NEUTRONS

1. Exposure Data

Exposure to neutrons can occur from the nuclear fission reactions usually associated with the production of nuclear energy, from cosmic radiation in the natural environment and from sources in which reactions in light target nuclei are used. The main exposures are related to occupation, medical irradiation and cosmic rays.

1.1 Occurrence

The occurrence and characteristics of neutrons are described in detail in the Overall introduction. Neutrons are uncharged particles that interact with the nuclei of atoms, whereas X- and γ-radiation interact primarily with orbital electrons. The spectrum of exposure to neutrons depends on their source, which is ultimately the atomic nucleus. The nuclear constituents are tightly bound, and several million electron volts are required to free a neutron from most nuclei.

Neutrons can be released in several ways, resulting in human exposure. In the interaction of high-energy cosmic radiation with the earth's atmosphere, neutrons are ejected at high energy from the nuclei of molecules in the air. In the fission or fusion of nuclei, nuclear energy is released and many neutrons are produced. Neutrons produced by fusion have more energy (~14 MeV) than those released upon nuclear fission. Fission neutrons (with energy up to several million electron volts) are themselves initiators of the fission event, but their energy must be reduced by collisions with a moderating medium (usually water or graphite) to allow a chain reaction to proceed. Neutrons in the environment of reactors therefore have very little energy. Neutrons produced by nuclear explosions and those that drive breeder reactors have more energy, but not as much as the neutrons resulting from interactions with cosmic radiation. A third way in which neutrons can be released is by collision of charged particles with a lithium or beryllium target, when part of the neutron binding energy in the nucleus of lithium or beryllium is converted into kinetic energy of 14–66 MeV. Radionuclides and ion accelerators that emit α-particles are used to initiate these reactions, and the neutrons emitted are used for radiography and radiotherapy.

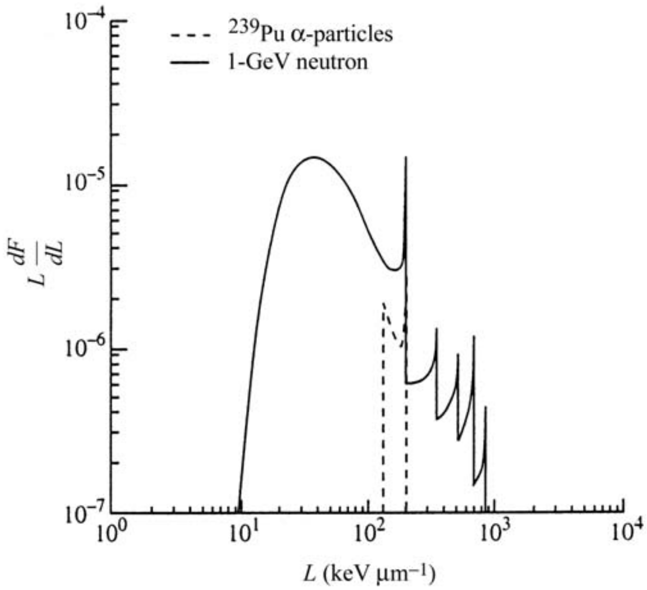
The mean free path of neutrons in tissues varies with their energy from a fraction to several tens of centimeters. Since neutrons are uncharged, they do not interact directly with orbital electrons in tissues to produce the ions that initiate the chemical events leading to cell injury. Rather, they induce ionizing events in tissues mainly by elastic collision with the hydrogen nuclei of the tissue molecules; the recoiling nucleus (charged proton) is the source of ionizing events. As about half of the neutron's energy is given to the proton on each collision, the low-energy neutrons provide an internal source of low-energy protons deep within body tissues. The low-energy protons form densely ionizing tracks (high linear energy transfer (LET)) which are efficient in producing biological injury. The ICRP (1991) therefore defined weighting factors for estimating the risks associated with exposure to neutrons which are larger than those for X- or γ-radiation. Neutrons with an energy of about 1 MeV are judged to be the most injurious (see Table 2 of the Overall introduction). After approximately 20–30 collisions with hydrogen, a 1-MeV neutron will come into equilibrium with ambient material and will continue to scatter, both losing and gaining energy in collision until nuclear absorption occurs, usually when hydrogen gives up 2.2-MeV of γ-radiation. Neutrons with > 50 MeV of energy interact mainly with large nuclei (e.g. C, N, O, Ca) in tissue in violent events, producing many low-energy charged particles with a broad distribution of LET (Figure 1; Wilson *et al*., 1995), and can produce secondaries such as α-particles, protons, deuterons and other neutrons. With increasing energy, the frequency of neutron-induced nuclear disintegration, which produces high-LET α-particles, increases. Exposure to high-energy neutrons is thus quite distinct from exposure to low-energy neutrons, in which only a single recoil proton with LET extending to 100 keV μm^{-1} is formed. The initial LET values of recoil protons are less than about 30 keV μm^{-1} and increase to about 100 keV μm^{-1} as the protons come to a stop. At 100 keV μm^{-1}, the spatial separation of the ionizing events is about 2 nm, comparable to the diameter of the DNA helix, therefore increasing the probability of double-strand breaks in DNA. All neutrons in the course of their interaction with matter generate γ-radiation.

1.2 Relative biological effectiveness

The difference in effectiveness between two radiation qualities, for example, neutrons and γ-radiation, is expressed as the relative biological effectiveness (RBE), which is defined as the ratio of the doses of the two types of radiation that are required to produce the same level of a specified effect. The ratio of the effect of neutrons per unit dose to that of reference low-LET radiation is greater than unity (ICRP, 1984). The reference radiation used has conventionally been X-radiation, but since many experimental and clinical data are derived from studies of the effects of γ-radiation, either X-radiation or γ-radiation can be used as the reference. The effects of X-radiation and γ-radiation at very low doses may, however, be significantly different. While this difference may be important in determining the RBE of stochastic events, it should not be of concern in the case of deterministic effects because of the higher doses required to induce most such effects.

A major disadvantage of RBEs is that they vary not only with radiation quality but also with dose, dose rate and dose fractionation, mainly because these factors affect the response to the reference radiation but only slightly, if at all, the response to neutrons.

Figure 1. Distribution of linear energy transfer produced by a 1-GeV neutron in tissue, and the spectrum of decay of α-particles from ^{239}Pu for comparison



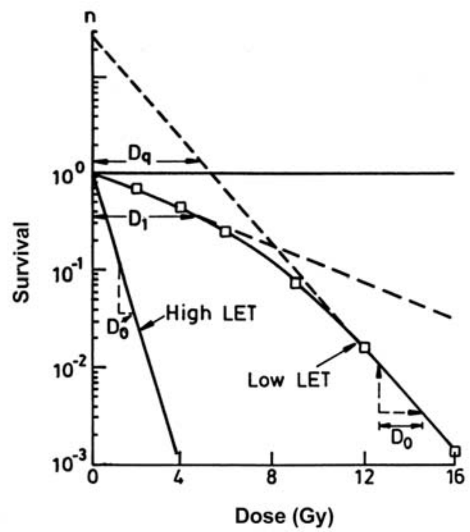
From Wilson *et al.* (1995)

The only singular RBE for any specific effect is the maximum RBE (RBE_M for stochastic effects and RBE_m for deterministic effects). In the case of stochastic effects, the RBE_M is defined as the ratio of the initial and linear slopes of the dose–response curves for the reference radiation and the radiation under study.

RBEs are based on the assumption that the effects of different types or qualities of radiation may differ quantitatively but not qualitatively. Since most deterministic effects depend on cell killing, the assumption that the nature of the induced effect is independent of radiation quality seems justified. In the case of heavy ions, the validity of this assumption has not been proven unequivocally.

The survival curves of cells exposed to neutrons *in vitro* appear to be linear on a semi-logarithmic plot, with little or no evidence of a shoulder and with a steeper curve, reflected in a lower D_0 value, than for low-LET radiations (Figure 2; see section 5.1 of the Overall introduction). The slope of the survival curve decreases and the RBE increases with decreasing neutron energy. The effectiveness of the neutrons is maximal at about 400 keV. The lack or the marked reduction of the shoulder of the survival curve reflects a greatly reduced or even completely absent ability to repair sublethal damage after exposure to neutrons (Barendsen, 1990). This lack of repair

Figure 2. Cell survival after exposure to radiation with low and high linear energy transfer (LET) as a function of dose



D_1, indicated here for low-LET radiation only, is the dose required to reduce the survival to 37%; *n* is the extrapolation number; and D_q is the 'quasi-threshold' dose, which, like *n*, is a measure of the shoulder on the low-LET survival curve. D_0 is the reciprocal of the slope of the linear portion of the curves. Note that the curve for high-LET radiation is steeper than that for low-LET radiation (D_0 is smaller) and that there is a shoulder on the low-LET curve.

results in little or no reduction in effectiveness when the neutron dose is fractionated or when the dose rate is reduced.

The dose–effect relationship of early-responding tissues can be predicted from the responses of the relevant clonogenic cells. There is no apparent difference in the ability of tissues to repopulate after exposure to neutrons, apart from a greater reduction in the number of proliferative cells per unit dose of neutrons than with low-LET radiation. The RBE increases with increasing LET and reaches a maximum, in the case of cell killing and mutagenesis, at LET values of about 100–200 keV μm^{-1}. At higher LET values, the effectiveness decreases. In 1990, a revision of the relationship between the radiation quality factor, which is based on RBEs, and the LET for stochastic effects was introduced which took into account the decrease in effectiveness of radiations with a very high LET. The relationship between RBE and LET for deterministic effects has not been codified explicitly, and the use of quality factors is restricted to stochastic effects. For deterministic effects, the influence of radiation quality is taken into account by using RBEs to adjust the absorbed doses (ICRP, 1990).

RBEs for deterministic effects are derived from the ratios of the threshold doses for neutron and reference radiation or of the doses required to induce a selected level of effect. Since deterministic effects have thresholds by definition, use of the ratio of the threshold doses seems a reasonable approach for determining RBEs. In 1990, however, an ICRP task group introduced the concept of RBE_m, which is comparable to the RBE_M for stochastic effects. The group suggested that singular RBE values for neutrons and other high-LET radiations could be obtained from the linear–quadratic model used to describe the survival curves of the cells responsible for the maintenance of tissues. In the case of deterministic effects, the threshold dose lies on the curved portion of the dose–response curve. Since, in general, deterministic effects result from the killing of a critical number of cells and assuming that the dose–response curve for cell killing can be described by a linear–quadratic model, it is theoretically possible to derive the initial slope of the response. Thus, a RBE_m can be obtained for specific end-points in specific tissues for which there are adequate data on dose–response relationships for different α:β ratios (see ICRP, 1990, for the method of deriving RBE_m). This approach is, of course, totally dependent on the validity of the linear–quadratic model at low doses at which effects cannot be measured.

The clinical importance of the difference between the effects of neutrons and low-LET radiations on normal tissues was revealed by the high incidence of tissue damage during the early use of neutrons to treat cancer. The effectiveness of fractionated neutrons is underestimated if it is based on the effects of single doses and if the difference in the repair of slowly dividing tissues is not taken into account.

1.3 Exposure

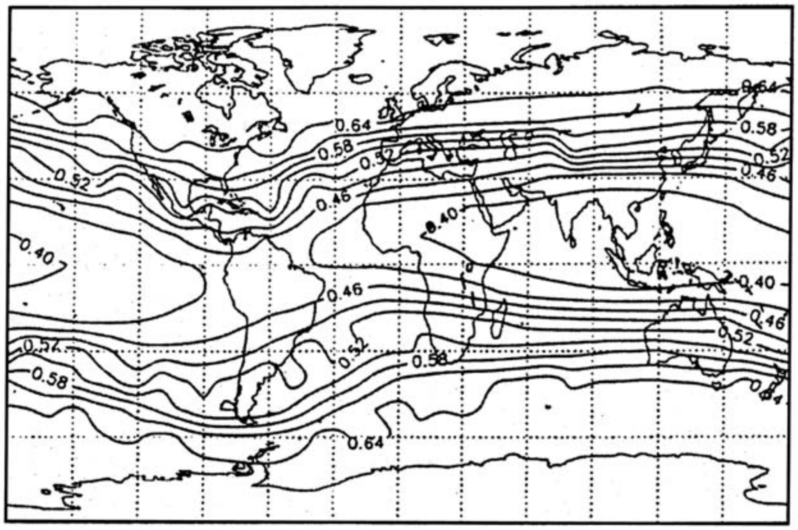
1.3.1 *Natural sources*

The effective dose equivalent rates of cosmic rays are discussed in the Overall introduction (section 4.4.1), in which the rates were evaluated on the basis of measurements with neutron spectrometers, tissue equivalent ion chambers and nuclear emulsion detectors augmented by Monte Carlo calculations. Dose equivalence is derived by summing dose contributions and weighting by LET-dependent quality factors. The ratio of the estimated neutron dose equivalent rate to the total dose equivalent rate according to the parametric atmospheric radiation model is shown for various altitudes in Figure 3. It can be seen that 40–65% of the dose equivalent at ordinary aircraft altitudes is due to neutrons, depending on the latitude and longitude of the flight trajectory. The fraction of neutrons depends on altitude, being nearly negligible at sea level and contributing over half of the exposure at aircraft flight altitudes. The fraction varies little over most of the altitudes at which aircraft operate. Since most commercial flights are at relatively high latitudes, approximately 60% of the dose equivalent is due to neutrons.

Although consistent measurements were made over most geomagnetic latitudes and altitudes during solar cycle 20 which started in October 1964, many of the individual

Figure 3. Fraction of dose equivalent due to neutrons at various altitudes, at minimum solar energy (1965)

$H_{neutron}/H$ at 40 000 ft [~12 000 m]



$H_{neutron}/H$ at 50 000 ft [~15 000 m]

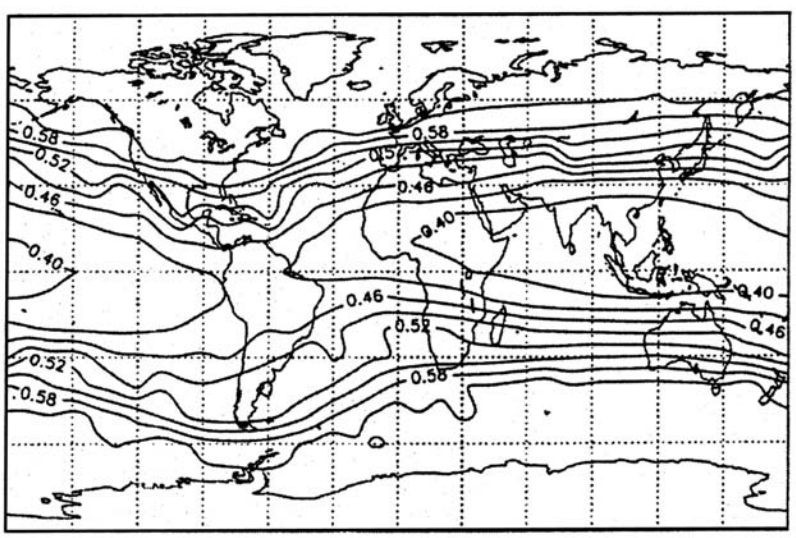
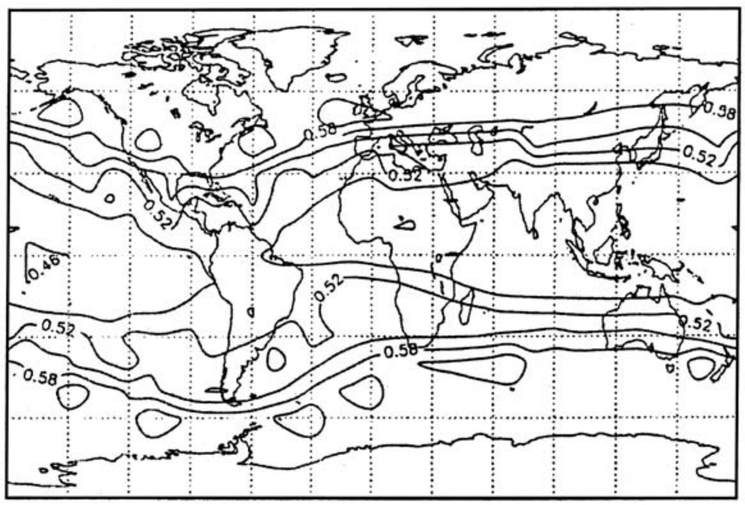
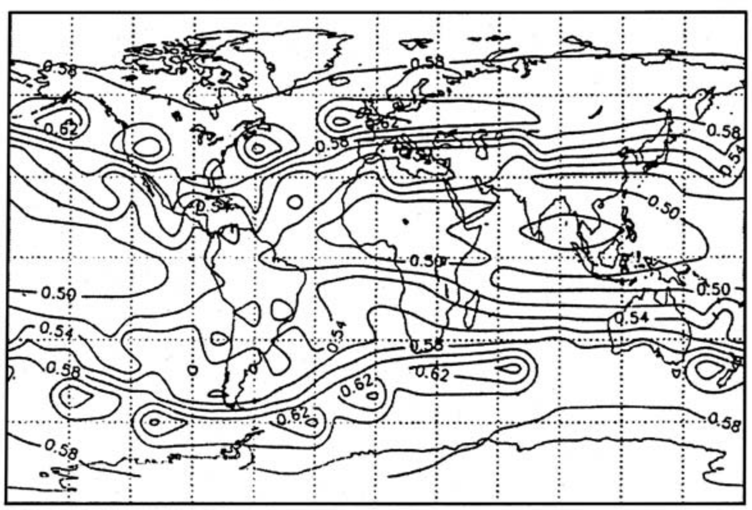


Figure 3 (contd)

$H_{neutron}/H$ at 65 000 ft [~20 000 m]

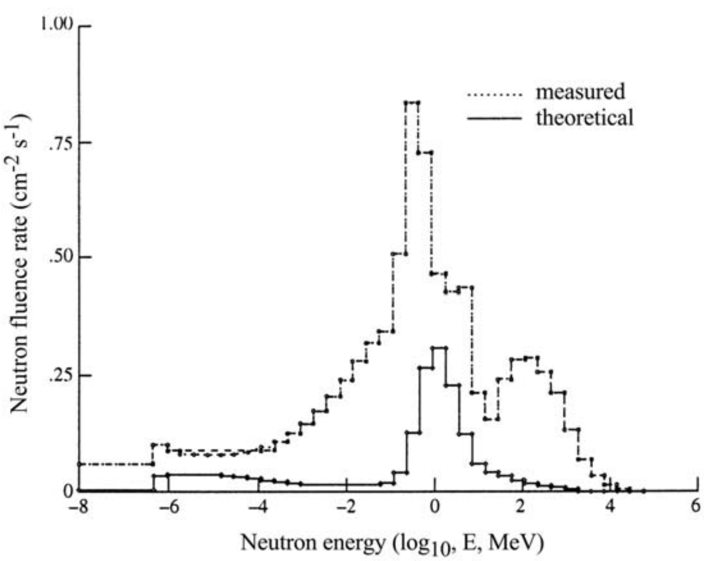


$H_{neutron}/H$ at 73 000 ft [~22 000 m]



From Wilson *et al.* (1995); H, equivalent dose components were not resolved because of instrumental limitations at that time. Most of the neutron spectrum therefore depends on theoretical calculations of proton interactions with the atmosphere (Hajnal & Wilson, 1992; National Council on Radiation Protection and Measurements, 1995). Early measurements of the atmospheric neutron spectrum are shown in Figure 4. Hess *et al*. (1961) measured the neutron spectrum in a bismuth fission chamber with a boron fluoride counter, supplemented by a model spectrum. Korff *et al*. (1979) used a liquid scintillator spectrometer (see section 2.1.1 in Overall introduction) sensitive mainly to 1–10-MeV neutrons with analysis assuming a simple power law spectrum. [The Working Group noted that the data of Korff *et al*. (1979) are for a higher altitude than those of Hess *et al.* (1961).] Hewitt *et al*. (1980) used a Bonner sphere set-up (see section 2.1.1 in Overall introduction) at subsonic flight altitudes and analysed the data after assuming a simplified spectral analysis. Their results confirm the importance of high-energy neutrons, although the exact nature of the spectrum remains uncertain owing to limitations of the analytical methods. Nakamura *et al*. (1987) used a Bonner sphere set-up at much lower latitudes and multiplied their results by three for a comparison of spectral shape. Incomplete knowledge of the neutron spectrum thus makes the present estimates uncertain (National Council on Radiation Protection and Measurements, 1995).

Figure 4. Neutron spectra measured at 17.46° N at 23.5 km by Hajnal and Wilson (1992) and that derived theoretically by Hess *et al.* (1961)



Estimates of dose equivalent rates for exposure to radiation from natural sources are available in a number of publications, but only a few give separate values for the contributions of neutrons. Bagshaw *et al*. (1996) reported that the average rate on long-haul flights from London to Tokyo was 3 μSv h^{-1} for neutrons; an additional 3 μSv h^{-1} for other components gave a total of 6 μSv h^{-1}. Table 1 shows the dose equivalent rates derived with a high-pressure ion chamber and a simplified form of a Bonner sphere, in relation to altitude and latitude (Akatov, 1993). Although the quality of the ionizing dose is not given, it can be seen that the neutron dose equivalent rate represents half or more of the exposure.

Table 1. Atmospheric dose equivalent rates measured on board a Tupolev-144 aeroplane during March–June 1977 (near solar minimum)

Altitude (km)	Latitudes (° N)					
	40–45		46–58		65–72	
	Ionizing (μGy h^{-1})	Neutrons (μSv h^{-1})	Ionizing (μGy h^{-1})	Neutrons (μSv h^{-1})	Ionizing (μGy h^{-1})	Neutrons (μSv h^{-1})
13	2.3	2.6	2.9	4.2	3.5	5.0
14	2.6	3.0	3.2	5.0	4.1	5.9
15	2.8	3.0	3.4	5.4	4.7	6.7
16	2.9	3.2	3.5	5.8	5.2	7.6
17	3.0	3.5	3.7	6.1	–	–
18	3.1	3.4	3.8	5.5	–	–

From Akatov (1993)

In estimating the collective dose equivalent, UNSCEAR (1993) assumed 3×10^9 passenger hours in flight during 1985 and an annual average rate of 2.8 μSv h^{-1} (~1.6 μSv h^{-1} of neutrons) resulting in a collective dose equivalent of 8400 person–Sv (5040 person–Sv of neutrons). By 1997, air travel had grown to 4.3×10^9 passenger hours in flight (ICAO, 1999) leading to a collective dose equivalent of 12 000 person–Sv (7200 person–Sv of neutrons).

1.3.2 *Medical uses*

The medical use of neutrons is limited, as no therapeutic benefit has been noted when compared with conventional radiotherapy; however, neutrons are used to a limited extent in external beam therapy and boron neutron capture therapy.

1.3.3 *Nuclear explosions*

In the reassessment of the radiation dosimetry associated with the atomic bombings of Hiroshima and Nagasaki, Japan (see Overall introduction, section 4.1.1; Fry & Sinclair, 1987), the estimated dose of neutrons was reduced in both cities, particularly in Hiroshima, where the new value was only 10% of the previously estimated level. The neutron doses were now so small (only 1–2% of the total dose in Hiroshima and less in Nagasaki) that direct estimates of the risk for cancer associated with exposure to neutrons were no longer reliable. The neutron dosimetry is once again under review and may be revised (National Council on Radiation Protection and Measurements, 1997; Rühm *et al.*, 1998).

1.3.4 *Occupational exposure*

Occupational exposure to neutrons occurs mainly in the nuclear industry. Compilations have been made of the exposure of nuclear workers in the United Kingdom for the years 1946–88 (Carpenter *et al.*, 1994) and of those in the USA for the years 1970–80 (Environmental Protection Agency, 1984). In the United Kingdom compilation, the upper limit of the neutron component was estimated to be 3% of the total exposure (Table 2). The estimates are uncertain because neutron dosimetry was implemented in fuel processing plants only in 1960, a few workers worked at reactors where there was a significant energetic neutron component for which the dosimetry is inadequate, and there were systematic under- and over-recordings when the dosimetry read-outs were below threshold of detection or the dosimeter was in some way inoperative. The average annual dose equivalent for all workers in the United Kingdom was reduced from 12.5 mSv year^{-1} (neutrons, < 0.4 mSv year^{-1}) in the early 1950s to < 2.5 mSv year^{-1} (neutrons, < 0.1 mSv year^{-1}) in 1985. The average cumulative doses

Table 2. Upper limits of estimated cumulative exposure to neutrons of radiation workers, by last site of employment, United Kingdom, 1946–88

Employer	No. of exposed individuals	Cumulative whole-body dose equivalent (mSv)	Collective dose equivalent (person–Sv)
Atomic Energy Authority	21 344	1.2	26
Atomic Weapons Establishment	9 389	0.3	3.1
British Nuclear Fuels, Sellafield	10 028	4.0	40
Total	40 761	1.7	69.1

From Carpenter *et al.* (1994)

were highest at the Sellafield nuclear fuel processing plant, where 22 workers had single annual doses > 250 mSv (neutrons, > 7.5 mSv year^{-1}), seven of whom had doses > 500 mSv year^{-1} (neutrons, > 15 mSv year^{-1}).

Occupational exposure to neutrons in the USA in 1980 based on data for 1977–84 are shown in Table 3. It was estimated that such exposure had decreased by a factor of two between 1970 and 1980 due to improved protection (Klement *et al.*, 1972; Environmental Protection Agency, 1984).

Table 3. Estimated exposure to neutrons of radiation workers in the United States, 1980

Employer	No. of exposed individuals	Average annual effective dose equivalent (mSv)	Collective effective dose equivalent (person–Sv)
Department of Energy contractors	25 000[a]	2.6	64
Nuclear power stations	1 100	0.5	0.6
US Navy	12 000	0.24	2.9
Total	38 100	1.8	67.5

From National Council for Radiation Protection and Measurements (1987)
[a] Total number of workers

Staff involved in radiotherapy with neutrons are exposed mainly to γ- and β-rays due to activation of the room and equipment. The dose rates are well below 1 μGy h^{-1} and are not detectable by personal dosimetry (Smathers *et al*., 1978; Finch & Bonnett, 1992; Howard & Yanch, 1995).

Neutron sources are used to chart progress in the search for gas and oil resources. The exposure of oil-well loggers has been monitored with film (Fujimoto *et al*., 1985) and nuclear track detectors (Inskip *et al*., 1991). Canadian workers were exposed to 1–2 mSv year^{-1} (Fujimoto *et al*., 1985), whereas Chinese workers monitored for three months had very low doses of neutrons, only seven of the 1344 workers having doses above the threshold of detection (0.02 mGy) (Inskip *et al*., 1991).

The exposure of commercial aircraft crews to neutrons depends not only on the flight route (see section 1.3.1) but also on the number of flight hours, which may be as many as 1000 per year. Hughes and O'Riordan (1993) estimated that long-haul crews are airborne for 600 h year^{-1}, while short-haul crews log only 400 h year^{-1}; they therefore used an average value of 500 h year^{-1}. Bagshaw *et al*. (1996) estimated that crews who fly both ultra-long-haul and long-haul flights fly for 600 h year^{-1}, while those who fly only ultra-long-haul flights fly for up to 900 h year^{-1}. Oksanen (1998) found that the annual average number of flight hours of cabin crews was 673 h, while that of the technical crew was 578 h, with a range of 293–906 h year^{-1}. Air crews have additional exposure during off-duty flights in returning to a home base, which are estimated to account for 20% of the actual flight hours logged.

Hughes and O'Riordan (1993) estimated an average dose equivalent of 3 mSv year^{-1} (neutrons, ~1.8 mSv year^{-1}) for crews on United Kingdom airlines and 6 mSv year^{-1} (neutrons, ~3.6 mSv year^{-1}) for near-polar flights. Montagne *et al*. (1993) estimated that the average exposure of Air France long-haul pilots was 2–3 mSv year^{-1} (neutrons, ~1.2–1.8 mSv year^{-1}). Wilson *et al*. (1994) estimated that the exposure of domestic crews in Australia in 1982–83 was 1–1.8 mSv year^{-1} (neutrons, ~0.6–1.1 mSv year^{-1}), while crews of international flights received 3.8 mSv year^{-1} (neutrons, ~2.3 mSv year^{-1}). Preston (1985) proposed an average dose equivalent of 9.2 μSv h^{-1} (neutrons, ~5.5 μSv h^{-1}) in British Airways operation of the Concorde in 1979, with a maximum observed rate of 38.1 μSv h^{-1} (neutrons, ~23 μSv h^{-1}). The average exposure of the technical crew was 2.8 mSv year^{-1} (neutrons, ~1.7 mSv year^{-1}) and that of the cabin crew was 2.2 mSv year^{-1} (neutrons, ~1.3 mSv year^{-1}). Similar differences (20–30%) between the exposures of personnel on the flight deck and in the cabin were observed by Wilson *et al*. (1994). Differences of up to 20% between aircraft type were also observed.

1.4 Summary

The average effective dose of neutrons received by the world population per year was estimated to be 80 μSv by UNSCEAR (1993). Assuming a 75-year life span, the average lifetime dose would be 6.0 mSv. The highest average lifetime effective dose of neutrons (67.5 mSv) is found in the high-altitude city (3900 m) of La Paz, Bolivia. Table 4 gives the individual and collective lifetime doses for a number of populations. The atomic bombings of Hiroshima and Nagasaki are estimated to have contributed not more than 2% of the total exposure of the survivors, as estimated from the total exposure of 24 000 person–Sv of 86 752 persons and the total exposure of 4 Sv of the 'worst-case' survivors. Insufficient information was available to estimate the individual average exposure of nuclear workers over a working lifetime. The maximal known lifetime exposure of contractors of the Department of Energy in the USA was estimated on the basis of a 50-year career. The collective dose of the world's nuclear workers is based on the assumption that workers in the United Kingdom and the USA represent 20% of such workers. UNSCEAR (1993) estimated that the average total exposure of the world population from air travel was 2 μSv year^{-1}, of which 60% is to neutrons, although the maximal individual exposure due to air travel depends mainly on flight duration. The collective dose for crew members is based on the assumption that there are five crew members for every 100 passengers.

Table 4. Exposure to neutrons of major exposed human populations

Population	Exposure path	Individual lifetime[a] dose (mSv)		Collective dose (person–Sv per year)	Variation
		Average	Maximum		
World (5800 million)	Natural sources (cosmic radiation)	6.0	67.5	4.64×10^5	Large
Tumour therapy	Collateral irradiation of healthy tissue				Highly skewed distribution
Survivors of atomic bombs	Fission neutrons	< 5.5	< 80.0	< 480	Relatively more important at lower exposures (?)
Nuclear workers[b]	Civilian and military nuclear fuel cycle	44.4	130[c]	350[d]	
Aircrews, courriers[e]	Flying at high altitude, cosmic secondary neutrons	30	46	320	Higher on flights over earth poles
Airline passengers	Flying at high altitude, cosmic fusion neutrons	0.09	–	7200	Higher on flights over earth poles

From UNSCEAR (1993)
[a] 75 years
[b] 50-year career
[c] Department of Energy contractors in the USA
[d] Workers in the United Kingdom and the USA assumed to represent 20% of all nuclear workers
[e] 30 years