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Service Personnel at Nuclear Weapons Tests
Board on Radiation Effects Research
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

In 1977, the Centers for Disease Control reported that a larger than expected number of cases of leukemia had occurred among soldiers who had participated in Shot Smoky, a 1957 military exercise that was part of Operation Plumbbob (Caldwell et al., 1980). A hearing conducted by the Committee on Veterans Affairs of the U.S. Senate on January 20, 1979, emphasized the need for additional information on the participation of Department of Defense personnel in the atmospheric nuclear testing program and for information on the radiation doses they received. The Defense Nuclear Agency (DNA) was given primary responsibility for conducting a Nuclear Test Personnel Review (NTPR), with the objectives of identifying all participants in all atmospheric nuclear tests and estimating the radiation dose received by each. DNA asked the National Research Council to review and comment on the scientific aspects of the methods used by the NTPR for determining radiation doses.

This report was prepared by the Committee on Dose Assignment and Reconstruction for Service Personnel at Nuclear Weapons Tests, which was assembled by the Board on Radiation Effects Research of the Research Council's Commission on Life Sciences. The Committee's purpose was to advise DNA on whether the methods used in the NTPR to assign doses of radiation are comprehensive and scientifically sound and to recommend improvements if needed. The charge to the Committee did not require it to make judgments about the biologic significance of the radiation exposure of participants at the atmospheric weapons tests, nor did it direct the Committee to conduct audits of dose assignments or reconstructions for specific individuals.

In the initial phase of the Committee's review, it was found that the methods used by DNA were outlined (Appendix A), but the details of the methods used were found only in compilations of information about the individual tests, scientific reports that dealt with specific questions that require study, and many relevant memoranda. The documents that were relevant to the scope of the Committee's review are listed in Appendix B.

Unfortunately, DNA had not prepared a single report that summarized the essential information with which it has been necessary for the Committee to deal. A summary report would have organized the essential information into a more manageable form, so that the details of the dose assignment procedures could have been summarized succintly, the special problem encountered could have been identified and discussed, and the uncertainties involved in the dose estimates could have been assessed.

In the absence of a summary report, the Committee staff was asked to review the mass of material accumulated by DNA and select the documents that should receive detailed study by the Committee. The Committee at all times had knowledge of the titles of all documents and from time to time requested that additional ones be made available for study. In addition, the Committee met on a number of occasions with DNA staff and contractors, and some members of the Committee had frequent telephone conferences concerning specific items of interest.

This report would not have been possible without the assistance of several individuals. Samuel B. McKee served as Research Council staff officer for the duration of the report. Norman Grossblatt edited the report, and Doris Taylor and Dorothy Powell assisted in preparation of the text. David Auton, Robert Devine, and Paul Boren of the Defense Nuclear Agency provided access to all documents the Committee wished to review and coordinated briefings by the service NTPR teams and their contractors, principally Science Applications International Corporation and Advanced Research and Applications Corporation. Finally, the Committee's report benefited greatly from comments by its reviewers, coordinated by Reuel Stallones. We thank all these contributors.

CONTENTS

EXECUTIVE SUMMARY

Between 1945 and 1962, about 203,000 military personnel, including civilian employees of the Department of Defense, participated in atmospheric nuclear weapons tests conducted at proving grounds in the southwestern part of the United States and in the Pacific Ocean. The Defense Nuclear Agency (DNA) has been assigned the responsibility for developing radiation dose estimates for all the participants at the tests. The decision to undertake the dose-assignment program was prompted by claims made by veterans and their families that the participants' health was damaged by exposure to ionizing radiation during or after the weapons tests. DNA instituted a program of dose assignment, known as the Nuclear Test Personnel Review (NTPR), and asked the National Research Council to review the scientific aspects of the program. The Board on Radiation Effects Research in the Research Council's Commission on Life Sciences thereupon formed the Committee on Dose Assignment and Reconstruction for Service Personnel at Nuclear Weapons Tests.

The NTPR involves the collection and processing of an extraordinary amount of information, and a major problem encountered by the Committee was that no single report summarizes the scope of the NTPR, the procedures used, and the uncertainties involved in the dose assignments. It was not feasible for the Committee to review all the material used by DNA in the NTPR. After consultation with DNA, a list of all reports used in the dose-assignment project was examined. The Committee then selected a number of the reports that described the various methods used in the dose assignment procedures. The reports submitted to the Committee for review and the formal presentations were devoted primarily to methods used by the Navy NTPR team, which are different in detail from but similar in overall design to those used by the other service teams. Therefore, comments and conclusions concerning the scientific credibility of the dose assignments are applicable mainly to the 107,000 Navy personnel (53% of the total) for whom the Navy NTPR methods were used and are applicable to other personnel to the extent that the Navy NTPR methods were used for them.

The principal sources of information on external radiation exposure are film-badge records that have been compiled into a master file by the Reynolds Electrical and Engineering Company, which has been involved in test site management for many years. This file contains more than 230,000 entries on about 143,000 of the 203,000 personnel. The design of the film badges, the methods of film processing, and the densitometric techniques and calibration procedures were relatively crude during World War II, but improved substantially during the 18-year period during which atmospheric weapons tests were conducted. On the basis of studies conducted by the National Bureau of Standards under controlled conditions during the 1950s, it is estimated that the film-badge data have a positive bias of about 45% (i.e., the badges read too high), and that their random uncertainty is about ± 100% between the minimal detection level and 100 mR and about ± 40% above 100 mR for gamma radiation exposure. Measurement of beta radiation exposure was nonexistent or of uncertain quality during the period of atmospheric testing, and external beta doses are not routinely calculated. The Committee notes in this connection that the dose from external beta radiation would be limited to the skin and would be greatly attenuated on those parts of the body covered by clothing.

The Committee found that the procedures used to estimate external radiation doses were reasonably sound. The procedures followed by DNA to estimate external doses depend on the kind and amount of information available. In the ideal case, a complete film-badge record is available, but it cannot always be ascertained that the film-badge records accurately reflect a person's total exposure throughout his participation in the nuclear tests. In the least favorable case, no film-badge data are available, and the estimate can only be inferred from other information; in such cases, the dose is reconstructed from information on a person's work schedule and records of survey meter measurements. When an unbadged person belonged to a group of which some members wore film badges, the dose assigned by the Navy to that person was the 95th percentile dose received by group members to whom badges were assigned. This procedure has the effect of increasing the dose estimates for most veterans whose dose was assessed in this way.

The NTPR has developed procedures that permit satisfactory estimates to be made of the external doses received by these participants. There are uncertainties in the dose estimates, but it appears that 99% of the personnel received doses of less than 5 rems, which is approximately the average dose received by the general population during the last 30 years from exposure to natural radiation and the use of ionizing radiation during medical procedures. The Committee believes that NTPR efforts in the future would be more productive if they were designed to determine, with a high degree of certainty, whether the dose received by a given person is less than some stated cutoff. The choice of a criterion dose is arbitrary, but 5 rems can be justified on the basis that an average participant would receive about that dose to his whole body from natural background radiation over a period of 50 years, or in 30 years from background plus medical and dental x rays.

Methods used to assign internal doses associated with inhalation or ingestion of radioactive material were in general based on unsupported assumptions. The methods often attempted to relate internal dose to the magnitude of external radiation and tended to overestimate possible internal doses. There is considerable evidence that, with the exception of doses to the thyroid, doses to any organ from internal emitters were far smaller than the external dose. The Committee came to this conclusion from follow up data obtained from Bikini natives, Japanese fishermen, and veterans who had been exposed to fallout from Shot Smoky. For these groups, modern methods of radiochemical analysis of urine and whole-body counting make it possible 20 or 30 years after exposure to set upper limits of dose commitments as low as 500 mrems from exposure to strontium-90 and plutonium-239.

Although the Committee concentrated only on methods, it found no evidence that the NTPR teams had been remiss in carrying out their mandate. If any bias exists in the estimates, it is probably a tendency to overestimate the most likely dose, especially for internal emitters or when the statistical procedure for assigning dose is used. The Committee does recommend that DNA prepare a comprehensive document that summarizes the procedures used and makes estimates of the uncertainties involved. Although the Committee also believes that estimates of internal doses could be improved, it hesitates to recommend a large effort to do so, in view of the minor impact on total doses expected. No matter what improvements are implemented, the Committee believes that further efforts to improve methodology are more likely to be fruitful if concentrated on doses expected to be at the higher end of the scale, for example above 5 rems.

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INTRODUCTION AND BACKGROUND

SCOPE OF REPORT

This report reviews the methods that the Department of Defense (DOD) developed and applied to estimate the radiation doses accumulated by DOD personnel as a result of their participation in atmospheric nuclear weapons tests in 1945-1962. During those years, about 203,000 military and civilian DOD personnel participated in 235 atmospheric tests of nuclear weapons.

The Defense Nuclear Agency (DNA) has been given primary responsibility by the DOD for developing these dose estimates. Each of the armed services has attempted to identify all its military and civilian personnel who participated in the atmospheric tests and is providing DNA and its contractors with whatever data are available concerning radiation doses to test participants, as well as other useful information.

HISTORY OF THE TESTING PROGRAM

The first test of a nuclear explosive, Operation Trinity, occurred at a remote site in New Mexico on July 16, 1945, and showed that the wartime program known as the Manhattan Engineering District had succeeded in developing an atomic bomb. Radioactive fallout from that test resulted in skin injury to cattle grazing downwind of the test. As far away as Iowa, corn shocks that were used in the manufacture of paper for packaging x-ray film became contaminated by fallout, and some of the film was later found to be spotted because of this contamination (Webb, 1949). The next two nuclear explosions were the strikes against Hiroshima and Nagasaki in August 1945. These were exploded sufficiently high above the ground that relatively minor amounts of fallout occurred.

Operation Crossroads, the first series of tests to provide information on the biologic and environmental effects of fallout, was conducted during July 1946 at Bikini Atoll in the Pacific Ocean. A nuclear explosive (Shot Able) with a yield of 23 kilotons was dropped from a plane on July 1 and detonated 520 feet above a target fleet of 90 ships assembled in Bikini Lagoon. Five ships were sunk by the explosion. There was little residual radioactivity, but most of it was a result of neutron activation, rather than of fallout, and it decreased rapidly; nearly all the remaining ships could be boarded within a day after the detonation.

The second device of the series (Shot Baker) was exploded 90 feet below a vessel anchored in the midst of the fleet. About 1 million tons of radioactive water that was thrown into the air settled on many of the ships of the target fleet, and other ships were enveloped by a base surge, a shock wave radiating from the explosion. Radioactive contamination of the lagoon water and ships by Baker was so great that a planned third shot was canceled.

In the spring of 1948, a series of three tests known as Operation Sandstone was conducted in the Pacific, at Enewetak Atoll in the Marshall Islands.

The USSR exploded its first atomic bomb in August 1948. This quickened the pace of U.S. weapons development, both to evaluate new devices and to study their effects. The difficulties and high costs of tests in the Pacific led to a search for a suitable location in the continental United States. In 1950, a site was chosen northwest of Las Vegas, Nevada, on part of an Air Force bombing and gunnery range.

The Nevada Test Site (NTS) was first used for nuclear weapons testing during January and February 1951 and again during October and November of that year. Because not all tests could be conducted at the Nevada site, construction of firing areas and support facilities was also begun at the Pacific Proving Grounds (PPG), which were based at Enewetak Atoll, but also included the area of Bikini. Four tests were conducted at Enewetak in April and May 1951 during Operation Greenhouse and two tests in November 1952 during Operation Ivy. The first large thermonuclear device, Shot Mike, with a yield of 10.6 megatons (Mt), was exploded in Operation Ivy on November 1, 1952.

On March 1, 1954, a 15-Mt device, Shot Bravo of Operation Castle, was exploded at the surface of an island in Bikini Atoll. The fallout from Bravo covered a large area to the east of Bikini and resulted in heavy exposure of three groups of persons: 23 Japanese fishermen aboard a ship about 90 miles from the explosion; Marshallese residents of Rongelap, Utirik, and Ailinginae Atolls; and 28 American servicemen on Rongerik Atoll.

A few special-purpose tests were conducted at locations other than the PPG or the NTS. One such test was the one-detonation Operation Wigwam in May 1955, which took place 6,510 feet below the surface of the Pacific Ocean, approximately 500 miles southwest of San Diego. Its primary purpose was to study the radiation and pressure phenomena associated with a deep underwater detonation. There was also a series of three small high-altitude tests detonated above the South Atlantic Ocean during Operation Argus in August and September 1958. Other high-altitude shots were detonated above Johnson Island in the Pacific, 1,200 kilometers southwest of Honolulu. The largest of these was the 1962 test, Starfish Prime, detonated at an altitude of 400 kilometers, which had a yield of 1.4 Mt.

Testing of nuclear explosives at both the PPG and the NTS continued at intervals until 1962, when a test-ban treaty between the United States and the Soviet Union prohibited further atmospheric detonations, but allowed underground tests, if whatever venting occurred would not be detected beyond the borders of the country that conducted the test.

All U.S. nuclear weapons tests were conducted underground after 1962. Because DOD personnel were rarely exposed to ionizing radiation by these tests, the underground detonations are not relevant to the NTPR or to this report.

POSSIBLE MECHANISMS OF PERSONNEL EXPOSURE

Military personnel can be exposed to radiation from nuclear weapons tests in several ways; each must be considered separately.

Exposures within seconds after detonation were usually less severe than those which occurred later. Direct radiation, including both gamma rays and neutrons, was minimized either by distance or by the shielding provided by bunkers or trenches (Goetz et al., 1980). The base surge does not carry radioactive material itself, but it can resuspend radioactive material deposited on the ground by fallout from previous tests.

Most of the exposure* of military personnel was due to fallout, rather than to radiation from the explosion itself. The amount and nature of fallout varied from test to test and were determined largely by the size, weapon design, and altitude of the explosions. At some locations, personnel who were required to enter the target area, either to perform special tasks or as part of group maneuvers, might have been exposed to radioactive fallout, either directly (externally) or through inhalation or ingestion of radioactive dust. The external exposure to fallout would have been to beta or gamma radiation.

A small number of personnel assigned to cloud tracking and sampling had potential for both external and internal exposure to radiation. The aircraft used in cloud tracking required servicing when they returned to their base; the personnel involved in such activities were exposed to the radioactive dust that often accumulated on the leading edges of the aircraft.

Among the largest groups of personnel with a potential for serious exposure were those who boarded the contaminated ships after Shot Baker of the Crossroads series to measure radiation and develop methods of decontamination.

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*In this report, exposure is used in its general dictionary sense, and not as the name of a specific quantity whose unit is the roentgen (see the final section of this chapter).

SOURCES OF EXPOSURE OTHER THAN NUCLEAR TESTS

To gain perspective on the magnitude of the radiation doses being estimated for the nuclear weapons test participants and the uncertainties in these doses, it is important to review other sources of radiation exposure. Everyone is exposed to ionizing radiation of natural origin, including cosmic radiation from outer space, external gamma radiation from terrestrial sources, and radiation from radionuclides in the human body (U.N. General Assembly, 1982; National Research Council, 1980).

Primary cosmic radiation enters the vicinity of the earth isotropically and at a generally constant rate. Cosmic radiation contains extremely-high-energy nuclear particles, but most of the ionization encountered by humans comes from the secondary radiation formed when charged particles of the primary radiation are absorbed by the atomic nuclei of the earth's atmosphere. As a result of this absorption, the cosmic-ray exposure of people living near sea level is less than that of people living at high altitudes. For example, the annual dose at Santa Fe, New Mexico, is more than twice the annual dose at New Orleans, Louisiana. At sea level in the United States, the average dose of cosmic radiation per person is slightly less than 30 mrems/year.

Some radioactive substances are always found in body tissues, most importantly radionuclides of potassium-40 and carbon-14, but also rubidium-87. The average radiation dose per person from substances occurring naturally in the human body is about 25 mrems/year.

Radiation sources outside the human body include uranium, thorium, and potassium, which are distributed throughout the surface of the earth. The average radiation dose per person from external terrestrial sources is about 26 mrems/year, but this value varies widely from place to place, depending on environmental conditions, such as local rocks and soils.

The total radiation dose to most parts of the body from all naturally occurring sources is therefore about 80-100 mrems/year. The lungs often receive considerably larger doses, because of inhalation of the naturally occurring radioactive gas radon and its decay products, whose concentration tends to be higher in the air inside homes than in outdoor air. The higher indoor concentration has recently become more pronounced, because of tighter sealing of buildings. The average dose to the bronchial epithelium has recently been estimated to be 3,000 mrems/year in the United States (NCRP, 1984).

People are also exposed to a number of man-made sources of ionizing radiation; the largest dose comes from medical and dental procedures. The average dose from medical uses of ionizing radiation has been estimated at nearly 100 mrems/year in the United States (National Research Council, 1980). However, not all the population is exposed to this type of radiation, medical procedures rarely lead to irradiation of the whole body, and the dose depends on the procedure. Radiation exposures during medical or dental procedures are not often recorded in the form of individual radiation histories.

It seems intuitively evident that more attention should be given to maximizing the accuracy of estimates of higher doses than to improving the accuracy of lower doses. The higher doses are more likely to cause adverse health effects. Less obvious is how to arrive at a criterion for defining a dose below which less attention is justified. Although any single criterion is necessarily arbitrary unless a threshold for health effects can be demonstrated, it is useful to estimate how much radiation a participant might receive under ordinary circumstances in the years after his exposure at a nuclear test. Suppose that a participant were 20 years old at the time of his participation and lived to age 70. He would accumulate a dose to his whole body of about (50 years)(100 mrems/year) or about 5 rems. Alternatively, a participant at a 1955 test would have accumulated an average of about 5 rems by 1985 from the combination of background radiation and typical medical and dental radiation. Also, 5 rems/year has been the annual average dose permitted during the working lifetime under the recommendations of the International Council on Radiation Protection (ICRP). The ICRP reached this conclusion on the basis of the rationale that the risks from such exposure would be no greater than the risks that exist in industries (e.g., electronics or service industries) that traditionally have enjoyed good safety records.

RADIATION QUANTITIES AND UNITS

Care has been taken to preserve a clear conceptual distinction between the quantities and their units. In 1945, when the first test of a nuclear weapon was conducted, all x-ray and gamma-ray measurements were expressed in units of a quantity related to the ionization produced by these kinds of radiation in a specified mass of air. This quantity, the roentgen (R), was used as a measure of both dose and exposure. To measure the effect on man of ionizing radiation other than x rays or gamma rays, the rep (roentgen equivalent--physical) was used, and later the rem (roentgen equivalent--man), with the understanding that, for photons and beta rays, the numerical value of a given quantity of radiation expressed in reps (later rems) would be approximately the same as that expressed in roentgens. For other types of radiation, such as neutrons, modifying factors (such as the biologic effectiveness of neutrons relative to photons) had to be applied to this numerical value.

The quantities used to measure radiation have changed several times. In the course of its review of various reports, the Committee encountered the terminology that was in vogue during the period of atmospheric nuclear weapons testing. No attempts were made to convert the units of that period to those now in use, because the changes in concepts and terms over the decades would not affect the conclusions drawn by the Committee. Currently accepted concepts and terms can be found in reports of the International Commission on Radiation Units and Measurements (Wyckoff, 1980).

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SOURCES AND RELIABILITY OF INFORMATION ON DOSES FROM EXTERNAL RADIATION

DNA's Nuclear Test Personnel Review (NTPR) is concerned with the identification, processing, and retrieval of an extraordinary amount of information. Approximately 40 summary reports have already been prepared that describe the activities of and the radiation doses received by more than 203,000 service personnel. In the course of preparing these reports, the NTPR located and used several collections of original documents (Defense Nuclear Agency, 1984). The Committee did not attempt to review all the material used by DNA during the NTPR, but, after consultation with DNA and a general review of the available reports and other documents, selected important documents that described the methods used by the NTPR for detailed study. The Committee also had the benefit of several briefings and conferences with personnel of DNA and its contractors and with representatives of veterans organizations. A summary of the procedure was published in the Federal Register and is reproduced in Appendix A. The documents provided to the Committee by DNA are listed in Appendix B.

The work of the Committee was impeded by the lack of an overview report that summarizes the NTPR. Without such a report, it was difficult for the Committee to grasp fully the scope of the NTPR, trace its procedures in detail, and assess the uncertainties associated with dose assignments.

Assignments of external doses were based either on data obtained by personal dosimeters (film badges or pocket ionization chambers) or on reconstructions based on radiation surveys that described the radiation environment over space and time and on knowledge of the movement of people through that environment.

SURVEY INSTRUMENTATION

Assessment of the radiation environment, an important basis for the reconstruction of personnel exposure, relied heavily on the records of survey-instrument readings provided by teams of radiologic monitoring crews. A preliminary report by a DNA contractor (Nelson and Brady, 1984) briefly discussed and summarized important features of the various portable radiation-survey instruments used and included estimates of the accuracies of data gathered by the various instruments and a list of references from which further information may be obtained.

ACCURACY OF SURVEY INSTRUMENTS UNDER LABORATORY AND FIELD CONDITIONS

The uncertainties inherent in survey-meter readings taken under laboratory conditions arise from the dependence of instrument response on photon energy, lack of compatibility of instrument scales between one range and another, statistical fluctuations in relatively weak signals, and high background noise. The accuracy of survey-meter response in the field is not likely to match the accuracy under ideal laboratory conditions, because in the laboratory the orientation of the instruments relative to the radiation source is accurately determined, temperature and atmospheric pressure can be controlled, and the energy characteristics of the radiation source and its intensity are known.

Day (1951) has provided correction factors measured in the laboratory for ionization-chamber and Geiger-counter types of survey meters exposed to x and gamma rays over a wide range of dose rates and spectral qualities. He found the dependence of the survey-meter response on the energy of incident radiation to be particularly pronounced for survey instruments of the Geiger-counter type. On the basis of the assumptions that, for the nuclear tests, the survey meters had been calibrated with x or gamma rays of an energy in the vicinity of 1 MeV and that roughly 10% of the direct and fallout radiation fields consisted of x rays with energies below about 0.2 MeV (Gates and Eisenhauer, 1955; Goetz et al., 1979; Smale, 1981), the uncertainty due to energy dependence of the response would amount to +10% for ionization-chamber survey instruments and +30% for Geiger-counter instruments. The plus sign signifies the tendency of the instrument to overestimate the radiation.

Day (1951) also obtained results from which one can deduce that the incompatibility of the instrument scales at different dose rates could have added an uncertainty of ± 25% to the readings of Geiger-counter instruments and ± 10% to those of ionization-chamber instruments, if no attempt had been made to preadjust the scales. Differences in temperature and barometric pressure between the calibration and the field environments could have added a further uncertainty of ± 20%, and differences in the direction of radiation incidence could have caused a positive bias (readings too high) by 10%, on the basis of assumption that the instruments of the 1950s were capable of meeting present-day requirements (International Electrotechnical Commission, 1972). The uncertainties due to instrument dead time can be considered to have been negligible.

CONCLUSIONS REGARDING SURVEY-INSTRUMENT RECORDS FOR NUCLEAR TESTS

On the basis of the preceding analysis, the Committee estimates the survey-meter readings at nuclear tests to be high by up to 40% for Geiger counters and up to 20% for ionization instruments and to have a total random uncertainty of ± 30% and ± 20%, respectively, for Geiger counters and ionization-chamber instruments (See also appendix C). This error must be considered in addition to the uncertainties in the reconstructed doses for personnel without complete film-badge records, because the uncertainty analysis of the dose reconstruction was based on the assumption that no error was associated with the survey records.

PERSONNEL DOSIMETRY

Film badges were the primary personnel dosimetry instruments used throughout the period of atmospheric testing to provide a permanent record of individual doses of external gamma radiation. Pocket ionization chambers were sometimes used to monitor doses received in the field. These dosimeters, although useful, were less suited to the field environment than were film badges.

Exposure information can be obtained directly from film-badge records to the extent that badges were issued to personnel. Many persons received two or more film badges during their participation in the tests. Others were issued no film badge or were issued a badge for only part of their participation. The radiation dose of some of these persons could be inferred from badges worn by other members of their units. For others, some or all of the dose had to be reconstructed from records compiled from radiation surveys.

USE OF FILM BADGES

Film-badge dosimetry practices for nuclear-test personnel changed considerably over the years. In the early 1950s, badges were issued to only a few members of any group of participants. By the end of the atmospheric testing program in 1962, film badges were being issued to all test personnel.

The dosimetry programs at the various tests were managed by different groups with different technical expertise; the differences in expertise were due in part to improvements in techniques over the years. The Eastman type K film packet, bearing two crossed lead strips, was used mainly at the initial Pacific tests, Operation Crossroads and Operation Sandstone. Optical-density measurements under the lead filter were used for the evaluation of the photon exposures. After 1951, Du Pont type 502 film was used extensively. It is less sensitive than either Eastman type K or Du Pont type 508 film (also used in later tests), according to Nelson and Brady (1984), but does not fog as readily. The Du Pont type 502 film was used first with a cadmium filter and later with a lead filter covering part of the film packet. Evaluation of photon dose was usually based only on readings obtained under the filter area.

A more sophisticated type of film badge that incorporates several filters and was capable of distinguishing roughly between photons of different energies in the presence of beta particles was used for the first time at Operation Plumbbob in 1957.

It should be noted that all the packets contained a less sensitive backup film, sometime capable of measuring radiation doses up to 500 R. This film was intended to be read only if the sensitive film was saturated. It was seldom used, because the doses received were usually low enough to be recorded by the more sensitive film. Calibrations in the field were performed with radium early in the program, and later with cobalt-60.

ACCURACY OF FILM DOSIMETRY UNDER LABORATORY AND FIELD CONDITIONS

Early in the weapons testing program, the National Bureau of Standards (NBS) was asked by the Atomic Energy Commission to undertake laboratory evaluations of the film badges used during the nuclear weapons tests (National Bureau of Standards, 1952, 1958) and to arrange for performance studies of personnel dosimetry services offered by other laboratories, some of which used film badges similar to those used during the nuclear weapons tests (Ehrlich and McLaughlin, 1953). A review of the NBS test results, which are consistent with those of others (Nelson and Brady, 1984), is given in Appendix C.

The NBS tests showed that dose can be overestimated by as much as 40% in the presence of radiation with energy less than about 0.2 MeV (see Table C-1, Appendix C). The extent to which this effect could have introduced a bias at the weapons tests depends on the type of film used, the badge filters, and the gamma-ray spectrum encountered. Assuming that the badges had been calibrated with roughly 1-MeV photons and that only about 10% of the direct and fallout radiation consisted of radiation below about 0.2 MeV in energy (Gates and Eisenhauer, 1955; Goetz et al., 1979; Smale, 1981), the effect would result in an overestimation of dose of 30-40%.

The NBS tests also showed that the uncertainties introduced by variations in film-processing techniques and in the measurement of optical density ranged from about ± 25% for doses above 100 mR to ± 100% in the vicinity of the minimal detectable dose (about 10 mR for Eastman type K film and 30 mR for Du Pont type 502 film) (Table C-2, Appendix C). These results are applicable under laboratory conditions of ambient temperature and relative humidity and for calibrated radiation beams perpendicular to the film-badge surface (Appendix C).

In field use, where the direction of incidence varies, exposure estimates are lower than for perpendicular incidence by an amount that increases with decreasing radiation energy and depends on the atomic number and thickness of the metallic filters over the film surfaces (Herz, 1969). For a given type of radiation, errors in the irradiation of the calibration films developed with the films used in the field can range from ± 5% to ± 20%. Heat and high relative humidity, depending on their range and combination during irradiation and storage, can cause fogging or fading of the undeveloped film, introducing an additional uncertainty estimated as ± 10% for films read daily and ± 30% for films read weekly. The total of these effects could have been the cause of an additional uncertainty of ± 10% to ± 30%, depending on whether the film badges were read daily or weekly.

CONCLUSIONS REGARDING FILM-BADGE DOSIMETRY RECORDS FOR NUCLEAR TESTS

On the basis of the data presented in the preceding section, the Committee concludes that the film-badge exposure estimates have a positive bias that makes them high by up to 40%, because of the energy dependence of the film and an additional random uncertainty of between +110% and -100% for gamma-ray exposures between the minimal detection level and about 100 mR. For higher exposure, above 100 mR, the random uncertainty is about ± 40% and ± 30% for weekly and daily film readout, respectively, in addition to the positive bias of up to 40% (Appendix C).

The use of film badges for beta dosimetry during the period of atmospheric weapons testing was not uniform. At some tests, badges were read only under the metallic filters; therefore, no information was obtained on beta dose. At Operation Sandstone, films were also read in areas outside the filters; however, the readings in these areas were assigned to beta dose, rather than to beta plus gamma dose, which, in the presence of low-energy photons, resulted in a serious overestimation of beta dose (Nelson and Brady, 1984). Thus, film-badge estimates of beta exposure might be nonexistent in some cases or of uncertain quality in others. In this connection, the Committee notes that the dose would be reduced or often eliminated on portions of the body covered by clothing or equipment. The Committee concludes that the absence of reliable film-badge records for beta doses does not represent a serious difficulty, because external beta doses were reduced by clothing.

3

METHODS OF ASSIGNING EXTERNAL DOSES

The methods used by NTPR teams provide an estimate of external dose for each participant. The procedures depend on the information available. Where a complete film-badge record is available, it is used for assigning the gammà dose. When the film-badge record is incomplete, there are two possibilities: a person did not wear a film badge, or the badge record is missing, but was assigned to a group in which some film badges were issued; or no film badges were worn, or no badge records survive, for any of the people in the group to which the person was assigned. If the film-badge record is incomplete, the missing portion of the exposure is estimated by reconstructing the dose or inferring the dose from film-badge records of other participants, as described in Appendix A.

About one-third of the participants had external dose assignments based entirely on film-badge records; about two-third were based on dose reconstructions or a combination of film-badge records and dose reconstruction. A few assignments were based on inference of dose from film-badge records of others (see Table 1).

Assignment of external doses from neutrons or beta radiation is based on dose reconstructions, because they were not recorded by film badges.

ESTIMATES FROM AVAILABLE FILM-BADGE RECORDS

When estimating external doses from film-badge records, it is necessary to determine that the entire period of potential exposure is covered by film-badge records. Troop movement are taken from locations of units and from interviews with participants. This task was complicated by the practice of transferring individuals into or out of units during a test series.

TABLE 1

Methods Used to Assign External Doses of Gamma Radiation

Armed Service	Total Number of Participants[a]	Dose Assignments Based Only on Film Badge Records	Dose Assignments Based on Dose re-Construction and Film-Badge records	Dose Assign-Based on Other Methods
Marine Corps	11,500	3,500	8,700	100
Air Force	26,500	17,300	9,000	1,000
Army	59,000	21,000	39,000	2,400
Navy	107,000	37,400	75,000	6,400
TOTAL	204,250	79,200	131,000	9,900

[a]Dose assignments based on film-badges records, dose reconstructions, and other methods total to more than number of participants, because dose assignments for some participants are based on two methods.

INFERRING DOSE FROM FILM-BADGE RECORDS OF OTHER PARTICIPANTS

For some units, film-badge data were available for most participants. However, film-badge data were missing or incomplete for some members of these units. The NTPR teams used different procedures to assign doses to these participants. The Marine Corps and Army teams favored dose reconstructions, but the Navy and Air Force teams inferred doses from the film-badge data on other members of the unit. Before such extrapolations were performed, the activities of the unit were reviewed to ensure that an unbadged person had the same potential for exposure as members of the unit that were badged. The Navy team assigned the unbadged person the 95th percentile dose for the unit, whereas, the Air Force team assigned the highest recorded dose. Both approaches, although ensuring that a participant was not penalized by lacking missing film-badge data, probably inferred a higher dose than the participant received.

In a few cases (less than 0.1% of film-badge records), the film-badge record was judged to be erroneous. Defective film-badge data can result from moisture caused by mechanical failure of the badge cover, processing errors, or other factors. However, a bias can be introduced each time a reviewer concludes that a badge was defective. Great care must be exercised in this rejection process. The Navy practice of using a three-person board for each dose assignment is commendable and should be considered by other NTPR teams.

ESTIMATES BASED ON DOSE RECONSTRUCTIONS

When film-badge records were missing or incomplete, the estimates had to be made by other means. The basic steps were to estimate the radiation fields over time and space, determine the movements of test participants through radiation field(s), and calculate the dose received for each period. An error analysis was performed for the reconstructed doses. When film-badge data were available, they were compared with the reconstructed doses.

Radiation fields were determined from data on the particular test or series of tests. Prompt radiation was determined by transport equations that used data on the characteristics of the weapon, and atmospheric conditions. Prompt radiation contributed to the dose received by some personnel at the Nevada tests, but not at the Pacific tests, because the personnel were aboard ship several miles from the explosion.

Residual radiation resulted primarily from fallout. Survey-meter data were obtained during the tests, to determine where personnel access should be limited or prohibited. These readings were extrapolated to the areas and times of interest. In the Pacific tests, measurements were made of contaminated seawater and ships. During Nevada tests, residual radiation fields also resulted from neutroninduced activities. Examples of dose reconstructions are shown in Table 2.

Troop movements through the radiation fields were obtained from records of ship and unit movements. Although unit movements were known, detailed movements or actions of individuals were often not recorded. When detailed information was lacking, it was assumed that normal practice, such as routine ship watches, was followed.

The uncertainty of dose reconstructions was analyzed. The analysis considered uncertainties introduced by necessary assumption and uncertainties in the data, such as the time and place of troop movements, decay rate, and extrapolation of survey-meter readings. Uncertainty of the dose reconstructions varies from test to test, depending on the quantity and quality of available data. The uncertainty analysis provides a quantitative estimate of the uncertainties of specific elements of the reconstructions. Although these estimates seem reasonable, the uncertainty within the survey-meter readings (see Table C-6) is not included. Including the uncertainty in survey-meter readings would lead to somewhat higher estimates of uncertainty.

Table 2

Examples of Reconstructions of External Doses

Operation	Date	Dose Reconstruction and Data Used
Pacific Tests:		
Crossroads	1946	Contaminated target ships: survey-meter readings on target ships, time spent on them Contaminated seawater: meter reading of sea water, time spent on deck Hull contamination: contaminated seawater, shielding factor for ship, time spent on deck and below deck
Greenhouse	1958	Contaminated ships: survey-meter reading of fallout on decks of ships, shielding factor for ship, time spent on deck and below deck
Ivy	1952	Contaminated ships: readings on fallout samples collected on 10 ships, shielding factor, time spent on ship
Nevada Tests:		
Upshot-Knothole	1953	Fallout: survey-meter readings, decay factor, troop movements
Plumbbob (Taskforce Warrior)	1957	Prompt radiation, neutrons and gamma: weapon characteristics, radiation transport equations, shielding from trench Fallout field: survey-meter readings, fallout from six shots considered, decay factors for each shot

4

METHODS OF ASSIGNING INTERNAL DOSES

REVIEW OF DOSIMETRY MODELS

The internal deposition of radioactivity is difficult to estimate accurately, even for well-documented exposure conditions. Under the conditions experienced by military participants in nuclear weapons tests, for which there are few relevant measurements, this task is generally impossible. One can often, however, calculate approximate upper limits of potential radiation doses.

Inhalation and ingestion were the most important exposure pathways. Minor deposition by absorption through skin or puncture wounds was also possible, but these pathways are normally important only when people have contact with large quantities of highly radioactive material in soluble forms. The Committee believes that the only routes of notable internal exposure of participants in nuclear weapons tests were inhalation and ingestion.

INHALATION

DNA estimated organ doses of inhaled radioactivity (Lee et al., 1983; Science Applications, Inc. 1983) with currently accepted dosimetry models recommended by the International Commission on Radiological Protection (ICRP, 1979). These calculations begin when that radioactivity enters the body and end with detailed estimates of doses to individual organs. Unfortunately, the extent of detail and specificity in the procedures can obscure the large uncertainties involved in estimating quantities of radionuclides that entered the bodies of test participants 20-40 years earlier. Moreover, no actual measurements of the concentrations of radioactivity in air are available.

Estimates of air concentrations of radioactivity were sometimes based on ambient radiation measurements made with portable survey instruments. In other cases, they were based on film-badge dosimetry measurements by assuming that exposures were to both radioactivity in the air and that falling out on nearby ground surfaces. These methods involve assumptions about relationships between airborn and deposited fallout that are not scientifically valid, and their reliability, even for establishing upper limits of internal radiation doses, is unknown. For example, fallout radioactivity might have been in the form of particles that were too large to be inhaled, as in the heavy fallout exposures of people on Rongerik and Rongelap and on the Japanese fishing boat Lucky Dragon (Eisenbud, 1973). Particles greater than 200 um in diameter are not readily inhaled, but they can have 10^4-10^6 times the radioactivity of a 2 um particle, depending on whether radioactivity is proportional to surface area or mass. Thus, the larger particles could dominate external radiation doses but contribute little to internal organ doses.

In one study, the concentrations of radioactivity to which participants were exposed were estimated from ambient radiation doses (Lee et al., 1983). Particle sizes and terminal settling velocities were estimated from the stabilization height of the mushroom cloud and the time required to arrive at the site of exposure. Particles were estimated to be spheres about 200 um in diameter. Such particles would not cause large radiation doses to the lung, because few of them would be inhaled, they would be deposited high in the respiratory tract, and they would be cleared rapidly by mucociliary action. Most of the large particles cleared from the respiratory tract in this way would be swallowed, causing some exposure to the gastrointestinal tract and possibly resulting in absorption of some radioactive elements.

Despite the assumption that the fallout consisted of spheres having a median diameter of 200 um, a particle diameter of 2.5 um was later used for calculation of internal dose. This is inconsistent and probably resulted in large overestimates of radiation exposures.

The fallout particles near weapons test participants could also have been smaller than estimated. For example, portions of the fallout clouds could have taken indirect paths before reaching the areas of troop maneuvers, thereby providing more than the estimated time for smaller particles to descend. Vertical convective motions, rather than gravitational settling, might also have controlled the deposition of particles and brought small particles down more quickly (and larger ones more slowly) than would be estimated with a fallout model that depended solely on particle size. Both these factors could lead to higher calculated air concentrations of respirable radioactivity than those reported--but, again, this is uncertain.

An additional difficulty in calculating internal doses is that particle solubilities were estimated without any empirical basis. The chemical properties of the particles were assumed to be those used by the ICRP Task Group on Lung Dynamics for pure compounds (ICRP, 1979), which are not representative of the complex chemical mixtures formed in a fallout cloud. For example, the high temperatures might form relatively insoluble particle matrices that could trap more soluble radioactive compounds; this could lead to markedly different doses and organ-dose distribution patterns than those reported.

INGESTION

Radiation exposure by ingestion was largely ignored in the design of monitoring programs when the tests were in progress. For the dose reconstructions, food was assumed to be protected from contamination by fallout, except for minor amounts of radioactivity that might have accumulated while it was exposed to the atmosphere during meals.

Some fallout radionuclides, notably iodine-131, could have been present in food obtained from local sources, such as milk produced in southern Utah. After some weapons tests, especially Shot Harry in 1953, local milk containing several microcuries of iodine per liter might have been consumed at the Nevada Test Site (U.S. Department of Energy, 1983). Recent calculations by the Dose Assessment Advisory Group supported by the DOE indicated that some Utah residents could have received thyroid doses as large as several hundred rems from ingesting iodine in milk. Doses from ingested radiostrontium and other fission products have been estimated by the Dose Assessment Advisory Group to be much smaller than the dose from iodine.

Little attention was paid to measurements of fallout radioiodine in the environment before 1957, partly because instrumentation for convenient measurement had not been developed. Radionuclides transported through food chains might not always be the most important source of exposure by ingestion. Direct ingestion of dust deposited on surfaces can be an important pathway for exposure, probably involving transfer from soiled hands to food, smoking materials, or other objects put into the mouth. This might be important for some adults living under field conditions. Such exposure of military participants in nuclear weapons tests to radioactive fallout probably cannot be measured.

SUMMARY OF ESTIMATED RADIATION EXPOSURES FROM INTERNALLY DEPOSITED RADIONUCLIDES

One NTPR study discussed above focused on internal doses calculated for 23 groups of personnel that seemed to have serious potential for internal deposition of radioactivity (Lee et al., 1983). The 23 groups, chosen to illustrate a variety of exposure conditions, included about 10,000 men among the total of more than 200,000 military participants in the tests. About 6,000 were estimated to have received thyroid doses over 1 rem, but fewer than 500 over 10 rems. The highest estimated thyroid dose was 60 rems; such doses were received by men who were exposed on Rongerik Atoll after Shot Bravo of Operation Castle.

Other organs, such as bone and large intestine, received substantially smaller doses than the thyroid. About 1,500 men might have received gastrointestinal tract doses that exceeded 1 rem, of which 120 exceeded 10 rems. Fewer than 400 men were estimated to have received 50-year bone-dose commitments that exceeded 1 rem, and the highest of these doses was estimated to have been the 5.3 rems received by four men during an excavation operation at the Trinity site.

Of all military personnel, the 28 men who were stationed on Rongerik were exposed to the highest concentrations of fallout. Two independent estimates of the internal-organ doses of these personnel have been made (Lee et al., 1983; Science Applications, Inc., 1983). The first assumed 100% inhalation of fallout particles, whose sizes, as noted earlier, were estimated on the basis of the time of arrival of the fallout and the known height at which the cloud stabilized. The second estimate was based on analyses of fission products and plutonium in urine collected from the exposed personnel. For the reasons given earlier, the Committee believes that dose estimates based on direct estimates of materials inhaled require so many unverifiable assumptions that little credibility can be assigned to them. There are also serious uncertainties in the estimates based on the limited data from urinalysis, but the Committee concludes that greater credibility can be assigned to them. The results of the two methods for estimating dose are compared in Table 4. The two columns of numbers are roughly similar, although estimated doses to the thyroid and lower intestine based on urinalysis are higher than those based on the inhalation model. By both methods of estimation, doses to the other three organs are much lower than those to intestine or thyroid.

TABLE 3

Comparison of 50-Year Organ-Dose Commitments to Personnel Stationed on Rongerik Atoll from Fallout During Operation Castle, Estimated by Environmental Modelling and from Urinalysis

Organ	Estimated Dose, rems	
	Environmental Modeling[a]	Urinalysis Data[b]
Bone	1.4-3.9	0.57-0.76
Lung	1.1-2.1	0.10-0.14
Thyroid	22-59	120-170
Lower large intestine	11-29	35-54
Testes	0.07-0.18	0.29-0.39

[a]Data from Lee et al. (1983)
[b]Data from Science Applications, Inc. (1983)

The amounts of radioactivity inhaled or ingested by military participants in the nuclear tests that took place between 1945 and 1962 cannot now be estimated without bioassay information. Reliable information on how much radioactivity was inhaled or ingested and on its movement to other organs is lacking. Thus, the NTPR dose calculations for internally deposited radioactivity are not considered by the Committee to be scientifically defensible. Whole-body counts and urinalysis can still be done today and used to estimate the magnitudes of exposures to strontium and plutonium and, by inference, to other radionuclides, if these exposures resulted in substantial uptake of fallout radionuclides.

Nonetheless, the important conclusion can be drawn that thyroid doses due to radioiodine absorption were probably the highest internal doses received. Radioiodine results primarily in thyroid exposure, because radioiodine doses to other parts of the body are about 0.1% of that delivered to the thyroid.

MEANS OF VALIDATING INTERNAL-DOSE ESTIMATES

Because of the large uncertainties in estimating internal deposition of radioactivity in nuclear weapons test participants, some dose-model validation is necessary. One available method of direct validation is to measure long-lived radionuclides deposited in bone. For example, ingested or inhaled strontium is absorbed from the blood and deposited in bone; after 20 years, about 12% of the initial deposit remains and is eliminated in urine at a fractional rate of about 2×10^{-4} per day (ICRP, 1973). Current bioassay methods could be used to estimate exposures to strontium that occurred 20 years ago, if the exposures resulted in dose commitments greater than about 1.5-5 rems to bone.

Recent analyses of urine samples from 16 participants in Shot Smoky have shown the mean daily excretion rate of strontium-90 to be 0.63 ± 0.33 (SD) pCi/day (Toohey et al., 1981), which was not different from the excretion rate for seven control subjects (0.66 ± 0.33 pCi of strontium-90 per day). Thus, the servicemen exposed at Smoky excreted no more strontium-90 than control subjects who were exposed to the small amounts of fallout present in the general environment. If the strontium-90 body burdens of the servicemen were 100 nCi or more 20 years ago, evidence of such exposures could be detected by this method. Because the permissible body burden for radiation workers is 2,000 nCi, the method would permit detection of body burdens that were originally only 5% of the current limit. Measurements of plutonium were similarly negative.

The analysis performed by NTPR has neglected important information on internal exposures that is available from studies of at least two groups of nonmilitary personnel heavily exposed to fallout after Shot Bravo of the Castle series. These include 67 Marshallese who were then living on Rongelap and the Japanese fishermen aboard the Lucky Dragon. Published information on the internal contamination of the Rongelap natives and Japanese fishermen indicates that, except for the thyroid, internal doses were smaller than external doses (Conard, 1975; Kumatori et al., 1980). The most dramatic example is that of the 23 Japanese fishermen who lived for 13 days on a boat that was estimated to have been contaminated with fresh (4-hour) fallout at 50 Ci/m^2 (Tajima, 1956). The fishermen received near-lethal doses of external gamma radiation and developed severe beta burns from fallout particles deposited on their skin. They received high doses to the thyroid from absorbed radioiodine, but doses due to absorption of other radionuclides were minor, according to the results of urinalysis and postmortem radiochemical analysis of tissues from one fisherman who died about 6 months after the fallout occurred. Studies of a second fisherman, who died more recently, produced no evidence of increased radionuclide deposition (Kumatori et al., 1980).

Analyses of about 3,000 urine samples collected during Operation Crossroads from personnel with possible internal contamination are also relevant. Stafford Warren, who was responsible for radiation safety during that operation, related that only slight increases in beta activity were observed in these urine samples (Warren, 1946). David Bradley, a physician assigned to the radiologic monitoring group during Operation Crossroads, also referred to these samples in his published diary (Bradley, 1948). His entry on August 20, 1946, 26 days after Shot Baker, stated that the number of urinalyses was approaching the 3,000 mark with "no definite evidence of radioactivity." Every effort should be made to find the original records of these urinalyses. Newer methods of bioassay permit the development of useful upper bounds on the dose commitments from long-lived radionuclides, such as plutonium-238 and strontium-90.

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CONCLUSIONS

The Committee's findings and the opportunities that exist for improving the NTPR program are listed below.

The methods used by the NTPR team to assign external gamma doses are generally reasonable and make appropriate use of available data. They provide a data base and a system of dose assignment that will permit estimating the external doses received by persons who participated in atmospheric tests of nuclear weapons.

A key requirement of the dose assignment procedure is that it be possible for an independent party to understand how any individual dose assignment was produced and to identify readily the assumptions made and the uncertainties in the assigned dose. No summary report describes the procedures used and the unavoidable uncertainties involved in the assumptions made. This made it difficult for the Committee to follow the detailed procedures. To assist others who might wish to review the NTPR procedures in the future, a technical report should be issued that compiles, in summary form, the sources of information and the details of the dose assignment procedures and includes assessments of the overall uncertainty in the dose assignments.

Additional efforts in data retrieval and analysis, although possible, are not likely to improve materially the accuracy or precision of estimated external doses. However, to the extent that additional data retrieval and analysis are deemed necessary, priority should be given to improving the assignments for personnel thought to have received the highest doses. The Committee noted that about 99% of the estimated doses are smaller than the doses received by the personnel from natural and medical sources of ionizing radiation (about 5 rems in 30 years).

Dose assignments based on film-badge data are likely to be more accurate, on the average, than those based on dose reconstructions. Film-badge data have a positive bias of about 45% and a random uncertainty of about ± 100% between the minimal detection level and 100 mR and about ± 40% above 100 mR for gamma radiation exposure.

The external dose from beta radiation was difficult to measure during the period of atmospheric testing, because of limitations in the film badges then in use. The characteristics of beta radiation are such that the dose would be limited to the skin and the dose received by parts of the body covered by clothing would be greatly reduced or eliminated.

Data available from sources of information identified in this report lead the Committee to conclude that persons subjected to heavy fallout exposure sustained internal doses that were much smaller than their external doses, except perhaps for doses to the thyroid. The methods used by the NTPR teams to estimate internal doses are not as well developed or as scientifically defensible as those used to estimate external doses. That is because of the lack of data on amounts of radioactive material inhaled or ingested by test participants. The lack of data places serious constraints on any method of estimating internal doses. However, methods are available that would at least place realistic upper limits on the internal doses received, and the Committee suggests that they be used in selected cases.

Absolute uncertainty in the external dose estimates tends to increase with higher doses, but relative uncertainty is generally greater at smaller doses. High precision should not be attempted at doses below 100 mrems, which is near the limits of instrumental resolution. For example, a 100-mrem dose that had an uncertainty of ± 100% would have the same absolute uncertainty (100 mrems) as a 1,000 mrem dose that has a ± 10% uncertainty. If the assigned doses are used to assess the probability that a given case of disease is causally related to the radiation exposures, the absolute uncertainties, rather than the relative uncertainties, will be most important. Efforts to narrow the uncertainties of the largest dose estimates will be most effective in dealing with this problem. It is more important to know that for a specific person the dose was below a criterion dose, such as 5 rems, rather than achieving great accuracy or precision in estimating such a dose.

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APPENDIX A

DEPARTMENT OF DEFENSE
Defense Nuclear Agency

32 CFR Ch. 1

Guidance for the Determination and Reporting of Nuclear Radiation Dose for DOD Participants in the Atmospheric Nuclear Test Program (1945-1962).

AGENCY: Defense Nuclear Agency, DOD

ACTION: Request for comments on proposed guidelines.

SUMMARY: We propose to establish guidance to DOD components for the determination and reporting of ionizing radiation dose for DOD participants in the atmospheric nuclear test program (1945-1962). These proposals are based upon a review of the existing film badge dosimetry data base and established scientific principles. The methodology by which a film badge dose or an absorbed radiation dose may be established for individual test participants is outlined. The use of individual film badge data as well as records existing for other individuals, radiological surveys, weapons effects data, and modeling techniques based the laws of the physical sciences form the basis of the guidance.

DATES: All written comments in response to this request are welcome and must be received by July 15, 1982 in order to be considered.

ADDRESS: Written comments should be addressed to the Director, Defense Nuclear Agency, ATTN: NTPR, Washington, D.C. 20305.

We will send a copy of the Fact Sheet on the Nuclear Test Personnel Review Program to anyone requesting it. This fact sheet describes the background and scope of the program and some of the findings to date. Please send requests to Col. Thomas J. Haycraft at the address above.

FOR FURTHER INFORMATION CONTACT: Mr. Robert L. Brittigan, Defense Nuclear Agency, ATTN: GC. Washington, D.C. 20305 (Telephone 202-325-7681).

SUPPLEMENTARY INFORMATION:

Authority

On March 26, 1982, the United States District Court for the District of Columbia filed a Memorandum Order in the case of Gott v. Nimmo, Civil Action No. 80-906. The order requires the Defense Nuclear Agency to promulgate "rules which establish methodologies and standards to calculate radiation exposure." A notice of appeal has been duly filed and, in the event the decision of the District Court is reversed, this proposed rule will be withdrawn.

Previous Actions by the Department of Defense

Between 1945 and 1962 the Atomic Energy Commission (AEC) carried out some 235 atmospheric nuclear tests, principally in Nevada and the Pacific Ocean. An estimated 220,000 Department of Defense (DOD) personnel, military and civilian, were involved in this testing, and many were exposed to low levels of ionizing radiation in the performance of various activities. The doses generally were well within established radiation dose limits.

DOD in December 1977 began a program of wide-ranging actions on behalf of the atmospheric nuclear test participants. The Defense Nuclear Agency (DNA) was appointed the DOD Executive Agency for this effort. The Nuclear Test Personnel Review (NTPR) program was established by DNA to carry out these responsibilities.

DOD has made a commitment to Congress to provide the recorded exposure, or to estimate the most probable exposure, for each test participant. The principal issue addressed herein is the method for calculating the nuclear radiation dose for the individual participants.

Radiation Dose Determination

The basic means by which to measure dose from exposure to ionizing radiation is the film badge. Of the estimated 220,000 Department of Defense participants in atmospheric nuclear weapons tests, about 145,000 have film badge dose data available. The records have been converted to a standard format and are being provided to each military service, which can use the film badge dose data to obtain a radiation dose for a particular individual from that service. This is done upon request from the individual, the individual's representative, the Veterans' Administration, or others as authorized by the Privacy Act.

From 1945 through 1954, the DOD and Atomic Energy Commission (AEC) policy was to issue badges only to a portion of the personnel in a homogeneous unit such as a platoon of a battalion combat team, a Naval ship or an aircraft crew. Either one person was badged in a group performing the same function, or only personnel expected to be exposed to radiation were badged. After 1954, the policy was to badge all personnel. But, some badges were unreadable and some records were lost or destroyed, as in the fire at the Federal Records Center in St. Louis. For these reasons the NTPR Program has focused on determining the radiation dose for those personnel (about 75,000) who were not issued film badges or for whom film badge records are not available.

In order to determine the radiation dose to individuals for whom film badge data are not available, alternative approaches are used as circumstances warrant. All approaches require investigation of individual or group activities and their relationship to the radiological environment.

First, if it is apparent that personnel were not present in the radiological environment and had no other potential for exposure, then their dose is zero. Second, if some members of a group had film badge readings and others did not--and if all members had a common relationship with the radiological environment--then doses for unbadged personnel can be calculated. Third, where sufficient badge readings or a common relationship to the radiological environment does not exist, dose reconstruction is performed. This involves correlating a unit's or individual's detailed activities with the quantitatively determined radiological environment.

The three approaches are described as follows: A. Activities of an individual or his unit are researched for the period of participation in an atmospheric nuclear test. Unit locations and movements are related to areas of radiation. If personnel were far distant from the nuclear detonations(s), did not experience fallout or enter a fallout area, and did not come in contact with radioactive samples or contaminated objects, they were judged to have received no dose.

B. Film badge data from badged personnel may be used to estimate individual doses for unbadged personnel. First, a group of participants must be identified that have certain common characteristics and a similar potential for exposure to radiation. Such characteristics are: individuals must be doing the same kind of work, referred to as activity, and all members of the group must have a common relationship to the radiological environment in terms of time, location or other factors. Identification of these groups is based upon research of historical records, technical reports or correspondence. A military unit may consist of several groups or several units may comprise a single group.

Using proven statistical methods, the badge data for each group is examined to determine if it adequately reflects the entire group, is valid for use in statistical calculations, or if the badge data indicate the group should be subdivided into smaller groups.

For a group that meets the tests described above, the mean dose, variance and confidence limits are determined. An estimated dose equal to 95% probability that the actual exposure did not exceed the estimate is assigned to unbadged personnel. This procedure is statistically sound and will insure that unbadged personnel are assigned doses much higher than the average/mean for the group.

C. Dose reconstruction is performed if film badge data are unavailable for all or part of the period of radiation exposure, if film badge data are partially available but cannot be used statistically for calculations, special activities are indicated for specific individuals, or if other types of radiation exposures are indicated. In dose reconstruction, the conditions of exposure are reconstructed analytically to arrive at a radiation dose. Such reconstruction is not a new concept; it is standard scientific practice used by health physicists when the circumstances of a radiation exposure require investigation. The underlying method is in each case the same. The radiation environment is characterized in time and space, as are the activities and geometrical position of the individual. Thus, the rate at which radiation is accrued is determined throughout the time of exposure, from which the total dose is integrated. An uncertainty analysis of the reconstruction provides a calculated mean dose with confidence limits. The specific method used in a dose reconstruction depends on what type of data are available to provide the required characterizations as well as the nature of the radiation environment. The radiation environment is not limited to the gamma radiation that would have been measured by a film badge, but also includes neutron radiation for personnel sufficiently close to a nuclear detonation, as well as beta and alpha radiation (internally) for personnel whose activities indicate the possibility of inhalation or ingestion of radioactive particles.

The first approach in subparagraph A above is straightforward; the second in subparagraph B uses standard statistical procedures; the third approach in subparagraph C is discussed in more detail in the section titled, Dose Reconstruction Methodology.

General Procedures

The following procedures govern the approach taken in dose determination:

a. Use individual film badge data where available and complete.

b. Identify group activities and locations for period(s) of possible exposure.

c. Qualitatively assess the radiation environment in order to delineate contaminated areas. If no activities occurred in these areas, and if no other potential for exposure exists, a no-dose-received estimate is made.

d. If partial film badge data are available, define group(s) of personnel with common activities and relationships to radiation environment.

e. Using standard statistical methods, verify from the distribution of film badge readings whether the badged sample adequately represents the intended group.

f. Calculate the mean dose with variance and confidence limits, for each unbadged population. Assign a dose equal to 95% probability the actual exposure did not exceed the assigned dose.

g. If badge data is not available for a statistical calculation, conduct a dose reconstruction.

h. For dose reconstruction, define radiation environment through use of all available scientific data, e.g., measurements of radiation intensity, decay, radioisotopic composition.

i. Quantitatively relate activities, shielding, position, and other factors to radiation environment as a function of time. Integrate dose throughout period of exposure.

j. Where possible, calculate mean dose with confidence limits; otherwise calculate best estimate dose or, if data are too sparse, upper limit dose.

k. Compare calculations with available film records to verify the calculated doses.

l. Where identified as a contribution to total dose, calculate initial or internal radiation dose.

Dose Reconstruction Methodology

A. Concept

The specific methodology consists of the characterization of the radiation environments to which participants, through all relevant activities, were exposed. The environments, both initial and residual radiation, are correlated with the activities of participants to determine accured doses due to initial radiation, residual radiation and/or inhaled/ingested radioactive material, as warranted by the radiation environment and the specific personnel activities. (5,6) Due to the range of activities, times, geometries, shielding, and weapon characteristics, as well as the normal spread in the available data pertaining to the radiation environment, an uncertainty analysis is performed. This analysis quantifies the uncertainties due to time/space variations, group size, and available data. Due to the large amounts of data, an automated (computer-assisted) procedure is often used to facilitate the data-handling and the dose integration, and to investigate the sensitivity to variations in the parameters used. The results of the calculations are then compared with film badge data as they apply to the specific period of the film badges and to the comparable activities of the exposed personnel, in order to validate the procedure and to identify personnel activities that could have led to a typical doses. Radiation dose from neutrons and dose commitments due to inhaled or ingested radioactive material are not detected by film badges. (5,6) Where required, these values are calculated and recorded separately.

B. Characterization of the Radiological Environment

This step describes and defines the radiological conditions as a function of time for all locations of concern, that is, where personnel were positioned or where personnel activities took place. The radiation environment is divided into the two standard categories--initial radiation and residual radiation.

The initial radiation environment results from several types of gamma and neutron emissions. Prompt neutrons and gamma radiation are emitted at the time of detonation, while delayed neutrons and fission-product gamma, from the decay of radioactive products in the fireball, continue to be emitted as the fireball rises. In contrast to these essentially point sources of radiation, there is gamma radiation from neutron interactions with air and soil, generated within a fraction of a second. (8) Because of the complexity of these radiation sources and their varied interaction properties with air and soil, it is necessary to obtain solutions of the Boltzmann radiation transport equation. (9) The radiation environment thus derived includes the effects of shot-specific parameters such as weapon type and yield, neutron and gamma output, source and target geometry, and atmospheric conditions. The calculated neutron and gamma radiation environments are checked for consistency with existing measured data, as available. In those few cases displaying significant discrepancies that cannot be resolved, an environment based on extrapolation of the data is used if it leads to a larger calculated dose. (7)

The residual radiation environment is divided into two general components--neutron-activated material that subsequently emits, over a period of time, beta and gamma radiation; and radioactive debris from the fission reaction or from unfissioned materials that emit alpha, beta, and gamma radiation. (8) Because residual radiation decays, the characterization of the residual environment is defined by the radiation intensity as a function of type and time. Radiological survey data are used to determine specific intensities at times of personnel exposure. Interpolation and extrapolation are based on known decay characteristics of the individual materials that comprise the residual contamination. (5,7) In those rare cases where insufficient radiation data exist to adequately define the residual environment, source data are obtained from the appropriate weapon design laboratory and applied in standard radiation transport codes (10,11,12) to determine the initial radiation at specific distances from the burst. This radiation, together with material composition and characteristics, leads to a description of the neutron-activated field from each location and time of interest. In all cases, observed data, as obtained at the time of the operation, are used to calibrate the calculations.

C. Activities of Participants

This step uses official historical records, augmented by personal interviews where gaps exist, to depict a scenario of activities for each individual or definable group. For military units, whose operations were closely controlled, the scenario is usually well defined. The same is true for observers, (7) who were restricted to specific locations both during and after the nuclear bursts. Ships' locations and activities are usually known with a high degree of precision from deck logs. Aircraft tracks and altitudes are also usually well defined. Personnel engaged in scientific experiments often kept logs of their activities; moreover, the locations of their experiments are usually a matter of record. Where the records are insufficiently complete for the degree of precision required to determine radiation exposure, participant's comments are used and reasonable judgements are made to further the analysis (13). Possible variations in the activities, as well as possible individual deviations from group activities, with respect to both time and location, are considered in the uncertainty analysis of the radiation dose calculations.

D. Calculation of Dose

The initial radiation doses to close-in personnel (who were normally positioned in trenches at the time of detonation) are calculated from the above-ground environment by simulating the radiation transport into the trenches. Various calculational approaches, (10,14) standard in health physics, are employed to relate in-trench to above-trench doses for each source of radiation. Detailed modeling of the human body, in appropriate postures in the trench, is performed to calculate the gamma dose that would have been recorded on a film badge and the maximum neutron dose. (15) The neutron, neutron-generated gamma, and prompt gamma doses are accrued during such a short time interval that the posture in a trench could not be altered significantly during the exposure. The fission-product gamma dose, however, is delivered over a period of many seconds. (5) Therefore, the possibility of individual reorientation (e.g., standing up) in the trench is considered. (7,15)

The calculation of the dose from residual radiation follows from the characterized radiation environment and personnel activities. Because radiation intensities are calculated for a field (i.e., in two spatial dimensions) and in time, the radiation intensity is determinable for each increment of personnel activity regardless of direction or at what time. (5,7) The dose from exposure to a radiation field is obtained by summing the contribution (product of intensity and time) to dose at each step. The dose calculated from the radiation field does not reflect the shielding of the film badge afforded by the human body. This shielding has been determined for pertinent body positions by the solution of radiation transport equations as applied to a radiation field. (5) Conversion factors are used to arrive at a calculated film badge dose, which not only facilitates comparison with film badge data, but serves as a substitute for an unavailable film badge reading.

The calculation of the dose from inhaled or ingested radioactivity primarily involves the determination of what radioisotopes entered the body in what quantity. Published conversion factors (17,18) are then applied to these data to arrive at the radiation dose and future dose commitments to internal organs. Inhalation or ingestion of radioactive material is calculated from the radioactive environment and the processes of making these materials inhalable or ingestible. Activities and processes that cause material to become airborne (such as wind, decontamination or traffic) are used with empirical data (19,20) on particle lofting to determine airborne concentrations under specific circumstances. Volumetric breathing rates and durations of exposure are used to calculate the total material intake. Data on time-dependent weapon debris isotopic composition and the above-mentioned conversion factors are used to calculate the dose commitment to the body and to specific body organs. (6,22)

E. Uncertainty Analysis

Because of the uncertainties associated with the radiological data or calculations used in the absence of data, as well as the uncertainties with respect to personnel activities, confidence limits are determined where possible for group dose calculations. The uncertainty analysis quantifies the errors in available data or in the model used in the absence of data. Confidence limits are based on the uncertainty of all relevant input parameters, and thus vary with the quality of the input data. They also consider the possible range of doses due to the size of the exposure group being examined. Typical sources of error include orientation of the weapons, specific weapon yields, instrument error, fallout intensity data, time(s) at which data were obtained, fallout decay rate, route of personnel movements, and arrival/stay times for specific activities. (5,7)

F. Comparison with Film Badge Records

Calculations of gamma dose were compared with film badge records for two military units at Operations PLUMBBOB to initially validate this methodology.

Where all parameters relating to radiation exposure were identified, direct comparison of gamma dose calculations with actual film badge readings was possible. Resultant correlations provided high confidence in the methodology. (5,6)

Film badge data may, in some cases, be unrepresentative of the total exposure of a given individual or group; nevertheless, they are extremely useful for direct comparison of incremental doses for specific periods, e.g., validating the calculations for the remaining, unbadged period of exposure. Moreover, a wide distribution of film badge data often leads to more definitive personnel grouping for dose calculations and to further investigation of the reason(s) for such distributions. (5) In all cases, personnel film badge data are not used in the dose calculations, but rather are used solely for comparison with and validation of the calculations. For dose reconstruction accomplished to date, comparison has been favorable and within the confidence limits of the calculations. (5,6)

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Dated: May 17, 1982.
M. S. Healy,
OSD, Federal Register Liaison Officer,
Department of Defense.

APPENDIX B

DOCUMENTS PROVIDED BY DNA THAT DESCRIBE METHODS OF ASSIGNING DOSES TO MILITARY PERSONNEL*

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*The documents listed in this appendix are available for review at the Defense Nuclear Agency, Washington, D.C. 20305 or the Civilian Information Center, Department of Energy, Nevada Operations Office, Las Vegas, Nevada. In addition, a series of volumes describing the atmospheric testing program has been distributed to over 700 locations (public libraries, VA regional centers, etc.).

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APPENDIX C

AN EVALUATION OF THE QUALITY OF FILM-BADGE DOSIMETRY PRACTICES AT ATMOSPHERIC NUCLEAR TESTS

To obtain information on the quality of film-badge dosimetry at tests of nuclear weapons, the National Bureau of Standards (NBS), under contract to the Atomic Energy Commission, studied under laboratory conditions two of the film dosimeters used in the field. NBS was the logical agency to conduct such a study, because it maintained (and still maintains) the U.S. primary standards for x-ray and gamma-ray exposure.

One set of studies (NBS, 1952) determined the energy dependence of the Eastman type K film badge and later of Du Pont type 502 film. Heavily filtered x-ray beams and cobalt-60 gamma radiation were used as sources of radiation. Photon incidence was essentially perpendicular to the film badge. Table C-1 summarizes the results of these measurements.

Table C-2 shows the results of an analysis of the uncertainties in the interpretation of small exposures--uncertainties due solely to variability in photographic procedures. The results bear out the estimates of uncertainty given by others (Nelson and Brady, 1984).

Tables C-3 and C-4 show performance in the laboratory of two of the dosimeters used during atmospheric nuclear tests, both incorporating Du Pont type 502 film as the more sensitive element. Dosimeter performance was tested by having the groups that developed the dosimeters send batches of them to NBS, where the badges were irradiated over a wide range of photon energies and magnitudes of exposure. NBS then returned the irradiated dosimeters for processing and evaluation.

Table C-3 shows the results of such a performance test of the cadmium-shield dosimeters developed and used by the Los Alamos Scientific Laboratory. Because the dosimeters were exposed only to photons, the evaluation could rely

TABLE C-1

Changes in Sensitivity with Photon Energy for Sensitive Component of Personnel Dosimeters Used Most Frequently During Military Operations at Early Atmospheric Nuclear Tests[a]

Eastman Film Type K[b]

Approximate Effective Energy, MeV	Relative Sensitivity[a]	
	Under 0.72 mm of lead ("lead cross")	Without Lead
0.03	1.3	5.5
0.07	1.2	5.1
0.12	1.4	3.0
0.17	1.5	1.4
0.21	1.2	1.2
0.50	1.0	0.9
0.80	1.0	1.0

[b] Data from Day (1948).

Du Pont Film Type 502

Approximate Effective Energy, MeV	Relative Sensitivity[a]	
	Under 1 mm of Cadmium[c]	Under 0.72 mm of Lead[d]
0.04	Not available	Near zero
0.07	1.25	1.22
0.12	1.95	0.99
0.17	1.25	1.02
0.21	0.98	0.94
1.25	1.00	1.00

[a]Sensitivities shown were computed relative to sensitivity obtained with highest effective photon energy used.
[b]Data from Day (1948).
[c]Data from Ehrlich (1952a).
[d]Data from Ehrlich (1952b).

TABLE C-2

Uncertainty in Exposure Interpretation at Low Exposure Levels Due Solely to Variability in Photographic Processing and Densitometry Evaluation Procedures

	Eastman Film Type K[a]	Du Pont Film Type[b]
Type of Radiation Used	Filtered Bremsstrahlung 1.4 MeV Exciting Potential	Cobalt-60 Gamma Radiation (1.25 MeV)
Limits in reproducibility of densitometer readout of optical density (D)	D = ± 0.01 corresponding to ± 5 mR	D = ± 0.01 corresponding to ± 20 mR
Variation of optical density (D) over film area	Not available, but probably similar to that for Du Pont film type 502	D = 0.02 - 0.03
Resulting uncertainty in exposure interpretation at low levels	10 mR ± 10 mR 50 mR ± 10 mR	30 mR ± 30 mR 50 mR ± 30 mR

[a]Data from National Bureau of Standards (1948).
[b]Data from National Bureau of Standards (1952).

TABLE C-3

Objective Performance Test
Los Alamos Scientific Laboratory, 1953[a]

Dose		Energy	
Actual	Reported	Actual MeV	Reported keV
2.00	1.80	0.21	200
0.030	0.050	1.25	-
0.100	0.110	1.125	200
0.100	0.150	0.21	200
0.500	0.440	1.25	200
4.00	Appr. 5.00	0.07	200
0.030	0.050	0.21	-
0	0.050	--	-
0.990	0.150	0.04, 0.21,1.25	50
0.500	0.400	1.25	200
0.100	0.100	1.25	200
0.100	0.170	0.21	200
8.00	6.60	1.25	200
2.00	1.70	1.25	200
0.990	0.150	0.04,0.21,1.25	50
2.00	1.80	0.21	200
0.030	0.050	1.25	-
0.030	0.070	0.21	200
2.00	1.60	1.25	-
0.030	0.050	0.07	100
0.500	0.900	0.07	150
8.00	Appr. 5.00	0.07	200
0.500	0.900	0.07	150
0.030	0.050	0.07	100

[a]Data from Ehrlich and McLaughlin (1953). Identity revealed with permission of Los Alamos National Laboratory.

TABLE C-4

Objective Performance Tests, Lexington Signal Depot, 1958:
Value of Dose in Roentgens

Complete Results for the Period March through August 1958

March		April		May		June		July		August	
Assigned by NBS	Reported	Assigned by NBS	Reported	Assigned by NBS	Reported	Assigned by NBS	Reported	Assigned by NBS	Reported	Assigned by NBS	Reported
					1.25 MeV						
0.300	0.275	0.050	0.090	1.50	1.50	0.005	0	0.200	0.345	2.07	2.20
0.050	0.045	0.005	0.045	0.100	0.100	0.010	0.002			0.200	0.300
				0.020	0.020					0.005	0
					0.07–0.2 MeV						
0.120	0.115	0.540	0.745	0.020	0.020	0.010	0.004	0.060	0.100	0.020	0.020
3.04	3.00	0.034	0.037	0.020	0.020	0.010	0			0.200	0.200
		0.054	0.100	1.50	1.50	0.005	0.003			0.010	0.020
		0.680	0.620	0.100	0.100	0.010	0.013				
						0.005	0				
						0.005	0				
					0.04 MeV						
0.360	0.600	0.005	0.045	0.100	0.200	0.005	0.009	0.020	0.020	0.020	0.020
0.061	0.070	0.200	0.400	0.020	0.035	0.010	0.002			0.005	0.006
		0.010	0.050	1.50	2.50					0.010	0.010
										0.020	0.023
					Mixed Energies						
0.361	0.090	—	—	0.400	0.525	—	--	--	--	--	--
				0.400	0.500						

Results for High Exposures for September 1958 through February 1959

1.25 MeV		0.02 to 0.2 MeV		Mixed Energies	
Assigned by NBS	Reported	Assigned by NBS	Reported	Assigned by NBS	Reported
11	15.0	15	14.9	15	19.6
38	30.0	15	36.8		

[a]Data from Ehrlich (1982). Identity revealed with permission of U.S. Army Ionizing Radiation Dosimetry Center, Lexington, Ky.

in part on an energy discrimination based on the optical density in the area under the cadmium filter, compared with the density in the uncovered area--a procedure that would not have been possible in field use, because of the presence of beta particles.

Additional data on dosimeter performance are shown in Table C-4. They were obtained in 1958 from an NBS cooperative study in which the Lexington Blue Grass Depot (now the U.S. Army Ionizing Radiation Dosimetry Center) participated (NBS, 1958). For this study, the Lexington laboratory used an improved multifilter badge that was developed for nuclear tests and used initially during Operation Plumbbob in 1957. This badge permits some energy discrimination in the presence of beta particles.

All these results were obtained for laboratory irradiations with radiation essentially perpendicular to the film badges. In field use, where angles of incidence vary, exposure estimates would be lower than those for perpendicular incidence by an amount that increases with decreasing radiation energy and depends on the atomic number and thickness of the metallic filters over the film surfaces (Herz, 1969).

The uncertainties introduced by energy dependence of the film, photographic processing, temperature and relative humidity, and direction of radiation incidence are summarized in Table C-5.

The data in Table C-5 show that film-badge readings have a bias to read higher than the "true" value by 45%, and if the dose is above 100 mR, have a random uncertainty of $\pm$ 30% of the "true" value when read daily. The result of these uncertainties is that 90 of 100 badges exposed to 1.0 R would be expected to read between 1.15 R and 1.75 R. Results of a similar analysis of the uncertainty of survey-meter readings are shown in Table C-6.

Table C-5

Estimated Uncertainties in Field Measurements with Film Badges

Item	Estimated systematic uncertainty (bias) in assigned dose[a]	Estimated Random Uncertainty: Dose between minimal detection level and 100 mR	Estimated Random Uncertainty: Dose greater than 100 mR
Film calibration (with radium or cobalt-60)	--	± 20%	+ 5%
Photographic process (development, densitometry)	--	± 100%	± 25%
Difference between x and gamma ray during calibration and in the field	+ 35%		
Difference between temperature and relative humidity during film calibration and storage and during field use	--	Read out daily, ± 10% Read out weekly, ± 30%	Read out daily, ± 10% Read out weekly, ±30%
Difference between direction of radiation incidence during calibration and in the field	+ 10%	--	--
Total (rounded)[b]	+ 45%	Read out daily, ± 100% Read out weekly, + 110% - 100%	Read out daily, ± 30% Read out weekly, ± 40

[a]Plus sign signifies positive bias, i.e., tendency to overestimate dose.
[b]Individual random uncertainties were combined in quadrature; individual systematic uncertainties were added algebraically.

Table C-6

Estimated Uncertainties in Field Measurements with Survey Instruments

Cause of Uncertainty	Estimated Systematic Uncertainty		Estimated Random Uncertainty (Bias)[a]	
	Geiger Counters	Ionization[b] Chambers	Geiger Counters	Ionization[c] Chambers
Difference between calibration and field spectrum	+ 30%	+ 10%	--	--
Incompatibility of instrument scales[c]	--	--	± 25%	± 10%
Differences in temperature and barometric pressure during calibration and in field	--	--	± 20%	± 20%
Differences in direction of radiation incidence during calibration and in field	+ 10%	+ 10%	--	--
Total (rounded)[d]	+ 40%	+ 20%	± 30%	± 20

[a]Plus sign signifies positive bias, i.e., tendency to overestimate dose.
[b]Because they are less sensitive, ionization-chamber instruments can be used only for dose rates greater than 5 mR/h. Navy used ionization-chamber instruments more often than Geiger counters.
[c]Applicable only when scales are not preadjusted.
[d]Individual random uncertainties were combined in quadrature; individual systematic uncertainties were added algebraically.

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