summary of the BUSTER-JANGLE tests.

Operation BUSTER-JANGLE Events

Event	Date	Type	Yield (kt)
ABLE	10/22/51	Tower	<0.1
BAKER	10/28/51	Airdrop	3.5
CHARLIE	10/30/51	Airdrop	14
DOG	11/01/51	Airdrop	21
EASY	11/05/51	Airdrop	31
SUGAR	11/19/51	Surface	1.2
UNCLE	11/29/51	Crater	1.2

Personnel Exposed

According to Shipman, only NPG test personnel entering potential radiation-exposure areas were issued film badges during BUSTER-JANGLE by the NPG radsafe group. The number of personnel issued film badges by NPG Rad-Safe was 1,749, a total of 226 at Kirtland Air Force Base (AFB) in New Mexico, at Indian Springs AFB near NPG, and the rest at NPG (Shipman 1953).

Desert Rock military personnel took part in military maneuvers after tests, were observers, or were support troops. According to Kean, badging for these personnel took place at Camp Desert Rock, a 6th Army camp two miles south of the NPG main entrance through Camp Mercury. Badges issued at Desert Rock for Exercise I included 883 to combat-team members, 1,587 to support troops, and 2,796 to observers. At least 260 observers and inspection-team personnel were badged for Exercises II and III. (Kean 1951; Fitch 1951). Desert Rock troops entered and exited NPG in convoys.

AEC maximum permissible *exposure* limits of 3.0 R for most NPG and Desert Rock personnel and 3.9 R for cloud-sampling personnel were established for BUSTER-JANGLE. Three cloud-sampling personnel received exposures of 3.94, 4.02, and 4.4 R and three Desert Rock personnel were in the group of less than 50 non-cloud-sampling personnel exposed to between 3 R and a maximum below 6 R (Shipman 1953; Ponton et al. 1992).

Type of Film Badge

The Du Pont 553 film packet was used during BUSTER-JANGLE by both the NPG and Desert Rock Rad-Safe groups. The 553 contained component types 502 (0.02 – 10 R), 510 (5 – 50 R), and 606 (10 – 300 R). NPG film packets were in the Los Alamos brass-cadmium badge with 0.020-inch-thick brass and cadmium filters plus an open window. Desert-Rock film packets were in sealed, clear plastic envelopes, and probably had 0.020-inch-thick lead filters, as were used a few months later at NPG during operation TUMBLER-SNAPPER (Kean 1951; Shipman et al. 1951; Storm 1951).

Environmental damage did not appear to be a problem during BUSTER-JANGLE. Film badges were issued for short periods of time, seldom more than one day. Environmental conditions at NPG did not cause film-emulsion problems experienced in Pacific Operations, particularly with the cool fall temperatures that prevailed during BUSTER-JANGLE.

Other limitations of film badges in general include spectral response, angular response, and shielding by the body. These limitations were discussed in previous parts of this report, and are addressed under *Estimated Bias and Uncertainty* in this part. Generally, well-trained dosimetry technicians, a three-filter badge at NPG, and moderate environmental conditions minimized bias and uncertainties, while use of only 0.020 inch-thick filters increased spectral sensitivity and resulting bias and uncertainty. Remaining limitations of film badges are related to field use, including film-packet damage. Because wearing periods were short, and perhaps because self-reading pocket dosimeters also were worn when participants entered radiation areas, no mention is made in BUSTER-JANGLE Rad-Safe reports of problems with damaged film badges.

Overlap problems experienced with two-component film packets used during other test operations were not a problem during BUSTER-JANGLE. The three-component Du Pont 553 packet provided more overlap than needed; however, no overlap was necessary because the highest *exposures* were less than 6 R and well within the range (0.02-10 R) of the type 502 film component.

Badge Issue and Exchange

Not all support personnel at NPG were issued film badges during BUSTER-JANGLE. Participants entering radiation areas, Air Force cloud-sampling pilots and crews, supporting Air Force personnel, and participants who might be exposed to radioactive material from experiments were issued film badges which were to be processed by the NPG Rad-Safe Unit. All personnel entering radiation areas were required to check through the Rad-Safe Unit, where film badges were issued before entering, and upon exit, when film badges were collected for processing on the same day. Film badge requirements for personnel of operational aircraft were met by the Rad-Safe Unit and such film badges were processed by the Rad-Safe Unit at Control Point Building 2 (CP-2) (LASL 1951).

Desert Rock Battalion Combat Team (BCT) member film badges were issued on D-1 (day prior to test) at Camp Desert Rock and collected on D-day in the forward area prior to return to camp. Observer film badges were issued by the III Corps Visitors Bureau when each individual reported to Camp Desert Rock, and were collected by the Bureau after the test was observed when the observers returned to camp. Personnel of the III Corps were not in a central-issue location, so some badges were issued in camp on D-1 and others on D-day during muster in the forward area. After test activity, the majority of badges were collected at a designated check point in the forward area, and the remainder after individuals returned to camp (Kean 1951).

NPG film badge issue, processing, and results data were maintained on 5x8-inch cards, usually one for each individual. Cards listed Name, Contractor (organization usually listed), Badge (number), Dates (usually one-day badges), Gamma (in mR), Gamma Total (cumulative), Beta (column was not used), Beta

Total (not used), Dosimeter (self-reading pocket, sometimes listed), D Total (seldom used), and Remarks (REECo 1988).

Perhaps the pocket dosimeter readings were for comparison with film badge readings, or were entered on the card in case films were found to be damaged after development. The dates that film badges were worn were used to show statistics on film badges issued for each test, and cumulative gamma totals were used to prepare exposure reports.

Desert Rock roster sheets were used to issue film badges and show exposure results. Each sheet had a date and columns for Name, Rank, ASN (Army Serial Number), Organization, Home Station, Film Badge No., and Total Dosage (in mR). The last two columns were hand-written while the remaining information usually was typed (REECo 1988). Data were tabulated to show, by BCT members, observers, and III Corps participants, badges worn, badges reported, percentage reported, maximum reading, minimum reading (20 mR), and average reading. These data were reported (Kean 1951), and the films and records "kept on file in Headquarters, Armed Forces Special Weapons Project until further disposition is directed". Source documents and some films were retrieved from archives by REECo about IS years later.

Calibration, Processing, and Interpretation

NPG film badges were processed at Rad-Safe Building CP-2 by Los Alamos Scientific Laboratory (LASL) and military personnel using LASL equipment and procedures; 10 LASL H-Division and 3 military personnel handled dosimetry and records (Shipman 1953). Los Alamos records show radium 226 source, number 231, was used for calibrating personnel film badges during this time. The radium source was NBS-calibrated. Control and standard calibration films were developed with each batch of personnel films under carefully controlled conditions at 68 $\pm$ 0.5°F (Littlejohn 1988a).

Desert Rock film badges were processed in a mobile photo-laboratory truck at NPG by qualified Army Signal Corps personnel. Films were developed for 5 minutes at 68°F using Kodak liquid dental x-ray developer. Films were calibrated with a cobalt 60 source (Kean 1951).

The 13 personnel handling NPG dosimetry and records were experienced (10 LASL personnel) and trained (3 military personnel) in LASL procedures. The Weston densitometer was used for measuring film densities up to 3, and the Ansco was used as backup to density 6 (Littlejohn 1988a). The NPG minimum reportable *exposure* was 60 mR according to the radiological safety report (Shipman 1953), but *exposure* records indicate the minimum detectable exposure depended on the processing date and usually varied from 40 mR to 70 mR. Desert Rock film densities were measured with an Ansco-Sweet photo-densitometer, and the Desert Rock minimum reportable *exposure* was 20 mR (Kean 1951).

Current Availability of Records

REECo has in its source document archives copies of the 5x8-inch individual *exposure* record cards used at NPO and the Desert Rock roster sheets used to record *exposures*. At least some of the developed films and various *exposure* listings are also stored at REECo. Loos Alamos National Laboratory has in storage dosimetry work sheets that led to entries on the 5x8-inch cards, and REECo has copies.

Estimated Bias and Uncertainty

Bias and uncertainties for BUSTER-JANGLE *exposures* greater than 200 mR are listed in the following table.

Bias (B) and Uncertainty (K) for Operation BUSTER-JANGLE

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.3		1.3	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.1		1.4
Environmental		1.0		1.1
Overall (*Exposure*)		1.1		1.5
Conversion to Dose-Deep Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.5

In the above table, a laboratory bias of 1.0 and an uncertainty of 1.2 reflect well-trained dosimetry technicians and good procedures of the experienced Los Alamos Health Division. Spectrum bias of 1.3 and uncertainty of 1.3 are higher than for some test series because brass and cadmium filters used were only 0.020 inches thick compared to the 0.028 inch-thick lead filter later determined to be optimum for maintaining reasonably uniform response over a wide range of fission and activation product photon energies. This determination was made at a meeting in August 1952 between representatives from major laboratories and government agencies (AEC 1952). Environmental bias of 1.0 and uncertainty of 1.1 reflect moderate environmental conditions in Nevada during the fall of 1951 and usual film badge wearing periods of only one day.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the BUSTER-JANGLE series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for BUSTER-JANGLE given above. Readings below 0.2 R may be converted by reading directly from the table; these

Deep-Dose Equivalent and 95% Confidence Limits for Operation BUSTER-JANGLE

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00,0.06)
0.05	0.03	(0.02,0.07)
0.06	0.04	(0.02,0.08)
0.07	0.05	(0.03,0.08)
0.08	0.05	(0.03,0.09)
0.09	0.06	(0.04,0.10)
0.10	0.07	(0.04,0.11)
0.12	0.08	(0.05,0.13)
0.14	0.09	(0.06,0.15)
0.16	0.11	(0.07,0.16)
0.18	0.12	(0.08,0.18)
0.20	0.13	(0.09,0.20)
>0.20	0.67 E	(0.44 E,1.00 E)

where E is the film badge *exposure* (R)

values allow for additional laboratory uncertainty for low readings, as described in Section 53 under *Laboratory Uncertainties*.

No overlap problem would have been experienced with the 3-component types used in BUSTER-JANGLE; however, no film badge exposures were above the range of the most sensitive component.

OPERATION TUMBLER-SNAPPER

Background

Operation TUMBLER-SNAPPER was the third series of nuclear tests conducted at the Nevada Test Site (NTS) from I April 1952 to 5 June 1952. It consisted of eight low-to intermediate-yield tests in two phases. The first was the Tumbler phase of four tests on weapons effects. The second was the Snapper phase consisting of four tests to improve the design of nuclear weapons. The eight test shots are summarized in the following table:

Operation TUMBLER-SNAPPER Events

Event	Date	Type	Yield (kt)
ABLE	4/01/52	Airdrop	1
BAKER	4/15/52	Airdrop	1
CHARLIE	4/22/52	Airdrop	31
DOG	5/01/52	Airdrop	19
EASY	5/07/52	Tower	12
FOX	5/25/52	Tower	11
GEORGE	6/01/52	Tower	15
HOW	6/05/52	Tower	14

The test series had two purposes, to advance the development of nuclear weapons and to train troops in tactical nuclear warfare.

Personnel Exposed

According to the Operation TUMBLER-SNAPPER Radiological Safety Report to the Test Director, 2243 test personnel were issued film badges at the Nevada Proving Grounds (NPG) from April 1 to June 9, 1952. Of this number, 27 individuals accumulated *exposures* above the 3.9 R maximum established for the operation (Gwynn 1952). About 270 Air Force personnel were in radioactive debris cloud sampling activities, and about 80 of these actually flew in the sampling aircraft (GAO 1987).

The DNA historical report on TUMBLER-SNAPPER indicates that about 10,600 Department of Defense personnel were issued film badges at Camp Desert Rock, two miles south of the NPG main entrance, and these additional personnel participated in Desert Rock troop maneuvers or as observers after some of the nuclear detonations (Ponton and Maag 1982 a,b, Ponton et al. 1982a).

Type of Film Badge

Two types of films badges were used. The first was the NPG Badge which was issued to NPG test participants, including radioactive debris cloud-sampling aircraft and ground crews, and provided to and processed for Desert Rock participants. Tlie badge consisted of a Du Pont 558 film packet with a 0.020-inch-thick lead filter required to cover an area one-half-inch wide by one-inch long on each side of the packet. The packet was embossed with an identification number before being heat-sealed in a 0.002-inch-thick polyethylene envelope. The lead was improperly folded around the packet by the manufacturer in the first group of badges, extending only 1/4-inch over one side of the packet until corrected by the manufacturer after shot ABLE to cover equal areas on both sides.

The second type of badge was the Los Alamos Scientific Laboratory (LASL) badge which was issued only to radioactive debris cloud-sampling pilots. It contained a piece of Du Pont 502 film, paper wrapped, enclosed in a 0.020-inch-thick brass holder, with two windows on each side of the holder, one open to the air and one covered on both sides with 0.020-inch-thick cadmium. Density readings for *exposure* and calibration were made under the cadmium window (AEC undated).

The stated range and accuracy of the film badge packets are summarized by Brady and Nelson (1985). The 508 film component was reported to have a range of 0.01 R to 6 R. However, a calibration curve was found for the TUMBLER-SNAPPER series going up to 10 R. The 1290 film had a reported range of 20 to 3000 R. However, it appears that the highest individual badge readings were all below 10 R and it never was necessary to read the 1290 film component. The 502 film component had a reported range of 0.02 to 10 R.

Badge Issue and Exchange

NPG badges were issued to NPG test participants, including personnel involved in radioactive debris cloud-sampling, and to Desert Rock participants. Badges were issued and exchanged at Indian Springs Air Force Base by Air Force personnel, at Camp Desert Rock by Desert Rock personnel, and at NPG by NPG Rad-Safe personnel. All badges were provided and processed, however, by NPG Rad-Safe. In addition, LASL badges also were worn by cloud samplers after Shot ABLE in lieu of pocket dosimeters, which were found to be leaking in Shot ABLE. It appears (Fackler 1953, page 115) that after Shot BAKER, the two badges were worn, taped side by side; their readings were averaged because of doubt as to the reliability of one reading.

According to Gwynn (1952) "A permanent record of these dosage readings was made against the individual's name & organizations." and that "Daily preparation, for submission to the director of Rad-Safe Group, of integrated dosage reports showing each individual's name, grade, and organization, and by indicating by red underscore all individuals who had exceeded a total integrated dose of 2 R." It is pointed out, however, that most of these records are no longer available (Goetz et al. 1985).

Calibration, Processing, and Interpretation

Reported calibration procedures were found only for the NPG badges. These were described by Gwynn (1952) as follows: "Film badges were calibrated and processed by standard techniques daily and made available by 0800 hours the following day to provide the director of Rad-Safe with the cumulative doses prior to the re-entry of persons into a contaminated area." The Rad-Safe Group consisted of one officer plus 18 enlisted men, working in two shifts day and night to issue and process all films. Six radium sources on loan from the U.S. Navy Bureau of Ships were used as calibration sources at the NPG. The LASL badges used on some cloud-sampling personnel also were calibrated against a radium source at Los Alamos and processed at Los Alamos. For processing the NPG badges, Eastman X-ray Developer & Fixer were used. The films were processed in the developer for 5 minutes or for 4.5 minutes with mechanical agitation. A stop bath of acetic acid was used for 10 sec. The films were fixed for 10 minutes and then washed for 20 minutes. The densitometer was calibrated with neutral density filters.

A memorandum was found in REECo files concerning intercomparisons of NPG and LASL badges (AEC undated) with an unsigned four page summary of film badge discrepancies. Apparently some cloud sampling personnel wore both type of badges for Shots BAKER through HOW. For reasons that were never uncovered, the NPG readings were consistently higher than the LASL readings by about 45% on average, ranging from about 12% for Shot FOX to 72% for Shot CHARLIE. For Test EASY, both types of badges were exposed mounted on a Masonite phantom and compared to readings obtained with a Victoreen surface chamber. Ile NPG badges read about 31% to 38% high and the LASL badges read 3% to 8% high. Accordingly there appears to be a bias of around +35% for the NPG badges due to energy spectrum differences between the radium emission spectrum and the energy spectrum of the radiation released by the test shots.

According to Gwynn (1952), there were some contamination problems. He reported that "It was found that fine particles of radioactive dust adhered to this covering and that the gamma rays and beta particles emitted by this dust contributed to the indicated film badge dose. This film badge was designed to be worn in the individual's pocket. Often, "hot" dust stirred up by winds or vehicles lodged in the pocket and contaminated the film badge cover." Design changes were recommended.

(N.B. Ile badges of some of the exposed personnel were examined at REECo. and no apparent "hot spots" were observed. The darkest type 508 exposed film found had a optical density of about 3.2. No processed type 1290 films were found.)

Current Availability of Records

Most film badges, some dosimetry log sheets, and most *exposure* rosters for both NPG and Desert Rock participants are available in REECo archives at Las Vegas, Nevada. Many Desert Rock films are missing, as are posted *exposures* on many Desert Rock rosters.

Estimated Bias and Uncertainty

A GAO report (1987) recommends that the integron readings for the ionization chambers carried on the aircraft of the cloud samplers should be given more weight when such readings appear in conflict with the reported film badge readings. However, this contention was disputed by reviewers of the GAO report (1987, pp. 76–81). There is no way of determining the correct ratio between the two readings. Two badges were worn side by side by most of the flight personnel, and their readings represent the best estimate of personnel *exposure* . The integron readings represent the *exposure* received by the integron which could be quite different from the *exposure* of flight personnel.

The following tables list the estimated bias and uncertainty at 95% confidence level for various sources of error at the 200 mR level, assuming a lognormal distribution of errors.

Bias (B) and Uncertainty (K) For Operation TUMBLER-SNAPPER (Ground Personnel)

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.5		1.3	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.3		1.4
Environmental		1.2		1.2
Overall (*Exposure*)		1.6		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		2.1		1.6

Bias (B) and Uncertainty (K) For Operation TUMBLER-SNAPPER (Flight personnel)

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.3		1.3	
Wearing	0.9		1.1	
Backscatter	1.1		1.1	
Combined Radiological		1.3		1.3
Environmental		1.1		1.1
Overall (*Exposure*)		1.4		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.8		1.5

Note that the bias due to the energy spectrum for ground personnel includes an apparent calibration discrepancy between the LASL badges and the NPG badges (which read about 35% higher) worn by Ground Personnel and a 10% bias introduced by the brass/cadmium filter used in the LASL badges. Hence for ground personnel, the total bias due to the energy spectrum is 1.35 x 1.10 = 1.5. For cloud samplers (flight personnel) the bias is taken to be about 30% since both badges were worn and the readings were averaged.

Application of Bias and Uncertainty

The following two tables give deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the TUMBLER-SNAPPER series. Film badge readings above 02 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for TUMBLER-SNAPPER given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties.*

Deep-Dose Equivalent and 95% Confidence Limits for Operation TUMBLER-SNAPPER (Ground personnel)

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.02	(0.00,0.04)
0.05	0.02	(0.01,0.05)
0.06	0.03	(0.01,0.06)
0.07	0.03	(0.02,0.06)
0.08	0.04	(0.02,0.07)
0.09	0.04	(0.02,0.08)
0.10	0.05	(0.03,0.08)
0.12	0.06	(0.03,0.10)
0.14	0.07	(0.04,0.11)
0.16	0.08	(0.05,0.13)
0.18	0.09	(0.05,0.14)
0.20	0.10	(0.06,0.15)
>0.20	0.48 E*	(0.30 E, 0.76 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.26 and 0.86. However, there appear to be no individual badge readings in this overlap region for Operation TUMBLER-SNAPPER.

Deep-Dose Equivalent and 95% Confidence Limits for Operation TUMBLER-SNAPPER (Flight personnel)

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.02	(0.00,0.05)
0.05	0.03	(0.01,0.06)
0.06	0.03	(0.02,0.06)
0.07	0.04	(0.02,0.07)
0.08	0.04	(0.03,0.08)
0.09	0.05	(0.03,0.09)
0.10	0.06	(0.03,0.09)
0.12	0.07	(0.04,0.11)
0.14	0.08	(0.05,0.12)
0.16	0.09	(0.06,0.14)
0.18	0.10	(0.07,0.15)
0.20	0.11	(0.07,0.17)
>0.20	0.56 E*	(0.37 E, 0.83 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10–15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.32 and 0.96. However, there appear to be no individual badge readings in this overlap region for Operation TUMBLER-SNAPPER.

OPERATION IVY

Background

Operation IVY was conducted in November, 1952 on Enewetak Atoll in the Pacific. Tlie test MIKE was the first acknowledged detonation of a fusion device and test KING was the detonation of a fission weapon. The following lists details of the two Operation IVY detonations.

Operation IVY Events

Event	Date	Type	Yield (Mt)
MIKE	11/01/52	Surface	10.4
KING	11/16/52	Airdrop	0.5

Approximately 11,650 people participated in the operation (Gladeck et al. 1982). Of these, 2,030 people were badged. There were less than 30 cumulative *exposures* that exceeded 3 R and the highest *exposure* was 17.8 R (Gladeck et al. 1982). These *exposures* exclude that due to fallout.

Personnel Exposed

The highest *exposure* was received by an individual performing a search and rescue mission in response to a lost cloud-sampling aircraft following the MIKE test.

Type of Film Badge

The film badge used at Operation IVY consisted of a Du Pont Type 558 film packet with a 0.020-inch (0.508 millimeter)-thick lead strip covering on both sides. The lead strip was 0.5 inches wide and one inch long on each side of the packet and provided sufficient area to evaluate the film underneath the filter (Maynard 1952).

The Du Pont Type 558 packet contained two films, Type 508 and Type 1290. The former had a range of approximately 0.05 R to 10 R while the latter measured *exposures* between 10 and 750 R (Brady and Nelson 1985).

Each film packet was embossed with a unique number enabling the cross referencing of a film badge packet to its user.

Two other special film badges were issued to pilots of aircraft sampling radioactive clouds. One of these badges consisted of the Du Pont Type 553 packet enclosed in the standard Los Alamos Scientific Laboratory film badge holder. This holder provided on both sides a brass filter, 0.020 inch (0.508 millimeters) thick, an open window, and a cadmium filter, 0.020 inch (0.508 millimeters) thick (Maynard 1952). The Type 553 packet contained three films, Type 502 measuring *exposures* 0.03 R to 10 R, Type 510 useful from 5 R to 50 R, and Type 606 used to measure *exposures* between 10 R and 300 R.

The second special badge issued to the pilots was one designed by the National Bureau of Standards. It consisted of a Type 553 packet; the holder was constructed of 8.25 mm Bakelite wrapped with 1.07 mm of tin and 0.3 mm of lead (Maynard 1952; Ehrlich and Fitch 1951). A number was x rayed onto the films instead of embossed. The NBS badge was not designed for personnel monitoring but for area monitoring of photons from approximately 0.1 MeV to 11 MeV (Ehrlich 1954).

Neither of the special badges was known to have significant limitations. The standard Operation IVY badge was also issued to the pilots and was usually the prime source of data for their dose assessment.

Badge Issue and Exchange

Detailed instructions were prepared for the distribution, development, calibration, and documentation of film badge results. Technician training in these procedures was noted in the reference by Maynard (1952).

Badges were issued at Parry Island located in the southern part of the Atoll. Issue also took place on the *USS Rendova* for about one day after the MIKE detonation. Pilots and personnel servicing aircraft used to sample the radioactive cloud were issued badges at the Kwajalein airfield.

Badges were usually issued on a mission basis and worn for approximately one day. Badges were returned to the decontamination center by Rad-Safe monitors who accompanied the reentry parties. Badges also were collected on the flight deck of the *USS Rendova* following the MIKE test.

Calibrations, Processing, and Interpretation

Calibrations were performed with either a radium or a cobalt 60 source. No source strength was documented. Exposures were made free in air at a fixed distance from the source with the time being varied to achieve different levels of exposure.

The frequency of calibrations was not well defined but procedures imply frequent checks, since one calibration film was required for each batch of developed film. Unexposed film accompanied each developing batch to account for base fog. All films were stored in refrigerators kept at temperatures between 40 and 50°F in relatively dry air (Maynard 1952).

Densities were evaluated with an Ansco densitometer. This densitometer had a range from 0 to 6.0 optical density units. A backup densitometer manufactured by Weston was available, but its range only extended to 3.0.

Assignment records detailing which badge number was issued to which participant were filled out by the Rod-Safe monitors and returned to the processing laboratory with the used badges. Records maintained during the operation included a personnel exposure history form, a consolidated list of exposures, and processing data sheets.

There was no reference to cohort badging in any of the reports regarding Operation IVY.

Current Availability of Records

Records available at the REECo, Las Vegas, Nevada, include the personnel *exposure* history forms and the consolidated list of *exposures*. Most personnel films, but not calibration films, are available. Processing data sheets indicating densities and the conversion to *exposure* are not available.

Estimated Bias and Uncertainty

Bias and uncertainty for factors influencing film badge performance for ground personnel and for flight personnel are listed in the following tables. This information is appropriate for *exposures* of about 0.2 R and above.

Thirteen low *exposure* films were reevaluated. These films were originally reported to have *exposures* less than 0.2 R. The base fog was found to be approximately 0.3 but ranged as high as 0.35. The combination of the base fog, film sensitivity and densitometer precision indicates a larger uncertainty in the laboratory bias estimate at lower *exposures.*

Less uncertainty caused by radiological factors exists for higher *exposures*. *Exposures* over 5 R were exclusively received by pilots flying through radioactive debris clouds. Four films reported with *exposures* over 10 R were reexamined and correlated well with reported data. The reproducible and uniform positioning of the pilots in their planes, the consistent placement of badges and protective shielding aprons, and the constant exposure geometry reduced the uncertainty attributed to badge wearing and source geometry components of the radiological factor.

Bias (B) and Uncertainty (K) For Operation IVY (Ground Personnel)

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.3		1.3	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.1		1.4
Environmental		1.0		1.1
Overall (*Exposure*)		1.1		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.6

Bias (B) and Uncertainty (K) For Operation IVY (Flight personnel)

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.1		1.2	
Wearing	0.9		1.1	
Backscatter	1.1		1.1	
Combined Radiological		1.1		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		1.1		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.4		1.5

The uncertainty attributed to, environmental factors for the higher exposures is less for the same reasons just mentioned. That is, the environment experienced by pilots was not particularly harsh and did not present the same probability for damage as might be expected for badges worn by individuals on boats or on the islands performing certain strenuous activities.

The environmental contribution to uncertainty is higher for *exposures* less than 0.2 R. Some people not expected to receive much *exposure* may have used badges for longer periods of time. It, is reasoned that badges worn for longer times have a higher risk of being affected by environmental conditions.

No information exists on *exposures* received by pilots who were issued the special badges. However, review of performance information for these badges suggests that their bias and uncertainties were not significantly different from the standard badge as it was used during Operation IVY.

Application of Bias and Uncertainty

The following two tables give deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the IVY series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for IVY given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation IVY (Ground personnel)

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.06)
0.05	0.03	(0.02, 0.07)
0.06	0.04	(0.02, 0.08)
0.07	0.05	(0.02, 0.09)
0.08	0.05	(0.03, 0.10)
0.09	0.06	(0.03, 0.11)
0.10	0.07	(0.04, 0.12)
0.12	0.08	(0.05, 0.14)
0.14	0.09	(0.06, 0.16)
0.16	0.11	(0.06, 0.18)
0.18	0.12	(0.07, 0.20)
0.20	0.13	(0.08, 0.21)
>0.20	0.67 E*	(0.42 E, 1.07 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.38 and 1.17. There appeared to be very few individual badge readings in this overlap region for Operation IVY (ground personnel).

Deep-Dose Equivalent and 95% Confidence Limits for Operation IVY (Flight personnel)

Film Badge Best *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.06)
0.05	0.04	(0.02, 0.07)
0.06	0.04	(0.02, 0.08)
0.07	0.05	(0.03, 0.09)
0.08	0.06	(0.03, 0.10)
0.09	0.06	(0.04, 0.11)
0.10	0.07	(0.04, 0.12)
0.12	0.09	(0.05, 0.14)
0.14	0.10	(0.06, 0.16)
0.16	0.11	(0.07, 0.18)
0.18	0.13	(0.08, 0.20)
0.20	0.14	(0.10, 0.21)
>0.20	0.71 E*	(0.48 E, 1.07 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.43 and 1.19. There appear to be several individual badge readings in this overlap region for Operation IVY (flight personnel).

OPERATION UPSHOT-KNOTHOLE

Background

Operation UPSHOT-KNOTHOLE was a series of 11 detonations conducted at the Nevada Test Site (NTS) from March 17 to June 4, 1953. The series consisted of seven tower shots, three airdrops, and one detonation of a nuclear artillery shell fired from a 280 mm cannon. This latter detonation is ordinarily designated as an airburst to differentiate it from airdrops or tower detonations.

Operation UPSHOT-KNOTHOLE Events

Event	Date	Type	Yield (kt)
ANNIE	3/17/53	Tower	16
NANCY	3/24/53	Tower	24
RUTH	3/31/53	Tower	0.2
DIXIE	4/06/53	Airdrop	11
RAY	4/11/53	Tower	0.2
BADGER	4/18/53	Tower	23
SIMON	4/25/53	Tower	43
ENCORE	5/08/53	Airdrop	27
HARRY	5/19/53	Tower	32
GRABLE	5/25/53	Cannon	15
CLIMAX	6/04/53	Airdrop	61

Personnel Exposed

The estimated number of DOD participants was close to 21,000 (Ponton et al. 1982b). These persons were largely involved in Exercise Desert Rock V, conducted in conjunction with the UPSHOT-KNOTHOLE tests, and included individuals engaged in troop maneuvers, or who were observers and may have been exposed to both prompt radiation, including neutrons, and subsequent fission product activity following the detonation (Ponton et al. 1982b). About 4,000 military and civilian participants received film badges, with the highest recorded *exposure* the NTS personnel received amounting to less than 10 R.

Type of Film Badge

Film dosimetry in Operation UPSHOT-KNOTHOLE has been documented in a report of radiological safety for the operation (Collison 1953). Dosimetry was performed with the Du Pont 559 film packet which contained two separate films, Type 502 and Type 606. The former was the more sensitive, with a reported range of 0.02 to 10 R (Brady and Nelson 1985). The range of the Type 606 was reported as 10–300 R; thus, for this series, there was apparently no region of overlap in the ranges of the two component films. The film packets were purchased for the manufacturer through H Division of Los Alamos Scientific (now National) Laboratory and the AEC Division of Biology and Medicine, and were to have a section 1/2 inch wide and 1 inch long covered front and rear with a lead strip 0.72 mm thick to minimize energy dependence. However, as initially received from the manufacturer, the lead coverage was 1 inch long on one side, and 1/2 inch on the other. Accordingly, 28,000 of the 35,000 film packets were returned for modification, and presumably these were the packets used in the field.

The original badge specifications also called for embossed five digit sequential numbering and enclosure of the film packet in a sealed polyethylene holder 0.005 inch thick, with an alligator clip for attachment to the clothing. There is no indication from later reports or documents that this polyethylene holder was in fact used; rather the available evidence suggests that only the bare film packets with the lead strip were used.

Badge Issue and Exchange

Issuance and processing of the film badges for the Exercise Desert Rock V was the responsibility of the military, specifically the 9778th Radiological Safety Support Unit (RSSU). An estimated 20% of the participants (about 4,000) were badged.

Available documents indicate that individual JTO and Desert Rock participants were issued film badges for Shots ANNIE and NANCY. At the BADGER event, the Marines participating were issued two badges per platoon. For the remaining shots, one badge per platoon was issued to troops who performed similar duties. Badges were normally worn on the trunk, outside the clothing, and were collected at the conclusion of each day for processing that night.

Calibration, Processing, and Interpretation

Calibration was carried out in the laboratory under controlled conditions using photons from a cobalt 60 source with a stated size of 83 mg radium equivalent, which would correspond to approximately 83 mCi. Exposures were typically made for a period of one hour at twelve predetermined specific identified locations or stations, which were at distances ranging from 20 to 195.5 cm from the source. The intensity range for these distances was calculated as 17.2 to 1645 mR/h in an internal document dated 3 September 1953. These values are in excellent agreement with calculated intensity values computed using the currently accepted values for the photon intensity from cobalt 60, and a source strength of 83 mCi.

Review of the records indicates that calibrations were conducted on at least 24 separate occasions during the months of March to May 1953, apparently on a daily basis during the period of exposure. The standard calibration exposure protocol was 12 individual films, one at each specified calibration location, exposed for one hour. The exposure location, unique identifying number, and net optical density obtained with the Ansco Model 475 densitometer were recorded on individual calibration sheets. On some sheets, the *exposure* was also recorded. These *exposure* values differed slightly from the calculated values reported in the 3 September 1953 internal document, being approximately 5% greater. Presumably the recorded values were used in drawing up the calibration curves and in assigning dose, but this is not known for certain. Review of the records of calibration runs suggest that the relationship between film response and *exposure* was not incongruous, and that background fog levels were not excessive.

With the exception of exercise Desert Rock V, processing of film badges collected during the day was carried out each night in the Film Badge Processing Laboratory in the Rad-Safe Building under the direction of the Los Alamos Scientific Laboratory. Based on the fragmentary data available, readout was apparently performed with an Ansco Model 475 densitometer and was limited to the portion of the film under the lead strip; five distinct areas under the lead strip were read by the densitometer. *Exposure* was reported in units of "mr" (milliroentgen) and should be reasonably representative of the *exposure* from photon radiations, as the lead strip should provide approximately constant NOD per unit *exposure* for photon energies as low as about 70 keV up to about 2 MeV.

There is nothing in the available records to suggest that calibration, processing, or readout procedures were inadequate or improperly carried out. Films were developed on a daily basis during the post-detonation activities for personnel involved in operations in the vicinity of ground zero; this, coupled with the typical environmental conditions recorded for the Test Site during the period under consideration, obviates adverse effects from temperature and humidity.

Current Availability of Records

Film dosimetry records for the Desert Rock V activities, in which most of the participants were involved, are lacking. The 82 records that do exist were all from a single listing dated April 9 of Fort Benning troops at Shot NANCY. As agreement between the calculated doses for these troops and the film badge results were excellent, it is likely that there is little error associated with these data (Edwards et al. 1985).

Estimated Bias and Uncertainty

Other than the possibility of a systematic calibration error that might account for a 5% overestimate in the assigned dose, as discussed above, there is nothing in the available records to suggest that calibration, processing, readout, or other laboratory procedures were inadequate or improperly carried out, or were respon sible for the introduction of a measurement bias. Since it cannot be established with certainty that the 5% systematic overestimate did in fact occur, the bias factor (B) is taken to be unity for laboratory conditions.

For the 502 film component, accuracy has been stated as ± 10% at levels >> 400 mR; at lower levels, greater uncertainty was reported, ranging to ± 100% at the reported minimum detection level of 10–20 mR. Other data relating to the accuracy of the densitometer and the film were obtained and reported (Brady and Nelson 1985); the estimates of accuracy based on these data were 1–2% of the *exposure* for the Type 502 film. For the higher-range Type 606, which was used for levels above 10 R, the reported accuracy is within 2.3 to 16 per cent of the *exposure* (Brady and Nelson 1985). These values refer to the calibration and laboratory procedures, and can be used in conjunction with the methodology presented elsewhere in Chapter 5 to obtain an estimate of the uncertainty factor, K, at the 95% confidence level, for the laboratory operations. This factor is estimated as 1.3 and includes the uncertainty with respect to the calibration bias discussed above.

Various radiological factors may also introduce bias or uncertainty in the results, as indicated in the table below. Energy dependence may introduce a bias into the interpretation of film badges exposed in the field when compared with calibration exposures made under laboratory conditions to the photon field from cobalt 60. The somewhat lower photon energy distribution in the field, approximately equivalent to an effective photon energy of 0.7 Mev, would produce slightly less darkening (i.e., net optical density) under the filter per unit *exposure* than the higher energy photons from cobalt 60. This would result in a slight underestimate of the *exposure* received by the film, which is offset by the slighter over-response to low energy photons; the bias, B, from this source is estimated as 1.0.

As the badges were worn on the trunk, body backscatter would produce an increased density per unit *exposure* as compared with the calibration films; this would result in an overestimate of dose, and the bias from this source is estimated as 1.1. Similarly, location of the film badge relative to the fallout field, which was the primary source of exposure, and the angular-dependence considerations of the badge result in a bias towards underestimation of dose and B from these sources which is estimated to be 0.8. No other radiological factors are likely to introduce a significant or measurable bias. The combined bias factor (B) for the radiological factors is thus 0.9.

In general, environmental conditions were such that no bias would be introduced from this source. Similarly, there are no indications that the badge assignment or collection procedures introduced bias in the results. Accordingly, for environmental factors, B = 1 and K = 1.1.

Bias (B) and Uncertainty (K) for Operation UPSHOT-KNOTHOLE

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.0		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Total Radiological		0.9		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		0.9		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.1		1.5

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the UPSHOT-KNOTHOLE series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for UPSHOT-KNOTHOLE given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings as described in Section 5.B under *Laboratory Uncertainties.*

Deep-Dose Equivalent and 95% Confidence Limits for Operation UPSHOT-KNOTHOLE

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.04	(0.00, 0.08)
0.05	0.05	(0.02, 0.09)
0.06	0.05	(0.03, 0.10)
0.07	0.06	(0.04, 0.12)
0.08	0.07	(0.04, 0.13)
0.09	0.08	(0.05, 0.14)
0.10	0.09	(0.05, 0.15)
0.12	0.11	(0.07, 0.18)
0.14	0.13	(0.08, 0.20)
0.16	0.15	(0.09, 0.22)
0.18	0.16	(0.11, 0.25)
0.20	0.18	(0.12, 0.27)
>0.20	0.91 E*	(0.61 E, 1.36 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.55 and 1.51. There appear to be a few individual badge readings in this overlap region for Operation UPSHOT-KNOTHOLE.

OPERATION CASTLE

Background

CASTLE was a six-detonation test series in the Pacific Proving Ground (PPG) at Enewetak and Bikini atolls in the northwestern Marshall Islands. The tests were conducted from March to May of 1954. All six detonations were surface bursts of high-yield, thermonuclear devices with yields ranging from 0.11 Mt to

15 Mt. The 15 Mt detonation was the highest yield of any U.S. nuclear weapons test (Martin 1982). The events of Operation CASTLE are summarized below:

Operation CASTLE Events

Event	Date	Location	Yield (Mt)
BRAVO	3/01/54	Bikini	15.0
ROMEO	3/27/54	Bikini	11.0
KOON	4/07/54	Bikini	0.11
UNION	4/26/54	Bikini	6.9
YANKEE	5/05/54	Bikini	13.5
NECTAR	5/14/54	Enewetak	1.69

Although the six detonations were thermonuclear devices, a significant portion of their energy was due to fission processes. Experiments conducted in conjunction with the detonations measured power and efficiency of the devices and attempted to gauge military effects of the explosions. Approximately 60 percent of the total support requirements were for the effects experiments.

Personnel Exposed

The tests were conducted by a joint task force of military, civil service, and contractor personnel of the Department of Defense and Atomic Energy Commission. Of the approximately 12,700 participants in the test series, there were approximately 10,900 personnel who were badged. Personnel expected to be exposed to radiation were initially badged, but several unbadged personnel received significant radiation doses.

The majority of personnel were aboard Navy ships in the test area. Many of the Navy ships received very high levels of fallout contamination on their decks after the first detonation, BRAVO. Personnel who were on islands or atolls downwind from the first detonation were evacuated within a few days of the detonation, and personnel later returned to these areas for brief periods. Prior to the evacuation, several personnel were exposed to very high levels of radiation from fallout contamination.

A contingent of cloud-sampling personnel and support personnel were on islands not greatly affected by fallout from the detonations. Sampling crews were exposed to radiation from airborne radionuclides during flights, and from contaminated planes and equipment after their flights.

Type of Film Badge

The film badge used in CASTLE consisted of a Du Pont 509 film packet with film types 502 and 606. These had been selected by the AEC in 1952 to provide the best coverage of the desired *exposure* range and photon energy range. An area 1/2 x 1 inch on each side of the packet was covered by a lead filter. The filter, 0.028 inches thick, was used to improve energy response of the film.

The CASTLE film pack was the same as for Operation TEAPOT and was encased in a plastic covering and an alligator clip for attachment purposes. There is evidence that these packets were not completely waterproof (Perkins 1981).

Limitations of this film badge are presented in Chapter IV of this report. Of importance for this test series are the several *exposures* which were determined to occur in the overlap range of the two films (10 – 15 R).

Badge Issue and Exchange

The initial plan for badging personnel was to badge all personnel expected to receive significant amounts of radiation exposure and a representative 10% of other personnel (Martin 1982). Although there was a need to badge all personnel immediately after the first shot, BRAVO, because of the extensive contamination due to fallout, there were not enough badges available to do this. Additionally, the staffing level of Task Unit 7.1.7, which provided radiological safety support, was insufficient to process a larger number of badges than were available.

For shots subsequent to BRAVO, there were more badges available and there was a greater emphasis on personnel monitoring. Nevertheless, all personnel involved in the series were not monitored with individual personnel dosimeters.

Individuals performing selected activities were uniformly badged. For example, all crew members of aircraft expected to fly within 185 km of the shot site at H-hour were badged.

Calibration, Processing, and Interpretation

The primary radiation standard for calibration of films used in CASTLE was radium 226. Cobalt 60 sources were used in some instances, but corrections were applied where necessary to produce results consistent with radium 226 (Perkins 1981). The low-range film (Du Pont 502) was calibrated from 40 mR to 10 R, and the high-range film (Du Pont 606) was routinely calibrated from 10 R to 60 R, with an initial calibration up to 200 R. Calibrations were performed using a calibration range with reproducible exposure geometry.

New calibration curves were to have been generated whenever developing solutions were changed and between each shot. Recalibration also was required whenever there were temperature control problems, changes in emulsion, or excessive correction factors.

Film badges given a known *exposure* were used as standards and processed with field badges. Standard films were given an *exposure* of 500 mR prior to the first shot and stored with unissued film. One standard film was included with each batch of film to be developed (Perkins 1981). Control films also were processed with each batch.

Film badge processing laboratories were air-conditioned. Film badges were to have been stored in a refrigerator at a temperature of 40°F. A desiccant was to have been used in each refrigerator to reduce humidity. Film badge standards and controls were allowed to come to room temperature before development.

Current Availability of Records

Development was usually done at night, after collection of film badges worn during the day, in three stainless steel tanks containing developing solution, stop solution, and fixer. The solution temperature was to have been kept at 68°F. After development, film badges were washed in running water of the same temperature. All development was done under safelights.

Films were read on a Los Alamos densitometer Model FD-1. Film processing and readout technicians were trained by Los Alamos dosimetry personnel prior to the first shot in the series.

Processing laboratories were established on Parry Island and aboard the *USS Bairoko* prior to the operation. During the operation, there was radioactive contamination of both of these locations in varying degrees. The impact on film dosimetry of high radiation levels due to contamination in these locations was not determined during the operation.

Developed films for nearly all personnel dosimeters, personnel *exposure* rosters, individual radiation *exposure* records, and other hard-copy records are currently stored at REECo in Las Vegas, Nevada. Calibration and control dosimeters have not been found for all batches. Hard-copy *exposure* records are incomplete in some cases.

An analysis of radiation exposures of Navy personnel during operation CASTLE was prepared for the Defense Nuclear Agency (DNA 1984). The principal report describing the operation is *CASTLE Series, 1954* (Martin 1982).

Estimated Bias and Uncertainty

The large source of uncertainty (K = 1.8) for environmental effects is a consequence of the high levels of fallout contamination at both field-exposure locations and at badge storage and processing locations. The presence of such contamination can lead to uncertainties in a number of ways, including badge contamination, excessive exposure of controls, exposure of badges prior to issue, and exposure of badges during processing.

Estimated Bias (B) and Uncertainty (K) For Operation CASTLE

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.3	
Wearing	0.8		1.3	
Backscatter	1.1		1.1	
Total Radiological		1.0		1.5
Environmental		1.0		1.8
Overall (*Exposure*)		1.0		2.1
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		2.1

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the CASTLE series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for CASTLE given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation CASTLE

Film Badge Best *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.09)
0.05	0.04	(0.01, 0.10)
0.06	0.05	(0.02, 0.11)
0.07	0.05	(0.02, 0.13)
0.08	0.06	(0.03, 0.14)
0.09	0.07	(0.03, 0.16)
0.10	0.08	(0.03, 0.17)
0.12	0.09	(0.04, 0.20)
0.14	0.11	(0.05, 0.23)
0.16	0.12	(0.06, 0.26)
0.18	0.14	(0.07, 0.29)
0.20	0.15	(0.07, 0.32)
>0.20	0.77 E*	(0.37 E, 1.62 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of 95% confidence limits, represented by the substitution of multiplication factors of 0.34 and 1.76. There appear to be several badge readings in this overlap region for Operation CASTLE.

OPERATION TEAPOT

Background

Operation TEAPOT was the fifth series of continental U.S. (CONUS) tests and included 14 nuclear detonations and one non-nuclear detonation carried out at the Nevada Test Site (NTS) from February 18 to May 15, 1955. The series consisted of 10 tower shots, three airdrops, and one cratering shot detonated at the shallow depth of 67 feet below surface. Two shots—one an air burst and the other a tower shot—were detonated on the same day, although at different parts of the Test Site.

Operation TEAPOT Events

Event	Date	Type	Yield (kt)
WASP	2/18/55	Airdrop	1
MOTH	2/22/55	Tower	2
TESLA	3/01/55	Tower	7
TURK	3/07/55	Tower	43
HORNET	3/12/55	Tower	4
BEE	3/22/55	Tower	8
ESS	3/23/55	Crater	1
APPLE-1	3/29/55	Tower	14
WASP PRIME	3/29/55	Airdrop	3
HA	4/06/55	Airdrop	3
POST	4/09/55	Tower	3
MET	4/15/55	Tower	22
APPLE-2	5/05/55	Tower	29
ZUCCHINI	5/15/55	Tower	28

Personnel Exposed

Approximately 11,000 personnel participated in the TEAPOT series at NTS, of whom about 8,000, largely military, participated in Exercise Desert Rock VI (Johnson et al. 1986). Of the remaining 4000 personnel, about half were AEC-affiliated and half DOD-affiliated. Dosimetry was carried out by the 1st NTS and Desert Rock Radiological Safety Support Unit. About 15,000 film packets were used by onsite personnel and 3,264 were used by Air Force personnel stationed at supporting air bases. *Exposure* records indicate that 56 persons received cumulative *exposures* over 3.9 R (Collison 1955).

Type of Film Badge

The film dosimetry program for Operation TEAPOT is summarized in an AFSWP Report (Collison 1955), the radiological safety report for the operation. Film dosimetry was performed with the Du Pont 559 film packet, also identified as the 502606 film packet for the two different film types it contained. The packet was similar to that used in Operation UPSHOT-KNOTHOLE. As was the case in Operation UPSHOT-KNOTHOLE, each film badge was provided with a lead strip covering an area of 1/2 inch x 1 inch on both the front and rear of the film packet. The thickness of this lead filter was nominally 0.028 inch (0.72 mm) based on a study of optimum filter thickness by the NBS. For the initial 25,000 packets ordered, the lead filter was found to have a measured thickness of 0.028 ± 0.002 inch of lead; for the final 10,000 packets, this thickness was determined to be 0.026 ± 0.002 inch.

An empirical study of the energy response of the film with different thicknesses of lead was made by the NBS as reported by Collision (1955). Three lead thicknesses were studied. 0.0311 inch, 0.0283 inch, and 0.0256 inch; these will be identified as the thick, normal, and thin filter, respectively. For photon energies above 300 keV, density differences under the various filter thicknesses were negligible. The dose from photons with energies below 300 keV down to the effective lower-energy cutoff of the filter (approximately 70 keV) was consistently overestimated with the thin filter. For the normal thickness filter, the dose was overestimated in the photon energy region of 70 – 95 keV, and underestimated for the region 95 – 300 keV. In the energy region of 200 – 300 keV, the error was very small. For the thick filter, the dose was significantly underestimated for photon energies below 300 keV. Based on these results, it was decided that if it was necessary to use the additional 10,000 film badges with the thin filters, an appropriate correction would be made. However, given the source term and film-response characteristics, these slight variations in filter thickness should not have resulted in significant errors in dose assessment in the field, probably less than ± 10 per cent.

As was the case for Operation UPSHOT-KNOTHOLE, the film badge specifications for Operation TEAPOT also called for embossed five digit sequential numbering. The film packets were sealed in a polyethylene holder 0.005 inch thick, and provided with a double alligator clip for attachment to the clothing. The polyethylene pouch, coupled with the excellent weather conditions and short wearing interval, should obviate any effects attributable to temperature and humidity or immersion in water.

The statistical variability of the film badge system was evaluated prior to the start of the operation by selecting one film packet from each box of 100 and exposing it to a predetermined level of 1, 20, or 47 R using a cobalt 60 source reported as standardized by the NBS as having an output of 1.01 R/h ± 10% at a distance of I meter. The total number of film badges used in this study was 327, about half of which were exposed at the lowest *exposure* level. The least amount of variability was found with the lowest exposure; the coefficient of variation was found to be 4 per cent. At the 20 and 47 R levels, the coefficients of variation were 8% and 5%, respectively. The excellent results are attributable in part to the *exposure* levels and source used, as well as to the use of the newly available Los Alamos Model FD-1 densitometer, which provided virtually absolute precision for density measurements (Collison 1955). This densitometer replaced the Ansco Macbeth Model 475 densitometer which was previously used. The FD-1 densitometer was unaffected by power supply variations and read a much larger area of the film (0.156 in^2) than the Ansco Macbeth (0.012 in^2).

Available calibration data indicate that for high-energy photon radiations, the usable *exposure* range of the films provided in the Du Pont Type 559 badge was approximately 0.02 – 10 R for the Type 502 component and 10 – 300 R for the Type 606 film (Brady and Nelson 1985). Thus, there was inadequate overlap in the ranges of the two film components. Film badges were stored under refrigeration at a temperature of 40°F and removed from storage as needed. However, some bulk issue of badges was made to off-site groups and certain operational training groups, which were charged with the responsibility for individual issue and return. Indian Springs Air Force Base, located adjacent to the Test Site, was issued 500 badges monthly, and given the responsibility for developing, reading and recording of results; it is not known with certainty what procedures were followed by the Indian Springs personnel, but the results do not suggest that there was a systematic error or other differences between the two groups.

Badge Issue and Exchange

Administrative procedures associated with the issuance of badges, readout, and recording of densities and doses appear to have been carried out well, and with a minimum of error. There is nothing to indicate systematic error in this part of the procedure, nor is there any indication that calibration, processing, or readout procedures were inadequate or improperly carried out. Films were maintained in refrigerated storage until shortly before issuance in the field. Personnel participating in the test were assigned a uniquely numbered film badge by the Dosimetry and Records Section; the film badge number and the assignee were manually recorded on a preprinted standardized form at the time of the assignment. The goal was to badge every test participant, and from a review of the records, it appears that this goal was for all practical purposes at least, if not completely, met. Once the film had been worn in the field, it was returned for processing; the time that the badge was returned was also recorded on the appropriate individual's form as were the *exposure* assignments.

Calibration, Processing, and Interpretation

Film calibration was initially carried out with cobalt 60 sources that had been calibrated by the NBS using both the Ansco Macbeth and Los Alamos FD-1 densitometers. Decay correction was based on a half-life of 5.2 y, only slightly different from the currently accepted value of 5.27 y; the error associated with this difference is negligible. Calibration checks were made with each batch of film processed.

In March 1955, a comparison of the response of the film packet to photons from cobalt 60 and radium 226 in equilibrium with daughters was done to verify the validity of the cobalt 60 calibration, and a more significant possible source of calibration error was identified. The shapes of the curves of NOD vs. *exposure* differed for the two sources; for the Type 502 film, the NOD per unit *exposure* was the same, irrespective of which source was used for *exposures* of up to about 1 R. Above this level, the two curves diverged, reaching a maximum difference of about 25% at 10 R, the uppermost range of the film. Thus, in the *exposure* range from about 1 R to 10 R, dose interpretations made from the radium 226 calibration curve would tend to be lower than those made from the cobalt 60 curve, with the maximum deviation of about 25% occurring at about 10 R.

Although the reason for this difference was not identified, it is likely that it is related to source-film geometry configurations and scattering. The radium 226 source, because of its broader distribution of energies was probably more representative of the energy distribution encountered in the field. Nonetheless, the cobalt 60 calibration was the one used to determine dose, and thus it is likely that doses from individual badges with *exposures* in the region from 1–10 R were slightly overestimated. Since numerous exposures were recorded in the 1–10 R region during Operation TEAPOT, it may be appropriate to revise these downward somewhat, as indicated by the comparative calibration data for the two sources. From a practical standpoint, however, any such adjustment would affect only a few films and would likely be on the order of 10 per cent or less, and hence is probably unwarranted.

A similar divergence of calibration curves was observed with the lower-sensitivity Type 606 film at *exposures* above about 150 R. However in this case, the NOD per unit exposure for cobalt 60 was greater than that for radium 226 in equilibrium with daughters. This divergence in calibration curves for the Type 606 is of interest only from an academic standpoint, as no personnel *exposures* were observed in the region of divergence.

Although the possibility of using the unfiltered portion of the film for interpretation of beta dose was considered, this was apparently not done. Readout was apparently limited to the portion of the film under the lead strip; five distinct areas were read by the densitometer. *Exposure* was reported in milliroentgen and should be reasonably representative of the exposures from photon radiations, as the lead strip should provide approximately constant NOD per unit exposure for photon energies as low as about 70 keV up to about 2 MeV. A few individuals associated with the University of California Radiation Laboratory (now Lawrence

Berkeley and Livermore National Laboratories) participating in shot WASP, which took place on February 18, 1955, were supplied with wrist badges using the Type 559 film dosimeter packet. These persons were civilians, and the wrist badges were used for beta dosimetry, using a natural uranium calibration source supplied by UCRL.

Current Availability of Records

Exposure records for the badged participants in Operation TEAPOT are available at the DOE records center operated by REECo in Las Vegas, NV. Available records include daily work sheets and calibration records.

Estimated Bias and Uncertainty

Since the type of film packet and associated filter used for Operation TEAPOT was the same as that used for Operation UPSHOT-KNOTHOLE, it is reasonable to assume that the biases and uncertainties associated with radiological factors were the same and certainly no greater than as those associated with UPSHOT-KNOTHOLE. An improved densitometer was used at TEAPOT, which reportedly reduced the random measurement uncertainty to near zero. However, this would probably not have a discernable effect on the measurement uncertainty. The discussion of uncertainty provided for UPSHOT-KNOTHOLE is also applicable to TEAPOT; the estimated bias and uncertainty factors for TEAPOT are summarized in the table below.

There is nothing in the available records to suggest that calibration, processing, readout, or other laboratory procedures were inadequate or improperly carried out, or were responsible for the introduction of a measurement bias. Similarly, environmental conditions were such that no bias would be introduced from this source. There are also no indications that the badge assignment or collection procedures introduced bias or other uncertainties in the results. Accordingly, then, for environmental factors, B = 1 and K = 1.1.

Bias (B) and Uncertainty (K) For Operation TEAPOT

Source		B		K
Laboratory		1.0		1.3
Radiological				
Spectrum	1.0		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Total Radiological		0.9		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		0.9		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.1		1.5

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the TEAPOT series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for TEAPOT given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation TEAPOT

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.04	(0.00, 0.08)
0.05	0.05	(0.02, 0.09)
0.06	0.05	(0.03, 0.10)
0.07	0.06	(0.04, 0.12)
0.08	0.07	(0.04, 0.13)
0.09	0.08	(0.05, 0.14)
0.10	0.09	(0.05, 0.15)
0.12	0.11	(0.07, 0.18)
0.14	0.13	(0.08, 0.20)
0.16	0.15	(0.09, 0.22)
0.18	0.16	(0.11, 0.25)
0.20	0.18	(0.12, 0.27)
>0.20	0.91 E*	(0.61 E, 1.36 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10–15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.55 and 1.51. There appear to be a few individual badge readings in this overlap region for Operation TEAPOT.

OPERATION WIGWAM

Background

Operation WIGWAM consisted of one test shot in the Pacific Ocean approximately 500 miles southwest of San Diego, California (Weary et al. 1981). The device was suspended by cable from a barge and detonated at a depth of 2,000 feet in water 16,000 feet deep on 14 May 1955 at 1300 hours Pacific Daylight Time. It was a fission device with a yield of 30 kilotons. The purpose of the test was to determine lethal distances for nuclear effects vs. submerged submarine hulls and to evaluate tactics for delivery of nuclear weapons against deep submerged submarines.

Personnel Exposed

Approximately 6,800 personnel and 30 ships took part in the Operation, including 6,344 DOD personnel. The projected maximum permissible *exposure* limit was 3.9 R for the duration of the Operation.

Type of Film Badge

The film badge used the Du Pont 559 film packet with film component types 502 and 606. Film type 502 had a reported range of 0.02 to 10 R. The minimum detectable level was stated to be 100 mR. Film type 606 had a reported range of 10 to 600 R. (N.B. Highest readings encountered were below 0.5 R). The filter consisted of (1) 0.020-inch cadmium, and (2) 0.04-inch vinyl tape (to facilitate the measurement of beta radiation; however, beta results were not reported).

Badge Issue and Exchange

Approximately 10,000 badges were issued. All personnel received one badge for the duration of the operation and many whose tasks might expose them to radiation were issued daily badges as well. All badges were identical and were worn on a chain around the neck. Each was sealed against moisture in a polyethylene bag.

Calibration, Processing, and Interpretation

The processing was carried out on the *USS Wright*. The dosimetry group consisted of one officer and 6 enlisted men. The processing capacity was 1200 badges a day. Of the 25,000 films prepared for the operation, 10,124 were used. The United States Naval Radiological Defense Laboratory was responsible for the film badge dosimetry quality control. Sources used for calibration were a 10-Curie cesium 137 gamma source, a 500-mCi radium source. A 50-mCi strontium 90 source (for betas, but beta results were not reported in WIGWAM *exposure* rosters.

Current Availability of Records

Rosters listing *exposure* results for each individual in the different organizations participating in Operation WIGWAM are on file at REECo in Las Vegas, Nevada.

Estimated Bias and Uncertainty

The following table lists the estimated bias and uncertainty at the 95% confidence level for various sources of error at the 200 mR level, assuming a lognormal distribution of errors.

Bias (B) and Uncertainty (K) for Operation WIGWAM

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.1	
Backscatter	1.1		1.1	
Total Radiological		1.0		1.3
Environmental Effects		1.0		1.2
Overall (*Exposure*)		1.0		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		1.5

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the WIGWAM series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for WIGWAM given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation WIGWAM

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.04	(0.02, 0.08)
0.06	0.05	(0.02, 0.09)
0.07	0.05	(0,03, 0.10)
0.08	0.06	(0.04, 0.11)
0.09	0.07	(0.04, 0.12)
0.10	0.08	(0.05, 0.13)
0.12	0.09	(0.06, 0.15)
0.14	0.11	(0.07, 0.17)
0.16	0.12	(0.08, 0.19)
0.18	0.14	(0.09, 0.21)
0.20	0.15	(0.10, 0.23)
>0.20	0.77 E	(0.51 E, 1.15 E)

where E is the film badge *exposure* (R)

There would have been increased uncertainty in the range 10 – 15 R, but there were no exposures at this level.

OPERATION REDWING

Background

REDWING was a 17-detonation test series in the Pacific Proving Ground (PPG) from May to July of 1956 (Jacks 1957). Eleven of the detonations were conducted at Enewetak Atoll and six detonations were conducted at Bikini Atoll. Of the total number of detonations, six were on barges in lagoons, three were surface blasts, six were on towers, and two were airdrops.

Operation REDWING Events

Event	Date	Type	Yield (kt)
LACROSSE	5/05/56	Surface	40
CHEROKEE	5/21/56	Airdrop	Several Mt
ZUNI	5/28/56	Surface	3.5
YUMA	5/28/56	Tower	*
ERIE	5/31/56	Tower	*
SEMINOLE	6/06/56	Surface	13.7
FLATHEAD	6/12/56	Barge	*
BLACKFOOT	6/12/56	Tower	*
KICKAPOO	6/14/56	Tower	*
OSAGE	6/16/56	Airdrop	*
INCA	6/22/56	Tower	*
DAKOTA	6/26/56	Barge	*
MOHAWK	7/03/56	Tower	*
APACHE	7/09/56	Barge	*
NAVAJO	7/11/56	Barge	*
TEWA	7/21/56	Barge	5 Mt
HURON	7/21/56	Barge	*

* Not Announced

The purpose of the series was to test high-yield fusion devices that could not be tested at the Nevada Test Site. Observers from the press and Civil Defense Officials observed the first two detonations. One of these, an airdrop detonation, CHEROKEE, was a demonstration that the United States could air-deliver multimegaton-yield fusion weapons from B-52 jet bombers. The yields of only five of the blasts were announced and these ranged from 13.7 kt to 5 Mt.

Additional safety precautions were implemented for REDWING as a result of fallout contamination during the earlier CASTLE series. The precautions included improved fallout-prediction capability, an expanded radiation monitoring program, and lower weapon yields than during the CASTLE series.

Personnel Exposed

The tests were conducted by a joint task force of military, civil service, and contractor personnel of the Department of Defense (DOD) and the Atomic Energy Commission (AEC). This was the first test series in the PPG in which all personnel were monitored for radiation exposure. A total of approximately 14,600 personnel were badged during the series. Of this total there were approximately 1450 Army personnel, 6650 Navy personnel, 2800 Air Force personnel, 250 Marine Corps personnel, 100 civilian DOD contractors, and 3350 AEC personnel or AEC contractors.

The majority of personnel were aboard Navy ships in the test area. Army and Air Force personnel were on Enewetak between tests but were on Navy ships during detonations. Cloud samplers and other personnel were on atolls, islands and ships in the area.

Approximately 600 personnel received doses exceeding the dose limit for the operation (3.9 R) as a consequence of fallout at Enewetak from the last detonation in the series at Bikini (TEWA). Many of these personnel, however, had been authorized to exceed the limit by the Joint Task Force Commander.

Type or Film Badge

The Du Pont film packet 559 was employed throughout the REDWING series with Du Pont Type 502 and Type 606 films in a cellulose acetate holder. After light damage and water damage was detected in a few badges after the initial deployment of six weeks, subsequent film packets were dipped in ceresin wax before sealing.

Badge Issue and Exchange

A "permanent" badge was issued to all personnel with instructions to with the badge at all times around the neck. Permanent badges were initially scheduled for exchange at six-week intervals. After light damage and water damage were detected in a few of these permanent badges after six weeks, the exchange interval was decreased to either three weeks or four weeks, depending on the task group. A total of 40,000 permanent badges were issued to and processed for approximately 14,600 individuals.

A "mission" badge also was issued to personnel who were required to enter contaminated areas (i.e., >10 mR/hr). Mission badges were exchanged daily. Approximately 45,000 mission badges were processed.

Cohort badging was not performed for any personnel in the REDWING series. Personnel on 15 Navy ships in the PPG at the time of the REDWING series do not have film badge dosimetry records. It is not clear from testing records whether these ships were not present during the shots and personnel on board were not badged or whether the records have been lost.

Calibration, Processing, and Interpretation

The primary radiation standard for calibration of film dosimeters used in REDWING was radium. Cobalt-60 sources were used in some instances, but corrections were to be applied where necessary to produce results consistent with radium exposures. Calibration procedures were the same as those used in the CASTLE series that preceded REDWING.

Standard films, having been given a 500 mR *exposure* prior to the first detonation in the series, were processed with each batch of film badges. Daily batch-control film dosimeters were processed with each batch.

Film badges were processed in the Rad-Safe building on Parry Island at Enewetak and in the Rad-Safe building on Enya at Bikini. A backup photodosimetry trailer was available on the *USS Ainsworth*, but the extent of use of this facility is not described. Film badge processing laboratories were air-conditioned and film was to be stored under controlled temperature and humidity conditions.

Dosimetry support, including processing, was provided by Task Unit 7 of Task Group 7.1. Personnel for TU 7.1.7 were provided by the Army's 1st Radiological Safety Support Unit, supplemented by a small number of Air Force and Navy personnel. In addition, civilians from naval shipyards served in the task unit. Selected photodosimetry personnel were trained at Los Alamos Scientific Laboratory.

All film processing and record posting was done manually. Such operations were subject to many errors which were not always caught by the re-checks. Development was usually performed at night after collection of film badges during the day. Development conditions were to have been strictly controlled, and dosimetry records do not indicate that there were processing-control difficulties.

Fallout from the last Bikini detonation, TEWA, fell on Enewetak base camp. Because the incident occurred toward the end of the series, some personnel stationed on Enewetak had already returned to the U.S. The remaining Enewetak personnel received from 2.0 to 3.3 R from this incident.

The highest *exposures* were recorded for Air Force Right officers performing cloud sampling. There were twelve officers with radiation *exposures* which exceeded 10 R. The highest recorded *exposure* was 16.4 R.

Current Availability

As stated earlier, dosimeter readings, dose interpretation, data and dosage records were recorded manually. Records included the name, exposure date, amount of *exposure* (mR), approximate duration of the exposure, and remarks. Records for military and DOD contractor personnel were sent to the units of permanent assignment for those personnel. Records for AEC-controlled and administered personnel were sent to their respective organization *exposure*-records departments.

Most films and all *exposure* records are available at REECo in Las Vegas, Nevada, for personnel who participated in REDWING, with the exception of personnel aboard 15 Navy ships. Included are 3 x 5-inch film badge issue cards, and 5 x 8-inch individual *exposure* record cards. As noted earlier, those personnel may not have been present during the tests (Bruce-Henderson et al. 1982), and therefore badging would not have been needed.

Estimated Bias and Uncertainty

Appropriate laboratory facilities, equipment, and procedures appear to have been used throughout the series. There is no indicated bias from the laboratory operations (B = 1.0). The contribution to the overall uncertainty in dose measurements due to the laboratory is a factor of 1.2 (K = 1.2).

Radiological parameters that could have introduced bias are the spectral dependence of the dosimeter, the film badge wearing location/geometry, and backscatter and body shielding. Contributions of these to the overall bias are, respectively, 1.1, 0.8, and 1.1. These parameters are estimated to contribute respective factors of 1.2, 1.2, 1.1 to the overall uncertainty.

Environmental effects are not judged to be significant, with the exception of the personnel exposures on Enewetak after the TEWA detonation and the badge damage identified in the first few weeks of the series. The bias associated with environmental effects is judged to be 1.0 (no bias), and the uncertainty is estimated to be a factor of 1.2.

The conversion from measured *exposure* (R) to dose (rem) at the standard depth has both a bias and uncertainty associated with it. These are, respectively, 1.3 and 1.2.

Application of Bias and Uncertainty

The overall bias and uncertainty are calculated as indicated in the following table:

Bias (B) and Uncertainty (K) For Operation REDWING

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Overall Radiological		1.0		1.3
Environmental		1.0		1.2
Overall (*Exposure*)		1.0		1.5
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		1.5

The following table gives deep-dose equivalent values and range of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the REDWING series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for REDWING given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation REDWING

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.04	(0.02, 0.08)
0.06	0.05	(0.02, 0.09)
0.07	0.05	(0.03, 0.10)
0.08	0.06	(0.04, 0.11)
0.09	0.07	(0.04, 0.12)
0.10	0.08	(0.05, 0.13)
0.12	0.09	(0.06, 0.15)
0.14	0.11	(0.07, 0.17)
0.16	0.12	(0.08, 0.19)
0.18	0.14	(0.09, 0.21)
0.20	0.15	(0.10, 0.23)
>0.20	0.77 E*	(0.51 E, 1.15 E)*

where E is the film badge *exposure* (R)

* For individual badge readings in the overlap region (10 – 15 R), the reported loss of accuracy would result in a slight increase in the span of the 95% confidence limits, represented by the substitution of multiplication factors of 0.42 and 1.39. There appear to be several individual badge readings in this overlap region for Operation REDWING.

OPERATION PLUMBBOB

Background

Conducted at the Nevada Test Site (NTS) from April 24 to October 7, 1957, Operation PLUMBBOB included the 30 nuclear detonation tests summarized in the table below. The series included six safety experiments, conducted to determine if a nuclear reaction would occur should the high explosive components of the device be accidently detonated during storage or transport (DOE 1988).

Largely a joint Atomic Energy Commission (AEC)/Department of Defense (DOD) effort, Operation PLUMBBOB was planned as an integral part of the continuing U.S. program for developing the means to conduct nuclear warfare in defense of the nation. The AEC wanted to test a number of nuclear devices scheduled for early production for the defense stockpile or those important to the design of improved weapons. The DOD used the series to continue its study of military weapons effects and, with Exercises Desert Rock VII and VIII, its training of personnel in nuclear operations.

Personnel Exposed

More than 10,000 persons participated in Operation PLUMBBOB under the auspices of the AEC (Wilcox 1957). About 15,000 DOD personnel participated in observer programs, tactical maneuvers, and scientific and diagnostic studies during Operation PLUMBBOB. Exercises Desert Rock VII and VIII, consisting of training programs, tactical maneuvers, and technical service projects, engaged the largest DOD participation. At shot HOOD, approximately 2,150 Marines took part in a maneuver involving the use of a helicopter airlift and tactical air support. An estimated 1,144 Army troops (Task Force BIG BANG) were interviewed at shot GALILEO to determine their psychological reactions to witnessing a detonation.

The maximum permissible *exposure* for Desert Rock troops was 5.0 rem of gamma radiation in any 6-month period, with no more than 2.0 rem to be from prompt radiation. Participants in activities of the AEC Nevada Test Organization (NTO) and the Air Force Special Weapons Center were limited to 3.0 rem for any 13-week period and 5.0 rem for one calendar year.

Type of Film Badge

All NTO personnel and some official observer groups, with the exception of Desert Rock personnel, were provided with a charge-a-plate (a metal tag bearing a person's name and other identifying information) and a film badge, both attached

Operation PLUMBBOB Events			
Event	Date	Type	Yield (kt)
PROJECT 57	04/24/57	Surface	Zero*
BOLTZMANN	05/28/57	Tower	12
FRANKLIN	06/02/57	Tower	0.140
LASSEN	06/05/57	Balloon	0.0005
WILSON	06/18/57	Balloon	10
PRISCILLA	06/24/57	Balloon	37
COULOMB-A	07/01/57	Surface	Zero*
HOOD	07/05/57	Balloon	74
DIABLO	07/15/57	Tower	17
JOHN	07/19/57	Air-to-Air Missile	About 2
KEPLER	07/24/57	Tower	10
OWENS	07/25/57	Balloon	9.7
PASCAL-A	07/26/57		Slight*
STOKES	08/07/57	Balloon	19
SATURN	08/10/57	Tunnel	Zero*
SHASTA	08/18/57	Tower	17
DOPPLER	08/23/57	Balloon	11
PASCAL-B	08/27/57	Shaft	Not announced*
FRANKLIN PRIME	08/30/57	Balloon	4.7
SMOKY	08/31/57	Tower	44
GALILEO	09/02/57	Tower	11
WHEELER	09/06/57	Balloon	0.197
COULOMB-B	09/06/57	Surface	0.3*
LAPLACE	09/08/57	Balloon	1
FIZEAU	09/14/57	Tower	11
NEWTON	09/16/57	Balloon	12
RAINIER	09/19/57	Tunnel	1.7
WHITNEY	09/23/57	Tower	19
CHARLESTON	09/28/57	Balloon	12
MORGAN	10/07/57	Balloon	8

* Safety experiments

to their security badges. Badges issued to NTO personnel were Du Pont 559 film packets consisting of Type 502 (0.02 – 10 R) and Type 606 (10 – 300 R) component films. The badge had 0.028-inch-thick lead filters on both sides, plus open areas, and was contained in a plastic bag. Processing was by Reynolds Electrical & Engineering Company (REECo). Different colored tape was used across the plastic bag each month to allow for easy and rapid determination of film badge validity.

Camp Desert Rock was two miles south of the main gate of NTS and was under control of the 6th Army. Desert Rock had a different dosimetry program from the one for NTO personnel at NTS. Each person was issued a film badge upon arrival at Camp Desert Rock. The film badges issued during 1957 Desert Rock activities contained Du Pont dosimeter film packets Type 559; these contained Type 502 and Type 606 component films. An Eberline model FD3 densitometer was used to read the optical density of the film components. The accuracy was reportedly as good as ± 10 percent in the low-density range for each film component; in the crossover region (about 10 roentgens) between the sensitive and less sensitive film components, however, accuracy was reportedly ± 50 percent.

The Desert Rock film packet holder was designed with an open window and a cluster of three metal filters-one aluminum, one copper, and one laminated tin/lead. The area covered by the foil cluster gave a flat response to gamma rays above about 70 keV. The open-window area of the badge responded to beta particles and gamma rays of all energies. Thus, if the low-energy component of the gamma source was small, the difference between the density change in the open window and the filtered area gave a crude estimate of the beta dose.

Badge Issue and Exchange

Badges were exchanged for on-site NTO personnel on a monthly basis and upon return from a mission in a radiation area. Federal Services Incorporated (FSI, an AEC contractor providing security-guard services) guards assisted in the film badge program by checking all personnel prior to entry into forward areas for possession of a valid film badge. IBM cards corresponding to numbered film badges were stamped (using the individual charge-a-plate) at the time of film badge issue. The cards were used to tabulate individual exposures and prepare the following reports:

- Daily exposure
- Weekly summary
- Quarterly summary
- Daily over 2 R
- Weekly over 2 R

These on-site dose reports were used by NTO supervisors to control each individual's accumulated exposure. The weekly summary reports at the end of the operation listed the accumulated exposures of more than 10,000 NTO personnel. A total of 74,500 NTO film badges were processed during PLUMBBOB (Wilcox 1957).

At Desert Rock, dosimetry teams from the Nucleonics Branch, Lexington Signal Depot, Lexington, Kentucky, processed and developed film badges in two specially equipped vans. The Radiological Safety Section, Camp Desert Rock, maintained dosimetry records, which were forwarded to Lexington Signal Depot, Lexington, Kentucky, and were later provided to the Army staff. The references do not specify a definite turn-in time for film badges. The issue and accession dates (date on which the film badge dose was recorded) shown in the Lexington records span varying time periods so a single-shot exposure cannot always be determined. Approximately 33,000 film badges were developed during Desert Rock VII and VIII.

Calibration, Processing, and Interpretation

Both NTO and Desert Rock had well-trained technicians and used standard calibration and processing procedures. Calibration sources employed cobalt 60, and were calibrated within the last few years by NBS. For example, the Office of Test Operations (OTO) source was NBS-calibrated in 1954 and was rotated during film packet calibrations. NBS-calibrated R-meters also were used to determine calibration exposures redundantly, and calibrations were performed for each new manufacturer's batch of film packets (about 25,000 film packets per batch). Two control and five, calibration standard films were processed with each batch of personnel films (about 280 films per OTO batch). Desert Rock used two control films, but the number of standards processed with each batch is unknown. The developing temperature for both processors was 68 degrees F $\pm$ 0.5 degrees.

OTO dosimetry personnel performed cross-calibrations with Desert Rock, Los Alamos Scientific Laboratory (LASL), University of California Radiation Laboratory (UCRL), and Sandia Laboratory (SL). Cross-calibrations were required because some Desert Rock personnel, who had NTS security badges, and large contingents of LASL, UCRL, and SL personnel wore OTO film badges while at NTS. REECo also performed several film badge radiation exposure studies during 1957.

Current Availability of Records

Extensive PLUMBBOB dosimeter records are in archives at REECo in Las Vegas, Nevada. Included are all developed personnel dosimetry films, issue cards, dosimetry processing log sheets, and numerous alphabetical and organiza tional exposure reports. Calibration data for all PLUMBBOB personnel film dosimetry also are available.

Estimated Bias and Uncertainty

Bias and uncertainties for PLUMBBOB *exposures* greater than 200 mR are listed in the following table:

Bias (B) and Uncertainty (K) for Operation PLUMBBOB

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.0		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		1.0		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		1.5

Because NTO and Desert Rock dosimetry programs were cross-calibrated, and procedures of both groups were standardized and implemented by well-trained technicians, the above B and K values apply to results of both dosimetry programs. Operation PLUMBBOB film dosimetry is considered optimum for the atmospheric test series in that great care was taken in every phase of the program as thoroughly documented in the REECo archival records. Studies were conducted, statistics compiled, and reports written to demonstrate the reliability of dosimetry results. In addition, physical factors including environmental and other conditions were such as to have little impact. Thus, the bias and uncertainty values listed are equal to or better than those for other test operations.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the PLUMBBOB series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for PLUMBBOB given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation PLUMBBOB

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.04	(0.02, 0.08)
0.06	0.05	(0.02, 0.09)
0.07	0.05	(0.03, 0.10)
0.08	0.06	(0.04, 0.11)
0.09	0.07	(0.04, 0.12)
0.10	0.08	(0.05, 0.13)
0.12	0.09	(0.06, 0.15)
0.14	0.11	(0.07, 0.17)
0.16	0.12	(0.08, 0.19)
0.18	0.14	(0.09, 0.21)
0.20	0.15	(0.10, 0.23)
>0.20	0.77 E	(0.51 E, 1.15 E)

where E is the film badge *exposure* (R)

Additional uncertainty in the overlap range of 10 – 15 R could have existed; however, no film badge *exposures* in this range occurred during PLUMBBOB.

OPERATION HARDTACK I

Background

The HARDTACK I test series was conducted at Enewetak and Bikini Atolls and near Johnston Island in the Pacific during 1958. From April 28 through August 18, 34 nuclear test detonations were conducted for weapons-related purposes and one as a safety experiment, including 26 nuclear devices on barges, four tests on the ground surface, two detonations underwater, two devices carried high above the earth by rockets, and one device carried aloft by a balloon. The highest nuclear yields announced were 8.9 and 1.37 megatons. Two other announced yields were 18 kilotons and less than 20 kilotons, two other yields were in the megaton range, and the remaining HARDTACK I test yields were unannounced (DOE 1988). The table below is a summary of HARDTACK I tests.

Personnel Exposed

Fallout had exposed unbadged participants in the Pacific during Operation CASTLE in 1954. As a result, an attempt was made to badge all participants during the 1956 REDWING Operation in the Pacific, and this policy was continued during HARDTACK 1.

About 18,000 individuals were badged during HARDTACK I, and about 62,000 personnel film badges were issued and processed. *Exposure* information also was recorded and reported (Jacks et al. 1958). Highest exposed participants were cloud-sampling aircraft pilots and their crews and experiment-recovery personnel, including radiation-monitoring personnel who preceded and accompanied them. *Exposures* were authorized up to 20 R for some individuals involved in cloud-sampling operations (Dunning 1958).

Type of Film Badge

The personnel film badge used during HARDTACK I consisted of a Du Pont 559 packet with Type 502 low-range (0.02 R – 10 R) and Type 834 high-range (5 R – 800 R) components, a 0.028-inch-thick lead strip wrapped around the packet to cover an area one-half inch wide by one inch long on each side, ceresin wax covering the packet after dipping, and rigid polyvinylchloride case holding the packet. The purpose of the wax dip and sealed case was to protect the films from moisture so that they might be worn for several months, if necessary, without moisture damage to the emulsions. During HARDTACK I, "badges were in use as long as six months with no significant failure observed" (Jacks et al. 1958).

Limitations of the film badge used were spectral response, angular response, shielding by the body, backscatter from the body, and environmental effects. Spectral-response limitations were discussed in parts 2.F and 4.A of this report, Operation HARDTACK I Events

Event	Date	Type	Yield
YUCCA	04/28/58	Balloon	
CACTUS	05/05/58	Surface	18 kt
FIR	05/11/58	Barge	
BUTTERNUT	05/11/58	Barge	
KOA	05/12/58	Surface	1.37Mt
WAHOO	05/16/58	Underwater	
HOLLY	05/20/58	Barge	
NUTMEG	05/21/58	Barge	
YELLOWWOOD	05/26/58	Barge	
MAGNOLIA	05/26/58	Barge	
TOBACCO	05/30/58	Barge	
SYCAMORE	05131/58	Barge	
ROSE	06/02/58	Barge	
UMBRELLA	06/08/58	Underwater	
MAPLE	06/10/58	Barge	
ASPEN	06/14/58	Barge	
WALNUT	06/14/58	Barge	
LINDEN	06/18/58	Barge	
REDWOOD	06/27/58	Barge	
ELDER	06/27/58	Barge	
OAK	06/28/58	Barge	8.9 Mt
HICKORY	06/29/58	Barge	
SEQUOIA	07/01/58	Barge	
CEDAR	07/02/58	Barge	
DOGWOOD	07/05/58	Barge	
POPLAR	07/12/58	Barge	
SCAEVOLA*	07/14/58	Barge	< 20 kt
PISONIA	07/17/58	Barge	
JUNIPER	07/22/58	Barge	
OLIVE	07/22/58	Barge	
PINE	07/26/58	Barge	
TEAK	08/01/58	Rocket	Megaton range
QUINCE	08/06/58	Surface	
ORANGE	08/12/58	Rocket	Megaton range
FIG	08/18/58	Surface	

* Safety experiment

and photon-energy-response variations under the lead filter used with the Du Pont 559 packet can be quantified. Use of this filter over the film packet resulted in a reasonably uniform film response to photons with energies above about 40 keV. Over-response to photon energies less than 100 keV in a scattered fission and activation-product spectrum would result in a positive bias in *exposure* determination. Other bias considerations are over-response when exposure was from the sides of the badge, under-response when exposure was through the body to a badge worn on the chest, and frontal exposure of the badge as it was calibrated. Backscattering of photons from the body, both through the lead filter and under filter edges is another bias consideration.

While the HARDTACK I radiological safety report (Jacks 1958). stated that film badges could be worn for six months with no significant failure observed, heat and ageing could be expected to cause some environmental damage, increasing with the time that film badges were worn or not returned. Damage of this type causes increased optical density with accompanying overestimates of *exposure*. Thus, *exposures* reported for HARDTACK I probably were higher than actual personnel *exposures* if film badges were worn for extended periods of time. Increased film optical density caused by environmental damage during HARDTACK I resulted in a positive bias. Remaining limitations of film badges related to field use include various types of physical damage to the film packets. The hard plastic case protected against most of these.

Film-component overlap limitations were discussed in Section 4.D. Figure 4-4 shows that selection of the Types 502 and 834 components essentially solved the overlap problems with previously used film component types. The response-curve slope in the overlap region of Figure 4-4 changes very little, compared to other film type combinations, indicating little change in uncertainty for exposures in the overlap range.

Badge Issue and Exchange

A single film badge wearing system was used during HARDTACK I (JTF-7 1958a). Film badge wearing instructions were: "The film badge will be worn at all times. In addition, badges will be exchanged after each entry into a contaminated area (exceptions will be made in the case of continuing-access permits). Lost badges should be reported immediately to TU-6. On return to home station badges will be turned in as part of the EPG check-out procedure." All badges were called in at 60-day intervals (Jacks 1958a).

Additional instructions for Task Group (TG) 7.1 during HARDTACK I were "Each individual in the Task Group will be issued a film badge that is to be worn at all times. Dog-tag chains will be provided for a convenient means of wearing the badges. If preferred, individuals may attach the film badges to the security badge rather than using the dog-tag chain." (Jacks 1958a).

From April 1 to August 20, 1958, TG7.1 was responsible for radiological safety at the Enewetak Proving Ground (EPG) (AEC 1958; JTF-7 1958b). On April 18, 1958, a message was sent from CJTF 7 to all task groups stating "All personnel in the, Enewetak Proving Ground are required to wear a film badge commencing 0600 21 April" (Richie 1958). Film badge exchange began the first two weeks of April 1958 at both mess hall exits and at the Rad-Safe Center Building on Elmer Island (Jacks 1958b). All personnel within EPG were provided with an addressograph (charge-a-plate) identification plate and a film badge. Film badges were exchanged bimonthly or upon return from a mission into a contamination area (AEC 1958) TG7.12., TU 6 issued film badges, associated record cards, and instructions concerning issue and wearing of film badges, and completed a record card for each individual. Record cards were sent to all ships and units of TG7.3 (CJTF-7 1959).

IBM cards corresponding to the numbered film badges were stamped using the charge-a-plates at the time the film badge was issued (AEC 1958). After issuing the film badge, the personnel identification information and film badge number were manually punched into IBM cards, which were used with an IBM 704 EDPM, and the information was stored on magnetic tapes. After film badges were processed, punched IBM cards from the FS-3 (see next section) were used to post dosimetry records on the IBM 704. This system reduced the human errors encountered during prior, fully manual posting operations. Identical film processing stations were established at Enewetak and Bikini Atolls for issuing, receiving and processing film badges. All records of the transactions performed at Bikini were forwarded by IBM data transceiver to Enewetak where a consolidation of information from both Atolls was made and data stored on tapes, using the IBM 704. New total-dosage information compiled by the 704 was then transmitted back to Bikini by data transceiver, where a duplicate file was maintained for daily use (Jacks 1958).

Calibration, Processing, and Interpretation

Calibration of film badges during HARDTACK I was in accordance with Los Alamos Scientific Laboratory procedures and included use of a cobalt 60 source and a recently NBS-calibrated R-meter, constant time-variable distance calibration exposures, and front-to-back film badge calibration to check for this possible variation in *exposure* results. The cobalt 60 source output was 8.67 R/h at 50 centimeters on 25 April 1958. Master calibration curves were prepared, and control and standard films were developed with each batch of personnel films. HARDTACK I calibration curves were checked for accuracy every two weeks (Minkkinen 1959). Film development was under carefully controlled and timed conditions at a temperature of 68 ± 0.5°F.

Personnel from the Army's 1st Radiological Safety Support Unit were trained in dosimetry procedures at the Los Alamos Scientific Laboratory before HARDTACK 1. The Eberline Instrument Corporation Film Badge Evaluation and Recording System, FS-3, was used in production during HARDTACK I for the first time. The system included an Eberline FD-II densitometer and a curve follower which electronically converted net optical density measurements to *exposure*. The curve follower provided the signal which operated an IBM Summary Punch. Thus, net optical density from the densitometer was automatically punched into an IBM card as *exposure* (Jacks 1958).

Current Availability of Records

Numerous *exposure* rosters for HARDTACK I are in storage at Reynolds Electrical & Engineering Co. (REECo) in Las Vegas, Nevada. Most of the developed films from HARDTACK I also are at REECo. Holmes and Narver 5x8-inch-card *exposure* records and film badge issue envelopes for personnel film badge dosimetry during non-operational periods during 1958 in the Pacific are stored at REECo.

Estimated Bias and Uncertainty

Bias and uncertainties for HARDTACK I film badge exposures greater than 200 mR are listed in the following table:

Bias (B) and Uncertainty (K) For HARDTACK I

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Combined Radiological		1.0		1.3
Environmental		1.2		1.1
Overall (*Exposure*)		1.2		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.5

Spectral film emulsion over-response in the low-energy photon region below 100 keV for scattered fission and activation product photons could result in a dose overestimate of a few percent, making the spectrum bias of 1.1 somewhat conservative. However, considering that variations in the balancing geometry and backscatter biases essentially would not change the combined radiological bias of 1.0, slight differences in any of these biases are unimportant in the overall dose-bias result.

Environmental bias of 1.2 for the hot, humid Pacific area test operations should be considered normal compared to a normal environmental bias for drier continental operational conditions of 1.0, or even 1.1 if badges had been worn for long time periods, as they had been in some Pacific operations.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the HARDTACK I series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for HARDTACK I given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation HARDTACK I

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.06)
0.05	0.03	(0.02, 0.07)
0.06	0.04	(0.02, 0.08)
0.07	0.05	(0.03, 0.08)
0.08	0.05	(0.03, 0.09)
0.09	0.06	(0.04, 0.10)
0.10	0.07	(0.04, 0.11)
0.12	0.08	(0.05, 0.13)
0.14	0.09	(0.06, 0.15)
0.16	0.11	(0.07, 0.16)
0.18	0.12	(0.08, 0.18)
0.20	0.13	(0.09, 0.20)
>0.20	0.67 E	(0.44 E, 1.00 E)

where E is the film badge *exposure* (R)

Use of the Type 834 film component to replace the Type 606 essentially solved the overlap problem previously experienced in the 10 – 15 R range (see Section 4.D).

OPERATION ARGUS

Background

ARGUS was a secret test operation conducted in and above southern Atlantic Ocean areas during August and September of 1958. Three nuclear warheads on missiles were detonated in the upper regions of the atmosphere with yields between I and 2 kt as shown in the following table (DOE 1988).

Operation ARGUS Events

Event	Date	Type	Yield (kt)
ARGUS I	08/27/58	Rocket	1–2
ARGUS II	08/30/58	Rocket	1–2
ARGUS III	09/06/58	Rocket	1–2

Nine U. S. Navy ships of Task Force 88 conducted these tests, including the missile trials ship *USS Norton Sound* (AVM-1), which launched the nuclear weapons. ARGUS was conducted to test the Christofilos theory, which stated that high-altitude nuclear detonations would create a radiation belt in the upper regions of the atmosphere. This belt of electrons could have important military implications regarding effects on electronic systems of military hardware. A charged-particle shell was created, demonstrating the validity of the theory and also the predicted effects (Jones et al. 1982).

Personnel Exposed

Task Force 88 included about 4,500 participants on nine ships. Because the detonations were in the upper regions of the atmosphere, there was no possibility of task-force personnel being exposed to radioactivity from the tests (Jones et al. 1982).

Type of Film Badge

There is some uncertainty regarding the type of film badge used. Although Lexington Signal Depot provided and processed the film badges, Lexington (now Lexington Blue Grass Depot) cannot now locate the badging records of any ARGUS participants. It can be assumed do the four-element Lexington badge issued at Camp Desert Rock during Operation PLUMBBOB and the Du Pont packet with Type 502 and Type 606 components were used at ARGUS because this badge and at least the Type 502 component were used at Lexington during August and September of 1958 (Abney 1989) and because the 559 packet with Type 502 and 606 components had been used during previous nuclear test series.

Badge Issue and Exchange

Security aspects of ARGUS resulted in a decision not to reveal to most personnel of the task force that nuclear testing was involved in their operations. A sufficient number of film badges (4,000) had been procured from Lexington Signal Depot to badge each individual on the seven ships near the launch location, should circumstances warrant such issue. The badges were distributed, however, only to those individuals who already were aware of the nuclear tests, including pilots of observation aircraft and *USS Norton Sound* personnel handling nuclear warheads. Film badges also were placed surreptitiously in exposed topside locations to remain for a period of six hours before and six hours after each test, 10 film badges per ship per test. Finally, "control" film badges were located in "radiation-free areas within ships".

According to the Lexington Signal Depot report, 21 of the 264 film badges distributed showed some indication of radiation exposure. The highest indicated dose was 0.025 rem, and this result was from a "control" badge. The highest dose recorded for an individual was 0.010 rem. It was concluded that no radiation dose was received by task force personnel as a result of the nuclear detonations.

Following a snowfall some seven hours after the first detonation, the *USS Norton Sound* reported detecting radiation intensity of 0.27 R/h at one location on deck. Because the detonation occurred very high above the surface, it was concluded that the reading was spurious, or at least not connected with Task Force 88 operations (Mustin 1959).

Calibration, Processing, and Interpretation

Because the film badges were provided and processed by Lexington Signal Dept, it can be assumed that the same procedures used at Camp Desert Rock during Operation PLUMBBOB in 1957 were used for ARGUS films.

Current Availability of Records

Lexington Blue Grass Depot was contacted previously (Jones et al. 1982) and recently (Abney 1989) with the same result. Lexington cannot identify records as being for ARGUS. This probably is a consequence of security classification precautions taken prior to and after ARGUS.

Estimated Bias and Uncertainty

The question of bias and uncertainties is moot, considering the conclusion that no radiation dose was received as a result of the ARGUS nuclear detonations.

The only uncertainty appears to be whether a radiation source aboard a ship caused the maximum indicated personnel film badge dose of 0.010 rem and control film badge dose of 0.025 rem, or whether the indications of exposure from 21 of the 264 film badges were spurious and below the minimum reportable *exposure* with that particular film badge.

OPERATION HARDTACK II

Background

Operation HARDTACK II was a series of 37 tests performed at the Nevada Test site (NTS) in the fall of 1958. It was the last nuclear weapons testing conducted before the United States began a unilateral nuclear-test moratorium that lasted until 1961.

The table below lists the tests of Operation HARDTACK II. The operation was administered by the Atomic Energy Commission; also participating were the Armed Forces Special Weapons Project and the Office of Civil and Defense Mobilization. Nineteen tests were related to weapons development and evaluation. The remainder were safety experiments that evaluated whether an accidental nuclear detonation could occur during transportation or storage of each type of nuclear device.

Personnel Exposed

About 7,650 people participated in the HARDTACK II test series (REECo 1958). All personnel who entered NTS during 1958 were required to wear film badges attached to their security badges, and security guards at each gate assured that the badge was valid for the particular month. Badges were exchanged monthly and upon exit from radiation areas if *exposure* of 100 Mr or more was suspected. The highest accumulated *exposure* during the operation was 10.9 R (Ponton et al. 1982c; REECo 1958).

Type of Film Badge

The Du Pont Type 559 film packet was the film badge used during Operation HARDTACK II. The packet contained a Type 502 film (0.02 R to 10 R) and a Type 834 film (5 R to 800 R). The packet had a 0.028-inch (0.711 millimeter)-thick lead strip, 0.5 inches wide by 1.0 inch long on the front and back surfaces. The packet and filter were enclosed in a polyethylene bag 0.004 inches thick, with a colored tape over the opening which indicated monthly validity.

Operation HARDTACK II Events

Event	Date	Type	Yield (kt)
Weapons Tests			
EDDY	09/19/58	Balloon	0.083
MORA	09/29/58	Balloon	2
TAMALPIAS	10/08/58	Tunnel	0.072
QUAY	10/10/58	Tower	0.079
LEA	10/13/58	Balloon	1.4
HAMILTON	10/15/58	Tower	0.0012
LOGAN	10/16/58	Tunnel	5
DONA ANA	10/16/58	Balloon	0.037
RIO ARRIBA	10/18/58	Tower	0.090
SOCORRO	10/22/58	Balloon	6
WRANGELL	10/22/58	Balloon	0.115
RUSHMORE	10/22/58	Balloon	0.188
SANFORD	10/26/58	Balloon	4.9
DE BACA	10/26/58	Balloon	2.2
EVANS	10/29/58	Tunnel	0.055
MAZAMA	10/29/58	Tower	*
HUMBOLDT	10/29/58	Tower	0.0078
BLANCA	10/30/58	Tunnel	22
SANTE FE	10/30/58	Balloon	1.3

* Slight or no measurable yield.

Badge Issue and Exchange

The film badge program was conducted by the Radiological Safety Division of the NTS operations contractor, Reynolds Electrical & Engineering Company, Inc. (REECo). The Division continued year-round issue and collection procedures that had been implemented January 1, 1957.

The issue and collection procedures included use of an identification plate and color-coded film badges. Identification data, including name, NTS number and organization code, were stamped on IBM issue cards with numbers corresponding to embossed numbers on the films being issued. Colors corresponded to monthly issue periods and facilitated collection of unreturned badges. Film badges were attached to security badges and guards would not allow passage through the main gate or gate to the forward areas unless the film badge was valid for the current month. Badges were issued at the main gate in Camp Mercury, and at the site Control Point by REECo Rad-Safe staff. Air Force personnel issued badges supplied by REECo at Indian Springs and Kirkland Air Force Bases.

All persons entering the test site wore film badges. Pilots and crews used for cloud tracking and sampling, and other Air Force personnel working with radioactive cloud samples or contaminated planes, also wore film badges.

Film badge records were maintained by REECo. IBM cumulative *exposure*

Event	Date	Type	Yield (kt)
Safety Experiments			
OTERO	09/23/58	Shaft	0.038
BERNALILLO	09/17/58	Shaft	0.015
LUNA	09/21/58	Shaft	0.0015
MERCURY	09/23/58	Tunnel	*
VALENCIA	09/26/58	Shaft	0.002
MARS	09/28/58	Tunnel	0.013
HIDALGO	10/05/58	Balloon	0.077
COLFAX	10/05/58	Shaft	0.0055
NEPTUNE	10/14/58	Tunnel	0.115
VESTA	10117/58	Surface	0.024
SAN JUAN	10/20/58	Shaft	*
OBERON	10/22/58	Tower	*
CATRON	10/24/58	Tower	0.021
JUNO	10/24/58	Surface	0.0017
CERES	10/26/58	Tower	0.0007
CHAVES	10/27/58	Tower	0.0006
GANYMEDE	10/30/58	Surface	*
TITANIA	10/30/58	Tower	0.0002

* Slight or no measurable yield.

reports were prepared each night to include results of all film badges processed for the day. These reports were at Rad-Safe stations the next morning to be consulted before personnel were allowed to enter radiation areas and receive more exposure. This helped to prevent cumulative *exposures* from exceeding the guides of 3 rem per calendar quarter and 5 rem per calendar year. Monthly, quarterly, and annual *exposure* reports were prepared for each of several hundred organizations at NTS.

Calibration, Processing, and Interpretation

Calibration, processing, and evaluation procedures had been implemented by REECo beginning in July 1955, and were used in the 1957 PLUMBBOB operation. These were continued during operation HARDTACK II.

Films were calibrated with a rotating cobalt 60 source to compensate for potential nonuniformity of the radiation field produced by the source. Calibration exposures were determined with NBS-calibrated R-meters. Calibration standard films were processed daily with each batch of personnel films processed. Also included were unexposed films to account for base fog (REECo 1958).

After developing and drying, films were analyzed with an Eberline Model FD-II densitometer. The net optical density under the lead filter was used to determine the whole-body exposure.

The total number of films developed during HARDTACK II was 16,624 with a maximum one day total of 1,128 (REECo 1958).

Current Availability of Records

The collection of HARDTACK II dosimetry films and records available at REECo in Las Vegas, Nevada, is essentially complete. The only records which have not been kept are some of the daily and monthly IBM reports.

Estimated Bias and Uncertainty

The film badge program at the NTS had served previous operations. Experienced staff and proven methods minimized the number and types of problems. The table shown below presents estimates of bias and uncertainty for *exposures* greater than 0.2 R. Uncertainty and bias estimates increased for lower *exposures*.

Performance of the 502 film was examined in a REECo report (1957). The report noted decreased relative precision at low *exposures*. Considering that most low *exposures* were assessed from badges worn for a month, additional variations probably arose from wearing and environmental factors.

Overall, the film badge uncertainties for Operation HARDTACK II were among the lowest of the atmospheric testing program.

Bias (B) and Uncertainty (K) for Operation HARDTACK II

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.1	
Backscatter	1.1		1.1	
Total Radiological		1.0		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		1.0		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		1.4

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the HARDTACK II series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for HARDTACK II given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation HARDTACK II

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.07)
0.05	0.04	(0.02, 0.08)
0.06	0.05	(0.03, 0.08)
0.07	0.05	(0.03, 0.09)
0.08	0.06	(0.04, 0.10)
0.09	0.07	(0.04, 0.11)
0.10	0.08	(0.05, 0.12)
0.12	0.09	(0.06, 0.14)
0.14	0.11	(0.07, 0.16)
0.16	0.12	(0.08, 0.18)
0.18	0.14	(0.10, 0.20)
0.20	0.15	(0.11, 0.22)
>0.20	0.77 E	(0.55 E, 1.08 E)

where E is the film badge *exposure* (R)

Use of the Type 834 film component to replace the Type 606 essentially solved the overlap problem previously experienced in the 10 – 15 R range (see Section 4.D).

OPERATION DOMINIC I

Background

Operation DOMINIC I took place in the Christmas and Johnston Island areas and at other locations in the Pacific. Of 36 test detonations, 29 were airdrops, six were on rockets, and one was a depth charge underwater. The highest yield was listed as "megaton range", the next highest as "low megaton" (one to several Mt). The remainder were "intermediate" yield (20 to 1000 kt for Operation DOMINIC I), low yield (less than 20 kt), or the yields were unannounced (DOE 1988). The table below is a summary of DOMINIC I nuclear detonation tests.

Operation DOMINIC I Events

Event	Date	Type	Yield
ADOBE	04/25/62	Airdrop	20 to 1000 kt
AZTEC	04/27/62	Airdrop	20 to 1000 kt
ARKANSAS	05/02/62	Airdrop	Low megaton
FRIGATE BIRD	05/06/62	Rocket	
YUKON	05/08/62	Airdrop	20 to 1000 kt
MESILLA	05/09/62	Airdrop	20 to 1000 kt
MUSKEGON	05/11/62	Airdrop	20 to 1000 kt
SWORDFISH	05/11/62	Underwater	<20 kt
ENCINO	05/12/62	Airdrop	20 to 1000 kt
SWANEE	05/14/62	Airdrop	20 to 1000 kt
CHETCO	05/19/62	Airdrop	20 to 1000 kt
TANANA	05/25/62	Airdrop	<20 kt
NAMBE	05/27/62	Airdrop	20 to 1000 kt
ALMA	06/08/62	Airdrop	<20 kt.
TRUCKEE	06/09/62	Airdrop	20 to 1000 kt
YESO	06/10/62	Airdrop	20 to 1000 kt
HARLEM	06/12/62	Airdrop	20 to 1000 kt
RINCONADA	06/15/62	Airdrop	20 to 1000 kt
DULCE	06/17/62	Airdrop	20 to 1000 kt
PETIT	06/19/62	Airdrop	<20 kt
OTOWI	06/22/62	Airdrop	20 to 1000 kt
BIGHORN	06/27/62	Airdrop	Megaton range
BLUESTONE	06/30/62	Airdrop	Low megaton

Personnel Exposed

Because all of the DOMINIC I tests, except the underwater test, were high-altitude airbursts, little or no fallout resulted and no residual radioactivity remained at surface ground zero, except for a radioactive pool of water after the underwater test. Film badge readings thus were generally low, with maximum exposures being reported for cloud-sampling pilots and crews, Navy personnel on the *USS Sioux* who sampled the radioactive water pool, personnel who retrieved instrumentation pods and rocket nosecones, and Rad-Safe monitors. An attempt was made to monitor all participants who had a potential for exposure, in a continuation of REDWING and HARDTACK I film badging policies. About 25,300 individuals were film badged. About 3,000 participants on remote islands, however, who were manning radiation detection instruments or conducting experiments at a distance from the tests, were not badged (Berkhouse et al. 1983b). About 43,000 film badges were used. Two dosimetry sections processed about 33,000 badges. The remaining approximately 10,000 badges were processed at the Nevada Test Site Rad-Safe laboratory after DOMINIC I (Mudgett 1964; Brady 1982).

Type of Film Badge

The film badge design used in DOMINIC I was the same as in HARDTACK I, a Du Pont packet with a 0.028-inch-thick lead filter dipped in wax and sealed in a rigid PVC holder. The Du Pont packet, however, was not the 559 with Type 502 and 508 components, but the 556 with Type 508 (0.02 – 10 R) and Type 834 (5–800 R) components. The badge was designed to be moisture-resistant, and it apparently functioned as intended during HARDTACK I. Near the end of DOMINIC I, however, sealing of the case was found to be defective, and some badges exhibited considerable excess film optical density from moisture damage (Knipp 1963). In addition, some 100 films were damaged when a band saw used to cut open the film badge cases nicked the film packets, causing light leaks and resulting in considerable excess optical density (Brady 1982).

Other limitations of the film badge used during the two test series were spectral response, angular response, shielding by the body, and environmental effects not discussed above. These limitations were discussed under *Type of Film Badge* and *Estimated Bias and Uncertainty* in the section on HARDTACK I, and the same bias and uncertainties apply to DOMINIC I, with certain exceptions involving environmental effects.

While the HARDTACK I radiological safety report stated that film badges could be worn for six months with no significant failure observed, examination of DOMINIC I films showed some environmental damage, increasing with the time film badges were worn or not returned. A large number of DOMINIC badges were worn or not returned for long periods of time, up to three or more months. This damage could be attributed to heat and emulsion ageing, also observed with badges used in continental desert environment tests, where humidity and moisture are not the problems. Damage of this type causes increased optical density with accompanying overestimates of *exposure*. Considering that only participants in the four categories previously mentioned should have had positive film badge readings, it is likely that almost all other reported *exposures* were the result of environmentally damaged film badge emulsions.

Remaining limitations of film badges related to field use include various types of physical damage to the film packets. As in HARDTACK I, most of these were avoided by use of the hard plastic case protecting the film packets. Only the band-saw damage observed for a small percentage of DOMINIC I packets appears to be a problem not easily dealt with by investigation of individual exposure conditions.

Film-component overlap limitations were discussed in Section 4.D. Figure 4-4 shows that selection of the Type 502 and 834 components essentially solved the overlap problems with previously used film-component types. The response-curve slope in the overlap region of Figure, 4-4 changes very little, compared to other combinations, indicating little change in uncertainty for *exposures* in the overlap range.

Badge Issue and Exchange

Two dosimetry sections were required for the DOMINIC I Operation. One was at Christmas Island and the other in Honolulu, Hawaii. The Dosimetry section on Christmas Island was responsible for film processing for the Johnston Island site and Barbers Point personnel (Knipp 1963). Film badge support locations and their functions for DOMINIC I were as follows:

Christmas Island:	
Film-badge issue and collection Photodosimetry services	04/25/62-07/11/62
Johnston Island:	
Film-badge issue and collection	06/03/62-11/03/62
Honolulu:	
Photodosimetry services	03/15/62-11/10/62
Nevada Test Site:	
Photodosimetry services (Mudgett 1964; Knipp 1963)	11/07/62-01/30/63

DOMINIC I Radiological Safety Regulations, Annex J to Op Plan 2–62 (Star-bird 1962), stated that "All task-force personnel will be required to wear film badges. Certain cases may arise, such as outlying stations, where such a requirement may not be practical." The regulations also stated that "all persons in aircraft at shot time, or at subsequent times, shall wear film badges when engaged in operations in or near the cloud or RADEX (radiation exclusion area) track."

Badge issuance was relatively complete; that is, almost all individuals who could be considered participants were badged. Personnel on remote islands providing support at a distance from the tests were not issued film badges. On Christmas Island, Task Group 8.4 (Air Force personnel) assisted in film badge issue and return. This task unit was responsible for issuing film badges to sampling aircrew mission members (including pilots, crew, and ground personnel). After each mission, Task Group 8.4 would collect all film badges used on the mission and return them to the JTF-8 dosimetry section for development (they were processed within 6 hours). Badges also were exchanged weekly for all 8.4 personnel exposed to radiation. Task Group TG 8.4 also maintained a record which listed all Task Group 8.4 personnel exposed to ionizing radiation. Approximately 2,500 film badges were issued by this task group. Near the end of the operation, the Christmas Island photodosimetry operation was closed and relocated with the Honolulu group (Knipp 1963).

Dosimetry record cards (5x8-inch cards) were prepared in the Honolulu section. Approximately 20,000 5x8-inch dosimetry cards were typed and initial doses posted (Knipp 1963). Use of the charge-a-plate identification system adopted for previous Pacific test series was initiated after the DOMINIC I operation began (Mudgett 1964).

The Honolulu Photodosimetry section was closed November 1, 1962 (Allen 1962; Rueter 1962). Photodosimetry equipment and both unexposed and exposed films were sent to the Nevada Test Site (NTS) for completion of processing and posting of exposure records. The NTS photodosimetry section processed approximately 10,000 film badges and posted approximately 30,000 records. These records then were finalized and coded for ADP (automatic data processing) keypunching. These dosimetry records were retained by Reynolds Electrical & Engineering Company, Incorporated (REECo) (Brady 1982).

Calibration, Processing, and Interpretation

Calibration of film badges during DOMINIC I was in accordance with the Los Alamos Scientific Laboratory procedures and included use of a cobalt 60 source, a recently NBS-calibrated R-meter, and constant time-variable distance calibration exposures. Master calibration curves were prepared, and control and standard films were developed with each batch of personnel films. Film development was under controlled and timed conditions at a temperature of 68 ± 0.5°F (Littlejohn 1988c).

During DOMINIC I, Joint Task Force 8 was responsible for radiological safety. George Littlejohn of Los Alamos trained the RSSU dosimetry personnel and developed films at the Christmas Island Facility with assistance from Holmes and Narver (the AEC support contractor) personnel. Mechanical difficulty with the curve follower first used in HARDTACK I prevented its use during DOM

INIC I, and the REDWING procedure of manually posting film badge results on 5x8-inch cards for each individual was resumed. Eberline FD-II densitometers were used at both the Christmas Island and Honolulu, Hawaii, facilities.

Current Availability of Records

Stored in the archives of REECo at Las Vegas, Nevada, are processed films from DOMINIC I film badges, 5x8-inch-card individual exposure records, NavMed 1432 forms listing personnel and their exposures by film badge on specific ships, an alphabetical summary report of DOMINIC I Participants and their exposures, for about 75 percent of the film badges issued, supplementary reports for the remaining 25 percent of the film badges processed at NTS, and organizational reports listing data from both the summary and supplementary reports.

Estimated Bias and Uncertainty

Estimated bias and uncertainties for DOMINIC I film badge exposures greater than 200 Mr are listed in the following table. Also included are overall B and K for *exposure*, B and K for conversion to dose, and overall B and K for dose. These B and K values, however, apply to only some of the DOMINIC I film badge results, as discussed after the table.

Bias (B) and Uncertainty (K) for Operation DOMINIC I

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Total Radiological		1.0		1.3
Environmental		1.2		1.1
Overall (*Exposure*)		1.2		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.5		1.5

The environmental bias of 1.2 expresses a normal positive bias for environmental damage in the Pacific not related to radiation exposure. While sealing of the film badge cases used during HARDTACK I apparently was adequate, and the bias of 1.2 applies, sealing of the cases for DOMINIC I was not adequate. Sealing failure resulted in moisture damage, and, together with long wearing periods and long times before processing, resulted in a large number of film badges which indicated exposure when no exposure had occurred. DOMINIC I film badge exposures should be related to known activities of the wearers. If an individual was not in a cloud-sampling and crew unit, not on the ship (*USS Sioux*) that sampled water from the radioactive pool, not involved in recovering instrument pods, nosecones, or other contaminated or activated material, or not a Rad-Safe monitor, then any indicated film badge *exposure* was likely to have been caused by environmental damage. The above B and K, then, apply primarily to film badge results of personnel who were in categories of participants that may have been exposed to gamma radiation, and thus whose film badges were exchanged more frequently than the majority.

Light damage from the band saw used to open film badge cases apparently occurred in DOMINIC I. Less than 100 badges were involved, and most of these have been reevaluated to verify reductions in *exposure* previously made by 1st RSSU personnel. All of the apparent *exposures* caused by band-saw damage light leaks have been verified as reduced to less than 3 R, except for about six film badges worn on the ship which was sampling water from the radioactive pool.

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the DOMINIC I series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for DOMINIC I given above. Readings below 0.2 R may be converted by reading directly from the table; these values allow for additional laboratory uncertainty for low readings, as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation DOMINIC I

Film Badge *Exposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00, 0.06)
0.05	0.03	(0.02, 0.07)
0.06	0.04	(0.02, 0.08)
0.07	0.05	(0.03, 0.08)
0.08	0.05	(0.03, 0.09)
0.09	0.06	(0.04, 0.10)
0.10	0.07	(0.04, 0.11)
0.12	0.08	(0.05, 0.13)
0.14	0.09	(0.06, 0.15)
0.16	0.11	(0.07, 0.16)
0.18	0.12	(0.08, 0.18)
0.20	0.13	(0.09, 0.20)
>0.20	0.67 E	(0.44 E, 1.00 E)

where E is the film badge *exposure* (R)

Use of the Type 834 film component to replace the Type 606 essentially solved the overlap problem previously experienced in the 10 – 15 R range (see Section 4.D).

OPERATION DOMINIC II

Background

Operation DOMINIC II (named Operation SUNBEAM by DOD) was conducted during mid-July at the Nevada Test Site (NTS). Four weapons were detonated to obtain data about the effects of low-yield explosions. Ancillary experiments were performed to evaluate the ability to detect nuclear detonations in foreign countries.

This Operation was comprised of the four tests listed below. Associated with Little Feller I was a military maneuver, Exercise IVY FLATS. This exercise centered on the test of a Davy Crockett weapon fired from a mobile rocket launcher under simulated tactical conditions.

Operation DOMINIC II Events			
Event	Date	Type	Yield (kt)
LITTLE FELLER II	07/07/62	Surface	Low*
JOHNIE BOY	07/11/62	Surface	0.5
SMALL BOY	07/14/62	15-foot tower	Low*
LITTLE FELLER I	07/17/62	Surface	Low*

* Low is less than 20 kt

Personnel Exposed

The actual number of people involved in conducting the Operation is unknown and difficult to reconstruct because all persons at the NTS wore film badges. Other nuclear testing programs were ongoing at NTS concurrent with Operation DOMINIC II. Many personnel from the Atomic Energy Commission and its contractors supported these programs and are not uniquely associated with one operation. The films and records are stored by process date and not by operation. Over 200,000 film badges were processed at NTS during 1962 for a permanent work force of several thousand personnel, and for transients of an equal or greater number. Approximately 3000 DOD-affiliated personnel participated in the DOMINIC II operation. The highest exposure received at NTS during the DOMINIC II operational period was 5.8 R.

Type of film Badge

The film badge for Operation DOMINIC II was the standard badge used at the NTS during 1962. Also used during Operation HARDTACK II, the badge consisted of a Du Pont Type 559 film packet containing Type 502 and Type 834 components with 0.028-inch-thick lead strip covering part of the front and back surfaces. The badge was enclosed in a polyethylene bag, 0.004 inches thick.

The U.S. Army created a separate radiation safety program for IVY FLATS within the NTS program. REECo provided technical support which included radiation-safety training, film badges, and instruments. All IVY FLATS participants wore the NTS film badge.

Records were established for all issued badges. Upon issue of film badges, individual IBM identification cards aided the process of relating a person to a film badge number.

Badge Issue and Exchange

The procedures for issuing and exchanging film badges were the same as those that had been used since 1957. The Radiological Safety Division of REECo, the site operating contractor, supervised all aspects of the film badge program.

Key to the issuance and exchange program was the union of the film badge with the security badge. Security officials were instructed to verify that an appropriate film badge was worn as an individual passed through various check points at the test site. Identification of the film badge was coded by an identification plate and colored tape. Different colors signified different monthly issue periods.

Film badges were issued at the main gate and the site control point by REECo staff. Participants in Exercise IVY FLATS were issued badges by Army personnel under the REECo Rad Safe Program. Air Force personnel issued badges supplied by REECo at Indian Springs and Kirtland Air Force Bases only to pilots, crew or others whose duty could result in exposure to radiation.

Badges were collected after entry to a radiation area, or if an *exposure* greater than 0.1 R was suspected. Badges were processed the evening of their collection so that *exposure* record cards could be updated by the next day. These cards were reviewed when permits were granted for access to radiation areas.

Calibration, Processing, and interpretation

Calibration, processing and evaluation procedures had been implemented by REECo in 1955 and had continued during the 1957 PLUMBBOB, 1958 HARDTACK II, and interim operations at the NTS. These were continued during Operation DOMINIC II. Films were calibrated with a cobalt 60 source. Calibrated films were processed with each developed batch of films worn by operation participants, as were two unexposed control films to account for base fog (REECo 1958). After developing and drying, films were analyzed with an Eberline Model FD-II densitometer. The film net optical density under the lead filter was used to determine whole body exposure.

Current Availability of Records

All films, issue cards, and exposure records for the DOMINIC II Operation period are stored at the REECo/DOE repository in Las Vegas.

Estimated Bias and Uncertainty

The film badge program at the NTS had served previous operations. Experienced staff and proven methods minimized the number and types of problems. The table below presents bias estimates and uncertainties for *exposures* greater than 0.2 R.

The performance of the 502 film was examined in a REECo report (1957). Laboratory reproducibility was good. The report noted decreased relative precision at low *exposures*. As discussed previously under DOMINIC I, use of the Type 502 and Type 834 film components essentially solved the overlap problem (See Figure 4-4). Unlike some other operations, additional uncertainties from long wearing periods and environmental factors were not significant because the operation was of short duration and moisture damage was riot a problem. The number of one-day participants in IVY FLATS also minimized the impact of environmental effects that would be more likely to affect monthly badges. Film badges were exchanged when personnel exited radiation areas and *exposures* of 100 Mr or more were expected. Otherwise, badges were exchanged monthly.

Overall, film badge uncertainties for Operation DOMINIC II were among the lowest of the atmospheric testing program.

Bias (B) and Uncertainty (K) for Operation DOMINIC II

Source		B		K
Laboratory		1.0		1.2
Radiological				
Spectrum	1.1		1.2	
Wearing	0.8		1.2	
Backscatter	1.1		1.1	
Total Radiological		1.0		1.3
Environmental		1.0		1.1
Overall (*Exposure*)		1.0		1.4
Conversion to Deep-Dose Equivalent		1.3		1.2
Overall (Deep-Dose Equivalent)		1.3		1.4

Application of Bias and Uncertainty

The following table gives deep-dose equivalent values and ranges of deep-dose equivalents within the 95% confidence limits resulting from application of the above overall bias and uncertainty factors to film badge readings in the DOW INIC II series. Film badge readings above 0.2 R may be converted by multiplying by the factors in the last line of the table, which were obtained from the overall bias and uncertainty factors for DOMINIC II given above. Readings below 0.2 R may be converted by reading directly from the table, these values allow for additional laboratory uncertainty for low readings as described in Section 5.B under *Laboratory Uncertainties*.

Deep-Dose Equivalent and 95% Confidence Limits for Operation DOMINIC II

Film Badge E*xposure* (R)	Best Estimate of Deep-Dose Equivalent (rem)	95% Confidence Limits for Deep-Dose Equivalent (rem)
0.04 (MDL)	0.03	(0.00,0.07)
0.05	0.04	(0.02,0.08)
0.06	0.05	(0.03,0.08)
0.07	0.05	(0.03,0.09)
0.08	0.06	(0.04,0.10)
0.09	0.07	(0.04,0.11)
0.10	0.08	(0.05,0.12)
0.12	0.09	(0.06,0.14)
0.14	0.11	(0.07,0.16)
0.16	0.12	(0.08,0.18)
0.18	0.14	(0.10,0.20)
0.20	0.15	(0.11,0.22)
>0.20	0.77 E	(0.55 E, 1.08 E)

where E is the film badge *exposure*

Use of the Type 834 film component to replace the Type 606 essentially solved the overlap problem previously experienced in the 10 – 15 R range (see Section 4.D).

7

Conclusions

A. TRACTABILITY OF THE PROBLEM

There is extensive documentation of the U.S. atmospheric nuclear tests that were conducted from 1945 through 1962. A repository of these documents is maintained for the Department of Energy by Reynolds Electrical & Engineering Company, Inc. It includes archives of records made at the time of the tests, correspondence and reports dating from that same period, detailed summaries of each individual test series written by Defense Nuclear Agency contractors after 1980, and numerous other reports, critiques, and criticisms that have appeared after the atmospheric test series.

The archival records are voluminous but not complete. For example, not all the original developed films from film badges are available, particularly for some of the earliest test series. Incomplete records and poor penmanship in some original film badge records in archives have left ambiguities in assignment of some badge readings to particular individuals. Incomplete records and inaccurate plotting of data for film badge calibration experiments produced uncertainties in the quality of some calibrations.

In spite of their deficiencies, the documents are sufficiently complete to provide a clear picture of the way film badges were used to record and determine x-and gamma-radiation *exposure* of participants who wore them. Records of film badge procedures leave no doubt that radiation safety of participants was a major concern in all of the tests. From the first atmospheric test, film badges were recognized as the most reliable means for documenting cumulative radiation *exposure* that participants received. The very large number of participants in atmospheric nuclear tests and the widely different test conditions made this a formidable undertaking.

The specific film badge dosimetry methodology that was used evolved with time through the different test series. Special circumstances in the field made individual tests unique and produced special problems. Nevertheless, the general approach to film badge dosimetry remained the same throughout the atmospheric testing period. This commonality has made the Committee's task of evaluating the reliability of results drawn from archival records a tractable problem. It enabled the Committee to develop a relatively simple means for expressing the most probable radiation *exposure* received by a single film badge and the limits within which the *exposure* can be determined with 95% confidence. Applying methodology recently developed by the International Commission on Radiation Units and Measurements (ICRU 1985), the Committee was able to translate a film badge *exposure* and its associated uncertainties into a best estimate of deep-dose equivalent for a person wearing that badge.

The uncertainty assessment for this report was based on careful quantification of bias and uncertainty from each of several sources, followed by evaluation of their combined effects based on statistical principles. In conducting this assessment, the Committee carefully evaluated the available evidence, and used their collective expertise to obtain factors for bias and uncertainty. However, the available evidence was not adequate to allow a rigorous statistical treatment of all uncertainty sources, and therefore the assessment necessarily had a subjective component. Nevertheless, the quantification of bias and uncertainty provided in this report is based on specific assumptions that are discussed in Chapter 5 and justified for individual test series in Chapter 6.

B. GAMMA RADIATION FROM FISSION PRODUCTS AND ACTIVATION PRODUCTS

Personnel exposure from atmospheric weapons testing was largely from x and gamma radiation in the energy region from 0.1 to 2 MeV associated with decay of fission and activation products (See Section 3.D). Less than 10% of the overall photon energy spectrum was below this energy range, and was primarily attributable to the scattering of photons from large area sources.

With few exceptions, neutrons did not contribute significantly to personnel exposure (Section 3.B). Unfissioned uranium, plutonium and other transuranium elements produced by the detonation were alpha-radiation emitters (Section 3.C). However, alpha radiation was not measurable by film badges used in these tests.

A significant beta-radiation component is associated with residual radiation fields (Section 3.C). Beta radiation is non-penetrating radiation and does not contribute as such to the deep-dose equivalent. Beta radiation interactions give rise to bremsstrahlung (x rays), but the contribution of this source to the overall photon field is small (Section 3.D). Therefore, film badges provided a reasonable basis for estimating deep-dose equivalent to participants in atmospheric testing operations.

C. CAPABILITIES AND LIMITATIONS OF FILM BADGE DOSIMETERS

Film packets utilized in film badge dosimeters during the period 1945–1962 changed only in the *exposure* ranges of emulsions and the number of components per packet (See Section 4.D for examples). Improvement in the range of *exposures* measured occurred as operational experience was gained with different film-component combinations (Section 4.D). Very few personnel *exposures*, however, were affected by film-emulsion range limitations.

Metallic filters used over film packets to establish more uniform film response varied during early test operations and generally were standardized in 1953 to have a 0.028-inch-thick lead filter. This filter was adequate for monitoring fission and activation-product photons over a wide range of energies (Section 4.A). Other filters used in earlier tests had the effect of overestimating *exposure* from photons below 100 keV.

Attempts were made during several test operations to estimate beta *exposure*. These attempts were not successful. Beta-dose results reported during atmospheric testing are therefore not reliable (Section 4.B).

Densitometry capability was a limiting factor only in CROSSROADS where the measurement range limited *exposure* determination to a maximum of 2 R. Only a few participants, however, exceeded this limit during one badge-wearing period.

The minimum detectable limit (MDL) of a particular film badge component type is a limitation in measuring low *exposures*. Conclusion F discusses this limitation.

D. BIAS AND UNCERTAINTY

Best estimates of the x-and gamma-radiation *exposure* of a single film badge and the 95% confidence limits were evaluated by combining uncertainties from a number of different origins. These have been grouped into laboratory, radiological, and environmental categories as described in detail in Section 5.B. Each source has been characterized by a lognormal distribution with a bias and an uncertainty as discussed in Section 5.A. The overall bias and uncertainty resulting from all sources were deduced by a combination of individual bias and uncertainties as also discussed in Section 5.A. The composite results vary considerably from one test series to another, as detailed for individual series in Chapter 6.

In all cases, the relative uncertainty increases at very low *exposures* (less than 0.2 R) because exposed optical density approaches optical density of unexposed film, which also varies to some degree. In the *exposure* range between 0.2 and 2 R, where this contribution to uncertainty is small, and for a well controlled test series such as PLUMBBOB, the net *exposures* are typically found to be unbiased and to have uncertainties within a factor of 1.4 above or 0.7 below the best estimate of *exposure*. Conversion of *exposure* to deep-dose equivalent yields a deep-dose equivalent in rem which is 0.8 times the *exposure* in R. Because there is an additional uncertainty of 1.2 in this conversion, the 95% confidence limits on the final deep-dose equivalent for PLUMBBOB would have an uncertainty of 1.5 for the best estimate. Somewhat larger values are obtained for less well controlled series.

Numerical values of reported estimates of *exposure* obtained from film badges are always larger than the corresponding calculated numerical values of the deep-dose equivalent.

E. METHODOLOGY FOR ASSESSING BIAS AND UNCERTAINTY

In this report (Section 5.A), the approach developed is a reasonable method for combining biases and uncertainties from several different sources and for estimating the deep-dose equivalent from film badge readings. Although the specific values for bias and uncertainty given in this report are strictly applicable only to atmospheric test series participants, the methods used to obtain these values could be applied to other personnel monitoring situations such as underground testing at NTS after 1962 and similar monitoring under field conditions, or with revised uncertainties, to monitoring for reactor and hospital radiation workers.

F. MINIMUM DETECTABLE EXPOSURE LEVEL

As defined in Section 5.C, the minimum detectable level of radiation *exposure* measured with a film badge is generally established as the point where the uncertainty of the reading at the 95% confidence level is $\pm$ 100% in normal distribution terms. Application of this concept to film dosimetry during the atmospheric tests generally results in an MDL of approximately 40 mR, indicating that 95% of a series of *exposures* at 40 mR would yield readings between 0 and 80 mR. Readings below the MDL appear in the records for some of the test series. The. general practice in film badge dosimetry is to make the best possible interpretation of the *exposures* in the region between zero and the MDL, reporting zero for those that favor that end of the range and a positive reading for those approaching the MDL, bearing in mind that there is no statistical difference between the two. This practice appears to have been followed in a majority of the test series.

G. CONVERSION FROM EXPOSURE TO DEEP-DOSE EQUIVALENT

The film badges used throughout the atmospheric weapons tests were designed, calibrated, and used to measure gamma and x-ray *exposures* . As mentioned in Chapter 4, occasional attempts to measure beta radiation in various series were generally unsuccessful, and were not considered in this study. The relationship of *exposure* to deep-dose equivalent is described in Section 5.E. Deep-dose equivalent is the quantity of interest in evaluating the potential for biological effects in an individual involved in the weapons test series. Therefore, each of the individual series evaluations in Chapter 6 include an overall bias and uncertainty that will effectively provide a mechanism for conversion from *exposure*, as reported on the film badges, to deep-dose equivalent. The Committee concludes that this conversion is a necessary element in the evaluation of an individual participant's radiation-*exposure* history.

8

Recommendations

A. REPORTING OF BIAS AND UNCERTAINTY

For each test series, this report lists the best estimate of the overall bias, B, for correcting film badge readings and converting them to deep-dose equivalents. It also lists the best estimate of the uncertainty, K, which quantifies the range of uncertainty at the 95% confidence level for these bias-adjusted values. Values assigned to both B and K take into account the specific exposure conditions and sources of uncertainty for each series. To obtain the best estimate of the deep-dose equivalent in rem, the reported film badge *exposure* in R is divided by the overall bias, B. To obtain the upper and lower limits of uncertainty at the 95% confidence level, this calculated best estimate of the deep-dose equivalent is multiplied by K and divided by K, respectively. The Committee recommends that these calculations be performed for each reported *exposure* under investigation. Tables for converting reported individual film badge *exposures* are provided for each test series in Chapter 6.

B. TREATMENT OF EXPOSURES REPORTED AS BELOW MINIMUM DETECTABLE LEVELS OR AS ZERO

The general recommendation of the Committee in circumstances where a large number of readings below the minimum detectable level (MDL) appear in a participant's record, or where the MDL is unusually high, due to unusual environmental circumstances, is to allot one-half of the MDL for each zero appearing in the record (Section 5.C. For consistency, recorded film badge readings below the MDL also should be interpreted as one-half the MDL, since, in fact, these readings are not distinguishable from zero. A review of the *exposure*-reading distribution for all test series leads the Committee to conclude that such a practice would probably overestimate the actual *exposure*, but that it would not greatly exaggerate the general results in any test series or the recorded *exposure* of any single participant. In special circumstances such as when the overwhelming majority of readings for a group of participants similarly exposed during a given exposure period were zero, zero is probably the reading of choice in terms of maximum accuracy and should be used accordingly.

The Committee emphasizes that this treatment of reported *exposures* below the MDL for assessment purposes is suggested only in individual cases where there is reason to investigate possible biological effects attributable to the radiation dose. It does not recommend changes to existing records.

C. UNCERTAINTIES IN THE SUMMATION OF SEVERAL FILM BADGE READINGS

Determination of an individual's total deep-dose equivalent will often require the summation of deep-dose equivalents obtained from more than one film badge reading. For this total, the upper and lower confidence limits can be estimated. by summing the upper and lower 95% confidence limits for the individual assessments of deep-dose equivalent. It should be noted that " procedure will overestimate the range of uncertainty at the 95% confidence level.

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Appendix A

Organizational Abbreviations

AEC	Atomic Energy Commission (now DOE)
AFSWP	Armed Forces Special Weapons Project
ANSI	American National Standards Institute
ASA	American Standards Association
BCT	Battalion Combat Team
DNA	Defense Nuclear Agency
DOE	Department of Energy
DOD	Department of Defense
DRP	Dosimetry Research Project
EPG	Enewetak Proving Grounds
GAO	General Accounting Office
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
LASL	Los Alamos Scientific Laboratory
NAS	National Academy of Sciences
NBS	National Bureau of Standards (now NIST-National Institute of Standards and Technology)
NCRP	National Commission on Radiation Protection and Measurements
NPG	Nevada Proving Ground
NRC	National Research Council
NTPR	Nuclear Test Personnel Review

NTS	Nevada Test Site
OTO	Office of Test Operations
PPG	Pacific Proving Grounds
REECo	Reynolds Electrical &. Engineering Company, Inc.
RSSU	Radiological Safety Support Unit
SAIC	Science Applications International Corporation

Appendix B

Glossary

AB-SORBED DOSE:	The amount of of energy imparted by radiation to a unit mass of absorbing material (100 ergs per gram), including tissue. The unit used prior to the SI is the rad; the SI unit is the gray (Gy).
ALPHA PARTICLE:	A particle emitted spontaneously from the nuclei of some radioactive elements. It is identical with a helium nucleus, having a mass of four units and an electric charge of two positive units.
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.
BREMSSTRAHLUNG:	Secondary photon or x radiation produced by deceleration of charged particles passing through matter.
COULOMB:	The standard unit for electrical charge.
CURIE:	A special unit of activity. One curie exactly equals 3.7 x 1010 nuclear transitions per second.

DEEP-DOSE EQUIVALENT:	Dose equivalent from penetrating radiation to soft tissue located at a depth of 10 mm in the body. Symbolized as HP(10). See also ABSORBED DOSE and DOSE EQUIVALENT.
DENSITOMETER:	An instrument utilizing a photocell to determine the degree of darkening of developed photographic film.
OPTICAL DENSITY (OD):	The degree of darkening of photographic film. D = log (I0/I), where I0 is the incident light intensity and I is the transmitted light intensity.
NET OPTICAL DENSITY (NOD):	Optical density of a film corrected (reduced) by subtracting the optical density of an unexposed "control" film.
DOSE:	As used in the general sense, dose denotes absorption of a quantity of ionizing radiation. See ABSORBED DOSE, DOSE EQUIVALENT.
DOSE EQUIVALENT:	A quantity used in radiation protection to normalize the biological effectiveness of the absorption of different radiations. It is defined as the product of the absorbed dose and certain modifying factors. The unit of dose equivalent used prior to the ST is the rem. The SI unit is the Sievert (Sv). See also DEEP-DOSE EQUIVALENT.
DOSIMETER:	An instrument for measuring and registering the total accumulated dose of (or exposure to) ionizing radiations. Instruments worn or carried by individuals are called personnel dosimeters or personal dosimeters.
ELECTRON:	A subatomic particle of very small mass, carrying a unit negative or positive charge. Negative electrons, surrounding the nucleus, (i.e., orbital electrons), are present in all uncharged atoms; their number is equal to the number of positive charges (i.e., protons) in the particular nucleus. The term electron, where used alone, commonly refers to negative electrons. A positive electron is usually called a positron.
ELECTRON VOLT:	The energy imparted to an electron when it is moved through a potential difference of I volt. It is equivalent to 1.6 x 10–12 erg. This is a basic unit for expressing the energy of atomic and nuclear radiations.
ERYTHEMA:	Abnormal redness of the skin due to capillary congestion (as in inflammation).

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.
FALLOUT:	The process or phenomenon of the descent to the earth's surface of particles contaminated with radioactive material from the radioactive debris cloud.
FILM BADGE:	It includes a pack of photographic film which measures radiation exposure for personnel monitoring. The badge may contain one to three films of differing sensitivities and filters to shield parts of the films from certain types of radiation.
FISSION:	The process whereby the nucleus of a particular heavy element splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy. The most important fissionable materials are uranium 235 and plutonium 239; fission is caused by the absorption of neutrons.
FISSION PRODUCT:	A nuclide, usually radioactive, formed by the fission process.
GAMMA-RAY INTERACTIONS	
PHOTO-ELECTRIC 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 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 that the incident photon.
PAIR PRODUCTION:	An absorption process for x and gamma radiation in which the incident photon is annihilated in the vicinity of the nucleus of an atom, with subsequent production of an electron and positron pair. This reaction only occurs for incident photon energies exceeding 1.02 MeV.
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 with x rays of high energy, the only essential difference being that x rays do not originate in the nucleus.

GRAY:	The SI unit of absorbed dose, abbreviated Gy. 1 Gy = 1 joule/kilogram = 100 rad.
GROUND ZERO:	The point on the earth's surface vertically below or above the center of a burst of a nuclear (or atomic) weapon.
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.
H-HOUR:	"Time zero" or the exact time of detonation to the minute, second, and fraction of a second; as opposed to H + 1 which implies one hour after detonation (unless indicated to be seconds or minutes).
INDUCED RADIOACTIVITY:	Radioactivity produced in certain materials as a result of nuclear reactions, particularly the capture of neutrons.
INITIAL NUCLEAR RADIATION:	Nuclear radiation (essentially neutrons and gamma rays) emitted during the first minute after a nuclear (or atomic) explosion.
INTEGRON:	An ion chamber device used on cloud-sampling aircraft to provide an immediate measure of gamma radiation present.
IONIZATION:	The separation of a normally electrically neutral atom or molecule into electrically charged components.
IONIZING RADIATION:	Electromagnetic or particulate radiation capable of producing charged particles through interactions with matter.
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.
KILOELECTRON VOLT (or keV):	An amount of energy equal to 1,000 electron volts.
MINIMUM DETECTABLE LEVEL:	The minimum exposure that can be distinguished from zero.
MONITORING:	Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination present in an occupied region.

AREA MONITORING:	Routine monitoring of the radiation level or contamination of a particular area, building, room, or piece of equipment.
PERSONNEL MONITORING:	Monitoring any part of an individual's body, his breath, excretions, or any part of his clothing.
NEUTRON:	A neutral particle (i.e., with no electrical charge) of approximately unit atomic mass, present in all atomic nuclei, except those of ordinary (light) hydrogen.
NOD:	See DENSITY.
NUCLEAR RADIATION:	Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes. The important nuclear radiations, from the weapons standpoint, are alpha and beta particles, x and gamma rays, and neutrons.
NUCLEUS (OR ATOMIC NUCLEUS):	The small, central, positively charged region of an atom which carries essentially all the mass. Except for the nucleus of ordinary (light) hydrogen, which is a single proton, all atomic nuclei contain both protons and neutrons.
OD:	See DENSITY.
PHOTON:	A unit or "particle" of electromagnetic radiation, carrying a specific quantum (particular level) energy.
PROTON:	A particle of approximately unit atomic mass carrying a unit positive charge; it is identical physically with the nucleus of the ordinary (light) hydrogen atom.
QUALITY FACTOR:	The factor by which absorbed doses are multiplied to obtain (for radiation-protection purposes) a quantity that expresses-on a common scale for all ionizing radiations-the biological effectiveness of the absorbed dose.
RAD:	An older unit of absorbed dose of radiation; 1 rad represents the absorption of 100 ergs per gram of absorbing material, such as body tissue.
RADIOACTIVITY:	The spontaneous emission of radiation, generally alpha or beta particles, often accompanied by gamma rays, from unstable atoms.

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".
RESIDUAL RADIATION:	Nuclear radiation, chiefly beta particles and gamma rays, that persist for a time following a nuclear explosion. The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and to some extent by earth and water constituents, and other materials in which radioactivity has been induced by the capture of neutrons.
ROENTGEN:	A unit of exposure to gamma (or x) 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 kilogram of dry air. An exposure of 1 roentgen is approximately equivalent to an absorbed dose of 1 rad in soft tissue.
SCATTERING:	The diversion of radiation from its original path as a result of interactions with atoms between the source of the radiations (e.g., a nuclear explosion) and a point at some distance away. Scattered radiations are typically changed in direction and of lower energy than the original radiation.
SERIES:	A particular group of nuclear detonation tests, often referred to as "Operation & Name".
SIEVERT:	The SI unit for dose equivalent, abbreviated Sv. 1 Sv = 100 rem.
SHIELDING:	Any material or obstruction which absorbs (or attenuates) radiation and thus tends to protect personnel or materials from the effects of a nuclear (or atomic) explosion.
SHOT:	A nuclear detonation.
SI:	Refers to Systeme Internationale, an international system of units adopted in 1975.
X RAY:	Ionizing electromagnetic radiation of extranuclear origin.

Appendix C

Biographical Sketches

COMMITTEE MEMBERS

FRANCIS X. MASSE (Chairman)

Director of Radiation Protection Programs, Massachusetts Institute of Technology

FRANCIS MASSE has been actively involved in applied health physics since 1956, when he was appointed Radiation Safety Officer at Tufts-New England Medical Center in Boston. He was appointed to the Radiation Safety staff at Massachusetts Institute of Technology in 1959, where he has remained to date, while retaining his RSO appointment at TNEMC. He has been the Director of the Radiation Protection Programs at MIT for the past decade.

Mr. Masse was certified by the American Board of Health Physics for the comprehensive practice of health physics in 1962, and has maintained his recertification schedule as necessary since that time. He has been active in committee activities, has served on the Board of Directors, and is currently the Treasurer of the Health Physics Society. He was awarded Fellow membership in the HPS in 1986. He has also been actively involved in the American Association of Physicists in Medicine since its inception, and has chaired an American National Standards Institute committee for more than a decade.

His experience in applied health physics at MIT, TNEMC, and the dozens of consulting appointments he holds has involved in-depth dealings with personnel dosimetry of all types. He has extensive experience with the monitoring of external radiation exposures with film badges and thermoluminescent dosimeters, and is internationally known for his work in whole-body counting for internal dosimetry measurement.

WALTER L. BROWN (Vice-Chairman)

Head, Radiation Physics Research Department, AT&T Bell Laboratories

WALTER BROWN received his education in Physics at Duke and Harvard Universities, receiving his B.S. from Duke in 1945 and his M.A. and Ph.D. from Harvard in 1947 and 1951. He joined Bell Telephone Laboratories in 1950 and undertook research on the physical properties of semiconductor surfaces and the nature of defects produced in semiconductors by high energy radiation. He was in charge of a scientific group that developed semiconductor radiation detectors for the Telstar satellites to monitor energetic particles in the Van Allen belts around the earth and studied the effects of radiation by those particles on the solar cells and other semiconductor devices on satellites in earth orbit. He has subsequently carried out research on ion implantation and channelling, laser annealing, sputtering of solids by both collisional and electronic processes and on ion bombardment induced crystallization and amorphization of solids.

Since 1957 he has been head of the Radiation Physics Research Department at AT&T Bell Laboratories, Murray Hill, New Jersey. He is a Fellow of the American Physical Society and a member of the Materials Research Society. In 1984 Walter Brown received the Arthur von Hippel Award from the Materials Research Society. In 1988 he was elected to membership in both the National Academy of Engineering and the National Academy of Sciences.

JUDITH AREEN (Member)

Professor of Law and Dean, Georgetown University Law Center

JUDITH AREEN is Executive Vice President for Law Center Affairs at Georgetown University and Dean of the Law Center. She is also a Professor of Law and a Senior Research Fellow of the Kennedy Institute of Ethics.

Dean Areen's areas of academic expertise include family law, constitutional law, and law, medicine and ethics. She is the author of a widely used law school casebook (Family law, 2nd edition, Foundation Press 1985), and co-author of another (Law, Science and Medicine, Foundation Press 1984). She was chosen on the basis of her scholarship to be a fellow of the Woodrow Wilson International Center for Scholars in Washington, D.C. during 1988–1989.

A graduate of Cornell University (1966) and the Yale Law School (1969), Dean Areen has worked in the private sector and in government at the local and federal levels. Between 1977 and 1980 she served in the Office of Management and Budget as Project Director, and then, as General Counsel to President Carter's Reorganization Project. She served as Special Counsel to the White House Task Force on Regulatory Reform during the same period.

Dean Areen, who is a member of the bar of the District of Columbia, currently serves as Chair of the Section on Law, Medicine and Health Care of the Association of American Law Schools. She has served as a governor of the District of Columbia Bar, as a consultant to the National Institutes of Health and the National Academy of Sciences, and as a director of the Society of American Law Teachers. In June, 1989, she was selected by the National Law Journal as one of the fifty most outstanding lawyers under fifty in the United States.

WILLIAM J. BRADY (Member)

Principal Health Physicist, Reynolds Electrical & Engineering Co., Inc.

WILLIAM BRADY participated in nuclear weapons testing since January 1952, including initial survey radiation monitoring, monitoring on flights through radioactive debris clouds, and other aspects of rad-safe, including training others. Positions during 33 years with the Reynolds Electrical & Engineering Company (REECo) rad-safe organization were Monitor, Senior Monitor, Supervisor, Reactor Branch Leader (Rover and Pluto Projects), Laboratory Branch Leader, Dosimetry Superintendent, Senior Health Physicist, Technical Advisor, and Principal Health Physicist currently. REECo is the prime contractor for the Department of Energy in Nevada.

While training others, he wrote REECo's initial *Basic Monitoring Manual* (1956) and *Emergency Monitoring Manual* (1957). He was an emergency monitoring team captain and one of four team members who responded to the SL-1 reactor accident in Idaho. As Laboratory Branch Leader, he developed a plutonium electrode position cell used at the Nevada Test Site (NTS) and University of Washington, the Drierite procedure for monitoring tritiated water vapor, and the film dosimeter worn at NTS from 1965 through 1986. He wrote the first Standard Procedures of REECo's Environmental Sciences Department and authored a number of historical volumes on DOD underground testing. He began collecting documents in 1957 and established by 1969 a computerized Master File of personnel dosimetry results dating back to the beginning of nuclear device testing in 1945.

Mr. Brady served on the NAS/NRC Committee on Ionizing Radiation Dosimetry which evaluated the U.S. Army thermoluminescent dosimeter. He has a

Bachelor of Science degree in mathematics with emphasis on geology and physics from the University of Nevada at Las Vegas and has been a member of the Health Physics Society for 30 years. He received the Department of Energy's Award of Excellence in 1989 from the Office of Military Application for significant contribution to the nuclear weapons program.

JOHN R. FRAZIER (Member)

Deputy Director, Nuclear Sciences, International Technology Corporation

JOHN FRAZIER graduated from Berea College in Berea KY, where he majored in physics and received the B.A. degree in 1970. He attended graduate school at the University of Tennessee in Knoxville and was awarded an Atomic Energy Commission Health Physics Fellowship. His Master of Science degree in physics, with emphasis in health physics, was received in 1973 followed by his Ph.D. with the same major in 1978.

From 1977 to 1980, Dr. Frazier served as Chief of the Radiation Physics Section of the Bureau of Radiological Health (BRH), Food and Drug Administration (FDA), where he directed the BRH x-ray calibration and external dosimetry programs. The expertise of John and his group was recognized when he was called upon to provide external dosimetry support for the FDA during the Three Mile Island crisis.

In February 1986, John became the Deputy Director of the Nuclear Sciences Group of International Technology Corporation. He coordinates health physics consulting activities, conducts audits and appraisals of nuclear facilities, serves as an expert witness and advisor in radiation litigation cases, and performs a wide range of health physics activities including internal and external dose calculations, environmental dose assessments, designing environmental sampling programs, and instrument calibrations. In 1988 Dr. Frazier received the Elda E. Anderson Award which honors young health physicists who have made outstanding contributions to their profession before reaching the age of 40.

ETHEL GILBERT (Member)

Staff Scientist, Pacific Northwest Laboratory

ETHEL GILBERT is a staff scientist in the Life Sciences Department at Pacific Northwest Laboratory, Richland, Washington. She has an A.B. degree in mathematics from Oberlin College, and the M.P.H. and Ph.D. degrees in biostatistics from the University of Michigan. Since 1975, Dr. Gilbert has been the principal investigator for a project sponsored by the Department of Energy providing for the development of statistical methods for examining the relationship of health effects and low-level chronic exposures, particularly to ionizing radiation. An important component of the project has been relating worker mortality data to occupational radiation exposure as measured by personnel dosimeters.

Dr. Gilbert has served as a consultant to the Committee on Interagency Radiation Research and Policy Coordination in preparing a report "Use of Probability of Causation by the Veterans Administration in the Adjudication of Claims of Injury due to Exposure to Ionizing Radiation". She was also a member of the working group responsible for revising the health effects model for the Nuclear Regulatory Commission Reactor Safety Study, and provided a model for estimating cancer risks resulting from the radiation exposure likely to be received by the general population from a nuclear reactor accident. During a year spent at the Radiation Effects Research Foundation in Hiroshima, Japan, Dr. Gilbert investigated questions related to random systematic dose measurements errors and their impact on analyses of data from follow-up studies of Japanese A-bomb survivors. Dr. Gilbert currently serves on the National Council on Radiation Protection and Measurement, on the National Academy of Sciences Committee on Epidemiology and Veterans Follow-up Studies, and is a Fellow of the American Statistical Association.

ROBERT O. GORSON (Member)

Professor of Radiology, Thomas Jefferson University

ROBERT GORSON is a Professor of Radiology (Medical Physics) and a Professor of Radiation Therapy and Nuclear Medicine (Medical Physics) at Thomas Jefferson University where he has taught radiological physics, health physics and radiation biology for 30 years after ten years in the same fields at the University of Pennsylvania where he earned B.S. and M.S. degrees in Physics in 1949 and 1951. He is certified by the American Board of Radiology and the American Board of Health Physics of which he is a past Chairman. He is currently Treasurer and board member of the American Board of Medical Physics and a member of the Board of Chancellors of the American College of Medical Physics. He is also a past president of the American Association of Physicists in Medicine and a Fellow in Physics of the American College of Radiology.

Professor Gorson has served on a number of committees of the National Council on Radiation Protection of which he was a member for 23 years and is now an honorary member. He was also a member of the International Commission on Radiation Protection Committee on the Medical Uses of Radiation for eight years. Professor Gorson has served on numerous committees concerned with radiation uses, effects and dosimetry, of the American College of Radiology, Radiological Society of North America, Health Physics Society, American Asso ciation of Physicists in Medicine, National Cancer Institute and a number of governmental agencies. He is author or co-author of 54 papers, chapters and peer reviewed reports on various subjects in medical physics including a study done in 1964 on the reliability of film badge dosimetry. He also chaired an ad hoc Committee on the hazards of spray asbestos in building construction in Philadelphia which in 1971 resulted in Philadelphia becoming the first city in the United States to forbid the use of spray asbestos fireproofing in new construction.

N. ANTHONY GREENHOUSE (Member)

Manager, Personal Dosimetry Office, LBL

N. ANTHONY GREENHOUSE is currently the manager of the Personal Dosimetry Office at Lawrence Berkeley Laboratory, where he provides dosimetry services for employees and guests, and conducts research into novel techniques for measurement of accelerator radiation doses. He has had twenty-two years of comprehensive work experience in health physics at Lawrence Livermore, Brookhaven and Lawrence Berkeley National Laboratories.

Mr. Greenhouse has a B.S. degree in Biophysics from Catholic University of America, a M.S. degree in Health Physics from the University of Rochester, a M.P.H. degree in Industrial Hygiene from the University of California (Berkeley), and is a Ph.D. Candidate in Public Health at the University of California (Berkeley).

Awards and Distinctions include an AEC Fellowship in health Physics, 1965; Diplomate of the American Board of Health Physics, 1971; Member of American Board of Health Physics, 1978 to 1982, and Chairman of ABHP in 1981 to 1982; Member, Board of Directors, Health Physics Society, 1986 to 1989; First recipient of the Burton J. Moyer Fellowship in Radiation Protection, 1986 to 1987.

RONALD L. KATHREN (Member)

Director of Health Physics, Hanford Environmental Foundation

RONALD KATHREN is Director of Health Physics at the Hanford Environmental Foundation and Affiliate Associate Professor of Radiological Sciences at the University of Washington. He holds degrees from U.C.L.A. and the University of Pittsburgh in health physics, and is a Diplomate of the American Board of Health Physics and the American Academy of Environmental Engineers. He is a member of several scientific societies and is currently President of the Health Physics Society. His honors include the Elda E. Anderson (1977) and Founders (1985) Awards of that organization, the Arthus F. Humm, Jr. Award of the National Registry of Radiation Protection Technologists, and electron to Delta Omega, the public health honorary.

His scientific work has been largely in the area of applied health physics, with emphasis on radiation dosimetry and instrumentation, environmental radioactivity, and the history of radiation protection. During the 1960's and 1970's, Professor Kathren performed research on photographic film dosimetry while at the University of Pittsburgh, Lawrence Radiation Laboratory and Battelle-Northwest Laboratories, and is the author of a number of scientific papers in that area. His current research is concerned with biokinetic modelling and dosimetry of the actinides in support of the United States Transuranium and Uranium Registries. He is the author of several scientific books including *Radioactivity in the Environment* and *Radiation Protection* and serves as a consultant to the U.S. Advisory Committee on Reactor Safeguards and Advisory Committee on Nuclear Waste.

NORMAN C. RASMUSSEN (Member)

McAfee Professor of Engineering, Massachusetts Institute of Technology

NORMAN RASMUSSEN received the B.A. degree from Gettysburg College in 1950 and a Ph.D. in Physics from MIT in 1956. He has been on the faculty of the MIT Department of Nuclear Engineering since 1956. From 1975–81 he was Head of the Department.

Professor Rasmussen's early research work was in the field of gamma ray spectroscopy and he did considerable work on the spectroscopy of neutron capture gamma rays. Recently, his research has been in the field of nuclear reactor safety. From 1972 to 1975 he directed the Reactor Safety Study (WASH-1400) for the AEC (later the NRC). He continues to work on improvements of the probabalistic risk assessment methods developed in the WASH 1400 study. He has authored or co-authored more than 100 technical articles.

Professor Rasmussen has served on numerous committees, boards, and panels, including the Defense Science Board, the National Science Board, and the National Council of Radiation Protection and Measurement. He has been a consultant to both government and industry. He is a member of the National Academy of Sciences and the National Academy of Engineering.

CRAIG R. YODER (Member)

Technology Manager, R. S. Landauer, Jr. and Company

Since 1983, Dr. Yoder has been the Technology Manager for Tech/Ops Landauer, Inc., a company that has been providing commercial radiation film badge services since 1954. In this capacity, he has specialized in the research and development of radiation monitoring methods based on film, thermoluminescent dosimeters and solid state nuclear track detectors. In addition, he is responsible for the performance evaluation of film badges and their accreditation by national and international authorities. He has recently become involved in the development of passive radon monitors as well as special dosimeter applications for use in quality assurance of diagnostic radiology procedures. Prior to this role, Dr. Yoder was a Senior Research Scientist at Battelle, Pacific Northwest Laboratory where he conducted research in the areas of radiological calibrations and dosimeter performance. Dr. Yoder developed a unique instrument for measuring the relationships between exposure and the dose delivered at different depths in tissue.

Dr. Yoder received a B.S. degree from Davidson College. He later was awarded M.S. and Ph.D. degrees in Bionucleonics from Purdue University. He is certified in Comprehensive Health Physics by the American Board of Health Physics and is a member of the Health Physics Society and the American Association of Physicists in Medicine. Dr. Yoder has served on various national and international committees developing radiation monitoring standards.

STUDY DIRECTOR

GEORGE LALOS

Consultant, Energy Engineering Board, National Academy of Sciences

GEORGE LALOS is a Consultant to the Energy Engineering Board, National Research Council of the National Academy of Sciences. He has a B.Ae.E. degree in Aeronautical Engineering from Rensselaer Polytechnic Institute, and a M.S. degree in Physics from The Catholic University of America. Mr. Lalos has played a major role in the fields of High Pressure Physics, High Energy Lasers, and Remotely Piloted Underwater Vehicles during his career with the Department of the Navy. Recent activities include work in advanced weapons concepts and in various areas of radiation protection.

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