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ABSTRACT

Release of small quantities of radioactive materials to the environment occurs at each stage of the nuclear fuel cycle. The paper reviews, on the bases of the assessments carried out by UNSCEAR, the releases and resulting collective dose contributions of mining, milling, fuel fabrication, reactor operation, reprocessing and waste management, normalized per gigawatt-year of electric energy generated. The collective dose from all stages of the cycle, delivered in few years after the releases is estimated to be about 6 man·Sv/$GW_{(e)}$·a. The long-term components of the collective dose from all stages are estimated to amount to 15, 25 and 300 man·Sv/$GW_{(e)}$·a for periods extending to 100, 500 and 10 000 years, respectively. According to these assumptions the complete normalized collective dose is about 3000 man·Sv/$GW_{(e)}$·a, distributed over millions of years. However, this extremely long-term assessment is qualified by the corresponding very large uncertainties. Its only merit is to provide perspective to the problem; the estimated complete collective dose, with the risk factors currently used, suggests that only a few tens of severe health effects will result from each gigawatt-year of electricity currently generated.

1. INTRODUCTION

Use of nuclear reactors for the production of electric power is now an established technology. By the end of 1981 the installed nuclear generating capacity was 144.4 $GW_{(e)}$ from 261 reactors; further 209.8 $GW_{(e)}$ is expected from 227 reactors under construction. Projections of the nuclear generating capacity in the year 2000 are somewhat speculative but at present are less ambitious than previously, the figure quoted by UNSCEAR (1) being about 1300 $GW_{(e)}$. This figure is a little over half of the previous estimate used by UNSCEAR (2) and lies in the middle of the range predicted by INFCE (3).

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 ^{35}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, 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 to assess the radiological impact of nuclear power in terms of collective dose commitments per unit energy generated, e.g. per $GW_{(e)} \cdot a$. In this way assessments can be normalized irrespective of the size of the expanding nuclear industry.

The purpose of this paper is to summarize the review and assessments related to the nuclear fuel cycle presented by UNSCEAR in its 1982 report (1). UNSCEAR, the United Nations Scientific Committee on the Effects of Atomic Radiation, in its reports to the General Assembly reviews the available information on human exposures to sources of ionizing radiation and on the effects of this radiation on man. Since 1972 these reports have included assessments of the exposures resulting from nuclear power production (1)(2)(4).

2. QUANTITIES USED IN THE ASSESSMENTS

In the 1982 UNSCEAR report, the evaluations of exposures from nuclear power production are presented in terms of collective effective dose equivalent commitments. The use of the effective dose equivalent quantity, introduced by the ICRP (5), allows the combination of the doses to several organs into a single figure related to radiation risk, regardless of whether the whole body is uniformly irradiated or if there is non-uniform or partial body irradiation. The effective dose equivalent, H_E, is defined as

$$H_E = \sum_T w_T H_T$$

where w_T is a weighting factor given by ICRP, representing the fraction of risk resulting from tissue T when the whole body is irradiated uniformly, and H_T is the dose equivalent in tissue T.

Some additional quantities are necessary for evaluations regarding the exposure of populations. Exposure of a population in many cases is delivered at a varying rate over a period of time. In these cases it is convenient to define a quantity wich represents the distribution of dose rate over the population, being equal to the product of the number of exposed individuals and the average dose rate. The collective effective dose equivalent rate, $\dot{S}(t)$, is defined as:

$$\dot{S}(t) = \int_0^\infty \dot{H}_E(t)\ N(\dot{H}_E,t)\ d\dot{H}_E$$

where $N(\dot{H}_E,t)$ is the population spectrum in effective dose equivalent rate at time t, $N(\dot{H}_E,t)\ d\dot{H}_E$ is the number of individuals receiving at time t an effective dose equivalent rate in the range $\dot{H}_E(t)$ to $\dot{H}_E(t) + d\dot{H}_E$.

The total collective dose equivalent rate from a source k, $\dot{S}_k$, is obtained by including in the population under consideration all individuals receiving a dose from the source k.

In some cases a population is committed to receiving radiation exposures by the introduction of a practice, the adoption of a decision or some finite origi-

nating event such as the generation of one $GW_{(e)}$·a. Exposure of the population could be delivered over a considerable time after the originating event. To have a measure of the total radiation impact on the population from the event, the collective effective dose equivalent commitment is used. The collective effective dose equivalent commitment S_k^c, due to a given event k is defined as the infinite time-integral of the collective effective dose equivalent rate, $S_k(t)$, caused by that event

$$S_k^c = \int_0^\infty S_k(t)\, dt$$

In this paper the term collective dose commitment, unless specifically qualified, is taken to mean the collective effective dose equivalent commitment. Similarly, the terms normalized collective dose commitment is used for the quantity collective effective dose equivalent commitment per unit electric energy generated.

3. BASES OF THE ASSESSMENTS

Because environmental releases from nuclear installations are subject to control, doses to individual members of the public are usually kept well below the recommended limits. There are three groups of people exposed to these releases: the local population residing within a few hundred kilometres of the plants, the regional population within a few thousand kilometres, and finally, the world population.

Since the concentrations of the effluents from nuclear installations are low at the point of release and extremely low in the surrounding environment, models must be used to estimate the doses to populations over long distances from the plants and over long periods of time. The values of the transfer parameters of the various radionuclides in these models are derived from environmental monitoring results and from experiments of various types. The most important input in these models is the amount and type of radioactive materials released from the various nuclear installations.

UNSCEAR has reviewed reported operational and discharge data for different installations of the fuel cycle and has estimated average values of releases for $GW_{(e)}$·a generated. Discharges into the atmosphere and into the aquatic environment have been considered separately. Obviously, these normalized releases do not apply to any one plant, but are deemed to be representative of the current technology for nuclear power generation. Model installations, characterized by such normalized releases, are postulated for the radiation impact assessments.

The environment receiving the typical release from each model facility was chosen to represent broad averages containing typical features of existing sites and reflecting the most common environmental pathways. Such generalizations are intended to give average exposures reflecting the overall impact of the nuclear power programme. They are not applicable to any one given site without due consideration of its own specific environmental pathways and of the particular radioactive release.

Using the stylized source terms and transfer models mentioned above, the local and regional exposures due to atmospheric and liquid releases have been calculated for each stage of the nuclear fuel cycle. On the other hand, the glo-

bal exposures due to the nuclides that are distribute worldwide have been calculated for the fuel cycle as a whole.

In the estimation of exposures due to long-lived nuclides, it has been assumed that the size of the world population will attain a steady-state value and that no major changes in age structure will occur. It has further been assumed that the dietary and other relevant habits in the population remain relatively constant. This is a reasonable assumption for short times, but is qualified by increasing uncertainties as longer times are considered.

4. EVALUATION RELATING TO THE FRONT PART OF THE FUEL CYCLE

The front part of the fuel cycle provides the fuel elements to the power reactors. It includes the mining and milling of uranium ores, conversion to nuclear fuel material, which usually includes enrichment of the isotopic content of ^{235}U, and fabrication of fuel elements.

Uranium mining operations involve the removal from underground of large quantities of ore containing uranium and its daughter products at concentrations up to several thousand times the concentrations of these nuclides in the natural terrestrial environment. The concentration of uranium in mined ores is between 0.1 and about 3% U_3O_8. World uranium production was about 40 000 t in 1979. The mining is carried out either by underground or open pit methods.

Gaseous radioactive effluents from operating uranium mines are almost entirely composed of ^{222}Rn. UNSCEAR has estimated that the radon emission normalized for uranium content is of the order of 1 GBq/t of ore and percent of uranium, both for underground and open pit mines. Since about 200 t of uranium needs to be extracted for the production of 1 $GW_{(e)}\cdot a$ of electrical energy (assuming no recycling), the normalized radon release is estimated to be about 2×10^3 $GBq/GW_{(e)}\cdot a$. Liquid effluents are considered to be substantially less important from the radiological point of view.

To assess the normalized collective dose commitment from radon released from mines, meteorological dispersion characteristics of semi-arid areas have been used in the atmospheric dispersion model adopted by UNSCEAR. The equilibrium factor for the short-lived radon daughters has been taken as 0.6 and it has been assumed that the indoor air concentrations are the same as outdoors. A population density of 3/km within 100 km of the mine and 25/km from this distance to 2000 km has also been assumed. The total normalized collective dose commitment from mining and milling is about 0.50 $man\cdot Sv/(GW_{(e)}\cdot a)$.

Operation of uranium mills results in the accumulation of large quantities of waste tailings containing significant quantities of uranium daughter nuclides. Uranium tailings are discharged from the mill, usually in slurry form at about 50% solids, to an impoundment area. The model mill used by UNSCEAR processes 600 000 t/a of 0.2% grade ore.

During mill operations radon and particulates are released. According to the assessments of UNSCEAR, the normalized collective dose commitment due to these releases is small (about 0.02 $man\cdot Sv/GW_{(e)}\cdot a$ for each).

The tailings remain after the mill has ceased operation and become a long-term source of radioactive contamination due to wind and water erosion, leaching and radon emanation. The dominant release is radon, the normalized annual

release being about 10^3 GBq/a per $GW_{(e)}$·a. Stabilization programmes are conducted or planned to alleviate erosion. Although only a few per cent of the original uranium isotopes remain in the tailings, the major source of long-lived activity for about 5 x 10^5 years is ^{230}Th ($T_{1/2}$ = 8 x 10^4 years), which continues to produce ^{226}Ra and corresponding radon releases. The diffusion of radon in the top few metres of tailings is responsible for most of the release and the release rate is independent of the depth of the tailings beyond about 3 m. The reduction in radon emanation by soil covering depends on the type and depth of cover.

The presence of ^{230}Th in the tailings provides a long-term source for radon emission. If the release rate were to continue for 10^4 years or throughout the mean lifetime of 1.1 x 10^5 years, then the emanation rate given above for ^{222}Rn would give normalized collective effective dose equivalent commitments of about 250 or 2800 man·Sv/$GW_{(e)}$·a, respectively. The corresponding particulate releases over 10^5 years are estimated to give an additional 50 man·Sv/$GW_{(e)}$·a. A small amount of ^{230}Th would still remain supported by the residual uranium in the tailings. These results must be considered highly speculative because of the assumptions of the duration of the constant release and of the fixed population density. This is particularly the case for the complete commitment value of 2800 man·Sv/$GW_{(e)}$·a.

In the INFCE studies the dose commitment from tailings was estimated on the assumption that the radon emanation continued for 10^3 years, by which time the tailings are assumed to have been eroded and lead to a further dose commitment from the aquatic environment (fresh water and marine). With UNSCEAR models, the normalized radon collective effective dose equivalent commitment for 10^3 years release is about 25 man·Sv/$GW_{(e)}$·a, and the aquatic contribution is 460 man·Sv/$GW_{(e)}$·a. These values compare well with the INFCE estimates of 10 and 360 man·Sv/$GW_{(e)}$·a, respectively.

In the 1977 Report (2) UNSCEAR used an assessment model based on comparison with natural radon emanation from soil. With this method, the model mine and mill used in the 1982 Report would correspond to a normalized collective dose commitment from tailings of about 760 man·Sv/$GW_{(e)}$·a.

It should be realized that these assessments cover doses at present and in the far future from technical solutions used at present and in the near future. If the tailings are immobilized by use of polyvinylchloride or asphalt coverings, the radon emanation rate can be reduced substantially. It must also be recognized that any decision to use extensively fast-breeder reactors, by more efficient utilization of uranium resources, could reduce the normalized collective dose equivalent commitment from tailings by two orders of magnitude.

Emissions of radionuclides from conversion, enrichment and fuel fabrication processess are small. They consist essentially of uranium isotopes (^{238}U and ^{234}U) and residual amounts of ^{230}Th and ^{226}Ra which are removed from the uranium ore concentrate in the conversion process. Most of the uranium compounds are solid and conventional equipment may be used to remove particulates from airborne effluents. Liquid wastes are collected in settling tanks or ponds. It should also be mentioned that after the enrichment process substantial quantities of depleted uranium remain in which the ^{235}U content is 0.3% or more. At present they are stored for possible use in breeder reactors and for other purposes.

Assessments of the normalized collective dose commitments carried out by UNSCEAR for these stages of conversion, enrichment and fuel fabrication are

based on the following assumptions: the location of the model installation has been chosen to be representative and the population distribution around the model facility has been assumed to be constant at 25 km^{-2}. The collective doses for the releases have been derived using the same models described for mining and milling. The particulate releases have been assessed for inhalation from the plume, ingestion of foodstuffs contaminated by activity deposited from the plume and by external irradiation from the ground deposited activity. For the radon releases, the distribution of weather categories has been assumed to be typical of a moderate climate.

The normalized collective dose commitment due to atmospheric discharges from conversion, enrichment and fabrication of fuel is estimated to be 2×10^{-3} man·Sv/$GW_{(e)}$·a. The main contribution is inhalation of uranium isotopes. The collective absorbed dose commitments from ingestion of foodstuffs are estimated to be a factor of about 10 below those due to inhalation. These collective dose commitments are estimated on the assumption that the radionuclides deposited onto the ground migrate downwards fairly rapidly and thus become unavailable. In fact, owing to the long half-lives of the nuclides of the uranium decay chain, they may in the far future return to man by various pathways, although the corresponding collective dose commitments are probably small.

5. EVALUATIONS RELATING TO REACTOR OPERATION

Most of the electrical energy currently generated by nuclear power is produced by thermal reactors. The main reactor types include the pressurized light-water moderated and cooled reactor (PWR), the boiling light-water-cooled and moderated reactor (BWR), the Magnox and advanced gas-cooled, graphite-moderated reactor (GCR), the light-water-cooled, graphite-moderated reactor (LWGR), and the heavy-water-moderated and cooled reactor (HWR). To these reactor types, the current modest contribution of the fast-breeder reactors (FBR) must be added.

The quantities of different types of radioactive materials released from reactors depend on the particular design and on the specific waste treatment plant installed. Radionuclides released to the atmospheric environment include noble gases from fission (krypton and xenon), activation gases (^{14}C, ^{16}N, ^{35}S, and ^{41}Ar), tritium, iodine and particulates. Radionuclides discharged to the aquatic environment in liquid effluents include tritium, fission products and activated corrosion products. Results are presented in Table 1 for normalized release, i.e. per unit of electrical energy generated, averaged over all reactors of a given type (PWR, BWR, etc.). The total release of radionuclides between 1975 and 1979 have been divided by the total production of electrical energy over the same years in order to obtain representative nominalized releases.

The local and regional collective effective dose equivalent commitments resulting from the normalized discharges of radionuclides presented in the previous paragraphs have been calculated by UNSCEAR for a model reactor site and using environmental models mainly based on those described in a study for the Commission of the European Communities (6) and dosimetric models of ICRP (7). The model site is most representative of the areas of Europe and the north-eastern United States of America, as those areas contain most of the power producing reactors. Agricultural production patterns and population distributions are most typical of these areas. For atmospheric effluents, an effective release height of 30 m has been chosen and doses are calculated up to a distance of 2000 km. For aquatic effluents a river and a typical marine environment have been defined.

Using these assumptions and models, UNSCEAR has estimated the values of local and regional normalized collective dose commitments due to reactor operation summarized in Table II.

With present reactor type distribution, the local and regional normalized collective dose commitment is about 4 man·Sv/$GW_{(e)}$·a. It should be noted that ^{14}C is a dominant contribution, being particularly important in the case of HWR.

6. EVALUATIONS RELATING TO FUEL REPROCESSING

At the fuel reprocessing stage of the nuclear fuel cycle, the elements uranium and plutonium in the irradiated nuclear fuel are recovered for use again in fission reactors. The spent fuel elements are stored under water (which serves both for radiation shielding and for cooling) while awaiting reprocessing. Fuel elements are usually left until all the short-lived isotope ^{131}I has decayed to insignificant amounts (usually at least 120 days).

The only reprocessing plants operating commercially in the world are at Windscale (United Kingdom), and at La Hague and Marcoule (France). In addition, there are several small reprocessing facilities. The assessment performed by UNSCEAR considered both the commercial reprocessing plants and a model facility established for representative calculations of collective and individual dose assessment.

The radionuclides of principal interest in reprocessing plant effluents are primarily the long-lived nuclides, ^{3}H, ^{14}C, ^{85}Kr, ^{90}Sr, ^{106}Ru, ^{129}I and ^{134}Cs, and isotopes of transuranic elements. In Tables III and IV the annual discharges for Windscale, La Hague and Marcoule are presented for atmospheric and liquid effluent discharges, respectively. The amount of activity in effluents depends not only upon the specific waste treatment and processing system of the reprocessing plant, but also on the type of fuel reprocessed, its irradiation history and storage time. The tables also include the model plant used by UNSCEAR for its evaluations.

The model plant does not consider retention of ^{3}H, ^{14}C, ^{85}Kr and ^{129}I. Releases of other nuclides are in the lower range of assessments for present and projected installations.

Evaluation of the local and regional collective dose commitments from reprocessing nuclear fuel requires a study both of the local and regional effects and of the global consequences of the releases. Estimates of the local and regional contribution to collective dose commitments have been carried out using the same environmental models as for the reactor releases. The adopted characteristics for the various sites are those of the existing sites; the model plant has been assumed to be located at Windscale.

The results show that at present the local and regional collective dose commitment from atmospheric releases is negligible (2%) compared with the contribution from liquid releases. For the model plant assumed by UNSCEAR for its assessments the local and regional normalized collective dose commitment is about 1 man·Sv/$GW_{(e)}$·a, 70% of which is contributed by liquid discharges.

7. EVALUATIONS RELATING TO GLOBAL EXPOSURES FROM RADIONUCLIDES OF WORLDWIDE DISTRIBUTION

Global contribution of the collective dose commitment made by radionuclides of worldwide 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 worldwide distribution ^{3}H, ^{14}C, ^{85}Kr and ^{129}I are of particular interest. Other long-lived nuclides such as ^{137}Cs are less mobile in the environment and become far less dispersed after deposition onto soil or sediments after realease into the local region. They have not been considered to give rise to global dose commitments.

Tritium is produced in nuclear reactors by ternary fision 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 700 $TBq/GW_{(e)}\cdot a$. 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% in the case of BWRs and GCRs, 20% in the case of PWRs and, on average, 130% in the case of HWRs (2).

The global model used by UNSCEAR for tritium assumes that discharged tritium, whether to the atmosphere or hydrosphere, is immediately dispersed and exchanged with the hydrogen content of the circulating waters of the hemisphere into which the discharge takes place. The subsequent circulation of tritium is determined by the exchange of waters between the two hemispheres and the deep oceans. The normalized collective dose equivalent commitment thus obtained is 0.02 $man\cdot Sv/GW_{(e)}\cdot a$, which is small in comparison with the local and regional component.

Carbon-14 is produced in LWRs and HWRs by (n,α) reaction with ^{17}O, presented in the oxide fuel and the moderator, by (n, p) reactions with ^{14}N present in the fuel as impurities, and by ternary fission. A direct calculation, assuming that the average thermal neutron flux density is the same in the fuel and moderator (2), indicates the ^{14}C production to be about 0.7 $TBq/GW_{(e)}\cdot a$ in LWRs. The amount released at the reactor is the amount produced in the moderator, which will vary depending on the moderator size. The ^{14}C produced in the fuel will presumably be released, at least partially, at the reprocessing plant. Similar calculations for HWRs estimate the ^{14}C production to be about 14 $TBq/GW_{(e)}\cdot a$, 90% being produced in the moderator and therefore presumably being released at the reactor.

The model chosen by UNSCEAR in its 1982 Report to assess collective doses from ^{14}C is an eight-compartment model allowing for two hemispheres comprising humus, circulating carbon, surface ocean and deep ocean. The normalized collective dose commitment averaged over electricity production by each reactor type is estimated to be 110 $man\cdot Sv/GW_{(e)}\cdot a$.

Kripton-85 is released from the fuel at the dissolution stage of reprocessing. Production of ^{85}Kr for a typical reactor fuel is 14 $PBq/GW_{(e)}\cdot a$ for GCRs and 11.5 $PBq/GW(e)\cdot a$ for LWRs.

Since krypton is an inert gas it disperses through the atmosphere and achieves a uniform concentration. UNSCEAR used a two-compartment model in which the released krypton is assumed to be instantaneously dispersed throughout the

troposphere of the hemisphere of the release. Exchanges take place between the troposphere of the two hemispheres with a half-time of about two years. Within a few years the ^{85}Kr becomes uniformly dispersed and the sole removal mechanism is radioactive decay. The normalized collective dose commitment is found to be 1.9 man·Sv/$GW_{(e)}$·a. All of this commitment is delivered within the first 50 years after release.

Production of ^{129}I depends on burnup and is assessed to be between 37 and 74 kBq/$GW_{(e)}$·a. To estimate the collective dose commitment, UNSCEAR has utilized a multi-compartment model taking into account the transfer between surface waters and the deep ocean. The resulting normalized global collective dose commitment for ^{129}I releases is 560 man·Sv/$GW_{(e)}$·a from reprocessing plant discharges, reactor releases being insignificant by comparison. Doses will be delivered gradually over very long periods of time. It should be recognized that the commitments referring to doses to be delivered over tens of millions of years are rather speculative and, in any case, are qualified by very large uncertainties.

It is of interest to describe the time evolution of the collective dose after a given committing release. For the four nuclides contributing to the global component of the collective dose commitment, the time evolution of the collective dose is summarized in Table V.

8. EVALUATIONS RELATING TO WASTE STORAGE AND DISPOSAL

The bulk of the radioactivity associated with the production of energy by nuclear fission is contained in the spent fuel and is considered waste except for nuclides of uranium and plutonium in the strategies involving reprocessing. This waste must be subjected to suitable treatment, some retrievable storage and eventual disposal in which control over the waste is relinquished. Disposal is necessarily involved due to the very long half-live of some of the relevant nuclides, much longer than any conceivable administrative control that could be established by the present society. Storage and disposal problems still exist even if the spent fuel is not reprocessed, the wastes being in this case merely in a different form. In addition to these wastes, reactor operations and other steps of the fuel cycle generate other wastes, including discarded components, which represent a problem because of their volume but which have a radioactivity of small relative importance compared with that of the spent fuel or of the high level wastes from fuel reprocessing.

UNSCEAR has not assessed the collective dose commitments arising from the storage and disposal of low- and intermediate-level wastes, with the exception of the important contribution of mill tailings. It is likely that the contribution of other low- and intermediate-level wastes to the collective dose commitment is negligible.

The majority of irradiated nuclear fuel that has been removed from reactors is currently stored, awaiting national decisions on whether to dispose of the fuel directly or to reprocess and recycle fissile nuclides. When reprocessing takes place high-level wastes are currently stored as liquids. The intent is to solidify them in some manner to facilitate further handling, storage and eventual disposal. Disposal of high-level radioactive wastes from nuclear power production has not yet taken place; there has only been storage under surveillance by national authorities, awaiting a final decision. Therefore, UNSCEAR had to make its estimate of the potential collective dose commitments from high-level waste disposal on the basis of theoretical studies.

The evaluation presented by UNSCEAR has been based on the INFCE analysis of waste disposal (3). The collective dose commitments due to waste disposal depend on whether unreprocesssed fuel or high-level reprocessing wastes are considered and from which fuel cycle they arose. The major components of the doses would not be received until after 10^5 or 10^6 years, so they will be subject to considerable uncertainty and the absolute numerical values should be used with caution. Assuming LWR fuel is reprocessed then, whether the plutonium is recycled through LWRs or in FBRs, the normalized collective effective dose equivalent commitment is between 20 and 50 man·Sv/$GW_{(e)}$·a.

9. CONCLUSIONS

The local and regional collective dose commitment contribution from fuel cycle operations is estimated to be about 5.5 man·Sv/$GW_{(e)}$·a; of this 0.5 is due to mining, milling and fuel fabrication, 4 to the reactor operation and 1 to fuel reprocessing. Most of this commitment is delivered in the year after discharge and the remainder over the next few years.

The global component of the collective dose commitment due to nuclides of worldwide distribution is estimated to be about 670 man·Sv/$GW_{(e)}$·a, contributed mainly by ^{14}C in the tens of thousands of years (110 man·Sv/$GW_{(e)}$·a) and ^{129}I in the tens of millions of years (560 man·Sv/$GW_{(e)}$·a). For all these future estimates the figures are uncertain.

The estimates presented by UNSCEAR for the contribution of mill tailings vary between 250 and 2800 man·Sv/$Gw_{(e)}$·a. Even the lower figure would make this contribution quite dominant. However, large uncertainties are involved. Climatic changes could affect the exposures substantially, and present estimates may not apply to future uranium industry. Different tailings management practices could reduce the collective doses committed in the near future, and the introduction of fast-breeder reactors may reduce uranium ore requirements by two orders of magnitude, which would affect the dose commitment from tailings by the same factor. In spite of all these qualifications, it is quite apparent that the contribution of mill tailings to the collective dose commitment is substancial.

Regarding the time of delivery of the collective doses from all stages of the fuel cycle, it can be estimated that the short-term component, delivered in the few years after the releases, is about 6 man·Sv/$GW_{(e)}$·a. The long-term components of the collective dose from all stages are estimated to amount to 15, 25 and 300 man·Sv/$GW_{(e)}$·a for periods extending to 100, 500 and 10 000 years, respectively.

Using the most pessimistic assessment for mill tailings contributions, the complete normalized collective dose commitment for the entire fuel cycle is about 3000 man·Sv/$GW_{(e)}$·a, delivered over many millions of years.

However, this extremely long-term assessment is qualified by the corresponding very large uncertainty. Its only merit is to provide perspective to the problem: the estimated complete collective dose, with the risk factor per unit dose currently used (1)(5), imply that only a few tens of severe health effects will result from each gigawatt-year of electricity generated at present.

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TABLE I. EMISSIONS FROM REACTORS ($TBq/GW_{(e)}\cdot a$)

	Normalized discharges			
	PWR	BWR	HWR	GCR
Airborne discharges				
Noble gases	430	8800	460	3200
^{3}H	7.8	3.4	540	11
^{14}C	0.2	0.5	17	1.1
Iodines	0.005	0.4	0.003	-
Particulates	0.002	0.5	0.00004	0.001
Liquid discharges				
^{3}H	40	1.4	350	25
Other radionuclides	0.2	0.3	0.5	5

TABLE II. LOCAL AND REGIONAL COLLECTIVE DOSES FROM REACTORS

($man\cdot Sv/GW_{(e)}\cdot a$)

	Reactor Type				Weighted Average
	PWR	BWR	GCR	HWR	
Airborne discharges					
Noble gases	0.04	1.9	1.0	-	0.7
^{3}H	0.08	0.04	0.1	5.6	0.5
^{14}C	0.39	0.92	2.2	30	2.8
Iodine	0.0007	0.02	-	-	0.006
Particulates	0.01	0.29	-	-	0.1
Aquatic discharges					
^{3}H	0.03	0.001	-	0.28	0.04
Other radionuclides					
River	0.001	0.003	-	-	0.001
Sea	0.006	0.04	0.18	-	0.03

TABLE III. ATMOSPHERIC DISCHARGES FROM FUEL REPROCESSING
($TBq/GW_{(e)} \cdot a$)

	ATMOSPHERIC DISCHARGES					
	^{3}H	^{14}C	^{85}Kr	^{129}I	Total α	Total β (^{3}H excluded)
Windscale	130	1.8	14000	0.002	0.0006	0.09
La Hague	3	-	14000	-	2×10^{-7}	0.0002
Marcoule	46	-	14000	-	4×10^{-6}	0.002
Model Plant	60	0.4	11000	0.0002	$\sim 10^{-5}$	$\sim$ 0.001

TABLE IV. LIQUID DISCHARGES FROM FUEL REPROCESSING
($TBq/GW_{(e)} \cdot a$)

	LIQUID DISCHARGES					
	^{3}H	^{90}Sr	^{106}Ru	^{129}I	Total α	Total β (^{3}H excluded)
Windscale	450	170	280	0.04	25	2700
La Hague	270	50	430	-	0.3	590
Marcoule	340	2	65	-	0.03	80
Model Plant		2	10	0.04	$\sim$ 0.5	$\sim$ 20

TABLE V. TIME EVOLUTION OF COLLECTIVE DOSE FROM GLOBAL CONTRIBUTORS
($man \cdot Sv/GW_{(e)} \cdot a$)

Radionuclide	INTEGRATION TIME (years)				
	10	10^{2}	10^{4}	10^{6}	10^{8}
^{3}H	0.015	0.02	0.02	0.02	0.02
^{14}C	3	10	70	110	110
^{85}Kr	0.9	1.9	1.9	1.9	1.9
^{129}I	-	0.02	0.2	28	560

REP01 - Beninson, D.; Migliori de Beninson, A.
"Radiological impact of radioactive waste management"

REP02 - Lucero Michaut, H.
"Aplicación de la geoestadística a la resolución de problemas estructurales en macizos rocosos homogéneos"

REP03 - Ventura, M.; Ferreri, J.C.
"Evolución temporal de un macizo granítico bajo cargas térmicas generadas por productos de fisión"

REP04 - Ventura, M.; Ferreri, J.C.
"Evolución temporal de un macizo granítico bajo cargas térmicas generadas por productos de fisión (estudio paramétrico)"

REP05 - Beninson, D.
"Radioactive emissions and radiation exposures resulting from nuclear power production"

REP06 - Beninson, D.; Lindell, B.
"Application of ICRP recommendations to radioactive waste isolation"

REP07 - Migliori de Beninson, A.; Cancio, D.
"Impacto radiológico de la gestión de residuos radiactivos del Programa Nuclear Argentino"

REP08 - Migliori de Beninson, A.; Palacios, E.
"Política en materia de gestión de desechos y su aplicación en Argentina"

REP09 - Palacios, E. y otros.
"Bases conceptuales para la construcción de un repositorio en la Argentina"

REP010- Palacios, E. y otros.
"Estudios para la selección del emplazamiento de un repositorio en Argentina"

REP011- Matar, J.A.; Girardi, J.P.; Sarquis, M.A. M. de
"Aplicación de técnicas geoestadísticas al estudio de una formación granítica destinada a la construcción de un repositorio"

REP012- Ferreri, J.C.; VENTURA, M.
"Numerical aspects of the study of the regional thermal impact of a radioactive waste repository"

REP013- Ferreri, J.C.; Caballero, C.H.
"Difusión de calor a partir de una fuente plana rectangular finita"

REP014- Beninson, D.; González, A.J.
"Radiological protection criteria for radioactive waste repositories"

REP015- Palacios, E.; Ferreri, J.C.
"Marco conceptual para el desarrollo de los modelos de predicción de los efectos locales de un repositorio de residuos radiactivos de alta actividad"

REP016- Ferreri, J.C.; Ventura, M.
"Aspectos numéricos del modelado de los efectos locales de un repositorio de residuos radiactivos de alta actividad"

REP017- Beninson, D.
"Criterios de radioprotección en el caso de eventos disruptivos probabilísticos"

REP018- Ferreri, J.C.; Grandi, G.
"Models for the study of the local effects produced by a high-level radioactive waste repository"

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Gerencia Protección Radiológica y Seguridad

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