COLLECTIVE DOSES FROM PRACTICES INVOLVING RADIATION EXPOSURES

D. Beninson
Secretary of UNSCEAR

1. INTRODUCTION

Radiation doses are determined or estimated in two main types of radiation protection assessments: a) individual-related assessments, where individual dose data are taken to indicate the level of risk incurred by exposed individuals; and b) source-related assessments, aiming at the evaluation of the total consequences of given radiation sources, and which take account therefore of all exposures caused by the sources. This paper reviews a number of sources and practices which involve radiation exposures, with the aim of providing source-related assessments. This review is based on the assessments carried out by UNSCEAR (1).

2. GENERAL CONSIDERATIONS

Practices involving radiation sources give rise to a distribution of doses in the exposed population. No single quantity can represent adequately the distribution for all risk assessment purposes. A useful quantity for source-related assessments is the collective dose. The collective dose in a population, S, is defined as the weighted product of dose and number of individuals of the exposed population. The collective dose is therefore given by the expression

$$S = \int_0^\infty D\, N_D(D)\, dD$$

where $N_D(D)$ is the population spectrum in dose, $N_D(D)dD$ being the number of individuals of the exposed population receiving a dose in a specified organ or tissue due to the source, in the range D to D + dD. The collective dose is an extensive quantity that can apply to one person, to a population group or to the whole world population. It is expressed in man rad (or man Gy), or in man rem, as appropriate.

In some cases, the exposure of the population is delivered over considerable time after the originating event. In order to have a measure of the total exposure of the population, caused by the source, the collective dose commitment is used. The collective dose commitment, S_k^c, due to a given event, decision or finite practice k is defined as the infinite time-integral of the collective dose rate, $\dot{S}_k(t)$, caused by that event, decision or finite practice

$$S_k^c = \int_0^\infty \dot{S}_k(t)\, dt$$

where the collective dose rate is the weighted product of dose rate due to the source and number of individuals in the exposed population

$$\dot{S}_k(t) = \int_0^\infty \dot{D}_k\, N_{\dot{D}_k}(\dot{D}_k)\, d\dot{D}_k$$

The calculation of collective dose commitment from source k requires that all individuals receiving a dose from the source are included in the population under consideration. As the integral remains unchanged if the population is made arbitrarily larger than the actual exposed group by adding unexposed persons, it is convenient to specify the population as the world population. This specification is not necessary when the exposed group is small and well defined in a way that every exposed person could be accounted for.

The collective dose commitment from a source is particularly useful for two purposes. On one hand it can be used in relative detriment assessments, on the assumption that the risk of deleterious effects is proportional to dose, while their severity is independent of the frequency of expression. On the other hand, it can be used to assess future exposures from continued practices.

A continued practice causing radiation exposure can be considered as a sequence of events, each delivering exposures over times which may exceed the duration of the event. The collective dose commitment is usually proportional to the size of the originating event. For example, if the event under consideration is the release of a radionuclide to the environment, the collective dose commitment is proportional to the activity released, provided all other influencing factors remain constant. It is therefore possible to define a collective dose commitment per unit practice, as for example in the case of nuclear power it is possible to define a collective dose commitment per MW(e)y of electric energy generated.

It can be shown that in the case of a continued practice the resulting average (per caput) dose rate will increase and eventually reach a steady state. In the simplified case of a constant population, the steady state per caput dose rate, $\bar{\dot{D}}_\infty$, is given by

$$\bar{\dot{D}}_\infty = \frac{R}{N} S_1^c$$

where R is the practice rate, namely the number of units of practice per unit time, N is the population size and S_1^c is the collective dose commitment per unit practice. In many cases it is possible to make rough projections of the practice rate per caput, R/N, such as, for example, the nuclear installed capacity per person, and it is then possible to predict the maximum per caput dose rate that will be experienced in the future.

For exposures delivered over a very long time, as in the case of exposures due to the release of carbon-14, it would not be realistic to assume a continued practice for such long times as required by the per caput dose rate to approach steady state. It can be shown that, in these cases, the maximum per caput dose rate to be experienced in the future is approximated by

$$\bar{\dot{D}}_{max} \simeq \frac{R}{N} S_1^\tau$$

where S_1^τ, called the incomplete collective dose commitment, is the time-integral of the collective dose rate caused by one unit of practice, $\dot{S}_1(t)$, over a period τ equal to the estimated duration of the continued practice

$$S_1^\tau = \int_0^\tau \dot{S}_1(t)dt$$

The incomplete dose commitment per unit practice clearly does not relate to the detriment per unit practice but only to a part of it. It is however useful to predict the maximum per caput dose rate due to a continuing but finite practice.

3. SOURCES OF HUMAN RADIATION EXPOSURES

Source-related assessments are particularly useful in cases where human decisions affect the resulting exposures, since collective dose commitments could be attached to such decisions, and could be taken to represent a measure of the consequential detriment. The natural radiation sources are in a special category because only part of the exposure to these sources can be influenced by human decisions. While there are "technologically enhanced exposures to natural sources", such as, for example, in high altitude flights or in the use of construction materials with high radium content, there is a background of exposure from natural sources from which these examples may be seen as more or less artificial deviations. This "unmodified" background varies with altitude and geographical location and is a useful reference level of radiation exposure.

3.1. "Unmodified" exposure to natural sources

The various natural radiation sources include *external* sources such as cosmic rays and radioactive substances in the ground and in usual building materials, and *internal* sources in the form of naturally occurring radioactive substances in the human body, particularly potassium-40. The contribution of natural sources to the per caput dose in areas of normal radiation background is summarized in Table 1.

	Gonads	Lung	Bone lining cells	Red bone marrow
External irradiation				
Cosmic rays	28	28	28	28
Terrestrial radiation	32	32	32	32
Internal irradiation				
Potassium-40	15	17	15	27
Radon-222 (with daughters)	0.2	40	0.3	0.3
Other nuclides	2	6.5	9.1	4
Total	78	124*)	85	92

TABLE 1

*) *A substantial fraction (37 per cent) of this dose is caused by alpha radiation which is expected to have a higher biological effectiveness than the beta and gamma radiations, which cause more than 90 per cent of the dose in the other tissues. An annual dose of the order of 300 mrad is received by the epithelial cells of the tracheo-bronchial tree.*

Much higher external doses are received by population groups living at high altitudes or in regions of high natural activity. Some population groups are also exposed to elevated internal doses, for example people living in houses of low ventilation rate in the colder climates, using radon-rich waters, or consuming from particular food chains.

The annual collective dose to the world population from natural sources is about $3\ 10^8$ man rad for most of the body tissues, and about 50 per cent higher for the lung. These values are useful in relative detriment assessments, because collective dose commitments due to given practices can be expressed as equivalent durations of exposure to natural sources, e.g. durations which would cause the same collective dose commitment as the practices.

3.2. Technologically enhanced exposures to natural sources

A total of about 10^9 passenger hours are spent travelling by air each year. Under average solar conditions the annual collective dose contributed by air travel is about 3 10^5 man rad. High radiation levels at high altitudes during solar flares are infrequent events which will not add significantly to the collective dose to the world population, but make it necessary to equip supersonic aircraft with monitoring devices to allow for prompt remedial actions. The collective dose commitment from one year of air travel is equivalent to about 9 hours of unmodified exposure of the world population to natural sources.

Very large quantities of phosphate rock are mined, some of the material being converted to fertilizers and some disposed as waste. As phosphate deposits contain usually high concentrations of the uranium-238 decay series, both practices may lead to exposure of the public. In addition, one by-product is chemical gypsum which may be used as a building material. The collective dose commitment from phosphate fertilizers is small, of the order of 10^{-4} man rad per tonne of rock. If all the phosphogypsum from the marketable ore were used in the building industry, however, the resulting collective dose commitment would be a few man rad per tonne of ore, equivalent to about 0.3 seconds of natural background per tonne of ore.

Anotherexample of technologically enhanced exposures to natural sources is the use of special building materials, either of natural origin or made from products of industrial processes. The dose rates in air from gamma radiation in buildings of such materials may be 2 to 20 times higher than the average normal dose rate from terrestrial radiation. The radon levels will also be considerably enhanced for a given ventilation rate.

3.3. Medical uses of radiation

The exposures of the patients during medical procedures are of particular interest since they contribute the highest man-made per caput doses in population, are given with high instantaneous dose-rates and cause the highest individual organ doses, except in accidents. The individual doses to the patients must be decided by the medical doctors on the basis of the need for a diagnosis or treatment. The patient's dose in various organs and tissues, therefore, may vary from entirely insignificant doses up to high doses which cause local tissue damage near treatment areas.

The collective doses from medical irradiations are therefore composed of a large variety of individual doses. However, the largest contributions to the collective doses come from types of exposures which involve large numbers of individuals, as is the case in some diagnostic x-ray examinations. In these cases the per caput doses to the organ of interest have been found to be roughly similar in magnitude, in many technologically developed countries being in the order of 100 mrad per year. This means that the annual collective dose from medical practices is of the order of 10^5 man rad per million of population.

It is estimated that the occupational exposure of workers in the medical field gives an annual collective dose in the order of 10^2 man rad per million of population. This occupational contribution is insignificant compared to that from the irradiation of patients. The annual global collective dose from medical procedures may be estimated to be of the order of 10^8 man rad, equivalent to about 120 days of natural radiation background.

3.4. Nuclear explosions

Not including the contribution from carbon-14, the per caput global dose commitment from all nuclear explosions carried out before 1976 range from about 100 mrad in the gonads to about 200 mrad in bone-lining cells. In the northern temperate zone the values are about 50 per cent higher while in the southern temperate zone they are about 50 per cent lower than these estimates. External exposures, mostly from caesium-137 and short-lived nuclides, contribute about 70 mrad to the global dose commitment for all tissues. Internal exposures are dominated by contributions from caesium-137 and from strontium-90 in the skeleton. The contribution from carbon-14 is about 120 mrad for the gonads and lung and 350 mrad for the bone lining cells and the red bone marrow.

The collective dose commitment from nuclear test explosions varies from $4\ 10^8$ to $8\ 10^8$ man rad in different tissues, if the carbon-14 contribution is not included. Since the carbon-14 doses will be delivered over many thousand years, it is interesting to assess the incomplete collective dose commitment from this nuclide. If the duration of atmospheric nuclear testing is taken to be about 30 years, the incomplete collective dose commitment is estimated to be $4\ 10^7$ to 10^8 man rad, adding a small contribution to the collective dose commitment from the other nuclides. The total collective dose commitment in different tissues from nuclear explosions is equivalent to about 18 to 27 months of exposure of those tissues to the corresponding natural radiation levels.

3.5. Nuclear power production

The use of nuclear reactors for the production of electric power is now an established technology. The total installed nuclear generating capacity in 1976 was about 80 GW(e) from 187 power reactors operating in nineteen countries. The projected capacity by the year 2000 is about 2000 GW(e).

The nuclear fuel cycle involves a series of steps, comprising the processes of mining and milling of uranium, conversion to fuel material (in most cases including enrichment in the isotope uranium-235), fabrication of fuel elements, utilization of the fuel in nuclear reactors, storage of the spent fuel, reprocessing of this fuel in cases where the fuel cycle is closed, transportation of materials between the various installations, and the ultimate disposal of radioactive waste. Almost all the radioactive material associated with the nuclear industry is present in the reactors and in spent fuel or in well-contained fractions separated from the fuel during the reprocessing operations. However, at each step of the fuel cycle, releases of small quantities of radioactive material into the environment occur.

The total collective dose to the world population may be assessed by estimating the contribution from four components, namely the occupationally exposed group, the local population in the vicinity of installations of the fuel cycle, the regional population and the world population. The last three components are the result of environmental releases of radioactive materials. Most of the radionuclides released are only of local or regional concern, because their half-lives are short compared to the time required for dispersion to greater distances. Some radionuclides, on the other hand, having longer half-lives or being more rapidly dispersed, can become globally distributed.

A special problem arises in the case of a few radionuclides which have very long half-lives. The most important examples are uranium-238 ($4.5\ 10^9$ y) and iodine-129 ($1.6\ 10^7$ y). The exposure periods of many million years make the collective dose commitments high. For example, uranium from the mining and milling industries and the related production of radon will cause collective dose commitments of the order of 100 man rad per MW(e)y in the lung, the bone-lining cells and the red bone marrow. Uranium from the fuel fabrication industry may contribute about ten times as much. Iodine-129, if released from reprocessing plants, would contribute about 2000 man rad in the thyroid per MW(e)y. However, the exposure periods are so long that the meaning of these commitments is unclear. In fact, to accumulate a collective dose of only 1 man rad per MW(e)y from these nuclides a period between 10^4 and 10^6 years would be necessary. The exposure from these nuclides is not discussed in the following considerations.

Carbon-14 presents similar problems. The collective dose commitment from carbon-14 released from light water reactors and related processing plants is estimated to be about 5 man rad per MW(e)y in soft tissues and 14 man rad per MW(e)y in bone lining cells and red bone marrow. One half of this collective dose will be delivered within 5700 years. Because it takes some time for carbon-14 to become dispersed in the oceans, as much as one fifth of the collective dose will be delivered within 500 years. If it is assumed that the nuclear industry can operate at the rate occurring in year 2000 for some 500 years, the incomplete collective dose commitments are therefore about 1 man rad per MW(e)y in soft tissues and 3 man rad per MW(e)y in bone marrow and bone lining cells.

The collective dose commitments in different tissues are summarized in Table 2. The values for gonads are in the lower range, while those for the thyroid and lung are the highest.

Step in cycle	S_1^τ [man rad/MW(e)y]	Type of exposure
Reprocessing	1.1 - 3.3	global
Research and development	1.4	occupational
Reprocessing	1.25	occupational
Reactor operation	1.0	occupational
Mining, milling and fuel fabrication	0.2 - 0.3	occupational
Reactor operation	0.25 - 0.35	local and regional
Reprocessing	0.2 - 0.8	local and regional
Whole industry	5.4 - 8.4	

In the summation for the whole industry the occupational contributions dominate. Because of the age distributions of those occupationally exposed and of the public, only about 30 per cent of the lower value of the range for the whole industry would be of genetic significance.

The estimated collective dose commitment for the whole industry per MW(e)y generated is equivalent to about 0.56 seconds of exposure to the natural radiation background. One year of operation at the 1976 installed capacity gives a collective dose commitment equivalent to about 1/2 day of natural irradiation, while one year of operation at the projected capacity for the year 2000 would be equivalent to about 12 days. This forecasts into the future are quite uncertain, because they depend on both technology and regulations which may vary substantially.

3.6. Consumer products emitting radiation

A variety of consumer products contain radionuclides which have been deliberately incorporated to satisfy a specific purpose. Main examples are radioluminous products, some electronic devices, antistatic devices, gas and aerosol detectors, ceramics and glassware containing uranium and thorium. In addition, some electronic products, such as television sets, may emit x rays.

Until the 1960's radium-226 was the most common nuclide in radioluminescent paint and therefore also in watches and alarm clocks. At present tritium is used for the same purpose. The wearer of an average radium activated wrist watch receives a gonad dose of a few mrad per year. A person wearing a tritium activated wrist watch may receive from tritium leakage a whole body dose of 0.1 to 0.2 mrad per year. The present use of radioluminescent paint in the watch industry may cause a collective dose to the world population of the order of 10^5 to 10^6 man rad in a year, equivalent to 2.5 to 25 hours of exposure to the natural radiation background. Too little is known about the number of products that are actually on the market in various countries and the amount of activity involved. It is difficult to assess, therefore, the average dose due to these products. However, there is a gradual improvement of control, and it seems likely that the annual collective dose to the gonads from the use of radiation-emitting consumer products is less than 4 10^6 man rad at present, corresponding to some 100 hours of natural irradiation.

REFERENCES

(1) Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. To be published as a report to the General Assembly and as a UN sales publication in 1977.