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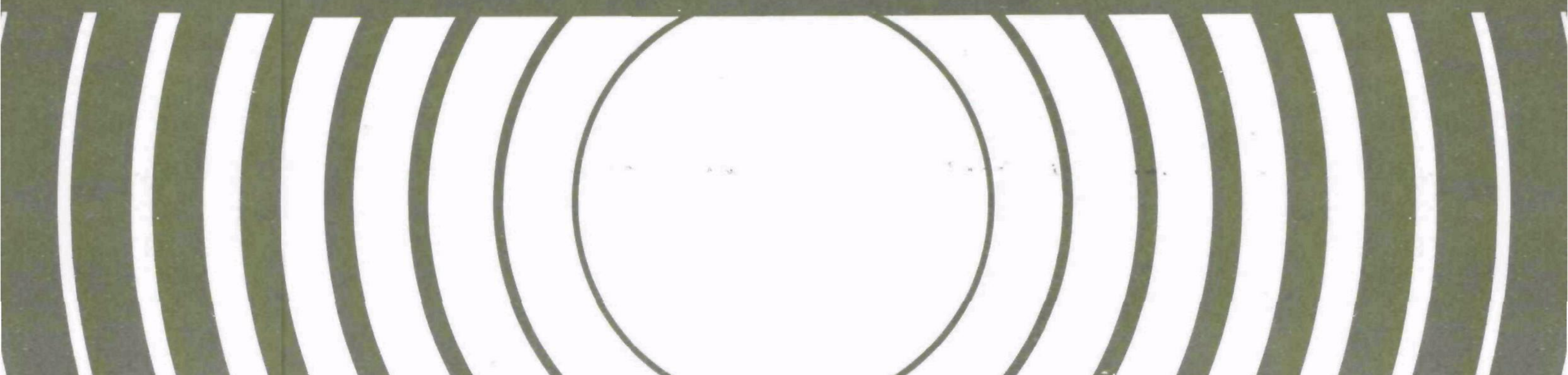
Occupational Exposure to Ionizing Radiation in the United States

A Comprehensive Review for the Year 1980 and a Summary of Trends for the Years 1960 -1985



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OCCUPATIONAL EXPOSURE TO IONIZING RADIATION IN THE UNITED STATES

A Comprehensive Review for the Year 1980 and a Summary of Trends for the Years 1960-1985

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September 1984

Office of Radiation Programs
U.S. Environmental Protection Agency
Washington, D.C. 20460

FOREWORD

The Environmental Protection Agency carries out a continuing program to evaluate exposure of the public to radiation, to recommend radiation protection guidance for the use of Federal agencies, to promulgate environmental radiation standards and regulations, and to advise the States on radiation protection matters, so as to protect public health and to assure environmental quality. The Agency's responsibility for radiation protection guidance to Federal agencies is derived from Executive Order 10831 and Public Law 68-373 (42 USC 2021(h)), which charge the Administrator of EPA to "...advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States." This study was carried out in support of that responsibility.

The number of workers exposed to ionizing radiation has increased significantly since Federal radiation protection guidance for occupational exposure was first issued in 1960. This report is the second of its kind; it provides a comprehensive review of exposure of workers for the year 1980 and a summary overview of trends for the period 1960-1985.

We acknowledge with particular gratitude the support of Shigeru Kumazawa, Senior Scientist, by the Japan Atomic Energy Research Institute and the Japanese Government during the years 1982 and 1983. This support enabled his invaluable contributions, which encompassed the major portion of the analyses contained in this report.

We would like to be informed of any errors or omissions in this report and of additional sources of information. Comments and suggestions for improvements in future reports are also welcomed. These should be addressed to Allan C.B. Richardson, Chief, Guides and Criteria Branch (ANR-460), Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, D.C. 20460.

Sheldon Meyers

Sheldon Meyers, Acting Director
Office of Radiation Programs

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SUMMARY

Occupational exposure to ionizing radiation in the United States for 1980 and for the period 1960-1980 may be summarized as follows:

1980

About 1.32 million U.S. workers were potentially exposed to ionizing radiation. About half of these workers received measurable doses that were distinguishable from normal background radiation. About 44% of all workers were employed in medicine, 23% in industry, 16% in government, and 11% in the nuclear fuel cycle.

The mean annual dose was 0.11 rem for all workers, with 15% exceeding this dose. About 6%, 2%, and 0.1% of all workers received doses greater than 0.5, 1.5, and 5 rems, respectively. The mean dose was 0.23 rem for all *measurably* exposed workers, with 20% of these exceeding this dose. Of all workers measurably exposed, those at nuclear power reactors received the highest mean dose - 0.65 rem.

The mean dose to all male workers (0.16 rem) was more than triple that to all female workers (0.05 rem). The median ages of male and female workers were 33 and 28, respectively.

The collective dose for all workers was about 150,000 person-rems. About 65% of this collective dose was incurred by the 5% of workers that received between 0.5 and 5 rems. About 70%, 40%, and 5% of this collective dose was incurred by workers with doses greater than 0.5, 1.5, and 5 rems, respectively. Workers in the nuclear fuel cycle

accounted for the largest share of the collective dose (37%), followed closely by those in medicine (27%) and industry (25%).

About 55% of all potentially exposed workers were male; these workers received 80% of the total collective dose. Seventy-five percent of the collective dose to women was to workers in medicine and 55% was to women less than 30 years old.

The mean cumulative dose for workers terminated during the period 1969-1982 was estimated to be on the order of one rem. Maximum cumulative doses for workers terminated during this period were estimated to be about 100 rems.

1960-1980 Summary of Trends

The number of potentially exposed workers in the United States was about one-half million in 1960 and has doubled every 14 or 15 years since that time. Expressed differently, while the mean annual growth rates of the labor force and the U.S. population were 2% and 1.2%, respectively, that of potentially exposed workers was about 5% during that period.

The mean annual dose to potentially exposed workers decreased by almost a factor of 2 between 1960 and 1980. It decreased by about 0.03 rem every 5 years between 1965 and 1975, but has decreased at a slower rate since 1975. The fraction of workers receiving less than the mean annual dose has remained constant at about 85%.

The collective dose to U.S. workers fluctuated around 120,000 person-rems between 1965 and 1975 and increased to about 150,000 person-rems between 1975 and 1980.

Since 1960, the distribution of doses above 1 rem has changed substantially, with a large decrease in the fraction of workers approaching or exceeding 5 rems. Since 1965, the absolute number of workers exceeding 3 rems has decreased, while the number exceeding 1 rem has increased, and the number exceeding 2 rems has remained relatively constant.

The fraction of collective dose due to workers exposed above 1.5 rems has decreased from 53% in 1965 to 40% in 1980; for doses above 5 rems, this fraction has decreased from 31% in 1965 to 5% in 1980.

Since 1970 the growth rate of collective dose was greatest for the nuclear fuel cycle. However, efforts to avoid exposures greater than 5 rems have resulted in the fraction of collective dose above 5 rems to be second smallest among the major categories of workers; only government workers have done better.

I. INTRODUCTION

Occupational exposure to ionizing radiation in the United States is governed by regulations established by a wide variety of Federal and State agencies. To assure uniform protection of workers, these regulations are governed by a single set of guides, called Radiation Protection Guidance for Federal Agencies, which is issued by the President (see Appendix G).

This system was established in 1959 by President Eisenhower through creation of the Federal Radiation Council (FRC), whose function it was to make recommendations to the President regarding radiation protection. In 1960 the FRC recommended the first Federal guidance for occupational exposure to ionizing radiation (FRC60a). That guidance has been the basis for all subsequent Federal and State regulations limiting occupational exposure to such radiation. In 1970, President Nixon created the U.S. Environmental Protection Agency (EPA) through a reorganization of Federal agencies (Reorganization Plan No. 3 of 1970), and in so doing abolished the FRC and transferred its functions to EPA. EPA proposed revisions to Federal occupational guidance in 1981; however, at the time this report was prepared those recommendations were still pending (EPA81).

Early estimates of the numbers of U.S. workers and their doses from exposure to ionizing radiation were made by the FRC when it developed the 1960 Federal occupational guidance (FRC60b). Those estimates were limited to workers exposed in medical applications of x rays, in industrial radiography, and in Atomic Energy Commission facilities. In 1972, EPA published somewhat more extensive estimates of exposure to workers (K172). In 1974, we began a review of Federal guidance for limiting occupational exposure. As part of that review, we published in 1980 our first comprehensive analysis of occupational exposure in the United States (Co80). That summary covered exposures for the year 1975 and, in addition to previously assessed groups of workers, also included estimates for groups of workers for which government agencies do not maintain records.

In the present report we have updated the 1975 analysis to 1980. In addition, we have examined historical trends in the number and exposure of workers during the 20-year period from 1960, when the first Federal occupational guidance was promulgated, to 1980, and have made projections for the year 1985.

We have tried to include all persons who are potentially exposed to ionizing radiation at their work places. Unfortunately, there is no simple index of information, such as a Bureau of Labor Statistics Standard Industrial Classification (SIC) code, that identifies such workers. Although we have not attempted to formulate an explicit definition of workers "potentially exposed to ionizing radiation," we have included essentially all groups of workers known to be associated with significant sources of ionizing radiation.

As noted above, radiation protection in the United States is administered by a number of Federal and State authorities. Although this arrangement has functioned effectively to limit the exposure of workers, no centralized system has been established to maintain exposure records for workers. As a result, our assessment of exposure of workers has depended upon data from a variety of sources. We have relied upon both complete and incomplete monitoring records to characterize various groups of workers. Because of the differences in these data, we have had to use, in many instances, modeling of numbers of workers and their exposure distributions to provide reliable and consistent results. We use the term model in the broad sense to mean a system of postulates, data, and inferences used to mathematically estimate numbers and doses of groups of workers. The details of our approaches to this modeling are given in the appendices to this report.

Our review of occupational exposure has also included an historical analysis. The current patterns of occupational exposure have resulted from many influences, including changes in the types and utilization of sources of ionizing radiation, and the evolving practice of radiation protection as governed by limits provided by Federal occupational radiation protection guidance and Federal and State regulations, and recommendations of organizations such as the International Commission on Radiological Protection and the National Council on Radiation Protection and Measurements. However, recent influences, such as greatly increased attention to maintenance of exposures as low as reasonably achievable (ALARA), shortness of supply of workers in some occupations, increased awareness of radiation risks, and changing perceptions of the acceptability of occupational risks, have also played important roles. Recent studies of occupational exposure have examined some of these factors (As81; Bro83a,83b; Dr81; EPRI81; Ma81; UNSCEAR82).

To interpret occupational exposure data correctly, one must consider why workers are monitored. From a regulatory point of view, monitoring data usually result from efforts to minimize dose accumulation or to demonstrate compliance with dose limits for individuals. Since conservative (upper bound) values can suffice to simply show compliance, some data may provide overly conservative values of dose to workers. However, all Federal and State regulations now require realistic measurement of exposure of workers entering certain areas or likely to exceed certain (usually fairly low) doses. In addition, workers exposed at very low levels often are monitored only because of the simplicity of badging all workers in a facility or of the need to assure workers that they receive little or no exposure. As a result, the representativeness of monitoring data for workers with low exposure may vary because of differences in monitoring practices.

The interpretation of historical monitoring data is also affected by changes in the sensitivity and calibration of radiation dosimeters. The increased sensitivity of today's dosimeters allows detection of doses near background, in cases where previously no dose would have been reported. Uncertainties in calibration, especially for data obtained many years ago, lead to uncertainty in doses reported. There have been few requirements for adherence to dosimetry performance standards in the United States. The National Sanitation Foundation adopted a standard for film badge services in 1966 (NSF66) that only a few States (Illinois, Montana, and New York) required dosimetry services to satisfy before offering services in those States. However, recent approval by the American National Standards Institute of a standard for testing personnel dosimetry performance has had wide support (ANSI83) and should improve the reliability of personnel monitoring records. Although that standard is presently voluntary, the NRC has recently proposed its adoption as a regulatory requirement (NRC84). Only broad interpretations of historical exposure records can be made without examining these factors. We have not attempted to correct for such factors for this report.

Finally, other factors, such as the type of radiation measured and placement of dosimeters, can be significant. Our data base for occupational exposure of U.S. workers consists of reported personnel dosimeter readings, and we present the results of our analysis in terms of the same unit - the dose equivalent - that is assigned to these dosimeter readings. Dosimeter readings reflect worker exposure to various types and levels of ionizing radiation. However, although dosimeters may respond reproducibly to exposure of the dosimeter at its location on the worker, they may not necessarily provide accurate estimates of the dose to the worker. There are two principal sources of uncertainty: 1) the energy response of the dosimeter and 2) the source-to-dosimeter-to-worker geometry. Current dosimeters can provide adequate measurements of dose from x rays and gamma rays over an energy range from about 50 keV to a few MeV. When the exposure of workers involves large components of low-energy scattered radiation, such as for diagnostic medical x rays, appropriate calibration of dosimeters is necessary to obtain accurate estimates of the dose to the whole body. In addition, dosimeters are generally calibrated with unidirectional fields, even though actual exposures may involve a much different geometry of exposure due to the spatial relationship between the source and the worker. However, although large errors can be made in estimating doses to individuals (ANSI83; Ch78a,78b; ICRP82; ICRU76; NCRP78), we believe that the characteristic values obtained for large groups of workers are much less subject to the errors expected for specific individuals. An exception may be groups of workers exposed to predominately low energy radiation. In summary, it is important to recognize that this report deals with reported dosimeter readings, which may or may not accurately reflect actual doses to workers. Throughout this report, we use the terms "exposure" and "dose" to mean the values obtained as dosimeter readings.

One further aspect of the data used in this study is that the records we used to estimate "annual" exposures include the exposures of all workers, regardless of what fraction of the year they worked and were monitored. Such an analysis accurately represents the exposure of workers for that year. This was the objective of our study, and these results can be directly compared with those in national and international reports. However, the mean doses estimated in this report are smaller than would be estimated for workers who worked and were monitored for a full year. Our results should not be used, therefore, to infer the annual exposure of full-time employment in any of the categories or subcategories of work examined. Rather, they represent the average over all full- and part-time workers. We made a cursory examination of the difference to be expected between our results and exposure of full-time workers by examining a limited sample of 1980 dosimetry data. The mean doses for full-time workers range from 0-50 percent higher than those for all workers for the several groups examined. The results of this limited survey are given in Appendix C.

We have estimated, for the period 1960-1980, the number of workers potentially exposed to radiation and the distribution of their doses for five major categories of workers: those in medicine, industry, the nuclear fuel cycle, government, and miscellaneous occupations (education and transportation). From these distributions the mean dose, collective dose, and collective dose distribution for all workers were derived. We have also similarly examined smaller subcategories of workers when it was feasible.

Doses to workers were characterized according to age and sex for 1975 and 1980 from a large sample of commercial dosimetry data. These data provided the basis for estimating the age distributions for both male and female workers as well as their dose and collective dose distributions as a function of age.

We were particularly interested in examining dose distributions and historical trends to assess the effect of efforts to achieve exposures that are below regulatory limits and as low as reasonably achievable (ALARA). For this purpose, we fitted the hybrid lognormal distribution model (HLN model) to exposure data. These investigations are discussed in Chapter V.

Our methods for estimating the numbers of workers and their exposures are believed to be better than those used in our earlier study; that is, the values in this report should be more reliable and consistent. This is principally due to improved models for estimating the numbers of workers and the distribution of annual doses to various kinds of workers. We examined estimates of numbers of workers and dose distributions, for various levels of aggregation of workers, using several statistical methods and, where possible, compared the results of these estimation methods. We have the most confidence in our estimates for specific types of workers for which government agencies require or maintain comprehensive personnel dosimetry records. However, we made estimates for all significant categories of workers, even when there was a paucity of data. Similarly, projections of worker dose distributions and collective dose distributions by age and sex were based on data of variable completeness and accuracy.

Several groups of individuals, including students, visitors to DOE facilities, underground miners, and flight crews and attendants on passenger aircraft, are summarized separately in this report because of the nature of their job, exposure, or their uncertain status as workers. There are also a few identified groups of exposed workers not included in this study. One group consists of some Federal, and most State and local regulatory personnel. Dose records for some of these workers, such as NRC inspectors of commercial nuclear power stations, are included in the exposure data for those stations. Other inspectors, such as those for MSHA, OSHA, and State programs were not assessed in this report. There are also some groups of workers in some mineral extraction industries who are exposed to low levels of radiation and are generally not monitored. One example is the phosphate industry where, for a few workers, maximum doses have been estimated to range from 10 to 300 millirem (mrem) per year (EPA76). The above workers will be considered in further detail in future studies.

In addition, relatively few workers are monitored for internal exposure. These data are not normally reported to Federal or State agencies unless an overexposure has occurred. Because of its scarcity, internal exposure data are not presented or analyzed in this report. There are also insufficient data to generate a complete national summary of exposure of extremities (hands and feet). However, commercial extremity data are analyzed in Appendix C to obtain a rough measure of such exposure.

With these qualifications, we believe that this report on occupational exposure of workers to ionizing radiation in the United States provides a comprehensive and reliable summary for the year 1980 and overview for the years 1960 to 1985.

II. BACKGROUND FOR THE ASSESSMENT OF 1980 OCCUPATIONAL EXPOSURE

A. General Background

1. Types of Radiation Exposure

From a regulatory point of view, worker exposure to external or internal sources of radiation is generally examined for compliance against the whole body, partial body (including organs), and extremity radiation protection guides prescribed by Federal guidance (see Appendix G). External irradiation of the whole body is by far the most common type of exposure; it is primarily this type of exposure from x-ray, gamma-ray, and neutron sources that is assessed in this report.

Internal exposure occurs when radioactive material is inhaled, ingested, or absorbed into the body. Such material may concentrate in specific organs or tissues. Compared to external exposure, relatively few workers are exposed to or monitored for internal exposure. In addition, except for uranium miners, such monitoring data are currently not normally reported, and therefore available for analysis, unless an overexposure occurs. A special case of internal exposure is provided by exposure of miners to inhaled radon decay products. We separately summarize these data for underground miners in Chapter IV; these data are further discussed in Appendix C.

Extremity exposures are exposures of the forearms and hands, or lower legs and feet, almost invariably from an external radiation source. These exposures typically occur when the extremities are close to radioactive sources while the torso and head are shielded by a barrier or protected by distance. A crude national summary of extremity exposure based on our sample of commercial dosimetry data is given in Appendix C.

2. Sources of Exposure

Sources of occupational exposure include: naturally-occurring radioactive materials (including "source materials"* - uranium and thorium); "special nuclear materials"* (plutonium, uranium-233, and enriched uranium); radioactive "byproduct materials"* (radionuclides produced as a result of the fission of special nuclear materials); accelerator-produced radioactive materials; and electronic devices that emit ionizing radiation (e.g., x rays, electrons, protons, and neutrons).

Occupational exposure from source materials occurs principally in uranium mining and milling operations of the nuclear fuel cycle. The handling, fabrication, and use of special nuclear materials lead to exposure of workers in nuclear fuel cycle and nuclear weapons operations.

Radioactive byproduct materials are those yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear materials. They include activation products from nuclear reactors and plutonium-beryllium neutron sources, but not from other neutron sources, such as californium-252 or accelerators. Exposure to byproduct sources of radiation is the principal source of exposure in nuclear power reactor operations, but also occurs in practically every other major group of workers considered in this report. Only dental, chiropractic, and uranium mine and

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*Terminology for these radioactive materials is as defined in the Atomic Energy Act of 1954, as amended.

milling workers are not likely to receive exposure from such sources. Byproduct sources are used extensively for diagnostic and therapeutic purposes in medicine. Major industrial uses include well logging, nondestructive testing, tracer techniques, thickness gauging, and industrial radiography.

Naturally-occurring radioactive materials are of either primordial or cosmic ray origin. Naturally-occurring carbon-14 and tritium originate from cosmic rays, while potassium-40, radon-222, and radium-226 are examples of primordial materials, as are source materials. Occupational exposure from primordial materials occurs primarily as a result of such technological activities of man as mining. In addition to the mining operation itself, the milling of uranium and phosphate ores, for example, produces waste tailings that are sources of radiation exposure. The extraction and use of radium in medicine and for luminous dials led to significant occupational exposure in the past, but now leads to very little.

Electronically-produced radiation means radiation produced by equipment when it is electrically energized (e.g., by x-ray machines, electron microscopes, and particle accelerators). Examples are x rays, electrons, and protons. Some of these sources are widely used in medical and industrial applications. Accelerator-produced radioactive materials, such as technetium-99, are produced in increasing quantities for use in medical and research applications. Even though occupational exposures from these sources are controlled by shielding and/or on-off procedures, such exposures lead to the majority of doses for many medical and industrial workers.

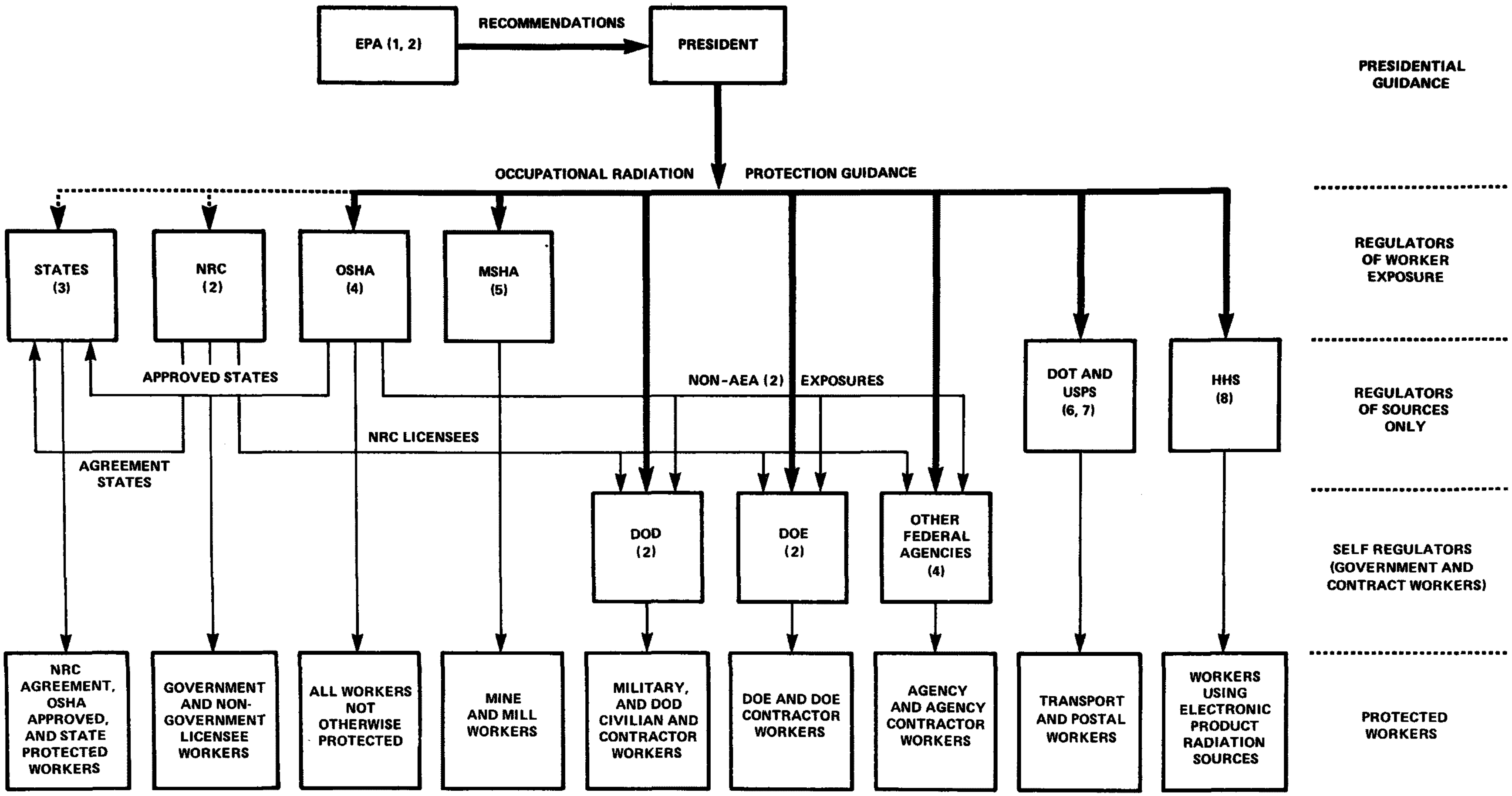
3. Personnel Monitoring

Personnel dosimeters commonly used to monitor exposure to penetrating radiation include radiation sensitive emulsions (film badges), thermoluminescent dosimeters (TLDs), and nuclear track detectors. TLDs are small, reusable plastic chips that are readily processed. Film badges are small and also provide a permanent record, but are not reusable nor as readily processed. Nuclear track detectors, which are used for monitoring some neutron exposures, are not reusable and are more difficult to process.

Dosimeters are generally capable of providing reasonably accurate measurements of dose to workers for radiations of known energy and for known irradiation geometries. For example, recent performance testing of U.S. processors of TLD and film badge dosimeters in a pilot study demonstrated fairly good (and improving) performance under ideal test conditions (NRC80). Dosimeter performance was tested for high- and low-energy photon, beta, and neutron radiations. For tests that were made in 1978, 78% of individual dosimeter readings deviated from the correct value by less than 50%; for tests made in 1982, 89% deviated less than 50%. The mean deviations of all dosimeter readings from the correct values in these tests were 24% in 1978 and 19% in 1982. Compared to these general results, commercial data used in this study exhibited significantly better average performance (a mean deviation of about 6% in 1982). We note that these mean deviations are small compared to other uncertainties associated with interpretations of the significance of occupational doses, such as prediction of the risk to health associated with a given dose. Further details of the above performance tests of dosimeters are given in Appendix C.

B. Regulatory Authorities and Standards in 1980

No single agency regulates the exposure of workers in the United States. This responsibility is carried out by five Federal regulatory agencies with direct jurisdiction over exposure of workers or sources of radiation exposure, by many Federal agencies who govern exposure of their own (or their contractors') employees, and by various agencies of the fifty States (Figure 1). Some State agencies regulate exposure of



(1) Executive Order 10831.
(2) Atomic Energy Act of 1954, as amended.
(3) State enabling legislation and State laws.
(4) Occupational Safety & Health Act of 1970.
(5) Federal Mine Safety & Health Act of 1977, as amended.
(6) Department of Transportation Act of 1974.
(7) Postal Reorganization Act of 1970.
(8) Radiation Control for Health & Safety Act of 1968.

━━ Federal Radiation Protection Guidance
── Regulations

Figure 1. Authorities for radiation protection of U.S. workers.

workers according to agreements with two of the Federal regulatory agencies, and some regulate independently. In this section we identify the government agencies, their major legislative authorities, the sources of radiation covered, and exposure standards and regulations as they existed in 1980 (Table 1). As noted earlier, these various sets of standards and regulations are each governed by Federal Radiation Protection Guidance and are therefore essentially similar in their net effect on worker exposure.

1. Federal Authorities

The Atomic Energy Act of 1954, as amended, provides for Federal control of three types of radioactive material: 1) source material; 2) special nuclear material; and 3) byproduct material. This authority was originally administered by the former Atomic Energy Commission (AEC). The Energy Reorganization Act of 1974 transferred regulatory authority for nonfederal use of these materials from the former AEC to the Nuclear Regulatory Commission (NRC).

The NRC licenses all users of significant quantities of special nuclear material, except for military applications by the Departments of Defense and Energy. About half of the States have agreements with the NRC (in 1980 there were twenty-six such "Agreement States") that give them limited authority to license users of source or byproduct materials. Such users in the remaining States are licensed directly by the NRC. All NRC licensees are governed by the occupational exposure regulations contained in Title 10, Part 20, of the Code of Federal Regulations (10 CFR 20). NRC Agreement States are required to have regulations comparable to those at 10 CFR 20.

Some special nuclear material operations at former AEC facilities need no NRC license. The Energy Reorganization Act of 1974 transferred regulatory authority over the AEC's research laboratories and other

Table 1. Major statutes and regulations pertaining to occupational exposure of workers to radiation

Agency	Legislative authority	Sources of radiation	Regulations
FEDERAL GUIDANCE			
Environmental Protection Agency	Executive Order 10831 and Atomic Energy Act of 1954, as amended, through the Reorganization Plan No. 3 of 1970	All	Federal Radiation Protection Guidance
REGULATORS OF COMMERCIAL WORKERS' EXPOSURE			
State Radiation Control Programs	State enabling legislation	All	SSRCR Part D(a)
Nuclear Regulatory Commission and their Agreement States	Atomic Energy Act of 1954, as amended	Source, special nuclear, and byproduct materials	10 CFR 20
Department of Labor			
Occupational Safety & Health Admin. and their approved States	Occupational Safety & Health Act of 1970	Electronic devices, NARM(b)	29 CFR 1910.96
Mine Safety & Health Administration	Federal Mine Safety & Health Act of 1977	Naturally-occurring radioactive materials(c)	30 CFR 57.5-37 to 47
REGULATORS OF SOURCES ONLY			
Department of Transportation	Department of Transportation Act of 1974	Source, special nuclear, and byproduct materials; and NARM(b)	49 CFR 108-109 and 174-177
U.S. Postal Service	18 USC 1716(a),(b) and 39 USC 401(2), 3001	Radioactive material(c)	Postal Publication 6
Department of Health & Human Services	Radiation Control for Health & Safety Act of 1968	Electronic devices	21 CFR 1020
SELF REGULATORS (GOVERNMENT AND CONTRACTOR WORKERS)			
Department of Energy	Atomic Energy Act of 1954, as amended	All	DOE 5480.1A
Department of Defense	Atomic Energy Act of 1954, as amended	All	DOD Instruc. No. 6055.8
Other Federal Agencies	Occupational Safety & Health Act of 1970	All	Various

(a) State Suggested Regulations for Control of Radiation, or a close equivalent, in most cases (HHS83).

(b) Natural and accelerator-produced radioactive materials.

(c) "Radioactive Material," means "any material having a specific activity greater than 0.002 microcuries per gram" (49 CFR 173.403(y)).

facilities to the Energy Research and Development Administration, which in 1977 became the Department of Energy (DOE). Contractors who operate DOE laboratories and facilities are exempt from NRC requirements when they use special nuclear materials to develop weapons or reactors for military vehicles or vessels. The DOE has its own internal regulations that govern such occupational exposure (DOE81).

The Department of Defense (DOD) is also exempt from NRC licensing requirements when it uses special nuclear materials for weapons or propulsion. The Army, Navy, and Air Force have developed their own regulations for occupational exposure consistent with uniform DOD instructions (DOD83).

The Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173) assigned to the Department of Interior (DOI) regulatory authority over occupational safety and health protection in all mines and mills except over radiation protection in NRC-licensed uranium mills. That DOI jurisdiction covered exposure to gamma rays and radon decay products in all mines and mills (except NRC-licensed uranium mills). However, the Federal Mine Safety and Health Act of 1977 (Public Law 95-164) amended the 1969 Act to establish the Mine Safety and Health Administration (MSHA), to transfer safety and health functions of DOI to the Department of Labor (DOL), and to extend regulatory authority to uranium mills. The MSHA and the NRC have a memorandum of understanding that governs their mutual regulatory responsibilities (MSHA79). The applicable occupational exposure regulations remain those specified at 30 CFR 57.

The Occupational Safety and Health Act of 1970 established broad authority for the regulation of occupational exposure by the Occupational Safety and Health Administration (OSHA) of the DOL. This authority applies to all occupational exposure of workers except that regulated by the NRC or MSHA. Federal agencies must establish programs that are consistent with OSHA standards. The OSHA also approves "State

Plans" under which State authorities may regulate occupational exposure. Twenty-two States had approved State Plans in 1980; eleven of those were also NRC Agreement States. An OSHA-approved State Plan must contain standards that are as effective as OSHA standards. The OSHA's occupational exposure regulations are specified at 29 CFR 1910.96.

2. State Authorities

As noted above, most States operate under NRC agreements and/or OSHA-approved State Plans. In general, Federal standards prevail unless the States' are more protective.

As a uniform guide for formulating regulations, many States use the "Suggested State Regulations for Control of Radiation" (SSRCR). These are prepared by the Conference of Radiation Control Program Directors with support from the EPA, the Department of Health and Human Services (HHS), and the NRC. Part D of the SSRCR contains standards for radiation protection of workers that are equivalent to those at 10 CFR 20.

3. Indirect Regulatory Authorities

The Department of Health and Human Services and the U.S. Postal Service have no direct authority for regulating exposure of workers, but indirectly affect occupational exposure through other regulations. The Department of Transportation also indirectly regulates worker exposure.

The Secretary of HHS has authority under the Radiation Control for Health and Safety Act of 1968 to regulate the manufacture of electronic radiation-generating devices to assure their safe performance. The Center for Devices and Radiological Health (CDRH) (formerly the Bureau of Radiological Health) of HSS issues regulations (21 CFR 1020) that limit radiation leakage from electronic source components and assemblies.

The Department of Transportation (DOT) indirectly regulates occupational exposure through its packaging, storage, and carriage regulations for radioactive materials. The DOT has authority under the Department of Transportation Act of 1974 to regulate, except for postal shipments, the interstate transport of all radioactive materials, including source, special nuclear, and byproduct materials (49 CFR Part 174-177). In addition, the Federal Aviation Administration (FAA) of the DOT regulates holders of FAA operating certificates for passenger operations who use x-ray systems for inspecting carry-on articles. These regulations require the certificate holder to use x-ray machines that meet the performance standards at 21 CFR 1020.40 or guidelines published by the FDA (38 FR 21442; August 8, 1973). Operators of these x-ray systems are required to receive training in radiation safety and to be monitored in accordance with regulations at 49 CFR 108.17 and 49 CFR 129.26 for domestic and international travel operations, respectively.

The U.S. Postal Service indirectly affects occupational exposure through limitations on the type and quantity of radioactive material that can be shipped in the U.S. mail. Postal shipments are covered by regulations in Postal Service Publication 6, "Radioactive Materials," September 1983; Domestic Mail Manual (124.37) and Publication 52 incorporate brief summaries of these regulations.

4. Radiation Protection Standards

Federal Radiation Protection Guidance (25 FR 4402; May 18, 1960) specifies the numerical doses or exposures which Federal agencies should not normally allow to be exceeded. These are called Radiation Protection Guides (RPGs). In addition, the guidance specifies that Federal agencies should make every effort to encourage maintenance of radiation doses "...as far below these guides as practicable," (this is commonly rephrased as "as low as reasonably achievable," or ALARA). The RPG for occupational exposure of the whole body permits doses up to 3 rems per quarter (or 12 rems per year) within an overall cumulative limit of 5(N-18) rems, where N is the age of the worker (see Appendix G for the entire set of RPG values). NRC regulations conform to this guidance. DOE and DOD regulations are more strict; they limit exposure of the whole body to 5 rems per year. OSHA regulations are comparable to those of the NRC, but do not require that doses be maintained ALARA. MSHA regulations require that no person in underground mines receive an exposure to radon decay products in excess of the RPG for such exposure (4 working level months in any calendar year; see Appendix G), and that annual individual gamma radiation exposure not exceed 5 rems. DOT and U.S. Postal Service regulations are designed to keep the maximum annual exposure below the RPG for whole-body exposure of the general public (500 millirems) for most situations, because the general public, as well as workers, can be exposed. Major specific regulations for each Agency are cited in Table 1.

C. Summary of Monitoring and Reporting Requirements

All radiation protection regulations containing numerical limits for worker exposure also contain requirements for personnel monitoring. These are typically equivalent to the NRC regulation (10 CFR 20.202) which requires monitoring of any individual who enters a restricted area and is likely to receive a whole-body dose in any calendar quarter of more than 312.5 millirems (i.e., 25% of 1.25 rems) or who enters locations defined as high radiation areas. Personnel monitoring is optional for workers likely to receive a lower dose, and actual practice in such situations varies widely.

Reporting requirements for monitored exposures exist for only some workers. That is, even when monitoring is required, the data are not necessarily reported or otherwise available. The NRC, for example, requires annual monitoring reports for four types of licensees where the generally highest exposures occur. On the other hand, the OSHA has no requirement for reporting radiation exposures unless its standards are exceeded.

The NRC requires an annual report of personnel monitoring from four categories of licensees: commercial nuclear power reactors; industrial radiographers; fuel processors, fabricators, and reprocessors; and manufacturers and distributors of specified quantities of byproduct material (10 CFR 20.407). This report must include a statistical summary of doses to individuals for whom personnel monitoring was either required or voluntarily provided during the calendar year. The NRC summarizes these data in annual occupational radiation exposure reports. In 1978, the NRC initiated a special two-year study for the years 1978 and 1979 during which <u>all</u> licensees were required to provide the above described statistical summaries of occupational exposure information (43 FR 44827; Sept. 29, 1978). Results from these summaries have been used in this report (Bro81,82).

MSHA monitoring, recordkeeping, and reporting requirements for gamma radiation and radon decay products in underground mines are listed at 30 CFR 57. Gamma radiation surveys are required in all underground mines where radioactive ores are mined. Dosimeters are required for all persons exposed and cumulative records are required when the average gamma radiation level exceeds 2.0 milliroentgens per hour.

The MSHA requires an initial measurement of radon decay products in the exhaust air of all mines. In uranium mines, if levels in excess of 0.1 Working Level* (WL) are found, levels are determined every one or every two weeks at random times in all active working areas, depending upon whether they are in excess of or less than 0.3 WL, respectively. Where uranium is not mined, the required frequency is once every three

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*"Working level" (WL) means any combination of the short-lived radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy. Exposure to these decay products over a period of time is expressed in terms of "working level months" (WLM). Inhalation of air containing a radon-decay-product concentration of 1 WL for a working month (173 hours) is defined as an exposure of 1 WLM.

months for levels between 0.1 and 0.3 WL and once every week for levels in excess of 0.3 WL.

Mine operators are required to measure radon decay product levels and to estimate and record individual exposures of all mine personnel working underground wherever uranium is mined. Where uranium is not mined, recordkeeping is required only for concentrations of radon decay products in excess of 0.3 WL. (Once recordkeeping has commenced for nonuranium miners, individual estimates may be discontinued below 0.3 WL, provided that a miner has not accumulated more than one-twelfth of a WLM times the number of months worked in that calendar year.) Mine operators report required data for all personnel annually.

The DOE requires personnel monitoring where the potential exists for a worker to receive a dose or dose commitment in any calendar quarter in excess of 10 percent of the quarterly regulation (e.g., 3 rems for the whole body). Contractors provide monitoring data that the DOE summarizes in an annual report on radiation exposure of DOE and DOE contractor employees (DOE76-82).

The DOD's personnel monitoring requirements parallel those of the DOE. The DOD also maintains permanent exposure records, but most exposure data are not published. However, the Naval Nuclear Propulsion Program, which monitors radiation exposures to Navy and civilian personnel from Naval nuclear propulsion plants and their support facilities, publishes comprehensive exposure information annually (Ri82, Sc83).

All States have personnel monitoring requirements. The NRC Agreement and/or the OSHA-approved Plan States, numbering 37, have requirements that workers likely to exceed twenty-five percent of 1.25 rems per quarter be monitored. In 1980, the remaining 13 States also required monitoring of persons within controlled or restricted areas or of persons routinely exposed. South Dakota (except for dental workers) and Illinois require monitoring of all persons routinely exposed to radiation, but this can be discontinued if monitoring shows exposures are less than about 25% of the limits. Only Illinois, of all the States, requires reporting of dose records for all individuals who are monitored.

III. DATA SOURCES AND ANALYSIS METHODS

In determining the occupational exposure of U.S. workers, we analyzed data of varying degrees of completeness. For some groups of workers within or regulated by Federal agencies, nearly complete data exist for both the numbers of workers and their exposures. For other groups of workers we used models to interpret the available data and to estimate these quantities. This chapter provides a general description of data used to assess occupational exposure in 1980 and the methods used to analyze these data. Appendix A contains more detailed information on the methods used to estimate the numbers of potentially exposed workers. Appendix B contains more detailed information on data used to determine the exposure of these workers.

A. Categories of Workers

We have grouped workers into five major categories: medicine, industry, the nuclear fuel cycle, government, and miscellaneous (Table 2). These groups are further subdivided, where possible, into more detailed occupational subcategories which range from specific professional groups to entire industrial sectors. For example, the data available permitted characterization of workers in dentistry, private medical practice, hospitals, veterinary medicine, chiropractic medicine, and podiatry as separate subcategories of medical workers. However, we could subdivide workers in industry into only one specific subcategory (industrial radiography) and two broad subcategories (manufacturing and distribution of radiation sources, and other industrial users of radiation sources).

Table 2. Description of occupational categories and subcategories

Category/Subcategory	Description
MEDICINE	Nonfederal occupations involving medical diagnostic or therapeutic use of naturally-occurring, byproduct, and accelerator-produced radioactive materials, and/or electronic sources of ionizing radiation.
Dentistry	Dentists, dental hygienists, and dental assistants.
Private Practice	Physicians, nurses, technologists, etc., in private or group/clinic practices (generally privately owned).
Hospital	Physicians, nurses, technologists, and medical physicists at nonfederal hospitals (military and Veterans Administration hospitals are included in Government category).
Veterinary Medicine	Veterinarians and assistants.
Chiropractic Medicine	Chiropractors and assistants.
Podiatry	Podiatrists and assistants.
INDUSTRY	Occupations that entail exposure from radionuclide and electronic sources in industry and private enterprise other than the practice of medical sciences.
Industrial Radiography	Nuclear Regulatory Commission (NRC), NRC Agreement State Licensee, and industrial x-ray radiographers.
Manufacturing and Distribution of Radiation Sources	Occupations associated with the manufacture, delivery, or installation of brachytherapy, radiopharmaceutical, and electronic sources of radiation.
Other Industrial Users of Radiation Sources	Other users of radionuclide and electronic sources for purposes such as nondestructive testing, well-logging, and thickness gauging.
NUCLEAR FUEL CYCLE	All nuclear fuel cycle occupations except uranium mining.
Nuclear Power Reactors	Maintenance, refueling, inspection, and reactor operations.
Fuel Fabrication and Reprocessing	Processing, fabrication, and reprocessing of reactor fuels.
Uranium Enrichment	Uranium enrichment activities at DOE contractor-operated facilities.

Table 2. Description of occupational categories and subcategories (Continued)

Category/Subcategory	Description
NUCLEAR FUEL CYCLE (Continued)	
Nuclear Waste Management	Low-level waste disposal. Nongovernment disposal operations only: includes removal, transportation, storage, or burial of byproduct wastes.
Uranium Mills	NRC-licensed uranium mills.
GOVERNMENT	Occupations involving exposure to ionizing radiation of government and nongovernment workers in government operations. Includes government-owned and contractor-operated, Veterans Administration and military medical, and Civil Defense facilities.
Department of Defense	Medical, special nuclear material and Nuclear Navy (ships and shipyards) operations.
Department of Energy	Department of Energy (DOE) and DOE-contractor operations.
Other Federal Government	Veterans Administration, National Institutes of Health, National Aeronautics and Space Administration, National Bureau of Standards, and Public Health Service*.
MISCELLANEOUS	Occupations involving radiation exposure in education and transportation.
Education	Faculty and staff involved with radiation sources at colleges, universities, technical schools, and community colleges.
Transportation	Personnel involved in freightage of radioactive materials and in airline baggage checks.
ADDITIONAL GROUPS	
Underground Miners	Underground miners exposed to radon decay products and gamma radiation.
Visitors (DOE)	Visitors to DOE facilities.
Students	Students exposed while attending classes and/or performing research work.
Flight Crews and Attendants	Flight crews and attendants on passenger airlines.

*Workers in various agencies and facilities covered by the Public Health Service Personnel Monitoring Program (see Table D-6 for details).

Unfortunately, the above choice of major categories, which was dictated by the nature of exposure data available for this study, does not provide a clean separation of some types of workers. The government category, for example, contains workers that could have been placed in other categories. First, this category contains both government employees and employees of private contractors operating government-owned facilities. Roughly 40% of the workers in this category (primarily DOE and Navy contractor operations) are not government employees. Second, some workers in this category work in defined occupational subcategories of other major categories, such as those in dentistry, veterinary medicine, and industrial radiography. In all, roughly 35% of workers in the government category work in medical occupations. In addition, some Federal regulatory and most State and local regulatory workers are not assessed in this study, as noted in the introduction. We estimated there were roughly 5 to 10 thousand such workers with mean doses on the order of 40 mrem. The detailed occupational characterization of Federal, State, and local workers in government was not pursued in this analysis, but is a topic clearly worthy of future study.

B. Assessment of the Number of Workers

Except for the Veterans Administration, Federal agencies provided comprehensive summary statistical data on the number of persons monitored and their exposures. These data covered not only workers in government and contractor facilities, but also workers in the nuclear fuel cycle. We have assumed that these numbers of monitored workers represent the number of potentially exposed workers in occupations or facilities where Federal agencies compiled such summaries of exposure records. Therefore, we did not need to use models to estimate the numbers of such workers in 1980, except for workers in the Veterans Administration, for which complete exposure records or summaries were not available. The numbers of workers in medicine, industry, and miscellaneous occupations had to be estimated from various sources of information. We summarize our methods for these three categories below.

1. Medicine

Workers in medicine were subdivided into those in dentistry, private medical practice, hospitals, veterinary medicine, chiropractic medicine, and podiatry. To estimate the numbers of these workers we used the correlation of the number of workers with the number of radiation sources or with the number of professionals within the medical specialty, as appropriate. Some workers in hospitals may be exposed to ionizing radiation from both electronic and radionuclide sources. We have no information on the numbers of such workers or the relative contributions to dose from these sources. Therefore, we avoided the use of correlations with sources as a primary basis for estimating numbers of workers in hospitals.

Dental workers comprise the largest subcategory of workers in medicine. Unfortunately, there is no recent study or data base available for deriving the numbers of various types of dental workers (i.e., dentists, dental assistants, and dental hygienists) that are potentially exposed to radiation. We found that use of data on the number of potenally exposed workers per dental facility (or per x-ray machine) reported for 1965 (Fe69), which was used in our 1975 report (Co80), leads to an obvious overestimate of the number of such workers. That is, the calculated number of potentially exposed workers is greater than the actual number of such workers. We therefore examined an alternate approach based on the total number of dental workers. As a result of discussions with dental professionals we concluded that about 80% of the combined total of active civilian dentists, dental assistants, and dental hygienists are potentially exposed to radiation. Although this assumption is somewhat arbitrary, it yields results consistent with earlier estimates, and we were unable to derive any more exact basis.

Workers in private practice comprised the second largest subcategory in medicine. We estimated the number of potentially exposed workers, excluding radiologists, from the number of x-ray machines in physicians' offices and in clinics (Fe69). The number of radiologists was taken as the number of radiologists working in private practice.

Most radiation-related work in hospitals has been supervised by radiologists (ACR75, PHS73). Therefore, our estimate of potentially exposed non-Federal hospital workers was based on the number of radiologists working in non-Federal hospitals.

Only about 7.5% of all workers potentially exposed to radiation in medicine work in veterinary medicine, chiropractic medicine, and podiatry. The number of these workers was estimated from the number of x-ray machines in each type of practice, except for podiatry, which was estimated from the number of podiatrists.

2. Industry

The industry category includes workers in industrial radiography, manufacturing and distribution, and in other industrial uses of radiation sources. The numbers of potentially exposed workers in industrial radiography and in manufacturing and distribution were estimated from the corresponding numbers of byproduct material licensees of the NRC and NRC Agreement States. The number of workers in other industrial uses was estimated from the numbers of byproduct licensees, facilities using nonmedical x-ray machines, and particle accelerator users. As noted in the introduction, we have not assessed workers in some mineral extraction industries that, with few exceptions, are exposed only to low levels of natural radiation.

3. Miscellaneous Occupations

This category consists of workers potentially exposed in education and transportation. There are little data and few exposure studies of these workers upon which to base our estimates.

Educational institutions use radiation sources in a variety of teaching and research situations. Except at relatively few accelerator, irradiator, and reactor engineering facilities, most uses do not carry a potential for large exposures of workers in a short period of time. These uses, for example, include most radionuclide tracer studies. The number of potentially exposed faculty and staff was based on rough estimates of the number of course offerings to students that involve the use of radiation.

There are many workers whose exposure is mainly due to handling and transporting radioactive materials. Since there are no separate recordkeeping and reporting requirements by government agencies for such workers, our estimates of the number of workers and their exposures were based largely on NRC studies (NRC77a,77b).

C. Assessment of the Exposure of Workers

The two major sources of occupational exposure information were data from Federal agencies and commercial dosimetry data. Federal exposure data provided nearly complete records of both the numbers of workers and their exposure. However, these data did not usually contain information on the age or sex of workers, nor on the number of quarters worked. Workers reported in Federal data comprise about one-quarter of the entire potentially exposed work force. These data are summarized in Appendix D. Our sample of commercial data contained a total number of exposure records equal to about one-half of the remaining work force. About half of these data included information on age and sex. To examine the internal consistency of these data, we compared the mean doses calculated from all records with those calculated from only those records with information on age and sex. For all groups of workers for which commercial data were used to derive mean doses the agreement was within 10 mrem. We therefore used age and sex coded data exclusively to determine all mean doses and dose distributions, to assure internal consistency for our estimates of dose distributions by age and sex.

1. Federal Exposure Data

Table 3 summarizes the results of our analysis of 1980 exposure data from Federal repositories. No Federal agency provided exposure data with sex information, and only the Air Force and the Public Health Service provided age information. Therefore, age and sex distributions for workers reported herein for the government category were constructed from the sample of commercial data for government workers.

The NRC reported the largest number of workers. Their exposure data are summarized annually for four categories of licensees. Exposure data for workers involved in power reactors and in fuel fabrication and reprocessing were assigned to the nuclear fuel cycle category, while that for workers in industrial radiography and in manufacturing and distribution were assigned to the industry category. Exposure summaries for workers in the nuclear waste management and uranium mills subcategories were obtained from an NRC special study (Bro83b) updated by more recent information (Bro83c).

The DOD reported the largest number of workers employed directly by the government or by government contractors. Within the DOD, the Navy reported the largest number of workers; this included Nuclear Navy personnel, Navy and contractor personnel in shipyards (Ri82), and medical workers. Air Force data included dose distribution summaries for 20 occupational categories and an age profile of workers.

The DOE reported the second largest combined government and government contractor work force, and published annual radiation exposure summaries for ten occupational groups (DOE76-82). We combined the DOE exposure data for workers in the research and development of fuel fabrication and fuel processing into one group. Exposure data for DOE contractor employees involved in uranium enrichment were assigned to the nuclear fuel cycle category in Table 4. Exposure data for visitors (including visiting workers) at DOE facilities are reported in Table 5.

Table 3. Summary of 1980 occupational exposure data from Federal agencies

Agency	Number of workers		Mean annual dose equivalent[a] (mrem)	
	Monitored	Exposed[b]	Monitored	Exposed[b]
Department of Defense	103,470	61,458	50	90
Navy	64,335	49,483	80	100
Army	21,050	8,104	10	30
Air Force	18,085	3,871	10	40
Department of Energy	85,465	40,411	80	160
Reactor Research	6,921	4,267	170	280
Fuel Fab. & Reprocessing	5,249	3,737	250	350
Uranium Enrichment	1,871	1,336	80	120
Weapon Fab. & Testing	15,904	7,245	40	90
General Research	36,110	13,177	30	100
Accelerators	5,315	1,968	70	190
Other	12,037	8,167	130	190
DOE Offices	2,058	514	10	40
DOE Visitors[c]	(87,590)	(10,545)	(10)	(60)
Nuclear Regulatory Commission	160,137	95,551	360	600
Power Reactors	133,712	80,635	390	650
Fuel Fab. & Reprocessing	10,204	5,900	100	170
Industrial Radiography	11,102	6,556	260	430
Manuf. & Distribution	5,119	2,460	180	380
Other Agencies[d]	17,094	4,513	20	60
PHS[e]	5,892	614	10	80
NIH	4,154	1,348	10	70
NASA	909	194	20	110
NBS	439	257	60	90
VA[f]	5,700	2,100	20	60
MSHA (Uranium miners)[c,g]	(13,484)	(7,556)	(0.5)	(0.9)
All Workers	366,166	201,926	190	340

[a] These values were estimated from the data using the hybrid lognormal distribution model and are rounded to the nearest 10 millirem.

[b] Workers who received a measurable dose in any monitoring period.

[c] These values are not included in the subtotal or the total.

[d] PHS-Public Health Service; NIH-National Institutes of Health; NASA-National Aeronautics and Space Administration; NBS-National Bureau of Standards; VA-Veterans Administration; MSHA-Mine Safety and Health Administration.

[e] Workers in the PHS Personnel Monitoring Program (see Table D-6 for details).

[f] The number of workers was estimated from VA data. Dose was estimated from commercial dosimetry data.

[g] Data is for exposure, measured in Working Level Months, to radon decay products.

The Public Health Service of the Department of Health and Human Services provided exposure summaries of workers for ten occupational categories (Table D-6b). These summaries also included exposure data grouped according to five-year age intervals (Table D-6a).

The MSHA summarizes annual exposure of uranium miners to radon decay products in terms of a specialized unit of exposure - the working level month (WLM). Since these units are not directly comparable to the units used to express exposure of other workers (usually reported in units of rem), radon decay product data are summarized separately. We also analyzed limited gamma-ray exposure data from MSHA for uranium miners. In addition, we made crude estimates of mean annual exposure to radon decay products and mean annual dose from gamma exposure of nonuranium miners. These analyses are contained in Appendix C and summarized in Table 5.

The NIH, NASA, and NBS summaries of exposure data provided no information on the age, sex, or occupations of monitored workers.

2. Commercial Exposure Data

Data from government agencies were insufficient for estimating exposures in many occupational categories. We therefore obtained commercial exposure data containing approximately 460,000 records. These records carried codes that could be identified with the subcategories used in this study (see Table 2), and about 254,000 of these included the age and sex of the worker. A smaller number of records, about 21,000, also contained information on dose to extremities. We examined the mean dose and corresponding dose distributions for all the records and just those records containing age and sex data, in each code group, and found significant differences for a few groups. Therefore, we chose to use only those records having age and sex data to provide maximum internal consistency in determining the dose, age, and sex distributions for workers.

In spite of the large sample (about one quarter of all workers not covered by Federal data) the commercial data we used may or may not be representative. Although most Federal agency data consists of complete records for well defined groups of workers, this is not usually the case for commercial data. Further, even though commercial dosimetry services often maintain permanent exposure records, spurious or questionable records may not be investigated and corrected by their customers. However, our results based on 1980 commercial data are believed to be more reliable than our previous results using 1975 commercial data, since they are based on a larger sample, and high dose records (12+ rems) were individually confirmed. The fraction of these 1980 data for workers with measurable dose is also consistent with Federal data for 1980; this was not true for the 1975 data (see Figures B-1 and B-2).

D. Analysis of the Exposure Data

In our analysis of exposure data for characteristics such as the mean dose and shape of the dose distribution, we fitted the data with the hybrid lognormal (HLN) distribution model (Ku81). This choice was a result of earlier findings (Ne82) showing the HLN model to have the following desirable features:

- It provides an excellent fit to actual exposure data over the entire range of observed doses;
- It permits characterization of dose distributions using only three parameters; and
- It includes a parameter that reflects the effect of active control efforts to limit worker exposure.

In this study, the HLN model was particularly useful because: 1) it provides a useful means for reconstruction of an entire dose distribution from incomplete or coarse-range dose data; 2) it lends itself readily to detailed examination of the consistency and trends of exposure data; 3) it provides a consistent and accurate basis for estimating collective dose; and 4) it can be used to project dose distributions satisfying predetermined conditions.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR82) and the NRC (Bro83a) have noted the improved fit of the HLN model but used the simpler lognormal distribution model to fit dose data. However, in most cases we find that the HLN model yields a better fit and more useful interpretation of dose data (see Appendix F for further discussion).

1. Dose Distributions

The mean dose, collective dose, and distribution of collective dose were obtained for each occupational category and subcategory by fitting the HLN model to the exposure data. Some complete dose distributions for subcategories of workers were obtained directly from Federal agency data. The remaining dose distributions were constructed from our estimates of the numbers of potentially exposed workers (Appendix A) and from commercial exposure data (Appendix B).

Each dose distribution was determined after careful examination of the input data. First, the validity of the dose data was checked in several ways. Each dose distribution was compared with similar data for the same year and/or for other years to examine its consistency and to identify atypical characteristics. The validity of data containing exposures above 5 rems, for example, was examined by comparing the goodness of fit with the HLN model with and without data above 5 rems (see Appendix B).

The dose distribution for each of the five major categories of workers was obtained by summing the dose distributions for their subcategories. The dose distribution for all potentially exposed workers in the United States is likewise the sum of the corresponding distributions for the five major categories of workers.

The collective dose distribution was determined analytically by fitting the HLN model to the exposure data and calculating the first moment distribution (see Appendix B). In the region above 0.5 or 1 rem, we also estimated the collective dose in each reported dose interval using a "midpoint" method, in which the number of workers is multiplied by the midpoint value of dose of that interval. We compared the collective doses calculated for each dose interval from the two methods and found good agreement, except where there were obviously insufficient data or large fluctuations in the data. We concluded that the first moment of the HLN dose distribution provides the best estimate of collective dose distributions and values for collective dose.

2. Age Distributions

We derived dose and collective dose distributions according to age, for both males and females, for each of the five major categories of workers. These distributions were based on the assumption that the 254,000 commercial records coded for both age and sex were representative. This assumption is supported by the observation that the limited age data from two Federal agencies (Air Force and PHS) were consistent with the age distribution for government workers obtained from commercial data.

The basic characteristics of distributions of all potentially exposed U.S. workers and their collective dose were further examined as a function of dose and age. The general results are presented in Chapter IV. In addition, these analyses were expanded in greater detail for some worker groups using the HLN distribution model for dose and the Johnson S_B distribution for age (Ai57, Jo70). To examine the parameters of these distribution models for two quite different types of occupationally exposed workers, we selected the subcategories of workers in hospitals and nuclear power plants. The results for these expanded analyses are given in Appendix F.

3. Cumulative Doses

Cumulative dose is defined here as the sum of all prior occupational doses received by a worker. Figure 2 shows a schematic model for worker employment in occupations having potential for radiation exposure during a working lifetime. Box "A" represents currently employed or "active" workers that have potential for radiation exposure. Box "B" represents workers that have temporarily or permanently terminated such employment. Initial entry to box "A" occurs at first employment as a potentially exposed worker. Flow of workers from box "A" to box "B" includes both permanently and temporarily terminated workers. There is a subgroup of permanently terminated workers in Box "B" who never again enter Box "A"; only the cumulative doses of these workers contribute to a lifetime occupational dose distribution.

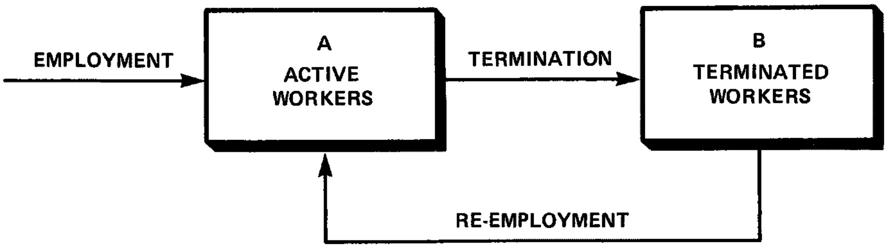


Figure 2. Model of worker employment for estimating cumulative dose.

We made preliminary estimates of mean term of employment, mean lifetime cumulative dose, and maximum lifetime cumulative dose for four licensee categories from limited NRC termination data (Bro78,83a,83b). These data contained records for some workers who do not actually leave their employer but are recorded as terminated (e.g., some workers who move from one licensee to another, while in the employ of a contractor to those licensees, are "terminated" as they leave each licensee; these are reported in NRC termination data, pursuant to 10 CFR Section 20.408). The length of employment determined from this data actually corresponds to the length of cumulative monitoring periods of workers for NRC licensees. We also examined limited termination data from DOE (DOE76-82) and some cumulative dose data from the Navy (Ri82).

Mean lifetime cumulative dose was examined by correlating the mean annual increment of the mean cumulative dose to the mean length of employment of groups of terminated workers. Maximum lifetime cumulative dose was examined by using a trend analysis of lifetime cumulative doses in descending order of magnitude on a log-log display (Ku80). These results are described in Chapter V. The analysis of mean length of employment involved fitting termination data with the Johnson S_B distribution, the HLN distribution or the lognormal distribution. The analysis of mean lifetime cumulative dose involved fitting the data with the HLN distribution model. We discuss these analyses in Appendix F.

IV. SUMMARY OF NATIONAL OCCUPATIONAL EXPOSURE FOR 1980

A. Principal Results

The estimated numbers of U.S. workers potentially exposed to radiation, as well as the number of just those measurably exposed, for each of five major categories and nineteen subcategories of workers are listed in Table 4. The estimated mean dose and collective dose for all workers and for those measurably exposed is also listed for each of these categories and subcategories.

Our analysis indicates that 1.32 million workers were potentially exposed to radiation in 1980, and that about half of these received a measurable dose. The mean dose equivalent to all workers was 110 mrem, and the dose to those measurably exposed was 230 mrem. The total collective dose equivalent to all workers was 150,000 person-rems. These values are compared to those for previous years in Chapter V.

Measurably exposed workers in medicine, industry, the nuclear fuel cycle, government, and miscellaneous occupations received mean dose equivalents of 150, 240, 600, 120. and 160 mrem, respectively. These mean doses to measurably exposed workers were roughly double those to all potentially exposed workers in each category. Of the various subcategories, workers at power reactors, in nuclear waste management, and in industrial radiography received the highest mean doses. Workers received very small doses in several subcategories: dentistry, chiropractic medicine, podiatry, the Department of Defense, and other Federal agencies. The three largest contributors to collective dose after power

Table 4. Summary of exposure of workers to radiation, 1980

Occupational category	Number of workers(a) (thousands)		Mean annual dose(b) equivalent (mrem)		Collective dose equivalent(d) (10^3 person-rem)
	All	Exposed(c)	All	Exposed(c)	
Medicine	584	277	70	150	41
Dentistry	259	82	20	70	5.6
Private Practice	155	87	100	180	16.0
Hospital	126	86	140	200	17.2
Veterinary	21	12	60	110	1.3
Chiropractic	15	6	30	80	0.5
Podiatry	8	3	10(e)	30(e)	0.1
Industry	305	156	120	240	38
Radiography	27	18	290	430	7.8
Manufact. & Distrib.	29	12	110	270	3.2
Other Users	249	126	110	210	26.5
Nuclear Fuel Cycle(f)	151	91	360	600	54
Power Reactors	133.7	80.6	390	650	52.3
Fuel Fab. & Reproc.	10.2	5.9	100	170	1.1
Uranium Enrichment	1.9	1.3	80	120	0.15
Nuclear Waste Mgt.	0.7	0.4	200	380	0.15
Uranium Mills	4.8	3.0	160	260	0.8
Government	204	105	60	120	12
Dept. of Energy(g)	83.6	39.1	80	160	6.3
Dept. of Defense	103.5	61.5	50	90	5.6
Other Agencies(h)	17.1	4.5	20	60	0.3
Miscellaneous	76	31	70	160	5
Education	26	14	60	110	1.5
Transportation	50	17	70	200	3.5
All U.S. Workers	1320	660	110	230	150

(a) Numbers of workers rounded to the nearest thousand are estimated values.

(b) These values are rounded to the nearest 10 millirem (mrem).

(c) Workers who received a measurable dose in any monitoring period.

(d) Collective doses are rounded to the nearest 1000 person-rems.

(e) Estimated from 1975 data (Co80).

(f) See Table 5 for uranium miners.

(g) Excludes uranium enrichment workers: see the nuclear fuel cycle.

(h) NASA, NBS, NIH, PHS, and VA (see Table 5 for MSHA data for miners).

reactor workers (those in other industrial uses, private medical practice, and hospitals) exhibited mean measurable doses less than the average for all measurably exposed workers.

Several groups - underground miners, passenger airplane flight crews and flight attendants, students, and visitors to DOE facilities - totaling 0.27 million persons, are not included in our main summary because their type of exposure is atypical. They are not in permanent jobs, or their exposure is small and has not been traditionally included with that of radiation workers (see Table 5 and Appendix C for more detail). Of these groups, the most significant exposure accrued to underground miners. We examined the exposure of underground uranium miners to radon decay products and gamma radiation separately. The largest exposure of these miners is to the lungs rather than to the whole body, as is usual for most other workers.

B. The Number of Workers and Collective Dose by Work Category

In Figure 3, the distributions of workers and their collective dose in the five major categories are illustrated for the year 1980. Although the largest number of workers are employed in medicine, workers in the nuclear fuel cycle made the largest contribution to collective dose. The collective dose for these workers was approximately one-third of that to all workers; collective doses for workers in medicine and industry were each about one-fourth that to all workers.

C. Dose Distributions

Figure 4 shows the estimated numbers of potentially exposed workers and collective doses by dose range and sex in 1980. About half of these workers did not receive a measurable dose; 84% received less than 100 mrem and 94% less than 500 mrem. Less than 0.1% of these workers received more than 5 rems. We estimate that those workers assigned a less-than-measurable dose contributed a negligibly small amount, less

Table 5. Summary of exposure of some additional groups of individuals to radiation, 1980

Whole body radiation	Number of persons[a] (thousands)		Mean annual dose equivalent (mrem)[c]		Collective dose equivalent (10^3 person-rem)
	All	Exposed[b]	All	Exposed[b]	
Workers					
Uranium miners	13.5	7.6	200	350	2.7
Nonuranium miners	4.2	2.8	150	220	0.6
Flight crews[d]	39	39	170	170	6.6
Flight attendants[e]	58	58	170	170	9.9
Entire Group	114.7	107.4	170	180	19.8
Others					
Students	67	31	50	100	3.3
Visitors to DOE facil.	87.6	10.5	10	60	0.6
Entire Group	154.6	41.5	30	90	3.9

Radon decay products	Number of persons[a] (thousands)		Mean annual exposure (WLM)[b]		Collective exposure (10^3 person-WLM)
	All	Exposed[b]	All	Exposed[b]	
Workers					
Uranium miners	13.5	7.6	0.5	0.9	6.7
Nonuranium miners	4.2	2.8	0.2	0.3	0.8
Entire Group	17.7	10.4	0.4	0.7	7.5

[a] Numbers of workers rounded to the nearest thousand are estimated values.

[b] Workers who received a measurable dose or exposure in any monitoring period.

[c] These values are rounded to the nearest 10 millirem (mrem).

[d] Flight crews are estimated to receive a mean incremental dose of 170 mrem from cosmic radiation; one-half of all flight crew members are estimated to receive a mean dose of 1 mrem from transportation of radioactive sources.

[e] Flight attendants are estimated to receive a mean incremental dose of 170 mrem from cosmic radiation; one-half of all flight attendants are estimated to receive a mean dose of 6 mrem from transportation of radioactive sources.

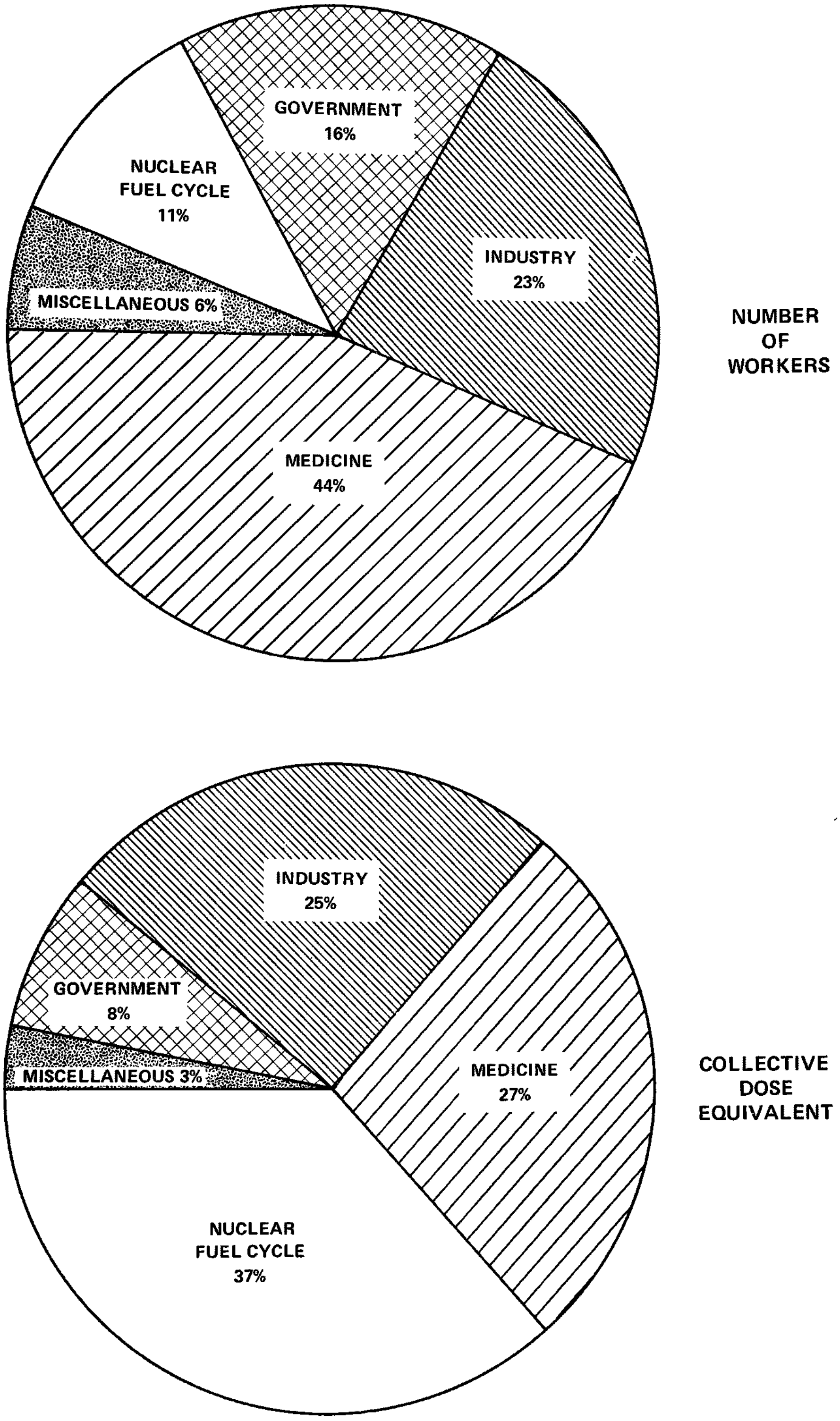


Figure 3. Distributions of potentially exposed workers and their collective doses by work category, 1980.

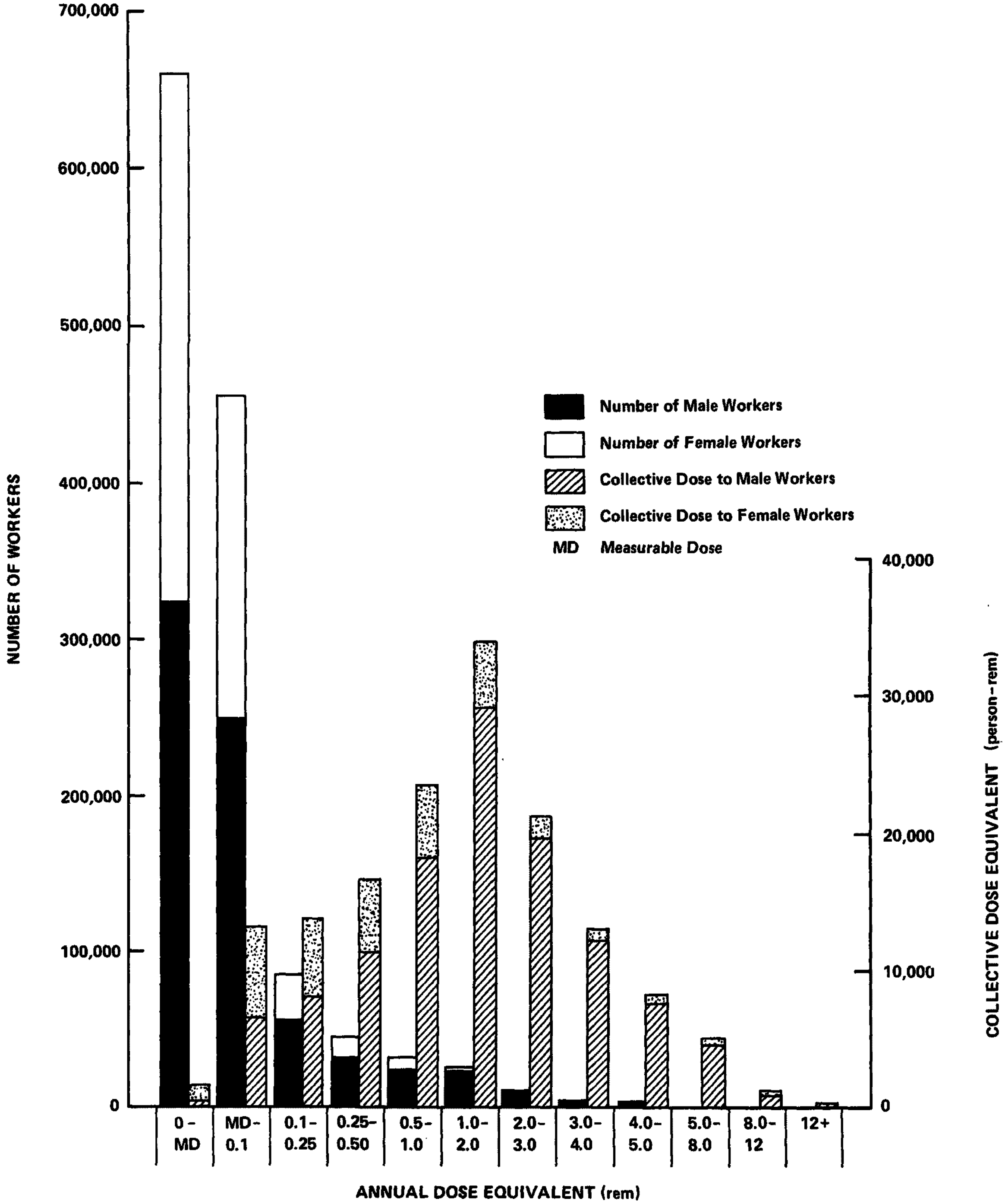


Figure 4. Potentially exposed workers and their collective doses by dose range, 1980.

than 1%, to the total collective dose (see Table C-3). About 9% of the collective dose came from individual doses less than 100 millirems and about 30% from those less than 500 millirems; about 5% was due to workers receiving more than 5 rems. Thus, about 65% of the collective dose resulted from workers with doses between 500 and 5000 mrem; these workers comprised only 5% of all workers. Men outnumbered women for each dose range except for the lowest range (i.e., those receiving a less-than-measurable dose). The fractions of all men and all women workers exposed above 500 mrem were 8% and 2%, respectively. The fractions of total collective doses to men and women receiving more than 500 mrem were about 75% and 40%, respectively.

Figure 5 provides a breakdown for each category of workers of the results shown in Figure 4. The number of workers or collective dose is given at the base of each block in this presentation. Each block also is divided to show the fraction attributed to male and female workers. About 85% to 90% of workers in each category received less than 100 mrem, except for nuclear fuel cycle workers for whom the fraction was only 64%. The fraction of workers above 5 rems ranged from zero for government workers to 0.2% for those in the nuclear fuel cycle. Men outnumbered women for all dose ranges in each work category except for doses below 2 rems for workers in medicine and below 1 rem for those in miscellaneous occupations.

The fraction of collective dose above 5 rems was second smallest (3%) for the nuclear fuel cycle, although this category is the largest contributor to the 1980 collective dose to all workers. The fraction of collective dose arising from individual doses above 5 rems was largest (8%) for workers in industry. This is consistent with NRC data for industrial radiographers (6%) and workers in manufacturing and distribution (11%) (Bro82). Collective doses to men were greater than those to women for all work categories except at doses below 2 rems in medicine and below 1 rem in miscellaneous occupations.

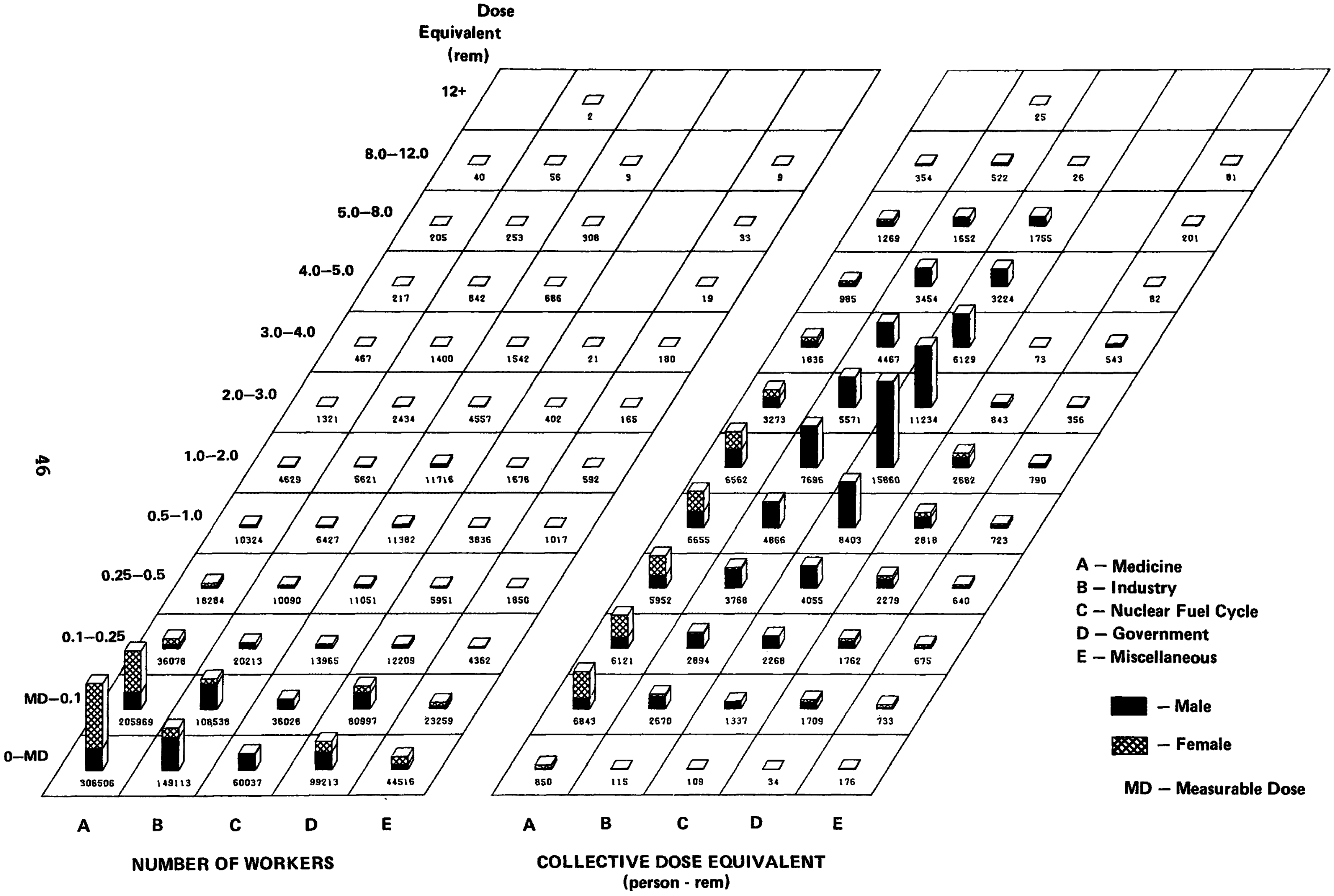


Figure 5. Potentially exposed workers and their collective doses by dose range and work category, 1980.

The individual and collective dose distributions for all U.S. workers were most closely approximated by those for workers in industry. The nuclear fuel cycle exhibited distributions distinctively different from those for all other major categories of workers. These differences not only reflect the existence of high dose tasks, but also a high level of effort to control high radiation exposures. This is exhibited by the presence of high mean doses coupled with a small fraction of workers exceeding the dose limits.

D. Age Distributions

Distributions of the numbers of potentially exposed workers and their collective dose by age are shown in Figure 6. These distributions were developed from the age and sex coded data sample of 254,000 commercial exposure records.

In 1980, the distributions of numbers of male and female workers and their collective doses by age are quite similar. The largest fractions (23%) of both workers and collective dose occur in the age range 25 to 29 years. Workers younger than 20 years of age constitute only about 2% of the 1980 work force and 1% of its collective dose. Workers older than 65 years account for only 0.6% of the work force and 0.4% of its collective dose. The median age of the work force and the age at which the collective dose distribution exhibits its median value are both 31 years.

Women outnumber men in 1980 for ages less than 30 years by about 3 to 2, while above 30 years of age men outnumber women by about 2 to 1. However, for workers over 20 years old, the fraction of total collective dose in each age range is larger for males than females. Women younger than 30 years constitute 58% of the female work force and received 55% of the collective dose to female workers. Men younger than 30 years account for 34% of the male work force and received 38% of the collective dose to male workers.

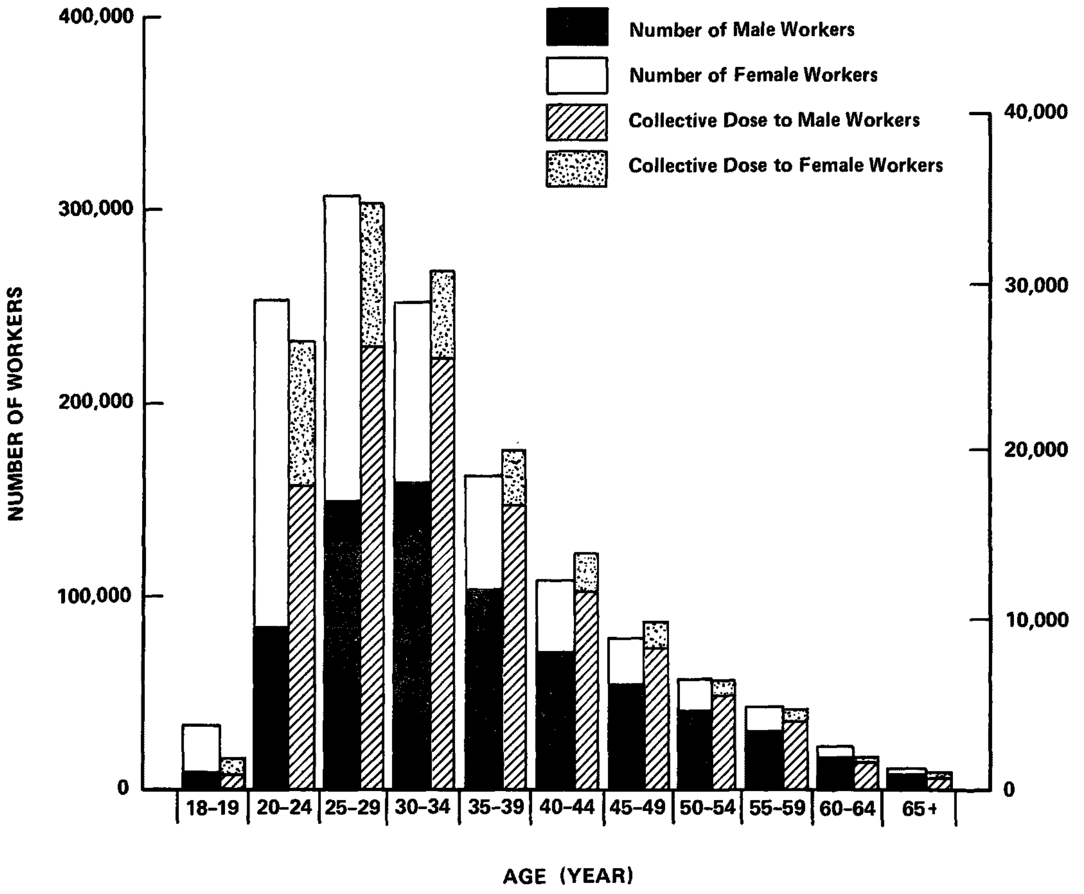


Figure 6. Potentially exposed workers and their collective doses by age range, 1980.

The estimated numbers of workers and their collective doses by age range in each work category are shown in Figure 7. The largest fractions (20% to 26%) of workers and collective dose are in the 25 to 29 year age range for each category, except for government workers (where the largest fractions of both workers and collective dose are in the 30 to 34 year age range) and miscellaneous workers (the largest fraction of workers is in the 20 to 24 year age range).

The fraction of workers younger than 20 years is largest for those in miscellaneous occupations (7%) and smallest for those in the nuclear fuel cycle (0.6%). The fraction of workers older than 65 years is also largest for miscellaneous occupations (2%) and smallest for those in the nuclear fuel cycle (0.3%). The median ages of male and female workers combined range from 29 to 33 years for the five work categories: medicine (29 years), industry (32 years), nuclear fuel cycle (33 years), government (32 years) and miscellaneous (29 years).

Since the distribution of workers by age and the corresponding distribution of collective dose as a function of worker age are often different for a given category, the median ages for the two distributions are generally different. There are also generally differences in these distributions according to sex. The median ages for the collective dose distributions for men and women are one year less than the median ages of these workers in industry (31 years) and the nuclear fuel cycle (32 years), and one to two years greater than the median ages of workers in medicine (30 years), government (34 years), and miscellaneous occupations (30 years).

Female workers in medicine and the nuclear fuel cycle exhibit the lowest median age (about 28 years) for both number of workers and collective dose age distributions, and, for both number of workers and collective dose distributions, the highest median age (32 years) occurs for workers in industry. Male workers exhibit a similar median age

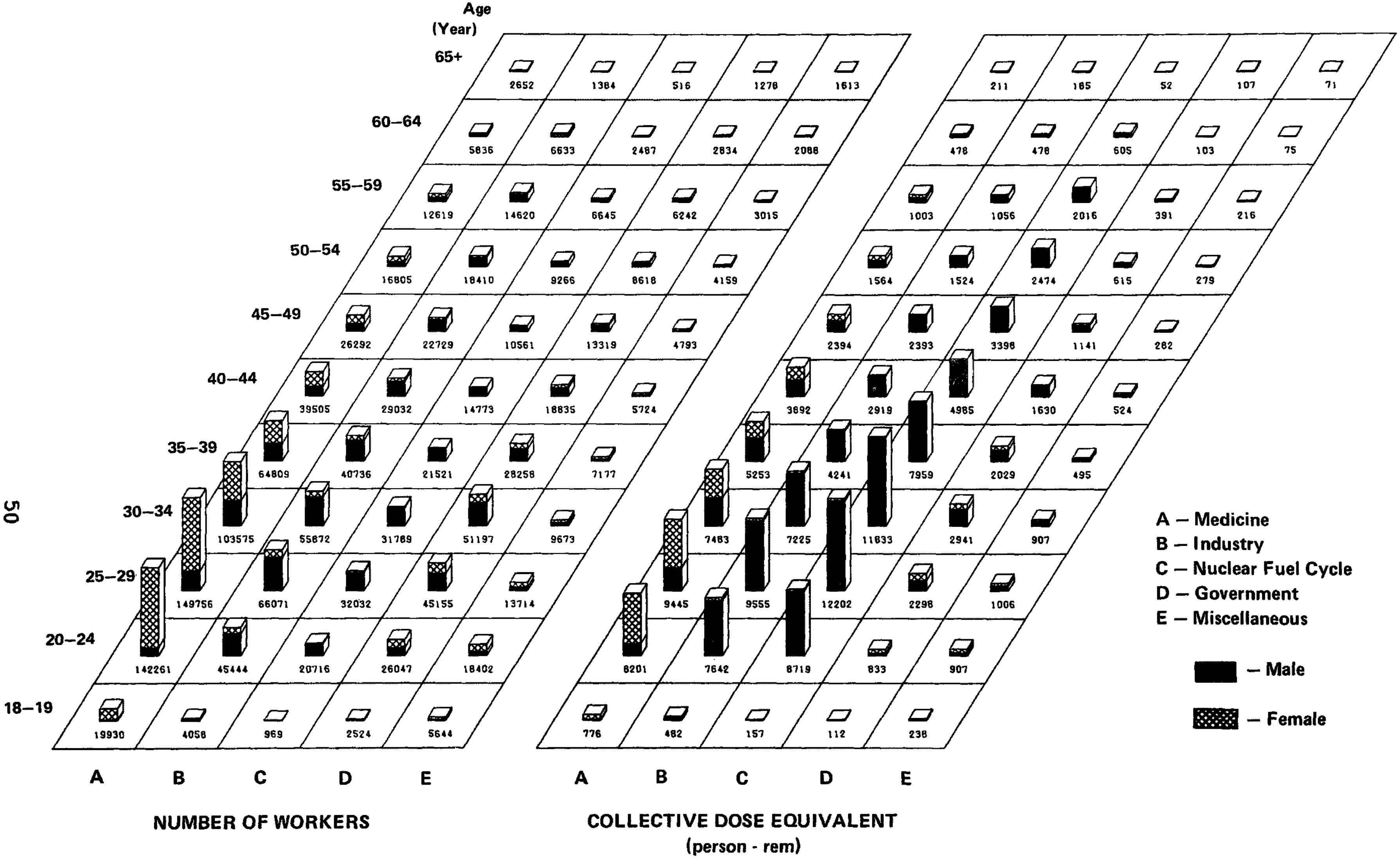


Figure 7. Potentially exposed workers and their collective doses by age range and work category, 1980.

(about 33 years) in all categories. However, males exhibit a variety of median ages of exposure for collective dose distributions, ranging from 31 years for those in industry to 35 years for those in government. See Table B-8 in Appendix B for details.

V. REVIEW OF TRENDS IN OCCUPATIONAL EXPOSURE

Substantial increases in the production and use of sources of ionizing radiation have occurred in the United States since the late 1950's. This has led to corresponding increases in the number of potentially and actually exposed workers, as well as in the collective dose to exposed workers. At the same time, there has been an overall decrease in the mean annual dose received by workers. Much of this decrease may reasonably be assumed to be related to changes in numerical requirements of regulations for radiation protection and to increased efforts to achieve as low as reasonably achievable (ALARA) exposures. However, we have not attempted to examine the correlation of such changes in regulations or increased ALARA efforts with trends of doses to workers; we simply present the observed trends.

In this chapter we examine trends in occupational exposure of workers from several perspectives. We first examine workers in the various occupational groups in terms of their number, mean annual dose, and collective dose. Next, we examine for these same groups of workers the distributions of individual and collective doses. Finally, we project the observed trends of number, mean annual dose, collective dose, and individual dose distributions for the period 1960-1980 to the year 1985. We also project the anticipated dose distribution for 1985 under the constraint of an annual dose limit of 5 rems. Finally, using the limited data available, we examine the average and maximum accumulation of dose during an individual's working lifetime. We summarize our analyses and results below; further details are given in Appendices A and B.

A. Trends in Major Indices of Occupational Exposure

1. Number of Potentially Exposed Workers

The numbers of potentially exposed workers in the United States from 1960 to 1980, with a projection for 1985, are shown in Figure 8. The number of workers in each occupational category is also indicated. We have estimated that about 0.50 million workers were potentially exposed to radiation in 1960; 0.69 million in 1965; 0.78 million in 1970; 1.00 million in 1975; and 1.32 million in 1980 (see Appendix A for the numerical breakdown by category of workers). This historical trend is approximated by a model which assumes the number of workers doubles every 14.5 years, starting from one-half million workers in 1960. Such a model yields 0.50 million workers in 1960, 0.63 million in 1965, 0.81 million in 1970, 1.02 million in 1975, and 1.30 million in 1980. Our estimates are slightly different from previously reported values of 0.46 million (K172) and 0.44 million (Co80) in 1960, 0.77 million in 1970 (K172), and 1.1 million in 1975 (Co80). A compendium of reported summaries of U.S. occupational exposure for 1960, 1970, and 1975 is given in Appendix E.

Our projected estimate of 1.64 million workers for 1985, shown with dashed boundaries in Figure 8, is based on a detailed examination of trends in the number of workers and of associated sources of exposure, principally for the period 1975 to 1980. This is in excellent agreement with the 1.65 million workers predicted by the doubling model. For perspective, we note that the doubling model corresponds to a mean annual growth rate of about 5% for potentially exposed workers during a period when the mean annual growth rates of the entire U.S. labor force and the U.S. population were 2.0% and 1.2%, respectively.

2. Sources of Occupational Exposure

We estimated the number of potentially exposed workers in the five major occupational categories by analyzing related indices over a twenty-

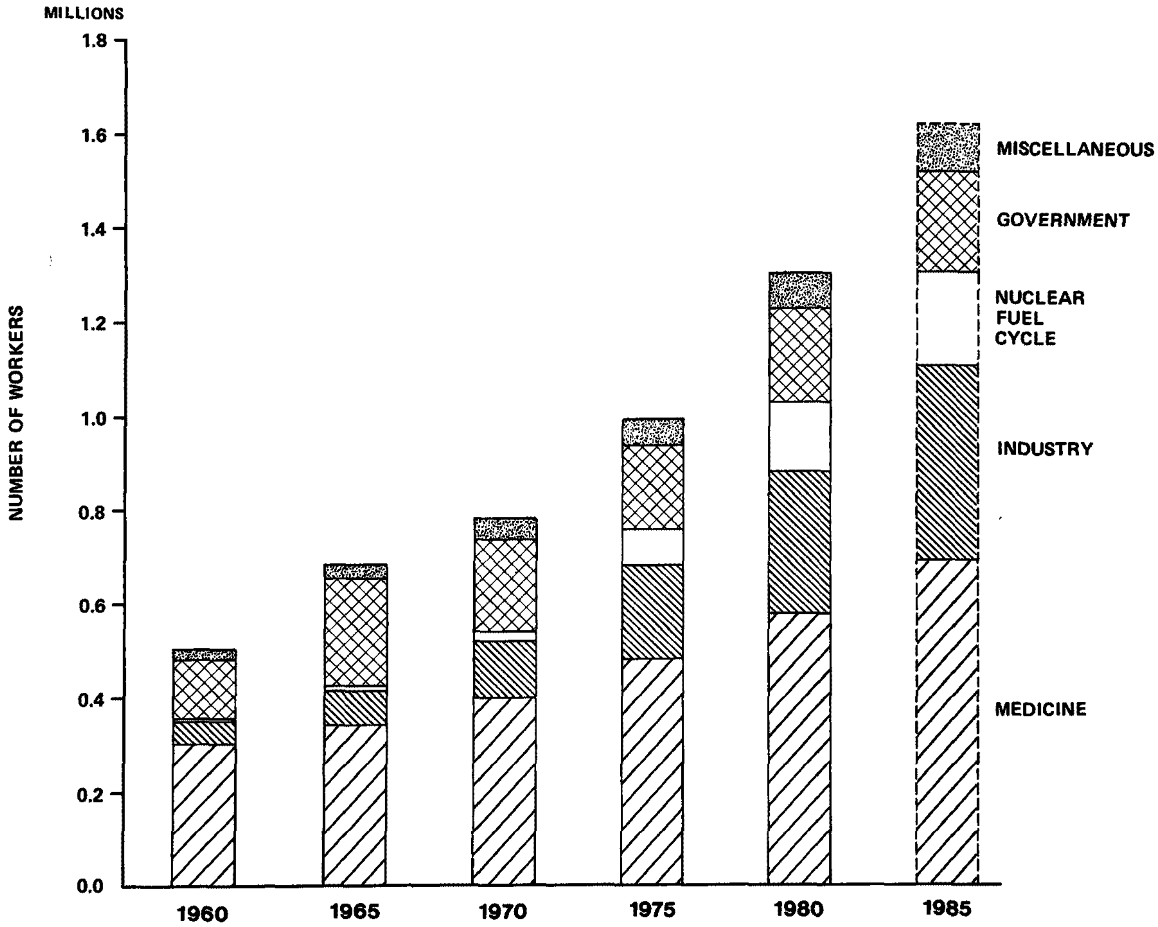


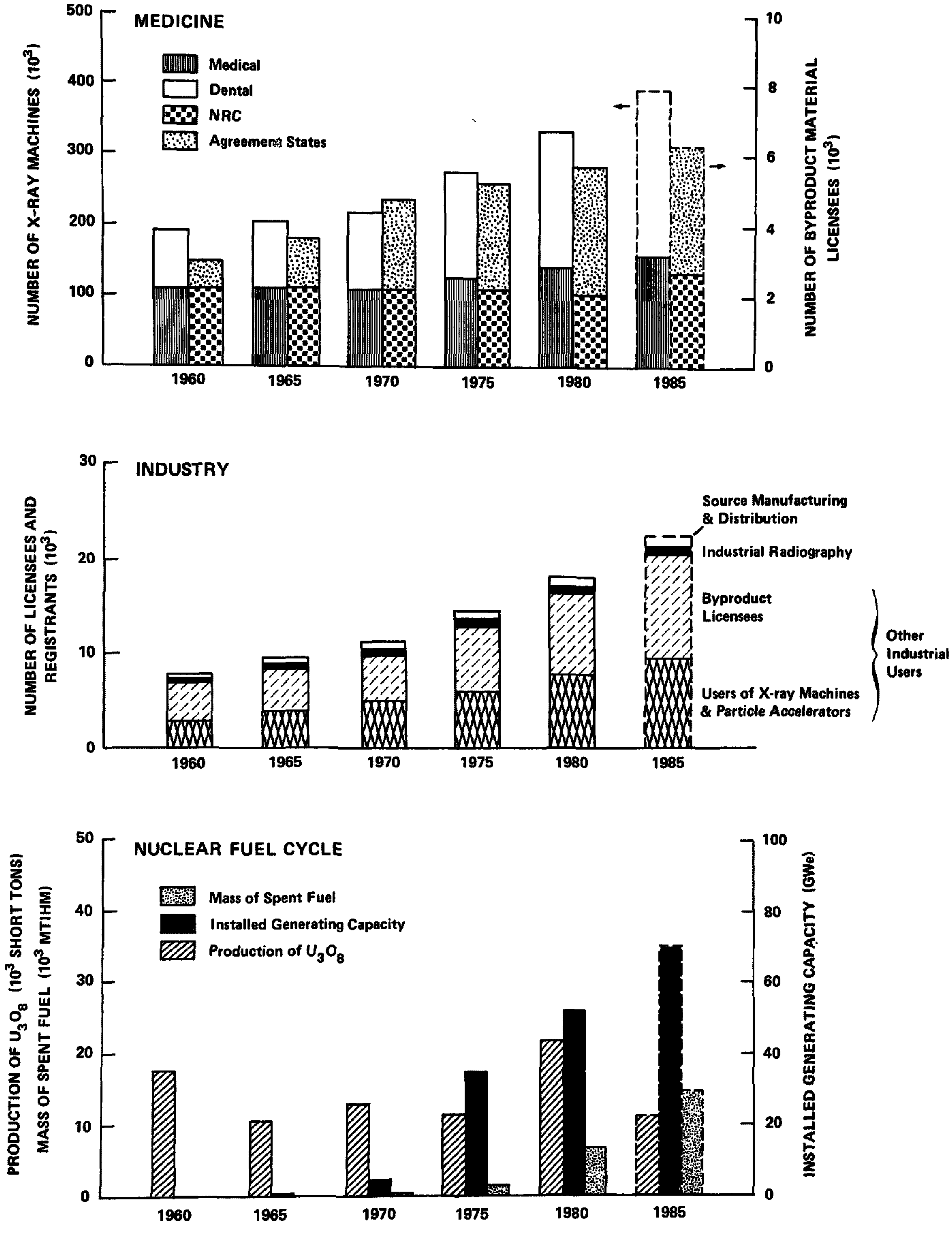
Figure 8. Estimated number of potentially exposed workers, 1960 to 1985.

year period. These relevant indices included numbers of x-ray machines, radioactive byproduct material licensees, and professionals in related occupations (see Appendix A).

The trends of numbers of radiation sources in medicine were examined in terms of the numbers of x-ray machines and byproduct licensees (shown in Figure 9). Major trends are summarized below; details are examined in Appendix A. The combined number of medical and dental x-ray machines has increased by about 58,000 every five years from an initial value of 218,000 in 1970. Dental x-ray machines have increased more rapidly than medical x-ray machines. Since 1965, we find that the number of potentially exposed workers in medicine can be approximated by multiplying the total number of x-ray machines by the factor 1.8. The number of medical byproduct licensees of the NRC and Agreement States increased by about 500 every five years from an initial value of 4,700 in 1970. We find that we can also roughly approximate the number of workers in medicine by multiplying the number of medical byproduct licensees by a factor of 100.

In industry we examined the numbers of byproduct material licensees and registrants of x-ray machines and particle accelerators (Figure 9). The combined number of licensees and registrants increased by about 3,000 to 4,000 every five years from 11,300 in 1970. The number of workers in industry can be roughly estimated by multiplying the combined number of licensees and registrants by the factor 8 in 1965 and increasing the value of this factor by 3 every five years thereafter.

The trends of radiation sources in the nuclear fuel cycle were examined in terms of the production of enriched U_3O_8, the installed generating capacity of nuclear power plants, and the mass of spent fuel (see Figure 9). Production of enriched U_30_8 rapidly increased during the 1950's, but more or less leveled off after 1960 (DOE83). Installed electrical generating capacity from nuclear power plants sharply increased in the early 1970's, but the rate of new installed



MTIHM – Metric tons initial heavy metal

Figure 9. Indices related to the numbers of potentially exposed workers in medicine, industry, and the nuclear fuel cycle, 1960 to 1985.

generating capacity has decreased since 1975 (AIF80, Bro83b, DOE82). We estimated the 1985 installed generating capacity to be about 70 GWe from a linear extrapolation of the 1975 to 1980 trend; this is smaller than estimates reported elsewhere (AIF83, DOE82). The amount of spent nuclear fuel has steadily increased, as shown in Figure 9 (DOE82). The large increase in numbers of workers in the nuclear fuel cycle during the 1970's was due both to the increased number of reactors and increased volume of maintenance activities. It is difficult to estimate the number of these workers for 1985 because of uncertainties in recent trends. However, we can roughly estimate the number of these workers by multiplying installed generating capacity of nuclear power plants by about 3 persons per MWe (a value that has been observed since the mid-1970's).

The trend of types and numbers of radiation sources was not evaluated for government workers. However, the number of workers identified here in government (employees of Federal agencies or government-owned, contractor-operated facilities) has been well monitored and has been fairly constant at about 0.2 million (within 16%) workers since 1965. This number is about 7% of all Federal government employees.

The numbers of workers in miscellaneous occupations can be correlated with the total number of NRC and Agreement State byproduct material licensees. These licensees have increased by 2,000-3,000 every 5 years from 9,600 in 1965. The associated number of workers can be roughly estimated by multiplying the number of licensees by a factor of 3 in 1965 and increasing the value of this factor by 0.5 every 5 years thereafter. The number of workers in education (faculty and staff) was correlated with the number of academic licensees of the NRC and the Agreement States. The corresponding number of workers since 1965 can be roughly estimated by multiplying the number of academic licensees by a factor of 30.

Using the trend analyses described above, our estimates for numbers of potentially exposed workers in 1985 are: 0.70 million in medicine, 0.42 million in industry, 0.20 million in the nuclear fuel cycle, 0.22 million in government, and 0.10 million in miscellaneous occupations (see Appendix A).

3. Mean and Collective Doses to Workers

The overall trend of occupational exposure was examined in terms of mean annual dose and collective dose. Figure 10 shows the trend of mean dose and collective dose to all potentially exposed workers since 1960. The contribution to collective dose is also indicated for each of the five occupational categories.

Our estimates of mean annual dose showed a decrease from about 180 mrem in 1960 to about 110 mrem in 1980. The mean dose did not change significantly between 1960 and 1965, but decreased about 30 mrem every 5 years from 1965 to 1975. Since 1975 the decrease has been less rapid; between 5 and 10 mrem every 5 years.

Our estimate of the mean annual dose for all workers agrees with the reported estimate of 120 mrem in 1975 (Co80), but not with the reported estimate of 210 mrem in 1970 (Kl72) (see Appendix E). The high value reported for 1970 is attributable primarily to an apparent over-estimate of the mean annual dose for medical workers (see Appendix B for our analysis).

Our estimate of the U.S. total collective dose shows an increase from 91,000 person-rems in 1960 to 150,000 person-rems in 1980. The historical trend can be approximated since 1975 by an increase of about 25,000 person-rems every 5 years, after small fluctuations around 120,000 person-rems between 1965 and 1975.

The projections of mean annual dose and collective dose for 1985 are shown by dotted line and dashed boundaries in Figure 10. These

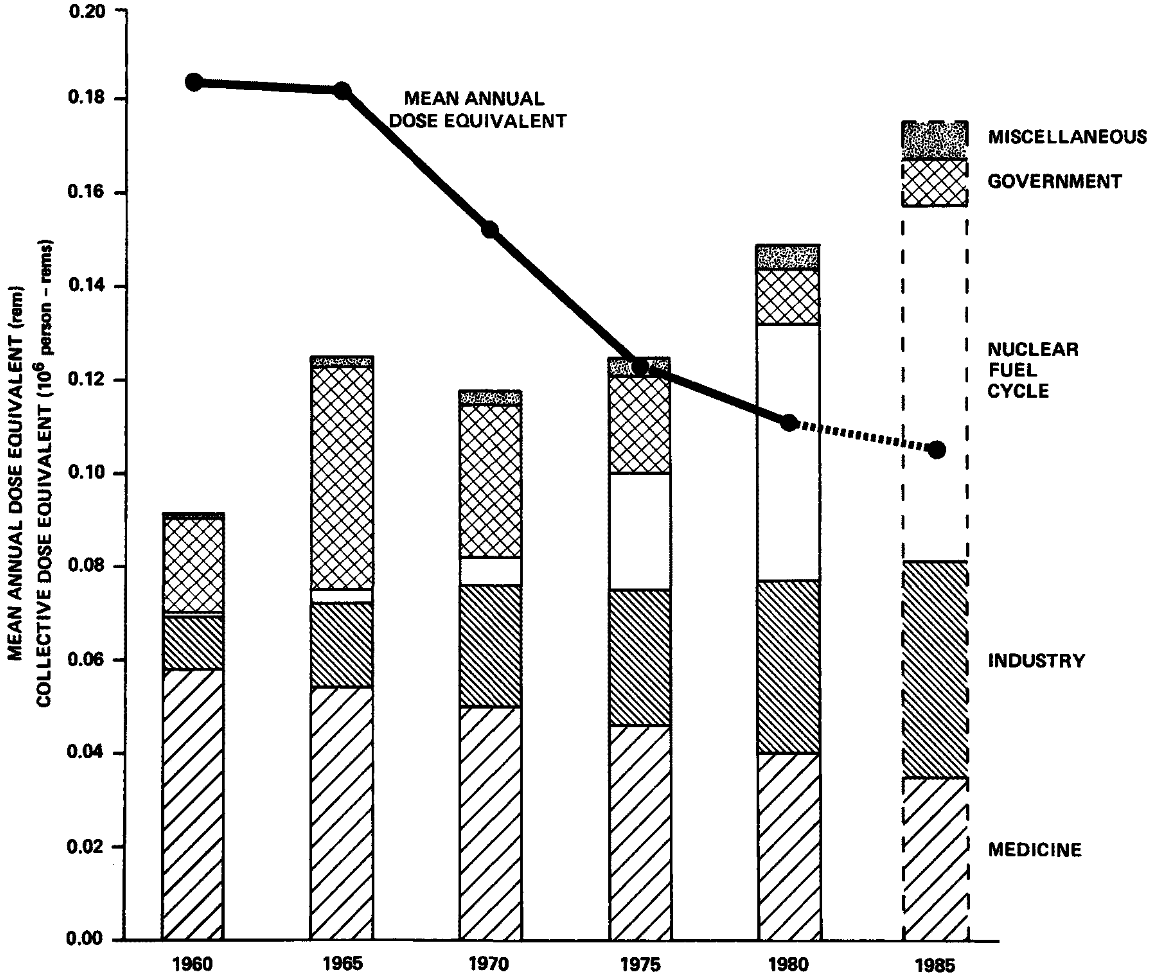


Figure 10. Mean annual dose and collective dose to potentially exposed workers, 1960 to 1985.

estimates are based on a detailed examination of trends, principally for the period 1975 to 1980, in the numbers of workers, mean annual dose, and our analysis of dose distributions.

4. Collective Dose Versus Number of Workers and Mean Annual Dose

We examined the trend of collective dose for the period 1960 to 1985 in terms of its underlying components: the number of workers and their mean annual dose. Figure 11 shows the trends of collective dose in each of the five occupational categories and for all U.S. workers combined. The values shown for five-year intervals, from 1960 to 1985, are tabulated in Appendices A and B. The diagonal lines are constant collective dose contours from 10^2 to 10^6 person-rems.

For medical workers, who exhibited the largest collective doses before 1980, the trend has been a decrease by about 5,000 person-rems every 5 years since 1960. This occurs because the decrease of the mean annual dose (see Figure B-3) has been larger than the increase of the number of workers (see Figure A-4). Workers in industry exhibit similar behavior, except that in this case their collective dose has increased an average of about 7,000 person-rems every 5 years since 1960. This occurs because the two-fold decrease in mean annual dose has not compensated the much larger increase in the number of workers.

The collective dose for government workers has decreased dramatically, primarily due to the decrease of mean annual dose, but also partly due to a decrease in the number of workers since 1966. The decrease in mean annual dose may, in part, reflect the adoption by the Navy (1967) and the AEC/ERDA/DOE (1974) of a maximum annual dose of 5 rems instead of the previous 3 rems per quarter. The relatively large increase of collective dose between 1960 and 1965 was due to a 65% increase in the number of workers in AEC facilities and a 250% increase in the number of workers in the Navy, with a simultaneous 270% increase in the mean annual dose.

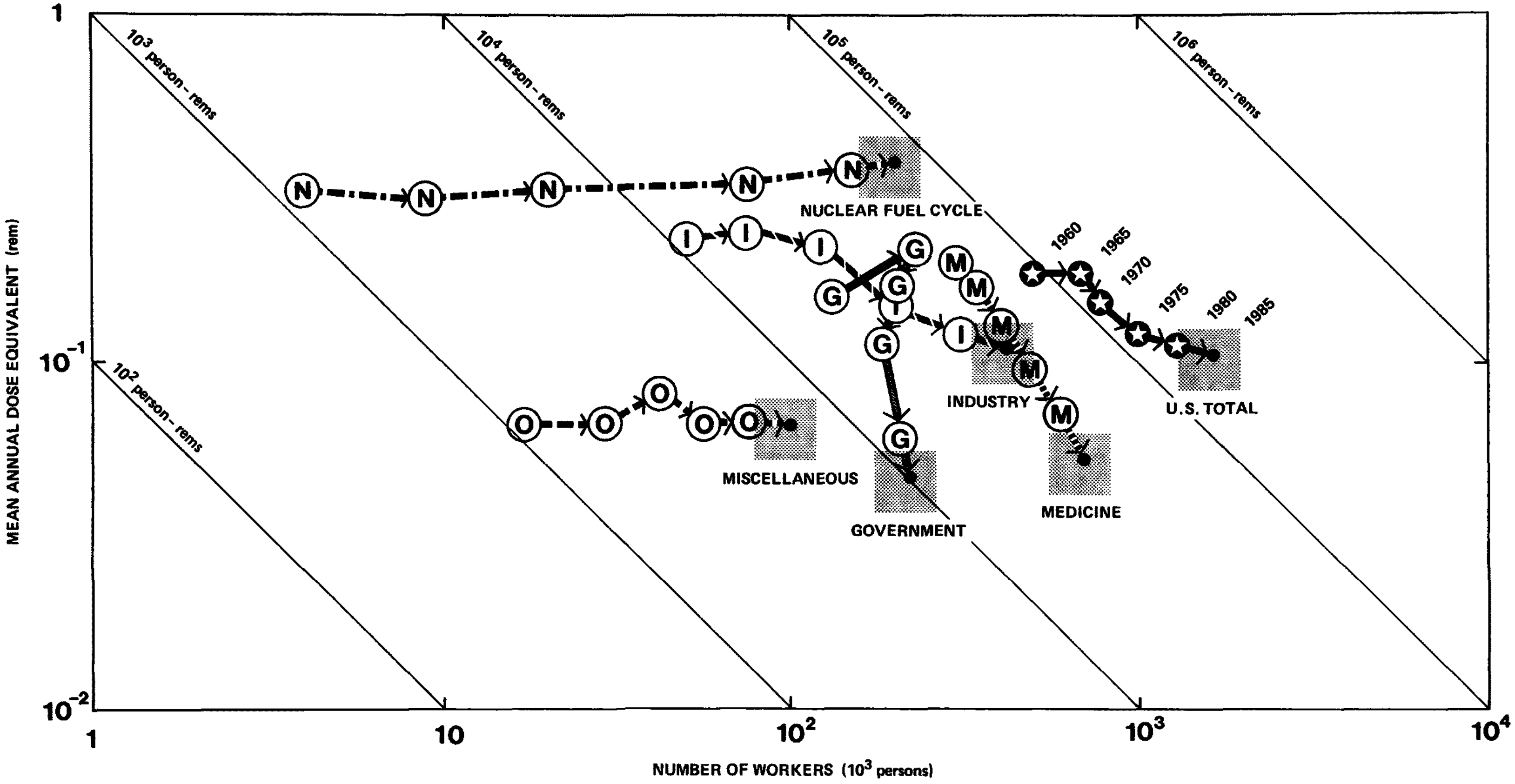


Figure 11. Trends in mean annual dose, collective dose, and the number of potentially exposed workers, 1960 to 1985.

In contrast to the decrease of collective dose for medical and government workers since about 1965, the collective dose for workers in the nuclear fuel cycle (and in miscellaneous occupations) steadily increased from 1960 to 1980, due largely to the increased number of facilities (and therefore workers). This has resulted in the nuclear fuel cycle becoming the largest contributor to collective dose, in contrast to being one of the smallest only a decade ago. It is noted that, in spite of the increasing average age of nuclear facilities and consequent need for repairs, the mean annual dose to workers in the nuclear fuel cycle has remained roughly constant over this time period.

The overall trend of the U.S. total collective dose can be characterized as only gradually increasing since 1960. The major contributions to growth were from government workers (during the period 1960 to 1965) and from workers in the nuclear fuel cycle and industry after 1975. Since 1975, increases in contributions from workers in the nuclear fuel cycle and industry have more than made up for decreases from workers in medicine and government.

The solid points within each shaded square of Figure 11 represent our estimates of the numbers of workers, mean annual doses, and collective doses for 1985. Each point was determined by linear extrapolation on the log-log plots (Figure 11) of the 1975 to 1980 trends in the numbers of workers and mean annual doses. These values were derived as described in Appendices A and B. This also provides an estimate of the collective dose for 1985. The shaded squares show an arbitrary estimated uncertainty of 20% about the projections of numbers of workers and the projected mean annual dose. In general, the mean doses predicted by these simple linear log-log extrapolations provide estimates that are in good agreement with estimates from our projected dose distributions obtained by extrapolation of the parameters of the HLN fits to 1975 and 1980 data. For example, the overall U.S. mean dose was 105 mrem from log-log extrapolation and 110 mrem from the HLN trend analysis; the mean dose to nuclear fuel cycle workers was 380 mrem from log-log extrapolation and 360 mrem from the HLN trend analysis. However, the mean dose to government workers was 50 mrem from log-log extrapolation and only 30 mrem from the HLN trend analysis. This relatively large difference is a result of extrapolating the large change in the dose distribution for government workers between 1975 and 1980 (see Figure B-7).

The 1985 projection of the total U.S. collective dose agrees with the sum of projections of collective dose for workers in the five categories, using either the log-log or HLN projections. Similarly, the projection of collective dose in each category also agrees with the sum of projections of collective dose in its subcategories using either the log-log or HLN projections.

B. Trends in Dose Distributions

1. Distributions of Annual Doses to Workers

The trend of doses to highest exposed individuals is one index of efforts to reduce individual exposures. Figure 12 shows, on a lognormal probability scale, the annual dose distributions obtained by fitting the HLN model to the dose distribution data determined in this study for U.S. workers for the years 1960, 1965, 1970, 1975, 1980, and 1985. (The dose distributions for 1960, 1965, 1970, and 1985 are not based on comprehensive data, but are shown to provide a chronological perspective for the more complete 1975 and 1980 distributions.)

There is a constantly increasing curvature of dose distributions in the dose range above about 1 rem since 1960. The increasing curvature above 1 rem may be interpreted, according to the HLN model, as a continuing trend of increased effort to limit individual doses. If no attention is given to reducing doses near the limits, the distribution of workers on a log probability scale would generally tend to be linear ("lognormal") rather than curved ("hybrid lognormal"). The lognormal case is approximated by the 1960 distribution and is also observed for 1958 AEC exposure data (FRC60b). This increasing curvature results in

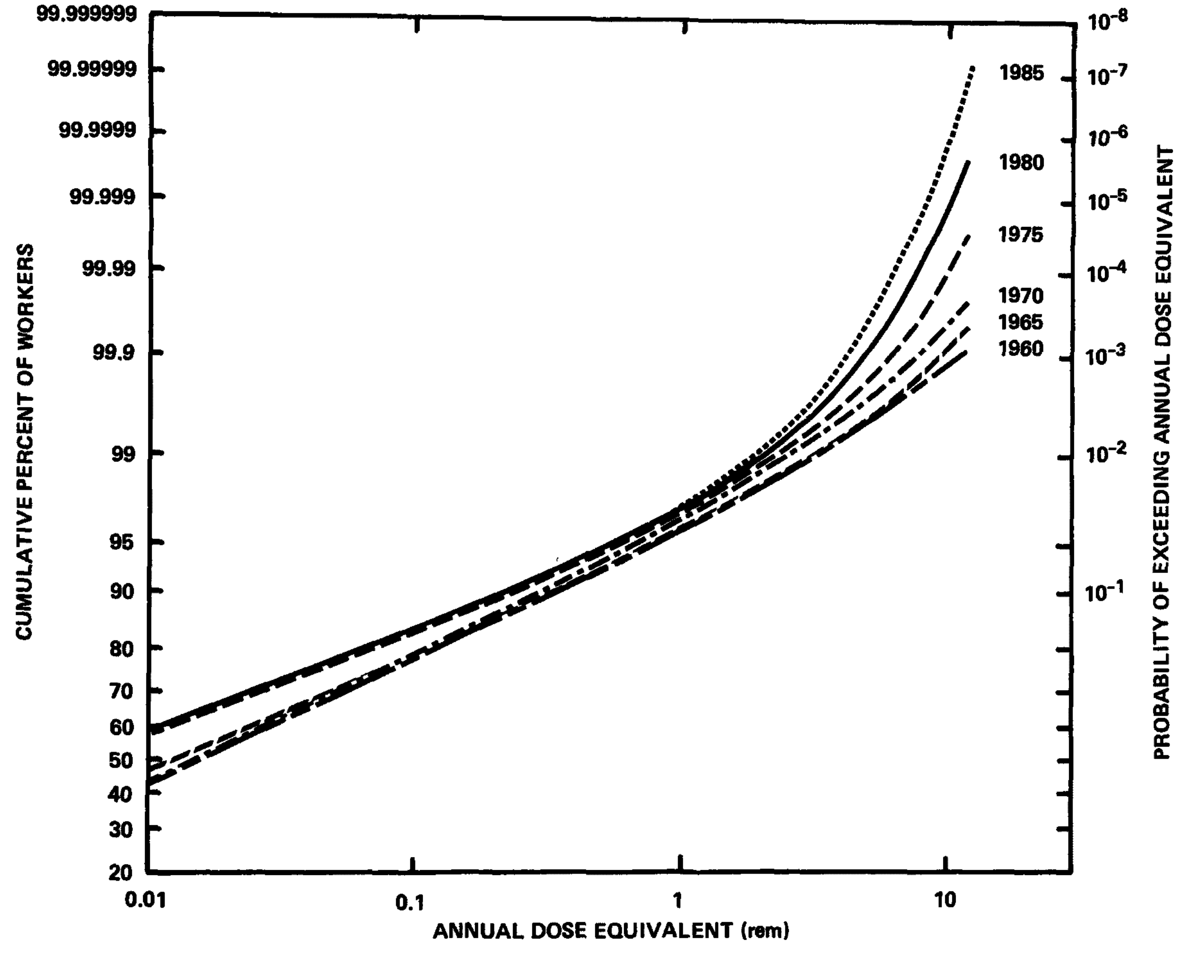


Figure 12. Dose distributions for potentially exposed workers, 1960 to 1985.

the fraction of workers above 1.5, 5, and 12 rems decreasing by factors of about 1.1, 2, and 10, respectively, every five years since 1970. At the same time, the fractions of workers above 0.1 rem and 0.5 rem have remained almost constant since 1970. Overall, the fraction of workers above the mean annual dose in any year has been approximately constant at about 15% since 1960.

Before 1975 the shapes of dose distributions are relatively uncertain below 1 rem, because summaries of exposure data typically contain no detail in this region, except for an AEC pilot study (AEC68a,68b, 70,71,73). Therefore, we examined all readily available data to reconstruct likely patterns of doses below 1 rem. From these reconstructions we estimate that the fraction of all potentially exposed workers that received less than measurable doses has ranged between 50% and 63% since 1960. From these results, we surmise that the minimum reported dose roughly decreased from about 20 mrem before 1970 to about 5 mrem in 1980 (see, for example, Figure 12). Although only a simplistic interpretation of the historical trend of dose distributions, this assumption is consistent with improved dosimeter sensitivity over these years and our reconstruction of the low dose portions of worker dose distributions.

There are a number of distinct features of the dose distributions for each of the five major occupational categories. Displays of these distributions are given in Figures B-4 to B-9 of Appendix B. Overall, workers in industry most closely parallel the national workforce in 1975, 1980. and 1985.

All workers in government operated under an annual limit of 5 rems in 1980. We examined this further by fitting the HLN distribution to exposure data below 2 rems to predict on that basis what fraction of workers would normally be expected to exceed 5 rems. This procedure predicted a much larger fraction (0.9%) than that actually observed (0.05%). We presume that this indicates the effect of increased efforts to limit doses, especially those to the most highly exposed workers.

The fraction of medical workers below 1 rem is similar to that for government workers. However, as in 1975, there continued to be some medical workers above 10 rems in 1980, although this fraction has decreased considerably since 1960. Some of these higher doses may be due to dosimeters worn outside protective clothing; we have not been able to evaluate this possibility.

Nuclear fuel cycle workers exhibit a unique dose distribution compared to other major groups of workers. The fraction (0.2%) of workers above 5 rems is the largest. (This fraction is smallest for government workers.) It is perhaps significant that these workers are regulated under a limit of 3 rems per quarter, rather than 5 rems per year.

The dose distribution for workers in miscellaneous occupations was similar to that for medical workers. No interpretive analysis was attempted for this relatively small and poorly defined group of workers.

We expect the 1985 dose distributions for each group of workers to reflect the trends discussed above. Thus, the overall dose distribution of U.S. workers should continue the 1960 to 1980 trend shown in Figure 12. The 1985 dose distribution was estimated by extrapolation of the trends in the values of the parameters of the HLN model for 1975 and 1980 exposure data. However, since the 1985 dose distribution obtained using the HLN model exhibits a mean annual dose of 110 mrem, and the previous estimate of mean annual dose was 105 mrem (see Figure 11), the 1985 dose distribution (shown in Figure 12) was adjusted slightly to give a mean annual dose of 105 mrem (i.e., the "ρ" parameter of the HLN model, detailed in Appendix F, was multiplied by the factor 110/105). This lognormal probability display of the 1985 distribution shows increased upward curvature above 0.5 rem, compared to the 1980 dose distribution, due to a presumed continuing trend of increased efforts to minimize exposure.

2. Distributions of Collective Dose to Workers

The collective dose distributions for U.S. workers are shown in Figure 13 for the years 1960, 1965, 1970, 1975, 1980, and 1985. These collective dose distributions were derived analytically from the HLN fits to the dose distributions shown in Figure 12.

The fraction of collective dose above 1.5 rems decreases from 60% in 1960 to 34% in 1985, while the fraction of workers above 1.5 rems remains roughly constant at about 2 to 3%. However, we again observe a long term trend in the reduction of high doses from the increasing curvature of the collective dose distributions above 0.5 rem. The contribution to collective dose from doses above 5 and 12 rems decreases from 15% to 3% and from 2% to 0.001%, respectively, between 1970 and 1985. The estimated decreases in the percent of collective dose above 0.5, 0.75, 1, 1.5, and 2 rems are, very roughly, 3%, 4%, 5%, 6%, and 7%, respectively, during each five year period between 1975 and 1985. We observe similar trends for each of the major categories of workers.

3. Projected Dose Distributions in 1985 Under a 5-rem Constraint

The projected 1985 dose distribution for 1.64 million potentially exposed workers having a mean annual dose of about 105 mrem, i.e., a collective dose of 175 thousand person-rems, has been presented above. This distribution contains about 600 workers exceeding 5 rems. Such a distribution is possible under current Federal Radiation Protection Guides, which permit doses up to 3 rems per quarter. Here we consider the possible change in the dose distribution for these same workers at the same mean annual dose (and therefore also the same collective dose), but constrained so that essentially no workers are exposed above 5 rems in a year.

In achieving a reduced dose limit in a given group of workers, one objective is not to increase the collective dose of that group or any

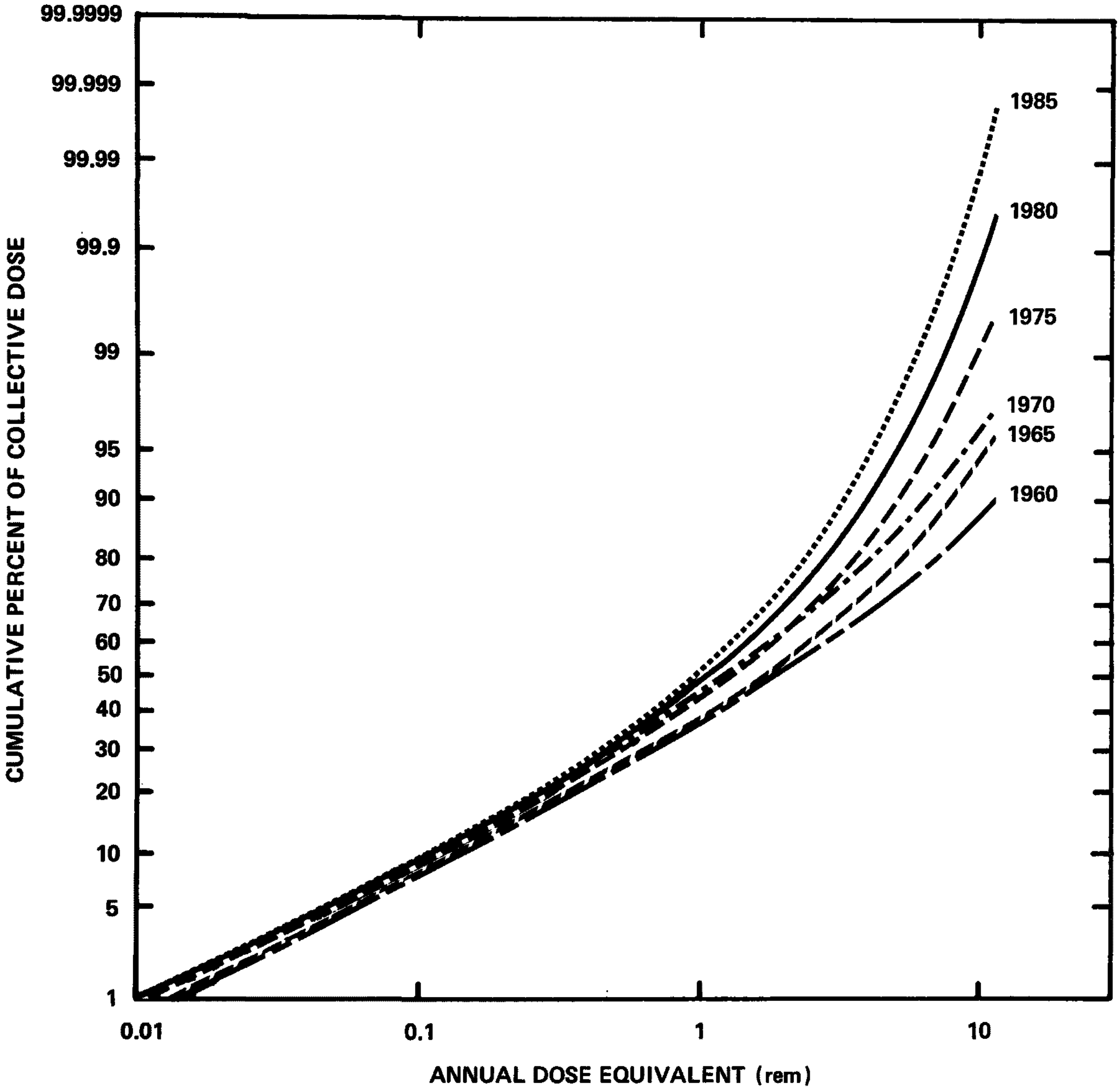


Figure 13. Collective dose distributions for exposed workers, 1960 to 1985.

other group of workers. Given a group of workers projected to receive a collective dose following some distribution of doses, it is often theoretically possible to change the distribution of individual doses without increasing the collective dose (Ku82c). We examined here, therefore, dose distributions that have the same collective dose. This, of course, is an arbitrary case, and, realistically, one would expect the collective dose to be decreased by a lower upper limit, although under special circumstances in small groups of workers, the converse is also possible.

We examined dose distributions having a mean dose of 105 mrem for 1.64 million workers, but with the constraint that effectively no workers exceed 5 rems. This was done by allowing only a miniscule fraction of all workers to exceed 5 rems; we assumed 1 worker above 5 rems (1 worker is given by the fraction $6.1\text{x}10^{-7}$ of 1.64 million workers). We then used the HLN model to construct dose distributions having a collective dose of about 175 thousand person-rems, i.e., a mean dose equivalent of about 105 mrem. Curve A in Figure 14 shows one of these dose distributions; it was constrained to have the same fraction of workers with a less-than-measurable dose (assumed to be 5 mrem) as that of Curve B. Curve B is our best estimate of the 1985 U.S. dose distribution, as shown in Figure 12. It was obtained from a linear extrapolation of the 1975 to 1980 trends in the values for the parameters of the HLN model. Curve C shows the 1980 U.S. dose distribution for comparison.

An interpretation of Curve A relative to Curve B can be made by noting their point of intersection. This occurs at about 800 mrem, or at about 97% of the cumulative probability of not exceeding a given dose. This intersection means that the 3% of Curve B workers above 800 mrem shift to lower exposures, so that the number of workers above 5 rems changes from 600 persons to one person. This change results in the fractions of collective dose above 0.8 rem and 1.5 rems being reduced from 55% to 42% and 34% to 15%, respectively. Because the collective dose is constrained to remain 175,000 person-rems, the workers below 800 mrem receive an increased mean exposure. Thus, the fraction of

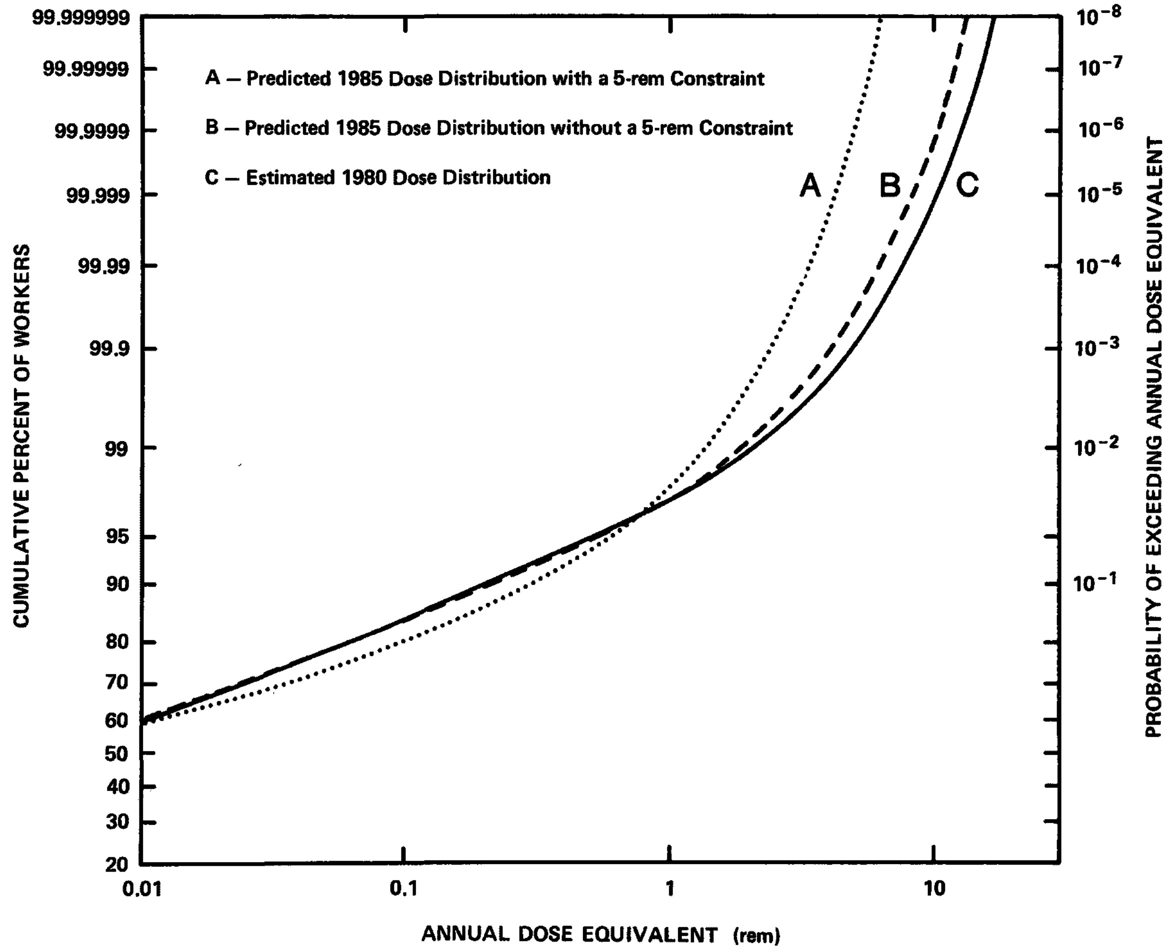


Figure 14. Projected dose distribution for potentially exposed workers for 1985, with and without a 5-rem constraint.

collective dose below 800 mrem increases from 45% to 58% while the fraction of collective dose below 100 mrem only increases about 0.6%. We believe Curve A provides a realistic estimate of the upper bound of doses that would result from virtual compliance with a 5 rem limit.

Another perspective on the difference between Curves A and B of Figure 14 is provided by the number of workers exceeding a specified dose, as shown in Figure 15. The projected numbers of workers for 1985, shown as squares and circles in Figure 15, were calculated from the Curve A and Curve B dose distributions of Figure 14, respectively. The numbers of workers for other years were calculated from the dose distributions shown in Figure 12.

The number of workers with a dose above 3 rems has decreased since 1965, while the number of workers with a dose above 1 rem has increased since 1965. Our projected changes in numbers of workers from 1980 to 1985 are shown by either the dashed or dotted lines in Figure 15. The dashed lines indicate a reasonable expectation of change based on recent trends (Curve B in Figure 14). On the other hand, we would expect a significant decrease in the numbers of workers above 2 or 3 rems and the possibility of an increase in the numbers of workers below 0.75 rem to achieve the changes, indicated by the dotted lines, that correspond to a 5 rem limit (Curve A in Figure 14). Under our model, the number of workers receiving greater than 2, 3, 4, and 5 rems would decrease by factors of 3, 13, 75, and 600, respectively, to achieve a 5 rem limit, while the number of workers receiving greater than 0.1, 0.25, 0.5 rem could increase by up to 23%, 27%, and 18%, respectively.

From the above analysis we conclude that achieving the Curve A (Figure 14) distribution of doses in 1985 will require positive supervisory control and effort, primarily for a few thousands of workers in industry, the nuclear fuel cycle, and medicine. We note that similar transitions took place before 1980 among government workers when the Navy Nuclear Propulsion Program and the Department of Energy adopted 5 rem/y limits in 1967 and 1974, respectively.

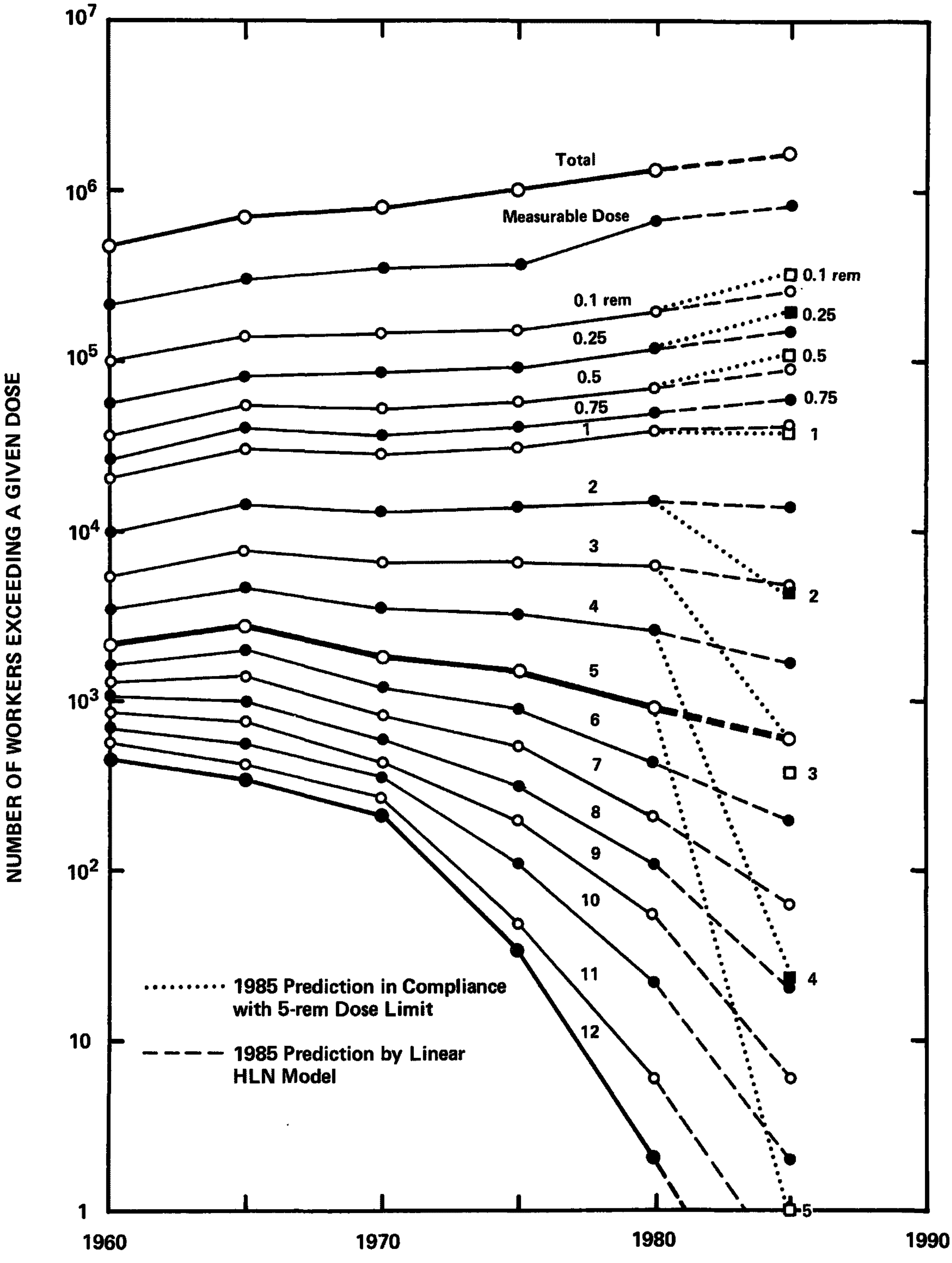


Figure 15. Number of potentially exposed workers exceeding a given dose, 1960 to 1985.

C. Estimated Cumulative Doses

There have been a number of approaches to estimating dose accumulated over the working lifetime of persons occupationally exposed to radiation (Ja74, UNSCEAR77, Wi77, Co80, AIF81, Ri82). Many of these approaches involve making assumptions on the length of a working lifetime. In our assessment, we have examined primarily historical data on cumulative dose to individual workers for which we have not had to make assumptions concerning the length of a working lifetime.

An analysis of termination data of monitored workers can potentially provide the basis for a characterization of working lifetime doses. Unfortunately, most termination data contain records for both permanently and temporarily terminated workers. In addition, it may not include cumulative doses from different periods of employment and/or different employers. Therefore, the calculation of mean length of employment and mean cumulative dose from such data will yield smaller values than those which would be calculated for only permanently retired workers whose complete employment record is included. We attempted to examine these effects by comparing the results for different termination periods. We also analyzed termination data for maximum cumulative doses. This latter assessment is affected much less than that for mean cumulative dose by the mixture of temporarily and permanently terminated worker data.

1. Mean Cumulative Doses

We examined mean cumulative dose to groups of terminated workers from NRC licensee data (Bro78,83a,83b,83c) and from DOE data (DOE76-82) by analyzing the trend of mean annual increment of the mean cumulative dose as a function of the mean term of employment.

Figure 16 shows the trend of mean cumulative dose for several worker groups with various mean terms of employment and various mean

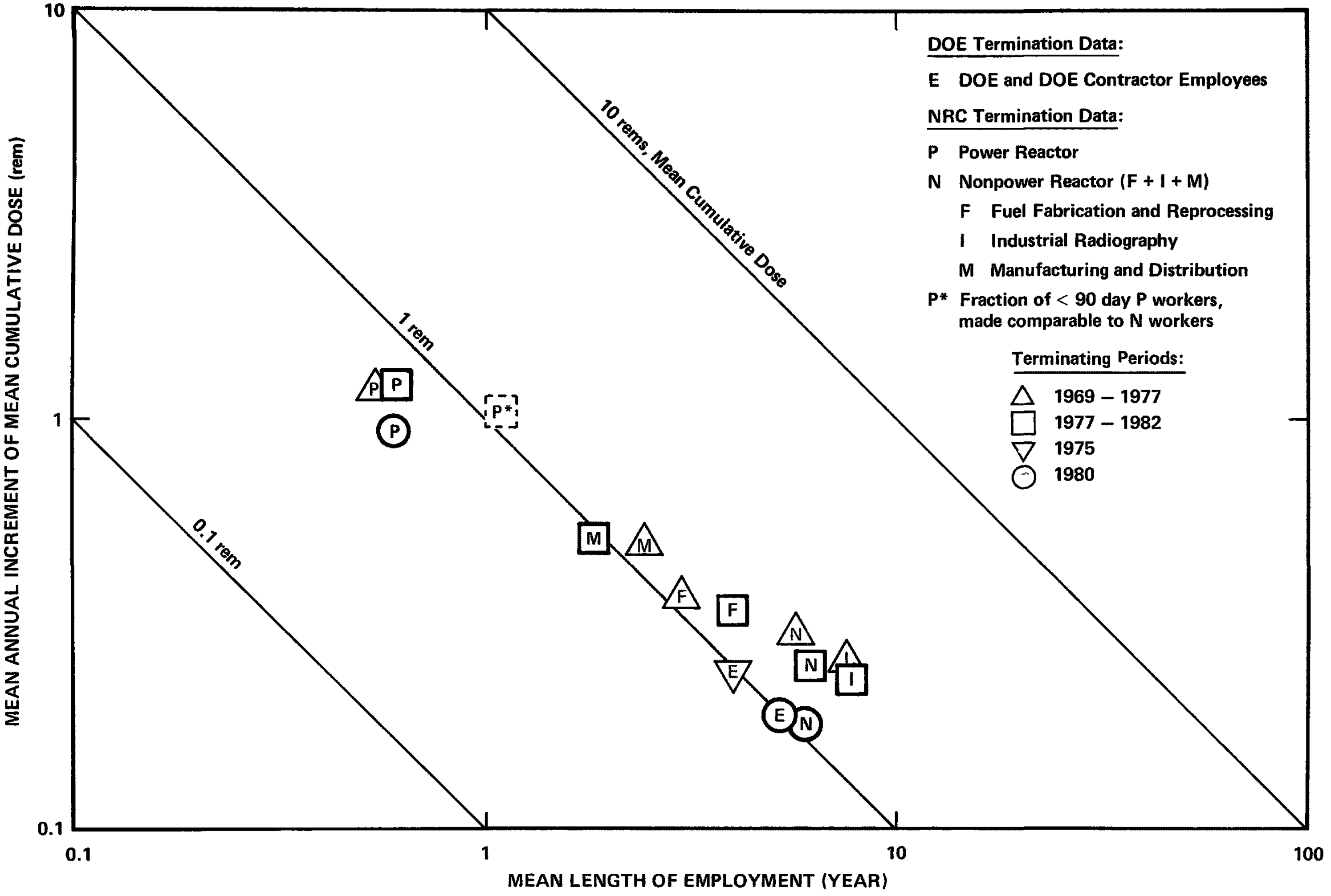


Figure 16. Mean cumulative doses for various groups of terminated workers.

annual increments of mean cumulative dose. The results for most groups of workers lie near the 1 rem contour of mean cumulative dose and in general have not moved far from this 1 rem contour during the decade examined (1969-1980). The termination data for DOE and NRC, except NRC data for power reactors, yield very similar mean annual increments of mean cumulative dose and mean term of employment (Figure 16). Our analyses of Navy data (Sc83) also yielded similar estimates of mean annual increment (0.22 rem) for a similar mean term of employment (about 5 years). The results for power reactors appear to be displaced below the 1 rem contour primarily due to a large fraction of short term (i.e., less than 90 days) workers. If the high fraction (60%) of power reactor workers terminated within 90 days is reduced to the fraction (20%) observed for NRC nonpower licensees or DOE, the results for the power reactor group lie close to a mean cumulative dose of 1 rem (shown by "P*" in Figure 16). From these results, terminated workers in the industry, nuclear fuel cycle, and government categories were estimated to have mean cumulative doses of about 1 rem.

In general, there appears to be only a small increase in mean cumulative dose with increasing mean term of employment for different groups of terminated workers. However, our analysis was not able to separately assess permanently and temporarily terminated workers, nor were we able to examine the possibility of previous periods of employment or doses from several different employers. Nevertheless, for the termination data available, the annual increment of mean cumulative dose to workers decreases with increasing mean term of employment. Therefore, we estimate, tentatively, that the mean cumulative occupational dose for U.S. workers terminated during the period of 1969-1980 is on the order of one rem.

2. Maximum Cumulative Doses

The trend of the logarithm of maximum cumulative doses, plotted in descending order versus the logarithm of the numerical ranking of these doses, is shown in Figure 17 for two groups of NRC licensees for the period 1977 to 1982. One group consisted of power reactor, fuel fabrication, and reprocessing workers; the other group consisted of industrial radiographers and workers in manufacturing and distribution of byproduct materials. The first group roughly approximates workers in the nuclear fuel cycle, while the latter group corresponds to about one-fifth of workers in industry. The descending trend and slope of cumulative doses by rank (r) for the 500 terminated workers receiving the highest doses was remarkably similar for both groups. This trend is proportional to the reciprocal of the descending order of ranking raised to the 0.3 power (i.e., $r^{-0.3}$). The maximum cumulative dose extrapolated from the above trend (by fitting the 500 largest doses) is about 110 rems for both groups. This value is identical to recorded maximum cumulative doses. In view of recent exposure trends, it appears unlikely that maximum cumulative doses will be larger in the future. Therefore, we estimate that maximum cumulative doses to U.S. workers in the future will be no larger than about 100 rems.

We examined NRC termination data to determine whether or not there was any indication of an overall active effort to limit individual cumulative dose. The mean cumulative dose for workers grouped according to length of employment generally increased with increasing length of employment, while the mean annual increment of cumulative dose generally decreased. Using the HLN model, we found that the inferred degree of effort to control cumulative dose decreased with length of employment in each NRC category. Thus, according to present termination data, the degree of active control appeared greatest in early years of employment, during the periods of highest mean annual doses. This result is also consistent with the larger degree of control of exposures inferred for terminated workers analyzed on a quarterly versus an annual basis. The above results are also consistent with those terminated workers with cumulative doses above 25 rems, who had a trend of smaller mean annual increment of cumulative dose with increasing length of employment. We

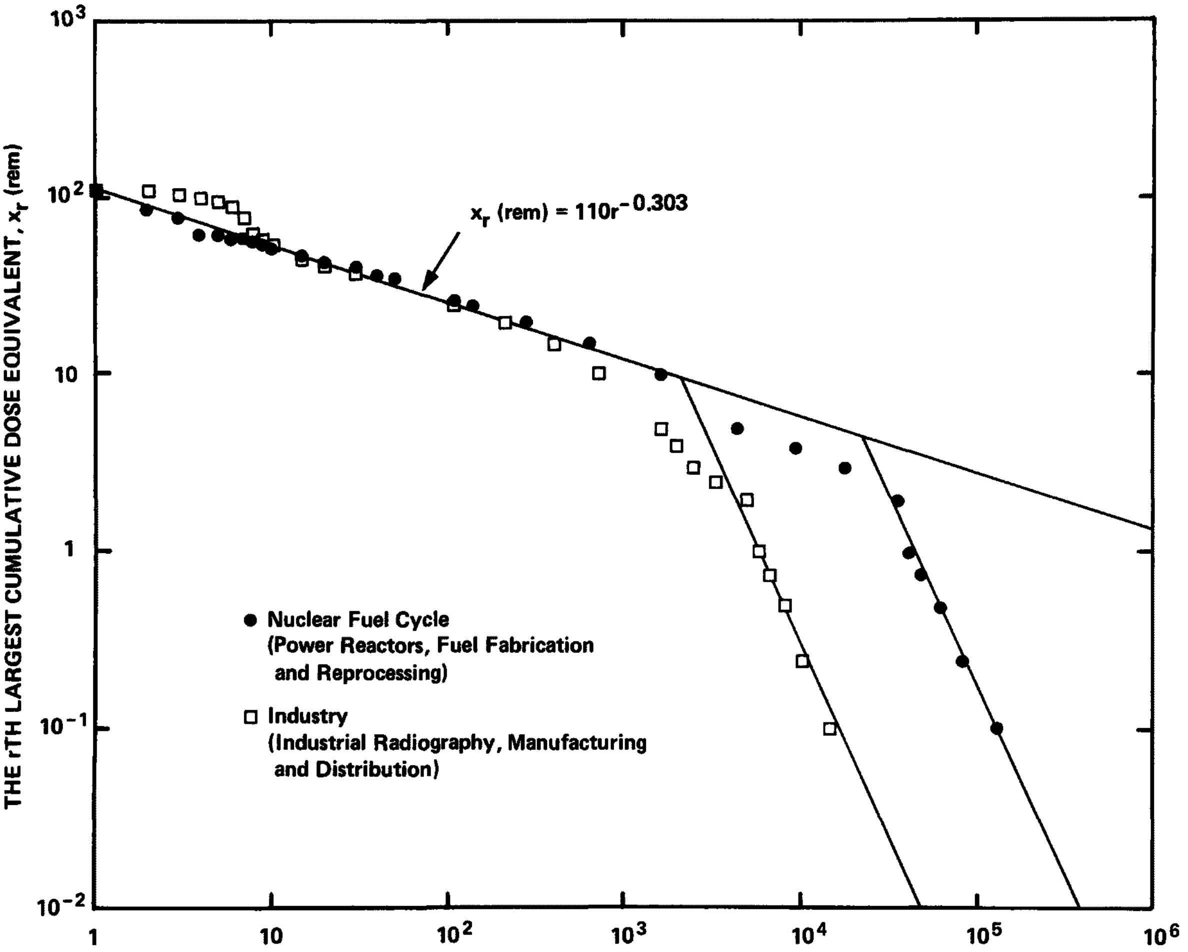


Figure 17. Cumulative doses, in descending order of magnitude, for terminated employees of NRC licensees, 1977 to 1982.

anticipate that cumulative doses will continue to be determined by efforts to limit annual doses and by the overall tendency of individual cumulative doses to have smaller mean annual increments for increasing length of employment.

VI. ERROR AND UNCERTAINTY

All of the estimates in our analyses are, inevitably, subject to a variety of sources of error and uncertainty. Although it was not always possible to make numerical assessments of error, we have tried to minimize the effects of errors by selecting and modeling the best data available to achieve the objectives of this study. These objectives were to summarize as accurately as possible: 1) the number of male and female workers potentially exposed to ionizing radiation in major occupational groups in the United States, and 2) the dose and age distributions of these workers. The methods used to minimize errors and uncertainties are described below.

A. Introduction

There is no single source of information, such as a Bureau of Labor Statistics Standard Industrial Classification code, that identifies potentially exposed workers. We had to rely on our general knowledge to identify significantly exposed groups of workers. This knowledge has increased over the years, and we are reasonably confident that all such groups of workers are now identified, and that this report addresses all significantly exposed groups. Two exceptions noted in Chapters 1 and 2 are some Federal, State, and local regulatory workers and some workers in mineral extraction industries. However, doses to these groups are small.

The available data on the number of workers reflect a wide variety of reporting practices, especially for workers who are exposed to very low levels of radiation. This variety reflects differences in Federal and State jurisdictions and responsibilities. In cases where complete reporting of the number of workers did not occur, we generally examined two quantities in estimating the number of workers: (1) key indices related to the size of the work force, and (2) the number of potentially exposed workers per unit index quantity.

The available exposure data reflect the effects of different levels of dosimeter performance and different monitoring requirements and practices. Dosimeter data may include errors and uncertainty related to the calibration of dosimeters for different radiation energy spectra and for different exposure geometries (see Appendix C). Monitoring requirements and practices reflect differences in the purposes for which personnel monitoring devices are used, e.g., to assure that limits are satisfied, to provide records demonstrating there is little or no exposure, or to measure the effectiveness of protective measures. In addition there may be uncertainty as to whether dosimeters are worn inside or outside protective clothing, e.g., the objective may be the determination of dose at the surface of clothing or to the head rather than dose to the whole body of the worker. Also, the misreading of dosimeters, reporting of incorrect data by licensees to regulatory agencies, and errors in data processing can contribute to errors. We did not assess the above sources of error and uncertainty; we simply identify them and the need for evaluation in future studies.

Personnel monitoring techniques used before 1960 have been discussed in early documents (NCRP52, Mo67). Indications of the level of accuracy of personnel monitoring devices supplied by commercial dosimetry services in the early 1960's have been reported for a pilot study (Wa64). Although we did not assess the effect of errors in the measurement of individual worker doses, we highlight here some of the results of a recent series of dosimetry performance tests, which are summarized in Appendix C, on the assessment of mean doses to large numbers of workers. The results of these tests show that the absolute value of the mean bias or deviation for the determination of whole body dose equivalent was 0.24 for low energy photons and 0.07 for high energy photons. These tests involved 56 processors, including participants from the military, private industry, national laboratories, nuclear power plants, and commercial processors, and incorporate a variety of mixes of the use of film and TLD dosimeters. For the commercial data that provided the basis for the majority of our analyses of worker dose in medicine and industry, the corresponding mean deviations were smaller: 0.01 (film) and 0.09 (TLD) for low energy photons and 0.04 (film) and 0.01 (TLD) for high energy photons. This data consisted of approximately 90% film and 10% TLD records. The uncertainty associated with biases in dose for the commercial data we used is less than the average for all participants in these performance tests. From these observations we judge that the mean values of annual dose and collective dose estimated in this study have mean biases no greater than about 0.2 for most worker groups due to errors in dosimeter readings.

Our estimates of dose distributions by age and sex were based on incomplete, but generally substantial samples of dose, age, and sex data (in most cases, approximately 10-30% of workers). Reliable estimates of the dependence of dose distributions upon worker age or sex require careful characterization of each worker group in terms of dose, age, and/or sex information (including historical trend analyses). In a few cases, this information was available for only a small fraction of the work force, as, for example, in dentistry (about 3%), and the representativeness of the data had to be carefully examined. (See Appendix B for a discussion of these analyses.)

We examined the data for each worker group for uncertainties and representativeness. In developing our estimates of dose and age distributions for all U.S. workers, we examined two basic sources of error and uncertainty: the estimated probability of workers belonging to specific dose/age ranges and the weighting factors related to sizes of worker groups and used to sum the contribution from each subcategory of workers to obtain aggregate distributions. These are discussed below.

B. Methodology

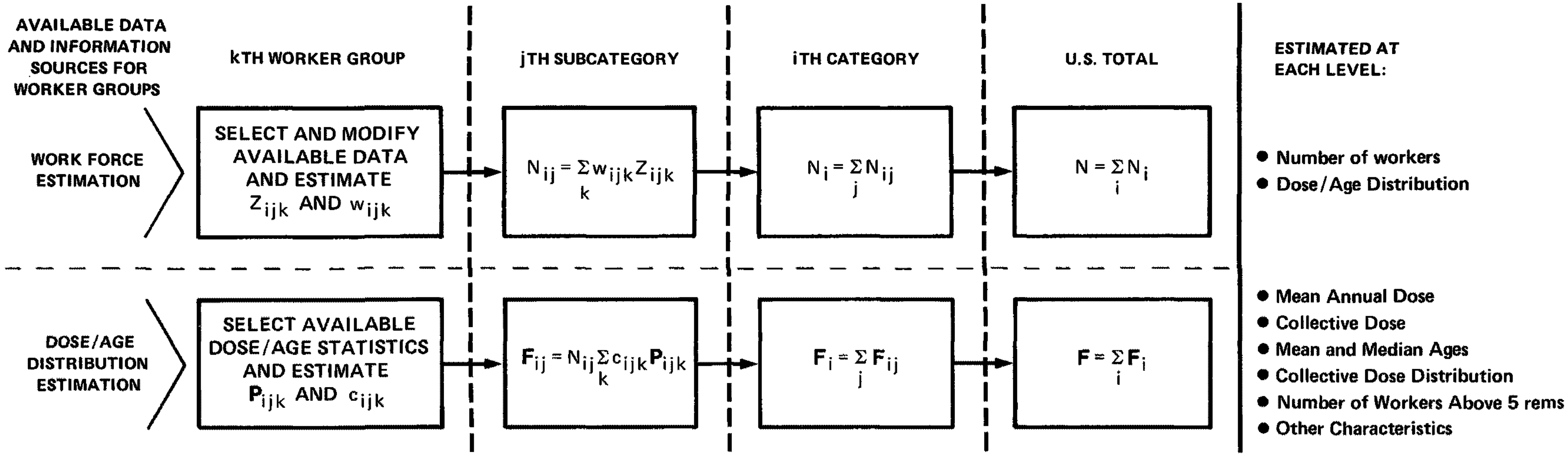
Figure 18 gives a simplified schematic of our basic methodology for (1) estimating the number of workers, and (2) estimating their dose and age distributions. The number of individuals and dose/age distributions for major occupational categories and for all U.S. workers were obtained as aggregations of occupational subcategories. From these we calculated mean dose equivalent, collective dose distributions, trend of the number of workers above specific doses, and other characteristics. The assumptions and models used for each worker category are given in Appendices A and B.

C. Number of Workers

The total number of potentially exposed workers in the United States, N, was calculated as the sum of the number of potentially exposed workers in five worker categories; $N = \sum N_i$. The number of potentially exposed workers in the ith category, N_i, was computed as the sum of the number of potentially exposed workers in j subcategories; $N_i = \sum N_{ij}$. In turn, we estimated the number of potentially exposed workers in the jth subcategory of the ith category, N_{ij}, from the summed product of w_{ijk} and z_{ijk}; $N_{ij} = \sum w_{ijk}z_{ijk}$, where w_{ijk} is the number of potentially exposed workers per unit index quantity and z_{ijk} is the index quantity for the kth worker group. Thus, the uncertainties and errors for the determination of N, N_i, and N_{ij} originate in the estimates of w_{ijk} and z_{ijk}.

In estimating the number of exposed workers, out of all those potentially exposed, we modeled the available data to assure reliable and historically consistent results. This modeling included examination of the trends in the ratio of actually exposed workers to potentially exposed workers in each sector of the work force.

To minimize uncertainties in the total number of U.S. workers, proportionately greater attention was given to minimizing uncertainties



Z_{ijk}, w_{ijk} — Key indices and numbers of workers per index quantity, respectively, for the kth worker group of the jth subcategory of the ith category.

N_{ij}, N_i, N — Number of workers in the jth subcategory of the ith category, in the ith category and in the U.S. total, respectively.

$\mathbf{P}_{ijk}, c_{ijk}$ — Estimated probability of workers in dose/age ranges, $\mathbf{P}_{ijk}$, and weighting factor for size of work force, c_{ijk}, for the kth worker group of the jth subcategory of the ith category.

$\mathbf{F}_{ij}, \mathbf{F}_i, \mathbf{F}$ — Dose/age distribution for the jth subcategory of the ith category, for the ith category and for the U.S. total, respectively.

Figure 18. Schematic of basic methodology for assessing occupational exposure to radiation.

in the larger categories and subcategories of workers. For example, since medicine is the largest category and dentistry is its largest subcategory, more effort was given to estimating the numbers of workers in dentistry than for the smaller subcategories such as podiatry and chiropractic medicine (see Appendix A).

The selection of data for Z_{ijk} and W_{ijk} was generally dependent upon what indices were most reliable, consistent, and available for the period 1960 to 1980. For hospital workers, for example, the number of hospital-based radiologists was used as a key index, rather than the number of hospital x-ray machines, for which no reliable source of data prior to 1975 was found. The number of potentially exposed workers per radiologist was estimated with information from an American College of Radiology manpower study (ACR77), a Public Health Service report (PHS83), and reported numbers of radiologic technologists (PHS79, ARRT80) (see Appendix A). The numbers of hospital x-ray machines and byproduct licensees were used as derived indices to examine the correlation with our estimates of potentially exposed workers in hospitals. Because the reported number of x-ray machines (HEW65-79; HHS80,82) fluctuated from year to year, due to the absence of data or uncertainties in the data from some States, we obtained a more reliable and consistent estimate of the number of x-ray machines through a lognormal model analysis of the number of x-ray machines by State and a trend analysis of the number of x-ray machines for major States (see Appendix A). We minimized the errors in estimates of N_{ij} for other subcategories by using similar models for estimating Z_{ijk} and W_{ijk} (see Appendix A).

Federal agencies generally provided reliable data for the number of monitored workers for each subcategory, N_{ij}. However, there were uncertainties in some data, and no data before 1970, from several of the small agencies. To minimize these uncertainties and make estimates where no data existed, we modeled the trend of N_{ij} for each worker group for Federal agencies since 1960 (see Appendix A).

To examine the reliability and consistency of our estimates of N, N_i, and N_{ij}, we compared trends of one group with those for similar or relevant worker groups at each level of worker aggregation. In addition, the trends of N and N_i were compared with the trends of the U.S. population, total labor force, and economic growth (see Appendix A). Thus, whenever possible at all levels of analysis, we sought to check the reasonableness and to examine uncertainties in estimated numbers of workers through examination of trends and intercomparisons with other suitable indices.

D. Dose/Age Distributions

The dose/age distribution for all U.S. workers potentially exposed to radiation, F, was calculated as the sum of the dose/age distributions for the five major categories; $F = \sum F_i$. Similarly, the dose/age distribution for workers in the ith category, F_i, was calculated as the sum of the dose/age distribution of its j subcategories; $F_i = \sum F_{ij}$. The dose/age distribution for workers in the jth subcategory of the ith category; F_{ij}, was estimated by forming the product of N_{ij} and the weighted sum of the dose/age distributions for each of k groups of workers in each subcategory; $F_{ij} = N_{ij} \sum c_{ijk} P_{ijk}$. The weighting factors, c_{ijk}, were estimated from the relative number of workers, facilities or licensees; and P_{ijk} is the normalized probability distribution for the kth worker group. Thus, the uncertainty and errors for the determination of F, F_i, and F_{ij} originate in the estimates of c_{ijk}, P_{ijk}, and the previously discussed N_{ij}.

As in the estimation of N_{ij}, we minimized errors in the estimates of F and F_i by giving greater attention to the F_{ij} where most workers were found. However, available dose/age statistics for P_{ijk} vary in completeness and degree of representativeness. Even statistics from government agencies may be incomplete because of differences in personnel monitoring programs and reporting requirements. As an example, not all licensees of NRC are required to report their monitoring data. Our dose and age data from commercial sources were unavoidably incomplete for any given category of workers and had unknown degrees of representativeness.

We sought to minimize uncertainties in the P_{ijk} by giving careful consideration to the characteristic shapes of dose and age distributions for the most important groups of workers by examining the reasonableness of fit of the data to the HLN and Johnson S_B distributions (see Appendices B and F). Similar care was given to estimates of c_{ijk}. As an example, since about 98% of exposed hospital workers are found in university and general medical and surgical hospitals, it was important to determine the number of these hospital workers and their weighting factors, c_{ijk}, accurately. We again attempted to minimize such errors through the use of trend analyses.

The relation of personnel dosimetry data to actual whole-body dose to the worker is also uncertain. Since 1960, most reported dosimeter readings are likely to correspond to maximum exposure of the worker due to careful choice of placement of dosimeters (AEC60, NCRP71, ICRP82). However, we did not investigate this factor and only summarize and analyze reported values for personnel dosimetry. Another source of uncertainty in the probability distribution of workers in dose/age ranges, P_{ijk}, is differences in personnel monitoring requirements. NRC (AEC60), OSHA, and States require the monitoring of any individual likely to receive a dose in any calendar quarter in excess of 25% of 1.25 rems (i.e., about 300 mrem). Based on our evaluations of monitoring data, we believe that essentially all workers receiving greater than 300 mrem quarter are monitored. For workers likely to be exposed to less than 300 mrem/quarter, there are effectively no requirements for monitoring. Even though the vast majority of monitoring records are for these workers, and for most installations a policy of monitoring all potentially exposed workers exists, there remains uncertainty concerning the real distribution of worker doses below 300 mrem. To attempt to generate completely verified values for P_{ijk} over the years and among different worker groups, extensive studies would be required. The need for such historical studies has not been assessed. Despite the above, we believe that the extensive data available for this study allowed development of reasonably accurate dose and age distributions, especially for the more highly exposed workers.

Exposure data for workers by age were available only for the years 1975 and 1980. Most of these data are commercial dosimetry data. Dose/age distributions derived from the commercial data were compared with some limited dose/age data available from several government agencies and we found these were quite consistent. We were unable to check the consistency of dose/age projections for other categories of workers.

E. Conclusions

We have particular confidence in our results for 1975 and 1980. For these years there was nearly complete reporting for workers in government and in the nuclear fuel cycle and a large sample of commercial dosimetry data was available for workers in the other major categories. Our estimates for the years from 1960 to 1970 have greater uncertainty due to the paucity of available data. For example, the number of workers in the nuclear fuel cycle was not well reported before 1970. However, we believe that our estimates of the total number of potentially exposed workers in the United States for this period are useful, as evidenced by their reasonable correlation with trends in the U.S. population, U.S. labor force, and other indices (see Figure A-5).

Mean dose, collective dose, and mean dose to measurably exposed workers were estimated from exposure data fitted to the HLN distribution model. Mean and median ages were estimated from age data fitted to the Johnson S_B distribution model. We examined the reliability and characteristics of the fit of data to these probability distribution models. In most cases, we estimate the error introduced by using these models to be well within $\pm5\%$. There are a few small subgroups of workers for which the introduced error might be as high as $\pm15\%$.

The collective dose distributions by dose range in each major category were estimated from the HLN fits of the data for the F_i dose distributions (see Appendix F). This provided a uniform and consistent method for collective dose evaluations. One source of uncertainty in calculations of collective dose is the assumption of some contribution from less-than-measurable exposures. According to our assessment, however, the estimated contribution of collective dose from workers assigned less-than-measurable doses was very small, in most cases less than 1%. Another source of uncertainty derives from the goodness-of-fit of the HLN distribution model to the data. However, the observed goodness-of-fit does not lead to significant bias. In most cases, the values of collective dose to workers belonging to a certain dose range were estimated to have an uncertainty of about ±10%.

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APPENDIX A

ESTIMATING THE SIZE OF THE WORK FORCE

CONTENTS

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TABLES (Continued)

FIGURES

APPENDIX A

ESTIMATING THE SIZE OF THE WORK FORCE

I. INTRODUCTION

Many factors influence the determination of the number of workers potentially exposed to ionizing radiation. The number of such workers in some professions (e.g., medical radiology and industrial radiography) is readily available. In other areas, such as industry, education, and transportation, the number of workers potentially exposed is difficult to obtain or estimate. Even government data on the number of monitored workers depend on a number of factors which must be considered when using the records. Some of these factors are: personnel monitoring requirements, objectives of monitoring practices, and categorization of monitored workers. These factors are important because there is no definition of potentially exposed workers. We have approached this problem by adopting working definitions of persons potentially exposed to radiation based on their profession or on monitoring practices. By examining the trends and characteristics of the numbers of workers over recent historical periods, we can better understand present distributions of potentially exposed workers in various work sectors and can reasonably project future distributions. We selected 1960, the year Federal Radiation Guidance was first promulgated, as the beginning year for our analysis.

Our numerical estimates of persons potentially exposed to radiation were based, wherever possible, on more than one index to minimize uncertainties associated with use of a single index. Then, numerical estimates from several indices were compared and basic assumptions for each method examined and adjusted until consistency was reached among them. Finally, as a test of the reasonableness of our estimates, we compared trends in the number of potentially exposed workers with trends in other indices, such as relevant economic indicators or the size of the U.S. work force.

Our procedure for estimating the number of potentially exposed persons in a specified group of workers was to:

1) Examine and select one or more indices (i.e., number of licensees, x-ray machines, or professional workers) for estimating the number of workers over a specified period of time;

2) Model the data for each index to determine the most consistent data for the relevant time period;

3) Model the number of workers per unit index quantity;

4) Estimate the number of workers for each index for the specific time period from the results of steps 2 and 3; and,

5) Compare estimates of the number of workers from each selected index. Where there was more than one relevant index, the procedure was to return to step 3 and iteratively examine and adjust model parameters or assumptions until satisfactory agreement of numerical estimates was obtained.

This procedure assured intercomparability of estimates over a period of years as well as the most consistent estimates for any year.

To illustrate the above procedure, we consider its application to estimating the number of potentially exposed workers in medicine. At step 1, we selected some input data, e.g., the reported numbers of x-ray machines, radioactive byproduct material licensees, or professionals in an occupational subcategory. The data for each index are not always complete or accurate. An example of incomplete data is the reported number of x-ray machines (HEW65-79, HHS80, 82). These annually reported data have not always included every State, the District of Columbia, and Puerto Rico, and some data consists of estimates, rather than accurate counts of registered machines.

At step 2, we modeled the data for each index. As an example, this was done for medical x-ray machines by first modeling and adjusting the reported data according to (1) the historical trend of the number of x-ray machines in each State and (2) the lognormal distribution of the number of x-ray machines by State. (This procedure was suggested by our statistical analysis, which showed that the number of x-ray machines were distributed lognormally among the States and that the total number of x-ray machines had a simple historical trend for the period 1965 through 1980.) Then, in a similar fashion, the number of x-ray machines for each subcategory of medicine was obtained from analysis of historical trends.

We next (step 3) determined the number of potentially exposed workers per unit index quantity. This, for example, was the number of potentially exposed workers per x-ray machine, per byproduct licensee, or per "professional" worker (e.g., radiologist). In step 4, we calculated the number of workers from the product of the index quantity and the number of workers per unit index quantity. At step 5, we cross-checked the estimated number of workers with the results of the other relevant indices or alternative approaches. The procedure was then iteratively repeated at step 3 until agreement was reached among the different approaches.

We indicate below, for each group of workers, the basic indices used to calculate the number of workers. We designate as derived indices the quantities checked for correlation with the results calculated from the basic indices.

II. ESTIMATES OF NUMBERS OF WORKERS IN THE MAJOR WORK CATEGORIES

We estimated the number of potentially exposed workers in the five categories and nineteen subcategories listed in Table 2. The numbers of these workers were estimated in each subcategory and category according to the methodology shown in Figure 18. We sought to obtain accurate estimates of the number of all types of workers, but especially for the largest groups. Since medical workers are the most numerous, we gave particular attention to these workers and to dental workers, their largest component.

In our 1975 report (Co80), the results of a study by Fess (Fe69), which related the number of potentially exposed workers to the number of medical x-ray machines, were used to estimate the number of potentially exposed workers in medicine. However, because the Fess study was based on 1965 data, we reexamined the validity of using this method and results for the entire period 1960-1985. We concluded that this approach was useful for estimating the number of workers in private practice (except radiology), veterinary medicine, and chiropractic medicine. However, for dentistry, hospital, and podiatric workers we used professional manpower data (PHS73b,75,76.79,82; DOE75,80,81; ACR75, 77,80; ARRT80), because the Fess method did not yield reasonable results. Since we had little direct data on the number of potentially exposed medical workers, we compared the trends of projected numbers of various potentially exposed medical workers to corresponding types of medical doctors and allied medical personnel.

Potentially exposed workers in industry comprised the second largest group of workers in 1980. The lack of detailed information precluded our generating estimates for many of the specific types of industrial occupations, such as well-logging, nondestructive testing, and radiopharmaceutical production. Therefore, we used the same three broad subcategories used in the 1975 study. We also relied heavily on trend analysis to assure consistent estimates for these workers over the period 1960 to 1980. Since this group of workers is projected to have the second largest collective dose in 1985, more detailed information is desirable for future summaries of national occupational exposure.

The number of workers in the nuclear fuel cycle was the second smallest among the five major categories of workers for the period 1960-1980. All data were obtained from the NRC and DOE, under the assumption that the number of potentially exposed workers was identical to the number of monitored workers. However, for the period before 1970 we used a trend analysis similar to that used for workers in industry to estimate the fraction of workers that should be assigned to each subcategory.

The number of potentially exposed workers in government has remained intermediate in size among the major categories of workers for the period 1960-1980. Due to the existence of relatively consistent and comprehensive recordkeeping practices, we believe that nearly complete data were obtained from Federal agencies. Some additional trend analysis was needed to estimate the numbers of some workers before 1970.

The number of workers in miscellaneous occupations amounted to less than 6% of all potentially exposed workers in the United States. To estimate the number of these workers, we used a method similar to that used in our 1975 report and checked the results against the trends for byproduct licensees and workers exposed to other sources of radiation.

A. Medicine

The specific method used to estimate the number of potentially exposed workers for each subcategory of medicine is described below.

1. Dental Workers

Table A-1 shows our estimates for the number of potentially exposed dental workers. We relied heavily on numbers of professional dental workers and correlated our estimates of potentially exposed workers with two indices: the number of dentists and number of x-ray machines. The data for the number of active civilian dentists is believed to be more reliable than that for the number of dental x-ray machines.

The number of potentially exposed dental workers lies somewhere between the total number of active dentists, as a lower estimate, and the total number of workers in the dental work force, as an upper estimate (see Figure A-1). The latter includes dentists, dental assistants, and dental hygienists. Many dentists have more than one x-ray machine and may have dental assistants and dental hygienists assisting them in or doing all dental radiography. From these considerations and examination of the number of potentially exposed workers per dentist and per x-ray machine (Fe69), we concluded that the number of potentially exposed dental workers for the period 1960 to 1980 was most simply expressed as 80% of the sum of active civilian dentists, dental assistants, and dental hygienists. The detailed modeling and considerations leading to this conclusion are summarized below.

a. Number of Potentially Exposed Workers per Dentist

Dental workers as a group are potentially exposed, but not all such workers are involved in dental x-ray procedures. The number of dentists practicing in offices is about 90% of active civilian dentists (PHS82).

Table A-1. Estimated number of potentially exposed workers in dentistry, 1960-1985

	1960	1965	1970	1975	1980	1985
Workers[a] (10^3)	134	150	177	215	259	304
Derived Indices						
Dentists[b] (10^3)	85	90	96	107	121	135
Workers/Dentist	(1.58)	(1.67)	(1.84)	(2.01)	(2.14)	(2.25)
X-ray Machines[c] (10^3)	81	94	107	149	191	233
Workers/Machine	(1.65)	(1.60)	(1.65)	(1.44)	(1.36)	(1.30)

[a] Workers potentially exposed to radiation from the operation of dental x-ray machines.

[b] Active civilian dentists; number obtained from PHS82, except for 1985 estimate.

[c] Adjusted or extrapolated 1985 number from lognormal analysis of reported data (HEW65-79; HHS80,82).

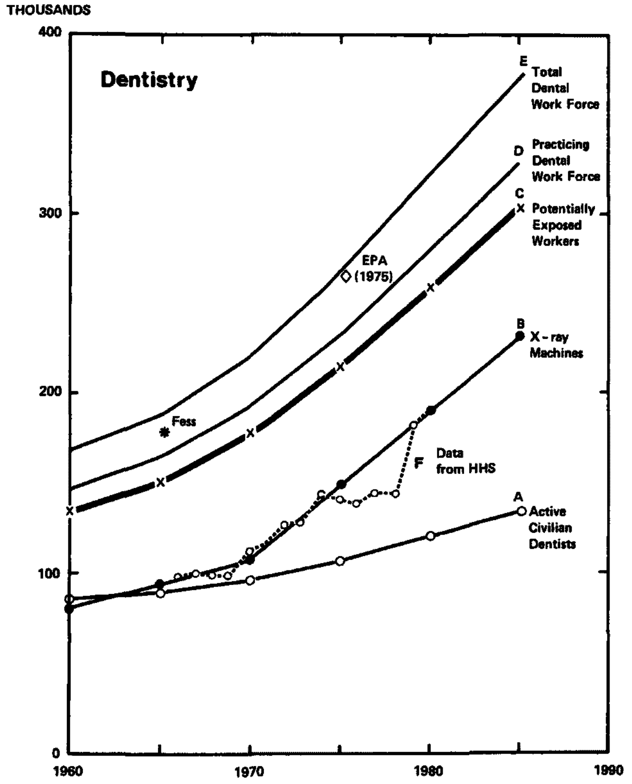

Figure A-1. Estimates of workers and x-ray machines in dentistry, 1960-1985.

We assumed that about 90% of dentists practicing in offices were potentially exposed; this is approximately equivalent to 80% of all active civilian dentists. We estimated that about 85% of all currently licensed dental assistants and dental hygienists were actively practicing, based on Public Health Service data (PHS82). We assumed that about 90% of practicing dental assistants and dental hygienists were potentially exposed. That is close to 80% of all dental assistants and dental hygienists. We did not consider laboratory technicians or clerical staff, even though they may be exposed or monitored in some dental offices. From these considerations and simultaneous comparisons with projections based on the number of x-ray machines, we approximated potentially exposed dental workers as 80% of active civilian dentists, dental assistants, and dental hygienists. From this result, the derived index for the number of workers per dentist was calculated and is given in Table A-1.

The number of active civilian dentists increased by 13% and 26% for the periods 1960-1970 and 1970-1980, respectively (PHS82). The number of active civilian dentists per 10^5 civilian population was nearly constant at about 47 from 1960 to 1970, but increased gradually to 53 by 1980 (PHS82). We projected the number of active civilian dentists for 1985 to be 135,000 (58 dentists per 10^5 civilian population) from the 1975-1980 trend. The numbers of dental assistants and dental hygienists were estimated from "Health Resources Statistics" before 1977 (PHS73b, 75,76,79), and from "Health Manpower Projections" (PHS81) and other information (We83) after 1977. Dental workers employed by the Department of Defense and the Veterans Administration are included in those subcategories, rather than in the dentistry subcategory of medical workers.

b. Number of Potentially Exposed Workers per X-ray Machine

Using the number of potentially exposed dental workers per dental x-ray machine derived from a study by Fess (Fe69), the number of potentially exposed workers in 1965 and 1975 is projected as about 91% and 100%, respectively, of the total number of all active and inactive dental professionals. Since these estimates were greater than the number of active dental workers, a more realistic approach was sought. By comparing the number of workers per dentist with the number of workers per x-ray machine, we concluded that about 80% of active civilian dentists, dental assistants, and dental hygienists are potentially exposed. This corresponds to a value of 1.65 workers per x-ray machine in 1960 (Table A-1). The number of workers per dental x-ray machine was roughly stable at about 1.65 until 1970 and then decreased gradually to a projected value of 1.3 in 1985. These results are consistent with numbers of persons found operating x-ray machines in contemporary dental offices having more than one machine (Cr84, Bo84, Brn84). Table A-1 summarizes these results for the period 1960 to 1985.

The total number of dental x-ray machines reported by HEW/HHS (HEW65-79; HHS80,82) has fluctuated from year to year, because not every State reported each year. These fluctuations are shown in Figure A-1 by curve "F." However, by adjusting the total number of dental x-ray machines (excluding Federal machines) according to a lognormal analysis of all dental x-ray machines by States and the historical trend for each major state, we obtained the simple trend given by curve "B." We believe that this adjusted number of dental x-ray machines also provides a reasonable index for estimating the number of potentially exposed dental workers.

c. Dental Summary

Figure A-1 shows the overall growth in the numbers of dentists, x-ray machines, and dental work force for the period 1960-1985. The number of potentially exposed workers estimated by Fess (Fe69) for 1965 lies between Curve D, all practicing dental workers, and Curve E, all dental workers. The 1975 number of potentially exposed dental workers used in our previous report (Co80) is also close to Curve E. Both of these values appear to be unrealistically high. We concluded that the number of dental workers potentially exposed to radiation is reasonably approximated by Curve C.

2. Hospital Workers

We used the number of radiologists as the basic index to estimate the number of potentially exposed workers in hospitals. We then used these estimated numbers of workers to examine their correlation with numbers of x-ray machines and numbers of byproduct licensees. These two correlations served as derived indices.

a. Number of Potentially Exposed Workers per Radiologist - Basic Index

Since the early 1960's most radiation-related work in hospitals has been done under the supervision of radiologists (ACR75, PHS73a). Therefore, the number of radiologists was selected as the basic index for estimating the number of potentially exposed workers in this subcategory. However, we first had to determine the number of radiologists working in hospitals. Figure A-2 shows our method for estimating the number of hospital-based and office-based radiologists in the nonfederal (civilian) sector.

The percentage of active radiologists (ACR77, ACR82) out of all physicians (PHS82) increased from 2.5% in 1960 to 4% in 1970. It increased much less between 1970 and 1980; and we project 4.3% in 1985. This growth corresponded to the number of active nonfederal radiologists increasing from 5,800 in 1960 (3.3 radiologists per 10^5 civilian population) to 18,800 in 1980 (8.3 radiologists per 10^5 civilian population). The percentage of active nonfederal radiologists has been essentially constant at about 91% (PHS73b,75,76,79). We

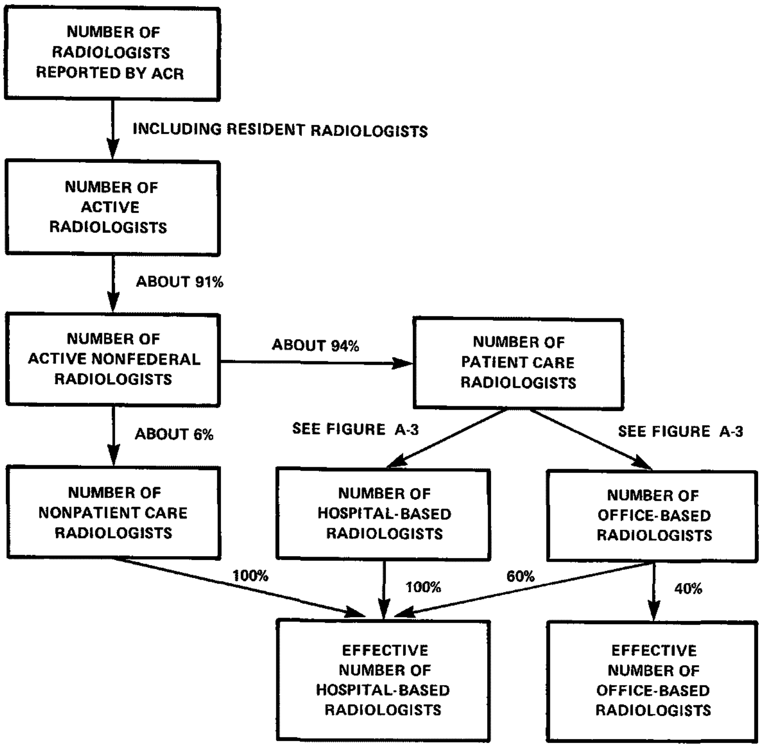

Figure A-2. Flow chart for estimating the numbers of hospital-based and office-based radiologists.

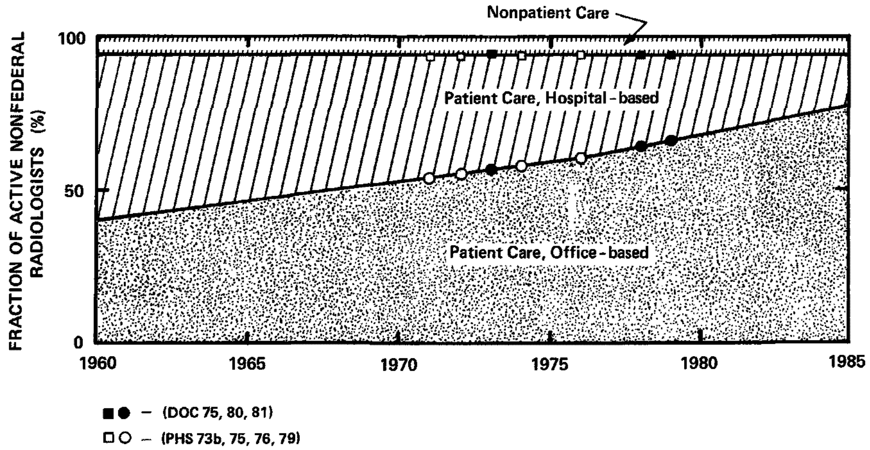

Figure A-3. Fraction of active nonfederal patient-care (hospital-based and office-based) and nonpatient-care radiologists.

Table A-2. Estimated number of potentially exposed workers in hospitals, 1960-1985

	1960	1965	1970	1975	1980	1985
Workers (10^3)	30	48	70	96	126	162
<u>Basic Index</u>						
Radiologists[(a)] (10^3)	4.6	6.9	9.1	11.3	13.7	16.2
Workers/Radiologist[(b)]	(6.2)	(7.0)	(7.7)	(8.5)	(9.2)	(10)
<u>Derived Indices</u>						
X-ray Machines[(c)] (10^3)	32	34	36	46	56	67
Workers/Machine[(d)]	(0.94)	(1.41)	(1.94)	(2.09)	(2.25)	(2.42)
Licensees[(e)] (10^3)	1.1	1.7	2.3	3.2	4.3	5.5
Workers/Licensee[(d)]	(26)	(28)	(30)	(30)	(29)	(29)

(a) Effective number of nonfederal radiologists in hospitals (see Figure A-2). Basic data from ACR82.

(b) Estimated or extrapolated from ACR75 and PHS83.

(c) Estimated or extrapolated from lognormal analysis of data (HEW66-79; HHS80-82, Fe69).

(d) The number of workers per machine or byproduct licensee was calculated from number of x-ray machines or licensees and the number of workers obtained from basic index approach.

(e) Estimated or extrapolated from NRC65-82.

project the number of active nonfederal radiologists to be 23,400 in 1985 based on the observed increase between 1975 and 1980.

The number of potentially exposed workers per active nonfederal radiologist was estimated using information from an American College of Radiology (ACR) manpower study (ACR77), "Statistics on Hospital Personnel" (PHS83), and the reported number of radiologic technologists (PHS79, ARRT80). We assumed that the number of workers per radiologist was the same in private practice and in hospitals.

The fraction of radiologists in patient and nonpatient-care out of all active nonfederal radiologists was assumed to be about 94% and 6%, respectively, from 1960 through 1985 (DOC75,80,81; PHS73b,75,76,79). The fraction of all radiologists active in patient care in hospitals was estimated from an ACR manpower study (ACR75), "Health Resources Statistics" (PHS73b,75,76,79), and other information (DOC75,80,81). The resulting distribution of these radiologists from 1960 through 1985 is shown in Figure A-3. Many radiologists work in more than one office and/or hospital (ACR75,77,82). According to a recent study, 80% of office-based radiologists reported serving in hospitals 75% of their time (ACR82). Therefore, we estimated 60% of office-based radiologists were effectively full-time hospital-based radiologists. From these considerations we define the effective number of office-based radiologists as 40% of the number of office-based radiologists and define the effective number of hospital-based radiologists as the sum of the numbers of all nonpatient care radiologists, all hospital-based radiologists, and 60% of the number of office-based radiologists (see Figure A-2).

We estimated the number of potentially exposed workers in hospitals from the effective number of hospital-based radiologists and the number of workers per radiologist. The number of workers (126,000) shown in Table A-2 is consistent with the number of hospital personnel (full- and part-time) in radiological services (99,000) reported for U.S. registered hospitals in 1980 (PHS83). From this we conclude that our model for calculation of effective numbers of hospital-based and office-based radiologists is reasonable.

b. Number of Potentially Exposed Workers Per X-ray Machine and Per Licensee - Derived Indices

We examined the correlation of the number of hospital x-ray machines reported by HEW/HHS (HEW65-79; HHS80,82) with the number of potentially exposed workers. Again, the number of machines fluctuated, because not all States were included each year. However, by modeling the number of x-ray machines (as we previously described for dental x-ray machines), we obtained the 1960-1985 trend shown in Table A-2. The number of hospital x-ray machines before 1971 was estimated from the total number of medical x-ray machines multiplied by the (back-extrapolated) ratio of hospital machines to the total number of medical machines. From the number of x-ray machines and the previously determined number of workers in hospitals, the number of workers per x-ray machine was estimated.

We also examined the correlation of the number of hospital workers with the number of byproduct material licensees. The growth in the number of NRC and Agreement State byproduct licensees in hospitals was relatively uniform except for 1976. From the number of licensees and the previously determined number of hospital workers, the number of potentially exposed workers per hospital byproduct licensee was derived and found to have been virtually constant at about 30 since 1970 (see Table A-2). This value is slightly larger than the number of monitored persons per licensee in the "medical institutional-other" category reported by NRC (Co78; Bro81,82): 29 in 1975, 22 in 1978, 26 in 1979. This would be expected since those workers associated only with x-ray machines need not be reported by licensees to the NRC.

Our trend analyses of numbers of x-ray machines, byproduct material licenses, and professional workers for the period 1960-1985 permitted us to examine the correlation with the number of potentially exposed workers. The increase in number of therapeutic and diagnostic x-ray machines (HEW65-79; HHS80,82) in the hospital subcategory was 56% for the period 1970-1980; we estimated it to be about 46% for the period 1975-1985. The growth in number of radioactive byproduct licensees (NRC65-82) for hospitals was 87% for the period 1970-1980; we estimated it to be about 70% for the period 1975-1985. The corresponding growth in the number of potentially exposed workers was estimated to be about 80% for the period of 1970-1980, and about 70% for the period 1975-1985. From these results, we concluded that the best derived index is the number of byproduct licensees. This correlation of number of workers with number of licensees appears to offer an alternative approach for future studies.

3. Private Practice

The number of potentially exposed workers in private practice is made up of the sum of workers for office-based physicians and radiologists. The number of workers associated with radiologists was described earlier. The number of workers associated with physicians was estimated from the number of physician x-ray machines and previous estimates of the number of workers per machine (Fe69).

a. Office-Based Practitioners

The number of active nonfederal office-based physicians increased slowly from 181,000 in 1960 to 189,000 in 1970. However, the number increased sharply thereafter from 204,000 (96 physicians per 10^5 civilian population) in 1974 by an annual average increment of about 9000 (PHS82, DOC81). From this, we projected the number of office-based physicians for 1985 to be 300,000 (129 physicians per 10^5 civilian population).

i. Nonradiologists

The number of potentially exposed workers associated with office-based physicians (except radiologists) was estimated from the number of physician x-ray machines (including those designated by HHS for clinics, x-ray vans, and others, but excluding those in private radiology practice (HHS82)) and the number of workers per x-ray machine. For lack of a better estimate, we have used the value of 2.24 workers per machine derived from Fess's 1965 data (Fe69) and assumed it to be roughly constant over the entire period 1960-1985. Because the reported number of physician x-ray machines (HEW65-79, HHS80,82) had large annual fluctuations, we adjusted them as previously described for the dental and hospital subcategories. The number of machines increased very slowly from 47,000 in 1960 to 48,000 in 1980 and was estimated to remain about 48,000 in 1985. Thus, the associated number of potentially exposed workers was calculated to be slowly increasing from about 105,000 in 1960 to an estimated 108,000 in 1985.

ii. Radiologists

The number of potentially exposed workers associated with office-based radiologists was estimated from the number of office-based radiologists (see Figure A-2) and the estimated number of workers per radiologist (described in hospital subcategory). The increasing specialization (among other changes) in medicine has caused the number of potentially exposed radiology workers to increase by factors of about 3 and 2.5 in the periods 1960-70 and 1970-80, respectively. The estimated numbers of radiology workers are given in Table A-3.

The total number of potentially exposed workers in private practice is the sum of nonradiology workers estimated for office-based physicians and radiology workers estimated for office-based radiologists. This result is shown in the first row of Table A-3.

b. Private Practice - Derived Indices

We also examined the correlation of the number of potentially exposed workers in private practice offices with the number of physicians in private practice, the number of x-ray machines, and the number of byproduct licensees. The derived correlations for these indices are shown in Table A-3. The number of workers per physician in private practice shows the most stable and consistent correlation.

4. Veterinary Medicine, Chiropractic Medicine, and Podiatry

The numbers of potentially exposed workers in veterinary and chiropractic medicine were estimated using x-ray machines as the basic index. For podiatry, we used the number of podiatrists.

Table A-3. Estimated number of potentially exposed workers in private practice of medicine, 1960-1985

	1960	1965	1970	1975	1980	1985
Workers (10^3)	111	116	123	136	155	180
Nonradiology workers(10^3)	105	105	106	107	108	108
Radiology workers (10^3)	6	11	18	29	47	72
<u>Derived Indices</u>						
Physicians(a) (10^3)	181	185	189	213	258	300
Workers/Physician	(0.61)	(0.63)	(0.65)	(0.64)	(0.60)	(0.60)
X-ray Machines(b) (10^3)	49	52	55	56	57	58
Workers/Machine	(2.26)	(2.23)	(2.24)	(2.43)	(2.72)	(3.10)
Licensees(c) (10^3)	1.3	1.8	2.3	2.1	1.5	0.9
Workers/Licensee	(85)	(64)	(53)	(65)	(103)	(200)

(a) Active nonfederal private office physicians, estimated from DOC81.

(b) X-ray machines in physicians' (including radiologists') offices, clinics, x-ray vans, and others. Values were estimated from HEW65-79 and HHS80,82 after adjustment using lognormal analysis.

(c) Estimated from NRC65-82.

a. Veterinary Medicine

The number of veterinarians increased by about 30% for the period 1960-1970 and 40% during the period 1970-1980 (PHS82). The number of veterinarians in 1985 was estimated from the 1975-1980 trend to be 42,800. The number of veterinary x-ray machines estimated from HEW/HHS reports (HEW65-79, HHS80,82) increased by about 20% and 70% for the periods 1960-1970 and 1970-1980, respectively. The number of x-ray machines in 1985 was estimated from the 1970-1980 trend to be 12,200. We estimated the number of workers by using the value 2.12 workers per veterinary x-ray machine (Table A-4) obtained from the Fess study (Fe69).

Table A-4. Estimated number of potentially exposed workers in veterinary, chiropractic and podiatry practices, 1960-1985

Occupation	1960	1965	1970	1975	1980	1985
Veterinary Medicine[a]						
Workers (10^3)	11	12	13	17	21	26
Basic Index						
X-ray Machines (10^3)	5	5.5	6	8.1	10.1	12.2
Workers/Machine[b]	(2.12)	(2.12)	(2.12)	(2.12)	(2.12)	(2.12)
Derived Index						
Veterinarians (10^3)	20.6	23.3	25.9	31.1	36.0	42.8
Workers/Veterinarian	(0.53)	(0.52)	(0.50)	(0.55)	(0.58)	(0.61)
Chiropractic Medicine[a]						
Workers (10^3)	11	11	12	14	15	17
Basic Index						
X-ray Machines (10^3)	9.3	9.6	9.9	11.5	13.1	14.7
Workers/Machine[b]	(1.18)	(1.18)	(1.18)	(1.18)	(1.18)	(1.18)
Derived Index						
Chiropractors (10^3)	14.3	14.8	15.5	17.9	20.3	22.7[d]
Workers/Chiropractor	(0.77)	(0.77)	(0.77)	(0.77)	(0.75)	(0.75)
Podiatry[a]						
Workers (10^3)	5	6	6	7	8	10
Basic Index						
Podiatrists (10^3)	6.7[c]	6.9[c]	7.1	7.3	8.9	10.8
Workers/Podiatrist	(0.8)	(0.8)	(0.8)	(0.9)	(0.9)	(0.9)
Derived Index						
X-ray Machines (10^3)	3.4	3.8	4.3	4.7	5.9	7.1
Workers/Machine	(1.5)	(1.5)	(1.5)	(1.4)	(1.4)	(1.4)

(a)Number of doctors estimated from PHS73b; PHS75,76,79,82.
(b)Fess study (Fe69).
(c)EPA estimate based on trend analysis.

b. Chiropractic Medicine

The number of chiropractors estimated from PHS reports (PHS73b,75, 76,79) increased by about 10% and 30% for the periods 1960-1970 and 1970-1980, respectively. The number of chiropractors was estimated from the 1970-1980 trend to be 22,700 in 1985. The number of chiropractic x-ray machines was estimated from HEW/HHS reports (HEW65-78, HHS80,82) and increased by about 5% for the period 1960-1970 and 30% for the period 1970-1980. The number of x-ray machines was estimated from the 1970-1980 trend to be 14,700 in 1985. We then estimated the number of potentially exposed workers using the value 1.18 workers per chiropractic x-ray machine given by Fess (Fe69).

c. Podiatry

The number of podiatrists was estimated to increase by about 5% and 25%, respectively, for the periods 1960-1970 and 1970-1980 (PHS82). The number of podiatrists in 1985 was estimated to be 10,800 in 1985 (PHS82). We found that the number of podiatry x-ray machines estimated from the HEW/HHS reports (HEW65-79, HHS80,82) increased by about 25% and 35% for the periods 1960-1970 and 1970-1980, respectively. The 1985 number of x-ray machines was estimated from the 1975-1980 trend to be 7,100. Because there are only about 30% fewer x-ray machines than podiatrists, the value of 2 workers per podiatry x-ray machine cited by Fess (Fe69) seems high. We therefore assumed 80% of active podiatrists for the period 1960-1975 and 90% thereafter as an estimate of potentially exposed workers in podiatry. The resultant number of workers per x-ray machine is 1.5 for the period 1960-1970 and 1.4 after that.

Table A-4 gives the results for veterinary medicine, chiropractic medicine, and podiatry. The number of x-ray machines was used as the basic index for veterinary and chiropractic medicine; the number of professional veterinarians and chiropractors as derived indexes. For podiatry, the number of podiatrists was used as the basic index, and the number of x-ray machines was used as a derived index. The total estimated number of potentially exposed workers roughly doubled over the period 1960 to 1985 for these groups of workers. Although the accuracy of these estimates may not be high, the combined contribution of these workers to the medical category was only about 8-9%.

5. Summary of Medical Workers

A summary of the number of potentially exposed workers in medicine is given in Table A-5. This work force can be divided into nearly constant fractions since 1960: dental subcategory, about 44%; combined veterinary, chiropractic, podiatry, about 8%; and combined hospital and private practice, about 48%. During the period 1960-1980, the number of workers in dentistry increased by a factor of 1.9, in hospitals by a factor of 4.2, and in private practice by a factor of 1.4. As shown in Table A-2, the effective number of hospital-based radiologists increased by a factor of about 3, and the number of byproduct licensees in hospitals increased by a factor of about 4, during the same period.

Table A-5. Estimated number of potentially exposed workers in medicine, 1960-1985

Occupation	Number (10^3)					
	1960	1965	1970	1975	1980	1985
Dentistry	134	150	177	215	259	304
Private Practice	111	116	123	136	155	180
Hospital	30	48	70	96	126	162
Veterinary Medicine	11	12	13	17	21	26
Chiropractic Medicine	11	11	12	14	15	17
Podiatry	5	6	6	7	8	10
Total	302	343	401	485	584	699

The trends of potentially exposed workers in medicine and its subcategories are shown in Figure A-4, along with the trends in numbers of x-ray machines (medical and dental), all physicians, active civilian dentists, active nonfederal radiologists, registered nurses (PHS80, DOC81), workers in hospitals and health services (BLS79,83; DOC75,81; Se81), and dollars spent for personal health care (DOC81). The work force in the health services industry increased by a factor of 3.4 between 1960 and 1980 (BLS79,83). Personal health care expenditures increased by a factor of 9 for the same period. The number of physicians and active civilian dentists increased by factors of 1.6 and 1.4, respectively, while active nonfederal radiologists increased by a factor of 2.9. The total number of potentially exposed workers in medicine increased by a factor of 1.9 for the same period.

The total number of potentially exposed workers in medicine had consistent correlation with the number of medical and dental x-ray machines and the number of medical byproduct licensees. This would be expected for x-ray machines, and they were used as the basic index for many subcategories. However, the correlation with the number of professionals is also important since we relied primarily on number of professional workers for estimating the number of workers in this work force. The ratio of all potentially exposed workers in medicine to the total number of medical and dental x-ray machines has been nearly constant at about 1.8 since 1965. The ratio of potentially exposed workers in medicine to the number of medical byproduct licensees has remained about 100 since 1965.

B. <u>Industry</u>

The use of the number of professionals as a basic index to estimate the number of potentially exposed workers generally worked quite well in medicine, but is not readily applicable to industry because there are few well-defined professional groups using sources of radiation. The obvious exception is industrial radiography. Therefore, the basic

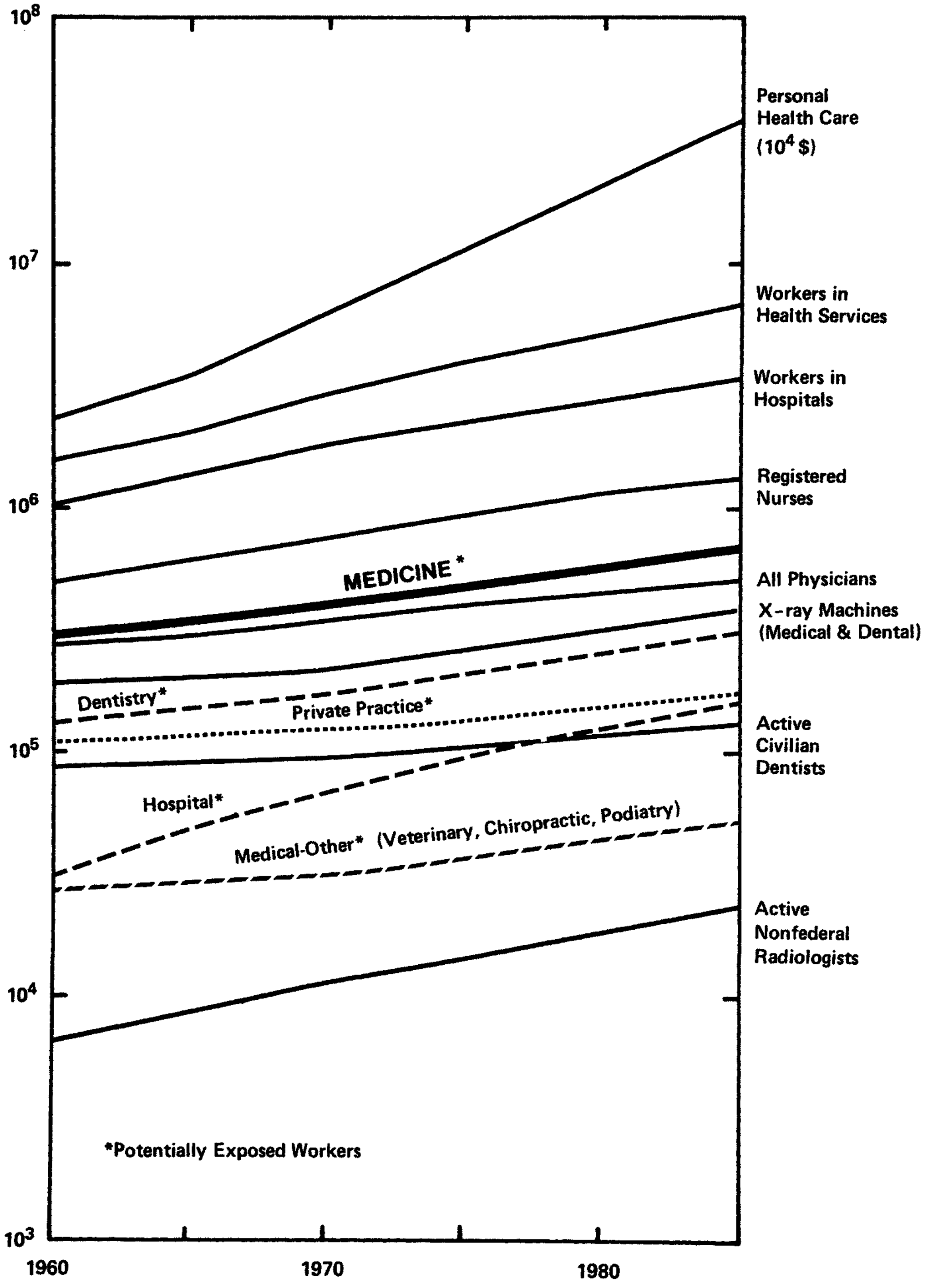

Figure A-4. Trends of health care costs, health care workers, and x-ray machines in medicine, U.S., 1960-1985.

index data used for industry included (1) the number of radioactive byproduct material licensees of NRC and Agreement States (NRC65-82), (2) the number of facilities using nonmedical x-ray machines, and (3) the number of particle accelerator users (HEW65-79; HHS80,82). These data are reasonably reliable since 1965; the corresponding numbers for 1960 were estimated by back extrapolation of 1965-1980 trends.

The number of byproduct licensees in industry is reported by NRC (formerly AEC) for only two categories: industrial radiography and industrial "total" (NRC65-82). The further separation of industrial "total" licensees into "manufacturing and distribution" and into "other users" was used in special NRC studies for the years 1975, 1978, and 1979 (Co78; Bro81,82,83a,83c). We adopted this same separation and made extrapolations for the periods before and after the NRC studies.

Industrial radiography depends primarily on the use of byproduct material sources, although there is some use of industrial x-ray machines (EPA83). Thus, the number of byproduct licensees of NRC and NRC Agreement States was used as a basic index, with a small adjustment for industrial x-ray machines, for estimating the numbers of potentially exposed workers in industrial radiography. The numbers of manufacturing and distribution licensees were determined from NRC studies (Co78; Bro81,82,83a,83c). These were used, with a small adjustment for industrial x-ray machines and particle accelerators, as the basic index to estimate the number of potentially exposed workers in manufacturing and distribution. The data for the two basic indices, numbers of licensees and numbers of facilities, for other users came from the remaining fraction of industry licensees and remaining numbers of facilities using industrial x-ray machines and particle accelerators. The small adjustments noted above to the basic indices for industrial radiography and manufacturing/distribution involved apportionment of industrial x-ray machine and particle accelerator registrants or facilities. The number of facilities using industrial x-ray machines was apportioned among the three subcategories according to the corresponding distribution of byproduct licensees in industry. Particle accelerator users were similarly distributed to other users and to manufacturing and distribution subcategories after apportionment of a fraction to medicine based on the ratio of medical byproduct licensees to total byproduct licensees.

The number of potentially exposed workers per licensee in industrial radiography was determined from AEC film badge studies (AEC71) and NRC occupational exposure reports (Co78; Bro81,82,83a). Similarly, the number of workers per licensee in source manufacturing and distribution was obtained from these and other NRC studies (Co78; Bro81,82,83a; NRC80).

There were two separate components to estimation of workers in the other industrial users subcategory: NRC licensees and facilities using industrial x-ray machines and particle accelerators. The number of workers per licensee was obtained from NRC studies (Co78; Bro81,82,83a; NRC80). The number of workers per facility was estimated from commercial dosimetry data for facilities using industrial x-ray units and for particle accelerator user facilities. This number of workers was reduced 20% to account for the overlap in use of different radiation sources by the same licensee-registrant (EPA78; Bro81,82).

A summary of the estimated numbers of potentially exposed workers in industry is given in Table A-6 for the period 1960 to 1985. We also examined the reasonableness of the increase in the number of these workers compared to other relevant factors. Our results show the average growth rate of the number of potentially exposed workers per year in industry for the period of 1960 to 1980 to be about 9.5%. We compared this growth rate with the growth rate of three broad industrial groups for the same time period. The average growth rates per year of manufacturing, construction, and mining work forces were 1% to 2% for the period 1960 to 1980 (DOC81). The average growth rates per year for industrial byproduct licensees and number of registrant facilities were both about 4% during the period of 1965 to 1980 (NRC65-82; HEW65-79;

Table A-6. Estimated number of potentially exposed workers in industry, 1960-1985

Occupation	1960	1965	1970	1975	1980	1985
Industrial Radiography						
Workers (10^3)	2	6	12	17	27	32
Basic Index						
Licensees (10^3)(a)	0.4	0.6	0.8	0.8	1.0	1.1
Workers/Licensee(b)	(5)	(10)	(15)	(21)	(27)	(29)
Manufacturing/Distribution						
Workers (10^3)	2	5	8	20	29	34
Basic Index						
Licensees (10^3)(a)	0.4	0.6	0.7	0.8	0.7	0.8
Workers/Licensee(b)	(5)	(8)	(12)	(25)	(41)	(42)
Other Users						
Workers (10^3)(c)	46	63	102	165	249	356
Two Basic Indices Combined						
(i) Licensees (10^3)(a)	4	4.4	4.8	6.9	8.6	11.0
Workers/Licensee(b)	(7)	(8)	(14)	(17)	(19)	(21)
(ii) Facilities (10^3)(d)	3	4	5	6	7.8	9.6
Workers/Facility(e)	(6)	(7)	(7)	(8)	(11)	(13)
Industry Total (10^3)	50	74	122	202	305	422

(a) Licensees refers to NRC or NRC Agreement State licensees for each subcategory.

(b) Estimated or extrapolated from AEC/NRC and other studies (AEC71; Co78; Bro81,82,83a; EPA78; NRC80).

(c) Sum of potentially exposed workers from licensees and facilities.

(d) Facility refers to those using nonmedical x-ray machines and to particle accelerator users for "other users" subcategory.

(e) Estimated or extrapolated from commercial dosimetry data.

HHS80,82). From the product of the general work force growth rate (1% to 2%) and the industrial byproduct licensee growth rate (4%), we obtain an overall average annual growth rate of about 4% to 8%. This rate is reasonably consistent with the 9.5% annual growth rate estimated here for potentially exposed workers in industry.

C. The Nuclear Fuel Cycle

The number of potentially exposed workers in the nuclear fuel cycle was estimated almost entirely from NRC and AEC/DOE data. The power reactor subcategory has contained the largest number of workers since the early 1970's, whereas the fuel fabrication and reprocessing subcategory previously contained the largest number. Before the late 1970's, uranium enrichment was estimated to contain the largest number of workers among the remaining subcategories (uranium enrichment, nuclear waste management, and uranium mills).

The numbers of nuclear fuel cycle workers for 1975, 1978, 1979, and 1980 were obtained directly from NRC and DOE reports (Co78; Bro81,82, 83a; DOE77-82). The numbers of workers in other years were estimated by modeling available data.

The number of licensees in fuel fabrication and reprocessing before 1973 was estimated by back extrapolating the number of licensees after 1973 (Bro82,83a), according to the observed trend of number of fuel fabrication facilities between 1967 and 1976 (NRC78). Similarly, the number of workers per licensee before 1973 was back extrapolated from the 1967 to 1976 trend in the number of employees per fuel fabrication facility (NRC78).

The number of potentially exposed workers for power reactors before 1969 was estimated from AEC film badge studies (AEC68a,68b,70) and number of reactors (AIF80; Bro82,83a). The number of workers after 1969 was obtained directly from NRC reports (Co78; Bro83a,83b).

The number of workers in uranium enrichment since 1974 was obtained directly from ERDA/DOE reports (DOE76-82). The number of workers in uranium enrichment before 1974 was back extrapolated from AEC data (DOE76-82).

The number of workers in uranium mills was estimated from NRC reports (Co78; NRC78; Bro81,82). The number of workers in radioactive waste management was estimated from AEC film badge studies for the period 1967 to 1971 (AEC68a,68b,70,72,73) and NRC reports (Co78; Bro81, 82,83b,83c).

The number of workers in the nuclear fuel cycle for 1985 was projected from the 1975 to 1980 trend in each subcategory. We summarize our results for the entire nuclear fuel cycle in Table A-7.

Table A-7. Estimated number of potentially exposed workers in the nuclear fuel cycle, 1960-1985

Occupation	Number (10^3)					
	1960	1965	1970	1975	1980	1985
Power Reactors	0.2	0.7	7.5	54.8	133.7	183
Fuel Fab. & Repro.	2.5	4.9	8.4	11.6	10.2	9
Uranium Enrichment	0.6	1.8	2.0	7.5	1.9	2
Nuclear Waste Mgt.	0.1	0.2	0.3	0.3	0.7	1
Uranium Mills	0.6	1.5	1.7	2.3	4.8	5
Total*	4	9	20	76	151	200

*Total numbers of workers have been rounded to the nearest thousand.

D. Government

We summarize, in Table A-8, for the period 1960 to 1985, the results of our analysis of numbers of potentially exposed or monitored

Table A-8. Estimated number of potentially exposed workers in government, 1960-1985

Agency	Number (10^3)					
	1960	1965	1970	1975	1980	1985
Dept. of Energy[a]	80	132	95	81	84	90
Dept. of Defense	45	93	97	92	103	110
Air Force	7	16	13	16	18	18
Army	16	21	23	16	21	22
Navy	22	56	61	60	64	70
Other agencies[b]	5	6	8	11	17	20
NASA	0.2	0.3	0.5	1.4	0.9	0.9
NBS	0.1	0.2	0.2	0.4	0.4	0.5
NIH	0.5	0.9	1.3	2.2	4.1	5.2
PHS	1.5	2.1	2.7	2.4	5.9	6.9
VA	2.3	3.0	3.6	4.9	5.7	6.2
Total[b]	130	231	200	184	204	220

[a] Excludes data on uranium enrichment workers (see Table A-7) and visitors (see Table 5 and Appendix C).

[b] Mine Safety and Health Administration data not included (see Appendix C). Total numbers of workers have been rounded to the nearest thousand.

NASA	National Aeronautics and Space Administration.
NBS	National Bureau of Standards.
NIH	National Institutes of Health.
PHS	Public Health Service.
VA	Veterans Administration.

workers for the Department of Energy (DOE); the Air Force, Army, and Navy of the Department of Defense (DOD); Public Health Service (PHS) (workers in various agencies and facilities covered by the PHS Personnel Monitoring Program--see Table D-6 for details); National Aeronautics and Space Administration (NASA); National Bureau of Standards (NBS); National Institutes of Health (NIH); and Veterans Administration (VA).

The DOE (previously the AEC) and DOD subcategories contained the majority of workers in the government category. The remainder came from PHS, NASA, NBS, NIH, and VA, and accounted for less than 4% before the 1970s.

The AEC and AEC contractors compiled annual exposure statistics for employees beginning in 1955. Exposure summaries for 10 separate occupational categories have been published since 1974.

The Navy has reported the largest number of monitored workers in DOD since 1960. The numbers of workers in nuclear ships, Navy shipyards, and private shipyards have been reported for the years 1954-1983 by the Naval Nuclear Propulsion program (Sc84). The Navy's Bureau of Medicine and Surgery (BUMED) reports annual exposure of personnel in nuclear ships, Navy shipyards, and dental/medical activities, but not in private shipyards (Co80, Ri82). We have adjusted the Navy's Naval Nuclear Propulsion and BUMED data to correct for overlap.

The numbers of workers in the Air Force and the Army for 1960 and 1970 were obtained from a previous EPA study (Kl72). The corresponding numbers for 1965 were interpolated from the 1960 and 1970 data by comparison with the 1960-1970 trends in the Navy.

We obtained exposure statistics from other government agencies, except VA, for the period 1975 to 1980. We estimated the number of workers in VA from their numbers of dentists, dental auxiliaries, radiologists, and other medical workers between 1975 and 1982. The number of potentially exposed workers in the VA before 1975 was extrapolated from the trend observed for workers monitored by PHS. It was found to be consistent with the trend for the total number of all VA employees.

The number of potentially exposed workers in 1960 for the NIH, NASA, and NBS was obtained from our earlier study (Co80). The number of workers for the PHS in 1965 was linearly interpolated from the data available for 1960 and 1970. The combined estimate of 2,000 workers (K172) for NASA, NBS, and NIH in 1970 was apportioned according to the fractions observed in 1980; the corresponding 1965 values were obtained by interpolation.

E. Miscellaneous Occupations

1. Education

The description and monitoring of potentially exposed workers in educational institutions are not well known, as there are few published data. We included only faculty and associated staff in our main summary of occupational exposure (Table 4). Students are considered separately below.

We used the same basic method to estimate the number of workers in education as used in our 1975 study (Co80). The numbers of faculty and associated staff are based on the number of students estimated to be in programs involving radiation sources. Workers in hospitals associated with educational institutions already are accounted for in the medicine category. We recognize that each educational institution is unique and that research programs may have little or no relationship to the number of students in various programs. Nevertheless, we have based the number of potentially exposed workers on the number of students. These estimated numbers of workers are consistent with the results of NRC studies (Bro81,82).

a. Students

Students pursue studies involving radiation sources in a variety of medical, allied health, and science related fields. We consider each of these fields separately.

Medical school enrollment in health professions was taken from "A Report to the President and Congress," April 10, 1980 (PHS82). Numbers of medical students for 1980 and 1985 were extrapolated from 1975-1979 values. Few undergraduate physician and osteopathic students have potential for exposure. Potential exposure of graduate medical students occurs in hospitals or other science degree programs, where they would already be accounted for. At some point in their studies, all students in programs for dentists, podiatrists, veterinarians, and chiropractors were assumed to have potential for radiation exposure. In any given year, 50% of dental, 25% of veterinary, 100% of chiropractic, and 100% of podiatric students were assumed to be enrolled in classes involving radiation. The total number of these students for 1980 was estimated to be 22,250.

We assumed that students in five allied health programs had classes involving sources of radiation. All those studying to become dental assistants, radiographers, therapy technologists, nuclear medicine technologists, and 50% of dental hygienists were included. Graduate students were neglected in these programs. The total number of these allied health students for 1980 was estimated to be 33,490.

For science programs in universities and colleges, we assumed that the number of bachelor degree recipients in any year represented approximately 25% of the undergraduate students in these fields. The number of graduate students was estimated by assuming that the number of master and doctor degree recipients in any year represented 50% and 25%, respectively, of these students. The number of graduates were obtained from "Digest of Education Statistics, 1982" (Gr82). Based on personal communications with faculty and staff of several institutions, we estimated that students were in classes involving radiation sources each year as follows: 10% of physics (general) majors, 5% of chemistry (general) majors, 5% of biological sciences majors, and 100% of nuclear physics and nuclear engineering majors. Students majoring in general biology were not included as biological sciences majors. Assuming the above values, the number of undergraduate and graduate students in science and engineering courses involving radiation was 11,410 in 1980. The total number of all students in programs involving sources of radiation was estimated to be 67,150 in 1980.

b. Faculty and Associated Staff

We estimated the number of potentially exposed faculty and staff workers from the estimated number of students (undergraduate and graduate) in programs that involve sources of radiation and from student/faculty and staff/faculty ratios. We estimated staff/faculty and student/faculty ratios from personal communications with radiation protection personnel at educational institutions. These ratios were not based on a representative survey and therefore can provide only rough estimates of potentially exposed faculty and staff. The derivation of the numbers of faculty and associated staff estimated to be potentially exposed workers is summarized in Table A-9.

c. Summary

The estimated number of students and faculty associated with sources of radiation at educational instititutions is, at best, a rough approximation. Although there is reliable published data on numbers of students and faculty, there is little concerning those potentially or actually exposed to sources of radiation. Our estimates of the number of workers in education are consistent with those projected by the NRC for their academic licensees (Bro82), if we assume an equal number of workers under Agreement State licenses and that about half of all NRC and Agreement State academic workers are found in academic health clinics and hospitals. It is known that NRC estimates for educational institutions also contain health clinic and hospital exposure data. Such clinic and hospital workers accounted for about 40% and 60% of the monitoring data at the University of Indiana (Bri83) and University of Missouri at Columbia, Mo. (Le83), respectively, that were used for the

Table A-9. Estimated number of potentially exposed faculty and associated staff in educational institutions, 1980

Education program	Medical	Allied Health	Sciences	Total
Undergraduate Program				
Students	22,250	33,490	7,890	
Faculty/Student	0.1	0.1	0.1	
Faculty	2,230	3,350	790	6,370
Graduate Program				
Students	-	-	3,520	
Faculty/Student	-		0.5	
Faculty	-	-	1,760	1,760
Faculty Subtotal	2,230	3,350	2,550	8,130
Staff/Faculty	1.0	1.0	5.0	
Associated Staff	2,230	3,350	12,750	18,330
Total*				26,500

*Does not include students (see Table 5 and Appendix C).

NRC estimates (Bro82). We considered such workers separately in the hospital workers subcategory.

Some students are undoubtedly monitored for exposure to radiation. However, there appear to be relatively few. Persons less than 20 and 22 years old comprise less than 5% and 15%, respectively, of the commerical dosimetry data for monitored individuals in education. We have not included students in our estimates of the number of radiation workers. If we were to count only the 33,490 students in the allied health subcategory, who are in training for specific jobs involving the use of radiation, as potentially exposed workers, the estimated number of workers in education would increase from about 26,500 to about 60,000.

The number of potentially exposed workers in education was also estimated for the years 1960, 1965, 1970, 1975, and 1985 (Table A-11). There was good correlation between the trends in number of educational byproduct licensees of the NRC and the estimated number of workers for the period 1960-1980.

2. Transportation

Many radioactive material shipments are low in radioactivity and do not require use of licensed shippers and handlers. Thus, not all transporters of radioactive materials are NRC or State licensed. Our analysis of transportation workers is based largely upon NRC's "Final Environmental Statement on the Transport of Radioactive Materials by Air and Other Modes" (NRC77b). This report provided collective dose and some worker dose estimates for 1975 and 1985. Since this NRC study relied on exposure data available in 1975, changes in shipping volume or work practices different from those projected would invalidate these dose estimates. We examined the 1980 commercial data sample for consistency with the NRC projections of mean doses. Unfortunately the data sample for transportation workers was questionable, since it contained more than half of all the commercial dose records that were greater than 12 rems (these high records averaged 25 rems). After investigating the commercial dosimetry data and consulting the Department of Transportation, we concluded that these high records were not reliable. If these high records are not included, the mean annual dose, was 60 mrem. This is in good agreement with the projection of 70 mrem based on the NRC study results.

Estimated numbers of potentially exposed workers associated with each transport mode (Table A-10) were obtained by dividing NRC collective dose estimates by best estimates of average doses. For the aircraft transport mode, the mean average dose of 90 mrem for workers was based on studies at five major airports (NRC77a). The mean annual dose of 70 mrem assumed for truck, rail, and ground handlers, was based on

Table A-10. Estimated number of potentially exposed workers in transportation, 1980[a]

Transport mode	Number of workers	Mean dose equivalent (mrem)	Collective dose equivalent (person-rem)
Primary Mode			
Aircraft[b]	7,800	90	700
Truck	11,400	70	800
Rail	1,400	70	100
Secondary Mode			
Ground handlers	25,700	70	1800
X-ray baggage check	4,100	20	80
All Workers	50,400	70	3480

[a] Based on NRC and DOT studies (NRC77b; DOT81).

[b] Does not include passenger aircraft crew members (39,000) and flight attendants (58,000) (see Table 5 and Appendix C).

our assessment of drivers and handlers, as characterized by an NRC study (NRC77b). The numbers of workers in transportation for 1975 and 1985 were similarly estimated from NRC data (NRC77b). The numbers of workers for the years 1960 to 1970 were obtained by back extrapolation of the 1975 to 1985 trend.

The number of operators of security x-ray baggage checks at airports was estimated as 4,100 from the number of x-ray units reported to Congress by the Federal Aviation Administration (DOT81). From the above, we estimate a total of about 50,000 workers potentially exposed in transportation in 1980.

There were an estimated 58,000 flight attendants and 39,000 flight crew members for passenger aircraft in 1980. These workers receive most of their doses from increased exposure to cosmic rays at high altitudes. Their mean annual dose from cosmic radiation is estimated to be 170 mrem (NRC77b). Flight attendants and crew members also receive very low exposures from radioactive materials on passenger aircraft; their estimated mean annual doses are 3 mrem and 0.5 mrem, respectively (NRC77b). Flight attendants and flight crew members are listed in our summary for additional groups (Table 5); their mean annual dose from transported radiation sources is only a few percent of their cosmic radiation doses.

III. SUMMARY

Table A-11 summarizes the number of U.S. workers potentially exposed to radiation by category and subcategory from 1960 through 1985. Government and nuclear fuel cycle workers together have comprised about one-fourth of all potentially exposed workers since 1960, except for 1965, when these two categories were about one-third. This exception was due to the 65% and almost 250% increases in the number of workers in the AEC and Navy, respectively. Workers in medicine and industry have comprised about two-thirds of all potentially exposed workers since 1970.

The dentistry subcategory contained the largest number of workers of all subcategories between 1960 and 1980. Workers at power reactors exhibited the largest growth rate during this period. Industrial "other users" and hospital subcategories exhibited the second and third largest growth rates, respectively. Before 1975, dentistry, private practice, industrial "other users," DOE (formerly AEC/ERDA), and DOD were the five largest subcategories. Since 1975, dentistry, private practice, hospital, industrial "other users," and power reactors have been the five largest subcategories.

The growth in the number of all potentially exposed workers (U.S. Total) and workers in each of the five categories are compared with the growth of the U.S. population, the U.S. labor force, and the U.S. gross national product (GNP; 1980 dollars) in Figure A-5. The number of

Table A-11. Estimated number of potentially exposed workers in the United States, 1960-1985

Occupation	Number (10^3)					
	1960	1965	1970	1975	1980	1985
MEDICINE						
Dentistry	134	150	177	215	259	304
Private Practice	111	116	123	136	155	180
Hospital	30	48	70	96	126	162
Veterinary	11	12	13	17	21	26
Chiropractic	11	11	12	14	15	17
Podiatry	5	6	6	7	8	10
Subtotal	302	343	401	485	584	699
INDUSTRY						
Radiographers	2	6	12	17	27	32
Manufac. & Dist.	2	5	8	20	29	34
Other Users	46	63	102	165	249	356
Subtotal	50	74	122	202	305	422
NUCLEAR FUEL CYCLE						
Power Reactors	0.2	0.7	7.5	54.8	133.7	183
Fuel Fab. & Repro.	2.5	4.9	8.4	11.6	10.2	9
Uranium Enrichment	0.6	1.8	2.0	7.5	1.9	2
Nuclear Waste Mgt.	0.1	0.2	0.3	0.3	0.7	1
Uranium Mills	0.6	1.5	1.7	2.3	4.8	5
Subtotal	4	9	20	76	151	200
GOVERNMENT						
Dept. of Energy(a)	80	132	95	81	84	90
Dept. of Defense	45	93	97	92	103	110
Other Agencies(b)	5	6	8	11	17	20
Subtotal	130	231	200	184	204	220
MISCELLANEOUS(c)						
Education	10	17	22	25	26	28
Transportation	7	12	20	31	50	71
Subtotal	17	29	42	56	76	99
Total	503	686	785	1003	1320	1640

(a)Uranium enrichment workers are included in nuclear fuel cycle category. Excludes data on visitors (see Table 5).

(b)Excludes data from MSHA for miners (see Table 5).

(c)Excludes data on students, passenger aircraft crew members, and flight attendants (see Table 5).

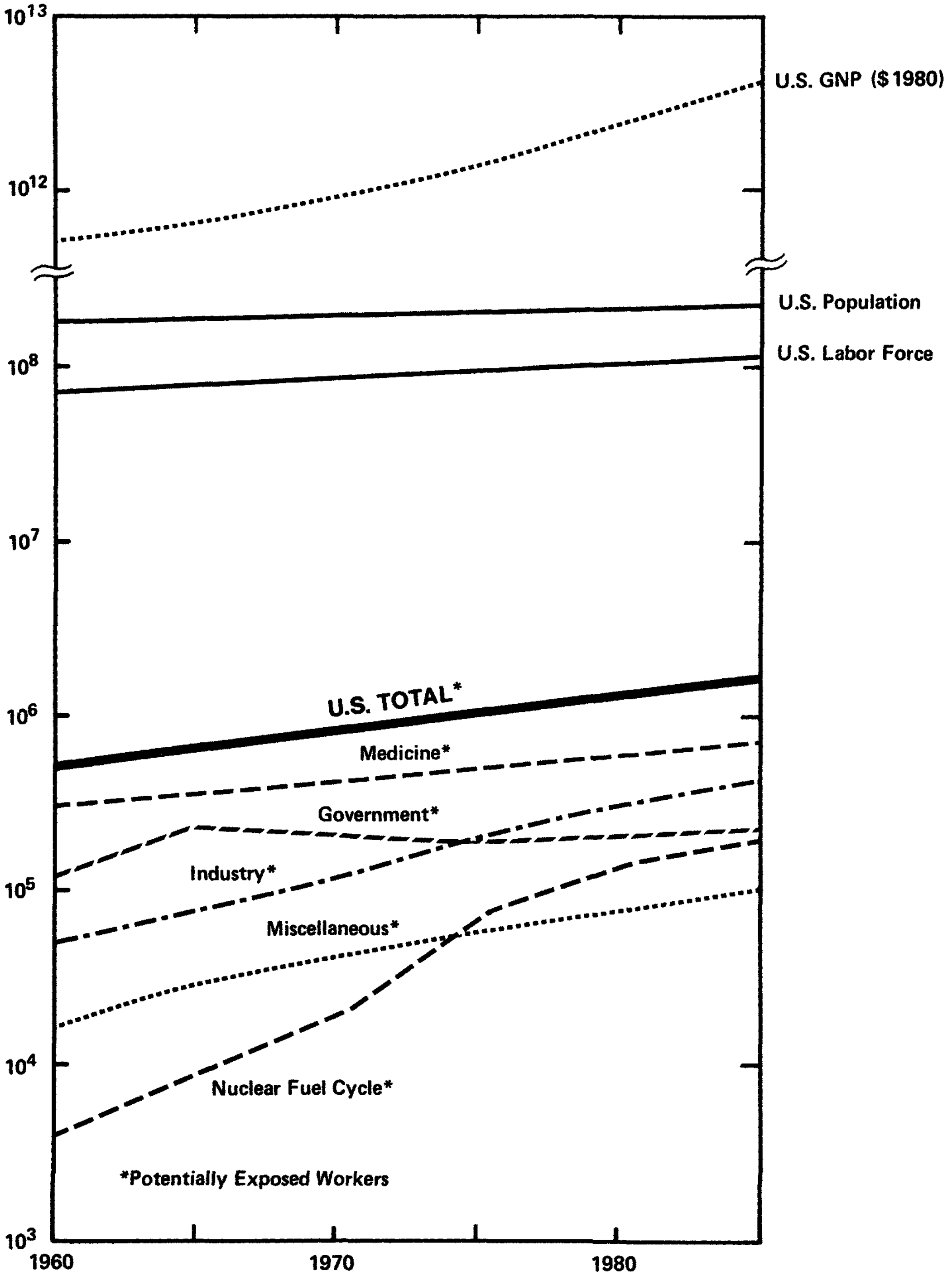

Figure A-5. Trends of U.S. population, labor force, gross national product, and potentially exposed workers, 1960-1985.

potentially exposed workers per 1,000 population increased from 3 in 1960 to 6 in 1980 (7 projected for 1985). The number of these workers per 1,000 labor force workers increased from 7 in 1960 to 12 in 1980 (14 projected for 1985). The number of potentially exposed workers per million dollars of GNP decreased from 1 in 1960 to 0.5 in 1980 (0.4 projected for 1985).

APPENDIX B

DOSE DISTRIBUTION ESTIMATES

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TABLES (Continued)

FIGURES

FIGURES (Continued)

APPENDIX B

DOSE DISTRIBUTION ESTIMATES

I. INTRODUCTION

In order to determine dose distributions for the different groups of exposed workers, we analyzed a variety of data. For many worker groups we used commercial dosimetry data, which had high accuracy, but unknown representativeness. In such cases, it was necessary to examine other sources of data to establish whether or not the data we used were reasonably representative. We also examined trends in the numbers of workers receiving less-than-measurable doses as well as numbers of workers receiving the highest doses. These and other considerations are examined here for each category and subcategory of potentially exposed workers.

Table B-1 provides a summary of sources and sample size of the data sets used to determine the dose distributions of workers for each subcategory. Some of the sets of data are almost complete and, therefore, present few analysis problems. Most others are sizable samples. In a few cases, however, notably for workers in dentistry, and, to a lesser extent, for workers in industry and transportation, the numbers of workers are large, and the size of the sample of exposure data is small.

Statistical analyses can reveal characteristics that are useful for examining the reliability of data and in making comparisons between

Table B-1. Summary of information used to estimate the numbers and dose distributions of potentially exposed workers, 1980

Occupational category	Index used to estimate number of workers	Number of potentially exposed workers (10^3)	Sample size used to obtain dose distribution (% of workers)
MEDICINE		584	28.5
Dentistry	Sum of professional dental workers	259	3.1
Private Practice	Number of private practice radiologists and x-ray machines	155	21.9
Hospital	Number of hospital-based radiologists	126	93.3
Veterinary	Number of veterinary x-ray machines	21	28.1
Chiropractic	Number of chiropractic x-ray machines	15	7.7
Podiatry	Number of podiatrists	8	0[a]
INDUSTRY		305	14.5
Radiography	Number of industrial radiography licensees	27	10.6
Manufacturing & Distribution	Number of manufacturing and distribution licensees	29	24.7
Other Users	Number of other licensees and facilities	249	13.7
NUCLEAR FUEL CYCLE		151.3	99.9
Power Reactors	Number of monitored workers	133.7	100
Fuel Fabrication & Reproduction	Number of monitored workers	10.2	100
Uranium Enrich.	Number of monitored workers	1.9	100
Nuclear Waste Management	Number of monitored workers	0.7	81
Uranium Mills	Number of monitored workers	4.8	99
GOVERNMENT		204.3	98.3
Dept. of Energy	Number of monitored workers	83.6	100
Dept. of Defense	Number of monitored workers	103.5	100
Other Agencies	Number of monitored workers	17.2	79.4
MISCELLANEOUS		76	49
Education	Number of students in radiation-related courses	26	(127)[b]
Transportation	Number of transportation workers	50	8.6[c]
U.S. TOTAL		1,320	45.3

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[a] Same dose distribution as used in the 1975 report (Co80).

[b] Exposure data for education included faculty and students and was separated according to age to characterize the annual doses to faculty and students.

[c] The available data for transportation corresponded to workers at airline baggage checks.

different sets of data. We examined a number of these characteristics for occupational exposure data and give examples in this appendix, primarily for the years 1975 and 1980, for which we had data for almost all occupational categories. Our analyses showed, for example, that 1980 Federal and commercial data were more self-consistent than were those for 1975. Figure B-1 shows the number of measurably exposed workers as a function of the total number of potentially exposed workers for the five major categories and the U.S. total in 1975 and 1980. The fraction of workers measurably exposed to radiation varied from one worker group to another. However, we found that the fraction of these workers was more consistent in the 1980 data than in the 1975 data. For example, the characteristics of the 1975 data for government and nuclear fuel cycle workers look much like that of the 1980 data. Figure B-2 shows the cumulative frequency of workers not exceeding a certain fraction of workers with a measurable dose in 1975 and 1980, according to the commercial data. From this data presentation we see that the distribution of measurably exposed workers was more nearly a normal distribution in 1980 than in 1975. In addition, the median fraction (52%) of measurably exposed workers in 1980 was approximately double the median fraction (29%) in 1975. This result is consistent with the observed trend in Figure B-1.

II. DISTRIBUTIONS OF WORKERS BY DOSES

Dose distributions for the various groups of potentially exposed workers were obtained or constructed from the variety of available data. Because of completeness of monitoring records, exposure information for government and the nuclear fuel cycle workers provided reliable dose statistics. Commercial data was particularly useful as it was coded for different groups of workers and contained age and sex information for about 50% of the individual dose records. Only these latter dose records containing age and sex information were used for computing mean doses, and these data also provided essentially all the age and

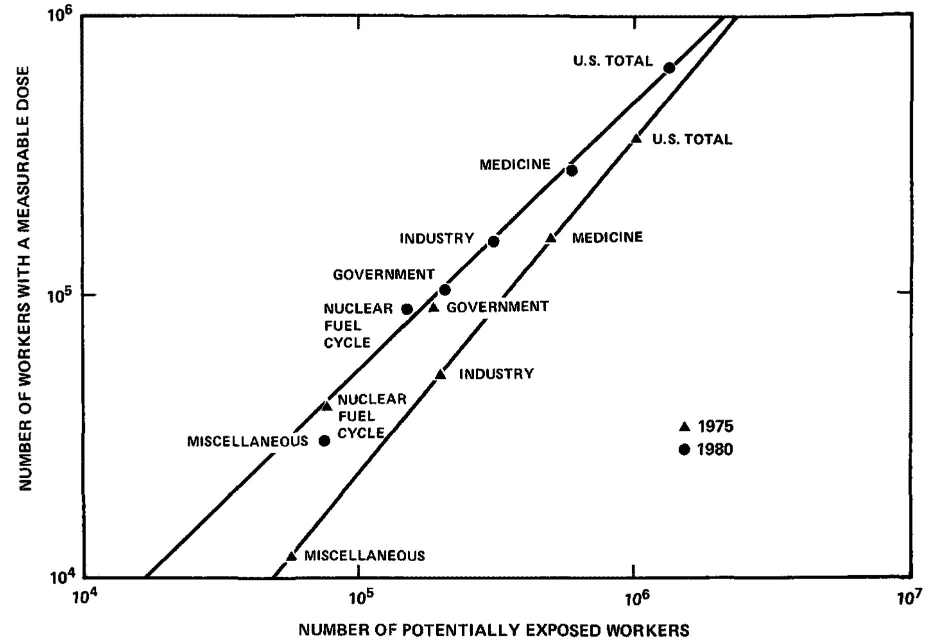

Figure B-1. Number of workers potentially vs. actually exposed, 1975 and 1980.

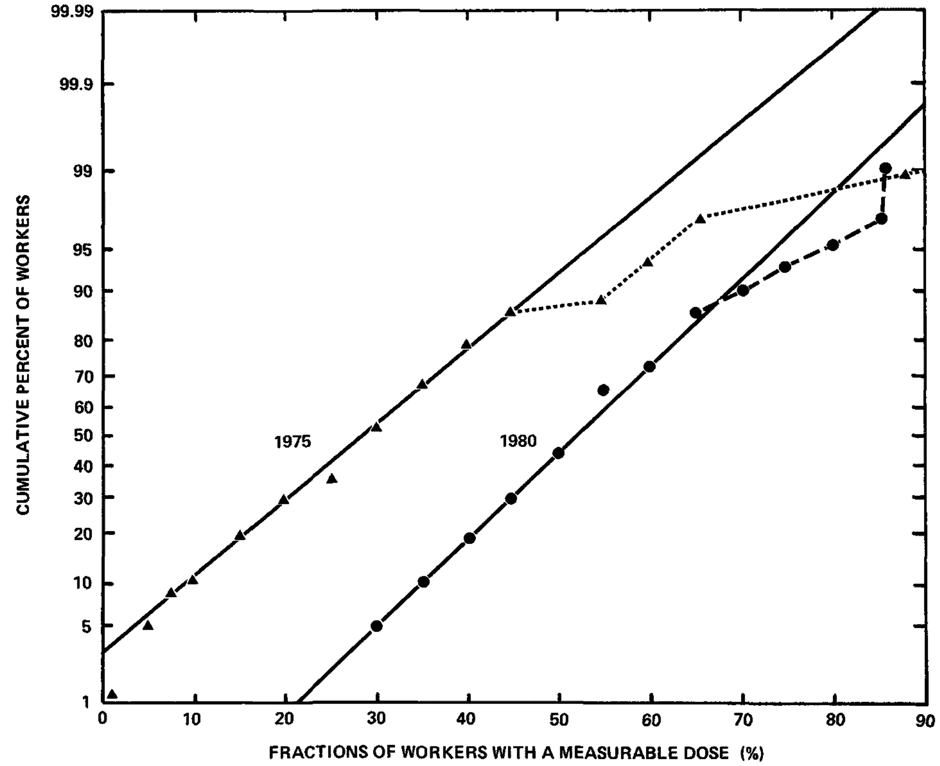

Figure B-2. Cumulative percent of workers by fraction of measurably exposed workers in selected groups from commercial dosimetry data, 1975 and 1980.

sex data for this study. Although these data were assumed to be representative, they were examined for irregularities by fitting the data to the HLN model (see Appendix F). We briefly discuss the dose distributions found for each of the five major categories of workers below.

A. Medicine

The dose distributions used for each subcategory of medical workers in 1975 and 1980 were constructed entirely from commercial data. We examined the distributions for each medical worker group with the HLN model to identify questionable data. The dose distribution for each subcategory was obtained from the weighted sum of dose distributions from relevant worker groups.

Since the dose distribution for dental workers consisted of data which comprised only 3% of the estimated number of those potentially exposed in 1980, we compared its composition by sex to that for all dental workers (PHS82). The consistency of the comparison provided one confirmation of its representativeness. In addition, we compared dose distributions of U.S. and West German dental workers (Dr81). We found very similar dose distributions for both sets of data.

The dose distribution for workers in private practice was the weighted sum of the dose distributions of workers in radiology and seven groups of workers in private practice.

The dose distribution for hospital workers was calculated from the sum of dose distributions for workers in seven hospital groups, weighted according to statistics of the American Hospital Association (AHA76,81). Since the largest hospital group (general medical and surgical hospitals) contained more than 80% of all potentially exposed workers and the second largest (university hospitals) more than 15%, the dose distribution for workers in hospitals was effectively determined by these two groups.

The distribution of doses for the combined workers in veterinary medicine, chiropractic medicine, and podiatry was constructed from the weighted sum of dose distributions for the chiropractic and veterinary workers only, because only the mean dose was available for workers in podiatry. For 1980, mean doses were estimated for each of these groups, and are shown in Table 4. The total number of workers was adjusted to include the numbers of workers in podiatry.

Dose distributions in each subcategory of medicine in 1960, 1965, and 1970 were constructed from the dose distributions for 1975 and 1980 using the trends of mean annual dose for the period 1960-1980. Mean annual doses for medical-byproduct-licensee workers were estimated using HLN analysis of dose statistics from NRC reports (Co78; Bro81,82, 83c) and limited 1966-1971 film badge reports from AEC and Agreement States licensee data (AEC68a,68b,70,71,73). The trend of these mean annual doses is approximated by a simple model of 310 mrem in 1960 that is halved every 14 years after that, as shown by the upper solid line in Figure B-3. We assumed that the trend of mean annual doses for all medical workers exhibits the same halving period, and fitted this trend to the estimated annual doses for 1975 and 1980. The mean annual dose for medical workers is shown by the lower solid line in Figure B-3. The numerical values of mean annual doses found for all medical workers were only about 60% of those determined by NRC for their medical licensees. This is primarily due to the large number of dental workers included in our analysis who have lower doses.

The mean annual doses to workers in hospitals and private practice were obtained similarly (Figure B-3). The mean annual dose in dentistry, shown by the broken line in Figure B-3, was chosen so that the collective dose for medicine would be equal to the sum of the collective doses from all subcategories for each year. The resulting annual decrease (about 18%) of the mean annual dose to dental workers is very close to the reported annual decrease (about 20%) of the mean exposure per dental film at skin surface between 1960 and 1970 (Ma80).

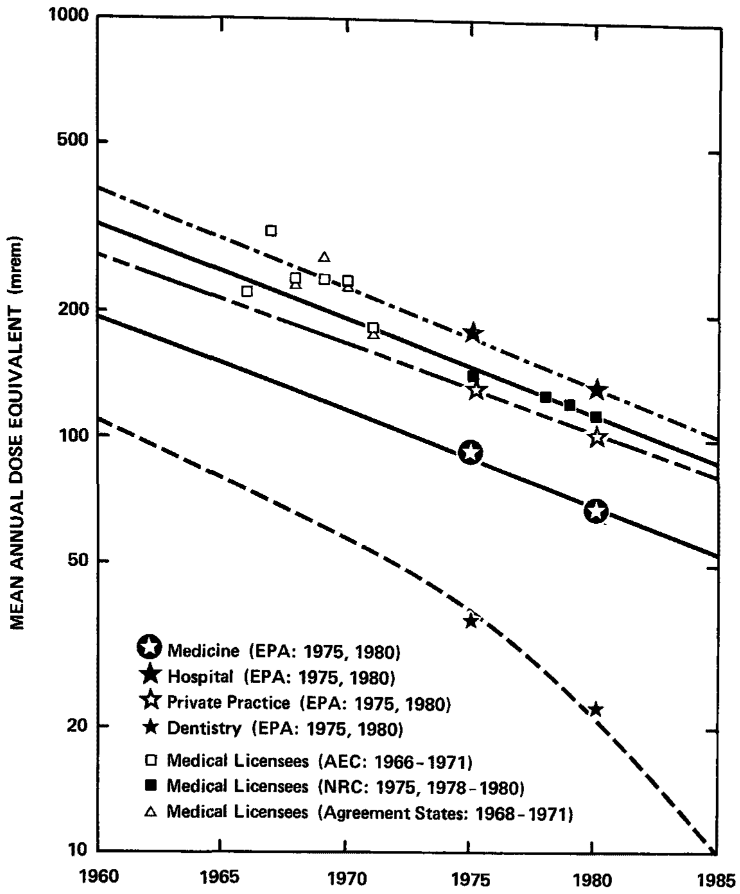

Figure B-3. Trends of mean annual dose equivalents for workers in hospitals, private practice, dentistry, and for all medical workers as estimated from various data.

The trend of mean annual doses for the combined workers in veterinary medicine, chiropractic medicine, and podiatry was assumed to be constant at 50 mrem because the dose changed only slightly from 1975 to 1980. These workers have contributed only a few percent of the total collective dose in medicine since 1960.

As noted above, we assumed that the dose distribution for medical workers in 1960, 1965, and 1970 could be derived from the 1975 dose distributions using the trend of the AEC/NRC data for mean dose, as analyzed by the HLN model (AEC68a,68b,70,71,73; Co78; Bro81,82,83c). The method used was to shift the 1975 dose distributions in the direction of higher doses on lognormal probability paper so that the mean of the dose distribution agreed with the corresponding mean dose determined in Figure B-3.

Figure B-4 shows the log-probability plots of the resulting dose distributions for medical workers in 1960, 1965, 1970, 1975, and 1980, and for the various subcategories of workers in 1960, 1975, and 1980. The curves were fitted to the estimated data using the HLN model.

The shapes of the sum of dose distributions for workers in hospitals and private practice were in good agreement with dose distributions for medical workers obtained from the data of AEC, Agreement States, and NRC medical licensees since about 1965. The primary difference in the shapes of dose distributions for medicine and AEC/NRC medical licensees is accounted for by the inclusion of the contribution of the dose distribution in dental workers in the former group.

Table B-2 gives a summary of mean annual dose and collective dose equivalents to workers in medicine in 1960, 1965, 1970, 1975, 1980, and 1985. The 1985 estimates in Table B-2 were obtained by extrapolating results shown in Figure B-3 and Table A-11. These 1985 estimates agreed well with those obtained from the log-log extrapolation of the mean annual dose and the number of workers in medicine from the 1975-1980 trend shown in Figure 11. All estimates in Table B-2 reflect the trends of mean annual doses shown in Figure B-3 and dose distributions shown in Figure B-4.

B. <u>Industry</u>

The 1975 and 1980 dose distributions for workers in each subcategory in industry were primarily constructed from commercial data. However, we constructed the dose distribution for workers in industrial radiography from NRC reports (Co78; Bro81,82,83a), while the dose distribution for workers in manufacturing and distribution was

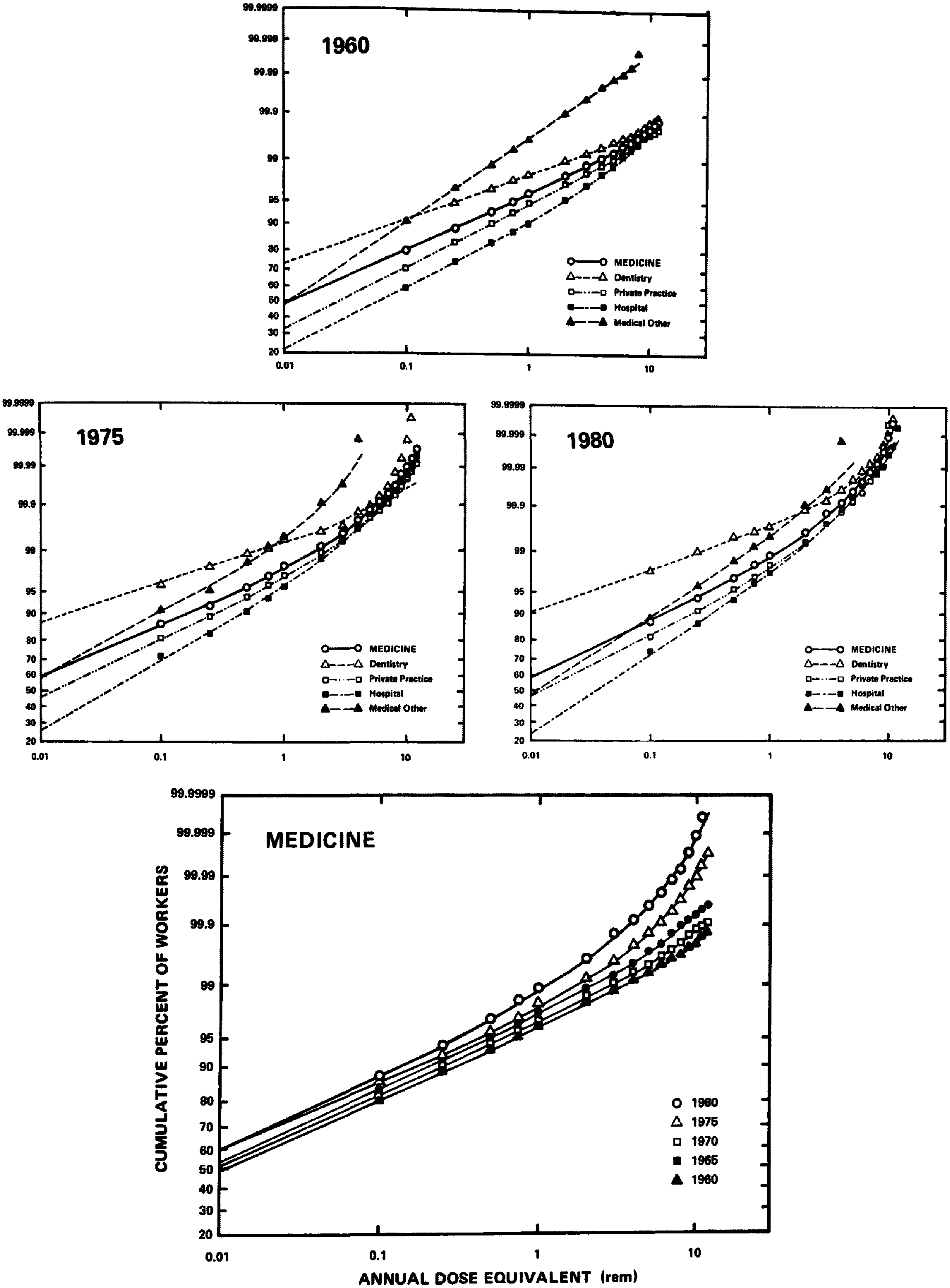

Figure B-4. Dose distributions for workers in medicine.

Table B-2. Summary of mean annual and collective doses to potentially exposed workers in medicine, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Dentistry	110	80	60	40	20	10
Private Practice	280	230	180	140	100	80
Hospital	400	300	230	190	140	100
Others*	50	50	50	50	50	60
Total	190	160	120	100	70	50

Occupation	Annual collective dose equivalent (10^3 person-rem)					
	1960	1965	1970	1975	1980	1985
Dentistry	15	12	10	8	6	3
Private Practice	31	26	22	18	16	14
Hospital	11	15	17	18	17	16
Others*	1	1	1	2	2	3
Total	58	54	50	46	41	36

*Veterinary medicine, chiropractic medicine, and podiatry.

based on both NRC reports (Co78; Bro81,82,83a) and commercial data. The dose distribution for the remaining workers in industry ("other users") was estimated from the sum of the dose distributions in eighteen industrial worker groups from commercial data.

The dose distributions for workers in each subcategory of industry for 1960, 1965, and 1970 were constructed from our analyses of 1966-1971 film badge reports for AEC and Agreement States licensees (AEC68a,68b,70, 71,73) and the trend of the corresponding dose distributions between 1975 and 1980.

Figure B-5 shows the log-probability plots of dose distributions for workers in industry in 1960, 1965, 1970, 1975, and 1980 in its three subcategories for 1960, 1975, and 1980. The smooth curves were fitted to the estimated distribution data using the HLN model. The relative shapes, positions, and trends of worker dose distributions among the different subcategories shown in Figure B-5 were consistent for the period 1960 to 1980. The dose distribution for all industry workers was influenced most by the characteristics of the distribution for "other users" workers. The shape of dose distributions above about 1 rem clearly became concave after 1970 for workers in industry.

The summary of mean annual dose and collective dose equivalents for workers in industry and its subcategories is given in Table B-3. The 1985 estimates in Table B-3 were obtained from the log-log extrapolation of mean annual dose and the number of workers according to their 1975-1980 trends (See Figure 11). The mean dose for workers in each subcategory has decreased since 1970 except for industrial radiography, which has remained practically constant.

C. Nuclear Fuel Cycle

Data for the 1975 and 1980 dose distributions of workers in the nuclear fuel cycle were obtained from NRC reports (Co78; Bro82,83a), except for data on uranium enrichment workers, which were obtained from ERDA/DOE reports (DOE76-82). We examined trends for the period 1960-1985 for three subcategories: power reactors, fuel fabrication and reprocessing, and other (uranium enrichment, nuclear waste management, and uranium mills).

The 1970 dose distribution for power reactor workers was obtained from an NRC report (Bro83b). The dose distributions for workers in each remaining subcategory for 1960, 1965, and 1970 were constructed from the 1966-1971 film badge reports for AEC and Agreement States licensees (AEC68a,68b,70,71,73) and the 1975-1980 trend of the dose distribution in each subcategory.

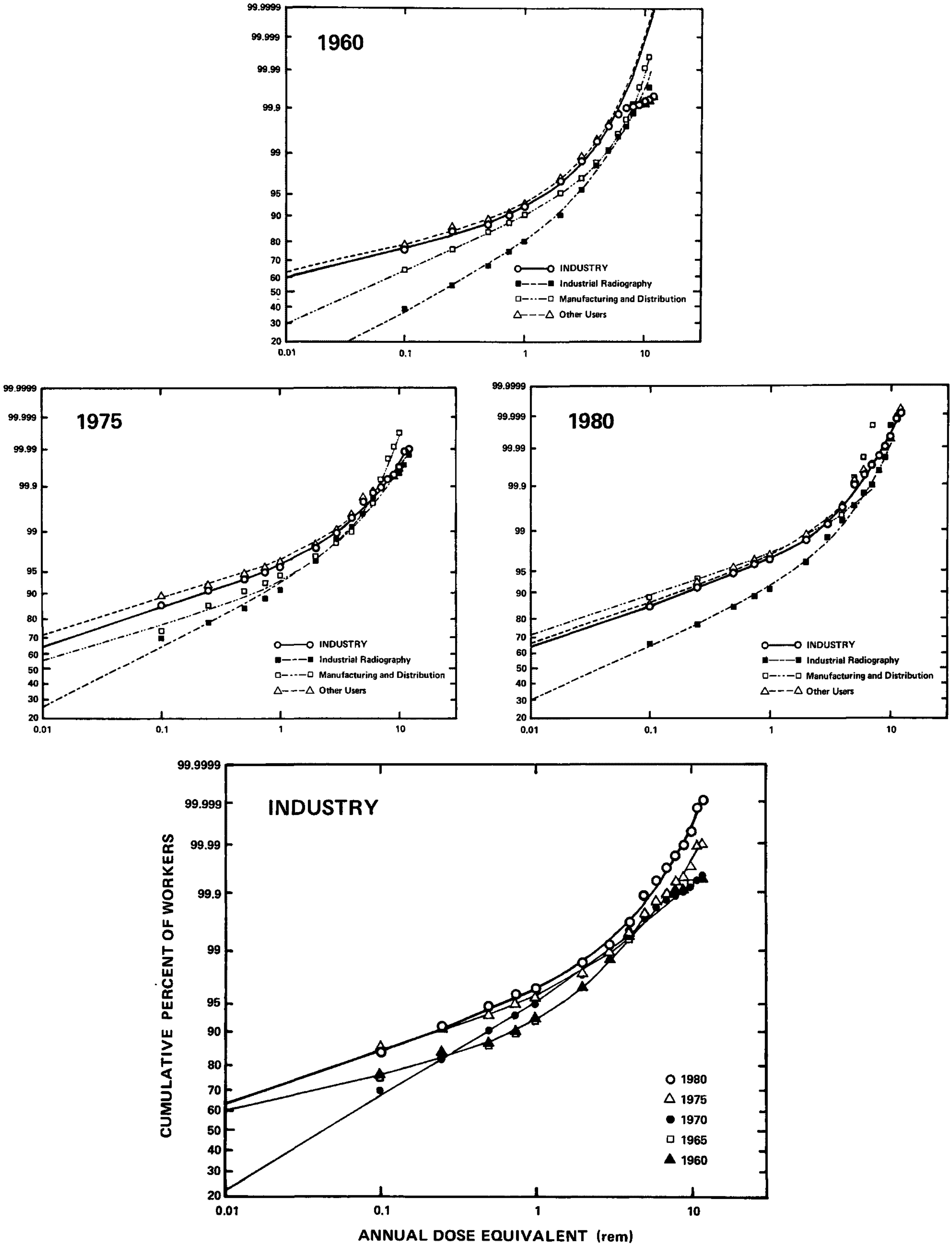

Figure B-5. Dose distributions for workers in industry.

Table B-3. Summary of mean annual and collective doses to potentially exposed workers in industry, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Radiography	630	490	310	280	290	300
Manufac. & Distr.	320	360	360	220	110	80
Other Users	210	210	200	120	110	100
Total	230	240	220	140	120	110

Occupation	Annual collective dose equivalent (10^3 person-rem)					
	1960	1965	1970	1975	1980	1985
Radiography	0.7	3	4	5	8	10
Manufac. & Distr.	0.6	2	3	4	3	3
Other Users	10	13	20	20	27	34
Total	11	18	27	29	38	47

Figure B-6 shows the log-probability plots of dose distributions for workers in the nuclear fuel cycle in 1960, 1965, 1970, 1975, and 1980 and for its three subcategories in 1960, 1975, and 1980. The smooth curves were obtained from HLN fits of the data. The composite dose distribution for workers in the entire nuclear fuel cycle most closely followed the fuel fabrication and reprocessing sector before 1970 and the power reactor sector after 1970.

The dose distribution for all workers in the nuclear fuel cycle shows the most pronounced concave shape in 1980. The distributions in different years had the greatest similarity and overlap in the dose range from 0.1 rem to 4 rems.

Table B-4 summarizes the mean annual dose equivalent and the collective dose equivalent for workers in the nuclear fuel cycle and

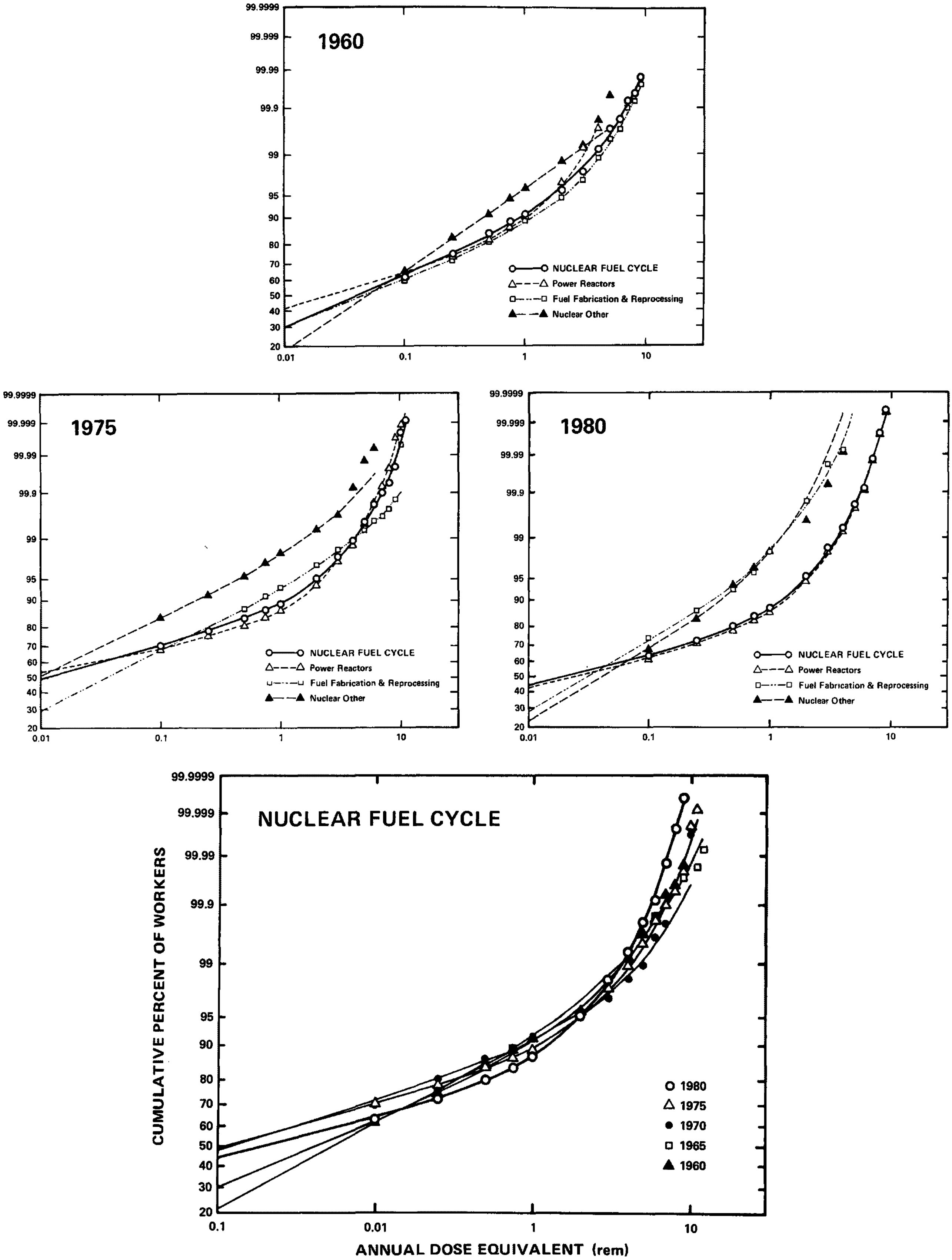

Figure B-6. Dose distributions for workers in the nuclear fuel cycle.

Table B-4. Summary of mean annual and collective doses to potentially exposed workers in the nuclear fuel cycle, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Power Reactors	300	290	400	380	390	400
Fuel Fab. & Repro.	380	370	310	280	100	90
Other*	200	210	210	100	140	150
Total	320	300	320	320	360	380
Occupation	**Annual collective dose equivalent (10^3 person-rem)**					
	1960	1965	1970	1975	1980	1985
Power Reactors	0.1	0.2	3	20	52	73
Fuel Fab. & Repro.	0.9	1.8	2.6	3	1	1
Other*	0.3	0.7	0.8	1	1	1
Total	1.3	2.7	6.4	24	54	76

*Includes workers in uranium enrichment, nuclear waste management, and uranium mills.

its three subcategories from 1960 through 1985. The 1985 estimates in Table B-3 were obtained from the log-log extrapolation of mean annual dose and the number of workers according to their 1975-1980 trends (see Figure 11). The mean annual dose for workers in the fuel fabrication and reprocessing subcategory decreased substantially, while that in power reactors remained essentially constant since 1970. The mean annual dose for workers in the entire nuclear fuel cycle was essentially constant prior to 1975; it increased after 1975 due to the dominant contribution from power reactor workers.

D. Government

The dose distribution for workers in government in 1975 and 1980 was determined from nearly complete data from Federal agencies, except for the Veterans Administration, which was estimated from commercial dosimetry data. The determination of reliable dose distributions for the years 1960, 1965, and 1970, during which the government category comprised the second largest category of workers, was also possible because government data are quite complete for these years. That is, the AEC (now DOE) and Navy, which both made annual exposure summaries for these years, accounted for about 80% of potentially exposed workers in government.

The 1960-1970 exposure data from the AEC had no dose range breakdown below 1 rem, so this portion of the dose distributions was reconstructed with six dose ranges using the HLN model. The dose distributions for workers monitored by the Navy were constructed from the sum of dose distributions for nuclear ship, shipyard, and medical groups, as available. However, since the summaries for the medical group for the period 1960-1975 gave only the collective dose and the number of workers, we estimated their dose distributions from the trend of their annual mean dose and their corresponding dose distributions in 1975 and 1980. There also were few dose ranges in the exposure data for personnel in nuclear ships and shipyards. Thus, the dose distributions for these workers were reconstructed according to NRC dose-range format using the HLN model.

The mean doses in 1960 for the Air Force and Army workers were obtained from our previous report (Co80); those in 1970 were recalculated according to the trend of mean doses between 1960 and 1980 and those in 1965 were interpolated. The corresponding dose distributions for workers in the Air Force and Army in 1960, 1965, and 1970 were then constructed from the trends of their mean doses and their respective dose distributions between 1975 and 1980. For lack of either supporting or contrary evidence, the mean doses and the dose distributions for workers in other agencies in 1960, 1965, and 1970 were assumed to be similar to those in 1975.

The dose distribution for all workers in government was obtained from the weighted sum of the dose distributions of the DOE/AEC, DOD, and other Federal agencies. DOE/AEC and DOD combined have in effect determined the worker dose distribution for the government category since 1960. Figure B-7 gives the log-probability plots of this distribution in 1960, 1965, 1970, 1975, and 1980 and for its three subcategories in 1960, 1975, and 1980. The smooth curves to the data points were fitted using the HLN distribution model.

Table B-5 gives the summary of the mean annual dose equivalent and collective dose equivalent for workers in government and its three

Table B-5. Summary of mean annual and collective doses to potentially exposed workers in government, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Dept. of Energy	200	180	160	140	80	60
Dept. of Defense	80	260	180	100	50	40
Other Agencies*	30	30	30	30	20	10
Total	150	210	160	110	60	50
Occupation	**Annual collective dose equivalent (10^3 person-rem)**					
	1960	1965	1970	1975	1980	1985
Dept. of Energy	16	24	15	11	6	5
Dept. of Defense	4	24	17	9	6	5
Other Agencies*	0.1	0.2	0.2	0.3	0.3	0.2
Total	20	48	32	20	12	10

*Includes PHS (workers in various agencies and facilities covered by the PHS Personnel Monitoring Program (see Table D-6 for details)), NIH, NASA, NBS, and VA. Excludes MSHA (see Table 5 and Appendix C).

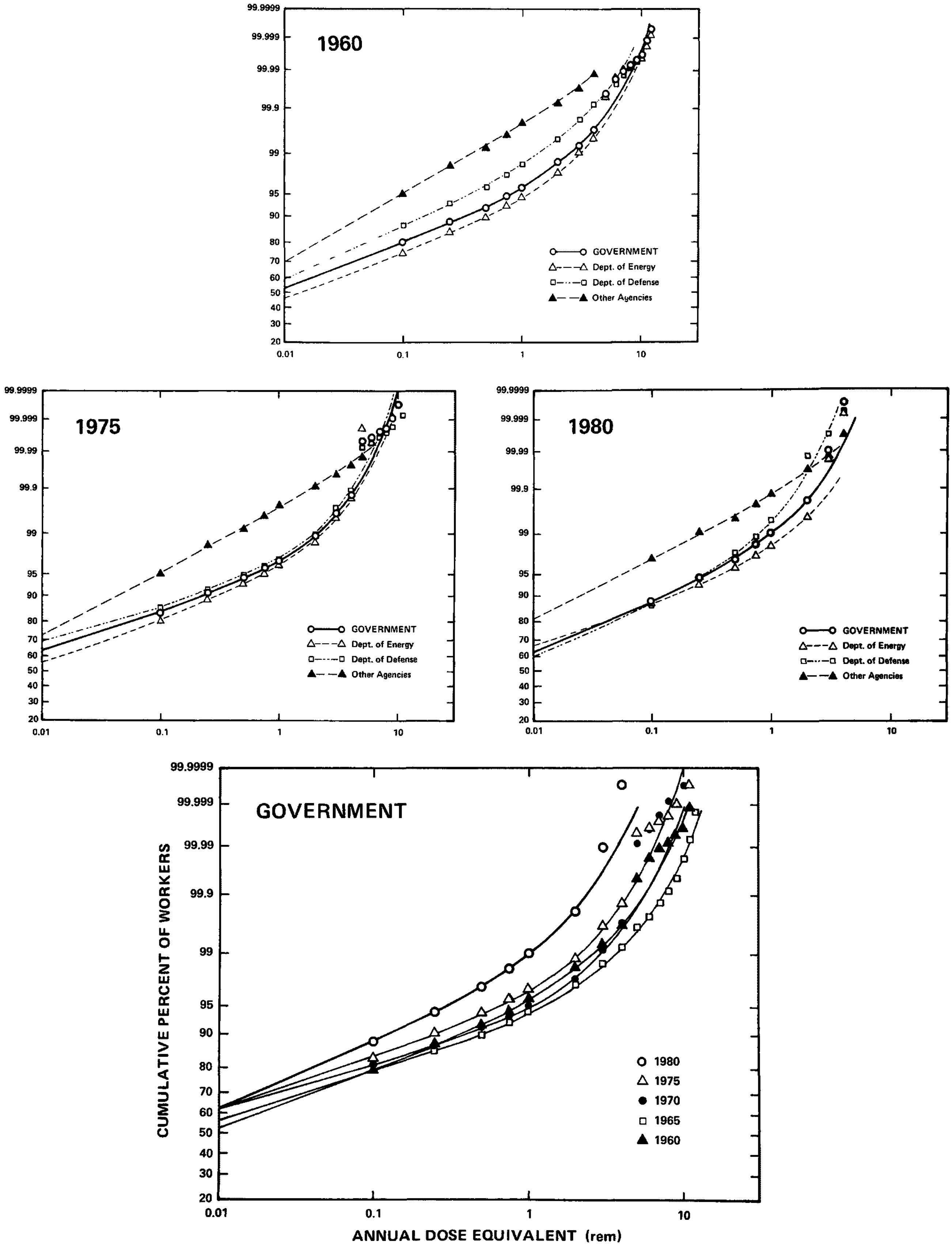

Figure B-7. Dose Distributions for workers in government.

subcategories from 1960 through 1985. The 1985 estimates were obtained from the log-log extrapolation of mean annual dose and the number of workers according to their 1975-1980 trends (see Figure 11). Both mean dose and collective dose have decreased since 1965.

E. Miscellaneous

The dose distributions for workers in miscellaneous occupations (education and transportation) in 1975 and 1980 were based primarily on commercial data. The dose distributions for workers in education were obtained from the weighted sum of the dose distributions corresponding approximately to three groups identified as medical, allied health, and sciences personnel. The dose distributions for transportation workers were derived from commercial data, but with consideration of NRC studies (NRC77a,77b). That is, the commercial dose distributions were adjusted so that their mean doses would approximate the mean doses derived from an NRC study (NRC77b).

The dose distributions for workers in education and transportation for the years 1960, 1965, and 1970 were based on academic and transportation licensee data obtained in 1966-1971 AEC film badge studies (AEC68a,68b,70,71,73).

Figure B-8 shows the log-probability plots of the dose distributions for all workers in miscellaneous occupations in 1960, 1965, 1970, 1975, and 1980 and for its two subgroups for 1960, 1975, and 1980. The shapes of the dose distributions in 1975 and 1980 are clearly more concave than those before 1975. However, the mean dose has remained approximately constant at about 70 mrem since 1960.

Table B-6 shows the summary of mean annual dose and collective dose equivalents for workers in miscellaneous occupations from 1960 through 1985. The 1985 estimates in Table B-6 were obtained from the log-log extrapolation of mean annual dose and the number of workers

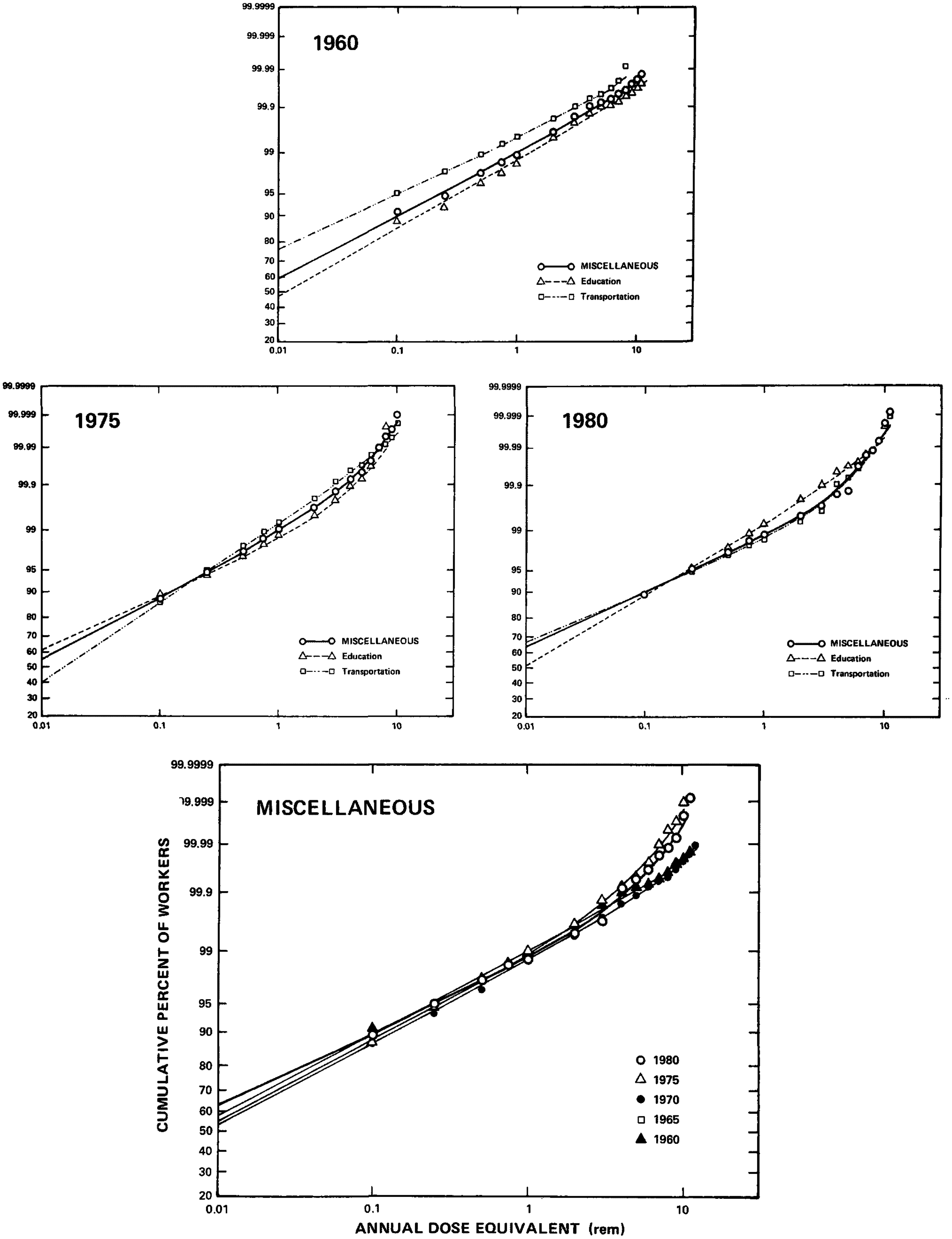

Figure B-8. Dose distributions for workers in miscellaneous occupations.

Table B-6. Summary of mean annual and collective doses to potentially exposed workers in education and transportation, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Education	90	90	110	70	60	40
Transportation	30	40	40	70	70	70
Total*	70	70	80	70	70	70

Occupation	Annual collective dose equivalent (10^3 person-rem)					
	1960	1965	1970	1975	1980	1985
Education	0.9	1.5	2.5	1.8	1.5	1.2
Transportation	0.2	0.4	0.9	2.0	3.5	5.3
Total*	1.1	1.9	3.4	3.8	5.0	6.5

*Excludes students, passenger aircraft crew members, and flight attendants (see Table 5 and Appendix C).

according to their 1975-1980 trends (see Figure 11). The mean dose for workers in education increased and in transportation decreased by about a factor of two during this period, while the overall mean dose remained roughly constant.

F. U.S. Total

The dose distribution for all potentially exposed workers (U.S. Total) was estimated as the sum of the dose distributions of the five categories used in this analysis. Figure B-9 gives the log-probability plots of these dose distributions for all U.S. workers for 1960, 1965, 1970, 1975, and 1980 and for the five categories in 1960, 1975, and 1980. The display of these dose distributions on lognormal probability paper clearly shows their departure from a lognormal distribution, which would be a straight line. There were significant changes in the rela-

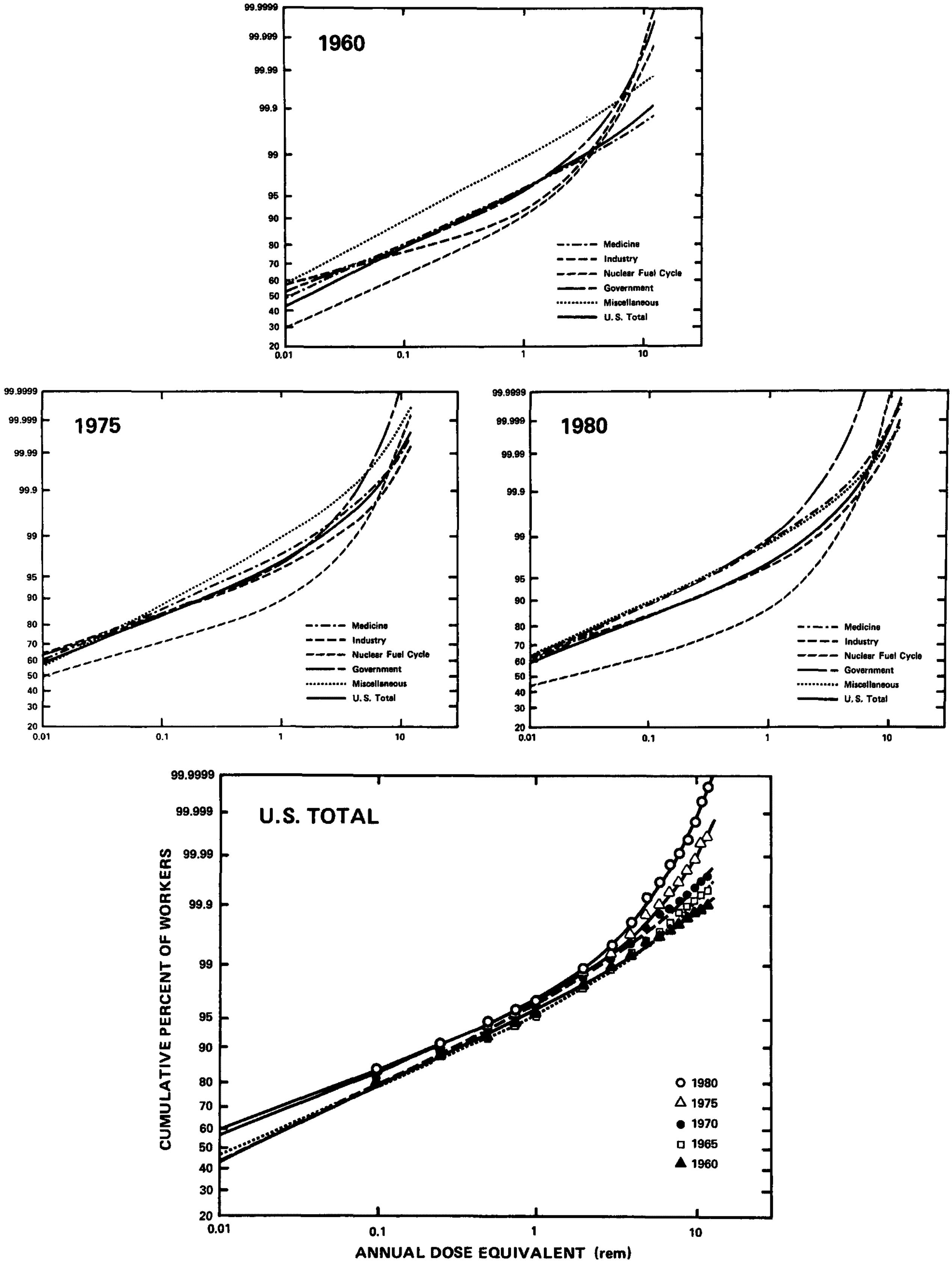

Figure B-9. Dose distributions for all workers.

tionships of the distributions for the five categories for the period 1960 to 1980. The dose distribution for workers in medicine was very close to that for all workers in 1960, but departed considerably from it in 1980; that for industry was quite different from that for all workers in 1960, but became very close to it in 1980; and those for the nuclear fuel cycle and the miscellaneous workers remained quite different from that for all workers for the entire period from 1960 to 1980, while that for government workers was reasonably similar except for in 1980.

The data for the dose distributions for all workers for 1960, 1965, 1970, 1975, and 1980 were fitted very well using the HLN model, as shown in Figure B-9. The bottom graph clearly demonstrates the increasing curvature of the distributions since 1960. This is interpreted to mean that there have been increasing efforts to reduce higher exposures since 1960.

In Tables B-7 and B-8, we summarize the mean annual dose equivalent and the annual collective dose to workers potentially exposed to radiation by subcategory, category, and for all workers, for the period 1960 to 1985. The collective dose equivalents in Table B-8 were determined from the numbers of potentially exposed workers given in Table A-11 and the mean annual dose equivalents given in Table B-7 before rounding off these latter values. The 1985 estimates for the entire work force in Tables B-7 and B-8 agree well with those obtained by the log-log extrapolation of the mean annual dose and the total number of workers from their corresponding 1975-1980 trend (see Figure 11). The mean annual dose in 1960 and 1965 was approximately constant at 180 mrem, but decreased by about 30 mrem every five years between 1965 and 1975. After 1975, the mean annual dose decreased more slowly to a projected dose of 105 mrem in 1985. The total collective dose increased by about 25,000 person-rems every five years after 1975, while it fluctuated around 120,000 persons-rems between 1965 and 1975.

Table B-7. Summary of mean annual dose to potentially exposed workers, 1960-1985

Occupation	Mean annual dose equivalent (mrem)					
	1960	1965	1970	1975	1980	1985
Medicine	190	160	120	100	70	50
Dentistry	110	80	60	40	20	10
Private practice	280	230	180	140	100	80
Hospital	400	300	230	190	140	100
Other(a)	50	50	50	50	50	60
Industry	230	240	220	140	120	110
Radiography	630	490	310	280	290	300
Manufac. & distr.	320	360	360	220	110	80
Other users	210	210	200	120	110	100
Nuclear Fuel Cycle	320	300	320	320	360	380
Power reactors	300	290	400	380	390	400
Fuel fab. & repro.	380	370	310	280	100	90
Other(b)	200	210	210	100	140	150
Government	150	210	160	110	60	50
Dept. of Energy	200	180	160	140	80	60
Dept. of Defense	80	260	180	100	50	40
Other agencies(c)	30	30	30	30	20	10
Miscellaneous	70	70	80	70	70	70
Education	90	90	110	70	60	40
Transportation	30	40	40	70	70	70
All Workers	180	180	150	120	110	105

(a) Veterinary medicine, chiropractic medicine, and podiatry.

(b) Uranium enrichment, nuclear waste management, and uranium mills.

(c) PHS (workers in various agencies and facilities covered by the PHS Personnel Monitoring Program (see Table D-6 for details)), NIH, NASA, NBS, and VA.

Table B-8. Summary of annual collective dose to potentially exposed workers, 1960-1985

Occupation	Annual collective dose equivalent (10^3 person-rem)					
	1960	1965	1970	1975	1980	1985
Medicine						
Dentistry	15	12	10	8	6	3
Private practice	31	26	22	18	16	14
Hospital	11	15	17	18	17	16
Other[a]	1	1	1	2	2	3
Subtotal	58	54	50	46	41	36
Industry						
Radiography	0.7	3	4	5	8	10
Manufac. & distr.	0.6	2	3	4	3	3
Other users	10	13	20	20	27	34
Subtotal	11	18	27	29	38	47
Nuclear fuel cycle						
Power reactors	0.1	0.2	3	20	52	73
Fuel fab. & repro.	0.9	1.8	2.6	3	1	1
Other[b]	0.3	0.7	0.8	1	1	1
Subtotal	1	3	6	24	54	76
Government						
Dept. of Energy	16	24	15	11	6	5
Dept. of Defense	4	24	17	9	6	5
Other agencies[c]	0.1	0.2	0.2	0.3	0.3	0.2
Subtotal	20	48	32	20	12	10
Miscellaneous						
Education	0.9	1.5	2.5	1.8	1.5	1.2
Transportation	0.2	0.4	0.9	2.0	3.5	5.3
Subtotal	1	2	3	4	5	6
Total	91	125	118	123	150	175

(a)Veterinary medicine, chiropractic medicine, and podiatry.

(b)Uranium enrichment, nuclear waste management, and uranium mills.

(c)PHS (workers in various agencies and facilities covered by the PHS Personnel Monitoring Program (see Table D-6 for details)), NIH, NASA, NBS, and VA.

III. DISTRIBUTIONS OF COLLECTIVE DOSES

One approach for calculating the value of collective dose is the midpoint method. This method entails multiplying the number of individuals in a given dose range by the midpoint value of that range and then summing this product for all dose ranges. Because of the large span of dose ranges for much of the published exposure data, this method is not very precise and results in an overestimate of the actual collective dose.

To obtain the best and most consistent estimates of 1975 and 1980 collective doses, collective dose distributions for each of the major categories were derived from the first moments of the hybrid lognormal (HLN) fits to the dose data (see Appendix F). The distributions of collective dose derived from either the sum of the collective dose distributions for the major categories or from the first moment distribution of exposure data for the entire work force were consistent. We note that, in general, the sum of five separate hybrid lognormal distributions does not assure a composite distribution that is well described by a hybrid lognormal distribution. Nevertheless, the difference between elements of collective dose distributions calculated from these two methods was less than 10 percent. Similarly, the sum of the distributions of collective doses in subcategories differed only slightly from the first moment distribution of exposure data for the entire category.

Estimates of collective dose in the higher dose ranges are quite sensitive to small changes in the number of workers exposed. Because of statistical fluctuations in these data, we adjusted the calculated first moments to obtain consistency with the original data. For example, where there was a significant difference between the number of workers and the value from the HLN fit, it was sometimes necessary to reassign some collective dose (i.e., first moment) to an adjacent range to assure that the mean dose (collective dose divided by number of workers in that range) fell in the appropriate range. These adjustments to assign collective dose to adjacent ranges were minor and are reflected in Figures 4 and 5. We also separately analyzed the collective dose distributions for males and females in the five categories and for the entire work force (see Appendix C).

Figure B-10 gives the log-probability plots of the distributions of collective dose for all male, all female, and combined for all male and female workers. The smooth curves give the HLN first moment distributions calculated from the corresponding dose distributions for male, female, and all workers. The collective dose data points obtained in each dose range by summing the contributions from the five categories separately for males and females lie very close to the corresponding calculated curves.

Figure B-11 shows the log probability plots of the distribution of collective dose for all workers in 1960, 1965, 1970, 1975, and 1980 and the five categories in 1960, 1975, and 1980. These were calculated from the first moments of the HLN fits of the dose distributions (see Appendix F).

The distribution of collective dose for the nuclear fuel cycle has the most concave curvature among the five categories since 1960. In 1960, the distribution of collective dose for medical workers is comprised of relatively higher worker doses than that for all workers; while in 1975 the situation is reversed. The distribution of collective dose for government workers alone is always comprised of lower doses than for all workers.

The distribution of collective dose for all workers shows little change for doses below 1 rem since 1960, but a sizable change for doses above 1 rem. This can be seen in Figure B-11. The fractions of collective dose above 1.5 rems were 0.53, 0.53, 0.44, 0.46, and 0.40, in 1960, 1965, 1970, 1975, and 1980, respectively. These values correspond to

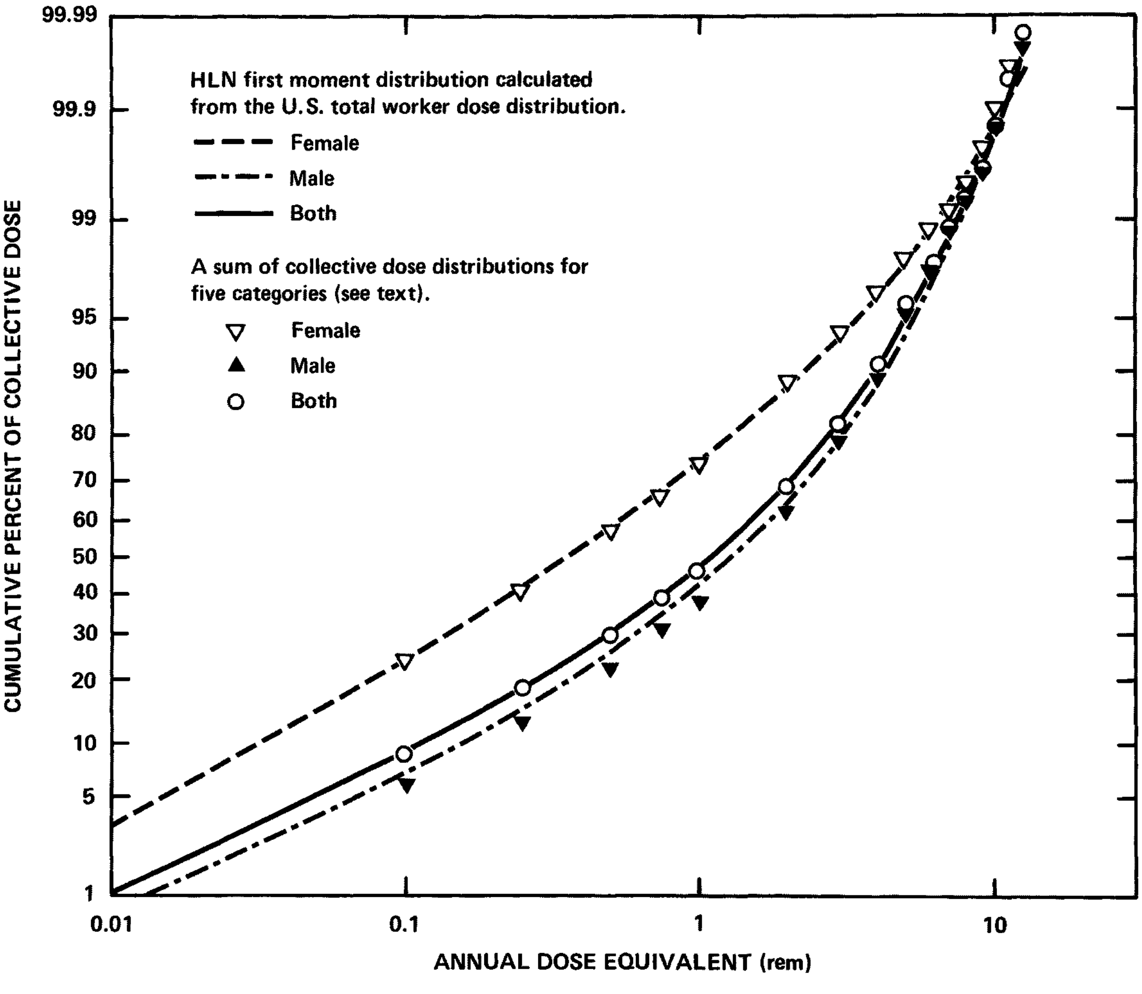

Figure B-10. Collective dose distributions for males, females, and all workers, 1980.

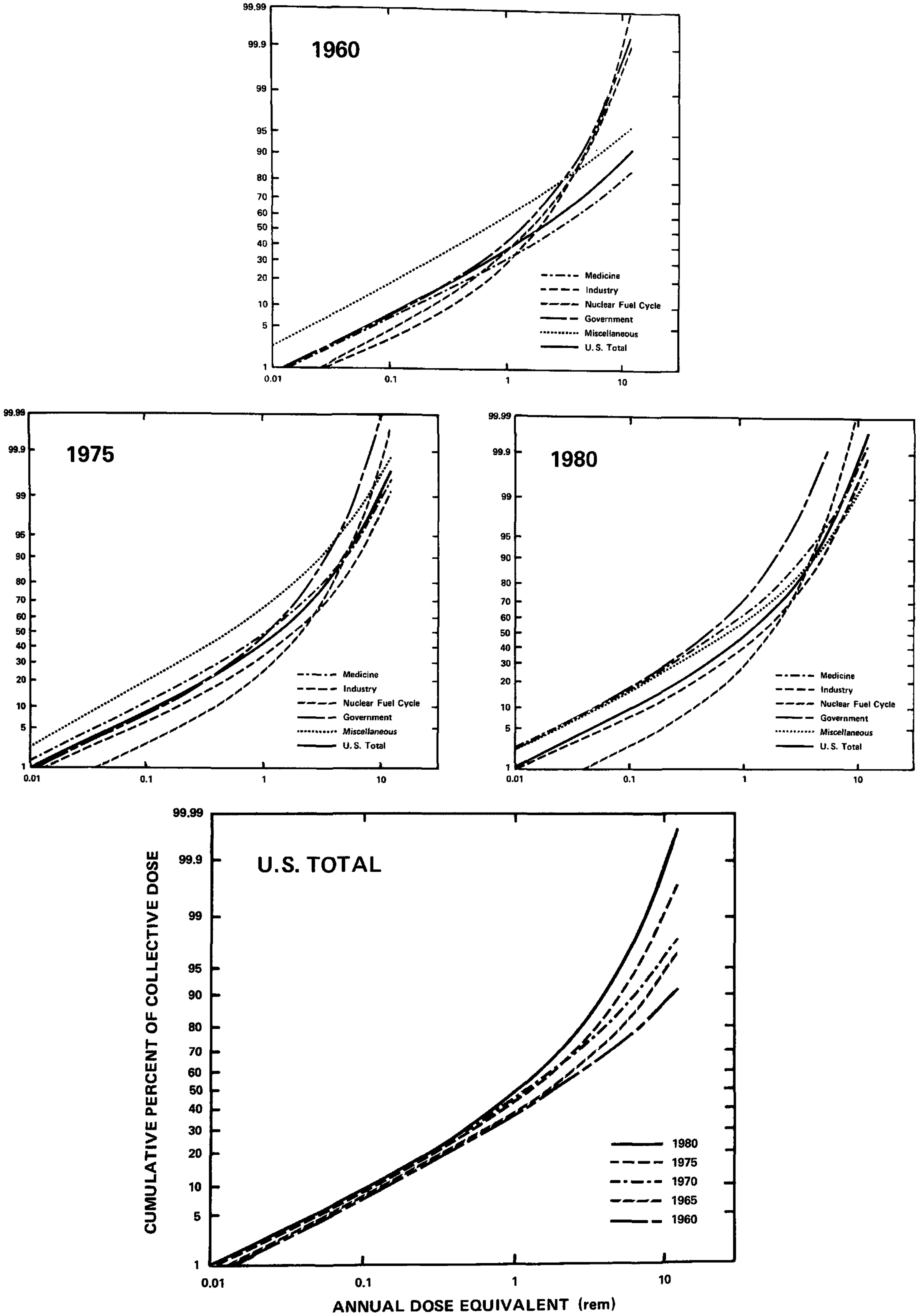

Figure B-11. Collective dose distributions for all workers.

the "collective dose distribution ratio," MR, defined by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The latest UNSCEAR report (UNSCEAR82) states that normal values of MR lie between 0.05 to 0.5. The values of MR for U.S. workers fall within this range since 1970 and show a decreasing trend for the 1960-1980 period. Compared to the decrease in MR values between 1960 and 1980, the fractions of collective dose above 5 rems showed a sharper decrease as follows: 0.25 in 1960, 0.31 in 1965, 0.15 in 1970, 0.1 in 1975, and 0.05 in 1980. Also, the median for the collective dose distributions decreased from 1.7 rems in 1960 to 1.1 rems in 1980.

IV. AGE DISTRIBUTIONS

A. Distribution of Worker Ages

Age distributions of workers in the five categories and for all workers were estimated from commercial dosimetry data for males and females in both 1975 and 1980. We used the Johnson S_B distribution to examine the characteristics of age distributions for each worker group in the commercial data (see Appendix F). We then used these to construct age distributions in each subcategory of the five categories of workers. The age distribution for each category was obtained by combining the age distributions of its subcategories. Finally, the age distribution for the entire work force was obtained from the weighted sum of distributions for the five categories.

Figure B-12 shows the age distributions for potentially exposed male and female workers and the age distributions for male and female workers of the entire U.S. labor force in 1975 and 1980 using a Johnson S_B probability plot (see Appendix F). The horizontal axis is the quantity $\ln[(y-a)/(b-y)]$ where y is worker age (years). The four curves for the U.S. labor force show the age distributions in 1975 and 1980 for males and females tightly grouped together. The age distribution

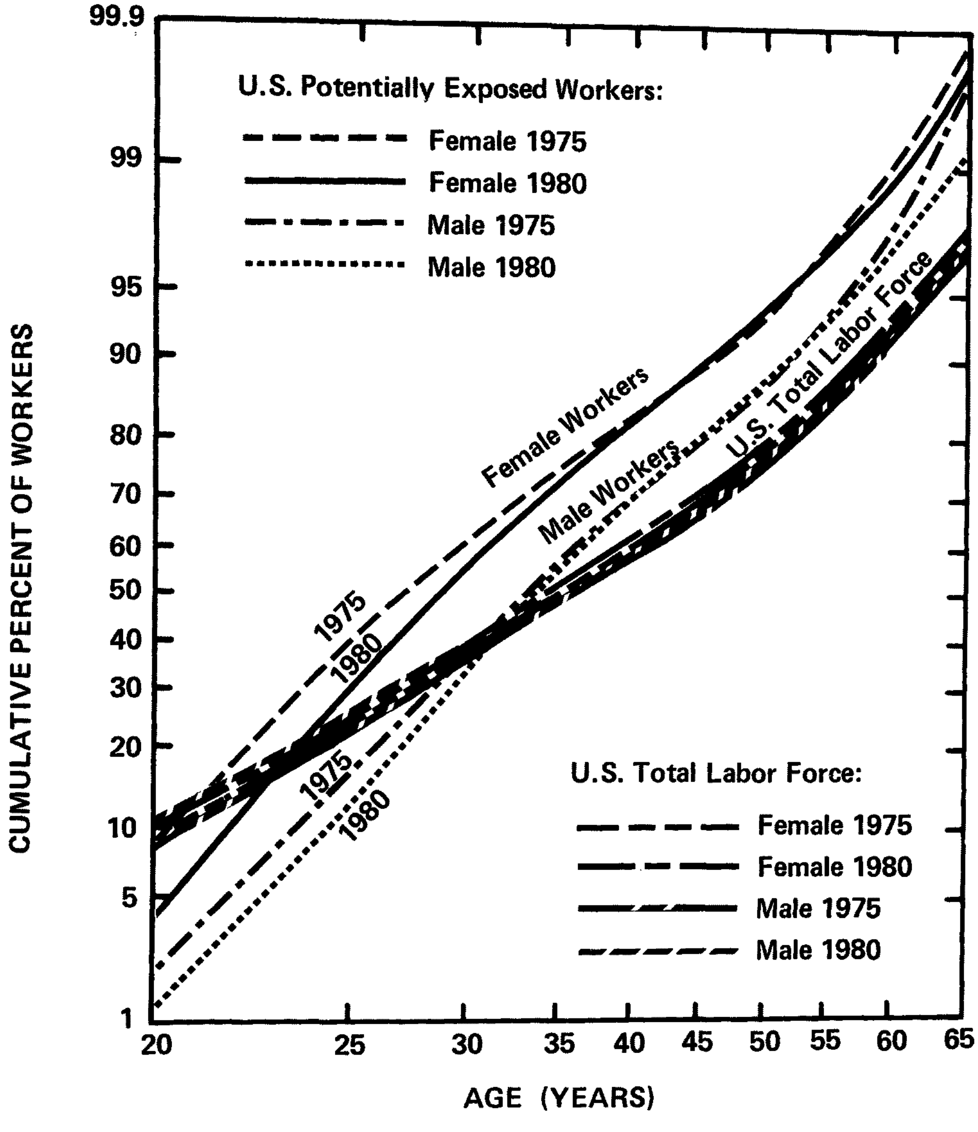

Figure B-12. Male and female age distributions for potentially exposed workers and age distributions for the U.S. labor force, 1975 and 1980.

for the entire U.S. labor force in 1980 was slightly younger than that for 1975. The age distribution for female workers was slightly younger than that for male workers both in 1975 and 1980.

The age distributions for workers potentially exposed to radiation were significantly different from those for all workers in the U.S. labor force. Potentially exposed workers were slightly older in 1980 than those in 1975 for both sexes. The ages of potentially exposed female workers were considerably younger than that of potentially exposed male workers in both 1975 and 1980.

Figure B-13 shows the combined male and female age distributions for the entire U.S. labor force and all potentially exposed workers in 1975 and 1980 and for the U.S. population in 1980. The age distribution of the U.S. population in 1980 was the broadest with about 33% and 12% of persons being younger and older than 20 and 65 years of age, respectively. The distribution of the potentially exposed workers in 1980 was the narrowest with about 5% and 0.5% of workers being younger and older than 20 and 65 years of age, respectively. The age distribution of the entire U.S. labor force in 1980 was between these with about 10% and 3% of workers being younger and older than 20 and 65 years of age, respectively. We conclude that potentially exposed workers have a quite different age distribution than that of the entire U.S. labor force.

B. Distribution of Collective Doses by Worker Age

The distributions of collective dose by worker's age were estimated for 1975 and 1980 from commercial data for males and females for each of the five categories. We examined the characteristics of these distributions for each worker group in the commercial data. We then estimated the collective dose distribution in each subcategory from the weighted sum of these collective dose distributions.

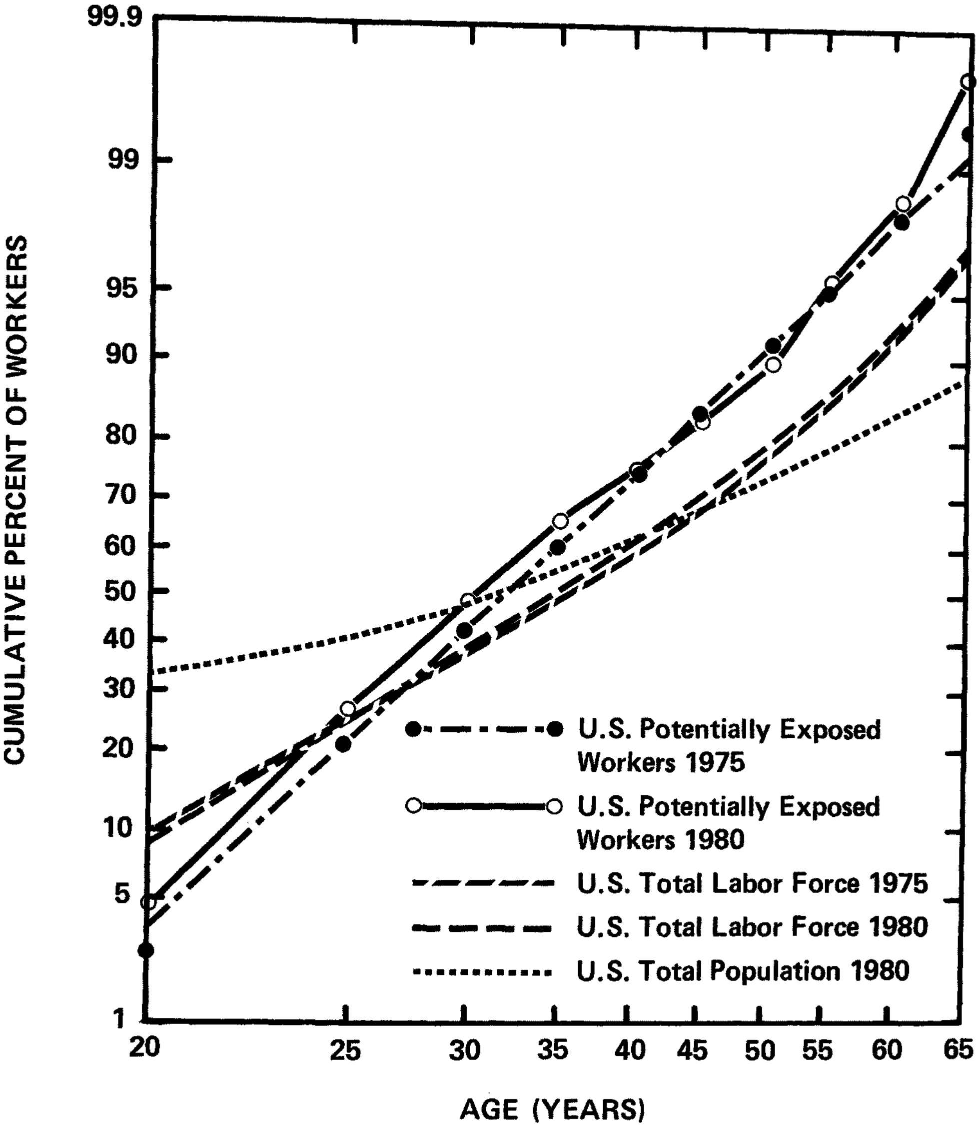

Figure B-13. Age distributions for potentially exposed workers and U.S. labor force, 1975 and 1980, and U.S. population, 1980.

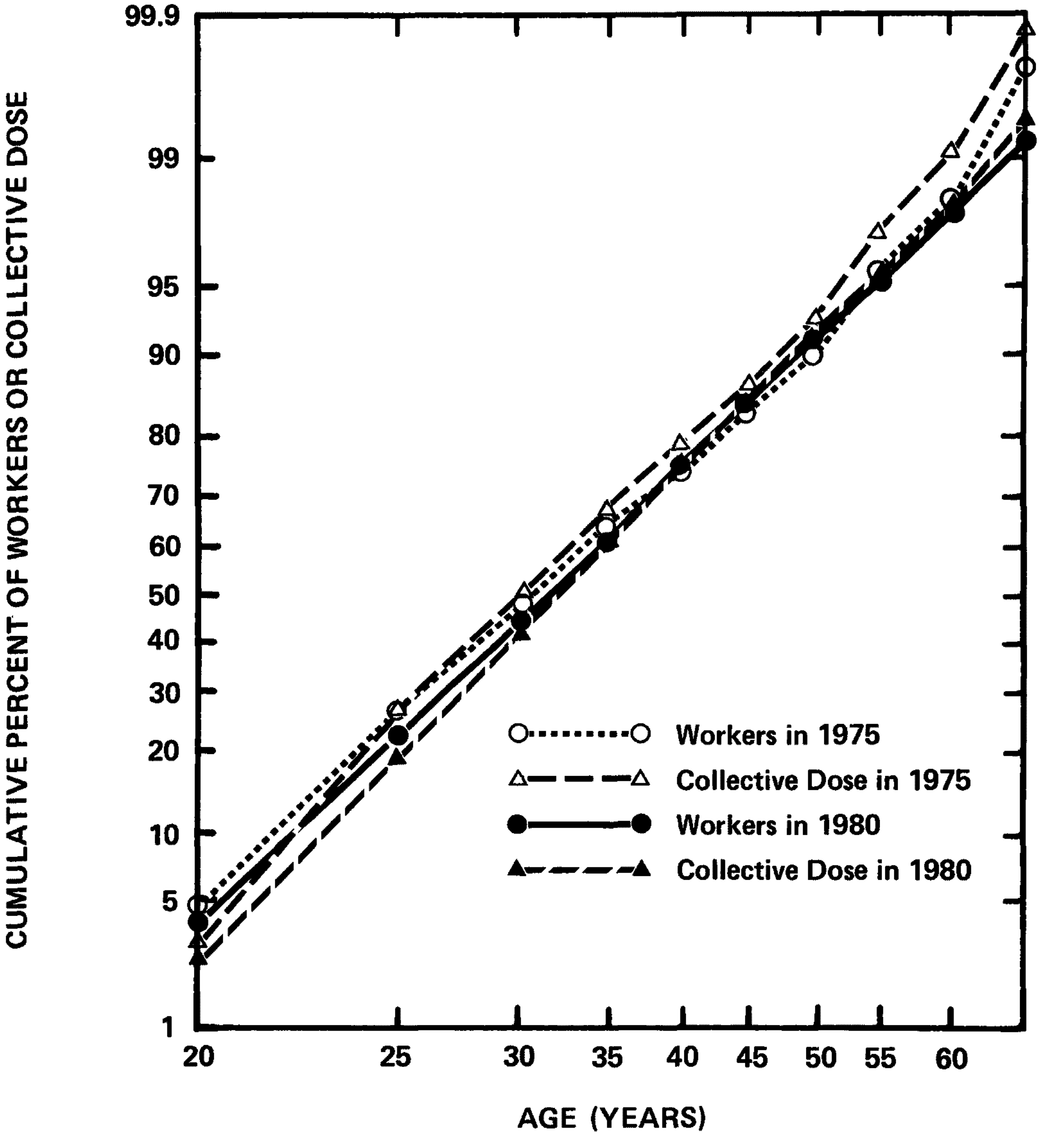

Figure B-14. Age distributions for potentially exposed workers and of collective dose, 1975 and 1980.

Figure B-14 shows the distributions of age of potentially exposed workers and of their collective dose in 1975 and 1980. The collective dose-weighted median age of workers is slightly larger than the median age of workers in 1980, while the reverse is true for 1975. The fraction of workers below 25 years is slightly greater than the fraction of collective dose delivered to workers below 25 years both in 1975 and 1980. The fraction of workers above 45 years is slightly greater than the fraction of collective dose delivered to workers above 45 years both in 1975 and 1980. From these observations we conclude that the distributions of collective dose by worker age are slightly narrower than the distributions of worker age in both 1975 and 1980.

C. Summary

The age distribution of all U.S. workers is narrower than that of the entire U.S. population, as expected, since relatively few persons work before age 18 or after age 65. The age distribution of potentially exposed workers was found to be narrower than that of all U.S. workers. This means that potentially exposed workers, on the average, start working later and leave these jobs earlier than the average U.S. worker.

Table B-9 gives the summary of mean and median values of the age of potentially exposed workers and of collective dose-weighted age for the entire work force and five categories for male, female, and both sexes in 1980. In general, the mean age of workers was two to three years greater than their median age.

Table B-9. Estimated mean and median age of workers potentially exposed to radiation, by sex, 1980

Occupation	Mean age (yr)					
	Potentially exposed workers			Collective dose		
	Both sexes	Male	Female	Both sexes	Male	Female
Medicine	31	36	29	33	36	30
Industry	35	35	35	33	33	35
Nuclear Fuel Cycle	35	36	30	34	34	29
Government	34	35	32	36	37	33
Miscellaneous	33	35	32	34	34	33
Total	33	35	30	34	34	31

Occupation	Median age (yr)					
	Potentially exposed workers			Collective dose		
	Both sexes	Male	Female	Both sexes	Male	Female
Medicine	29	34	27	30	34	28
Industry	32	32	32	31	31	32
Nuclear Fuel Cycle	33	33	28	32	32	27
Government	32	33	30	34	35	30
Miscellaneous	29	32	28	30	32	29
Total	31	33	28	31	32	29

APPENDIX C

ADDITIONAL INFORMATION AND RESULTS FOR 1980

CONTENTS

CONTENTS (Continued)

TABLES

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APPENDIX C

ADDITIONAL INFORMATION AND RESULTS FOR 1980

I. INTRODUCTION

This appendix summarizes 1980 data on exposure of some additional groups of individuals, extremity exposures, and numbers of U.S. workers and their collective doses in dose and age ranges by sex and by category. In addition, we summarize some results of recent testing of personnel dosimetry performance and make a cursory comparison of doses to full-time workers with doses to combined part- and full-time workers.

II. ADDITIONAL GROUPS OF INDIVIDUALS POTENTIALLY EXPOSED TO RADIATION

A. Summary of Principal Results for 1980

Table 5 in Chapter IV summarizes our results for groups of persons potentially exposed to radiation not included in the national summary for 1980 in Table 4. We summarize the basis for these results below.

1. Whole Body Radiation

We estimate about 0.27 million persons were potentially exposed to occupational sources of radiation in 1980 as flight personnel or miners, as visitors to DOE facilities, or as students; about 55% of these are estimated to have received a measurable dose. The mean annual dose equivalent was 90 mrem for all such persons potentially exposed and 160 mrem for those measurably exposed. The total collective dose equivalent to these individuals was about 23,700 person-rems, of which 70% is for flight personnel. Students potentially received the second largest collective dose, about 3300 person-rems. Underground uranium miners exhibited the highest mean annual dose and visitors to DOE facilities had the smallest.

2. Radon Decay Products

The roughly 18,000 potentially exposed underground miners were estimated to have received a mean annual exposure of 0.4 WLM in 1980 and a collective exposure of about 7,500 person-WLM from exposure to radon decay products. Nearly 60% of these miners were estimated to have a mean measurable annual exposure of 0.7 WLM. About 90% of the collective exposure was incurred by about 13,500 uranium miners with a mean annual exposure of 0.5 WLM. Their mean measurable annual exposure was 0.9 WLM.

3. Cosmic Radiation Exposure

Cosmic radiation is not usually considered in the assessment of occupational exposure, because it is simply a part of natural background radiation to which everyone is involuntarily exposed whether on the job or elsewhere. However, for flight personnel, who spend many working hours at high altitudes, the contribution from cosmic radiation exposure is higher than and is a significant addition to normal exposure to background radiation. In 1980, there were about 97,000 flight crew members and attendants, who were estimated to have a mean incremental annual dose of 170 mrem and a collective dose of about 16,500 person-rems from cosmic radiation exposure. Their collective dose from transport of radioactive materials was estimated to be only about 200 person-rems.

B. Underground Miners

1. Number of Underground Uranium Miners

The U.S. uranium mining industry has experienced marked changes in activity since 1960. Shipments of uranium mine ore dropped rapidly from 8 million short tons in 1960 to half that in 1965. During the next ten years ore shipments made a gradual recovery, approaching the 1960 level by 1975. This gradual recovery was followed by a very rapid increase in shipments that more than doubled by 1979, but then dramatically decreased after 1979 (DOC81, DOE83).

The number of miners has closely paralleled the quantity of uranium shipped. We estimated there were 7,000 underground uranium miners in 1960, about 4,000 in 1965, about 5,000 in 1970, and about 6,000 in 1975, from modeling historical data reported by MSHA (Pa84) and others (DOC80, 81). The reported number of miners in 1980 was 13,484, decreasing from a peak of 14,578 in 1979. We previously reported 3,344 underground uranium miners for 1975, but this number represented only those miners estimated to be exposed above 0.01 WLM (Co80); our estimate for the number of all underground uranium miners in 1975, regardless of exposure level, is about 6,000.

2. Radon Decay Product Exposure of Underground Uranium Miners

The exposure of U.S. underground uranium miners to radon decay products was correlated with an increase in their lung cancer in the 1960's (FRC67). In 1971, the Environmental Protection Agency (EPA71) adopted the 4 WLM per annum standard approved on a trial basis in 1969 (FRC69) in place of the earlier 12 WLM per annum standard that had been recommended by the Federal Radiation Council in 1967. A marked reduction in exposures was achieved during the early 1970's. However, accurate exposure records for U.S. uranium miners were not available until the mid-1970's.

We obtained statistics on the exposure of underground uranium miners to radon decay products from MSHA for the period 1974 to 1981 and from the Atomic Industrial Forum (AIF) for the period 1976 to 1980. The MSHA statistics for the period after 1980 are reported in exposure ranges of 0-1 WLM, 1-2 WLM, 2-3 WLM, 3-4 WLM, and more than 4 WLM, and include a range of less-than-measurable exposure. These annual exposures of underground uranium miners show a normal distribution above 1 WLM. We obtained additional exposure detail below 1 WLM (exposure range widths of 0.1 WLM) for the 1980 data (S184) to examine the distribution of the lowest exposures. HLN modeling of these data confirmed our presumption of lognormal characteristics in exposure ranges below 1 WLM.

Figure C-1 shows log probability plots of the annual exposure of underground uranium miners to radon decay products in 1980. The data for all miners and for measurably exposed miners fit a HLN distribution well. From these HLN data fits, we calculated mean annual exposures of 0.5 WLM and 0.9 WLM for all and measurably exposed underground uranium miners, respectively, in 1980.

The dotted curve in Figure C-1 shows the collective exposure distribution (in person-WLM) calculated from the first moment distribution of the HLN-fitted annual exposure distribution of underground uranium miners. The exposure distributions of all miners, measurably exposed miners, and the collective exposure distribution all exhibit a pronounced curvature, as shown in Figure C-1. This curvature indicates the presence of active efforts to limit exposure of miners as they approach an accumulation of 4 WLM.

Since exposure data for other years do not contain dose distribution details below 1 WLM, there is uncertainty in the data fits made to the HLN model. However, by comparing the annual exposure distributions above 1 WLM for the years 1974 through 1981, we found that the fraction of underground uranium miners exposed to more than 2 WLM has apparently

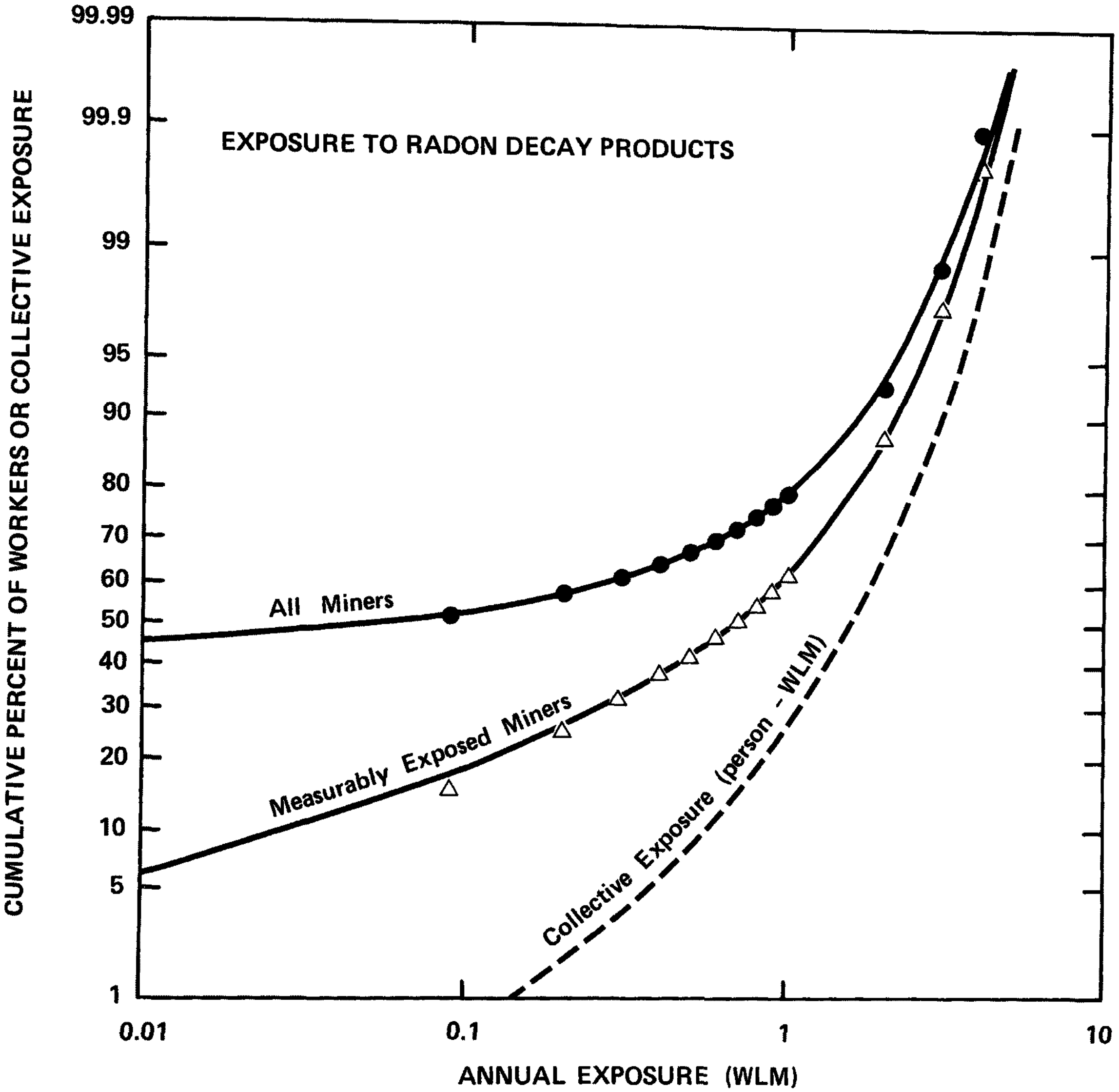

Figure C-1. Log probability plots of annual exposure to radon decay products for potentially exposed and measurably exposed underground uranium miners, 1980.

been decreasing slowly. The median annual exposure of measurably exposed miners decreased from 0.8 WLM in 1975 to 0.7 WLM in 1980. The mean annual exposure for measurably exposed miners was estimated to decrease from 1.1 WLM in 1975 to 0.9 WLM in 1980.

The AIF statistics on the annual exposure of underground uranium miners to radon decay products are valuable, since they contain detailed data on type of occupation and on the number of annual working hours. About 50% of these miners worked in production and development, about 20% were in service work (motorman, haulage crews, etc.), and the rest were in maintenance and other work (engineers, supervisors, etc.). Production and development miners had the largest annual exposure, followed by those in service work.

Our analysis appears to indicate that the AIF data only include measurably exposed miners, since the annual exposure distributions above 1 WLM agree with MSHA distributions for measurably exposed miners. Using HLN fits to the AIF data, we estimated that underground uranium miners who worked 1500 hours or more in 1980 had a mean annual exposure of 1.3 WLM, compared to a mean annual exposure of 1.0 WLM for all underground uranium miners.

In summary, we estimate that the mean annual exposure of all underground uranium miners was 0.6 WLM in 1975 and 0.5 WLM in 1980; for measurably exposed underground uranium miners, the mean annual exposure was 1.1 WLM in 1975 and 0.9 WLM in 1980.

3. Gamma-ray Exposure of Underground Uranium Miners

Underground uranium miners are also exposed to significant levels of gamma radiation. We have only limited data on gamma ray exposure of workers in uranium mine operations in 1980; these data are assumed to be only roughly indicative of such exposure. The mean dose to 83 measurably exposed workers was about 160 mrem per quarter and about 350 mrem per year, respectively, for workers monitored for one quarter and for one year. Assuming an average annual working time of 1600 hours, the mean doses of 160 mrem/quarter and 350 mrem/year correspond to gamma exposure rates of approximately 0.2 milliroentgen/hour (mR/h) and 0.4 milliroentgen/hour (mR/h), respectively.

MSHA mine inspectors have made limited measurements of the distribution of gamma exposure rates. On a given day, the set of data for various locations at a mine exhibit a lognormal distribution. The median exposure rates at different mines ranged from 0.04 mR/h to 2.5 mR/h; the geometric mean is about 0.3 mR/h. As the exposure rate of 2.5 mR/h is believed to correspond to only a very few mines with atypical exposures, the typical exposure rate may be somewhat less than 0.3 mR/h. However, it is consistent with the calculated exposure rates for the above monitored miners.

From the above, we estimate a mean annual dose equivalent of 200 mrem to all miners and 350 mrem to measurably exposed miners in 1980. However, since these values are based upon very limited data, we present them only as a rough measure of the magnitude of gamma exposure of miners.

4. Radon Decay Product and Gamma-ray Exposure of Nonuranium Miners

Nonuranium miners include workers in other metal, nonmetallic mineral, coal, and stone mines. Those potentially exposed to significant (compared to background) levels of radon decay products and gamma radiation are mostly workers in underground metal mines. The number of nonuranium metal mining workers has generally ranged between 90,000 and 100,000 since 1960 (DoC81). In 1980, about 4% of workers at nonuranium metal mines were assessed for exposure to radon decay products (S184), because these mines contained concentrations of radon decay products in excess of 0.3 WL. We assume that this same fraction was also similarly exposed to elevated levels of gamma radiation. This leads to an estimate of about 4,200 nonuranium miners (compared with 13,500 uranium miners) exposed to radon decay products and gamma radiation. Based on limited data, we estimated the mean annual radon decay product exposure to be 0.2 and 0.3 WLM for these potentially and measurably exposed miners, respectively, and the mean annual gamma-ray dose to be 150 and 220 mrem for potentially and measurably exposed miners. We have not made estimates for the much larger group of miners exposed to less than 0.3 WL.

C. Other Worker Groups

This section briefly describes radiation exposures of visitors to DOE facilities, students, flight crew personnel, and flight attendants.

Since 1977 about 50% of the DOE and DOE-contractor monitoring data has been for visitors; before that time, about 40% was for visitors (DOE76-82). The mean annual dose to DOE visitors has been approximately 10 mrem since 1974 (DOE76-82). The number of DOE visitors is estimated to be about 90,000 in 1985 (see Table A-11), based on the assumption that the fraction of DOE monitoring data representing visitors remains at 50%.

The number of students in U.S. colleges doubled during the period 1965 to 1975, but has remained almost constant since 1975 (DOC81). The method for estimating the number of students potentially exposed to radiation was described in Appendix A. We estimated approximately 26,000 potentially exposed students in 1960; 35,000 in 1965; 49,000 in 1970; 64,000 in 1975; and 67,000 in 1980. Since 1965, these estimates of potentially exposed students corresponded to about 0.6% of all U.S. college students. We estimated that about 68,000 students will be potentially exposed in 1985. Estimated doses to students were obtained from commercial dosimetry data.

The number of flight crew personnel doubled during the period 1960 to 1970, while the number of flight attendants tripled (DOC81). The number of flight crew personnel was almost constant from 1970 to 1975 (DOC81), but doubled during the period 1975 to 1980. Flight attendants increased about 15% from 1970 to 1975 (DOC81) and increased about one-and-a-half times from 1975 to 1980. We have estimated that flight crews will number about 47,000 persons in 1985, and flight attendants about 82,000 persons. The overwhelming source of exposure of these persons is cosmic radiation, which averages about 170 mrem per year over that normally received at the earth's surface (1000 hours/yr x .23 mrem/h x 75% flying time at 9 km altitude). The estimated dose contribution from radioactive materials is small, averaging only 1 mrem and 6 mrem, respectively, to 50% of flight attendants and crew members (NRC77b).

D. Projection for 1985

The number of potentially exposed persons in these additional groups (miners, flight crews and attendants, DOE visitors, and students) is estimated to be about 0.3 million in 1985. This is about 18% of the estimated 1.64 million potentially exposed workers in the entire work force in 1985 (see Table A-11).

III. EXTREMITY EXPOSURES IN 1980

A. Number of Exposed Workers

In most cases there were little or no data available for exposed extremities. However, based on some limited records, we can estimate the number of workers receiving exposure of extremities per thousand workers potentially exposed to radiation. These values can then be used to extrapolate the number of workers receiving extremity exposures out of the total number of potentially exposed workers.

In 1980, there were about 21,000 records of extremity exposures by age and sex in our commercial dosimetry data. This number of records was about four times larger than that available in 1975. The number of records with age and sex information increased 10% for males and 17% for females. However, the distribution of the numbers of extremity records per thousand workers potentially exposed (the specific number exposed) for the worker groups in the commercial data for 1980 were very similar to those for 1975. Therefore, we assumed that these data would be suitable for estimating extremity exposures in the entire work force.

The number of workers potentially receiving extremity exposures per thousand potentially exposed workers was estimated to be about 50 for the total work force (60 for male workers and 30 for female workers) and 40 for medicine, 80 for industry, 20 for the nuclear fuel cycle, and 50 for the government and miscellaneous occupations. Among subcategories of workers in medicine, the number of workers potentially receiving extremity exposures per thousand workers ranged from about 1 for dentistry to about 100 for hospitals.

B. Extremity Doses

The mean annual extremity dose for those workers potentially receiving extremity exposures was estimated to be about 0.4 rem; for males, about 0.5 rem, and for females, about 0.3 rem; for workers in medicine, 0.4 rem; for those in industry, 0.3 rem; for nuclear fuel cycle workers, 0.8 rem; for government workers, 0.3 rem; and for workers in miscellaneous occupations, 0.25 rem. The mean annual extremity dose among subcategories of workers in medicine ranged from about 0.02 rem for those in dentistry to about 0.6 rem for those in private practice. The subcategories of workers in industrial radiography, manufacturing and distribution, and fuel fabrication and reprocessing all had mean annual extremity doses greater than 1 rem.

Our estimates of numbers of workers and mean annual dose equivalents for exposure of extremities are summarized in Table C-1.

Table C-1. Crude estimates of radiation exposure to worker extremities, 1980

Occupational category	Number of workers[a]		Dose to extremities		
			Mean annual dose equivalent (mrem)		Collective dose equivalent (person-rem)
	All	Exposed[b]	All	Exposed[b]	
Medicine	21,600	15,100	400	570	8,600
Dentistry	300	60	20	100	6
Private Practice	8,800	6,200	640	900	5,600
Hospital	12,200	8,700	240	330	2,900
Other[c]	300	140	280	570	80
Industry	24,200	11,500	340	710	8,200
Radiography	500	350	1,400	2,000	700
Manufac. & Distr.	2,700	1,700	1,630	2,590	4,400
Other Users	21,000	9,450	150	330	3,100
Nuclear Fuel Cycle	2,800	1,900	800	1,680	3,200
Power Reactors	1,600	1,060	750	1,130	1,200
Fuel Fab. & Repro.	1,000	700	1,900	2,710	1,900
Other[d]	200	140	500	710	100
Government	11,400	4,800	280	670	3,200
Dept. of Energy	5,000	2,000	300	750	1,500
Dept. of Defense	4,100	1,800	340	780	1,400
Other Agencies[e]	2,300	1,000	130	300	300
Miscellaneous	3,800	1,600	180	440	700
Education	2,800	1,400	250	500	700
Transportation	1,000	200	10	30	5
All U.S. Workers	63,800	34,900	370	680	23,900

[a] Estimated numbers of workers are generally rounded to the nearest 100, mean doses to the nearest 10 mrem, and collective doses to the nearest 100 person-rems.

[b] Workers who received a measurable dose in any monitoring period.

[c] Veterinary medicine, chiropractic medicine, and podiatry.

[d] Uranium enrichment, nuclear waste management, and uranium mills.

[e] PHS (workers in various agencies and facilities covered by the PHS Personnel Monitoring Program--see Table D-6 for details), NIH, NASA, NBS, and VA.

IV. SUMMARY OF WORKER EXPOSURE BY OCCUPATION, SEX, AGE, AND DOSE RANGE

The estimated numbers of workers in 1980 and the collective doses to workers in various dose and age ranges by sex and occupational category are shown in Tables C-2 through C-5 (see also Figures 4 through 7).

The values shown in Tables C-2 through C-5 are given to a larger number of significant figures than their inherent accuracy warrants for consistency and completeness only.

Tables C-6 and C-7 show the mean annual dose equivalent in age ranges by occupational category for male and female workers; Tables C-8 and C-9 show the mean measurable annual dose equivalent.

V. PERSONNEL DOSIMETRY PERFORMANCE

A. Introduction

The occupational exposure of persons can involve partial or whole body irradiation from sources of ionizing radiation that may be external or internal to the body. However, the major objective of this study has been to summarize occupational exposure to external penetrating radiation in terms of the readings of personnel dosimeters. One of the uncertainties that affects the accuracy of our estimates is the performance of personnel dosimeters.

Most doses to workers from penetrating radiation result primarily from high and low energy photons in the form of gamma rays and x rays. Therefore, we particularly examine the uncertainties in the measurement of doses from these types of radiation.

Recent studies of personnel dosimetry performance indicated fair performance, but with considerable room for improvement (P183). For

Table C-2. Estimated number of potentially exposed workers by dose range, occupation, and sex, 1980

Annual dose equivalent (rem)	Number of workers											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-MD	322398	336987	75460	231046	113750	35363	54835	5202	61819	37394	16534	27982
MD-0.1	248041	206750	59079	146890	90045	18493	32466	3562	56932	24065	9519	13740
0.1-0.25	54280	32547	12296	23782	18239	1974	13052	913	8939	3270	1754	2608
0.25-0.5	30901	16325	6627	11657	9043	1047	10521	530	4091	1860	619	1231
0.5-1	29021	7965	4422	5902	5867	560	11300	82	2829	1007	603	414
1-2	20991	3245	2438	2191	5385	236	11605	111	1119	559	444	148
2-3	8158	721	734	587	2366	68	4524	33	402	0	132	33
3-4	3389	221	279	188	1400	0	1523	19	21	0	166	14
4-5	1662	102	117	100	842	0	686	0	0	0	17	2
5-8	716	83	128	77	251	2	305	3	0	0	32	1
8-12	91	17	24	16	56	0	3	0	0	0	8	1
12+	2	0	0	0	2	0	0	0	0	0	0	0
U.S. Total	715650	604963	161604	422436	247246	57743	140820	10455	136152	68155	29828	46174

MD Measurable dose.

Table C-3. Estimated collective dose to exposed workers by dose range, occupation, and sex, 1980

Annual dose equivalent (rem)	Collective dose (person-rem)											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
0-MD	383	901	142	708	82	33	96	13	16	18	47	129
MD-0.1	6701	6591	1880	4963	2232	438	1213	124	1174	535	202	531
0.1-0.25	8150	5570	1971	4150	2553	341	2145	123	1240	522	241	434
0.25-0.5	11426	5268	2245	3707	3429	339	3875	180	1581	698	296	344
0.5-1	18101	5364	2930	3725	4486	380	8343	60	1912	906	430	293
1-2	28928	4735	3371	3191	7362	334	15700	160	1843	839	579	211
2-3	19544	1733	1873	1400	5392	179	11154	80	843	0	282	74
3-4	12137	838	1106	730	4467	0	6064	65	73	0	500	43
4-5	7326	419	575	410	3454	0	3224	0	0	0	73	9
5-8	4380	497	806	463	1640	12	1739	16	0	0	195	6
8-12	829	154	209	145	522	0	26	0	0	0	72	9
12+	25	0	0	0	25	0	0	0	0	0	0	0
U.S. Total	117930	32070	17108	23592	35644	2056	53579	821	8682	3518	2917	2083

MD Measurable dose.

Table C-4. Estimated number of potentially exposed workers by age, occupation, and sex, 1980

Age (yr)	Number of workers											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
18-19	8035	25090	1749	18181	3094	964	662	307	949	1575	1581	4063
20-24	84336	168534	12564	129697	35296	10148	17905	2811	12448	13599	6123	12279
25-29	147742	158986	31685	118071	53714	12357	29005	3027	27742	17413	5596	8118
30-34	157869	94237	40135	63440	46704	9168	29816	1973	36770	14427	4444	5229
35-39	104636	57865	27789	37020	33387	7349	20598	923	20049	8209	2813	4364
40-44	69220	38649	15502	24003	23722	5310	14107	666	13777	5058	2112	3612
45-49	52934	24760	12070	14222	18632	4097	10310	251	10168	3151	1754	3039
50-54	39650	17608	8030	8775	14672	3738	8929	337	6462	2156	1557	2602
55-59	30781	12360	6635	5984	11533	3087	6506	139	4751	1491	1356	1659
60-64	14489	5389	3511	2325	5259	1374	2473	14	2089	745	1157	931
65+	5958	1485	1934	718	1233	151	509	7	947	331	1335	278
U.S. Total	715650	604963	161604	422436	247246	57743	140820	10455	136152	68155	29828	46174

MD Measurable dose.

Table C-5. Estimated collective dose to exposed workers by age, occupation, and sex, 1980

Age (yr)	Collective dose (person-rem)											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
18-19	841	924	138	638	450	32	137	20	27	85	89	149
20-24	17996	8306	1573	6628	7193	449	8498	221	345	488	387	520
25-29	26082	8424	3005	6440	9155	400	11913	289	1359	939	650	356
30-34	25202	5187	3718	3765	6926	299	11696	137	2189	752	673	234
35-39	16750	3227	3063	2190	4012	229	7877	82	1482	547	316	179
40-44	11565	2385	2169	1723	2772	147	4950	35	1389	241	285	239
45-49	8148	1460	1454	940	2229	164	3386	12	912	229	167	115
50-54	5351	1105	910	654	1391	133	2456	18	483	132	111	168
55-59	3983	699	600	403	921	135	2009	7	312	79	141	75
60-64	1472	267	320	158	414	64	605	0	93	10	40	35
65+	540	86	158	53	181	4	52	0	91	16	58	13
U.S. Total	117930	32070	17108	23592	35644	2056	53579	821	8682	3518	2917	2083

MD Measurable dose.

Table C-6. Mean annual dose equivalent to potentially exposed workers by occupation, sex, and age, 1980

Age (yr)	Mean annual dose equivalent (mrem)											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
18-19	100	40	80	40	150	30	210	70	30	50	60	40
20-24	210	50	130	50	200	40	480	80	30	40	60	40
25-29	180	50	90	50	170	30	410	100	50	50	120	40
30-34	160	60	90	60	150	30	390	70	60	50	150	40
35-39	160	60	110	60	120	30	380	90	70	70	110	40
40-44	170	60	140	70	120	30	350	50	100	50	130	70
45-49	150	60	120	70	120	30	330	50	90	70	100	40
50-54	130	60	110	70	90	40	280	50	70	60	70	60
55-59	130	60	90	70	80	40	310	50	70	50	100	50
60-64	100	50	90	70	80	40	240	20	40	10	30	40
65+	90	60	80	70	150	30	100	0	100	50	40	50
U.S. Total	160	50	110	60	140	40	380	80	60	50	100	50

Table C-7. Mean annual dose equivalent to potentially exposed workers by occupation and age, 1980

Age (yr)	Mean annual dose equivalent (mrem)					
	Total	Medicine	Industry	Nuclear Fuel Cycle	Government	Miscellaneous
18-19	50	40	120	160	40	40
20-24	100	60	170	420	30	50
25-29	110	60	150	380	50	70
30-34	120	70	130	370	60	90
35-39	120	80	100	370	70	70
40-44	130	100	100	340	90	90
45-49	120	90	110	320	90	60
50-54	110	90	80	270	70	70
55-59	110	80	70	300	60	70
60-64	90	80	70	240	40	40
65+	80	80	130	100	80	40
U.S. Total	110	70	120	360	60	70

Table C-8. Mean annual dose equivalent to measurably exposed workers by occupation, sex, and age, 1980

Age (yr)	Mean annual dose equivalent (mrem)											
	Total		Medicine		Industry		Nuclear Fuel Cycle		Government		Miscellaneous	
	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
18-19	220	110	140	100	290	140	680	290	50	170	160	100
20-24	420	120	220	120	440	120	760	180	50	80	160	100
25-29	320	120	180	120	300	90	700	160	90	130	240	100
30-34	290	120	190	130	260	80	620	140	110	110	310	110
35-39	290	130	210	120	220	80	610	150	140	160	240	240
40-44	290	130	240	150	210	70	510	140	190	90	300	150
45-49	280	100	230	100	220	100	650	110	140	130	220	90
50-54	240	130	200	150	170	80	470	90	150	120	150	150
55-59	250	110	170	190	180	100	490	120	110	100	240	90
60-64	210	110	170	130	160	140	420	20	140	40	90	80
65+	140	80	120	110	220	40	140	0	140	60	90	70
U.S. Total	300	120	200	120	270	90	620	160	120	110	220	110

Table C-9. Mean annual dose equivalent to measurably exposed workers by occupation and age, 1980

Age (yr)	Mean annual dose equivalent (mrem)					
	Total	Medicine	Industry	Nuclear Fuel Cycle	Government	Miscellaneous
18-19	140	100	270	580	110	120
20-24	230	130	380	710	70	120
25-29	230	140	270	650	100	160
30-34	230	150	240	600	110	150
35-39	240	160	200	590	140	240
40-44	240	190	190	500	160	210
45-49	220	150	200	640	140	140
50-54	210	180	160	460	140	150
55-59	210	150	170	490	110	150
60-64	190	150	160	420	120	80
65+	130	110	200	140	120	80
U.S. Total	230	150	240	600	120	160

56 processors that participated in a 1981-1982 study, the mean bias for "deep" dose was 0.24 for low energy photons and 0.07 for high energy photons (P183). The study included both thermoluminescent and film type dosimeters. The commercial dosimetry data used in the present study had less bias. The corresponding mean biases were 0.01 (film) and 0.09 (TLD) for low energy photons and 0.04 (film) and 0.01 (TLD) for high energy photons. The performance of dosimeters by all 56 processors for other radiations are discussed below.

B. Dosimeter Performance

A recent NRC-sponsored study of personnel dosimeter performance (P183) indicated that many processors would have difficulty passing the performance standards proposed by the Health Physics Standards Committee and subsequently adopted by the American National Standards Institute as N13.11 on June 17, 1982 (ANSI83). In a series of three tests, 22% (May-October 1978), 14% (November 1978-April 1979) and 11% (November 1981-April 1982) of individual dosimeters were in error by more than 50%.

Test #3 of the NRC study (November 1981-April 1982) showed improved results for the absolute value of the mean bias, P, of reported doses for a number of types of radiation. P is defined:

$$P = \frac{1}{n} \sum_{i=1}^{n} (D_i - D_o)/D_o,$$

where D - reported dose, D_o = delivered dose, and n = number of reported doses (all D_o values were less than 10,000 mrem).

The absolute values of the mean bias for all tested dosimeters from all processors were (a) 0.24 (deep) and 0.33 (shallow) for low energy photons [x rays from 15 to 30 kev], (b) 0.07 (deep) for high energy gamma rays [cesium-137 gammas from 1.1 to 2.0 Mev], (c) 0.19 for strontium-90 betas, (d) 0.15 for moderated californium-252 neutrons plus high energy photons, (e) 0.21 (deep) and 0.31 (shallow) for a high and low energy photon mixture, (f) 0.12 (deep) and 0.17 (shallow) for high energy photon and beta mixtures.

The terms "deep" and "shallow" refer to absorbed doses delivered at 1.0 and 0.007 cm depths, respectively, in a standard ICRU soft tissue sphere (see ICRU Report 25). If we assume that all dosimeters of this study, excluding accident categories, are representative of dosimetry used for U.S. workers, the average weighted (absolute) bias was 0.21 for the determination of mean doses in 1981-82.

Not all dosimetry data are equally reliable. The number of individual dosimeters irradiated in Test #3 that were within a 50% tolerance limit for P, were 98% (military), 97% (private industry), 91% (nuclear power plants), 90% (national laboratories), 87% (DOE prime contractors), and 86% (all commercial processors). The corresponding mean performances within a ± 30% tolerance limit for P were 89% (military), 81% (national laboratories), 81% (nuclear power plants), 75% (DOE prime contractors), and 76% (all commercial processors). The commercial dosimetry data used for this study had even better performance results than the military. The corresponding performances within a ± 50% and ± 30% tolerance limit for P were 99.4% and 97.0%, respectively. These results were obtained under test conditions for which it might be expected that each participating processor would do its best. Since Test #2 was conducted in 1978-1979 and Test #3 was conducted in 1981-82, it was assumed that actual performance for U.S. dosimetry in 1980 was intermediate between Test #2 and Test #3 results, giving a predicted bias of between 0.24 (Co80) and 0.21 (P183).

VI. COMPARISON OF DOSES TO FULL-TIME WORKERS AND DOSES TO COMBINED PART- AND FULL-TIME WORKERS

In this report we summarize all exposure data for a given year, since the purpose of this study is to assess total worker exposure.

Some of these exposure data are for "part-time" workers who were employed (or, more precisely, monitored) for shorter periods than one year. Thus, these mean doses for combined part- and full-time workers will be lower than for full-time workers only.

We made a cursory examination of the above two types of mean doses for four groups of workers (hospital, dental, nuclear power, and industrial radiography workers) using a sample of commercial data, which contains quarterly dose records. (The mean doses for these samples of workers are not necessarily the same as those reported for our general results because they are calculated from incomplete data.) The mean doses for full-time workers only and for all workers are shown in Table C-10; the differences ranged from 0-50%. The differences in mean dose were generally less for those workers receiving measurable doses than for all monitored workers.

Table C-10. Mean annual dose equivalent to full-time workers and to combined part- and full-time workers

	Mean annual dose equivalent (mrem)			
	Part- and full-time workers		Full-time workers only	
Worker Group	All	Exposed*	All	Exposed*
Dentistry	20	70	30	70
Hospital	140	200	200	240
Industrial Radiography	300	440	410	530
Nuclear Power Reactor	740	900	1110	1340

*Workers who received a measurable dose in any monitoring period.

APPENDIX D

FEDERAL AGENCY EXPOSURE DATA FOR 1980

CONTENTS

TABLES

Table D-1. Summary of Federal occupational radiation exposure data, 1980

Federal Agency	Dose equivalent range (rem)															Total number of monitored workers
	0–MD	MD–0.1	0.1–0.25	0.25–0.5	0.5–0.75	0.75–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	>9	
DOE[a]	44,519	28,523	4,538	2,587	1,225	687	1,112	387	16	0	0	0	0	0	0	83,594
DOD																
Navy[b]	14,852	37,230	6,838	3,114	1,098	679	517	4	3	0	0	0	0	0	0	64,335
Army	12,946	7,534	331	137	48	20	29	5	0	0	0	0	0	0	0	21,050
Air Force[c]	14,214	3,636	177	36	13	3	3	3	0	0	0	0	0	0	0	18,085
Subtotal	42,012	48,400	7,346	3,287	1,159	702	549	12	3	0	0	0	0	0	0	103,470
Other agencies																
NASA	715	172	16	2	2	0	1	0	1	0	0	0	0	0	0	909
NBS	182	202	39	4	3	7	2	0	0	0	0	0	0	0	0	439
NIH	2,806	1,245	71	14	8	5	4	1	0	0	0	0	0	0	0	4,154
PHS	5,278	525	56	19	9	1	4	0	0	0	0	0	0	0	0	5,892
VA[d]	3,607	1,881	139	37	21	6	6	2	1	0	0	0	0	0	0	5,700
Subtotal	12,588	4,025	321	76	43	19	17	3	2	0	0	0	0	0	0	17,094
NRC	63,684	37,915	14,449	11,377	6,931	5,044	12,262	4,779	1,644	761	204	103	19	5	0	159,177

Federal Agency	Exposure range (working level month)															Total number of monitored workers
	0–MD	MD–0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1	1–2	2–3	3–4	>4	
MSHA																
Uranium Miners	5,928	1,146	759	550	437	336	339	281	297	299	296	1,913	731	159	13	13,484

(a) Does not include uranium enrichment and visitors (see Table D-2).
(b) Includes an additional 3,731 persons in Navy contractor shipyards.
(c) Distribution of doses recalculated using the HLN model because of different dose ranges (see Table D-5).
(d) Distribution of doses is based on commercial data.
MD = Measurable dose.

Table D-2. Department of Energy/Department of Energy contractors, occupational radiation exposures, 1980

		Workers in Dose Equivalent Range (rem)										Collective
Facility Type	Number Monitored	Less than Meas.	Meas. -0.10	0.10 -0.25	0.25 -0.50	0.50 -0.75	0.75 -1.00	1-2	2-3	3-4	>4	Dose (person-rem)
Reactor Research	6921	2654	2569	699	449	171	77	165	135	2	0	1185
Fuel Fabrication	2102	734	793	266	143	57	43	55	11	0	0	323
Fuel Processing	3147	778	1041	356	329	199	116	237	91	0	0	1047
Uranium Enrichment	1871	535	861	364	87	19	4	1	0	0	0	156
Weapons Fabrication and Testing	5904	8659	5967	629	315	143	82	93	14	2	0	869
Gen. Research	36110	22933	10749	1225	558	296	155	163	24	7	0	1611
Accelerator	5315	3347	1244	360	159	77	45	70	11	2	0	412
Other	12037	3870	5670	982	631	282	169	329	101	3	0	1773
Visitors	87590	77045	10109	341	62	18	9	4	2	0	0	619
DOE Offices	2058	1544	490	21	3	0	0	0	0	0	0	29
Totals	173055	122099	39493	5243	2736	1262	700	1117	389	16	0	
Collective Dose (person-rem)		0	1975	918	1026	789	612	1676	972	56	0	8024

Table D-3. U.S. Navy,* occupational radiation exposures, 1980

Range (rem)	Number of personnel
No measurable dose	14,005
0.001-0.019	18,080
0.020-0.049	9,757
0.050-0.099	7,269
0.100-0.249	6,448
0.250-0.499	2,936
0.500-0.749	1,035
0.750-0.999	640
1.000-1.249	223
1.250-1.499	118
1.500-1.749	55
1.750-1.999	31
2.000-2.249	1
2.250-2.499	1
2.500-2.749	2
2.750-2.999	0
3.000-3.249	1
3.250-3.499	0
3.500-3.749	0
3.750-3.999	2
>4.0	0
Total personnel monitored	60,604
Total collective dose (person-rem)	4,793

*Excludes Navy contractor shipyards.

Table D-4. U.S. Army, occupational radiation exposures, 1980

Whole-body exposure range (rem)	Number of personnel	Collective dose (person-rem)
No measurable dose	12,946	00.00
Exposure less than 0.100	7,534	119.09
0.100 to 0.250	331	50.63
0.250 to 0.500	137	48.34
0.500 to 0.750	48	28.92
0.750 to 1.000	20	17.61
1.000 to 2.000	29	40.23
2.000 to 3.000	5	12.95
3.000 to 4.000	0	0.00
4.000 to 5.000	0	0.00
Total	21,050	317.77

Table D-5. U.S. Air Force,* occupational radiation exposures, 1980

Occupational category	Dose equivalent range (mrem)													Collective dose (person-mrem)
	0	1-100	101-200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000	1001-2000	2001-3000	
Medical maintenance	449	126	1	1	1	0	0	0	0	0	0	0	0	2,360
Medical x-ray technician	860	937	46	11	6	1	2	0	1	0	0	1	0	42,500
X-ray physician: radiologist	68	111	22	3	1	2	0	1	0	1	0	0	0	11,795
X-ray physician: all others	172	86	11	2	1	0	2	0	0	0	0	0	0	5,849
X-ray nurse/nurse anesthesiologist	284	130	1	0	0	0	0	0	0	0	0	0	0	2,286
Medical technician	713	152	4	2	0	0	0	0	0	0	0	0	0	3,648
Medical x-ray student	178	3	0	0	0	0	0	0	0	0	0	0	0	50
Dental technician	2,940	288	1	0	1	0	0	0	0	0	0	0	0	2,269
Dentist: general	556	56	0	0	0	0	0	0	0	0	0	0	0	417
Dentist: oral surgeon	55	4	0	0	0	0	0	0	0	0	0	0	0	0
Dental x-ray student	444	7	1	0	0	0	0	0	0	0	0	0	0	231
Veterinarian	88	30	0	0	0	0	0	0	0	0	0	0	0	636
Veterinarian: technician	163	42	0	0	1	0	0	0	0	0	0	0	0	803
Military working dog handler	35	19	1	0	0	0	0	0	0	0	0	0	0	437
Radioisotopes: physician	36	25	4	0	0	0	0	0	0	0	0	0	0	1,229
Radioisotopes: technician	96	61	18	7	4	1	5	0	3	0	0	2	3	23,467
Radioisotopes: nurse	6	10	1	0	0	0	0	0	0	0	0	0	0	365
Industrial radioisotopes	1,303	179	4	2	1	0	0	0	0	0	0	0	0	3,806
Industrial x-ray	2,126	833	32	8	0	0	0	0	0	0	0	0	0	28,190
Industrial x-ray: student	160	22	0	0	0	0	0	0	0	0	0	0	0	170
Radar personnel	134	63	0	0	0	0	0	0	0	0	0	0	0	10
Special weapons	294	99	0	0	0	0	0	0	0	0	0	0	0	337
Professionals	647	122	3	1	0	0	0	0	0	0	0	0	0	3,849
Air Force contractors	65	20	0	0	0	0	1	0	0	0	0	0	0	856
Radioactive waste disposal	17	0	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance personnel	205	70	6	0	0	0	0	0	0	0	0	0	0	1,708
Admin. & supply personnel	142	12	0	0	0	0	0	0	0	0	0	0	0	80
Disaster control personnel	48	6	0	0	0	0	0	0	0	0	0	0	0	
Explosive ordnance disposal personnel	701	60	0	0	0	0	0	0	0	0	0	0	0	301
Visitors	1,080	51	0	0	0	0	0	0	0	0	0	0	0	747
All others	149	12	0	0	0	0	0	0	0	0	0	0	0	18
TOTALS	14,214	3,636	156	37	16	4	10	1	4	1	0	3	3	138,844
	Total monitored:		18,085					Average dose equivalent						= 7.68 mrem

*Compiled from the USAF Master Radiation Repository, Brooks AFB, Texas, January 1983.

Table D-6a. U.S. Public Health Service,* occupational radiation exposures by age, 1980

Age (yr)	Dose equivalent range (mrem)										Total personnel monitored	Collective dose (person-mrem)
	<10	10-24	25-49	50-74	75-99	100-249	250-499	500-749	750-999	1,000-4,999		
Under 18	4	0	0	0	0	0	0	0	0	0	4	0
18-19	11	0	0	0	0	0	0	0	0	0	11	0
20-24	445	11	10	5	6	3	1	0	1	0	482	3,030
25-29	1,063	46	26	4	4	7	1	2	0	0	1,153	4,690
30-34	1,295	69	28	13	12	12	6	2	0	2	1,439	11,330
35-39	816	57	22	13	6	7	5	4	0	2	932	10,460
40-44	548	24	23	7	3	9	1	1	0	0	616	4,175
45-49	389	21	12	9	4	8	3	0	0	0	446	3,645
50-54	321	18	12	6	4	8	0	0	0	0	369	2,400
55-59	190	10	12	3	1	1	0	0	0	0	217	1,040
60-64	94	7	3	2	1	0	1	0	0	0	108	690
65+	102	4	3	3	1	1	1	0	0	0	115	1,120
Total	5,278	267	151	65	42	56	19	9	1	4	5,892	42,580

*See footnote at end of Table D-6b.

Table D-6b. U.S. Public Health Service,* occupational radiation exposures by occupation, 1980

Occupation	Dose equivalent range (mrem)										Total personnel monitored	Collective dose (person-mrem)
	<10	10-24	25-49	50-74	75-99	100-249	250-499	500-749	750-999	1,000-4,999		
Radiologist	37	3	8	3	1	6	1	3	0	2	64	5,845
Physician	479	11	10	5	6	5	4	1	0	0	521	4,400
Dentist	560	18	7	2	1	3	2	0	0	0	593	2,035
X-ray tech.	315	31	33	17	11	10	2	3	0	0	422	7,590
Dental tech.	851	26	11	4	1	5	1	0	0	0	899	1,975
Tech. other	1,206	55	19	11	9	9	2	1	1	2	1,315	9,120
Nurse	456	33	11	4	4	1	0	0	0	0	509	1,555
Scientist	870	57	25	11	6	9	3	0	0	0	981	4,935
Nuclear tech.	2	2	1	0	0	2	1	0	0	0	8	565
Other	502	31	26	8	3	6	3	1	0	0	580	4,560
Total	5,278	267	151	65	42	56	19	9	1	4	5,892	42,580

*In 1980, the PHS Personnel Monitoring Program monitored workers in the following agencies: Indian Health Service, PHS Hospitals, U.S. Coast Guard, Food and Drug Administration (including the Center for Devices and Radiological Health and others), Bureau of Prisons, Centers for Disease Control (including the National Institute for Occupational Safety and Health), U.S. Capitol Police, PHS Outpatient Clinics, National Institutes of Health (National Institute of Environmental Health Sciences and Gerontology Research Center only), Environmental Protection Agency, U.S. Customs, Supreme Court Police, National Institute for Mental Health (St. Elizabeth's Hospital), Occupational Safety and Health Administration, Federal Bureau of Investigation, U.S. Senate Post Office, National Center for Health Statistics, U.S. Merchant Marine Hospitals, and Federal Emergency Management Agency.

Table D-7. National Aeronautics and Space Administration, occupational radiation exposures,* 1980

Total personnel monitored	Exposure range (rem)									
	Less than measurable	<0.10	0.10 0.25	0.25 0.50	0.50 0.75	0.75 1.00	1-2	2-3	3-4	4-5
909	715	172	16	2	2	0	1	0	1	0

*Occupational categories of personnel monitored include:

Health physicist
Maintenance worker
Inspector
Aircraft technician
Electronics technician
Biomedical engineer
Reactor worker
Medical technician
Nurse
Physician
Chemist
Animal caretaker
Industrial radiologist
Scientist
X-ray technician
Warehouse worker
Other

Table D-8. National Bureau of Standards, occupational radiation exposures, 1980

Dose range (rem)	Number of workers
No measurable dose (MD)	182
MD less than 0.10	202
0.10 - 0.25	39
0.25 - 0.50	4
0.50 - 0.75	3
0.75 - 1.00	7
1.00 - 2.00	2
2.00 - 3.00	0
3.00 - 4.00	0
4.00 - 5.00	0
Total	439

Table D-9. National Institutes of Health*, occupational radiation exposures, 1980

Exposure range (rem)	Number of individuals
No measurable dose	2,806
0.0 - 0.1	1,245
0.1 - 0.25	71
0.25 - 0.5	14
0.5 - 0.75	8
0.75 - 1.0	5
1.0 - 2.0	4
2.0 - 3.0	1
3.0 - 4.0	0
4.0 - 5.0	0
5.0 - 6.0	0
6.0 - 7.0	0
7.0 - 8.0	0
8.0 - 9.0	0
9.0 - 10.0	0
10.0 - 11.0	0
11.0 - 12.0	0
12.0+	0
Total	4,154

*Data is for the Isotope Laboratory, NIH, Bethesda, Maryland, complex only.

Table D-10. Nuclear Regulatory Commission, licensee occupational radiation exposures, 1980

	Number of individuals with whole-body doses in ranges (rem)																Total collective dose (person-rem)
License category	No measurable dose	Measurable to <0.10	0.10-0.25	0.25-0.50	0.50-0.75	0.75-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	>9	Total number monitored	
Industrial radiography																	
Single location	740	579	134	87	32	12	19	4	2	0	1	0	1	0	0	1,611	174
Multiple locations	3,806	2,291	1,046	776	478	303	496	186	66	33	5	3	0	2	0	9,491	2,805
Subtotal	4,546	2,870	1,180	863	510	315	515	190	68	33	6	3	1	2		11,102	2,979
Manuf. & Distrib.																	
Broad	2,007	893	313	155	83	42	126	61	35	41	6	2	0	0	0	3,764	941
Other	652	547	109	28	2	2	10	1	3	1	0	0	0	0	0	1,355	92
Subtotal	2,659	1,440	422	183	85	44	136	62	38	42	6	2	0	0	0	5,119	1,033
Fuel Fab. & Reproc.	4,304	3,737	1,082	510	254	167	137	12	1	0	0	0	0	0	0	10,204	1,111
Power reactors*																	
BWRs	13,971	9,765	4,671	4,283	2,803	2,090	5,884	2,831	1,073	503	129	60	2	0	0	48,065	29,530
PWRs	38,204	20,103	7,094	5,538	3,279	2,428	5,590	1,684	464	183	63	38	16	3	0	84,687	24,544
Subtotal	52,175	29,868	11,765	9,821	6,082	4,518	11,474	4,515	1,537	686	192	98	18	3	0	132,752	54,074
Total	63,684	37,915	14,449	11,377	6,931	5,044	12,262	4,779	1,644	761	204	103	19	5	0	159,177	59,197

*Includes all light water reactors (BWR-Boiling Water Reactor; PWR-Pressurized Water Reactor) that reported, although all of them may not have been in commercial operation for a full year. This does not include data from the one commercial gas-cooled power reactor.

Table D-11. Mine Safety and Health Administration, occupational radiation exposures - underground uranium miners,* 1980

Exposure range (WLM)	Number of miners
0 - ME	5,928
ME - 0.1	1,146
0.1 - 0.2	759
0.2 - 0.3	550
0.3 - 0.4	437
0.4 - 0.5	336
0.5 - 0.6	339
0.6 - 0.7	281
0.7 - 0.8	297
0.8 - 0.9	299
0.9 - 1.0	296
1.0 - 2.0	1,913
2.0 - 3.0	731
3.0 - 4.0	159
>4	13
Total	13,484

*Exposure data are for radon decay products in units of working level months (WLM) (see definition on p. 20).

ME Measurable Exposure.

APPENDIX E

OCCUPATIONAL EXPOSURE SUMMARIES FOR 1960, 1970, AND 1975

CONTENTS

TABLES

Table E-1. Occupational exposure summary for 1960*

Occupational group	Number of persons	Mean whole-body dose (millirem)**
A. Federal Agencies		
U.S. Air Force	6,800	30
U.S. Army	16,400	30
U.S. Navy		
1. Nuclear Propulsion Program		
a. government	4,685	230
b. contractor	10,394	50
2. Non-Nuclear Navy (government)	7,420	220
Atomic Energy Commission and Contractors (some Federal - mostly contractor employees)	82,195	220
Public Health Service (PHS)(b) Bureau of Radiological Health (HEW)	1,500	—
Mining Enforcement and Safety Administration (privately employed uranium miners)	5,800	—
National Aeronautics and Space Administration	200	—
National Bureau of Standards	100	—
National Institutes of Health	530	—
SUBTOTAL, Federal Agencies	136,024	170***
B. Healing Arts	250,000	
C. Industry	50,000	
TOTAL	436,024	

*Source: "Occupational Exposure to Ionizing Radiation in the United States: A Comprehensive Summary for the Year 1975" (Co80).

**Values for mean whole-body dose are rounded to the nearest 10 millirem.

***Mean whole-body dose for AEC and Department of Defense personnel and contractor personnel.

Table E-2. Occupational exposure summary for 1970* (Co80)

Category	Number of persons	Collective dose (person-rem)	Mean whole-body dose per person (millirem)
AEC			
Contractors	102,918	20,361	198
Reporting Licensees			
AEC	62,090	13,365	215
Agreement State	24,519	6,715	274
Non-reporting Licensees			
AEC	93,000	5,022	54
Agreement State	3,000	822	274
Military			
Army	7,445	744	100
Air Force	17,591	1,555	88
Navy	55,051	10,879	198
PHS	508	65	129
Other Federal	2,000	258	129
Medical			
Radium	37,925	20,480	540
Non-Federal			
Medical x-ray	194,451	62,253	320
Dental x-ray	171,226	21,403	125
TOTAL	771,814	163,922	210

*Source: Estimates of Ionizing Radiation Doses in the United States 1960-2000, USEPA, Office of Radiation Programs, Criteria and Standards Division, Table IV-4, Page 148.

Table E-3. National occupational exposure summary for 1975(a)

Occupational subgroup	Number of workers		Mean whole-body dose (millirem)		Collective dose (person-rem)
	Total(b)	Exposed(c)	Total(b)	Exposed(c)	
MEDICINE					
Hospital/Clinic	100,000	55,100	220	400	22,000
Private Practice	137,800	53,300	160	410	21,700
Dental	265,700	41,400	20	140	5,800
Podiatry	10,100	2,100	10	30	100
Chiropractic	14,600	3,700	30	110	400
Veterinary	18,100	6,200	80	230	1,400
Entire Subgroup	546,300	161,800	90	320	51,400
INDUSTRY(d)					
Industrial Radiography Licensees	19,800	9,700	290	580	5,700
Other Industrial Users					
Licensees	114,100	18,800	100	610	11,400
Registrants	55,900	16,000	110	370	5,900
Source Manuf. & Distr.					
Licensees	7,000	3,900	350	630	2,500
Registrants	4,000	800	40	200	200
Entire Subgroup	200,800	49,200	130	520	25,600
NUCLEAR FUEL CYCLE					
Power Reactors	54,763	28,034	390	760	21,400
Fuel Fabrication and Reprocessing	11,405	5,495	270	560	3,100
Uranium Enrichment	7,471	5,664	50	70	400
Nuclear Waste Disposal	300	100	310	920	100
Uranium Mills	300	100	20	50	--
Entire Subgroup	74,200	39,400	340	630	24,900

See footnotes at end of table.

Table E-3. National occupational exposure summary for 1975(a) (Continued)

Occupational subgroup	Number of workers		Mean whole-body dose (millirem)		Collective dose (person-rem)
	Total(b)	Exposed(c)	Total(b)	Exposed(c)	
GOVERNMENT					
Dept. of Energy	80,954	39,451	150	300	11,800
Dept. of Defense	92,500	55,800	110	180	10,100
Other Federal Govt.	13,400	4,400	90	280	1,300
Entire Subgroup	186,800	99,700	120	230	23,100
MISCELLANEOUS					
Education (faculty):					
2-year Institutions	7,000	2,300	60(e)	170	400
4-year Institutions	14,800	4,900	80(e)	230	1,100
Transportation	77,000	11,800	30	200	2,300
Entire Subgroup	98,800	19,000	40	200	3,800
ALL WORKERS	1,106,900	369,100	120	350	128,800
ADDITIONAL GROUPS(f)					
Transportation (Flight Attendants; radionuclides)	30,000	10,000	--	10	100
Education (Students):					
2-year Institutions	35,000	11,700	60(e)	170	2,000
4-year Institutions	54,800	18,300	80(e)	230	4,200
All Additional Groups	119,800	40,000	50	150	6,100

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*Source: "Occupational Exposure to Ionizing Radiation in the United States: A Comprehensive Summary for the Year 1975" (Co80).

(a) Extrapolated numbers of workers are rounded to the nearest 100, mean doses to the nearest 10 mrem, and collective doses to the nearest 100 person-rems.

(b) All monitored and unmonitored workers with potential occupational exposure.

(c) Workers who received a measurable dose in any monitoring period during the year.

(d) "Licensee" means NRC and NRC agreement state licensees for use of radionuclides. Doses from electronic (e.g., x-ray) sources are also included. "Registrant" means state registrants who have electronic sources only.

(e) These estimated doses are based on small samples that may not be representative.

(f) Persons who are only incidentally exposed or not normally considered workers; the estimates listed are very uncertain.

APPENDIX F

THE HYBRID LOGNORMAL AND JOHNSON S_B DISTRIBUTIONS

CONTENTS

FIGURES

APPENDIX F

THE HYBRID LOGNORMAL AND JOHNSON S_B DISTRIBUTIONS

We made extensive use of two statistical distributions: the hybrid lognormal (HLN) distribution to analyze the distributions of workers and collective dose as a function of dose, and the Johnson S_B distribution to analyze the distribution of workers and collective dose as a function of age. A brief description and mathematical expression are given here for each of these distributions, but the interested reader should refer to the appropriate references for further detail. We also illustrate briefly our use of these statistical distributions with several groups of workers.

I. THE HYBRID LOGNORMAL DISTRIBUTION

The hybrid lognormal (HLN) distribution is the transformation of of the variable x given by ($\ell n \rho x + \rho x$) that has a normal distribution with mean μ and variance σ^2 (Ku81). The variable x is the dose equivalent (in units of rem) and ρ is a parameter (in units of reciprocal rem) indicating the degree of active control used to avert some level of radiation exposure. The HLN distribution is derived from the lognormal distribution by including a feedback mechanism that relates active control of future doses to previous cumulative doses (Ku82a, Ku82c). The HLN distribution is similar to the lognormal distribution in lower range values of ρx and to the normal distribution in upper range values of ρx.

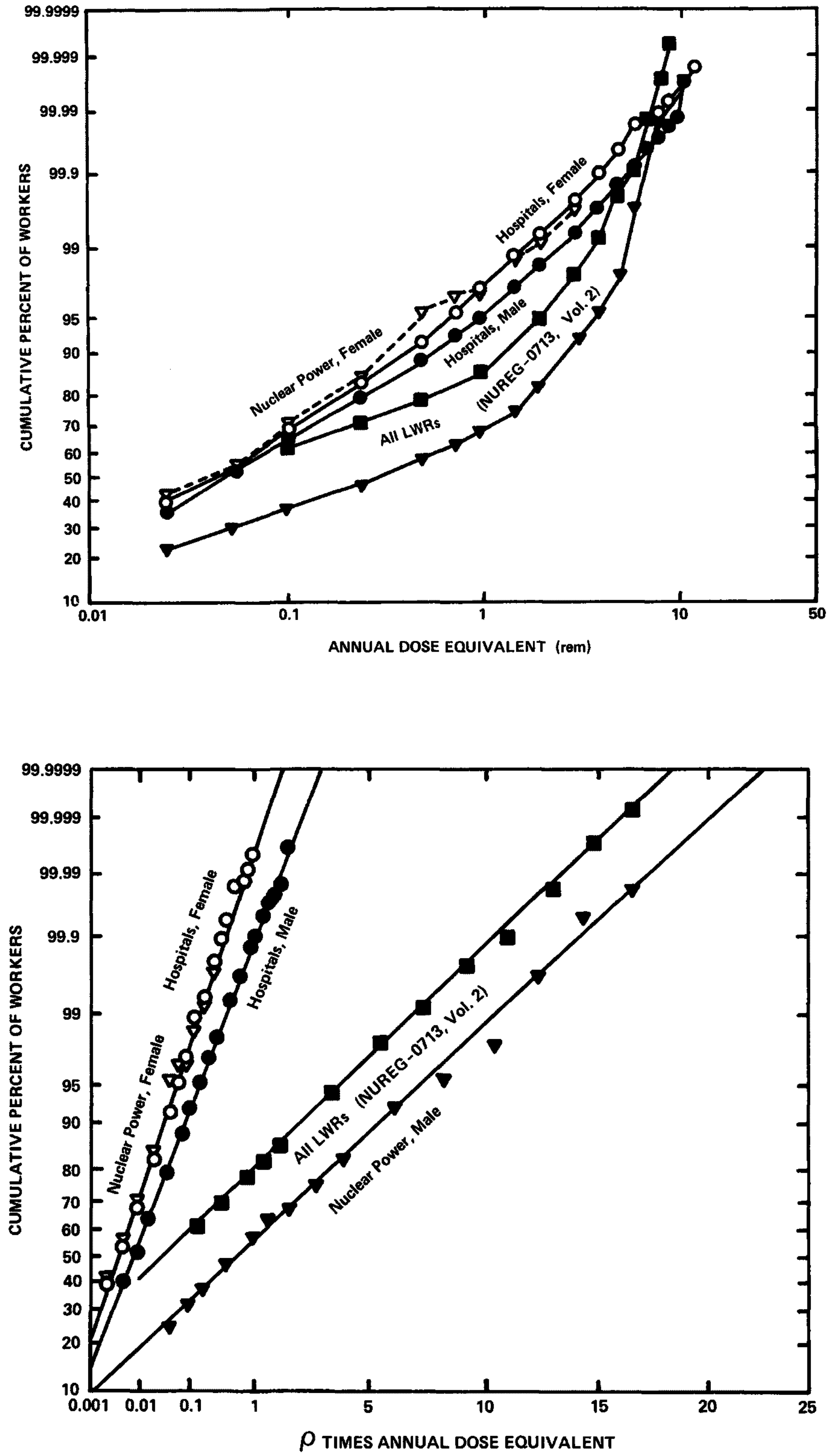

Figure F-1. Lognormal and hybrid lognormal probability displays of dose distributions for all light water reactor (LWR) workers, 1982, and for a sample of male and female hospital and nuclear power workers, 1980.

The HLN distribution function, $\Omega(x)$, is given by

$$\Omega(x) \;=\; \int_{o}^{\rho x} \frac{1}{2\pi\,\sigma}\left(\frac{1}{t} + 1\right) \exp\left[-\,\frac{(\ell nt + t - \mu)^2}{2\,\sigma^2}\right] dt, \qquad \text{(F-1)}$$

$$(o < x < \infty,\ o < \rho < \infty,\ -\infty < \mu < \infty,\ o < \sigma < \infty)$$

The collective dose distribution function, $\Omega_1(x)$, or first moment distribution of the HLN distribution is given by

$$\Omega_1(x) \;=\; \int_{o}^{\rho x} t\; d\Omega(t) \Big/ \int_{o}^{\infty} t\; d\Omega(t) \qquad \text{(F-2)}$$

where $d\Omega(t)$ is the integrand in equation F-1.

The fraction of the entire collective dose equivalent contributed by the κth dose range is calculated as $N\bar{x}\{\Omega_1(x_\kappa) - \Omega_1(x_{\kappa-1})\}$, where N is the number of workers and $\bar{x}$ is the mean dose equivalent for the entire dose distribution.

We used a computer program to fit the HLN model to dose data and to obtain the three HLN parameters (μ, ρ, σ^2), the arithmetic mean dose equivalent, the first moment distribution, and other characteristics (Ku81, Ku82b).

Figure F-1 gives five examples of hybrid lognormality of annual dose equivalent distributions of workers (Ne82). The upper figure gives a lognormal presentation and the lower figure gives an HLN presentation of the same data. Each HLN data fit gives an approximate straight line, whereas the corresponding lognormal data fit typically does not. The straight portion of HLN distributions that is located in the linear scale region of ρx (i.e., $\rho x > 5$) corresponds to the more sharply curved region of the lognormal presentations of the same data.

Figure F-2 shows the estimated active control parameter ρ as a function of the mean annual dose equivalent for three worker groups in

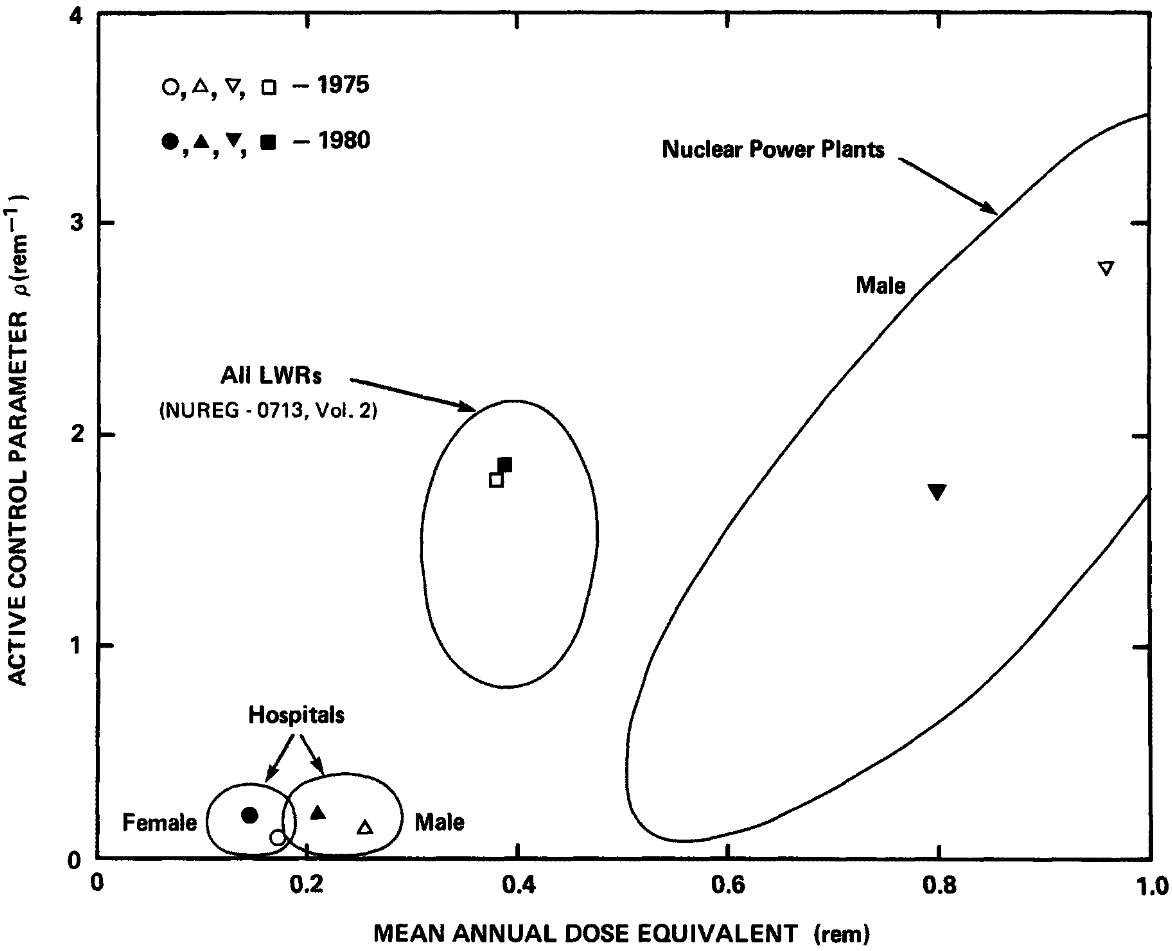

Figure F-2. Active control parameter ρ (rem^{-1}) versus average annual dose for all light water reactor (LWR) workers and by sex for a sample of hospital and nuclear power workers, 1975 and 1980.

1975 and 1980 (Ne82). Worker groups with higher mean annual dose equivalents show higher active control. Each of the indicated regions encircling the mean values of ρ in Figure F-2 represent the extent of variation of the active control parameter according to mean dose in different age groups for the hospital and nuclear power groups. The variation of ρ for All Light Water Reactors (All LWRs) represents the extent of yearly variations from 1975 to 1980. The group of nuclear power workers from commercial dosimetry data is a subset of the All LWR group of the NRC. The workers of this subset incurred higher mean annual exposures than for All LWR workers.

The HLN distribution model proved useful in consistently fitting annual dose distribution data and analyzing annual collective dose distributions. We also used the HLN model for analysis of annual dose data and termination data where it provided a measure of the degree of active control used to reduce, respectively, the frequency of annual doses approaching dose limits and the accumulated career doses of workers according to their length of employment. Finally, we used the HLN distribution model for predicting the 1985 dose distributions for the five occupational categories and for all workers from the trends of the corresponding distributions for the period 1960 to 1980.

II. THE JOHNSON S_B DISTRIBUTION

Workers potentially exposed to radiation, like most workers, are primarily distributed between 18 and 65 years of age. For modeling purposes, such workers can be considered to have a lower age limit of 18 years and an upper age limit of 65 years. The Johnson S_B distribution (double-bounded lognormal) is particularly well suited to fitting such age distributions where there are relatively sharp cut-offs in the number of persons below some age "a" and above some age "b". The Johnson S_B distribution is the transformation of variable y given by $\ell n \{(y-a)/(b-y)\}$ that has a normal distribution with mean μ and with variance σ^2 (A157, Jo70). The S_B distribution function is given by

$$S_B(y) = \int_a^y \frac{(b-a)}{(t-a)(b-t)} \exp\left[-\frac{(\ell n\{(t-a)/(b-t)\} - \mu)^2}{2\,\sigma^2}\right] dt, \qquad \text{(F-3)}$$

$(a < y < b, -\infty < a < b < \infty, -\infty < \mu < \infty, o < \sigma < \infty)$.

We used a computer program to estimate model parameters (a, b, μ, and σ^2) from age distribution data. Figure F-3 gives examples of S_B fits of worker age distribution data. For both hospital and nuclear power workers, the age distributions for female workers are similar and those for male workers are similar. From these analyses, the lower limit age parameter "a" for the distribution of workers in hospitals is lower than that in nuclear power, while the upper limit age parameter "b" for the distribution of workers in hospitals is higher than that in nuclear power. Also, the "a" parameter was always smaller and the "b" parameter always larger for the distributions of males as compared to the distributions of females. We found that the mean age is about 30 for females and about 35 for males in 1980. For 1975, the corresponding mean ages were about 3 to 4 years younger.

In this limited study, we found that age data always could be fitted with the S_B distribution so as to yield a reasonably straight line on lognormal probability plots. Thus, the S_B distribution function appears useful for studying age distributions of workers. The S_B distribution also provided good fits to most distributions of collective dose as a function of worker age.

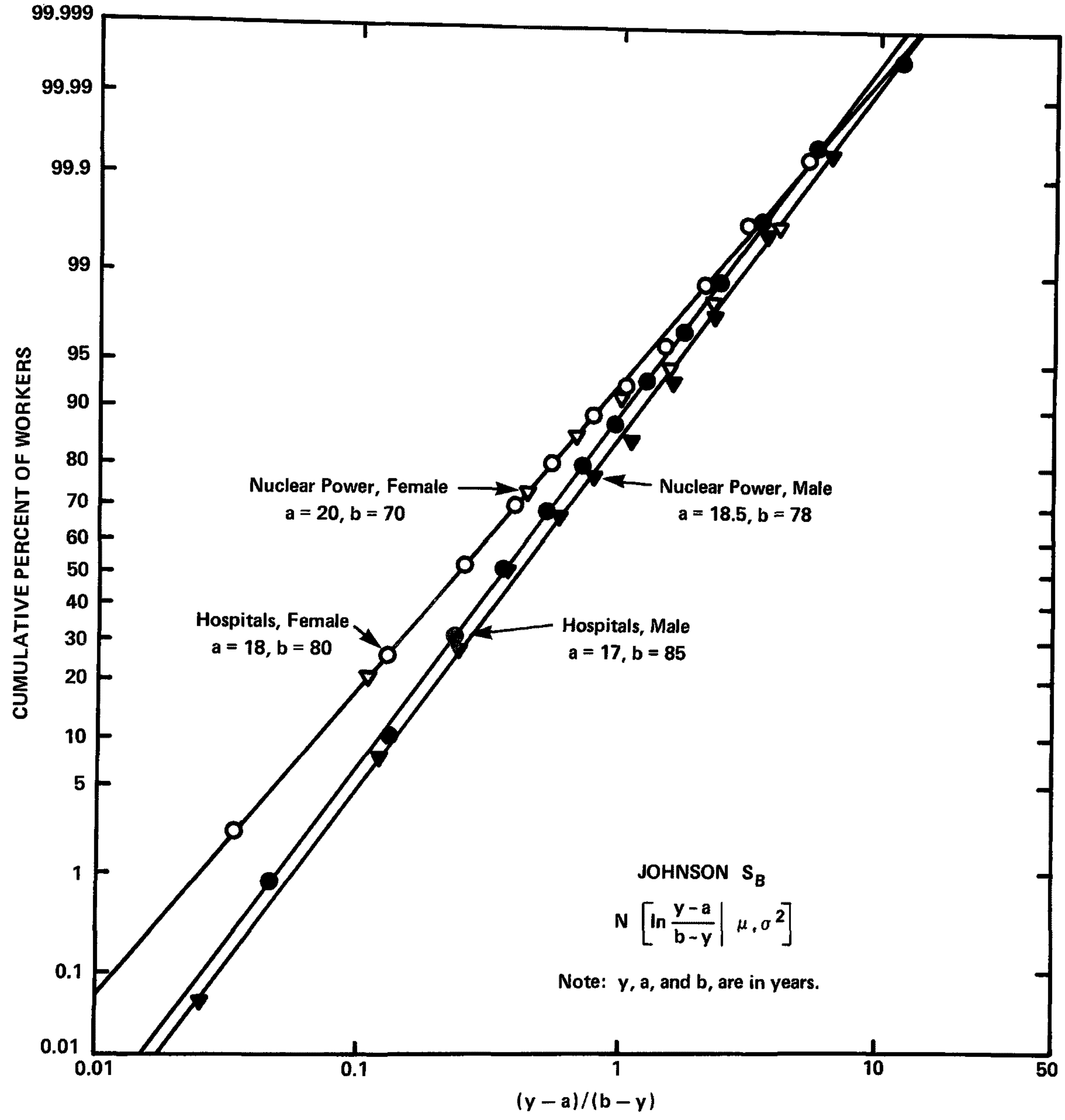

Figure F-3. Johnson S_B probability plot of the distribution of age (Y) by sex for a sample of hospital and nuclear power workers, 1980.

APPENDIX G

FEDERAL RADIATION PROTECTION GUIDANCE

CONTENTS

FEDERAL RADIATION COUNCIL

RADIATION PROTECTION GUIDANCE FOR FEDERAL AGENCIES

Memorandum for the President

Pursuant to Executive Order 10831 and Public Law 86-373, the Federal Radiation Council has made a study of the hazards and use of radiation. We herewith transmit our first report to you concerning our findings and our recommendations for the guidance of Federal agencies in the conduct of their radiation protection activities.

It is the statutory responsibility of the Council to "* * * advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States * * *"

Fundamentally, setting basic radiation protection standards involves passing judgment on the extent of the possible health hazard society is willing to accept in order to realize the known benefits of radiation. It involves inevitably a balancing between total health protection, which might require foregoing any activities increasing exposure to radiation, and the vigorous promotion of the use of radiation and atomic energy in order to achieve optimum benefits.

The Federal Radiation Council has reviewed available knowledge on radiation effects and consulted with scientists within and outside the Government. Each member has also examined the guidance recommended in this memorandum in light of his statutory responsibilities. Although the guidance does not cover all phases of radiation protection, such as internal emitters, we find that the guidance which we recommend that you provide for the use of Federal agencies gives appropriate consideration to the requirements of health protection and the beneficial uses of radiation and atomic energy. Our further findings and recommendations follow.

Discussion. The fundamental problem in establishing radiation protection guides is to allow as much of the beneficial uses of ionizing radiation as possible while assuring that man is not exposed to undue hazard. To get a true insight into the scope of the problem and the impact of the decisions involved, a review of the benefits and the hazards is necessary.

It is important in considering both the benefits and hazards of radiation to appreciate that man has existed throughout his history in a bath of natural radiation. This background radiation, which varies over the earth, provides a partial basis for understanding the effects of radiation on man and serves as an indicator of the ranges of radiation exposures within which the human population has developed and increased.

The benefits of ionizing radiation. Radiation properly controlled is a boon to mankind. It has been of inestimable value in the diagnosis and treatment of diseases. It can provide sources of energy greater than any the world has yet had available. In industry, it is used as a tool to measure thickness, quantity or quality, to discover hidden flaws, to trace liquid flow, and for other purposes. So many research uses for ionizing radiation have been found that scientists in many diverse fields now rank radiation with the microscope in value as a working tool.

The hazards of ionizing radiation. Ionizing radiation involves health hazards just as do many other useful tools. Scientific findings concerning the biological effects of radiation of most immediate interest to the establishment of radiation protection standards are the following:

1. Acute doses of radiation may produce immediate or delayed effects, or both.

2. As acute whole body doses increase above approximately 25 rems (units of radiation dose), immediately observable effects increase in severity with dose, beginning from barely detectable changes, to biological signs clearly indicating damage, to death at levels of a few hundred rems.

3. Delayed effects produced either by acute irradiation or by chronic irradiation are similar in kind, but the ability of the body to repair radiation damage is usually more effective in the case of chronic than acute irradiation.

4. The delayed effects from radiation are in general indistinguishable from familiar pathological conditions usually present in the population.

5. Delayed effects include genetic effects (effects transmitted to succeeding generations), increased incidence of tumors, lifespan shortening, and growth and development changes.

6. The child, the infant, and the unborn infant appear to be more sensitive to radiation than the adult.

7. The various organs of the body differ in their sensitivity to radiation.

8. Although ionizing radiation can induce genetic and somatic effects (effects on the individual during his lifetime other than genetic effects), the evidence at the present time is insufficient to justify precise conclusions on the nature of the dose-effect relationship at low doses and dose rates. Moreover, the evidence is insufficient to prove either the hypothesis of a "damage threshold" (a point below which no damage occurs) or the hypothesis of "no threshold" in man at low doses.

9. If one assumes a direct linear relation between biological effect and the amount of dose, it then becomes possible to relate very low dose to an assumed biological effect even though it is not detectable. It is generally agreed that the effect that may actually occur will not exceed the amount predicted by this assumption.

Basic biological assumptions. There are insufficient data to provide a firm basis for evaluating radiation effects for all types and levels of irradiation. There is particular uncertainty with respect to the biological effects at very low doses and low-dose rates. It is not prudent therefore to assume that there is a level of radiation exposure below which there is absolute certainty that no effect may occur. This consideration, in addition to the adoption of the conservative hypothesis of a linear relation between biological effect and the amount of dose, determines our basic approach to the formulation of radiation protection guides.

The lack of adequate scientific information makes it urgent that additional research be undertaken and new data developed to provide a firmer basis for evaluating biological risk. Appropriate member agencies of the Federal Radiation Council are sponsoring and encouraging research in these areas.

Recommendations. In view of the findings summarized above the following recommendations are made:

It is recommended that:

1. There should not be any man-made radiation exposure without the expectation of benefit resulting from such exposure. Activities resulting in man-made radiation exposure should be authorized for useful applications provided in recommendations set forth herein are followed.

It is recommended that:

2. The term "Radiation Protection Guide" be adopted for Federal use. This term is defined as the radiation dose which should not be exceeded without careful consideration of the reasons for doing so; every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable.

It is recommended that:

3. The following Radiation Protection Guides be adopted for normal peacetime operations:

Type of exposure	Condition	Dose (rem)
Radiation worker:		
(a) Whole body, head and trunk, active blood forming organs, gonads, or lens of eye.	Accumulated dose	5 times the number of years beyond age 18.
	13 weeks	3.
(b) Skin of whole body and thyroid	Year	30.
	13 weeks	10.
(c) Hands and forearms, feet and ankles	Year	75.
	13 weeks	25.
(d) Bone	Body burden	0.1 microgram of radium-226 or its biological equivalent.
(e) Other organs	Year	15.
	13 weeks	5.
Population:		
(a) Individual	Year	0.5 (whole body).
(b) Average	30 year	5 (gonads).

The following points are made in relation to the Radiation Protection Guides herein provided:

(1) For the individual in the population, the basic Guide for annual whole body dose is 0.5 rem. This Guide ap-

plies when the individual whole body doses are known. As an operational technique, where the individual whole body doses are not known, a suitable sample of the exposed population should be developed whose protection guide for annual whole body dose will be 0.17 rem per capita per year. It is emphasized that this is an operational technique which should be modified to meet special situations.

(2) Considerations of population genetics impose a per capita dose limitation for the gonads of 5 rems in 30 years. The operational mechanism described above for the annual individual whole body dose of 0.5 rem is likely in the immediate future to assure that the gonadal exposure Guide (5 rem in 30 years) is not exceeded.

(3) These Guides do not differ substantially from certain other recommendations such as those made by the National Committee on Radiation Protection and Measurements, the National Academy of Sciences, and the International Commission on Radiological Protection.

(4) The term "maximum permissible dose" is used by the National Committee on Radiation Protection (NCRP) and the International Commission on Radiological Protection (ICRP). However, this term is often misunderstood. The words "maximum" and "permissible" both have unfortunate connotations not intended by either the NCRP or the ICRP.

(5) There can be no single permissible or acceptable level of exposure without regard to the reason for permitting the exposure. It should be general practice to reduce exposure to radiation, and positive effort should be carried out to fulfill the sense of these recommendations. It is basic that exposure to radiation should result from a real determination of its necessity.

(6) There can be different Radiation Protection Guides with different numerical values, depending upon the circumstances. The Guides herein recommended are appropriate for normal peacetime operations.

(7) These Guides are not intended to apply to radiation exposure resulting from natural background or the purposeful exposure of patients by practitioners of the healing arts.

(8) It is recognized that our present scientific knowledge does not provide a firm foundation within a factor of two or three for selection of any particular numerical value in preference to another value. It should be recognized that the Radiation Protection Guides recommended in this paper are well below the level where biological damage has been observed in humans.

It is recommended that:

4. Current protection guides used by the agencies be continued on an interim basis for organ doses to the population.

Recommendations are not made concerning the Radiation Protection Guides for individual organ doses to the population, other than the gonads. Unfortunately, the complexities of establishing guides applicable to radiation exposure of all body organs preclude the Council from making recommendations concerning them at this time. However, current protection guides used by the agencies appear appropriate on an interim basis.

It is recommended that:

5. The term "Radioactivity Concentration Guide" be adopted for Federal use. This term is defined as the concentration of radioactivity in the environment which is determined to result in whole body or organ doses equal to the Radiation Protection Guide.

Within this definition, Radioactivity Concentration Guides can be determined after the Radiation Protection Guides are decided upon. Any given Radioactivity Concentration Guide is applicable only for the circumstances under which the use of its corresponding Radiation Protection Guide is appropriate.

It is recommended that:

6. The Federal agencies, as an interim measure, use radioactivity concentration guides which are consistent with the recommended Radiation Protection Guides. Where no Radiation Protection Guides are provided, Federal agencies continue present practices.

No specific numerical recommendations for Radioactivity Concentration Guides are provided at this time. However, concentration guides now used by the agencies appear appropriate on an interim basis. Where appropriate radioactivity concentration guides are not available, and where Radiation Protection Guides for specific organs are provided herein, the latter Guides can be used by the Federal agencies as a starting point for the derivation of radioactivity concentration guides applicable to their particular problems. The Federal Radiation Council has also initiated action directed towards the development of additional Guides for radiation protection.

It is recommended that:

7. The Federal agencies apply these Radiation Protection Guides with judgment and discretion, to assure that reasonable probability is achieved in the attainment of the desired goal of protecting man from the undesirable effects of radiation. The Guides may be exceeded only after the Federal agency having jurisdiction over the matter has carefully considered the reason for doing so in light of the recommendations in this paper.

The Radiation Protection Guides provide a general framework for the radiation protection requirements. It is expected that each Federal agency, by virtue of its immediate knowledge of its operating problems, will use these Guides as a basis upon which to develop detailed standards tailored to meet its particular requirements. The Council will follow the activities of the Federal agencies in this area and will promote the necessary coordination to achieve an effective Federal program.

If the foregoing recommendations are approved by you for the guidance of Federal agencies in the conduct of their radiation protection activities, it is further recommended that this memorandum be published in the FEDERAL REGISTER.

ARTHUR S. FLEMMING,
Chairman,
Federal Radiation Council.

The recommendations numbered "1" through "7" contained in the above memorandum are approved for the guidance of Federal agencies, and the memorandum shall be published in the FEDERAL REGISTER.

DWIGHT D. EISENHOWER

MAY 13, 1960.

[F.R. Doc. 60-4539; Filed, May 17, 1960; 8:51 a.m.]

UNDERGROUND MINING OF URANIUM ORE

Radiation Protection Guidance for Federal Agencies

On May 25, 1971, the Environmental Protection Agency published a notice in the FEDERAL REGISTER (36 F.R. 9480) concerning guidance for the protection of underground uranium miners. The notice stated: "The Administrator does not find a basis for modifying the guidance approved by the President that an annual exposure level of 4 WLM be effective as of July 1, 1971." The notice also stated that "All interested persons who desire to submit written comments for consideration in connection with this matter should send them to the Administrator, EPA, Washington, D.C. 20460, within 30 days after publication of this notice in the FEDERAL REGISTER. Comments received after that period will be considered if it is practicable to do so, but assurance of consideration cannot be given except as to comments filed within the period specified."

All written comments received on or before June 28, 1971, have been reviewed. Letters of comment have been received from industry, other Government agencies and a labor union. These comments are available for inspection at EPA Headquarters, 1626 K Street NW., Washington, DC 20460.

Several questions were raised on the scientific basis for setting the guidance of 4 WLM per year and in particular challenged the validity of the PHS epidemiologic report.

The Environmental Protection Agency has fully considered the methodology of the PHS epidemiologic study on uranium miners as well as the limitations of the study data for the setting of standards for underground uranium miners.

In addition EPA has evaluated a considerable body of other scientific information, both experimental and epidemiologic, available on radiation induced lung cancer for its relevance to establishing radiation protection guidance for uranium miners. EPA has also taken into account reports from several expert and advisory groups[1] established to review and interpret the problem of radiation induced lung cancer.

Based on the reports of these expert groups and the other considerations noted above, EPA concludes that guidance not to exceed 4 WLM per year is warranted in order to afford adequate radiation protection of uranium miners. Furthermore, it is emphasized that the exposure levels of concern are not "low" in the context of usual occupational radiation protection practices; an annual exposure greater than 4 WLM would probably result in a dose in rems to the critical tissue of the lung that exceeds the occupational radiation standard generally accepted in the nuclear industry.

Therefore, it has been concluded that the comments suggesting that EPA should recommend less stringent radiation protection guidance than the present 4 WLM per year do not provide an adequate basis for doing so. Accordingly, EPA does not recommend any change in the guidance approved by the President and published in the FEDERAL REGISTER (34 F.R. 576, 35 F.R. 9218) of 4 WLM per year effective July 1, 1971.

Several comments were received which referred to the means of implementing the 4 WLM guidance. As the May 25, 1971, FEDERAL REGISTER notice indicated, decisions concerning the means of implementing the guidance for uranium mines, including any procedures for variances which may be made available to individual mining operators, must be made by the regulatory agencies which adopt this guidance. It should be noted that the Secretary of the Interior on June 30, 1971, signed proposed amendments to regulations under the Federal Metal and Nonmetallic Mine Safety Act. These proposed amendments relate to variances applicable to underground uranium mines. EPA will provide such comments as it deems appropriate on these proposed amendments directly to the Department of the Interior at a later date. Copies of all of the comments which EPA has received in response to the May 25, 1971, FEDERAL REGISTER notice and copies of this FEDERAL REGISTER notice have been sent to the Secretaries of the Interior and Labor under cover of a letter dated July 1, 1971.

Dated: July 1, 1971.

WILLIAM D. RUCKELSHAUS,
Administrator.

[FR Doc.71-9697 Filed 7-8-71;8:49 am]

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[1] The DHEW review group, May 1967; (2) NAS/NRC Advisory Committee to FRC 1968; (3) NAS/NRC Advisory Committee to FRC, 1970/71; (4) Subgroups I-A and I-B of the Interagency Uranium Mining Radiation Review Group, 1970/71; (5) NCRP Report 39, 1971; and (6) ICRP Publication 14, 1969.

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