1. Executive Summary

Detailed information on the exposure of the U.S. population to ionizing radiation, based on evaluations made in the early 1980s, was presented by the National Council on Radiation Protection and Measurements (NCRP) in Report No. 93, *Ionizing Radiation Exposure of the Population of the United States* (NCRP, 1987a). Since that time, the magnitude and distribution among the various sources of radiation exposure to the U.S. population have changed primarily due to increased utilization of ionizing radiation in diagnostic and interventional medical procedures. Documented in this Report are the contributions from all radiation sources in 2006. This Report neither quantifies the associated health risks nor specifies the radiation protection actions that should be taken in light of these latest data because these subjects are beyond the scope of this Report.

The radiation exposure to the U.S. population for 2006 is presented in five broad categories:

- exposure from ubiquitous background radiation, including radon in homes;
- exposure to patients from medical procedures;
- exposure from consumer products or activities involving radiation sources;
- exposure from industrial, security, medical, educational and research radiation sources; and
- exposure of workers that results from their occupations.

The dose assessments for the five categories and components within each category are derived from disparate types of information and variable methods of analysis. While not identical, these categories are closely aligned with those in NCRP (1987a).

The principal results are presented as annual values for:

- average effective dose to an individual in a group exposed to a specific source (E_{Exp}) (millisievert), which excludes individuals that are not subject to exposure from the specific source of radiation;

- collective effective dose (S) (person-sievert), which is the cumulative dose to a population of individuals exposed to a given radiation source or group of sources; and
- effective dose per individual in the U.S. population (E_{US}) (millisievert), computed by dividing S by the total number of individuals in the U.S. population (300 million in 2006) whether exposed to the specific source or not.

S and E_{US} provide useful indices for comparison among radiation sources and different time periods.

1.1 Ubiquitous Background Exposure

For purposes of analysis, this category was separated into four subcategories:

1. external exposure from space radiation (solar particles and cosmic rays);
2. external exposure from terrestrial radiation (primarily ^{40}K and the ^{238}U and ^{232}Th decay series);
3. internal exposure from inhalation of radon and thoron[1] and their progeny; and
4. internal exposure from radionuclides in the body.

An appendix to Subcategory 4 provides an independent assessment from domestic water supplies; however, the contribution from all food and water is already included in the evaluation for radionuclides in the body. Particular attention was given to evaluating the variability in these sources; arithmetic and geometric means and associated statistics for the effective dose distributions in each of the four subcategories were included. Estimates of effective dose for each subcategory were derived as follows:

1. *Space radiation*: A computer code was used for estimating outdoor ground level effective doses for 99 of the most populated U.S. urban areas and then adjusting for indoor levels and time spent outdoors and in dwellings.
2. *Terrestrial radiation*: Data from the National Uranium Resource Evaluation (NURE) Program for concentrations of uranium and thorium (parts per million by weight) and potassium (weight percent) in surface soil and rocks

[1]Radon is the common name for the radionuclide ^{222}Rn and thoron is the common name for the radionuclide ^{220}Rn. In this Report, the common names are generally used, and radon without qualification refers to ^{222}Rn.

at 10,650 locations across the continental United States were used to obtain activity concentrations for the principal radionuclides (^{238}U, ^{232}Th, and ^{40}K). The concentrations were then converted to air kerma and effective dose using age-dependent conversion coefficients, and adjusted for building attenuation for the time spent indoors.

3. *Radon and thoron and their progeny*: Radon concentrations ($Bq\ m^{-3}$) from the National Residential Radon Survey (NRRS) [conducted by the U.S. Environmental Protection Agency (EPA)], supplemented by data from the University of Pittsburgh and Lawrence Berkeley National Laboratory (LBNL), adjusted for equilibrium factors (Glossary) and fractions of time spent in various locations (indoors at home or away and outdoors) were used to obtain the potential alpha-energy exposure [in working level months (WLM)]. The dose conversion coefficient for radon and its progeny (millisievert effective dose per WLM) and its uncertainty are discussed.[2] Adjustments were made for estimated exposure to thoron and its progeny.
4. *Radionuclides in the body*: Age- and gender-dependent potassium measurements (gram of potassium per kilogram of body mass) from the U.S. Department of Energy's Hanford Site were used to derive activity concentrations for ^{40}K. Age- and gender-dependent dose conversion coefficients were obtained from the Radiation Dose Assessment Resource. For the ^{232}Th and ^{238}U series, effective dose estimates for the U.S. population were derived from reference values published by UNSCEAR (2000) and data for the United States. For the separate assessment of domestic water supplies, data for radium, uranium and radon concentrations in water supplies from the National Inorganic and Radionuclide Survey (NIRS) (public supplies) and the U.S. Geological Survey (USGS) (private wells), (adjusted for consumption rates), published dose conversion coefficients, and census data for number of individuals exposed were used.

[2]The dose conversion coefficient for radon and its progeny used in this Report is 10 $mSv\ WLM^{-1}$ (Section 3.5.10). This value agrees with that obtained from a dosimetric analysis and is consistent with that used previously by NCRP (1987b). It is similar to that obtained in recent epidemiological analyses by Tomasek *et al*. (2008). The value of 10 $mSv\ WLM^{-1}$ is greater than that used by UNSCEAR (2000), and more than twice that used by ICRP (1993) for exposure in homes based on a previous epidemiological analysis. Use of other dose conversion coefficients would result in a proportionate difference in S and E_{US}.

The results in 2006 for ubiquitous background radiation for S and E_{US} are 933,000 person-Sv and 3.1 mSv (arithmetic mean), respectively, compared with 690,000 person-Sv and 3 mSv in the early 1980s. The higher value for S reflects the 30 % increase in the U.S. population between the two time periods; the value for E_{US} is comparable with that for the early 1980s. The percent contribution to the total S and total E_{US} for this category from each of the four subcategories for 2006 is (in decreasing order):

- radon and thoron (73 %)
- space radiation (11 %)
- radionuclides in the body (9 %)
- terrestrial radiation (7 %)

The contribution to E_{US} from only ^{222}Rn (radon) for 2006 (2.1 mSv) (Table 3.14) is comparable with that for the early 1980s (2 mSv), given the uncertainty in derivation of the values. Since all members of the U.S. population are exposed to ubiquitous background radiation, E_{US} is also E_{Exp}. Values for total E_{Exp} and its components, including arithmetic means (AM), standard deviations (SD), geometric means (GM), geometric standard deviations (GSD), and 2.5 and 97.5 percentiles are given in Table 3.14 along with the factors affecting the variability of each component.

1.2 Medical Exposure of Patients

This category was separated into five subcategories for analysis grouped by medical modality:

1. computed tomography
2. conventional radiography and fluoroscopy
3. interventional fluoroscopy
4. nuclear medicine
5. external-beam radiotherapy

While a dose assessment was conducted for external-beam radiotherapy, the results are not included in the total for this category because of unique considerations, namely, E_{Exp} was 0.4 Sv, the population exposed is small (<3 % of the total U.S. population) and is a special group with life-threatening illness, and absorbed doses to some tissues or portions of tissues outside but nearby the treatment volume could approach and exceed 1 Sv. Thus the inclusion of this source in the assessment of dose to the U.S. population may not be applicable (Section 4.6).

The number of procedures for each modality for 2006 was derived mainly from several commercial market benchmark reports produced by IMV Medical Information Division [IMV (Des Plaines, Illinois)] that identify the universe of facilities providing the services. Supplemental sources of data that were available included: Medicare (administrative claims for fee-for-service enrollees), the U.S. Department of Veterans Affairs (VA) (administrative claims for VA health plan enrollees), a large national employer plan (LNEP) (administrative claims), and a commercial source for dental bitewing film packs. Effective doses for procedures were derived from the published literature as follows:

- *Computed tomography*: Based on data for dose length product and age and body region specific conversion coefficients.
- *Conventional radiography and fluoroscopy*: Based on data for effective dose.
- *Interventional fluoroscopy*: Based on data for kerma-area product (*KAP*) and protocol-specific dose conversion coefficients.
- *Nuclear medicine*: Based on data for dose conversion coefficients expressed as effective dose per unit administered activity.
- *External-beam radiotherapy*: Based on absorbed doses to organs and tissues located outside the treatment volume.

The available information on effective dose was not sufficient to permit an analysis of statistical measures of variability, nor was there sufficient information available to determine E_{Exp} for medical exposures.

The results for medical exposure of patients (excluding radiotherapy) for 2006, as contrasted with the early 1980s, show a marked increase in S (a factor of 7.3) and E_{US} (a factor of 5.7) during the intervening ~25 y. Some of the increase in S is due to the 30 % increase in the U.S. population during that time (230 million in 1980; 300 million in 2006). Since E_{US} is an effective dose per individual in the U.S. population, the effect of population growth is removed, and the increase is due primarily to increased utilization of CT, interventional fluoroscopy, and nuclear medicine. The percent contribution to the total S (899,000 person-Sv) and the total E_{US} (3 mSv) for medical exposure from each of the four modalities for 2006 is (in decreasing order):

- computed tomography (49 %)
- nuclear medicine (26 %)
- interventional fluoroscopy (14 %)
- conventional radiography and fluoroscopy (11 %)

1.3 Consumer Products and Activities

To analyze exposures in this category, it was divided into seven subcategories grouped by the origin of the source:

1. building materials
2. commercial air travel
3. cigarette smoking
4. mining and agriculture
5. combustion of fossil fuels
6. highway and road construction materials
7. glass and ceramics

The number of individuals exposed to a particular source was derived in various ways: updates of the values used by NCRP for the early 1980s to adjust for change in U.S. population (building materials, mining and agriculture, combustion of fossil fuels, and highway and road construction materials); numbers of passengers from the Bureau of Transportation Statistics (commercial air travel); the National Health Interview Survey (cigarette smoking); and assumptions for the small numbers of individuals involved (glass and ceramics). Estimates of effective dose for each subcategory were derived as follows:

- Subcategories 1, 4, 5 and 6. *Building materials*, *mining and agriculture*, *combustion of fossil fuels*, and *highway and road construction materials*: Based on the effective dose equivalent (H_E) (or updates of the values) used in deriving the estimates for the early 1980s.
- Subcategory 2. *Commercial air travel*: Based on effective doses calculated using the computer code CARI-6 for various flight segments and published by the U.S. Department of Transportation.
- Subcategory 3. *Cigarette smoking*: Based on published estimates for the effective dose from smoking one cigarette per day for a year, estimates from the Centers for Disease Control and Prevention on the average number of cigarettes smoked per day by an individual smoker, and the total number of smokers.
- Subcategory 7. *Glass and ceramics*: Based on published values from NRC expressed as H_E.

The available information on effective dose was not sufficient to permit an analysis of statistical measures of variability.

An extensive discussion of radiation exposure from consumer products is contained in NCRP Report No. 95 (NCRP, 1987d). Much of that information is still relevant. In this Report exposures from some of the more significant sources have been updated and information is included about some additional sources. The potential sources that are not discussed in any detail in this Report are noted as "other sources."

The results for consumer products or activities for 2006 for S and E_{US} are 39,000 person-Sv and 0.13 mSv, respectively, compared with 12,000 to 29,000 person-Sv and 0.05 to 0.13 mSv in the early 1980s [presented only in terms of ranges in NCRP (1987a)]. However, the collections of sources included in this category for 2006 and the early 1980s are dissimilar and no specific conclusions should be drawn from the S and E_{US} values other than that this category is a small contributor to U.S. population dose. The percent contribution to the total S and the total E_{US} for this category from each of the seven subcategories and the other sources for 2006 is (in decreasing order):

- cigarette smoking (35 %)
- building materials (27 %)
- commercial air travel (26 %)
- mining and agriculture (6 %)
- other sources (3 %)
- combustion of fossil fuels (2 %)
- highway and road construction materials (0.6 %)
- glass and ceramics (<0.03 %)

This category is characterized by sources that deliver small annual effective doses [*i.e.*, the range for E_{Exp} among the included subcategories is 1 to 300 μSv (Table 5.8)] to much of the U.S. population (Table 5.8).

1.4 Industrial, Security, Medical, Educational and Research Activities

This category was divided into six subcategories for analysis, grouped by the nature of the activity and associated type of source:

1. nuclear-power generation
2. DOE installations
3. decommissioning and radioactive waste
4. industrial, medical, educational and research activities
5. caregiving or other contact with nuclear-medicine patients
6. security inspection systems

The effective doses to members of the public (*i.e.*, not employees) and the number of individuals exposed for a particular source were derived as follows:

1. *Nuclear-power generation*: Based on H_E used by NCRP for the early 1980s adjusted for the current total power generation by nuclear reactors.
2. *DOE installations*: Based on DOE site environmental reports with doses expressed as H_E.
3. *Decommissioning and radioactive waste*: Based on various federal agency reports with doses expressed as H_E [or total effective dose equivalent (TEDE)].
4. *Industrial, medical, educational and research activities*: Based on projections to members of the public from the number of occupationally-exposed individuals and the effective doses for occupational exposures for similar facilities.
5. *Exposure from nuclear-medicine patients (as a result of caregiving or other contact)*: Based on projecting the annual number of procedures and the published effective dose per procedure (to a member of the public) in NCRP Report No. 124.
6. *Security inspection systems*: Based on assumptions for the small numbers of individuals receiving detectable exposure and the published literature data for dose equivalent from other than cabinet x-ray systems.

The available information on effective dose was not sufficient to permit an analysis of statistical measures of variability.

The estimates for industrial, security, medical, educational and research activities for 2006 for S and E_{US} are 1,000 person-Sv and 0.003 mSv, respectively, compared with 200 person-Sv and 0.001 mSv in the early 1980s. However, the collections of sources included in this category for 2006 and the early 1980s are dissimilar and no specific comparative conclusions should be drawn from the S and E_{US} values other than this category is a very small contributor to the U.S. population dose. The percent contribution to the total S and total E_{US} for this category from each of the six subcategories for 2006 is (in decreasing order):

- caregiving or other contact with nuclear-medicine patients (72 %)
- nuclear-power generation (15 %)
- industrial, medical, educational and research activities (13 %)

- DOE installations («1 %)
- decommissioning and radioactive waste («1 %)
- security inspection systems («1 %)

This category is characterized by sources that deliver very small annual effective doses to individuals who are in proximity to these activities (E_{Exp} for the included subcategories is 1 to 10 μSv).

1.5 Occupational Exposure

Six subcategories grouped by the nature of employment and associated type of source were used to analyze this category:

1. medical
2. aviation
3. commercial nuclear power
4. industry and commerce
5. education and research
6. government, DOE and military

Personal monitoring programs, accredited by either the National Voluntary Laboratory Accreditation Program or the DOE Laboratory Accreditation Program provided data for the numbers of workers monitored and doses for those with recordable dose (*i.e.*, doses greater than a minimum detectable level) in all the subcategories except aviation. Internal doses are included for those occupations where internal exposure is of concern. Since airline crews are not monitored, the numbers of airline crew were obtained from information published by the U.S. Department of Labor, and associated occupational doses were derived from calculations for space radiation based on altitude and latitude of typical flight routes. Effective doses were based on the following sources:

- Subcategories 1, 4 and 5. *Medical*, *industry and commerce*, and *education and research*: Personal monitoring data provided by Global Dosimetry Solutions, Inc. (Irvine, California) and Landauer, Inc. (Glenwood, Illinois), recorded as deep dose equivalent.
- Subcategory 2. *Aviation*: Effective dose estimates for various flight segments published by the U.S. Department of Transportation.
- Subcategory 3. *Commercial nuclear power*: Personal monitoring data provided by the U.S. Nuclear Regulatory Commission, recorded as TEDE.

- Subcategory 6. *Government, DOE and military*: Personal monitoring data provided by Global Dosimetry Solutions, Inc. and Landauer, Inc. for government agencies, by the military services for the Air Force, Army, Navy and Marines (all recorded as deep dose equivalent), and by DOE (recorded as TEDE).

For all subcategories except aviation, distributions of dose are presented for the monitored workers with recorded doses.

The results for occupational exposure for 2006 for S and E_{US} are 1,400 person-Sv and 0.005 mSv, respectively, compared with 2,000 person-Sv and 0.009 mSv in the early 1980s.

The percent contribution to the total S and the total E_{US} for this category from each of the six subcategories for 2006 is (in decreasing order):

- medical (39 %)
- aviation (38 %)
- commercial nuclear power (8 %)
- industry and commerce (8 %)
- education and research (4 %)
- government, DOE and military (3 %)

The estimate of E_{Exp} for 1.22 million workers (includes those with recordable doses and airline crew) is 1.1 mSv, and the variation in E_{Exp} among the included subcategories ranges from 0.6 mSv for government, DOE and military to 3.1 mSv for aviation. Distributions of annual effective dose for workers with recordable dose for each of the monitored subcategories (Figures 7.5, 7.7, 7.9, 7.10 and 7.11) indicate that the vast majority of individual dose values for those workers is <1 mSv.

1.6 Overall Results for 2006

The estimated totals from all sources for 2006 are 1,870,000 person-Sv for S and 6.2 mSv for E_{US}, based on a U.S. population of 300 million. Nearly all the S or E_{US} (98 %) results from ubiquitous background (50 %) and medical exposure of patients (48 %). Consumer products and activities account for 2 % and the remaining two categories (industrial, occupational) contribute very little (on the order of <0.1 % each). Figure 1.1 gives the percent contributions of various sources of exposure to the totals for S and E_{US}; the major sources are radon and thoron (37 %), CT (24 %), and nuclear medicine (12 %). Other background sources (external plus

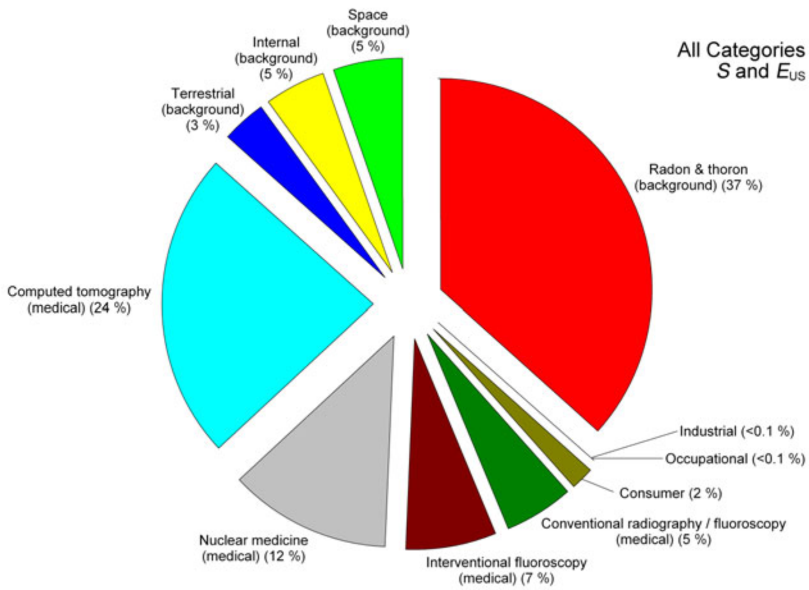

Fig. 1.1. Percent contribution of various sources of exposure to the total collective effective dose (1,870,000 person-Sv) and the total effective dose per individual in the U.S. population (6.2 mSv) for 2006. Percent values have been rounded to the nearest 1 %, except for those <1 % [see Table 1.1 for the values of S (person-sievert) and E_{US} (millisievert)].

internal) contribute 13 %, and other medical exposure (interventional fluoroscopy plus conventional radiography and fluoroscopy) contribute 12 %. The values for S (person-sievert), E_{US} (millisievert), and E_{Exp} (millisievert) for the five exposure categories and the main subcategories are provided in Table 1.1. In addition, thumbnail sketches are provided at the beginning of Sections 3 through 7 that provide a succinct overview of the results for each of the five exposure categories.

The value for S increased by a factor of 2.2 from the early 1980s to 2006. This includes an increase due to the change in number of individuals in the U.S. population between 1980 (230 million) and 2006 (300 million).The value for E_{US} increased by a factor of 1.7 from the early 1980s to 2006, primarily due to increased utilization of the medical modalities of computed tomography, nuclear medicine and interventional fluoroscopy. The values for S (person-sievert) and E_{US} (millisievert) for these comparisons are provided in Table 8.3.

TABLE 1.1—*Collective effective dose (S), effective dose per individual in the U.S. population (E_{US}), and average effective dose for the exposed group (E_{Exp}) for 2006.*[a]

Exposure Category	S (person-Sv)	E_{US} (mSv)	E_{Exp} (mSv)
Ubiquitous background	*933,000*	*3.11*	*3.11*
Internal, inhalation (radon and thoron)	684,000	2.28	2.28
External, space	99,000	0.33	0.33
Internal, ingestion	87,000	0.29	0.29
External, terrestrial	63,000	0.21	0.21
Medical	*899,000*	*3.00*	—[b]
CT	440,000	1.47	—[b]
Nuclear medicine	231,000	0.77	—[b]
Interventional fluoroscopy	128,000	0.43	—[b]
Conventional radiography and fluoroscopy	100,000	0.33	—[b]
Consumer	*39,000*	*0.13*	*0.001 – 0.3*[c]
Industrial, security, medical, educational and research	*1,000*	*0.003*	*0.001 – 0.01*[c]
Occupational	*1,400*	*0.005*	*1.1*
Medical	550		0.8
Aviation	530		3.1
Commercial nuclear power	110		1.9
Industry and commerce	110		0.8
Education and research	60		0.7
Government, DOE, military	40		0.6
Total	*1,870,000*[d]	*6.2*[d]	

[a]See Table 8.1 for more detail.
[b]Not determined for the medical category because the number of patients exposed is not known, only the number of procedures.
[c]The range of values for the various subcategories in this category.
[d]Rounded values.

Uncertainty in the 2006 estimates for effective dose (E), E_{Exp}, and S (and by extension E_{US}) are due to uncertainty in the underlying measurements from which these quantities are estimated, in the dosimetric models and their parameters, in the number of individuals exposed, and in the assumptions made in the absence of information. A detailed uncertainty analysis was possible only for E_{Exp} for ubiquitous background radiation (Table 3.14). In that case, the analysis applies also to S and E_{US} since all individuals in the United States are exposed and the number of individuals is relatively well known. The uncertainty in the estimates of E, E_{Exp}, and S for other exposure categories cannot be inferred from that analysis. For other exposure categories, at the present time, one is limited primarily to identification of the factors that contribute to uncertainty.

There are clearly two major contributors to the exposure of the U.S. population from ionizing radiation: exposure to ubiquitous background radiation and medical exposure of patients. As a word of caution in interpreting these results in terms of health detriment (*i.e.*, the stochastic health risks due to radiation exposure), it is important to recognize that the populations exposed to these two sources are not the same. Those exposed to ubiquitous background radiation represent the entire U.S. population in age, gender and health status. Groups of patients exposed to medical radiation often have distributions that are skewed in age to older individuals and in health status to sicker individuals. There also may be a skewed gender distribution. In addition the risk associated with the type of radiation encountered may differ from one source to another. The exposure to ubiquitous background radiation is generally to high-energy gamma rays and high-energy particles while the exposure from diagnostic medical procedures is generally to low-energy x rays. The radiation weighting factors (w_Rs) used in the calculation of effective dose may not be the most appropriate in all cases for evaluation of radiation detriment for the type of radiation encountered. Therefore, the fact that S and E_{US} are approximately equal for the two populations does not convey that there is equal stochastic risk to the two populations. This caution, of course, applies to all sources of radiation exposure. Determination of radiation detriment was outside the scope of this Report.