COLLECTIVE DOSE COMMITMENTS FROM NUCLEAR POWER PROGRAMMES

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1. INTRODUCTION

The use of nuclear reactors for the production of electric power is now an established technology. The total installed nuclear generating capacity in the world in 1976 was 75.9 GW(e) from 187 power reactors operating in nineteen countries (1). Recent estimates of the growth of nuclear power project a figure of about 2000 GW(e) by the year 2000.

The nuclear fuel cycle serving the production of electric power consists of the processes of mining and milling of uranium, conversion to fuel material, usually including enrichment in the isotope $^{235}$U, fabrication of fuel elements, utilization of the fuel in nuclear reactors, reprocessing of spent fuel, transportation of material between fuel cycle installations and disposal of radioactive wastes.

At each step of the fuel cycle occupational exposure to radiation occurs and small quantities of radioactive materials are released into the environment. These releases cause some population exposure. As the scale of the fuel cycle is related to the nuclear installed capacity it serves, it seems reasonable for some purposes to assess such exposures in terms of collective dose commitments per unit energy generated, e.g. per MW(e)y. In this way the assessments can be normalized irrespective of the size of the expanding nuclear industry.
The total collective dose to the world population may be assessed by estimating the contributions from four components, namely the occupationally exposed group, the local population in the vicinity of installations involved in the fuel cycle, the regional population and the world population. The last three components are the result of releases of radioactive materials to the environment. 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.

2. BASIC CONCEPTS

The assessments presented in this paper are expressed in terms of collective dose commitments. The collective dose commitment $S_k^c$, due to a given event, decision or finite practice $k$ involving radiation exposures is defined as the infinite time-integral of the collective dose rate, $\dot{S}_k(t)$, caused by that event, decision or finite practice

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

The collective dose rate is the weighted product of dose rate due to $k$ and number of individuals in the exposed population

$$\dot{S}_k(t) = \int_0^\infty \dot{D}_k \, N_k^*(D_k) \, dD_k$$

where $N_k^*(\dot{D}_k)$ is the population spectrum in dose rate, $N_k^*(\dot{D}_k) \, d\dot{D}_k$ being the number of individuals receiving a dose rate due to the source $k$, in the range $\dot{D}_k$ to $\dot{D}_k + d\dot{D}_k$. The calculation of the 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 also be used to assess future exposures from continued practices, which can be considered as sequences of events, each delivering exposures over times which may exceed the duration of the event.

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 (2). In the simplified case of a constant population, the steady state per caput dose rate, $D_\infty$, is given by

$$D_\infty = \frac{R}{N} S_1$$

where $R$ is the practice rate, namely the number of units of practice per unit time, $N$ is the population size and $S_1$ 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

$$D_\text{max} = \frac{R}{N} S_1^T$$

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

$$S_1^T = \int_0^\tau S_1(t) dt$$

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. OCCUPATIONAL EXPOSURE FROM THE NUCLEAR POWER CYCLE

3.1 Assessment procedures

The doses from occupational exposure are monitored and, within the limitations of this monitoring, some information on the dose distribution in the different steps of the fuel cycle is available. In this case, the collective dose, $S$, could conceptually be assessed by summation

$$S = \sum \bar{D}_i N_i$$

Where $\bar{D}_i$ is the per caput dose in the group $i$, and $N_i$ is the number of individuals in the group.

However a practical difficulty is encountered in the recording of doses which fall below the "minimum detectable level" of the monitoring system. These may be recorded either as the minimum detectable level or as zero. Since records usually do not indicate the procedures according to which doses were derived, it is not in general possible to correct for instrumental effects or for the natural radiation background which may have been included. Furthermore, the coverage by personal monitoring programmes of workers who are likely to receive only very low doses is quite variable, as it is not recommended by the ICRP (3) for the purpose of radiation protection.
Because of these problems and in view of the large number of doses falling in this category the collective dose contribution from the lowest dose interval is often not known.

It is therefore necessary to develop an analytical procedure which can be applied to the distribution of doses at the higher levels to obtain an estimate of the per caput dose for the occupation. This procedure is based on the observation, derived from very extensive surveys, that in most occupations involving radiation exposure, not only in the production of nuclear power, the individual doses follow a log-normal distribution (4) (5) (6). In one of these surveys (4), annual doses as low as 12 mrad were estimated with sufficient precision, taking advantage of the increased film sensitivity for low energy x rays.

Since this is the case, a simple version of 'probit analysis' can be used to assess the parameters of a given distribution of occupational doses. The plot of cumulative frequency against dose on log-normal paper is therefore expected to give a straight line. Least-square fitting can then be used to determine the parameters of the distribution, namely the geometric mean dose (median), $D$, and the geometric standard deviation, $\sigma_g$.

It can be shown from the characteristics of the log-normal distribution (8) that the per caput dose, $\bar{D}$, of the distribution is given by

$$\bar{D} = D \ e^{\frac{1}{2} (\ln \sigma_g)^2}$$

The collective dose, $S$, therefore, is

$$S = N \ D \ e^{\frac{1}{2} (\ln \sigma_g)^2}$$

where $N$ is the number of individuals in the distribution.

In practice it is difficult to decide which individuals should be included as occupationally exposed in any given circumstance. The number $N$, therefore, will depend on subjective considerations. It can be shown, however, that an arbitrary inclusion of unexposed individuals would modify both $\bar{D}$ and $N$ of the distribution, in a way that the value of $S$ remains constant.

### 3.2 Occupational collective doses

In the 1972 report, UNSCEAR (9) estimated that occupational exposure accounted for a substantial part of the collective dose due to the nuclear fuel cycle. It was estimated in the report that the occupational collective dose due to the production of electricity by nuclear fission was about 2 to 3 man rad per megawatt year of electrical output, most of this dose being incurred during the reprocessing of nuclear fuel. It was anticipated that improved technology could result in lower collective doses per megawatt year.

The values summarized in this paper were assessed, as far as possible, by the procedure outlined above. In those cases where the data are insufficient or they deviate significantly from a log-normal distribution, the collective dose can still often be estimated by direct calculation from the raw data, but then involving substantial uncertainty. In the follow-
ing paragraphs the various steps of the nuclear fuel cycle are discussed in turn, in relation to the whole body collective doses. Other collective doses to individual organs are not reviewed in this paper.

Some information is available on the external gamma irradiation in uranium mines (10) (11). Typical dose rates in air vary from 0.5 mrad/h up to 100 mrad/h in places with exceptionally rich ore. The average of many different measurements of dose rate in air in American underground uranium mines is about 1.3 mrad/h. Assuming a $3\pi$ geometry and 2000 hours of work per year, this average dose rate in air corresponds to an annual mean whole body dose of about 1.6 rad. However, measurements of the external dose to French underground miners show a decrease in the annual average dose from about 1.0 rad in 1971-1972 to 0.5 rad in 1975. It therefore seems reasonable to assume that an annual dose of the order of 1 rad is representative for current conditions in uranium mines worldwide.

The assessment of collective doses per unit electric energy produced from mining operations requires an estimation of the number of miners involved in the extraction of ore necessary to produce 1 MW(e)y. Assuming that one miner in a year produces 3 metric tons of U$_3$O$_8$ and that 160 metric tons of U$_3$O$_8$ are required to fuel one 1000 MW(e) light water reactor for a year, it is estimated that about $5 \times 10^{-2}$ man year are occupationally exposed in the mines per MW(e)y. The collective dose contribution from uranium mining is therefore about:

$$S = 1.0 \text{ rad} \frac{y}{y} \times 5 \times 10^{-2} \frac{\text{man} \cdot \text{y}}{\text{MW(e)y}} = 0.05 \text{ man rad per MW(e)y}$$

There are very few data allowing the assessment of the occupational collective dose resulting from milling operations and fuel fabrication. From information on occupational exposures available in the US for 1973 and 1974, together with the amount of nuclear energy generated in the same years (12) (13), a value of about 0.25 man rad per MW(e)y is obtained. This value is probably an overestimate, since part of the fabricated fuel was used in reactors which did not contribute significantly to power production in these years, due to the rapidly expanding industry.

A comprehensive summary of occupational radiation exposures in United States light water cooled reactors (LWRs) has recently been published (13). Collective doses were obtained either by multiplying the number of people in a dose range by the midpoint dose in that range and summing the results or, as was possible in a small number of cases, by summing the actual recorded doses of all individuals. The occupational collective dose per unit energy generated, for the period 1969 to 1974, was about 1.3 man rad per MW(e)y. Most occupational exposure at reactors is incurred during maintenance and repair (65 per cent of the collective dose).

Similar collective doses per unit energy generated (about 1 man rad per MW(e)y) can be calculated for Heavy water reactors (HWRs) (14), and for the Gas cooled reactors (GCRs) in the UK (15) in the period 1972-1974 (0.73 man rad per MW(e)y) and in Japan (1.2 man rad per MW(e)y) (16).
The major commercial fuel reprocessing installation which has been in operation during recent years is at Windscale in the United Kingdom. In its 1972 report, UNSCEAR estimated the occupational collective dose due to reprocessing to be about 1.6 man rad per MW(e)y. Recent information on the dose distribution in the Windscale installation in the period 1971 to 1975 (15), together with the assumption that the collective dose can be related to the nuclear electrical output in the same years, result in an estimate of about 1.2 man rad per MW(e)y.

Occupational exposures of workers involved in transportation of materials between fuel cycle installations cannot be assessed from direct measurements, as many of these workers are not subject to individual monitoring, and those who are may also be involved in other radiation work within the industry. Dose calculations are, therefore, based on assumptions as to the dose rates at different distances from the packages and the times spent by workers in various operations (17). These calculations show that the collective dose per unit energy generated, contributed by transportation, is quite small, of the order of $10^{-3}$ man rad per MW(e)y.

When the nuclear fuel cycle is considered as a whole, some account must be taken of exposures in the research and development organizations devoted largely to servicing the nuclear industry. Assuming that all occupational doses in such organizations are received in support of the nuclear power industry, it is possible to obtain an upper limit for the collective dose contributed by research and development. Using this assumption and information from UK (15) and the US (18), a value of about 1.4 man rad per MW(e)y is derived.

From the values given in previous paragraphs, it appears that the occupational collective dose from a nuclear power programme is in the range of 3 to 4 man rad per MW(e)y.

4. EXPOSURES FROM ENVIRONMENTAL RELEASES OF RADIOACTIVE MATERIALS

4.1. Assessment procedures

The chain of events leading from the release of radioactive substances to the irradiation of humans can be schematically represented by compartment models. Compartment models, even when very complex, imply considerable simplification of the real transfer processes.

Since the dose commitment from a release is the integral over infinite time of the per capita dose rate resulting from the release (2), steps in the sequence from input to the final dose commitment can be conveniently described by the quotient of the infinite time-integral of the appropriate quantity in step $j$ of the sequence to the infinite time-
integral of the appropriate quantity in the preceding step \( i \). These quotients define the transfer factors \( P_{ij} \) in the pathway from input of radionuclides into the environment to the subsequent radiation dose in man:

\[
P_{ij} = \frac{\int_0^\infty M_j(t) \, dt}{\int_0^\infty M_i(t) \, dt}
\]

where \( P_{ij} \) is the factor relating compartments \( i \) and \( j \), and \( M_i(t) \) and \( M_j(t) \) are the appropriate quantities (i.e. activity concentration) in the compartments at time \( t \). Transfer factors, for a number of nuclides and environmental compartments, have been extensively studied by UNSCEAR (9).

The network of pathways linking the release of radioactive materials to the dose commitment consists of steps in series and in parallel. The total transfer factor of a branch in series is the product of the transfer factors involved; the total transfer factor of several branches in parallel is the sum of the transfer factors of the branches.

The calculation of the collective dose commitment, \( S^C \), from the dose commitment, \( D^C \), (9) is simple if the population size, \( N \), remains constant over the period contributing to the defining integrals (\( S^C = D^C N \)). In the more general case, however, a constant population can not be assumed and the calculation of collective dose commitments therefore often requires the selection of a population growth model. A convenient function for this purpose is the logistic function, which assumes an upper bound for the population size. For short projections into the future, the logistic function is approximated by an exponential growth. Some of the values of collective dose commitment presented in this paper are based on an assumed upper bound for the world population of \( 7 \times 10^9 \) individuals, and a fractional growth rate of 0.02 per year, the value which seems to apply at present.

In some instances, it is possible to assess the collective dose commitment even though the distribution of individual doses is not known. For example, under an assumed fixed age distribution and consumption pattern, the dose due to an intake of an activity \( A \) of a radionuclide, is proportional to the intake and can be expressed as \( D = kA \). The collective dose due to the presence of this radionuclide in food can then be assessed as

\[
S = \int_0^\infty D N_D(D) \, dD = k \int_0^\infty A \frac{dN}{dA} \, dA
\]

where the last integral is the total (collective) intake of activity. This total activity intake can be estimated as the product of the average activity concentration and the total amount of food consumed, without knowing where or by whom.
A similar procedure applies in cases where the individual dose depends on the activity present or deposited per unit area as a function of location, and the population density is constant over the region of interest. The collective dose commitment in these cases is proportional to the total activity present (or deposited) and is independent of the pattern of distribution of the activity.

4.2. Collective dose commitments from radionuclides of world-wide distribution

The collective dose commitment contribution made by radionuclides of world-wide distribution can be discussed for the fuel cycle as a whole. These radionuclides have substantial half-lives and characteristics leading to relatively short dispersion times. They can therefore become widely distributed when released to the environment. In this category of nuclides of world-wide distribution, krypton-85, tritium and carbon-14 are of particular interest. As only exposures to the whole body are discussed in this paper, the very long lived iodine-129 which leads to thyroid exposure will not be included.

4.2.1. Krypton-85

Krypton-85 is a beta emitter with a maximum energy of 670 keV. In 0.4 per cent of the disintegrations a gamma photon of 514 keV is emitted. External gamma irradiation causes whole-body doses, while the beta radiation gives only skin doses (19) (20). Internal irradiation due to inhalation is negligible in comparison with external irradiation. The whole-body dose rate from a homogeneous air concentration can be readily assessed by the immersion model \( (1.7 \times 10^4 \text{ rad/year per Ci/m}^3, \text{ equivalent to } 2 \times 10^7 \text{ rad/year per Ci/g}) \).

The collective dose commitment from \(^{85}\text{Kr}\) is due almost entirely to the release from reprocessing plants, the release from reactors being quite small in comparison. The thermal fission yield for \(^{85}\text{Kr}\) is 0.285 per cent for \(^{235}\text{U}\) and 0.144 per cent for \(^{239}\text{Pu}\), corresponding to 505 and 255 Ci/MW(e)y for \(^{235}\text{U}\) and \(^{239}\text{Pu}\) respectively. Assuming that 41 per cent of the fissions are of \(^{239}\text{Pu}\) in LWR fuel with 33,000 MWD(t)/tonne burn-up, the \(^{85}\text{Kr}\) generation rate is about 400 Ci/MW(e)y.

As the solubility of krypton in water is negligible, there is no sink for the krypton released into the atmosphere and rather uniform concentrations are achieved in a period of about two years. The distribution of krypton is taken to be almost homogeneous over the surface of the globe and throughout the troposphere. This assumption is substantiated by results of measurements of \(^{85}\text{Kr}\) in ground-level air at different latitudes (21).
Neglecting the local and regional contributions to the collective dose commitment (about 1 per cent), assuming uniform mixing in the troposphere and using a short term exponential population growth as outlined in 4.1, the collective dose commitment per unit activity released is found to be about $4 \times 10^{-4}$ man rad per Ci (22). This value, combined with the production quoted above, corresponds to 0.16 man rad per MW(e)y.

### 4.2.2. Tritium

Tritium, in the form of tritiated water, is widely dispersed in the circulating waters, which can also include the water in body fluids. A concentration of 1 pCi/g in body fluids would deliver a dose rate to the whole body of about $10^{-4}$ rad/year.

Tritium is produced in nuclear reactors by ternary fission and by activation reactions on deuterium (mainly in heavy water reactors) and on additives used for reactivity control. The production rate due to fission has been estimated to be about 20 Ci per MW(e)y (22) (23). Most of this tritium is released during reprocessing. The contribution from activation reactions is extremely variable depending on, among other factors, the reactor type and the additives used. These additional contributions are of the order of 1 per cent in the case of BWRs and CCRs, 20 per cent in the case of PWRs, and on average, 130 per cent in the case of HWRs.

The collective dose commitment per unit activity of tritium released can be assessed using the relationship determined for tritium released by nuclear explosions (24), and the procedures outlined in 4.1. By this procedure, the collective dose commitment is estimated to be $5 \times 10^{-3}$ man rad per Ci released. The initial distribution of the released tritium, however, is different for explosions and for effluents from the nuclear industry.

An alternative procedure (22) (25) consists of assuming that all significant discharges of $^3$H as tritiated water in the near future will occur in the Northern hemisphere, and that the tritiated water will be dispersed in the circulating waters of that hemisphere (about $10^{22}$ g). It is also assumed that the time of exchange with the Southern hemisphere and with waters below the thermocline is substantially longer than the half-life of tritium. This approach leads to a lower estimate of the collective dose commitment ($10^{-3}$ man rad per Ci released), because the higher concentrations of $^3$H in surface waters before complete mixing occurs are neglected.

Using an intermediate value of $3 \times 10^{-3}$ man rad per Ci, the production of tritium by ternary fission corresponds to a collective dose commitment of $6 \times 10^{-2}$ man rad per MW(e)y. Activation reactions in the reactor may increase this value at most by a factor of about 2 (HWR).

### 4.2.3. Carbon-14

Carbon-14 is produced in LWRs and HWRs by $(n,\alpha)$ reactions with $^{17}$O, present in the oxide fuel and in the moderator, by $(n,\gamma)$ reactions with $^{14}$N, present in the fuel as impurities, and by ternary fission. Several estimates of the production of carbon-14 and measurements of its release
from reactors have been published (26) (27) (28) (29) (30) (31) (32). A direct calculation, assuming that the average thermal neutron flux density is the same in the fuel and moderator and that the cross sections follow the $\frac{1}{\nu}$ law, indicates the $^{14}\text{C}$ production to be about 0.02 Ci/MW(e)y in LWR. The amount released at the reactor, 30 per cent of the total production, is the amount produced in the moderator. The amounts produced in the moderator will vary depending on the moderator size. The $^{14}\text{C}$ produced in the fuel will presumably be released, at least partially, at the reprocessing plant. Similar calculations for HWRs estimate the $^{14}\text{C}$ production to about 0.4 Ci/MW(e)y, over 90 per cent being produced in the moderator and therefore presumably being released at the reactor.

Estimates of $^{14}\text{C}$ production by HTGRs range from 0.06 Ci/MW(e)y (33) to 0.25 Ci/MW(e)y (27), due primarily to the $^{13}\text{C}(n, \gamma)^{14}\text{C}$ reaction. Natural graphite contains 1.107 per cent $^{13}\text{C}$. An insignificant amount of $^{14}\text{C}$ will be released from these reactors, most of the $^{14}\text{C}$ being released at the reprocessing plant (33).

The dose commitment from $^{14}\text{C}$ releases from nuclear power installations can be assessed by assuming that the environmental distribution and behaviour will follow that of the natural $^{14}\text{C}$. The dose commitment per unit activity released has been estimated by this procedure to be approximately $4.3 \times 10^{-9}$ rad per Ci for the whole body. As this dose is delivered over a very long time, much longer than the time required by the world population to reach an equilibrium value, it can be shown that the collective dose commitment is very approximately given by $\frac{D}{N} \approx \frac{D}{N_N} \frac{N}{N_N}$, where $N_N$ is the assumed upper bound of the population size. Assuming for $N_N$ a value of $10^{10}$, the collective dose commitment per unit activity released is $430$ man rad per Ci.

The combined $^{14}\text{C}$ release from LWRs and reprocessing plants (assumed to be 0.02 Ci per MW(e)y) will therefore cause a collective dose commitment of about 9 man rad per MW(e)y. As discussed in section 2, it would not be realistic to use this collective dose commitments to assess the maximum per caput annual dose in the future, because it can not be assumed that the practice will continue for such a long time as required to approach steady state conditions. The incomplete commitment is the relevant quantity for this purpose. Assuming that power production by nuclear fission will last for a few hundred years (for example 500 years), the incomplete whole body collective dose commitment is estimated to be 2 man rad per MW(e)y.

4.3 Local and regional contributions to the collective dose commitment

The local and regional contributions to the collective dose commitment must be discussed separately for each component of the fuel cycle. Furthermore, the contributions depend strongly on local conditions such as population distribution, meteorology, hydrology, and food production and distribution. Therefore only representative examples can be mentioned in this paper. As in previous sections, only whole body doses are discussed.
The assessment of collective dose commitments from uranium mining and milling, and from fuel fabrication presents special problems because some very long lived nuclides are involved. The most important example is uranium-238 ($4.5 \times 10^9$ y). The exposure period of many million years makes the calculated collective dose commitments extremely uncertain. Uranium from the mining and milling industries and the related production of radon can be estimated to cause collective dose commitments of the order of 100 man rad per MW(e)y; uranium from the fuel fabrication industry may contribute about three times as much. However, the exposure periods are so long that even the meaning of these commitments is unclear. In fact, to accumulate a collective dose of only 0.1 man rad per MW(e)y from this nuclide a period of the order of $10^6$ years would be required. The incomplete collective dose commitments from these steps of the nuclear fuel cycle are negligible.

The local and regional collective dose commitment to the whole body from the operation of power reactors are due mainly to fission noble gases, activation gases and tritium discharged into the atmosphere, and to a variety of radionuclides discharged in liquid effluents, mainly tritium and radioisotopes of cesium and cobalt. A very extensive literature exists on this subject and only a few illustrative references are mentioned (34) (35) (36) (37) (38) (39) (40) (41).

Typical local and regional contributions from reactors to the collective dose commitment range from $10^{-2}$ (PWR) to 0.5 man rad per MW(e)y (BWR) for the atmospheric pathway. Taking into account the installed capacity of the various reactor types, an average value of 0.2 man rad per MW(e)y is obtained. For the aquatic pathway the collective dose commitment is of the order of $6 \times 10^{-3}$ man rad per MW(e)y.

The contribution of reprocessing plants to the collective dose commitment is almost entirely due to nuclides of world-wide distribution (42). Local and regional contributions to the collective dose commitment (34) (43) (44) (45) are small. The aquatic pathways are dominant, contributing of the order of $2 \times 10^{-2}$ man rad per MW(e)y, while atmospheric discharges contribute about one order of magnitude less.

Public exposure during transportation between installations of the fuel cycle (17) seems to be a small contributor to the collective dose commitment, of the order of $10^{-3}$ man rad per MW(e)y.

5. CONCLUSIONS

It is estimated that the collective dose commitments from nuclear power production are 3 to 4 man rad per MW(e)y, contributed by occupational exposures, and 2 to 3 man rad per MW(e)y (incomplete commitment), from exposure of the public.

The estimated collective dose commitment for the whole industry per MW(e)y generated is equivalent to about 0.6 seconds of exposure of the world population to the natural radiation background. One year of operation at the 1976 nuclear 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 13 days. However, this forecast into the future is quite uncertain, because it depends on the evolution of both technology and regulations, which may vary substantially and can not be readily predicted.

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