IONIZING RADIATION: SOURCES AND BIOLOGICAL EFFECTS

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on the Effects of Atomic Radiation

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NOTE

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ANNEX F

Exposures resulting from nuclear power production

CONTENTS

Introduction

1. The use of nuclear reactors to generate electric power has increased since the Committee's previous assessment of the releases of radioactive materials from the nuclear fuel cycle and their resulting dose commitments in Annex D of the 1977 report [U1]. The total installed nuclear generating capacity in the world in 1979 was about 120 GW(e) from some 235 power reactors operating in 22 countries [I1, K12]. This represents an approximate doubling of nuclear generation during the years 1975 to 1979 covered by this Annex. In 1981 the installed electric generating capacity was 144.4 GW(e) from 261 reactors with 209.8 GW(e) (227 reactors) under construction [I12]. Projections of the world nuclear generating capacity in the year 2000 are somewhat speculative, but the figure seems likely to be about 1300 GW(e), or a little over half of the estimate reported by the Committee in Annex D of the 1977 report [U1]. This expectation is based on revised estimates of about 400 GW(e) nuclear generating plant in North America by the year 2000 [I9], towards 350 GW(e) for the Soviet Union and Eastern Europe [U2, I9], and the remainder being made up of perhaps 300 GW(e) in Western Europe [W1, I9], 100 GW(e) for Japan [M8] and 150 GW(e) in developing countries. In the International Nuclear Fuel Cycle Evaluation (INFCE) [I9] a range of 1030–1650 GW(e) was predicted for world installed nuclear capacity in the year 2000.

2. The nuclear fuel cycle includes the mining and milling of uranium ores, conversion to nuclear fuel material, which usually includes enrichment of the isotopic content of ^{235}U, fabrication of fuel elements, production of power in the nuclear reactor, reprocessing of irradiated fuel and recycling of fissile and fertile nuclides recovered, and disposal of radioactive wastes. In addition, nuclear fuel materials are transported between installations at various stages in the cycle. In recent years several reports by the United Nations Environment Programme have assessed the environmental impact of the nuclear fuel cycle [E7, U5] and in the INFCE studies radiation risks were also considered [I9].

3. Almost all of the artificial radionuclides associated with the nuclear fuel cycle are present in the irradiated nuclear fuel, although some neutron activation of structural and cladding materials takes place, and the naturally-occurring radionuclides are present at the uranium mining and milling stage. The majority of irradiated fuel elements are currently stored. However, where reprocessing takes place, the radioactive fission products and transuranium elements are stored as highly active liquors in tanks isolated from the environment. At each step of the fuel cycle releases of small quantities of radioactive material to the environment may occur. Most of the radionuclides released to the environment are only of local or regional concern because of their short radioactive half-lives or limited environmental mobility. Some radionuclides, because of a combination of long radioactive half-lives and rapid dispersal in the environment, become globally distributed.

4. The interest of the Committee is in assessing the overall health detriment and the doses to individual members of the public due to the releases of radioactive materials at each stage of the nuclear fuel cycle. Because of the system of control applied to environmental releases from nuclear power installations, doses to individual members of the public are generally well below the relevant dose limits and correspond to low levels of individual risk. Individual dose levels decrease rapidly with distance from a given source and the doses to most exposed individuals vary widely from installation to installation and between one location and another. In this Annex an indication of the range of doses to the most exposed individuals at each stage of the nuclear fuel cycle is given. To evaluate the total impact of nuclides released at each stage of the fuel cycle, calculated results are first presented in terms of collective absorbed dose commitments to various body organs or tissues, normalized to the production of unit quantity of electric energy generation, expressed as man Gy per GW(e) a. Annex A describes the way in which the absorbed doses may be combined to give the quantity "collective effective dose equivalent" which is assumed to be proportional to health detriment. Values of collective effective dose equivalent commitment per unit of electrical energy actually generated are thus calculated for each stage of the nuclear fuel cycle.

5. The collective dose commitment from nuclear power arises in four population groups: the occupationally exposed, the population within a few hundred km from the site, the population within a few thousand km from the site, and the total world population. This Annex deals only with exposure of the public, as occupational contributions are dealt with in Annex H. Each stage of the nuclear fuel cycle is considered separately and the local and regional dose commitments are given for atmospheric and aquatic discharges. The global contributions from those nuclides which irradiate the world population are then discussed for the fuel cycle as a whole. Finally, the disposal of solid wastes from the nuclear fuel cycle is reviewed.

6. Collective dose commitments to local and regional populations must be estimated by environmental modelling, as the activity concentrations from effluents from the nuclear fuel cycle are very low, both in the general population and in environmental materials. Monitoring of activity concentrations due to effluent releases has concentrated on areas surrounding nuclear facilities to ensure compliance with applicable regulations. In recent years computer models have been developed which enable estimates to be made of doses to large populations over long periods of time [C10, E1, M1]. The values of parameters for the transfer of radionuclides in these models are taken from environmental monitoring results or from experimental observations.

7. The source terms for the releases of radioactive effluents from nuclear installations are usually readily available to the Committee and reflect the operating histories, including abnormal periods of operation. The Committee has reviewed reported discharge data and has produced average releases per GW(e) a generated. These normalized releases do not apply, therefore, to any one plant, but are deemed to be representative of current nuclear power generation. They, therefore, reflect differences in reactor design and changes in release rates between newer and older installations. Future practices may give rise to results considerably different from those derived from past and current experience and any extrapolation to the future must be undertaken with caution. To estimate the collective dose commitments corresponding to these averaged releases, the Committee has decided that a model facility at a representative site be established for each

stage of the fuel cycle: mining and milling, fuel fabrication, reactor operation and reprocessing. The environment receiving the typical releases 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 dose commitments reflecting the overall impact of the nuclear power programme and will not be applicable to any one given site without due consideration of its own specific environmental pathways and of the particular radioactive release.

8. The calculation of the collective absorbed dose commitment to any organ or tissue requires the integration over infinite time of the collective absorbed dose rate in that organ or tissue. As described in Annex A, it is convenient in evaluating the collective dose commitment, and other similar quantities, to distinguish between external and internal irradiation of the body. For external irradiation the calculation is straightforward, but for internal emitters the integration is complex, particularly for nuclides of long retention times, when detailed knowledge is required of the time variation of dose equivalent rates in body organs and tissues following intake. The Committee, therefore, decided to represent the collective dose commitment for internal radiation as the integral of the collective intake multiplied by the committed dose per unit intake. The collective intake of a nuclide is a quantity readily calculable and tabulations of dose per unit intake are available. The Committee decided to use the committed dose, defined as the 50 year integral of dose rate in any organ or tissue following intake, for the average dose per unit intake in a normal population. This may lead to a slight overestimate of average dose for nuclides of long retention times in the body, since the mean life expectancy of a population is a little less than 50 years. This formulation of collective dose commitment can also lead to slight overestimates of its truncated value for time periods comparable with the mean life expectancy of the population, but the error is small and compensated by the ready availability of tabulations from which committed absorbed dose to the particular body organs of interest may be obtained [I2, A1, C10].

9. In the estimation of collective dose commitments, it is clear that assumptions have to be made about the size and habits of the exposed future populations. For this study it is assumed that the magnitude of the world population remains stable and that no major changes in age structure occur. It is further assumed that the dietary and other habits of the population remain constant, which is a reasonable assumption for short times, although the uncertainties must increase as longer times are considered. Finally, it is assumed that the whole population is represented by adults for the purposes of evaluating doses from inhalation and ingestion. This assumption is valid when estimating collective dose commitments for populations, because children only comprise a fraction of the total, and the difference in their dose per unit level of activity in environmental materials is small, except for a very few nuclides such as those of transuranium elements and ^{90}Sr.

10. Very long-lived nuclides pose a special problem. One example is ^{129}I ($1.6\ 10^7$ a). Another example is radon from mill-tailings containing ^{230}Th ($8\ 10^4$ a) and ^{238}U ($4.5\ 10^9$ a). Assessments of human exposures over such periods of time are obviously hypothetical and their relevance is doubtful. Dose commitments assessed for the purpose of calculating the maximum dose rate in the future, however, should only include integration over periods of time equal to the expected length of the practice that causes environmental pollution. Assuming this period to be 500 years for nuclear power production, the long life-time of some nuclides will not influence the assessment of such truncated dose commitments. The problem therefore only arises when the complete dose commitment is assessed. That assessment will be extremely uncertain for the long-lived nuclides and should therefore not be presented as single figures but preferably in tables or diagrams which indicate when the late dose contributions are expected to occur. One long-lived nuclide, ^{14}C (5730 a), does not pose as great a problem as indicated by its long half-life. The early disappearance of this nuclide from the human environment causes as much as about 10% of the complete dose commitment to be delivered within 70 years.

11. In addition to the small releases of radioactive materials which take place during normal operation, unplanned releases may occur. This Annex also reviews reactor accidents which have led to unplanned releases of activity into the environment, together with estimates of the resulting collective doses.

I. MINING AND MILLING

12. Uranium is obtained from ore mined in several countries of the world, the major producers being Canada, France, South Africa, United States, with Australia soon to join them. Major efforts in uranium exploration and production are also being made in countries such as Algeria, Argentina, Brazil, Gabon, India, Iran and Niger, while many other developing countries are making moderate efforts at uranium exploitation [B25]. World uranium production was 38 000 t in 1979 [H13] and the planned capacity for 1990 is 120 000 t. However, the growth of nuclear power needs to be more predictable in order to provide the incentive and lead times to establish the necessary mining and milling operations. Table 1 shows the 1979 uranium production capability from the major producers and gives for guidance the estimated "reasonably assured" resources in those countries, assuming a price of US $ 130 per kilogram of uranium. The estimates of uranium resources vary widely depending upon the price of uranium assumed; unconventional sources, e.g., coals and lignites, are not included.

13. 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. The mining is carried out either by underground or open pit methods and these techniques accounted for nearly all new uranium production in 1979. Each method produced about the same amount of uranium, although more ore was produced by open pit mining, as it is generally of lower grade. Some underground mines are less than 30 m below the surface and, conversely, some open pit mines operate to depths of 150 m. In recent years in situ solution mining has been carried out, although that, together with heap leaching techniques, only accounted for a few percent of world production. The main radioactive release from underground mining is ^{222}Rn in the mine ventilation air,

while for open pit mining there are also radioactive dust emissions.

14. Uranium milling operations involve the processing of large quantities of ore to extract the partially refined uranium. The uranium concentrate is called yellowcake, which is then used as feed at the fuel fabrication plant, where it is further refined, converted and enriched, if necessary, for use in reactors. Because of the large quantities of ore to be processed, mills tend to be near the uranium mines to minimize transportation. In some cases, where ore is treated locally by heap leaching, precipitated preconcentrates are transported to the mills. In 1979 more than 50 uranium mills were in operation [G1, F5, S16] which processed over 65 million tons of ore. Approximately half of the ore was new and the remainder was tailings from existing operations such as the gold mining industry in South Africa. The process of uranium extraction involves the following steps: crushing, grinding, chemical leaching, separation of the uranium from the leach solution, precipitation, drying and packing of the yellowcake. The mill processes fall into three general types, acid leach solvent extraction, acid leach ion exchange, and alkaline leach; most mills use the acid leach solvent extraction process. The steps in the milling process which lead to the major emissions of radioactive materials are the front end crushing operations and the drying and packaging of yellowcake.

A. EFFLUENTS

15. Gaseous radioactive effluents from mines are almost entirely composed of ^{222}Rn in the ventilation air which is discharged in large quantities. Liquid wastes result from mine drainage and process feed water; they are discharged to ponds for settling of solids and the water is either allowed to evaporate or is released to the environment. Mine drainage water can also be used as process feed for the mill, or may be diluted, treated and discharged [C7]. Leaching of mine tailings may also be a source of liquid waste but generally wastes from the milling process are of more importance. Solid waste is composed of rock and very low grade ore. Only limited information is available on radionuclide emissions from underground uranium mines, and in general only ^{222}Rn emissions are reported, as this gas represents the major airborne radioactive component of the effluent [N21, L8]. Particulate emissions are believed to be far less significant. In a 1978 survey of underground mines in New Mexico, ^{222}Rn emissions per unit mass of ore mined in the range of 0.4 to 8 GBq t^{-1} were reported [J1]. The variation is mainly dependent upon the grade of ore mined, with ores containing up to 1 or 2% uranium at Nabarlek in Australia giving 1–2 GBq t^{-1} [L9] and 0.1% ores at underground Canadian mines giving results 10 times lower [W6].

16. The major airborne radioactive component in effluents from open pit mining is also believed to be ^{222}Rn [E1, C7, W6]. As large areas are involved, it is not possible to directly measure the radon emissions, but they may be inferred from emission rates from particular surfaces of the mine or from ^{222}Rn concentrations downwind of the mine. The results at the Ranger Mine in Australia for radon release per unit mass of ore produced during mining were 0.1 GBq t^{-1} [D7] and the emanation rate per unit ore grade is the same as Nabarlek underground mine. Results for several open pit mines in Canada average 0.2 GBq t^{-1} for ore at about 0.25% uranium [E8]. In a recent study of eight open pit uranium mines in Wyoming, an estimate of the ^{222}Rn emission per unit mass of ore produced was 0.2 GBq t^{-1} [N3]. The grade of ore obtained from open pit mines are typically 0.1–0.2% uranium and thus the radon emission normalized for uranium content seems similar for underground and open pit mines at 1 GBq per tonne and per cent of uranium.

17. Uranium ore requirements per unit of electrical energy generated vary somewhat between the commercial nuclear reactors currently in use. In the recent INFCE studies [I9] the light water reactors (LWRs) are assumed to require 205.4 t of uranium heavy metal to be extracted for the production of 1 GW(e) a of electrical energy, while heavy water reactors (HWRs) operating on the uranium cycle require 178.8 t [GW(e) a]$^{-1}$ of heavy metal. It is estimated by the Committee that gas cooled reactors (GCRs) using natural uranium metal require 270 t [GW(e) a]$^{-1}$ of uranium metal, assuming a mean fuel burnup of 4.5 GW d t^{-1} and a thermal efficiency of 30%, whereas advanced gas-cooled reactors require 219 t [GW(e) a]$^{-1}$ of heavy metal. These uranium requirements are calculated on a "once through" basis in that no recycling of uranium or plutonium is assumed. Were plutonium to be recycled in LWRs or HWRs, the heavy uranium metal requirements would be reduced to 120 and 75 t [GW(e) a]$^{-1}$, respectively. The introduction of fast breeder reactors (FBRs) would reduce the heavy metal input to 1 t [GW(e) a]$^{-1}$ of uranium for plutonium recycle, an improvement of a factor of about 200 in uranium utilization. A heavy water reactor operating on a uranium-thorium cycle breeding ^{233}U would require 7 t [GW(e) a]$^{-1}$ of thorium metal.

18. The grade of ore mined is variable but is usually between 0.1 and about 3.0% U_3O_8. In the United States it is higher from underground mines at an average 0.2% U_3O_8, than from open pit mines with 0.11% U_3O_8 [E1]. Thus the LWR uranium heavy metal requirement of 205 t [GW(e) a]$^{-1}$ corresponds to a mining rate of $1.2\ 10^5$ t of ore from a United States underground mine or $2.2\ 10^5$ t from a United States open pit mine. The Nabarlek mine in Australia produced 2% U_3O_8 ore, so that the LWR requirement is met by an ore production of just over $1.2\ 10^4$ t [L9]. However, since the corresponding normalized ^{222}Rn releases appear to be similar for underground and open pit mines per unit concentration of uranium in ore, the Committee estimates radon releases to be 20 TBq [GW(e) a]$^{-1}$. This compares with the Committee's estimate in Annex D of the 1977 report [U1] of 6.3 TBq [GW(e) a]$^{-1}$ from mining and milling.

19. The activity content of the mined ore is predominantly due to ^{238}U and its daughter products; there is very little, if any, natural thorium in most ores. However, ore from the Elliot Lake region in Canada averages about 0.2% natural thorium. One tonne of ore containing, say, 2 kg of U_3O_8 has an activity of 21 MBq from each of the 14 principal members of the ^{238}U decay chain, a total of about 0.29 GBq [S1]. The operation of uranium mills has thus resulted in the accumulation of large quantities of waste tailings containing significant quantities of uranium daughter nuclides. There are currently known to be some 120 million tonnes of tailings stored at active mill sites mainly in the United States and Canada [N21] and current uranium demand trends would increase this figure to about $5\ 10^8$ t by the year 2000. About 14% of the total activity in the ore feed appears in the uranium concentrate which achieves better than 90% uranium

extraction. In the resulting solid wastes, with the parent nuclides removed and short-lived daughters ^{234}Th ($T_{1/2}$ 24.1 d), ^{234m}Pa ($T_{1/2}$ 1.17 min) and ^{231}Th ($T_{1/2}$ 25.5 h) quickly decaying, some 70% of the original activity remains and is essentially due to ^{230}Th ($T_{1/2}$ 8 10^4 a) and its daughters.

20. Uranium tailings are discharged from the mill usually in slurry form at about 50% solids, to an impoundment area. Tailings piles typically cover areas of between 30 and 60 hectares. The tailings comprise about 70% sand and 30% slimes and about 85% of the activity is contained in the slime fraction [S1, N21]. Although in the early days of uranium mining and milling liquid effluents were discharged to local watercourses [G2], the present practice is to minimize liquid effluent by recycling or evaporation of the water.

21. In dry climates there are essentially no liquid discharges which lead to radiation exposure of the public. This has been confirmed by environmental monitoring which has not detected measurable water contamination beyond plant sites [S2, S3, S4]. Studies on tailings piles in Illinois indicate that thorium and radium concentrations fall off to background levels within 1 m below the bottom of the tailings and that the activity does not migrate into groundwater [N2]. In contrast, Canadian mills operate in a wet environment and the usual practice is to use small lakes and depressions for tailings disposal [W6]. Tailings are contained by dams and the overflows treated with barium chloride to co-precipitate the radium as $Ba(Ra)SO_4$. Further barium chloride addition and settling may be allowed before discharge of effluents to waters available to the public. After treatment, the dissolved ^{226}Ra concentrations are usually less than 0.4 Bq l^{-1} with 0.2–7 Bq l^{-1} suspended ^{226}Ra [M10]. Typical annual releases of ^{226}Ra from tailings into the watershed are of the order of 40 GBq, corresponding to less than 1 GBq [GW(e) a]$^{-1}$.

22. Sources for atmospheric emissions of radionuclides are the ore crushing and grinding circuits, the yellowcake drying and packaging operations, and the tailings. Emission rates from different plants vary widely, owing in part to different process and control technologies. For a typical mill processing about 2000 t of ore per day, the major source of atmospheric dust emissions is from the yellowcake drying and packaging processes; the reported ranges of emissions are 1–4 GBq a^{-1} for ^{238}U; 0.2–2 GBq a^{-1} for ^{230}Th, ^{226}Ra and ^{210}Pb; and 1–7 TBq a^{-1} for ^{222}Rn [N4, N5, N21, E8, D7, N6, N7]. More recent mills may achieve releases from the crushing and storage processes of about 0.04–0.16 GBq a^{-1} particulate emissions [N2, N8]. Atmospheric emissions from the tailings area are in the ranges of 7–500 MBq a^{-1} for ^{238}U and ^{234}U; 0.1–8 GBq a^{-1} for ^{230}TH, ^{226}Ra and ^{210}PB; and 500 GBq to 300 TBq a^{-1} for ^{222}Rn [N2, N3, N4, N5, N6, N7, N8, N21, D7]. The amount of particulate airborne emissions from tailing areas depends upon the size of dry tailings beach areas which are subject to wind and weather erosion, while the radon emission depends on diffusion from the ground. The radon exhalation rate appears to be about 1 Bq m^{-2} s^{-1} per Bq g^{-1} of ^{226}Ra in the tailings [N2], although the figure can vary by an order of magnitude depending on meteorological conditions such as wind speed, atmospheric stability and rainfall [T1]. The release of radon from an uncovered tailings pile containing about 21 Bq g^{-1} of ^{226}Ra will thus be about 21 Bq m^{-2} s^{-1}. Tailings impoundment areas almost completely covered by water will have very low radionuclide emissions [N8].

23. To estimate the environmental releases, a model mill facility has been established based on the data given for the United States [E1, N21, S1]. The model mill processes 600 000 t per year of 0.2% grade ore. Dust from ore crushing is assumed to contain all radionuclides in equilibrium but yellowcake drying and packaging contributes to the uranium release and accounts for the lack of equilibrium in the release. The mill is assumed to produce uranium at a rate equivalent to 5 GW(e) a per year and to operate for 20 years. The normalized atmospheric releases from the milling operations and from the tailings piles are shown in Table 2 together with the mining contribution from ^{222}Rn. The typical tailing impoundment area assumed is 60 hectares with a radon emission rate of 6.7 TBq ha^{-1} a^{-1}. The mill processes ore equivalent to 100 GW(e) a and thus tailings areas amount to 0.6 ha [GW(e) a]$^{-1}$. It is assumed that there is a 2 m covering of earth which reduces the radioactive emissions by a factor of 4. The dust emission data for the tailings disposal area were based on assumptions that average wind speeds produced 0.017 g ha^{-1} s^{-1} of particles smaller than 10 μm; 10–80 μm particles accounted for 0.04 g ha^{-1} s^{-1} with assumed nuclide compositions of 3 Bq g^{-1} for ^{238}U and 60 Bq g^{-1} of all the daughter radionuclides [E1, S1]. Activities of ^{235}U and daughters are some two orders of magnitude below the values for ^{238}U.

24. The tailings remain after the mill has ceased operation and can become a long-term source of radioactive contamination due to wind and water erosion, leaching and radon emanation. Hence the normalized releases quoted in Table 2 for tailings are quoted per year per unit electric generation. Stabilization programmes are generally conducted or planned so that erosion is alleviated using materials which may be native soils, gravel or so-called Rip-rap cover, clays, or even artificial or synthetic covers or sealants such as asphalt or polyvinyl chloride [N2, N21, C7]. Although up to a few per cent of the original uranium isotopes remain in the tailings, the major source of long-lived activity for about 5 10^5 a is ^{230}Th ($T_{1/2}$ 8 10^4 a) 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 [S5]. The reduction in radon emanation by soil covering depends on the type and depth of cover. In part because of its small particle size, clay can hold moisture and present a more effective barrier to radon diffusion than more common soils. Hence, incorporation of clay can reduce the depth of soil cover required to achieve radon exhalation rates similar to those of normal soils [N2].

B. LOCAL AND REGIONAL COLLECTIVE DOSE COMMITMENTS

25. The uranium mining and milling sites tend to be in areas of low population density. In many areas the conditions are arid and not suitable for farming while those mines in areas of high precipitation are usually remote with again little local farming. In arid areas there is negligible release of radionuclides to the aquatic environment and the radiation doses to the public arise predominantly from airborne effluents. In areas of high precipitation, it is established that the liquid effluent population doses are dominated by ^{226}Ra in drinking water and aquatic foodstuffs [E8, K10, W6]. In a detailed study of Canadian uranium mines and mills which discharged radionuclides to

lakes and water courses, the collective doses resulting from drinking water, fish consumption and external radiation from sediments were in general significantly less than the collective doses due to the atmospheric releases from the mine, mill and tailings areas [E8]. The ^{226}Ra concentrations in surface waters were found to be no higher than 10^{-1} Bq l^{-1}. The levels of maximum individual dose reported were less than 80 μSv a^{-1} [E8].

26. Under the assumption that adequate waste treatment prevents seepage of process liquid effluents directly into rivers, the local and regional collective dose commitments are assumed by the Committee to depend upon the airborne releases which contribute to external exposure from deposited material and to internal irradiation via the inhalation and ingestion pathways. In Annex D of the 1977 report [U1], the Committee has previously used a population density of 3 km^{-2} within a few hundred km of the mine and mill and a uniform population density of 25 km^{-2} from this to 2000 km. These figures still remain suitable on the basis of reported population densities in areas of mining and milling [S1, E1, E2, E8, W6]. The collective dose commitments to the local and regional population from the particulate releases from the model mill (Table 2) were derived using the values presented for the naturally-occurring radionuclides in Annex C, modifying the population density to 25 km^{-2} from the value of 100 km^{-2} used for estimating the impact of coal fired power stations. A deposition velocity of 10^{-2} m s^{-1} was chosen for particulate releases and the majority of the collective dose arises within the first few hundred km.

27. For radon releases an atmospheric dispersion calculation was undertaken to estimate collective doses. The meteorological dispersion characteristics of the representative site are shown in Table 3. They are typical of the local environment in arid areas and are the values chosen in the Rasmussen study as applying to a semi-arid area [R3]. Rainfall occurs for only 0.3% of the time and only in neutral conditions (Pasquill category D); the effective height of release is 10 m. The high incidence of category F conditions is a phenomenon local to the mine environment and the conditions are assumed to persist only up to 100 km. Beyond that distance the meteorological conditions are assumed to become neutral out to 2000 km. The assumption of an equal frequency of all wind directions is considered reasonable for this study since uniform population distributions are assumed. The atmospheric dispersion modelling has been fully described in Annex A and has been utilized here in computer calculations using the methodology developed for the Commission of the European Communities for the assessment of effluent releases [C10]. The dosimetry for radon inhalation was that assumed in Annex D, which gives an average effective dose equivalent per unit inhaled activity of radon daughters of $1.3 \cdot 10^{-8}$ Sv Bq^{-1}. Only effective dose equivalent calculations are presented for radon in this Annex. The equilibrium factor for the short-lived radon daughters is taken as 0.6.

28. The resulting normalized local and regional collective dose commitments from mining and milling are shown in Tables 4 and 5. For the particulate releases inhalation, ingestion and external irradiation all contribute to the dose commitment and a further description of the analysis can be found in Annex C. The resulting collective effective dose equivalent commitment is approximately half that estimated for the radon releases from milling operations. The total normalized collective effective dose equivalent commitment from mining and milling is 0.54 man Sv [GW(e) a]$^{-1}$, of which 93% is from the mining operation. The results are generally similar to those estimated by the Committee in Annex D of the 1977 report [U1]. It is assumed in all these calculations that the indoor air concentrations are the same as outdoors.

29. The estimated doses to most exposed members of the public are highly dependent upon the characteristics of the particular location of the mine and mill. Annual effective dose equivalents between a few hundred μSv to several mSv have been estimated for typical emissions from mines and mills [E1, E8, N21, M10]. For the model mine and mill used by the Committee the annual effective dose equivalent at 500 m from the source is 900 μSv from radon releases, assuming an atmospheric dilution factor of $5\ 10^{-6}$ Bq s m^{-3} per Bq released, and doses from the particulate releases are 50 times lower.

30. As discussed in section I.A., ^{230}Th in tailings piles will provide a long-term source of radon emission. If the release rate were to continue throughout the mean lifetime of $1.1\ 10^{5}$ a, then the emanation rate given in Table 2 for ^{222}Rn would give a normalized collective effective dose equivalent commitment of about 2800 man Sv [GW(e) a]$^{-1}$. The corresponding particulate releases are estimated to give an additional 50 man Sv [GW(e) a]$^{-1}$. 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 and habits. Table 6(a) shows how the normalized collective effective dose equivalent commitment from the tailings varies with the period of time over which the radon and particulate releases are assumed to be released. The results must be extremely uncertain over such geologic time scales and indeed present day tailings management may lead to radon emanation rates no greater than the ambient levels for soils in the mill vicinity, so that almost no long term dose commitment arises.

31. In the INFCE studies [I9] the dose commitment from tailings was estimated on the assumption that the radon emanation continued for 10^{3} a, by which time the tailings are assumed to have been eroded and lead to a further dose commitment from the aquatic environment (freshwater and marine). The dose commitment from the aquatic environment is enhanced by the small percentage of uranium left in the tailings, here assumed to be 10% The regional marine model described in Annex A has been used to estimate the collective dose commitment from the tailings, assuming they are eroded into coastal waters and disperse throughout the world's oceans. The resulting normalized collective effective dose equivalent commitments are shown in Table 6(b) and, because of the nuclide content, these dose commitments are almost independent of the time at which they are released into the marine environment. The normalized radon collective effective dose equivalent commitment for 10^{3} a release is about 25 man Sv [GW(e) a]$^{-1}$ and the uranium figure is 460 man Sv [GW(e) a]$^{-1}$. These figures compare with the INFCE estimates of 10 and 360 man Sv [GW(e) a]$^{-1}$, respectively.

32. Previously the Committee has also used a simplified model for estimating the normalized collective effective dose equivalent commitment from

tailings by comparing with natural radon emanation from soil and the corresponding radon concentration in air. With the model mine and mill data from Table 2 and the normal radon exhalation rate of 20 mBq m^{-2} s^{-1}, leading to a standing equilibrium equivalent radon concentration of 1.8 Bq m^{-3} (Annex D), and an effective dose equivalent per unit of integrated air concentration of 9.2 10^{-5} Sv per Bq m^{-3} a (Annex D), the normalized collective effective dose equivalent commitment from tailings over the mean life of ^{230}Th is calculated to be

$$S^c = (6.7\ \text{TBq ha}^{-1}\ \text{a}^{-1})\,(0.6\ \text{ha [GW (e) a]}^{-1}\,(0.25)$$
$$\left(\frac{1.8\ \text{Bq m}^{-3}}{0.02\ \text{Bq m}^{-2}\ \text{s}^{-1}}\right) \times (25\ 10^{-6}\ \text{man m}^{-2})$$
$$(1.44 \times 80\ 10^{3}\ \text{a})\,(9.2\ 10^{-5}\ \text{Sv Bq}^{-1}\ \text{m}^{3}\ \text{a}^{-1}) \times$$
$$\times\ (3.17\ 10^{-8}\ \text{a s}^{-1}) = 760\ \text{man Sv [GW (e) a]}^{-1}.$$

This is in agreement with the value of 2800 man Sv [GW(e) a]$^{-1}$ calculated using the atmospheric dispersion model (Table 6). The previous estimate by the Committee, in Annex D of the 1977 report [U1], based on the tailings release rate assumptions and radon dosimetry, was equivalent to a collective effective dose equivalent commitment of 2300 man Sv [GW(e) a]$^{-1}$. These values must be extremely uncertain and depend upon future practice, both in the choice of fuel cycle, since plutonium recycle in fast reactors could reduce the uranium ore requirement per unit energy generated by a factor of about 200 with the resulting same reduction in collective dose, and in the management practices of the tailings themselves. Also the downwards migration of radionuclides in soils at rates of 2 10^{-3} m a^{-1} could reduce the collective dose commitment from radon releases by up to two orders of magnitude.

II. URANIUM FUEL FABRICATION

33. The uranium ore concentrate produced at the mills is further processed and purified and often enriched in the isotope ^{235}U before being converted into uranium oxide or metal and fabricated into fuel elements. Natural uranium which contains 0.7% ^{235}U can be utilized in graphite or heavy-water moderated reactors (HWRs). Light water reactors (LWRs) and advanced gas-cooled reactors (AGRs) require enriched fuel of between about 1 and 4% ^{235}U. Before uranium can be enriched it must be converted from the oxide form U_3O_8 to uranium hexafluoride (UF_6), the gaseous form for use in enrichment plants.

34. Conversion takes place, for example, at two UF_6 production facilities in the United States at Sequoyah, Oklahoma and Metropolis, Illinois and in the United Kingdom at Springfields, although other conversion facilities exist. Two industrial processes are used for UF_6 production, dry hydrofluor and solvent extraction and each is responsible for about half the UF_6 production in the United States. The hydrofluor process consists of reduction, hydrofluorination and fluorination of the ore concentrates to produce crude UF_6, followed by fractional distillation to obtain a pure product. The solvent extraction process employs a wet chemical solvent extraction step at the start of the process to produce high purity uranium for the subsequent reduction, hydrofluorination and fluorination steps.

35. Enrichment of the isotopic content of ^{235}U usually takes place at a gaseous diffusion plant, although increasing use is made of centrifuge techniques. At a gaseous diffusion installation the UF_6 is pumped through a series of porous membranes which discriminate against the passage of the heavier isotope of uranium by a factor of 1.0043 at each stage. Some 1700 stages are required to produce an enrichment of 4% [U3]. Centrifuge technology utilizes rapidly rotating cylindrical vessels to separate the isotopes of uranium and utilizes only ten stages to reduce to the normal tailings levels using only 10% of the electricity used by a diffusion plant [C7]. In the final fuel fabrication step the UF_6 is chemically converted to UO_2 or to uranium metal for use in fuel elements. For use in LWRs or AGRs the dioxide powder is sintered into pellets and loaded into zircaloy or stainless steel cladding to produce fuel pins which are filled with helium and welded with end caps. Uranium metal without enrichment is used in Magnox reactors clad in a magnesium alloy (Magnox) can. For HWRs unenriched uranium dioxide is normally used. After the enrichment process large quantities of depleted uranium remain in which the ^{235}U content is 0.3% or more. This uranium may become a source of public exposure if it is disposed of; at present it is stored for possible use in breeder reactors and for other purposes.

A. EFFLUENTS

36. Emissions of radionuclides from the conversion, enrichment and fuel fabrication processes are small. 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. Estimates of releases from typical installations have been published previously in the United States [U3]. More recently the United States Nuclear Regulatory Commission has reported environmental releases from fuel fabrication plants at six-month intervals [N18].

37. Residual amounts of ^{230}Th and ^{226}Ra are removed from the uranium ore concentrate in the conversion process and small amounts of these nuclides and uranium appear in effluent streams. Atmospheric annual discharges from typical conversion plants in the United States are reported at about 3 GBq for ^{238}U, ^{234}U, ^{234}Th; 33 MBq for ^{230}Th; 3 MBq for ^{226}Ra; and 74 MBq for ^{235}U [E1, N18]. In the United Kingdom, British Nuclear Fuels Ltd. published annual reports on radioactive discharges and monitoring [B2, B22]. The annual atmospheric discharge from Springfields has been about 0.02 TBq of natural uranium from 1977 to 1979. The release of uranium from the Capenhurst enrichment plant in the United Kingdom was reported at 0.2 GBq in 1977 and 1979 and at 0.15 GBq in 1978 [B2, B22]. The Swedish fuel fabrication facility released between 13 and 60 MBq of 2 or 2.3% enriched uranium per year to the atmosphere between 1976 and 1979 [G3].

38. Annual liquid discharges from Capenhurst contain about 1 GBq of uranium and 0.5 GBq of beta activity, and Springfields releases about 1 TBq a^{-1} of uranium. The effluent from Springfields is released into the tidal waters of the river Ribble, while waste from Capenhurst is now discharged through the sewage system. The total beta activity in Springfields liquid effluent discharges greatly exceeds the alpha activity because of the removal and discharge of the short-lived isotopes ^{234}Th (24.1 d) and ^{234m}Pa (1.17 min). Annual

liquid effluent discharges of ^{238}U at United States sites are about 40 GBq for conversion, 67 GBq for enrichment and 17 GBq for fuel fabrication [U3].

39. Table 7 shows discharges from the model fuel conversion, enrichment and fabrication facilities. The atmospheric emissions of the model conversion facility were based on operating data taken from Sears et al. [S6] for plant with low impurity feed. The atmospheric discharges from the model fuel fabrication facility were based on the work of Pechin et al. [P1]. The model enrichment facility is based on the Capenhurst discharges to atmosphere [B2]. The throughput of fuel is assumed to be 10^4 t a^{-1} of uranium at the conversion facility and enrichment plant, which is reduced to 1500 t a^{-1} of enriched fuel for the fabrication plant. The liquid discharges from the model facilities were derived from Capenhurst [B2, B22] and United States data [U3]. The model plant is assumed to be at a site discharging into fresh water. The discharge data for the model facility are about half those used in Annex D of the 1977 report [U1] for airborne releases and the same for liquid effluents.

B. LOCAL AND REGIONAL COLLECTIVE DOSE COMMITMENTS

40. The exposure as a result of liquid effluents from United Kingdom fuel fabrication operations has been reported as mainly due to external irradiation by the sediments on the river bank near the Springfields plant. The annual collective effective dose equivalent has been estimated at less than 10^{-3} man Sv [T4]. For liquid releases into a freshwater environment Pechin has shown that the most exposed individual receives a dose of less than 10% of that received from the gaseous release and has estimated a representative normalized collective effective dose equivalent commitment of about 2 10^{-4} man Sv [GW(e) a]$^{-1}$ to the population exposed to aquatic pathways from the river [P1]. There is great variability in the behaviour of effluents released to the aquatic environments and the collective dose commitment can only be regarded as indicative of the order of magnitude. It seems probable, however, that the major exposure of the population from fuel conversion and fabrication processes arises as a result of the discharges to the atmospheric environment.

41. The location of the model facility has been chosen to be representative of the northern United States and northern Europe. The most significant pathway that emerges, which leads to exposure of the population, is the direct inhalation route, as will be shown below. The population distribution around the model facility is assumed to be constant at 25 km^{-2} and the collective doses for the particulate releases are derived using the results given in Annex C for technologically enhanced releases of radionuclides. The results are modified for the different isotopic composition and population density. The particulate releases are 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 a meteorological dispersion calculation was performed using an effective dose equivalent per unit inhaled activity of radon daughters of 1.3 10^{-8} Sv Bq^{-1} and an equilibrium factor of 0.6 between radon and its short-lived daughters from Annex D. For the calculation of radon releases the distribution of Pasquill weather categories is typical of a moderate climate in which rain is assumed to occur in near neutral conditions (categories C and D) and accounts for some 10% of the annual frequency distribution (Table 8).

42. The normalized collective absorbed dose equivalent commitments for the particulate releases are shown in Table 9, where it can be seen that inhalation of uranium isotopes is the main route of exposure. 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. The estimated collective absorbed dose commitments from ingestion of foodstuffs are estimated to be a factor of about 10 below those due to inhalation.

43. In summary, the normalized collective effective dose equivalent commitment due to uranium fuel fabrication is estimated to be 2 10^{-3} man Sv [GW(e) a]$^{-1}$, as shown in Table 10. The main contribution is inhalation of the isotopes of uranium. Radon releases contribute about 20% of the total. This figure is higher than that estimated in Annex D of the 1977 report [U1] for a similar discharge, but is small compared with the doses from mining and milling. It has been reported that the critical group for uranium fuel fabrication plants are those exposed to sediments on banks of waterways near the site [B22]. For the Springfields site in the United Kingdom this critical group may be exposed at 10^{-9} Sv a^{-1}, but the pathway contributes little to the total collective effective dose equivalent.

III. REACTOR OPERATION

44. Most of the electrical energy generated by nuclear power is produced by thermal reactors in which the fast neutrons produced by the fission process are slowed down to thermal energies by use of a moderator. The smaller the atomic mass of the moderator, the more efficiently it removes energy from the neutrons. The most common materials which have been employed as moderators in thermal power reactors are light water, heavy water and graphite. The choice of moderator greatly affects the design of the reactor, its size and heat removal system.

45. The uranium fuel is contained in discrete pins, both to prevent leakage of produced radioactive fission products into the coolant circuit and also to improve the neutron economy by reducing the parasite neutron captures in the resonance neutron energy region of ^{238}U. The heat generated in the fuel pins by the slowing down of the fission fragments is removed by forced convection. The most usual coolants are light or heavy water and carbon-dioxide gas. In the case of fast-breeder reactors, the neutrons are not moderated and induce fissions with their energies close to those at which they were produced. The usual heat removal system from the core is by means of liquid sodium metal, which is a better heat transfer medium and does not significantly moderate the neutrons.

46. The number of operational reactors of each type and the generating capacity for each country or area utilizing commercial reactors together with the installed capacity per caput are shown in Table 11. There were 235 reactors in 22 countries with an installed capacity

of about 120 GW(e) in 1979 [I1, K12]. The reactor types include the pressurized water moderated and cooled reactor (PWR), the boiling water moderated and cooled reactor (BWR), the Magnox and advanced gas-cooled graphite moderated reactors (GCR), the light-water cooled graphite moderated reactor (LWGR), the heavy-water moderated and cooled reactor (HWR) and the fast breeder reactor (FBR). The average installed capacity per caput was 0.07 kW(e) with the highest value being 0.46 in Sweden and the other developed countries averaging between 0.1 and 0.2 kW(e).

A. EFFLUENTS

47. During the production of power by a nuclear reactor radioactive fission products are formed within the fuel and neutron activation produces radioactive components in structural and cladding materials. Radionuclides are found in the coolant both because the coolant becomes activated, because of diffusion of fission product elements with radioactive nuclides from the small fraction of the fuel with defective cladding, and because of corrosion of the structural and cladding materials. All reactors have treatment systems for the removal of radionuclides from gaseous and liquid wastes which arise from leakage out of the core or from clean-up of the coolant. Low level releases which occur are controlled and monitored.

48. 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, ^{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 for annual normalized release, i.e., per unit of electrical energy generated in that year, averaged over all reactors of a given type (PWR, BWR, etc.). Normalized results are not presented for individual sites because releases in any one year often reflect the need for maintenance or irregular procedures which are the result of a number of previous years operation. The total releases of radionuclides between 1975 and 1979 have been divided by the total production of electrical energy over the same years in order to obtain a representative normalized release over the period covered by this Annex. These results are subsequently used to assess collective dose commitments. In the tables which follow open entries mean that no data were available, entries characterized by a dash mean that no releases were reported.

1. Fission noble gases

49. There are at least nine radioactive isotopes of krypton and eleven radioactive isotopes of xenon formed by the fission process. Most of them have very short half-lives (seconds to minutes) and decay before they migrate significantly within the fuel. A fraction of the noble gas inventory of the fuel pins diffuses to the free space between the fuel and the cladding, leading to a build-up of gas pressure. The presence of noble gases in the coolant is generally due to fuel cladding failure.

50. In PWRs the primary coolant is in a sealed loop and off-load refuelling is employed. Short-lived radioactive noble gases, therefore, only appear because of leakages of the primary circuit water. The primary water coolant in a PWR is continually purged for control of chemical composition and purification. Gaseous wastes are released in the process and are held under pressure in tanks for between 30 and 120 days for decay of short-lived nuclides. Other gaseous effluent streams in PWRs originate from the condenser exhaust on the steam circuit, secondary coolant blowdown, reactor building ventilation, including containment purges (about 4 a^{-1}), and turbine plus ancillary building ventilation [N9].

51. Table 12 lists the reported discharges of noble gases from PWRs. The information is taken from Phillips and Gruhlke [P2], Beebe [B23], Luykx and Fraser [L1, L6], Decker [D6], van Daatsellar [D8], Kumatori [K4], Errera [E9], Godas [G3], Norlinder [N19] and Salo [S14]. The releases span more than three orders of magnitude partly because of variation in design and partly because of the need for irregular operations or maintenance. For this reason, the average noble gas release from PWRs was obtained by dividing the total release by the actual total amount of electrical energy generated. The normalized annual release has been similar over the five years 1975 to 1979. The average normalized release over that period was 430 TBq [GW(e) a]$^{-1}$. The composition of the release from PWRs is predominantly from ^{133}Xe ($T_{1/2}$ 5.3 d) but some shorter-lived nuclides are present, particularly ^{135}Xe ($T_{1/2}$ 9.2 h). In Table 13 the nuclide composition of noble gases is presented for United States PWRs in the year 1979 [B23] and the normalized release per unit of electrical energy generated is given. It can be seen that ^{85}Kr ($T_{1/2}$ 10.7 a) represents 5% of the normalized release. Figures for the nuclide composition of noble gases in European PWRs are essentially similar [L1, L6].

52. In BWRs non-condensable gases in the steam flow are continuously removed by the main condenser air-ejector system. This is the main source of noble gas release into the gaseous waste stream. Secondary pathways include the purging system for the turbine gland seals, the condenser mechanical vacuum pump and any leakage of process fluids to ventilated building spaces [N10]. Table 14 lists the discharges reported from BWRs in consecutive years derived from references [B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]. The releases vary by more than six orders of magnitude per unit of installed capacity. The value averaged over all operating experience has been falling year by year from 56 PBq [GW(e) a]$^{-1}$ in 1970, to 37 PBq [GW(e) a]$^{-1}$ in 1974 and to 4.4 PBq [GW(e) a]$^{-1}$ for BWRs in 1979. This consistent reduction in discharges of noble gases from BWRs is partly a result of the commissioning of new plants with lower release rates, but is also due to reductions in discharges from many existing plants for the same annual electrical output. About 85% of the noble gas discharges from BWRs in 1979 came from three plants. The average normalized release from 1975 to 1979 was 8800 TBq [GW(e) a]$^{-1}$.

53. Table 15 gives the nuclide composition of noble gas releases from BWRs in the United States during 1979 [B23]. The release composition varies greatly, depending on the waste treatment hold-up time which varies from less than half an hour on older plants to several hours on newer BWRs. The normalized releases per unit of electricity generated by all United States BWRs is also given and it can be seen that contributions to the total activity released are made by a number of nuclides including ^{138}Xe ($T_{1/2}$ 17 min), ^{135m}Xe ($T_{1/2}$

15 min), ^{135}Xe ($T_{1/2}$ 9.2 h), ^{133}Xe ($T_{1/2}$ 5.3 d), ^{88}Kr ($T_{1/2}$ 2.8 h), ^{87}Kr ($T_{1/2}$ 76 min), ^{85m}Kr ($T_{1/2}$ 4.4 h) and ^{85}Kr ($T_{1/2}$ 10.7 a).

54. In gas-cooled reactors noble gas releases are insignificant. For reactors of the Magnox type utilizing uranium metal fuel, because of the magnesium alloy cladding, temperatures must be kept below 650°C and the reactors are equipped with detection systems for failed fuel pins which are quickly removed from the operating core. The AGR utilizes enriched uranium oxide fuel in stainless steel cladding with CO_2 coolant. Again, early operating experience does not indicate that noble gas releases occur. As with Magnox reactors, AGRs employ on-load refuelling and failed fuel pins are easily removed.

55. Releases of noble gases for heavy water reactors are presented in Table 16 using data from Argentina [B21] and Canada [M10]. The normalized release averaged between 1975 and 1979 is 460 TBq [GW(e) a]$^{-1}$. There is little release reported for fast breeder reactors in France and the United Kingdom [F1]. There has been little exploitation of high temperature reactors in recent years, although one or two experimental facilities remain.

2. Activation gases

56. Although gas-cooled reactors do not generally release noble gas fission products as do BWRs and PWRs, several activation gases are formed in GCR operation. Direct activation of the oxygen in the CO_2 coolant gives rise to ^{16}N by the (n,p) reaction on ^{16}O. Argon-41 arises from (n,γ) reactions in the stable ^{40}Ar content of air, either present as an impurity in the coolant circuit or used for shield cooling in early GCRs with steel pressure vessels.

57. The amount of ^{41}Ar ($T_{1/2}$ 1.8 h) released depends upon the detailed design of the reactor. Release rates of ^{41}Ar are not measured routinely in the United Kingdom, but measurements have been reported by Clarke and Wilson [C1] and give averages of between about 2 and 15 PBq [GW(e) a]$^{-1}$ or between about 20 and 150 MBq s^{-1}. For AGRs the primary source of ^{41}Ar releases is from the leakage of the coolant to atmosphere and releases of the order of about 0.1 PBq [GW(e) a]$^{-1}$ are reported [L6]. The activation gas discharges from GCRs are given in Table 17 for the years 1975–1979. The average normalized release between 1975 and 1979 was 3.2 PBq [GW(e) a]$^{-1}$.

58. Another airborne gaseous effluent of GCRs is ^{35}S ($T_{1/2}$ 87.5 d) arising from (n, γ) reactions on ^{34}S present as an impurity in the graphite core, and from (n,p) reactions on ^{35}Cl also present as an impurity. Discharge rates have been reported in the range of about 1 to 4 GBq d^{-1} [G4] but may reduce as the reactors come to full power. The impurity levels of sulphur and chlorine in the moderator graphite are reported as approximately 50 and 2 ppm, respectively [P3]. Measured releases of ^{35}S from Oldbury and Wylfa (Magnox) and from Hinkley B (AGR) in 1976 were 52, 89 and 81 GBq, while in 1977 they were 17, 200 and 211 GBq, respectively [G4]. In 1978 the values were 28, 174 and 204 GBq, respectively. The average normalized discharge was 170 [GW(e) a]$^{-1}$ and the chemical form was carbonyl sulphide.

59. Nitrogen-16 ($T_{1/2}$ 7 s) provides essentially only direct external irradiation at nuclear power plants. The photons produced in its decay have energies of 6.1 and 7.1 MeV. In BWRs the ^{16}N generated is in part transported with the steam to the turbine buildings producing an external gamma field. External gamma dose rates at the perimeter fence of Central Electricity Generating Board nuclear power stations in the United Kingdom have been reported as being mainly due to ^{16}N [G4].

3. Tritium

60. In LWRs tritium arises from ternary fission in the nuclear fuel and from neutron activation reactions with lithium and boron isotopes dissolved in or in contact with the primary coolant. The normalized tritium production rate has been estimated for LWRs as 0.56 PBq [GW(e) a]$^{-1}$ from ternary fission [E3], assuming a yield of 0.85 10^{-4} per thermal fission in ^{235}U [F2] and 2 10^{-4} per thermal fission in ^{239}Pu and ^{238}U [E3]. The estimate assumes that 55% of the integrated number of fissions have occurred in ^{235}U, 41% in ^{239}Pu and 4% in ^{238}U. Other estimates have given production rates of 0.85 PBq [GW(e) a]$^{-1}$ [O1, K2]. An average value of about 0.75 PBq [GW(e) a]$^{-1}$ is assumed here.

61. Estimated generation rates of tritium from activation reactions depend on the assumed concentrations of the parent nuclide. In PWRs it is thought to be mainly due to reactions with the boron in the coolant water which is used for reactivity control. In BWRs it is mainly from boron in control rods. In GCRs it is due to lithium impurities in the graphite and to the presence of water vapour in the core. For HWRs it is principally due to activation of the deuterium moderator and coolant [K1, S7, T2]. The generation rate from activation only exceeds the ternary fission source for HWRs, where the activation rate is some 30 times higher at about 25 PBq [GW(e) a]$^{-1}$. About 1% of the tritium formed in the fuel elements is usually assumed to appear in the coolant circuit and to find its way to effluent streams.

62. Table 18 gives the reported tritium discharges in airborne effluents for LWRs and HWRs. For BWRs the annual normalized release of tritium to atmosphere is fairly constant and averages 3.4 TBq [GW(e) a]$^{-1}$ for 1975–1979, while for PWRs the value varies between 4 and 15 TBq [GW(e) a]$^{-1}$ and the 1975–1979 average is 7.8 TBq [GW(e) a]$^{-1}$. The atmospheric discharges of tritium are seen to average 540 TBq [GW(e) a]$^{-1}$ for HWRs between 1975 and 1979. The discharges of tritium in liquid effluents are shown in Table 19 and the normalized average release derived for 1975–1979 is 1.4 TBq [GW(e) a]$^{-1}$ for BWRs and 38 TBq [GW(e) a]$^{-1}$ for PWRs. For European PWRs with stainless steel fuel clad, the tritium figure in liquid discharges is 300 TBq [GW(e) a]$^{-1}$. Gas-cooled reactors are seen to release 25 TBq [GW(e) a]$^{-1}$ of tritium in liquid discharges averaged between 1975 and 1979. The highest releases of tritium in liquid effluents are from HWRs with an average normalized release of 350 TBq [GW(e) a]$^{-1}$.

63. Bonka [B5] has recently quoted discharges per unit of electrical energy generated of 4 TBq [GW(e) a]$^{-1}$ to air and 40 TBq [GW(e) a]$^{-1}$ to water for PWRs and normalized rates of 2 TBq [GW(e) a]$^{-1}$ (atmospheric) and 6 TBq [GW(e) a]$^{-1}$ (aquatic) for BWRs. For AGRs the atmospheric discharge rate of tritium amounts to about 10 TBq [GW(e) a]$^{-1}$, about the same as the level in

liquid discharges [G6]. In Magnox reactors, the coolant circuit is continually dried to remove water vapour and tritium produced in the circuit appears primarily in the liquid effluent removed by the humidryers.

64. Gorman and Wong [G7] have estimated ^{3}H normalized production in Canadian HWRs to be up to 89 PBq [GW(e) a]$^{-1}$ in the moderator, compared with 0.74 PBq [GW(e) a]$^{-1}$ in the fuel and the normalized emission is given as 630 TBq [GW(e) a]$^{-1}$ for airborne effluents and 260 TBq [GW(e) a]$^{-1}$ in liquid discharges. These are comparable with the normalized atmospheric and liquid discharges reported here averaged over the years 1975–1979. In HWRs the build-up of tritium in the moderator depends upon the irradiation history and on the leakage rate of deuterium from the core, which will be at least 0.5% and perhaps a few per cent of the inventory per year. These conditions affect the environmental releases, as can be seen from Table 19, where there is a general upward trend in tritium in liquid effluents. However, tritium control and removal systems are being developed and releases could be expected to reduce. Averaged over the years 1975–1979 the reported HWR releases to atmosphere are similar to those to the aquatic environment.

4. Carbon-14

65. Discharges of ^{14}C have been of increasing interest in recent years because of the long half-life (5730 a) of the isotope and its significant contribution to the collective dose commitments. Carbon-14 is produced in LWRs and HWRs by (n,α) reactions with ^{17}O present in the oxide fuel and moderator; by (n,p) reactions with ^{14}N present in the fuel as impurities; and by ternary fission. The production rate by ternary fission is virtually independent of reactor design, while the normalized production of ^{14}C by the other routes depends on the fuel enrichment, the relative masses of fuel and moderator, the concentration of nitrogen in the fuel, and the fuel and moderator temperatures. In gas-cooled graphite moderated reactors, the graphite moderator is a major source of ^{14}C production due to the ^{13}C (n, γ) ^{14}C reaction and the ^{14}N (n,p) ^{14}C reaction on nitrogen impurities. Production of ^{14}C from the CO_2 coolant has been estimated to give only a few per cent of the total contribution from all sources. Because of the large moderator mass, ^{14}C is produced mainly from ^{17}O reactions in the moderator in HWRs.

66. The ^{14}C content of LWR fuels per unit energy generated has been estimated at 0.22 TBq [GW(th) a]$^{-1}$ [K2], i.e., 0.67 TBq [GW(e) a]$^{-1}$, assuming a reactor thermal efficiency of 33%. As noted above, such estimates are dependent upon the assumptions on nitrogen impurity levels in the fuel and values up to 1.9 TBq [GW(e) a]$^{-1}$ have been reported [M2]. More recent estimates by Davis [D2] gave values of 0.74 TBq [GW(e) a]$^{-1}$ for both PWRs and BWRs and a study carried out for the Swedish power reactors [L2] estimates 0.52 TBq [GW(e) a]$^{-1}$ for PWRs. Hayes and MacMurdo have estimated ^{14}C normalized production to be 0.22 and 0.55 TBq [GW(e) a]$^{-1}$ for PWRs and BWRs, respectively [H2]. Bonka et al. [B4] gave values of 0.9 TBq [GW(e) a]$^{-1}$ for PWRs and 1.1 TBq [GW(e) a]$^{-1}$ for BWRs. It was estimated in Annex D of the 1977 report [U1] that approximately 30% of the ^{14}C total production is in the moderator for both PWRs and BWRs. This is the likely source of release to the environment from the reactor while, based on experimental studies, most of the content of the fuel appears to be released during reprocessing [S8].

67. In gas-cooled reactors a normalized production within the fuel of 0.96 TBq [GW(th) a]$^{-1}$ has been estimated [K2] which, assuming a thermal efficiency from Magnox reactors of 30%, gives a normalized production of 3.2 TBq [GW(e) a]$^{-1}$. The primary source of ^{14}C is the graphite moderator in which a normalized production of 9.3 TBq [GW(e) a]$^{-1}$ has been estimated. The normalized production in the carbon dioxide coolant by the ^{17}O (n,α) ^{14}C has been estimated at 0.11 TBq [GW(e) a]$^{-1}$ for Magnox and 0.37 TBq [GW(e) a]$^{-1}$ for AGRs [K2]. For HWRs the normalized ^{14}C production is estimated at 0.74 TBq [GW(e) a]$^{-1}$ in the fuel and at 21 TBq [GW(e) a]$^{-1}$ in the moderator [W3].

68. A programme of measurements have been made in the Federal Republic of Germany by the Bundesgesundheitsamt [R1, S15], the results of which are given in Table 20. In European PWRs only a small fraction of the ^{14}C is in the form of CO_2; it is mostly present in methane or other hydrocarbons. The normalized discharge is about 220 GBq [GW(e) a]$^{-1}$ [L1, S15, R1]. For European BWRs the release of ^{14}C appears to be more than 95% as CO_2 and the normalized release rate is about 520 GBq [GW(e) a]$^{-1}$. In a detailed study of the Oyster Creek (United States) BWR Blanchard has measured ^{14}C normalized releases of 220 GBq [GW(e) a]$^{-1}$ from the condenser air ejector and 74 GBq [GW(e) a]$^{-1}$ from building ventilation air [B3]. The same study revealed liquid discharges of ^{14}C at 0.74 GBq [GW(e) a]$^{-1}$. For a PWR, Kahn et al. have reported ^{14}C measured atmospheric discharges of 37 GBq [GW(e) a]$^{-1}$ [K3].

69. Carbon-14 discharges from gas-cooled reactors result from the leakage of the primary coolant (typically a few per cent per day) which contains radionuclides released to the coolant by corrosion of the graphite moderator; estimated normalized releases are 0.22 TBq [GW(e) a]$^{-1}$ for Magnox and 0.63 TBq [GW(e) a]$^{-1}$ for AGRs [P3]. Groome has reported [G6] that the total ^{14}C discharge from Magnox reactors is 3.7 TBq, corresponding to 1.1 TBq [GW(e) a]$^{-1}$, and that AGRs are expected to give similar normalized release.

70. For HWRs it is reported that about half the ^{14}C moderator production is released to atmosphere, giving a normalized release of 10 TBq [GW(e) a]$^{-1}$ [W3], while other reported normalized releases are about 17 TBq [GW(e) a]$^{-1}$ [B21].

5. Iodine

71. The volatile element iodine is produced in the fission process. Its yield is almost independent of whether uranium or plutonium isotopes are undergoing fission. The isotopes of iodine of interest in radiological assessments are ^{129}I ($T_{1/2}$ 1.6 10^{7} a), ^{131}I ($T_{1/2}$ 8.04 d), ^{132}I ($T_{1/2}$ 2.3 h), ^{133}I ($T_{1/2}$ 21 h), ^{134}I ($T_{1/2}$ 53 min) and ^{135}I ($T_{1/2}$ 6.6 h). Owing to the short half-lives of all the isotopes except ^{129}I, equilibrium activity concentrations are achieved quickly and releases depend on the number of fuel cladding failures and coolant leakage rate. Iodine-131 has been studied for many years in view of its mobility in the environment and selective human organ irradiations. In recent years ^{129}I has received more attention, although its release rate is extremely low, because of its contribution to the collective dose commitment through its long availa-

bility in the environment. Of particular interest in fuel reprocessing, ^{129}I is not generally reported in routine discharges from nuclear power plants.

72. Table 21 gives the year by year reported atmospheric discharges of iodines from power reactors in various countries. There are wide differences both in the quantities and in the nuclide composition of the releases due to different waste treatment systems. Table 22 gives the isotopic composition of atmospheric releases of iodine from United States PWRs and BWRs in 1979, together with the normalized release rates. The annual iodine normalized discharge for PWRs has been fairly constant and averages 5.0 GBq [GW(e) a]$^{-1}$ between 1975 and 1979. For BWRs the 1975–1979 averaged normalized discharge is 410 GBq [GW(e) a]$^{-1}$. The comparable figures for HWRs are between 0.08 and 3.1 GBq [GW(e) a]$^{-1}$ [M10]. It is clear from Table 22 that while for PWRs ^{131}I contributes about one third of the total iodine discharge, for BWRs it represents less than 10% of the iodine release. The normalized releases are not typical of any one reactor but reflect the average for the nuclear power industry. Few data are available on the proportions of organic and inorganic forms of the iodine released to the atmosphere, but analysis for power stations in the Federal Republic of Germany shows that usually less than 1% of the iodine released in gaseous effluent is in particulate form [W2].

73. Measurements at six power reactors in the United States indicated that on average 73% of the iodine in the reactor off-gases was in the organic form, 22% was hypoiodous acid and 5% elemental [P7]. All forms were also present in ventilation exhaust air, though the release rate from this source is usually much less than from the reactor off-gas system. The release of iodine isotopes depends strongly on the filtration system used at the plant.

6. Particulates in airborne effluents

74. Radionuclides in particulate form can arise directly or as decay products of fission noble gases or may arise from corrosion of materials in the primary coolant circuit. Aerosols are generated because of primary coolant leaks or because of maintenance work on active components removed from the primary circuit. The air in all areas where aerosols might arise is continually purged and the plenum activity is filtered through high efficiency particulate (HEPA) filters which retain all but the finest aerosols. Releases of particulate activity are very low and the nuclide composition is essentially unique to each operating plant; it depends on the particular impurities in cladding and structural materials, coolant chemistry and fuel failure modes. The releases also vary from time to time because of different operational and maintenance needs and practices.

75. As a consequence, the range of reported nuclides in particulate atmospheric discharges is very large, up to several tens of nuclides at any one plant [D3, B23, B24]. Radionuclides identified and reported at various plants include: ^{7}Be, ^{22}Na, ^{24}Na, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{59}Fe, ^{57}Co, ^{58}Co, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{76}As, ^{88}Rb, ^{89}Sr, ^{90}Sr, ^{91}Sr, ^{95}Zr, ^{97}Zr, ^{95}Nb, ^{99}Mo, ^{99m}Tc, ^{103}Ru, ^{105}Ru, ^{106}Ru, ^{108m}Ag, ^{110m}Ag, ^{113}Sn, ^{115}Cd, ^{122}Sb, ^{124}Sb, ^{125}Sb, ^{123m}Sn, ^{123m}Te, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{139}Ce, ^{140}Ba, ^{140}La, ^{141}Ce, ^{144}Ce, ^{182}Ta.

76. It is thus clear that averaging the nuclide composition of particulate releases by reactors is difficult and may mean little. There is no indication in current discharge data of any one nuclide dominating the release for any given reactor type. In Table 23, the average particulate discharges from reactors year by year are given as the reported sum of activity. Over the period 1975–1979 normalized releases of particulates from PWRs averaged 2.2 GBq [GW(e) a]$^{-1}$, while the BWR normalized releases to atmosphere were 53 GBq [GW(e) a]$^{-1}$. The normalized release from GCRs was 1.0 GBq [GW(e) a]$^{-1}$, from the Argentinan HWR was 0.044 GBq [GW(e) a]$^{-1}$, from the Canadian HWRs 0.9 GBq [GW(e) a]$^{-1}$ [M10] and from the fast reactor Phénix was 4.8 MBq [GW(e) a]$^{-1}$ [L6].

7. Liquid effluents

77. The sources of radionuclides other than tritium in liquid effluents are essentially the same as those described for particulate releases to the atmosphere and the discharges reported are equally as varied. The amount and composition of the discharge depends upon the design and operating practice of the reactor, impurity levels and trace quantities of materials in structural and cladding components. The available discharge data for 1975–1979 are given in Table 24 for operating reactors. Table 25 shows the isotopic composition of liquid effluent discharges for reactors in the United States in 1979. The isotopic composition of liquid effluents from GCRs in the United Kingdom for 1979 is shown in Table 26.

78. The normalized release levels based on the reported discharges for each reactor type using the actual reported generation of electrical energy averaged between 1975 and 1979 are approximately (Table 24):

PWR: 180 GBq [GW (e) a]$^{-1}$
BWR: 290 GBq [GW (e) a]$^{-1}$
GCR: 4800 GBq [GW (e) a]$^{-1}$
HWR: 470 GBq [GW (e) a]$^{-1}$.

Canadian HWR averaged results are some 10 times lower [M10]. The elevated levels for GCRs in the United Kingdom reflect the fact that discharges are made (with the exception of Trawsfynydd) to the marine environment. Swedish reactors also discharge to the sea and have slightly higher normalized liquid effluent release rates than LWRs of the United States or Europe. In Annex D of its 1977 report [U1], the Committee quoted normalized releases for PWRs, BWRs and GCRs of 296, 2220 and 5550 GBq [GW(e) a]$^{-1}$. The average normalized aquatic releases for BWRs over the 5-year period 1975–1979 have been reduced by about an order of magnitude and normalized discharges in the last few years have been even lower. This reduction does not appear to have been due to removal of specific nuclides from the liquid waste streams, but appears to be applicable to all the nuclides constituting the release.

79. In 1979 the isotopes ^{134}Cs and ^{137}Cs represented 10% and 35% of the activity concentration in liquid discharges from the United States PWR and BWR systems, respectively. In Annex D of the 1977 report [U1], the Committee found that caesium isotopes contributed 70% of the discharged activity concentration for BWRs and GCRs, and 30–50% for PWRs. For LWRs the remaining contributions to activity in aqueous discharges arise from a number of nuclides; cobalt isotopes ^{58}Co and ^{60}Co contribute about 65% of the

activity in PWRs and iodine isotopes some 6%. For BWRs cobalt isotopes contributed 10% of the liquid effluent activity concentration in 1979 and iodines 5%.

80. The isotopic ratio of ^{134}Cs to ^{137}Cs from GCRs was 0.28 in 1977, compared with 0.2 found by the Committee in Annex D of the 1977 report [U1]. The increase in ^{134}Cs level probably reflects the increasing fuel irradiation time achieved in Magnox reactors (now approximately 4.5 GW d t^{-1}). As fuel burnup increases, the amount of the long half-life isotope ^{137}Cs increases almost linearly, whereas ^{134}Cs is produced primarily from neutron captures in the stable fission product ^{133}Cs, and, since the amount of ^{133}Cs increases linearly with burnup, the production of ^{134}Cs increases nearly as the square of the fuel burnup. Its radioactive half-life (2.1 a) means that some radioactive decay takes place, but the $^{134}Cs/^{137}Cs$ ratio should increase nearly linearly with burnup. For BWRs the $^{134}Cs/^{137}Cs$ ratio is 0.77 and for PWRs it is 0.57.

81. The release of ^{131}I into liquid effluents contributed about 4.7 GBq [GW(e) a]$^{-1}$ for BWRs in the United States in 1979. In the same year, ^{131}I normalized releases from PWRs average out at 4.6 GBq [GW(e) a]$^{-1}$ in the United States, 4.8 GBq [GW(e) a]$^{-1}$ in Sweden and 6.7 GBq [GW(e) a]$^{-1}$ in western Europe. The liquid discharges of ^{131}I are therefore similar for BWRs and PWRs and compare with the atmospheric normalized releases of ^{131}I of 42 GBq [GW(e) a]$^{-1}$ from BWRs, and 1.9 GBq [GW(e) a]$^{-1}$ from PWRs. The normalized releases of other iodine isotopes in liquid effluents amount to about 3 GBq [GW(e) a]$^{-1}$ from ^{133}I and ^{135}I in PWRs, and 2 GBq [GW(e) a]$^{-1}$ in BWRs.

82. There is a wide range of activation products and fission products reported in liquid discharges and results vary widely from reactor to reactor. It is apparent that one or two nuclides consistently contribute to the discharge from LWRs. Amongst these, ^{24}Na is widely reported and contributes to radionuclide discharges from both BWRs and PWRs. Also ^{58}Co discharges are as high or higher than ^{60}Co discharges and ^{89}Sr contributes to BWR liquid effluents.

83. For GCRs the next most significant contributions to aqueous releases after caesium are from ^{35}S and ^{90}Sr. The ^{35}S is collected in the humidryers which remove water from the gas circuit and appears in the liquid effluent stream at a normalized release of 547 GBq [GW(e) a]$^{-1}$, compared with 170 GBq [GW(e) a]$^{-1}$ in gaseous releases (paragraph 58).

B. LOCAL AND REGIONAL COLLECTIVE DOSE COMMITMENTS

84. National authorities usually require an environmental monitoring programme in the vicinity of a nuclear power plant to be carried out either by the operator, or by another competent agency, or both. Detailed investigative studies have been reported [K3, E4, B3] and, in general, levels of radioactive contamination are not readily detectable except in the immediate vicinity of the plant. Dose assessments for the population, therefore, rely on modelling the environmental transport and transfer of radioactive materials. In recent years trajectory modelling has been developed for long-range atmospheric dispersion calculations in which historical meteorological data is used to calculate the paths of discrete masses of air [Z1]. The Committee has felt these models are not yet sufficiently developed to offer advantages over the models described in Annex A.

85. The object of the Committee in making its present assessment is to give a representative value of the collective dose commitments per unit electric energy generated by nuclear power stations and to reflect the levels of dose received by most exposed individuals. The results will not apply to any one reactor or location and the collective dose commitments should not be applied to the known discharge rate of a given reactor to obtain estimates of total health detriment. To undertake such a study the values of parameters in the models used would need to be specific to that site (for example, for the meteorological dispersion) and to the particular local terrestrial pathways.

86. In the following sections, the normalized discharges of radionuclides found in the previous sections are assessed at a model reactor site using the methodologies outlined in Annex A. The site is most representative of the areas of Europe and the North-Eastern United States, as those areas contain the majority of the power producing reactors. Agricultural production patterns and population distribution are most typical of those areas. The parameter values in the models necessary for the assessment of each of the source terms are described in turn below.

1. Fission noble gases

87. The exposure of the population from noble gas discharges to the atmosphere is by external β- and γ-radiation. For β-irradiation a semi-infinite cloud model is adequate, but for γ-exposure, because of the long mean free path of γ rays in air, a finite cloud model must be used. The models are described in Annex A. The finite cloud-γ calculation integrates contributions to the photon fluence from radioactive source terms throughout the volume of the plume. For the present calculations the computer code ESCLOUD has been used [J2] which is essentially similar to other codes developed in the Federal Republic of Germany by Vogt [V1] and Rohloff [R2] and in the United States at the Oak Ridge National Laboratory [M1].

88. The energy deposition build-up factors for the γ-exposure at each downwind distance of interest were taken from Chilton [C2]. The absorbed dose in air is calculated using values of absorbed dose in air per unit fluence [H1] and the ratios of the absorbed doses in human body organs and tissues per unit absorbed dose in air have been obtained from Poston and Snyder [P4]. The effective dose equivalent is calculated using the procedure outlined in Annex A for presentation of summary results. The absorbed doses in skin have been taken into account using a weighting factor of 0.01. The nuclear decay schemes have been taken from Nichols [N11, N12], Nair [N13] and Despres et al. [D9]. These same data sources were used for the β-energies for skin dose equivalent calculations.

89. The meteorological data applicable to the model site are given in Table 27. The frequency distribution of Pasquill meteorological categories is assumed to be the same in each sector, which is an approximation to observations. A representative frequency distribution of wind directions has been taken. Rain is only assumed to occur for 3.5% of the time and only in near neutral conditions. A typical population distribution for Northern Europe and North-Eastern United States has

been taken and the summary of individuals in distance bands and cumulative population all round the site are also given in Table 27. The cumulative population within a radius of 2000 km from the site is 260 million people, giving an average population density of about 20 km^{-2}. The population density within 50 km of the site is an average of about 400 km^{-2}. An effective height of release of 30 m has been chosen for collective dose calculations, although the choice of height has only a secondary influence on the results. The individual dose to a member of a critical group is of course highly dependent upon stack height.

90. Using the normalized releases for PWRs from Table 12 for noble gas atmospheric releases and the nuclide composition from Table 13, the normalized collective absorbed dose commitments averaged between 1975 and 1979 from the model PWR facility have been calculated and are shown in Table 28. The normalized release term is 430 TBq [GW(e) a]$^{-1}$ and only those isotopes which contribute significantly to the collective absorbed doses are presented. The growth of daughter nuclides, e.g., $^{88}Kr \rightarrow {}^{88}Rb$ has been included in the calculations.

91. The normalized collective effective dose equivalent commitment totals 4.2 10^{-2} man Sv [GW(e) a]$^{-1}$, compared with the Committee's previous assessment in Annex D of the 1977 report [U1] of 2.5 10^{-2} man Sv [GW(e) a]$^{-1}$, even though releases have been reduced by about a factor of 2. About 80% of the collective dose commitment is given by the single isotope ^{133}Xe. Xenon-135 is responsible for about 11% of the collective dose commitment and ^{88}Kr for a further 4% of the total. The difference in the assessment is mainly due to the somewhat higher population density within the first few hundred km of the site (towards 300 km^{-2}) as compared with a value of 100 km^{-2} used previously. This reflects the closer siting of reactors to centres of population in the last decade. In Table 29 the spatial distribution of collective dose for the PWR is shown; of the collective dose, 90% is accumulated within 500 km, and the bulk of the contribution (nearly 60%) arises between 100 and 500 km. There is little contribution from inhalation of radioactive daughter products. The estimates made here include an allowance for the shielding from buildings and fraction of time spent outdoors.

92. For BWR normalized releases for the years 1975–1979, a value of 8800 TBq [GW(e) a]$^{-1}$ was taken from Table 14, together with the isotopic composition shown in Table 15, and the resulting collective dose commitments are shown in Table 30. The normalized collective effective dose equivalent commitment is 1.9 man Sv [GW(e) a]$^{-1}$, compared with the Committee's previous estimate in Annex D of the 1977 report [U1] of 5.5 man Sv [GW(e) a]$^{-1}$. The main isotope contributing to the normalized collective effective dose equivalent commitment is ^{88}Kr ($T_{1/2}$ 2.8 h) giving about 50% of the total with its daughter isotope ^{88}Rb ($T_{1/2}$ 15.4 min). This ^{88}Rb component is only due to the decay of the ^{88}Kr in the atmosphere. Most of the remainder of the normalized collective effective dose equivalent commitment arises from: ^{135}Xe ($T_{1/2}$ 9.2 h), 21%; ^{138}Xe ($T_{1/2}$ 17 min), 14%; ^{87}Kr ($T_{1/2}$ 1.3 h), 7% and ^{133}Xe ($T_{1/2}$ 5.27 d), 5%. The growth of ^{138}Cs ($T_{1/2}$ 32.2 min) from decays of ^{138}Xe is included in the dose calculations in Table 30. The collective dose commitments due to noble gases include a contribution from inhalation of the ^{88}Rb isotope. Only those isotopes contributing significantly to the collective dose commitments are included in Table 30.

93. The spatial distribution of the normalized collective effective dose equivalent commitment over distance for the model BWR is shown in Table 31. More than 80% of the collective dose is accumulated within 50 km of the site, and 40% within 10 km. This behaviour is caused by the dominant contribution of ^{88}Kr which decays by a half-life about every 40 km of travel distance, and by the fact that all the shorter-lived nuclides decay within the first tens of kilometres.

94. Martin and Nelson computed the collective doses to populations within 80 km of eight BWRs in the United States [M3]. The collective absorbed whole-body dose was 9 man Gy from 1.85 GW(e) a of power generation, corresponding to 5 man Gy [GW(e) a]$^{-1}$. There has been a very marked tendency for releases to be reduced partly as newer plants come into operation, and Martin's estimate is consistent with the assessment made here when allowance is made for the reduction in releases.

95. In summary, the normalized collective effective dose equivalent commitment from noble gas releases is 0.63 man Sv [GW(e) a]$^{-1}$, based on the weighted electricity production by PWRs and BWRs as a fraction of total nuclear generation over the years 1975–1979. The annual effective dose equivalents to most exposed individuals of hypothetical critical groups have been calculated at 40 μSv for the model BWR and more than 100 times lower for PWRs, taking an average over the first 2 km from the site. Reported levels of annual dose equivalent rates to most exposed individuals are generally a few tens of μSv, although one or two plants can give figures of a few hundred μSv [L1, L6].

2. Activation gases

96. The primary interest has been in the release of ^{41}Ar which, because of its short half-life (1.83 h), contributes most of its dose within a few tens of kilometres of the site, although the exact result is clearly highly dependent upon the close-in population density. The normalized release of ^{41}Ar from GCRs between 1975 and 1979 is taken from Table 17 as 3240 TBq [GW(e) a]$^{-1}$ and the associated normalized collective effective dose equivalent commitment from the model site is 0.95 man Sv [GW(e) a]$^{-1}$. Clarke and Wilson [C1] have reported collective doses in the United Kingdom which correspond to values between 0.3 and 1.0 man Gy [GW(e) a]$^{-1}$ and individual dose equivalents of up to a few hundred μSv for early GCRs, depending on the site, all of which are fairly remote. The weighted normalized dose commitment, allowing for GCR nuclear generation as a fraction of all electricity produced over the years 1975–1979, is about 0.1 man Sv [GW(e) a]$^{-1}$. For reasons of convenience, the doses arising from releases of ^{41}Ar from LWRs were included with the doses due to the fission noble gases (paragraphs 87 to 95).

97. The consequences of the release of ^{35}S from GCRs have been studied in some detail by environmental monitoring. The isotope is released in the form of carbonyl sulphide (COS) which has a very low deposition velocity and a slow reaction rate in air. The major route of exposure of the population is through the ingestion of milk; estimates of collective whole-body dose per unit activity released have been

made by Linsley [L7] which yield 2.2 10^{-4} man Gy $(GBq)^{-1}$ for typical United Kingdom conditions. Taking a normalized release rate of 0.17 TBq [GW(e) a]$^{-1}$ thus gives rise to 3.7 10^{-2} man Gy [GW(e) a]$^{-1}$ and the contribution to collective effective dose equivalent commitment weighted by the fraction of nuclear electricity from GCRs is 3.8 10^{-3} man Sv [GW(e) a]$^{-1}$.

3. Tritium

98. The transfer of tritium between the atmosphere and the terrestrial environment is particularly complex because of the hydrogen cycle in biological systems. Tritium released to the environment will make a contribution to the collective dose commitment by becoming globally dispersed and this is considered in chapter V. The assessment of the local and the regional collective doses from atmospheric discharges of tritium is performed slightly differently from the method outlined in the introduction to this Annex.

99. To assess the collective dose, a specific activity model has been assumed for transfer through the terrestrial environment. It is assumed that tritium in man and in the terrestrial environment rapidly achieves equilibrium with the tritium in the atmosphere. The specific activity of tritium taken into the body is equal to that in atmospheric water vapour at the point of interest. The specific activity of tritium in atmospheric water vapour is determined by the atmospheric dispersion to the point of interest and the concentration of water vapour in the atmosphere (8 g m^{-3} annual average value).

100. This specific activity approach assumes that all water taken in by humans, whether by inhalation and absorption through the skin or by ingestion of water or foodstuffs in normal diet, is contaminated at the specific activity appropriate to the point of interest. This is a conservative assumption. It also fails to distinguish any temporal distribution in the dose which may be extended over some considerable time. The dose is, therefore, only assessed on a specific activity model for the period of discharge. The annual intake of water has been obtained from the data given by ICRP in its publication 23 [I5]. The total water intake rate by all routes is assumed to be 3 kg d^{-1} for men and 2.1 kg d^{-1} for women; the respective inhalation and ingestion intake rates have been assessed assuming an annual average concentration of water vapour in air of 8.1 g m^{-3} and a mean adult inhalation rate of 20 m^3 d^{-1}. The intake by inhalation is assumed to be accompanied by an equal intake by skin absorption so that the net annual intakes of H_2O become 130 kg inhaled and 800 kg ingested.

101. The collective whole-body absorbed dose commitment to the local and regional population on this basis is evaluated, assuming normalized atmospheric discharges taken from Table 18 of 3.4 TBq [GW(e) a]$^{-1}$ for BWRs, 7.8 TBq [GW(e) a]$^{-1}$ for PWRs, 11 TBq [GW(e) a]$^{-1}$ for GCRs and 540 TBq [GW(e) a]$^{-1}$ for HWRs. The local and regional collective doses per unit electrical energy generated are shown in Table 32. The ingestion pathway appears to be more important by a factor of about 6 than the inhalation pathway and the collective absorbed doses to all body organs may be regarded to be the same as the collective effective dose equivalent because of the assumption of the models.

102. The collective effective dose commitment varies between 0.04 and 5.6 man Sv [GW(e) a]$^{-1}$. The previous estimation in Annex D of the 1977 report [U1] gave a normalized collective dose commitment of 4 10^{-4} man Gy [GW(e) a]$^{-1}$ for PWRs and a normalized discharge of 7.4 TBq [GW(e) a]$^{-1}$. The reason for the difference in collective dose commitment per unit discharge of a factor of about 200 higher in the present estimate is due to the previous estimate being given only for the local population within 100 km (about 25% of the local and regional collective dose); to the fact that the previous estimation only considered inhalation (about 15% of total intake); and to the greater by a factor of about 4 population density. In summary, the normalized collective effective dose equivalent commitment for atmospheric releases of tritium, weighted by the proportion of electricity generated, is 0.46 man Sv [GW(e) a]$^{-1}$. For the model site taken by the Committee, individual annual effective dose equivalents from LWRs and GCRs are about 10^{-6} Sv, while the HWR model results are about 10^{-4} Sv.

103. For tritium in liquid effluents the model river site (Table 38) gives a collective whole-body dose commitment per unit activity discharged of 8.1 10^{-4} man Gy TBq^{-1} on the assumption that the river is used as a source of drinking water. Using the normalized discharges for 1975–1979 in Table 19 (1.4 TBq [GW(e) a]$^{-1}$ for BWRs, 38 TBq [GW(e) a]$^{-1}$ for PWRs and 350 TBq [GW(e) a]$^{-1}$ for HWRs) leads to collective effective dose equivalent commitments of 1.1 10^{-3} man Gy [GW(e) a]$^{-1}$ for BWRs, 3.1 10^{-2} man Gy [GW(e) a]$^{-1}$ for PWRs and 0.28 man Gy [GW(e) a]$^{-1}$ for HWRs. The models indicate dose commitments 10 times lower for aquatic effluents than for atmospheric effluents per unit release, while the reported release data indicate the atmospheric pathways as the more significant. The contribution to the normalized collective effective dose equivalent commitment from liquid releases of tritium weighted by generation of each reactor type is 0.04 man Sv [GW(e) a]$^{-1}$.

4. Carbon-14

104. The local and regional collective doses due to ^{14}C releases from reactors only represent a small proportion of the total dose commitments. The main significance of ^{14}C is due to its entry into the carbon cycle and resulting global dispersion, leading to long-term irradiation which is considered in chapter V. The assessment of the first pass regional collective dose commitments may be made using the same specific activity approach that was used for tritium in the preceding subsection. For a release to atmosphere the specific activity will be determined by the atmospheric dispersion and the carbon concentration in the atmosphere, taken as 0.16 g m^{-3}. The intake of carbon is assumed to be that given by ICRP in publication 23 [I5], that is, 93 kg a^{-1} by ingestion and 1.2 kg a^{-1} by inhalation, based on the average level of carbon in the atmosphere and assuming a breathing rate of 20 m^3 d^{-1}. As with tritium, it is assumed that all components of the diet are contaminated at the specific activity applicable to the downwind distance of interest from the source.

105. The form of release of carbon-14 is taken to be as CO_2. The collective whole-body absorbed dose commitment, corresponding to the production of 1 GW(e) a, for the model site and discharges of 518 GBq for the model BWR, 222 GBq (PWR), 1100 GBq (GCR) and 17 TBq (HWR) are given in Table 33. The results range from 0.9 to 30 man Gy, and it is clear that the inhalation pathway accounts for little of the dose. The

study of the Nuclear Energy Agency of the OECD [N14] has given a regional collective effective dose equivalent commitment per unit activity associated with the release of ^{14}C of 0.68 man Sv TBq^{-1}. However, the majority of the collective effective dose equivalent commitment from the release will arise from the global contribution. The present estimates must be qualified for two reasons. Firstly, the figures will be overestimates because of the assumption of a specific activity model; and, secondly, the assumption of all components of diet being contaminated at the specific activity corresponding to that point means that the time distribution in the delivery of the dose is ignored. The normalized collective effective dose equivalent commitment, weighted by generation of electric energy, is 2.8 man Sv [GW(e) a]$^{-1}$. For the model site, the annual effective dose equivalents to most exposed individuals would be 2 μSv for the PWR, 5 μSv for the BWR, 10 μSv for the GCR and 200 μSv for the HWR.

5. Iodine

106. Releases of radioactive iodine from nuclear power plants are small and there is only a small contribution to the total local and regional collective dose commitments from reactor discharges. Iodine-129 because of its long half-life enters the global cycle for iodine and potentially irradiates the global population for many millions of years. The release of ^{131}I contributes only to the local and regional collective doses but its assessment is complicated by the chemical form in which the iodine is released, i.e., elemental, organic or particulate. Elemental iodine readily deposits on vegetation and enters the terrestrial foodchains. The deposition rate of organic iodine is between 200 and 100 times less per unit air concentration than that of the elemental form [H3, S9]. The exact value of deposition velocity for a particular circumstance depends upon the size of particles, the reactivity of the vapour, the nature of the underlying surface and the meteorological conditions. In this assessment 75% of the iodine released is assumed to be in organic form and 25% elemental (subsection III.A.5).

107. A representative deposition velocity of 5 10^{-3} m s^{-1} is used here for elemental iodine and is also applicable for particulates with mean aerodynamic diameters of a few micrometres depositing on a wide variety of surfaces. In particular circumstances with defined physico-chemical forms and specific vegetation, more appropriate values would be needed. In fact, elemental iodine becomes absorbed onto aerosols in the atmosphere and its behaviour is then governed by that of the aerosol. For organic iodine a deposition velocity of 5 10^{-5} m s^{-1} has been chosen as typical. These deposition velocities refer to removal from the plume and once the activity is removed, only a certain fraction is found on the surface of the vegetation.

108. Hoffman has shown that care must be taken to distinguish between the total removal from the air, and the fraction intercepted by the vegetation [H4] and that many experiments have been misinterpreted. Considerable variation has been observed in the measured values of interception factors and removal rates from plant surfaces [B6, G8, H4]. An interception fraction of 0.2 is used here as a compromise between the somewhat higher fraction for dry deposition and the lower one for wet deposition. The remaining fraction of the deposit, 0.8, is transferred directly to the ground surface. The removal of the radionuclides from plant surfaces due to the actions of wind and rain and plant growth is taken to occur with a half-life of 14 days for pasture grass [B6] and 30 days for all other plants [G8].

109. Calculations have been performed for iodine releases from the model PWR and BWR reactors into the model environment, using the computer codes developed by Simmonds et al. [S10] which provide a methodology for dealing with the assessment of the intakes of radionuclides by grazing animals and the transfer to human diet. The concentration factor for iodine in root vegetables, pasture and grain is assumed to be 0.02 and the translocation fractions to the edible portions are 0.1 for vegetables and grain [N15, F3].

110. The consumption rate of grass (dry weight) by cows is taken as 5.1 10^3 kg a^{-1}, the half-time in the bovine GI tract is 15 h, the mean-life of milk cows is taken as 6 a, the weight of meat 230 kg and the milk production rate 10 l d^{-1} [S11]. The time integrals of activity in animal products derived from cows grazing on contaminated pasture have been given [C10]. Assuming a unit deposition rate (1 Bq m^{-2} s^{-1}), the time-integrated concentrations of ^{131}I in beef, liver and milk are 4.4 10^4, 4.4 10^4 and 7.5 10^4 Bq a kg^{-1}, respectively.

111. The dosimetric and metabolic data for ^{131}I have been derived from Adams [A1] and ICRP publication 30 [I2]. The model site has production rates of foodstuffs typical of Europe and North-Eastern United States at the typical densities of production. The density of cattle in grazing areas is over 200 km^{-2} and averages out at about 15 km^{-2} over an area of radius 2000 km, similar to the average of values given by Eckerman et al. for the states of New York, Pennsylvania, Washington, Virginia, Illinois and Ohio [E2]. Vegetable production is given as a fraction of land, leading to 2 10^{-2} km^2 per km^2 averaged over the same area. The collective absorbed dose commitments are shown in Tables 34 and 35 for 1975–1979 normalized emissions to atmosphere of iodine: 410 GBq [GW(e) a]$^{-1}$ for BWRs and 5.0 GBq [GW(e) a]$^{-1}$ for PWRs, respectively (Table 21). HWR normalized releases appear to be similar to those for PWRs. The isotopic composition of the iodine released was assumed to be that averaged over United States PWRs and BWRs (Table 22).

112. For PWRs the normalized collective effective dose equivalent commitment is assessed at 6.6 10^{-4} man Sv [GW(e) a]$^{-1}$ and the collective thyroid dose at 2.1 10^{-2} man Gy. The largest component of the collective dose comes from inhalation, with ingestion contributing almost equally; most of the ingestion dose arises from milk. In the case of BWRs the normalized collective effective dose equivalent commitment is 1.9 10^{-2} man Sv [GW(e) a]$^{-1}$ and the normalized collective thyroid dose is 5.9 10^{-1} man Gy [GW(e) a]$^{-1}$. The fractional contributions by the ingestion pathways are smaller than for the PWR. The main route of exposure for ^{133}I and ^{135}I is, as expected, inhalation although these isotopes contribute about 22% to the collective thyroid dose for BWRs and 4% for PWRs. The normalized collective effective dose commitment averaged over the proportions of electricity generated is 6.5 10^{-3} man Sv [GW(e) a]$^{-1}$. Representative annual effective dose equivalents for individuals at about 1 km from the model site are 10 μSv for BWRs and some 30 times lower for PWRs.

6. Particulates in airborne effluents

113. As reported in subsection III.A.6, the quantities of radionuclides in particulate releases are highly variable between reactors of the same type and indeed for the same reactor from year to year. Also, there are several tens of nuclides identified which contribute significantly to the releases. The approach adopted here is to release the normalized discharge rate from PWRs and BWRs and assume that the rate is composed of equal amounts of activity concentration from a range of the nuclides most frequently reported to be present in atmospheric discharges. Again the releases take place from the model facility and the collective dose commitments evaluated via all the pathways. The transfer data for the nuclides in environmental materials have been taken from the work of Ng et al. [N15, N16], Fletcher and Dotson [F3] and Linsley et al. [L3].

114. Much of the external contamination on plants when harvested is removed before consumption by man (e.g., washing or milling of grain). There is recent evidence that 90% of the external contaminant is removed during preparation and processing before consumption by man, based on the observations on values for the transfer of plutonium from the outside surfaces of grain to flour [A2]. Other pathways which need to be considered are the root uptake of radionuclides migrating downwards through the soil, their resuspension from the ground onto plant surfaces, and their translocation from the surfaces of plants to the internal tissues. In addition, account must be taken of the regular removal of radionuclides by harvesting crops. A mean growing period of 100 days is assumed here.

115. The nuclides considered were: ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{65}Zn, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{95}Zr, ^{95}Nb, ^{124}Sb, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{140}Ba, ^{140}La, ^{141}Ce, and ^{144}Ce. The normalized total particulate release for PWRs was 2.2 GBq [GW(e) a]$^{-1}$, and that for BWRs was taken as 53 GBq [GW(e) a]$^{-1}$ corresponding to the 1975–1979 averaged discharges for release (Table 23). The resulting collective absorbed dose commitments per unit electrical energy generated are shown in Table 36. For both BWR and PWR the highest collective organ dose commitments are to bone lining cells, although most organs and tissues receive similar doses. In the case of GCRs, the normalized releases and resulting doses are similar to those for PWRs, while those for HWRs are about an order of magnitude lower.

116. For PWR releases the sum of the collective effective dose equivalent commitments by all routes is 0.012 man Sv [GW(e) a]$^{-1}$, most of which arises from the external dose and ingestion from ground deposits of activity. Results for GCR releases are essentially the same. The major contributions to this ground-γ dose are ^{137}Cs and ^{60}Co (80%) most of the remaining dose coming from ^{134}Cs and ^{54}Mn. The dose distribution through all the body organs is similar because it is from penetrating external radiation. Some 95% of the collective effective dose equivalent commitment is received in the first 50 years following ground deposition. The nuclides contributing to the collective effective dose equivalent commitment via grain are ^{90}Sr (30%), ^{134}Cs (30%), ^{137}Cs (30%) and ^{60}Co (5%). For the green and root vegetable routes, 80% of the collective effective dose equivalent commitment arises from ^{90}Sr and the remainder from ^{137}Cs. For beef, the two caesium isotopes and ^{90}Sr contribute equally to the collective effective dose equivalent commitment. In the case of the BWR releases the time distribution of the collective effective dose equivalent commitment is the same as for the PWR and the same isotopes and routes are important; the collective effective dose equivalent commitment is 0.29 man Sv [GW(e) a]$^{-1}$. The normalized result for all reactors thus becomes 0.1 man Sv [GW(e) a]$^{-1}$. Individual annual effective dose equivalents amount to 1 nSv for BWRs at typically 1 km; corresponding values for exposures to PWR releases are 10 times lower.

7. Liquid effluents

117. For releases of radionuclides into fresh water the receiving medium is usually a river or a lake, and the pathways leading to human exposures are drinking water, ingestion of fish, irrigation leading to contamination of foodstuffs, and external irradiation from sediments. For discharges to the marine environment it is usually sufficient to consider the ingestion of foodstuffs, including ocean fish and crustacea. Other pathways exist, such as swimming in contaminated waters and the consumption of unusual foodstuffs, but these contribute little to the collective dose commitments [P1, B7].

118. The collective doses resulting from discharges to the aquatic environment are more difficult to estimate using generalized models than are those from atmospheric releases. This is because the local dispersion from the discharge point is very dependent upon particular site characteristics, such as sedimentation and water volume flow patterns. The collective dose from a reactor discharge is, therefore, highly variable depending upon how much activity is transferred to the areas where foodstuffs are significantly harvested. Site-specific assessments have identified the critical pathways to man and estimated doses to critical groups for reactor liquid discharges. The reported annual doses to the critical group are estimated to be in general less than 5 μGy [H5, M4, B7, M10, W3].

119. Mitchell suggests that the annual collective dose to the United Kingdom from radioactive liquid effluents into the sea had come into equilibrium in 1976 [M5]. On this basis the collective whole-body absorbed dose to the United Kingdom population in 1976 resulting from the discharge of about 8 TBq of ^{137}Cs each year from all the coastal nuclear stations during the period 1974–1976 can be estimated at about 0.2 man Gy. Hetherington has estimated [H5] that the collective whole-body dose per unit discharge to the population of Europe is 0.16 man Gy TBq^{-1} at equilibrium for a continuous discharge of ^{137}Cs. This leads to an estimate of 1.0 man Gy as the collective absorbed whole-body dose to the United Kingdom and Europe for 1979 total ^{137}Cs discharges from United Kingdom reactor liquid effluents and corresponds to 0.24 man Gy [GW(e) a]$^{-1}$.

120. The Committee, in Annex D of the 1977 report [U1], discussed the difficulty of assigning values to parameters in assessing liquid effluents, in particular, the water utilization rate and flow rates for rivers, the fish production rates and sedimentation rates. Any assessment of a given site must, therefore, utilize site-dependent values of parameters and even models developed specifically to model the movements of activity in the local aquatic environment. Generalized models for a river and a typical marine environment have been described in Annex A and these models are

now applied to a model site either discharging into a river or into local coastal waters.

121. For the present assessment, the site environmental characteristics are chosen to be representative of the receiving media in northern Europe and the northern states of the United States and do not refer to any one particular site. The results are intended to be indicative of the collective dose commitments per unit of electricity generated by nuclear power stations and, therefore, the collective dose per unit discharge should not be combined with the discharges reported for a specific site in an attempt to estimate the collective dose commitment from that site.

122. The 1975–1979 normalized releases for PWRs, BWRs and GCRs given in Table 24 with the isotopic composition shown in Tables 25 and 26 are used as source terms for the model sites and shown in Table 37. Only those nuclides which contribute significantly to the collective dose from each installation are shown. Also shown in Table 37 are the concentration factors assumed for the freshwater and marine environments. The concentration factor is the quotient of the activity per unit weight of the animal considered (fish, crustacea, etc.) and the activity per unit volume of filtered water [Bq t^{-1}/(Bq m^{-3})]. The factors are based on dry weight of sediments and wet weight of the edible fraction of other materials. The marine concentration factors are taken from Ancellin et al. [A3] and the International Atomic Energy Agency work on models for use in sea dumping of radioactive wastes [I6].

123. The freshwater concentration factors for fish were taken from Thompson et al. [T3] and those for sediments from Booth's model [B8]. The quantities of fresh water extracted from the model river site for drinking purposes have been estimated assuming that populations bordering the river take their water at a rate per individual of 1.5 10^{-8} m^3 s^{-1}, given for a study of the Rhine-Meuse region by Bayer [B9]. The model river has three sections below the point of discharge and the relevant model data are given in Table 38.

124. Values in Table 38 are selected to be representative values and many vary by several orders of magnitude in both directions for any given site. Nevertheless they are deemed to reflect the situation averaged over several countries [B9]. The population along the sides of the river is assumed to be 20 km^{-1} for the purpose of calculating external exposure from sediments. This population is assumed to spend 200 h a^{-1} on average on the river bank [B9]. The doses per unit activity ingested were again consistent with Adams [A1] and ICRP publication 30 [I2].

125. The collective absorbed dose commitments for normalized releases to the freshwater receiving medium, the model river, are shown in Table 39 for PWR and BWR systems. The total normalized collective effective dose equivalent commitment for the BWR is estimated at 2.8 10^{-3} man Sv [GW(e) a]$^{-1}$; two-thirds of this dose comes from drinking water and one-third from fish consumption. For drinking water 20% of the collective effective dose equivalent commitment is from ^{131}I and nearly all the dose from ingestion arises from caesium isotopes. For the PWR the total normalized collective effective dose equivalent commitment is 1.0 10^{-3} man Sv [GW(e) a]$^{-1}$ with drinking water giving 78% of the total. The contribution from drinking water is given almost equally by ^{131}I, ^{60}Co, ^{134}Cs and ^{137}Cs. For ingestion, the caesium isotopes give more than two-thirds of the total normalized collective effective dose equivalent commitment. The normalized collective effective dose equivalent commitment, weighted for electricity generated, is 1.4 10^{-3} man Sv [GW(e) a]$^{-1}$.

126. For releases to salt water it is necessary to consider the dispersion close to the site where the effects of sedimentation may lead to a reduction in the activities which become available for dispersion on a regional scale. Using the local marine model described in Annex A, the values of parameters adopted for the model site are as follows: volume, 2 km^3; water depth, 15 m; rate of sedimentation, 100 g m^{-2} a^{-1}; suspended sediment load, 5 g m^{-3}; rate of renewal of water in the compartment, 50 a^{-1}. These values have been taken as typical of a coastal marine site from the data detailed by Booth et al. [B7] and the study for the Commission of the European Communities by the National Radiological Protection Board of the United Kingdom jointly with the Commissariat à l'Energie Atomique of France [C10]. In general, from 50% to 90% of the activity released to the local marine environment becomes available for the regional dispersal.

127. In the regional dispersal model the sedimentation rates in coastal waters on the continental shelf vary in the range of about 10 to 100 g m^{-2} a^{-1} [A3, I6] and the suspended sediment loads are of the order of 0.1 to 6 g m^{-3} [A3, I6, C10], with the lower values applying to the ocean compartments. At any given time the activity in the water column is partitioned between the water phase and the suspended sediment material. The fraction of activity remaining in solution will be high for elements such as caesium which do not concentrate on sediments, but for other nuclides such as ruthenium or plutonium the fraction remaining in the water phase can be reduced by a factor of 10 for suspended sediment loads approaching 100 g m^{-3} [H6].

128. Fish-catch data and production of other marine foodstuffs vary greatly from location to location. Reported landings of fish have been obtained from the Conseil International pour l'Exploitation de la Mer [C3]. Typical values from the Baltic Sea are 4.6 10^5 t a^{-1} and the North Sea catch is 2 10^6 t a^{-1}, while some 3 10^5 t a^{-1} are taken from the Arctic ocean. Catches of molluscs and crustacea vary in the range of 8 10^3 t a^{-1} for the Baltic and perhaps 2 10^5 t a^{-1} for the Bay of Biscay and the southern North Sea.

129. Using the normalized discharge rates given in Table 37, the collective effective dose equivalent commitments from the notional BWR, PWR and GCR on the model coastal site have been computed using the regional marine model prepared for the Commission of the European Communities [C10, C8]. The notional release was into the receiving waters of the eastern English Channel. This area is representative of many sites both in Europe and North America.

130. The resulting collective absorbed dose commitments are shown in Table 40. The dose per unit intake was again derived from the ICRP 30 models and metabolic data [I2] and the results presented by Adams which uses the same basic data [A1]. The collective doses were estimated by taking the time integrals of the activity in the filtrate fraction of the water in each compartment and multiplying by the concentration factors already listed for the marine environment in Table 37. The edible fraction of the marine foodstuffs has been taken as 50% for fish, crustacea and molluscs [C10].

131. A large proportion of the collective dose commitment for GCRs arises from isotopes of caesium. The radionuclide releases from the gas-cooled reactors are higher because they are essentially all coastal sited, whereas the normalized discharge figures for LWRs are based largely on inland siting experience. The collective effective dose equivalent commitment for gas-cooled reactors is 0.18 man Sv [GW(e) a]$^{-1}$ which can be compared with the estimate by Hetherington [H5] of 0.24 man Sv [GW(e) a]$^{-1}$. For BWRs the corresponding collective effective dose equivalent commitment is 4.2 10^{-2} man Sv [GW(e) a]$^{-1}$, mainly coming from ^{65}Zn in molluscs, and the remainder from fish, with the largest contributions from caesium and ^{65}Zn. The collective effective dose equivalent commitment for PWRs is 6.0 10^{-3} man Sv [GW(e) a]$^{-1}$, about one-third coming from caesium in fish and many of the isotopes contributing to the mollusc component. The normalized collective effective dose equivalent commitment, weighted by electricity production of each reactor type is 3.5 10^{-2} man Sv [GW(e) a]$^{-1}$ for marine discharges.

132. The collective effective dose equivalent commitment from caesium isotopes is not very dependent upon the location at which they enter northern European waters, the variation for unit discharge being between 150 Bq (integrated intake) for releases into the eastern Irish Sea, 130 Bq for the English Channel (east), 120 Bq for the southern North Sea and 27 Bq for a release into the Bay of Biscay. These results are per unit release into the relevant regional compartment from the local model. The results obtained may certainly be taken as typical of Europe and the collective effective dose equivalent commitment is essentially all delivered over the first few years after discharge.

133. Again it must be emphasized that the figures given in Tables 39 and 40 are representative of the generation of unit quantity of electricity and should not be applied to a specific site where particular environmental pathways exist which have not been considered here and might lead to significant changes of the collective dose contributions. The normalized collective effective dose equivalent commitment due to aquatic discharges has been estimated on the assumption that half the discharges are to freshwater and half to marine environments. The result amounts to about 0.02 man Sv [GW(e) a]$^{-1}$.

C. REACTOR ACCIDENTS

Collective dose commitments due to releases of radioactive materials in accidents

134. There have only been two reactor accidents which are known to have caused measurable irradiation of the public: Three Mile Island in March 1979 and the Windscale reactor accident in October 1957. The latter accident was at a military reactor, but the collective dose commitments have been included here on the grounds that the reactor contributed partly to the development of gas-cooled civil reactors.

135. It is impossible, on the basis of these two accidents, to retrospectively calculate a component of the collective dose commitments due to accidents involving public exposure from nuclear power. The Committee has decided that the probabilistic approaches, which predict the risk of reactor programmes by extrapolating into the future, while useful for other purposes, should not be used as a basis for estimating any speculative future component of collective dose commitment. Contributions from accidents to occupational exposures are dealt with in Annex H.

136. The accident at Three Mile Island has been the subject of many reports, particularly from the United States Nuclear Regulatory Commission and the President's Commission [K9]. The basic form of the accident was very simple, but the details were extremely complicated. The pumps providing feed water to the boilers stopped and the safety system shut down the turbine. A relief valve in the reactor primary cooling circuit opened correctly and the reactor was shut down automatically. A second fault was the failure of the relief valve to close when the reactor primary circuit pressure fell, while the control room instrumentation indicated closure. As the primary circuit pressure fell, high pressure emergency core cooling was automatically injected into the circuit but this flow was stopped by the operators in the mistaken belief that the reactor was too full of water. This action was caused by instrument readings correctly showing high water levels in part of the system, although it was caused by water being forced out of the core by the generation of steam. At this point severe damage to the fuel elements occurred.

137. Steam and fission products released from the damaged fuel are now thought to have left the reactor by a relief valve in the primary water makeup system which was kept running to maintain the boron concentration. The condensed water was retained in the containment building. This building is designed to seal automatically in the event of a pressure rise, but none occurred and it took four hours before the building was sealed. During this time fission product gases escaped to the atmosphere, and gave rise to irradiation of the public. Further releases took place later when contaminated waste water was discharged from the containment building. Most fission products were retained in the water but a release of about 370 PBq of noble gases, mainly ^{133}Xe, and some 550 GBq of ^{131}I were released to the atmosphere.

138. The accident released large amounts of activity from failed fuel in the core but the environmental releases and the resulting exposure of the public was small. The collective whole-body dose commitment was mainly due to the ^{133}Xe release and has been estimated at between 16 and 35 man Gy within 50 miles [B19]. The corresponding mean value and the value given in the Kemeney report [K9] is 20 man Gy. Individual levels of dose averaged 1.5 10^{-5} Gy within 50 miles of the plant and the maximum absorbed dose which any number of the public could have received has been estimated at 85 10^{-5} Gy [K9] from external gamma-irradiation. The contribution to the collective whole-body dose commitment due to ^{133}Xe dispersion beyond 50 miles can be estimated roughly from the results in Table 29 for the model PWR, where ^{133}Xe dominates the release. Over all distances the whole-body dose commitment might be expected to be twice that within 50 miles.

139. In the 1957 Windscale reactor fire, the accident began during a routine release of the Wigner Energy stored in the graphite (a phenomenon caused in low temperature graphite by neutron bombardment, leading to the creation of interstitials and the stressing of the moderator). Due to errors in operation, the fuel became overheated and, in the once-through air cooled system,

caught fire. The fire lasted for about three days and major releases of iodine occurred on two occasions; once when air flow was started through to core in an attempt to cool it, and secondly when water was pumped into the reactor which finally extinguished the fire. The Windscale reactor has never been utilized since.

140. A theoretical re-analysis of the Windscale accident has been given by Clarke [C6] who estimated the activities released and dosimetric consequences out to 50–100 km. Extensive environmental measurements were undertaken at the time of the accident, which can be used to evaluate the collective doses. Individual doses were re-examined by Baverstock and Vennart [B20]. The release of ^{131}I has been estimated at some 740 TBq accompanied by 44 TBq ^{137}Cs, 12 TBq ^{106}Ru and 1.2 PBq of ^{133}Xe. Collective dose estimates were not made at the time, but measurements of activity in the thyroids of adult individuals in Leeds and London indicated thyroid dose commitments of 10^{-3} and $4\ 10^{-4}$ Gy, respectively [B20], with young children receiving doses of twice this value. Maximum doses to local individuals close to the site were estimated to be of the order of 10^{-2} Gy to the thyroid of adults and perhaps 10^{-1} Gy to children's thyroids [C6, L10].

141. The contamination of pasture land was widespread, the majority of the released activity passing south-south-east from Windscale, passing directly towards London, and eventually passing over Belgium before turning northwards to Norway. In a new evaluation of the accident to assess the collective doses the principal route for irradiation was shown to be iodine in milk [C9]. Although other nuclides did not deposit as readily on pasture they have been shown to contribute significantly to the collective dose. The estimate given by Crick et al. [C9] for the collective thyroid dose commitment is $1.8\ 10^4$ man Gy of which about 25% was derived from inhalation and 75% from ingestion. The corresponding collective effective dose equivalent commitment is $6\ 10^2$ man Sv. The collective effective dose equivalent commitment from all isotopes and pathways was estimated to have been $1.3\ 10^3$ man Sv, of which somewhat less than 50% was due to iodine isotopes and thyroid irradiation. External irradiation from ground deposits of activity was estimated to contribute another 40%, while the remaining 10% arose mainly from ingestion of foodstuffs contaminated by nuclides other than iodine [C8].

IV. FUEL REPROCESSING

142. 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 waiting for reprocessing. Fuel elements are usually left until all the short-lived isotope ^{131}I has decayed to insignificant amounts (usually at least 120 days). One reprocessing plant can serve a whole nuclear reactor programme, so that the quantities of the nuclides significant from the health point of view which pass through the plant will be rather high in absolute terms, but may be small per unit of electrical energy generated. When the fuel elements are reprocessed the irradiated fuel is first taken out from its canning material and then dissolved in nitric acid. This is known as the head-end process.

143. A solvent extraction process is next used for the separation of uranium and plutonium from the fission products, and the remaining transuranic elements. Nearly all reprocessing facilities employ the PUREX process which uses the organic complexing compound tributyl phosphate to extract both the uranium and the plutonium into the organic phase. The uranium and plutonium can be separately recovered from the organic phase using nitric acid. The resulting nitrates are further purified and then converted to oxides suitable for storage until they are refabricated into fuel elements.

144. The only reprocessing plants operating commercially in the world are at Windscale (United Kingdom), La Hague and Marcoule (France). In addition, there are several small experimental reprocessing facilities, such as the one at Karlsruhe in the Federal Republic of Germany. The capacity of the Windscale plant is $2\ 10^3$ t a^{-1} and that of La Hague is 900 t a^{-1} for GCR fuel and 400 t a^{-1} LWR fuel. The capacity of the La Hague plant for LWR is thought likely to increase to 800 t a^{-1} in 1983/84, when essentially all the French GCR fuel will be reprocessed at Marcoule, except for some 150 t a^{-1} which will be used at La Hague to dilute the fast reactor fuel from Phenix when it is reprocessed at La Hague [L1]. The assessment performed here considers first the commercial reprocessing plants and then establishes a model facility for representative calculations of collective and individual dose assessment.

A. EFFLUENTS

145. The design and operation of reprocessing plants to avoid releases of large amounts of radionuclides is complex. The gaseous and volatile fission products (I, ^3H, C, Kr, Xe, Ru, Tc and Cs) are largely separated from the fuel solution at the dissolution stage. The dissolver off-gas is treated for nitric acid recovery and for iodine removal before being blended with the other off-gases from other vessels in the process. The vessel off-gas is usually treated by caustic scrubbing, drying and filtering through high efficiency filters before discharge from a tall stack. The aqueous wastes, containing almost all the fission products and transuranium elements are concentrated by evaporation and stored in double-containment stainless steel tanks to await further treatment before disposal.

146. The radionuclides of principal concern in reprocessing plants effluents are primarily the long-lived nuclides, ^3H, ^{14}C, ^{85}Kr, ^{90}Sr, ^{106}Ru, ^{129}I, ^{134}Cs, ^{137}Cs and isotopes of transuranium elements. There have been many publications on the releases, environmental pathway analysis and dosimetric consequences of reprocessing plant effluents [B2, B10, B11, K2, N17, P5, P6, V2]. Many other papers are to be found dealing with the specific nuclides of interest, particularly ^3H, ^{14}C, ^{85}Kr and ^{129}I, which have also been the subject of a special study group sponsored by the Nuclear Energy Agency of the OECD [N14].

147. In Tables 41 and 42 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 systems of the reprocessing plant, but also on the type of fuel reprocessed, its irradiation history and storage (cooling) time. The discharges of liquid effluents from Marcoule are controlled to lower amounts of radio-

nuclides than from the other two sites because Marcoule discharges into a river, the Rhone, which flows into the Mediterranean Sea. The other two sites are coastal and discharge to the sea. The sources of data for the discharges were Luykx [L1, L6] and British Nuclear Fuels [B2, B22]. For the liquid discharges from Windscale an isotopic breakdown of the discharge in successive years is given in Table 43.

148. The throughput of fuel at each reprocessing plant has been calculated on the basis of its reported ^{85}Kr discharges and the Committee's estimate of the ^{85}Kr content of fuels from different reactor types as given in the following paragraphs. These figures imply that at Windscale the throughput of fuel in 1978 corresponded to less than 2 GW(e) a and the ^{85}Kr discharges have fallen from the levels in previous years. The figures for 1979 imply an increase in fuel throughput; however the corresponding amounts of electricity generated by nuclear power stations do not agree with reported electrical energy production in the United Kingdom [C4]. The implication is that there is a time lag in reprocessing fuel and that there is a growing backlog of fuel committed for reprocessing.

1. Krypton-85

149. Krypton-85 is the only noble gas of interest released from reprocessing plants. It is essentially always totally released from the fuel at the dissolution stage and, consequently, knowledge of the ^{85}Kr discharge from a plant can be used to assess the throughput of fuel. The production of ^{85}Kr per unit energy generated in typical reactor fuels have been taken from White [W4] as 4.1 PBq [GW(th) a]$^{-1}$ for GCRs and 3.6 PBq [GW(th) a]$^{-1}$ for LWRs, on the basis of 3.5 GW d t^{-1} and 33 GW d t^{-1} fuel burnups. Assuming the average thermal efficiency of a GCR is 30% and that of the LWRs is 31% leads to an inventory of 14 PBq [GW(e) a]$^{-1}$ for GCRs and 11.5 PBq [GW(e) a]$^{-1}$ for PWRs. Bernero et al. [B10] have estimated for reprocessing fuel from LWRs in the United States that 45 GW(e) a generates 520 PBq of ^{85}Kr to be released to the atmosphere, corresponding to 11.5 PBq [GW(e) a]$^{-1}$ which is similar to the value derived here.

2. Tritium

150. It was estimated in paragraph 60 that the normalized production of tritium in LWR fuel totalled some 0.75 PBq [GW(e) a]$^{-1}$. Using these figures for GCR fuel, the total tritium inventory passing through Windscale in 1979 was about 1.9 PBq. In Table 42 it is seen that for the same year liquid effluent discharges totalled 1.2 PBq, while Table 1 indicates that 0.29 PBq were released to atmosphere. Thus, most of the tritium in the fuel appears in the effluent streams during reprocessing and perhaps about 20% is emitted to atmosphere. A recent retrospective study on the WAK reprocessing plant in the Federal Republic of Germany reveals that 2% of the tritium in LWR fuel is released to atmosphere [H7]. Releases of tritium to atmosphere per unit of electrical energy generated, averaged between 1975 and 1979, are 3.2 TBq [GW(e) a]$^{-1}$ (La Hague) 46 TBq [GW(e) a]$^{-1}$ (Marcoule) and 133 TBq [GW(e) a]$^{-1}$ (Windscale).

151. A portion of the tritium in LWR zircaloy clad fuel elements is immobilized as a solid zirconium compound. This has been estimated to account for 15% of tritium production [K5]. An analysis by Luykx and Fraser for European reprocessing plants [L1] indicated that for 1973–1974 at Eurochemic (Belgium, no reprocessing since 1974) tritium discharges were 0.48 PBq [GW(e) a]$^{-1}$, which corresponds to about 65% of the Committee's estimated throughput; 26% of this was to atmosphere. For the WAK Karlsruhe plant in the Federal Republic of Germany (1973–1976) the discharges were 0.44 PBq [GW(e) a]$^{-1}$, 60% of throughput, with 3% being discharged to atmosphere.

3. Carbon-14

152. Routine measurements of discharges of ^{14}C from the Windscale reprocessing plants are now available and reported in Table 41 [B22]. Schuettelkopf and Herrmann [S8] have reported that for a 2-year period, when PWR and BWR fuel was being reprocessed at Karlsruhe, normalized atmospheric discharges of ^{14}C in the form $^{14}CO_2$ were at a level of between 0.46 and 0.51 TBq [GW(e) a]$^{-1}$. The ^{14}C content of such fuels is taken as 0.66 TBq [GW(e) a]$^{-1}$ based on the results of Kelly [K2], assuming a thermal efficiency of 31% at the reactor, so that about 75% of the inventory was released to atmosphere. The ^{14}C levels in fuel are highly sensitive to nitrogen impurity levels in fuel.

153. For GCRs a normalized production rate within the fuel of 0.96 TBq [GW(th) a]$^{-1}$ is assumed [K2], and taking a reactor efficiency of 30% leads to a normalized production rate of 3.2 TBq [GW(e) a]$^{-1}$. The potential discharges from GCRs fuel are greater than those for the quantity of LWR fuel for the same electricity production. The throughput of ^{14}C at Windscale in 1979 can be assumed to be about 8 TBq on this basis and from Table 41 it can be seen that the reported atmospheric release was 3.5 TBq, i.e., 44% of throughput.

4. Iodine

154. The ^{131}I content of irradiated nuclear fuel varies depending upon the cooling time and the final power rating of the fuel before discharge. The ^{131}I normalized content of LWR fuel cooled to 180 days is estimated to be 2.8 TBq [GW(e) a]$^{-1}$, falling to 1.4 GBq [GW(e) a]$^{-1}$ at 270 days and to 550 kBq [GW(e) a]$^{-1}$ at 1 year. For ^{129}I the arisings depend on burnup and are assessed to be between 37 GBq and 74 GBq [GW(e) a]$^{-1}$. Since fuel is generally cooled to about a year before reprocessing, ^{131}I discharges are generally extremely small. For 1975–1978 at Windscale atmospheric releases of ^{131}I were averaging 1.7 GBq [GW(e) a]$^{-1}$, while La Hague averaged 32 GBq [GW(e) a]$^{-1}$ and Marcoule 144 GBq [GW(e) a]$^{-1}$.

155. Atmospheric discharges of ^{129}I are now reported for Windscale and average 2.2 GBq [GW(e) a]$^{-1}$. Discharge data for the WAK reprocessing plant in the Federal Republic of Germany indicate that in 1975–1976 the ^{129}I normalized releases averaged 11 and 0.4 GBq [GW(e) a]$^{-1}$, representing 25% and 1% of the ^{129}I throughput in fuel [B12]. The reduction in 1976 resulted from the installation of a new filtration system for the dissolver off-gases. In a series of measurements from November 1975 to August 1977 the average value for the components of ^{129}I discharges were reported as 74% inorganic, 23% organic, 2% aerosol [B12]. These averages conceal a wide variation composition, the

inorganic form having a range of 21–97%, organic 2–54% and elemental 0.04–14%. Annual liquid discharges of ^{129}I from Windscale are about 0.1 TBq, corresponding to about 40 GBq [GW(e) a]$^{-1}$.

5. Radioactive aerosols

156. In Table 41 figures are given for total α activity discharged to atmosphere. Although a wide variety of α-emitting nuclides are present, United States experience of a particular plant there suggests that the majority of the α activity will be from plutonium isotopes [F4]. Windscale reports [B2] that in 1978 of the activity associated with the α-emitting radionuclides released, 71% was from plutonium isotopes and the remainder was from ^{241}Am and ^{242}Cm. The percentage isotopic composition of the plutonium α emitters will roughly be as follows:

	^{238}Pu	^{239}Pu	^{240}Pu	^{242}Pu
GCR	16	44	40	0.1
LWR	78	9	13	0.04

The normalized release rate for α aerosols from Windscale in 1979 was 0.4 GBq [GW(e) a]$^{-1}$.

157. The beta aerosol results are also given in Table 41, the largest component at Windscale being ^{137}Cs discharges in aerosols. In addition, ^{90}Sr is separately identified, the remaining activity comprising the following nuclides: $^{95}Zr/Nb$, ^{106}Ru, ^{125}Sb, ^{134}Cs, ^{144}Ce. The discharges of ^{137}Cs and ^{90}Sr have been substantially higher since 1974 compared with previous years, reflecting higher discharges from the solid waste site used primarily for the storage of Magnox fuel cladding and these discharges are expected to be reduced in the near future [L4]. Of these discharges about half are released from high stacks. Approximately 50% of the ^{137}Cs and ^{90}Sr discharges took place from stacks of height less than 46 m [H8] and are associated with high active silos and cooling pond water. Site discharges of α activity to atmosphere mainly arise from the research and development laboratories and from the plutonium recovery plant [L4].

6. Liquid effluents

158. The liquid effluents discharged from Windscale, La Hague and Marcoule are shown in Table 42 for total α, total β and the releases of tritium, ^{90}Sr and ^{106}Ru. A wide range of nuclides appears in waste streams and the isotopic composition of Windscale liquid effluent discharges for 1977, 1978 and 1979 are shown in Table 43. The α-isotopic composition in Windscale liquid effluents largely reflects the isotopic composition of GCR fuel [H9]. Americium-241 has also contributed significantly to Windscale releases, although the percentage has been decreasing from over 50% of the total α-discharges in 1972 to about 10% of this value since 1977; this reduction is due to more efficient removal of ^{241}Am from waste streams prior to discharge [W5]. The normalized release rate of α activity from Windscale into liquid effluents is currently 25 TBq [GW(e)a]$^{-1}$, and the figures for Marcoule and La Hague are 0.016 and 0.24 TBq [GW(e) a]$^{-1}$, respectively. The Marcoule discharges are to the river Rhone.

159. The liquid discharges of β activity shown in Table 42 give normalized release rates of 3.7, 0.52 and 0.04 PBq [GW(e) a]$^{-1}$ for Windscale, La Hague and Marcoule, respectively, in 1978. The isotopic composition of the release varies between La Hague and Windscale. In liquid effluents from La Hague up to 1976, 65% of the total β activity concentration was from ^{106}Ru with 13% from ^{137}Cs, 12% from ^{144}Ce and 7.6% from ^{90}Sr. The isotopic composition for Windscale is 63% ^{137}Cs and ^{134}Cs, 11% ^{106}Ru, 8.3% ^{90}Sr, the remainder being composed of a number of nuclides. The Windscale caesium discharges which began to rise in 1974 are not due to reprocessing as such but are the result of the corrosion of Magnox fuel cans by water in the storage pond. Corrective action has now been undertaken to reduce the discharge levels by the use of ion exchange resins in the effluent treatment plant. The result has been that in 1979 the liquid effluent discharge was reduced to 1.6 PBq [GW(e) a]$^{-1}$.

B. LOCAL AND REGIONAL COLLECTIVE DOSE COMMITMENTS

160. The evaluation of the 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 are given here and the global contribution in chapter V. Monitoring of the local environment and regional distribution of activity from Windscale is extensive and widely reported in annual reports [B2, B22, H5, M4, M5] and in the open literature [H8, H9, P5, P6, W5]. Studies on the fate of liquid effluents from La Hague have also recently been published [V2]. In this section the collective absorbed dose commitments are evaluated for normalized discharges from Windscale and La Hague. However, since there are only three known operating commercial reprocessing plants, their contributions of collective dose per unit of electrical energy generated may not be representative of that which will be made by other installations when they commence processing irradiated fuel. Therefore a summary of collective dose commitments is given for typical discharge figures quoted for new designs of reprocessing plant. The characteristics of the population data and meteorological conditions used for the model plant are those applicable to the Windscale site in the United Kingdom and are shown in Table 44.

1. Krypton-85

161. The assessment of the averaged ^{85}Kr discharges from Windscale between 1975 and 1979 has been performed using the methodology provided for the Commission of the European Communities [C10]. The average annual release of ^{85}Kr was 35 PBq and the resulting collective absorbed dose commitments are shown in the summary Table 46. The collective effective dose equivalent commitment is estimated to be 0.074 man Gy from the cloud γ-irradiation, using the dose conversion factors of Poston and Snyder [P4]. A further contribution from the cloud-β irradiation amounts to 19 man Sv collective absorbed dose in skin, which contributes 0.19 man Sv to the collective effective dose equivalent commitment. The normalized local and regional collective effective dose equivalent commitment for the ^{85}Kr annual discharge from Windscale averaged from 1975 to 1979 is 0.1 man Sv [GW(e) a]$^{-1}$.

2. Tritium and carbon-14

162. In this case a specific activity model is used as described in paragraphs 99 and 100. The average

annual release of tritium to atmosphere from Windscale between 1975 and 1979 was 0.33 PBq, or 0.13 PBq [GW(e) a]$^{-1}$. The associated normalized collective dose commitments are shown in Table 45. The specific activity model chosen with the dosimetric results of Adams [A1] suggests that the individual organ doses (thyroid, gonad, etc.) expressed in gray are essentially the same as the effective dose equivalent expressed in sievert. The normalized release of ^{3}H to atmosphere leads to a local and regional collective effective dose equivalent commitment of 0.35 man Sv [GW(e) a]$^{-1}$. Releases to the regional marine environment lead to lower dose commitments: the normalized tritium release from Windscale in the period 1975–1979 was 0.45 PBq [GW(e) a]$^{-1}$ (Table 42) leading to a collective effective dose equivalent commitment of about 8 10^{-4} man Sv [GW(e) a]$^{-1}$, using the distributions of marine foodstuffs, water movements and sedimentation rates taken from chapter III.

163. For ^{14}C atmospheric releases the normalized collective effective dose equivalent commitment in the local and regional population is 0.69 man Sv [GW(e) a]$^{-1}$ for the population distribution within 2000 km of the Windscale site. The average annual throughput of fuel at Windscale from 1975 to 1979 corresponds to 2.6 GW(e) a, leading to a collective effective dose equivalent commitment per year of release of 1.8 man Sv. If the same discharge took place to the marine environment the regional model suggests the integrated activity found in foodstuffs would be 2.5 10^{-4} Bq a per Bq discharged. Thus the same annual release in the marine environment would lead to 2.7 man Sv, essentially the same figure as for the release to atmosphere.

3. Other atmospheric releases

164. Of the other nuclides released to the atmosphere, apart from ^{129}I which makes a significant contribution to the global collective dose commitment because of its long half-life (1.6 10^{7} a) and is considered in detail in chapter V, the remainder contribute only to the local and regional dose commitment. Again, the spatial patterns of population distribution and of agricultural production applicable to the United Kingdom and Europe were taken from Simmonds and Linsley [S12] and the study undertaken for the Commission of the European Communities [C10]. The release rates of the various isotopes discharged to atmosphere from Windscale given in Table 41 were used and the resulting collective dose commitments for those nuclides contributing are shown in Table 46. The total collective effective dose equivalent commitment comes to 6.2 man Sv as a result of one year of average atmospheric discharges between 1975 and 1979. The result is dominated by the collective effective dose equivalent commitment from ingestion (4.4 man Sv). Of the remainder, 1 man Sv arises from ground deposition (^{137}Cs), 0.48 man Sv from inhalation (^{3}H, ^{239}Pu, ^{240}Pu, ^{241}Am) and 0.26 man Sv from ^{85}Kr doses in the local and regional population.

4. Liquid effluents

165. In Table 47 the collective absorbed dose commitments are presented for releases of the nuclides in liquid effluents from both the Windscale and La Hague sites averaged from 1975 to 1979. The dose commitments include doses from the consumption of all marine foodstuffs from the areas of northern European waters, as described in Annex A and paragraphs 126–128. The releases occur to a local marine model and then subsequently into the regional model. The experimental evidence strongly suggests that a large proportion of the plutonium discharges into the eastern Irish Sea is rapidly fixed on to sediments in the local dispersion and only a small fraction is available for transfer into the regional waters. The large suspended sediment load in the Irish Sea accounts for the considerable difference in plutonium dose commitments per unit discharge between the Channel site and the eastern Irish Sea site.

166. In Table 47 the annual average releases from Windscale and La Hague from 1975 to 1979 have also been used with the Committee's models to obtain collective effective dose equivalent commitments. For Windscale the result is 311 man Sv of which 90% is due to ^{137}Cs discharges and the remainder nearly all due to ^{106}Ru. The normalized collective dose commitment is thus 124 man Sv [GW(e) a]$^{-1}$. For the La Hague discharges the collective effective dose equivalent commitment is 84 man Sv with 86% due to ^{106}Ru and the remainder due to ^{137}Cs discharges. The normalized collective dose commitment for La Hague is 53 man Sv [GW(e) a]$^{-1}$, although this is probably an overestimate because of the assumptions in the models used. The normalized results for La Hague and Windscale are seen to be similar. From Table 43 it is seen that in 1979 the releases of caesium and ruthenium from Windscale to the marine environment were half those in 1978, so that the collective effective dose equivalent commitment will be reduced to 62 man Sv [GW(e) a]$^{-1}$. Annual effective dose equivalents to most exposed individuals near Windscale were probably less than 0.5 mSv from 1979 discharges of ^{137}Cs.

5. Atmospheric and liquid effluents from a notional plant

167. There are significant uncertainties in predicting dose commitments over the long periods of time during which the long-lived isotopes may be available in the environment. Furthermore, the collective dose commitments derived from present day releases from Windscale and La Hague are probably not representative of future reprocessing practices if all LWR fuel currently stored were reprocessed. Notional reprocessing plant designs exist, some of which are sited inland, with very low discharges to the aquatic environment. Consideration is also being given to retention of ^{85}Kr, ^{3}H, ^{14}C and ^{129}I, nuclides which are currently released into the atmosphere. In order to obtain a more representative set of collective dose commitments, a model oxide fuel reprocessing facility is assumed which discharges into a marine environment. The discharges are based on the implied discharges of the British Nuclear Fuels Ltd. thermal oxide reprocessing plant (THORP) as reported at the Windscale Inquiry [P8]. Table 48 gives a summary of the notional discharges per unit energy generated for the model facility assuming a fuel throughput equivalent to 40 GW(e) power and the associated collective effective dose equivalent commitments. It has been assumed that there is no retention of ^{14}C or ^{85}Kr in atmospheric discharges and in this case ^{14}C is the main contributor to the collective effective dose equivalent commitment from atmospheric releases, although the ^{14}C content of LWR fuels is much less than for Magnox (paragraphs 66–67). On the basis of the very notional

discharges assumed here, the liquid effluents are as significant as the atmospheric releases with ^{137}Cs and ^{106}Ru being the main contributors. Iodine-129 releases contribute to the global collective dose and this is considered in chapter V. The representative local and regional normalized collective effective dose equivalent commitment from reprocessing is thus 1 man Sv [GW(e) a]$^{-1}$.

168. The representative values of doses to critical groups from the discharges at the model facility are presented in Table 49. For atmospheric releases the largest single contribution to individual effective dose equivalent is from ^{14}C and a representative annual effective dose equivalent to the critical group is 25 μSv. The liquid effluents contribute more to the total effective dose equivalent, with ^{137}Cs being the most important nuclide. The results must only be used to indicate the order of magnitude of doses foreseen in designs of reprocessing plants. The annual effective dose equivalent to the most exposed group amounts to 200 μSv for marine discharges. These doses for critical group exposures are similar to those from the proposed Barnwell Nuclear Fuel Plant in South Carolina, United States [P9].

V. COLLECTIVE DOSE COMMITMENTS FROM THE GLOBAL DISPERSION OF RADIONUCLIDES

169. The radionuclides that contribute to the global collective dose commitment are those which are sufficiently long-lived and readily migrate through the environment, thereby achieving widespread distribution. Those of primary interest are ^{3}H, ^{14}C, ^{85}Kr and ^{129}I and assessments of the global collective doses from the release of these nuclides have appeared in several reports [C10, K2, N14]. The environmental transfer of ^{3}H and ^{85}Kr is becoming fairly well established and more reliable estimates of collective dose commitments can be made. Long-lived nuclides such as ^{137}Cs and ^{239}Pu are less mobile in the environment and become far less dispersed after deposition onto soil or onto sediments, following release into the local region. Some other nuclides are considered which are released in the nuclear fuel cycle in a mobile form and have sufficiently long half-lives to irradiate populations beyond the regional area.

170. The very long-lived nuclides, for example, ^{129}I ($1.6\ 10^{7}$ a) pose a special problem because extrapolation far into the future is required to estimate the dose commitment. This introduces uncertainties because of the unknown population size, its dietary habits and, amongst other things, environmental changes. This implies that little weight can be placed on dose commitments for decision-making purposes. Estimates of the incomplete collective dose commitment from these nuclides is useful firstly in demonstrating the time distribution of the dose commitment, and secondly to calculate an estimate of the per caput annual doses resulting from a finite continuing practice. Thus, if electrical energy production by nuclear fission has a finite duration, of the order of a few hundred years, the incomplete collective dose commitment to that time divided by the mean population size will indicate the maximum per caput dose rate that may be experienced in the future from that practice. Collective dose commitments must be treated with caution since the significance of the results must be carefully interpreted. This topic is fully discussed in Annex A.

171. In the following paragraphs collective dose commitments (and incomplete values where of interest) have been estimated for those nuclides which become globally dispersed and irradiate the world population. This dose is received in addition to that received during the local and regional dispersion, the so-called first pass dose, from the point of discharge. Recently a report has been published by the Nuclear Energy Agency of the OECD which discusses the collective dose commitments from releases of ^{3}H, ^{14}C, ^{85}Kr [N14]. In this chapter extensive reference is made to the results obtained by the study group who produced the report for the Nuclear Energy Agency.

A. KRYPTON-85

172. The collective dose commitments from ^{85}Kr generated during nuclear power production arise almost entirely from the release at reprocessing plants, as reactor releases are small in comparison. Since krypton is an inert gas it disperses through the atmosphere and achieves a uniform concentration in a period of about two years. Although the assumption of instantaneous dilution in the world's atmosphere, as used in Annex E, gives a reasonable estimate of time integral of concentration, a two-compartment model similar to that proposed by Kelly et al. [K2] is used in which the released krypton is assumed to be instantaneously dispersed throughout the troposphere of the northern hemisphere which is assumed to have a height of 10 km and a mass of $1.9\ 10^{21}$ g. Exchanges take place between the troposhere of the two hemispheres with a half time of about 2 years. Within a few years the ^{85}Kr becomes uniformly dispersed and the sole removal mechanism is radioactive decay.

173. The concentration in air and the time integral of activity concentration of ^{85}Kr for a discharge of 1 Bq s^{-1} for a year is shown in Figure I. The whole-body absorbed dose commitment per unit time integral of air concentration of ^{85}Kr has been taken as $4.3\ 10^{-9}$ Gy (Bq a kg^{-1})$^{-1}$ [C10], and the collective skin dose commitment due to the β^{-}-irradiation as $5.4\ 10^{-7}$ Gy (Bq a kg^{-1})$^{-1}$. These values are in good agreement with the dose rates per unit air concentration of ^{85}Kr as given by ICRP publication 30 [12]. The collective absorbed dose commitment from the gamma contribution is $5.5\ 10^{-19}$ man Gy for a release of 1 Bq s^{-1} for one year, while the collective absorbed dose in skin for the same release is $7.4\ 10^{-17}$ man Gy.

174. The normalized ^{85}Kr discharges from reprocessing of nuclear fuel have been given in paragraph 149 as 11 PBq [GW(e) a]$^{-1}$ for a typical LWR and 14 PBq [GW(e) a]$^{-1}$ for a GCR. The corresponding collective effective dose equivalent commitments are calculated, assuming a world population of $4\ 10^{9}$ during the irradiation period, to be 0.81 man Sv [GW(e) a]$^{-1}$ of reprocessed LWR fuel and 0.98 man Sv [GW(e) a]$^{-1}$ for GCR fuel for the external gamma irradiation. The collective absorbed dose commitment to skin is 110 man Gy [GW(e) a]$^{-1}$ for LWR and 130 man Gy [GW(e) a]$^{-1}$ for GCR fuel, which adds 1.1 and 1.3 man Sv [GW(e) a]$^{-1}$ to the collective effective dose equivalent commitments, respectively. The total collective effective dose equivalent commitment weighted for energy produced is 1.9 man Sv [GW(e) a]$^{-1}$. All of the dose commitment is delivered within the first 50 years following the year of release. These results compare with the Committee's previous estimate in Annex D of the 1977 report [U1] of a gonadal dose commitment of

0.9 man Sv [GW(e) a]$^{-1}$. The results of the Nuclear Energy Agency expert group report give a collective effective dose equivalent commitment for ^{85}Kr global dispersion of 0.81 man Sv [GW(e) a]$^{-1}$ for LWR fuel, if the same world population is assumed as used here.

B. TRITIUM

175. The collective dose to the global population from reactor and reprocessing plant releases of tritium can be estimated from the evidence concluded from fallout measurements following atmospheric weapons testing. The absorbed dose commitment has been estimated to be 5 10^{-4} man Sv per TBq released (see Annex E).

176. In recent years a number of models have been proposed to describe the global circulation of tritium for predicting dose commitments [B13, B14, B15, C10, K2, N20]. In a very simple model emissions to atmosphere or to hydrosphere are not distinguished, since the exchange of water between the atmosphere and the remaining circulating waters of the globe is rapid. In such models it has been usual to assume that the released tritium is immediately and uniformly distributed in the circulating waters of the northern hemisphere to a depth of 75 m [B14, B15, U1]. More recent models [C10, K2] still assume that discharged tritium, whether to atmosphere or hydrosphere, is immediately dispersed and exchanged with the hydrogen content of the circulating waters of the hemisphere into which the discharge is made.

177. The subsequent circulation of tritium is determined, however, by the exchange of waters between the two hemispheres and the deep oceans. The model is described in Annex A and the exchange rates taken are shown below. The mass transfer rates are obtained by multiplying the exchange rates by the relevant mass of each component.

Circulating waters (N. hemisphere) → circulating waters (S. hemisphere)	0.1	a^{-1}
Circulating waters (S. hemisphere) → circulating waters (N. hemisphere)	0.05	a^{-1}
Exchange between deep oceans (N. hemisphere ⇄ S. hemisphere)	0.005	a^{-1}
Exchange between circulating surface waters and deep oceans	0.1	a^{-1}
Exchange between deep oceans and circulating waters	0.0014	a^{-1}

Using this model, the time integral of activity concentration in the circulating waters of the Northern hemisphere is shown in Figure I to be 1.4 10^{-11} Bq a kg^{-1} for a release of 1 Bq s^{-1} for a year. Assuming an individual

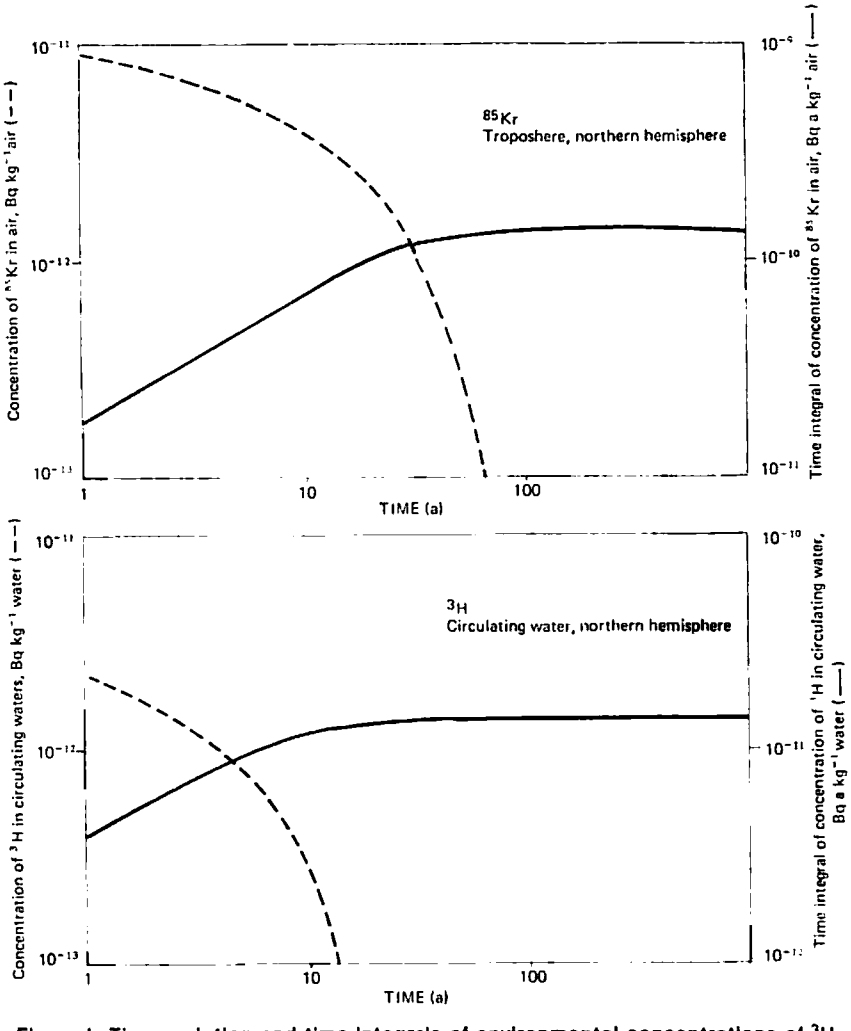

Figure I. Time variation and time integrals of environmental concentrations of ^{3}H and ^{85}Kr for releases of 1 Bq s^{-1} during one year [C10]

intake of water of 930 kg a^{-1}, as given by ICRP in publication 23 [15], a population of 4 10^9, and a dose per unit intake of 1.7 10^{-11} Gy Bq^{-1} [A1, I2], the collective effective dose equivalent commitment per unit release is estimated to be 2.8 10^{-5} man Gy TBq^{-1}. Assuming the normalized release of tritium in reprocessing to be 0.6 PBq [GW(e) a]$^{-1}$ plus about 40 TBq [GW(e) a]$^{-1}$ for the average of reactor discharges, gives a total of 0.64 PBq [GW(e) a]$^{-1}$ and a normalized collective effective dose equivalent commitment of 1.8 10^{-2} man Sv [GW(e) a]$^{-1}$. The result is directly proportional to the assumed population size.

178. The Nuclear Energy Agency expert group assumed a population of 10^{10} so the present model would predict 6.8 10^{-5} man Gy TBq^{-1}. The expert group derived a value of 4.6 10^{-4} man Gy TBq^{-1} and the Committee, in Annex D of its 1977 report [U1], gave a value of 8.1 10^{-4} man Gy TBq^{-1}. The figure derived from the comparison of the natural dose rate and production of tritium (see Annexes B and E) would be about 5 10^{-4} man Gy TBq^{-1} for a uniform production over the world, assuming a global population of 4 10^9. One reason for the smaller value obtained in this Annex is the inclusion of the removal rates of tritium to deep oceans which leads to a reduction of a factor of 4 to 5 in integrated tritium intakes. The local and regional effective dose equivalent commitment per unit energy generated for atmospheric releases of tritium amount to about 0.5 man Sv [GW(e) a]$^{-1}$, so that the global contribution is found to be small in comparison (paragraph 102).

C. CARBON-14

179. The global dose commitment from ^{14}C releases from the nuclear industry is estimated by constructing compartment models which reflect the environmental distribution and behaviour of naturally-produced ^{14}C. Models of varying degrees of complexity have been produced using between 2 and 20 compartments [H2, K2, K6, M2, S13, U1]. In the two-compartment model the stratosphere, troposphere and ocean surface are considered as one compartment which exchanges with the deep ocean [H2]. In the 20-compartment model there are four latitude bands each with compartments in the stratosphere, troposphere, terrestrial biosphere, mixed ocean and deep ocean [M6]. An additional input to some models is the increased stable carbon in the atmosphere due to the combustion of fossil fuels, which tends to decrease the specific activity of ^{14}C. It is not easy, therefore, to evaluate the various estimates of dose commitment. However, there is evidence [K6] that, owing to the long half-life of ^{14}C compared with the rate of environmental transport of carbon, estimates of dose commitment are fairly insensitive to the details of the environmental models except for the rate of transfer to the deep ocean which affects the result.

180. The model chosen for the present estimates has been described in Annex A and is an 8-compartment model allowing for two hemispheres comprising humus, circulating carbon, surface ocean and deep ocean. The circulating carbon compartment represents carbon in the troposphere and those parts of the terrestrial biosphere which are subject to rapid cycles of growth and decomposition. The humus compartment represents the carbon content of the terrestrial biosphere which circulates more slowly. Carbon-14 discharged to atmosphere or hydrosphere is assumed to be instantaneously mixed with the carbon in the compartment to which it is released. The subsequent circulation between compartments governs the specific activity of ^{14}C in all carbon inhaled or ingested by man, which is assumed to be taken from the circulating carbon in the northern hemisphere. The mass of circulating carbon in the northern hemisphere has been estimated at 3.6 10^{14} kg by Ekdahl et al. [E5] and this value is assumed to remain constant.

181. In Figure II the airborne concentration and the time integrals of activity concentration in carbon are shown for a release of 1 Bq s^{-1} for a year to either the atmospheric or aquatic environments. The doses in all

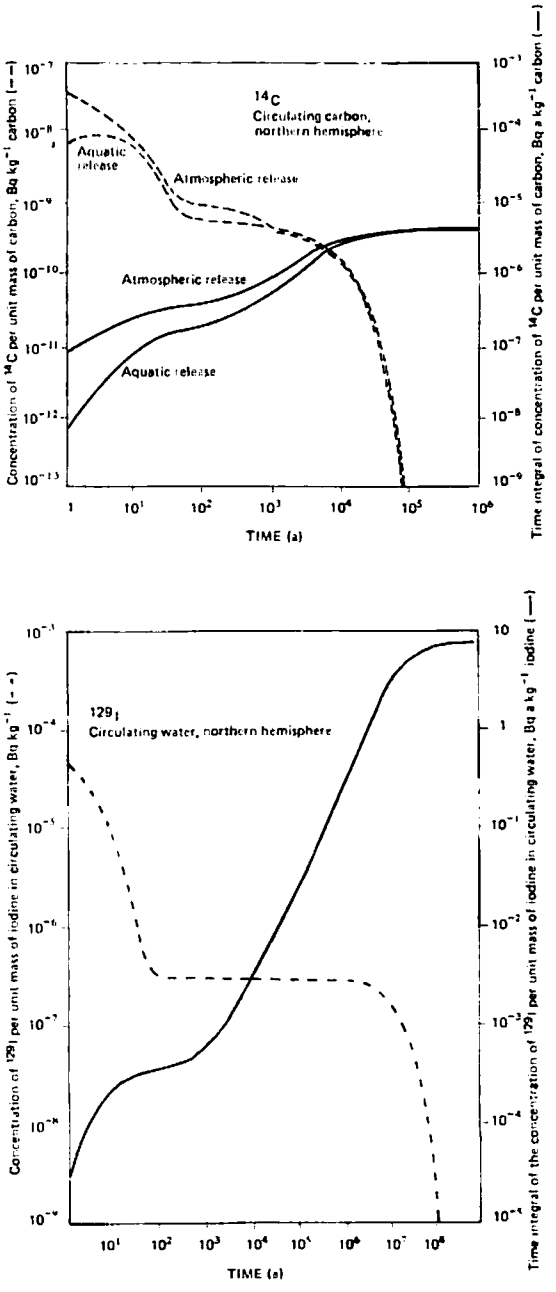

Figure II. Time variation and time integrals of environmental concentrations of ^{14}C and ^{129}I for releases of 1 Bq s^{-1} during one year [C10]

organs and tissues are assumed to be equal and the effective dose equivalent per unit intake is taken as 5.7 10^{-10} Sv Bq^{-1} for ingestion and 6.4 10^{-12} Sv Bq^{-1} for inhaled CO_2. The Reference Man [15] annual intakes of carbon are taken as 93 kg a^{-1} ingested and 1.2 kg a^{-1} inhaled. A population of 10^{10} is assumed for this calculation and is taken to be constant during the integration

period. This figure represents an estimated equilibrium population figure during the irradiation.

182. The collective effective dose equivalent commitment per unit release is estimated at 67 man Sv TBq^{-1} as an average for both atmospheric and aquatic releases. This compares with an estimate of the incomplete effective dose equivalent commitment per unit release given by the Nuclear Energy Agency expert group of 70 man Sv TBq^{-1} for the same population figure used here. The expert group, incomplete collective effective dose equivalent commitment was to 10^4 years, during which time they expected 67% of the dose commitment to have been delivered [N14]; thus their estimate of the complete collective effective dose equivalent commitment per unit release is about 105 man Sv TBq^{-1}. The answers are thus in good agreement given the assumptions made and the associated uncertainties over long time periods. Based on the dose rates due to natural ^{14}C production (Annex B), the collective effective dose equivalent commitment per unit release is 120 man Sv TBq^{-1}, confirming the results of the models.

183. The estimated local and regional collective effective dose equivalent commitments given in Tables 33 and 45 correspond to 2.0 or 0.5 man Sv TBq^{-1}, depending upon site, and thus represents a few per cent of the total collective effective dose equivalent commitment per unit release for ^{14}C. The normalized release of ^{14}C is given as 0.4 TBq $[GW(e)\,a]^{-1}$ from the model reprocessing plant handling LWR fuel (Table 48), and LWR reactor releases can be expected to contribute about the same amount (Table 33). The normalized collective effective dose equivalent commitment is thus 54 man Sv $[GW(e)\,a]^{-1}$ for LWRs, only half of which arises from atmospheric discharges at the reprocessing plant. HWR reactor operation leads to 17 TBq $[GW(e)\,a]^{-1}$ (Table 33) and reprocessing would give little addition; the global collective effective dose equivalent commitment per unit energy generated in HWRs is thus $1.1\ 10^3$ man Sv $[GW(e)\,a]^{-1}$. The 1000-year incomplete values are about 20% of the infinite values, 11 man Sv $[GW(e)\,a]^{-1}$ for LWR releases and 200 man Sv $[GW(e)\,a]^{-1}$ for HWR operation. The 1000-year incomplete collective effective dose equivalent commitment is 21 man Sv $[GW(e)\,a]^{-1}$ averaged over electricity production by each reactor type, and the infinite value is 110 man Sv $[GW(e)\,a]^{-1}$.

D. IODINE-129

184. Iodine-129 emitted to the atmosphere, because of its mobility in the environment, becomes rapidly incorporated in foodstuffs ingested by individuals. Iodine in the environment is not uniformly distributed and the highest concentrations are found in sea water. Models proposed for the environmental transport of ^{129}I have been discussed in Annex A, and range from simple assumptions of instantaneous mixing in the oceans with stable iodine, as in Annex D of the 1977 report [U1], to multicompartment models taking account of transfer between surface waters and the deep ocean [K7] and between these waters and the land and atmosphere [B16]. The most important feature to be included appears to be the transfer to the deep oceans [K7]. The model utilized here probably leads to an overestimate of collective dose commitment since effects such as sedimentation are not taken into account. It is extremely difficult to estimate dose commitments for periods of tens of millions of years. The increasing uncertainty with which doses can be predicted in the far future means that less weight can be placed on them for decision making.

185. In Figure 11 the integrated activity concentrations of ^{129}I are given for a 1 Bq s^{-1} for a year's discharge whether to atmospheric or aquatic environments. Once more an equilibrium population of 10^{10} is assumed and held constant throughout the irradiation time. These integrated concentrations are per kg of stable iodine so that collective dose commitments are found by multiplying the integral of activity concentration by the population size, the individual rate of intake of iodine and the committed dose per unit intake. The thyroid dose equivalent is $3.3\ 10^{-6}$ Sv Bq^{-1} ingested, giving an effective dose equivalent per unit intake of $9.9\ 10^{-8}$ Sv Bq^{-1} ingested [A1, I2]. The intake of iodine is $7\ 10^{-5}$ kg a^{-1} [I5]. The collective effective dose equivalent commitment per unit release is thus found to be $1.4\ 10^4$ man Sv TBq^{-1}, while the value truncated to 10^4 years would be 4.1 man Sv TBq^{-1}. The answers must clearly be very uncertain for this nuclide because most of the dose commitment is delivered beyond 10^6 years into the future.

186. The incomplete collective effective dose equivalent commitment per unit ^{129}I release for the same population as used here was estimated by the Nuclear Energy Agency expert group for an integration time of 10^4 years as 8.1 man Sv TBq^{-1} [N14]. The NEA group calculated 10^4 year incomplete collective dose equivalent commitments because they assumed this to be a feasible containment period and thus they were interested in detriment averted. The value here is just over half that value at 10^4 years, but the collective dose is increasing steeply with time at this point and the results are very sensitive to parameter values. The NEA group comment that the complete collective effective dose equivalent commitment per unit ^{129}I release is some 3500 times the 10^4 year value, i.e., $2.8\ 10^4$ man Sv TBq^{-1}, compared with the Committee's current estimate of $1.4\ 10^4$ man Sv TBq^{-1}. A factor of about 3400 has been found here between the 10^4 year incomplete value and the complete dose commitment. The normalized release for the model reprocessing plant discharge was 0.2 GBq $[GW(e)\,a]^{-1}$ (Table 48) to atmosphere and 40 GBq $[GW(e)\,a]^{-1}$ in liquid effluents, giving a total of 40 GBq $[GW(e)\,a]^{-1}$.

187. The resulting normalized global collective effective dose equivalent commitment for ^{129}I releases is thus 560 man Sv $[GW(e)\,a]^{-1}$ from reprocessing plant discharges, reactor releases being insignificant by comparison. The collective thyroid dose equivalent commitment is about 19 000 man Sv $[GW(e)\,a]^{-1}$. The local and regional collective effective dose equivalent commitment has been estimated as $4\ 10^{-3}$ man Sv $[GW(e)\,a]^{-1}$ for atmospheric releases and $8\ 10^{-3}$ man Sv $[GW(e)\,a]^{-1}$ for liquid discharges (Table 48). The local and regional collective dose commitments are delivered over a relatively short time scale due to environmental removal processes (less than 500 a) and over the same time period the normalized global collective effective dose equivalent commitment is about $3\ 10^{-2}$ man Sv $[GW(e)\,a]^{-1}$.

E. SUMMARY

188. A summary of the normalized releases of the nuclides of global significance, together with their

collective effective dose equivalent commitments, are shown in Table 50. Incomplete values of collective dose commitment are shown to illustrate their time dependence. It should be noted that, in addition to ^{3}H, ^{14}C, ^{85}Kr and ^{129}I, a fraction of those radionuclides released into the atmosphere with half-lives greater than a few days and deposition velocities of less than about 10^{-3} m s^{-1} will leave the regional area and potentially become globally dispersed. Their contribution to the collective dose commitment beyond the regional area has been estimated using the ^{85}Kr model and results. It may be deduced that the global dose commitment increases with increasing half-life and equals that from the regional area when the half-life is about 0.5 a. Short-lived nuclides such as ^{133}Xe ($T_{1/2}$ 5.3 d) and ^{131}I (8.05 d) in organic form can thus only be expected to add a few per cent to the regional dose commitment by becoming globally dispersed. The release of ^{35}S ($T_{1/2}$ 87.5 d) however would contribute an extra 50% of the local and regional dose commitment. These three nuclides contribute 2 10^{-3} man Sv $[GW(e)\,a]^{-1}$ from global dispersion which is 0.05% of the collective dose commitment from reactor operation.

VI. RADIOACTIVE WASTE STORAGE AND DISPOSAL

189. Only a small fraction of the artificial activity generated in the nuclear fuel cycle is released to the environment during normal operations. Except for the uranium, plutonium, and certain other nuclides present in spent fuel, the radionuclides generated by the nuclear fuel cycle are generally considered as waste which must be subjected to suitable treatment followed by storage or disposal. Storage is taken to mean any arrangement intended to enable retrieval of the waste at some future time; the waste may be temporarily inaccessible, but there is an intent, by surveillance and documentation, to retrieve. Disposal implies that control over the waste has been relinquished. It is useful to distinguish between high-level wastes, which may consist of unreprocessed fuel or may arise in liquid form following reprocessing of nuclear fuel and contain more than 99% of the fission product and actinide radionuclides in the fuel, and the low and intermediate level wastes which arise both in reprocessing and in reactor operation. The latter are, for example, used ion exchange resins, air and liquid filters, in-reactor components (control rods, instrumentation), contaminated clothing and equipment. A further category of waste is known as plutonium contaminated material, which is a low-level waste but because of the long half-lives of the α-emitting nuclides covered in this category, needs to be treated similarly to intermediate level wastes.

A. LOW AND INTERMEDIATE LEVEL WASTES

190. The tailings from uranium milling are one example of low-level solid waste, the radiological exposures from which have been considered in chapter I. Solid wastes may be treated by compaction or incineration to reduce their volume before being placed in storage or disposed of in shallow land or deep burial sites. Most nuclear sites have provision for the storage of solid wastes generated through the reactor lifetime and the final disposition of these wastes probably will depend upon the decision as to the final method of disposal of the reactor itself.

191. It is common practice to dump low-activity solid wastes untreated into trenches and to cover with earth. In the United States there were six commercial low-level waste burial facilities and five major active sites operated by the Department of Energy in 1978 [A4]. Three of the commercial facilities are currently inoperative, three of the sites are closed indefinitely and responsibility for perpetual care is expected to be placed upon the respective States. In general the wastes are placed as received into trenches excavated in the existing soil and the removed material used to cover the wastes once the trench is filled to capacity. The overburden is sometimes compacted and usually mounded to promote water run-off. The capacity of the currently open commercial sites is between 10^{5} and 10^{6} m^3 and typical areas would be of the order of 1.5 km^2, in low population density often semi-arid areas. A recent review of the radioactive waste inventory at the Maxey Flats site [G10] revealed the following radionuclides which are attributable to the nuclear fuel cycle:

^{3}H	20 PBq	^{137}Cs	0.93 PBq
^{14}C	1.3 PBq	^{226}Ra	0.18 PBq
^{60}Co	3.0 PBq	^{238}Pu	1.6 PBq
^{90}Sr	0.56 PBq	^{239}Pu	0.14 PBq

192. Emissions from waste handling operations have been studied at Maxey Flats [A4] and also at other waste disposal sites [D4, L5, M7, S17]. Atmospheric releases from normal waste handling and from leachate evaporators have been studied by Blanchard et al. [B17] and assessments made by the United States Environmental Protection Agency [E1] give estimates of collective effective dose equivalent commitment arising from one year of release of 4.2 10^{-2} man Sv per facility, leading to normalized collective effective dose equivalent commitments of less than 4 10^{-5} man Sv $[GW(e)\,a]^{-1}$.

193. Disposal of low-level packaged radioactive waste in the deep ocean is governed by the International Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (the London Convention). The special permits granted by the appropriate national authorities for radioactive waste should take into account the relevant IAEA definition of high-level waste unsuitable for disposal at sea and recommendations for the purpose of the London Convention. In addition, sea disposal operations undertaken by NEA member countries are required to conform to the terms of the Multilateral Consultation and Surveillance Mechanism which was established in 1979 by a decision of the OECD Council. This mechanism was set up to further the objectives of the London Convention and provides a framework for cooperation between participating countries. It provides for the development of standards, guidelines, practices and procedures for sea disposal operations and for international consultation on and surveillance of operations to verify that these are carried out in accordance with internationally established rules.

B. HIGH-LEVEL WASTES

194. The majority of irradiated nuclear fuel which 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 in some manner to facilitate further handling, storage and

eventually disposal. In France a decision has been made about the process for solidifying high-level wastes and a vitrification plant was commissioned at Marcoule in 1978. After about a year's operation during 1979 some 250 glass blocks had been produced and stored in air-cooled facilities. Other countries are pursuing research into the most appropriate form for solidifying high-level wastes, for containing the wastes, and to find the most suitable location for disposal. Assuming a world nuclear generating capacity of 1300 GW(e) by the year 2000, it might be expected that some 5000 GW(e) a will have been generated and assuming the waste is vitrified in a cylindrical form similar to those developed in the French AVM process several tens of thousands of cylinders will be required.

195. The procedures for disposal being studied widely are either disposal in deep geological formations, or disposal on or under the ocean bed. International studies are being undertaken on research needs to assess ocean disposal and many countries are actively investigating geologic disposal in either salt or hard rock (granite, gneiss or basalt). In addition, there is the possibility of using argillaceous rock as a repository. The main barriers which can prevent the return of activity to man's environment from a geologic repository or can influence the rate at which activity returns are: the waste form and its container; geologic containment of the waste within the rock formation; retardation of activity during transport through geologic media; and dispersion and dilution of activity in the biosphere.

196. Assessments of geologic disposal have been undertaken in many countries [E6, K8, K11]. In the United Kingdom [H11, H12], assessments estimate not only public health consequences but are performed with the intention of using the theoretical models to perform sensitivity analysis so that those parameters whose uncertainties have a significant effect on the overall result can be identified for further research. In the United States a number of studies have been undertaken on a range of geologic media and the present emphasis is also on the identification of areas of uncertainty, so that research needs and priorities can be properly co-ordinated in the development of the overall strategy for high-level waste disposal [E6]. In Sweden a comprehensive study of the radiological consequences of geological disposal of unreprocessed nuclear fuel and vitrified high-level waste has been undertaken [K8].

197. Disposal of high-level wastes from nuclear power production has not yet taken place. There has only been storage under surveillance by national authorities, awaiting a final decision on processing. Therefore the Committee has to make its estimate of the potential collective dose commitments from high-level waste disposal on the basis of theoretical studies. For normal operations in the preceding steps in the nuclear power cycle, truncated dose commitments per unit of electrical energy generated have been used as a tool for the assessment of the maximum dose rate in the future, if the practice were continued at constant rate. The integration period was taken to be equal to the expected length of the practice. For high-level waste contained over periods which are longer than the assumed period of practice, such truncated dose commitments are not needed, since the dose rate at the time when the radioactive material may reach the biosphere can be calculated directly and there would be no continued practice that would add to it in later years. The potential collective dose commitments given below have been based on the INFCE analysis of waste disposal [I9], as this was an exercise involving many countries active in the development of nuclear power. No assessment is made by the Committee of dose commitments, but rather the INFCE values are quoted. The INFCE analysis of geologic repositories assumes that the lifetime of stainless steel containers is 10^3 a and the retention time of wastes in a vitreous matrix is 10^4 a, although these figures have little influence on the overall result as the time scale of the subsequent geologic transfer is much greater. For a salt repository the waste is only exposed to groundwater due to a disruptive event which is assumed to have a probability of occurrence approaching unity in 10^5–10^6 a. A detailed analysis of this scenario showed that the mean arrival times of the nuclides of significance, ^{99}Tc, ^{129}I, ^{135}Cs and the actinides, in fresh water was of the order of several million years. In the repository in nominal hard rock, the canisters would be in contact with water which has a low flow velocity. Transport of dissolved species through the buffer material surrounding the canisters will be governed by diffusion which is extremely slow. Further retardation of many nuclides is expected by chemical interactions with the buffer material and the host rock. The INFCE study assumes that because of these processes it will be between 10^5 and 10^6 a before radionuclides from the waste arrive in fresh surface waters and the radiological consequences are calculated following the different pathways to humans [I10].

198. Dose commitments are first evaluated assuming the radionuclides are released to fresh water for which simple assumptions are made about turnover time (10 a), fractions of water drunk ($2.7\ 10^{-5}$ of the available volume per year) and fractions of fish content consumed ($3\ 10^{-8}\ a^{-1}$). These figures are global averages. It is assumed that all the long-lived nuclides released from a repository eventually reach the ocean where sedimentation processes become an important removal mechanism for radionuclides from the biosphere. In the consideration of population exposure, in addition to consumption of fish and other sea foods, resuspension of sediments provides inhalation doses and external exposure to sediments occurs along the shoreline.

199. The dose commitments due to waste disposal depend upon whether unreprocessed fuel or high-level reprocessing wastes are considered and from which fuel cycle they arose. The doses would not be received until after 10^5 or 10^6 a, so they will be subject to considerable uncertainty and the absolute numerical values should be used with caution. Their main virtue is in providing the ability to compare the cycles. Table 51 shows the collective effective dose equivalent commitments for the major fuel cycles under consideration for the future where the contribution from the uranium isotopes and their radioactive daughters are separately identified from other elements in the waste. Results are presented assuming both 10^5 and 10^6 a migration times through the geosphere to show the range to be expected for dose commitments. The once-through fuel cycles give higher values of collective dose commitment and the fast breeder reactor gives lower values because of its more efficient use of uranium. 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]$^{-1}$, regardless of the actual time chosen for migration through geologic media.

200. As regards the levels of individual dose associated with a geologic repository, studies on a salt medium [U5] and on hard rock [110, K8] have been undertaken, assuming wastes from 100 GW(e) a of electrical energy production are disposed of. For the salt repository the annual whole-body dose equivalent was between 5 10^{-8} and 3 10^{-5} Sv, some 3.5 10^{6} a after the event initiating ground water ingress. For hard rock, maximum individual annual dose equivalents were predicted some 4 10^{8} a after disposal and ranged from 10^{-8} to 10^{-6} Sv. These doses should be regarded as indicative rather than definitive and the conclusion to be drawn is that either disposal option for any fuel cycle will probably lead to very low levels of individual annual dose in the far distant future.

VII. MISCELLANEOUS CONTRIBUTIONS

201. Other aspects of the nuclear fuel cycle which contribute to the collective dose commitment from the use of nuclear power are transportation of irradiated nuclear fuel and the operation of nuclear research facilities.

A. TRANSPORTATION

202. Unirradiated nuclear fuel is transported to reactor sites from fuel fabrication facilities and irradiated nuclear fuel is transported from the reactor sites to reprocessing or fuel storage facilities. The transport of radioactive materials is subject to national regulations generally based on the IAEA regulations [17]. Shipments occur by road, rail and sea, and the number of shipments and distances travelled vary widely from country to country. Typical studies have been carried out in the United Kingdom [B18] and in the United States [U4] and for the Commission of the European Communities [C5].

203. Calculations can be performed knowing the dose rate distribution as a function of distance from the irradiated fuel flask and the population density along the routes used for transportation and up to a distance of perhaps 1 km away from the pathway. Estimates of the normalized collective effective dose equivalent commitment associated with irradiated fuel transport is in the range 10^{-3} to 10^{-2} man Sv [GW(e) a]$^{-1}$. This does not include any contribution from flask accidents which could lead to radiation exposures of the public. It is difficult to add any meaningful component to total health detriment from accidents since there is a probability distribution of a whole range of accidents leading to different releases, for each of which there are probability distribution functions representing the chance of different meteorological conditions (weather category and wind direction), and widely different population distributions depending upon the location of the incident and meteorology.

B. NUCLEAR RESEARCH INSTALLATIONS

204. A proportion of the radioactive materials released to the environment from nuclear research facilities may be attributed to support for continued operation or future development of nuclear power. However, other activities at nuclear facilities such as radioisotope production and processing and other types of research are usually responsible for a large fraction of the environmental releases. Since the fraction of the releases to the environment which may be attributed to the generation of electricity by nuclear power is unknown, it is not possible for the Committee to assess their contributions to overall dose.

205. Reported estimates of discharges have been used to calculate the associated collective doses in 1977–1978 from 27 nuclear research and operational institutions in the United States [E1]. The annual collective dose equivalents ranged from 10^{-10} man Sv up to 2 man Sv and the total value was about 6 man Sv from all installations, over half of this being due to ^{3}H releases from two sites (Savannah River and Ames Laboratory). One-third of the total was due to ^{41}Ar discharges from the Argonne National Laboratory. The collective doses from nuclear research facilities in the United Kingdom have been estimated [T4] based on reported discharge data. The only significant contribution is from the tritium discharged to the river Thames by the United Kingdom Atomic Energy Authorities' Research Establishment at Harwell, for which the annual collective dose equivalent via the drinking water pathway to the population of Greater London is estimated to be 1 man Sv. Data on radioactive materials released from the nuclear research centres Jülich and Karlsruhe and from research reactor sites in the Federal Republic of Germany have been reported and the collective doses associated with nuclear power production are negligible.

VIII. SUMMARY OF NORMALIZED COLLECTIVE EFFECTIVE DOSE EQUIVALENT COMMITMENTS TO THE PUBLIC FROM NUCLEAR POWER PRODUCTION

206. The preceding chapters contain the results of the Committee's assessments of collective dose commitments and collective effective dose equivalent commitments, excluding the contributions from occupational exposure, associated with nuclear power production. The collective effective dose equivalent commitments, which have been averaged over reactor types according to their total contribution to electrical power production, are summarized in normalized form, i.e., per unit of electrical energy generated, in Table 52. Normalized collective effective dose equivalent commitments are presented, so that different steps in the cycle may be compared and appropriate estimates of the health detriment may be estimated using the procedures outlined in Annex A. For releases during the operational phase in the nuclear fuel cycle, i.e., excluding waste disposal, the normalized collective effective dose equivalent commitment is 5.7 man Sv [GW(e) a]$^{-1}$, of which some 90% is delivered in the year the wastes are discharged and some 98% within 5 years. This estimate is made using the notional reprocessing plant effluents. Present day reprocessing may give normalized collective effective dose equivalent commitments 10–20 times higher; however, since less than 10% of fuel is reprocessed, the weighted contribution would be similar to that here.

207. For those long-lived nuclides which become globally dispersed incomplete normalized collective effective dose equivalent commitments are also given in Table 52. The incomplete dose commitments give an indication of the time distribution of the dose commitment and can also be used to derive the maximum annual per caput effective dose equivalents

by dividing by the mean population size, assuming the production of electricity by nuclear power continues throughout the period chosen for the integration time, and that the release rates remain constant. The normalized collective effective dose equivalent commitment due to global dispersion of nuclides released during fuel cycle operations is 670 man Sv [GW(e) a]$^{-1}$, 90% of which is delivered in the time period 10^4-10^8 a after release. The incomplete value to 500 a, which might be taken as the duration of the practice of generation of electricity by fission power is 18 man Sv [GW(e) a]$^{-1}$. If this figure is used to derive an annual per caput effective dose equivalent, it is comparable with that obtained from the local and regional normalized collective effective dose equivalent commitment.

208. Considerable caution must be exercised in extrapolation of doses into the future because the trend over the last five years has been for reactor releases to the environment to decrease despite the increasing electrical output of plants. This has been due partly to improvements in control technology and partly to the development of new concepts in radiation protection. Also, the collective doses due to global dispersion of radionuclides may not be typical of future practices; for example, in the model reactor and reprocessing facilities assumed here for LWR assessments, it was taken that long-lived nuclides such as ^{85}Kr and ^{14}C were emitted untreated to the atmosphere, whereas they may be contained and immobilized. Finally, when extrapolating thousands or millions of years into the future it is difficult to predict the population size, its dietary and other habits as well as medical services so that the estimation of global collective dose commitments must be regarded as highly speculative.

209. The results in Table 52 indicate that the largest contributions to the normalized collective effective dose equivalent commitments arise from mining and milling tailings. The incomplete dose commitments are proportionally less and depend entirely on the assumptions made about the amount and type of covering on tailings and the time before the activity either migrates downwards into the ground and becomes unavailable, or is eroded into the aquatic environment. If the tailings are immobilized by use of polyvinylchloride or asphalt coverings, the radon emanation rate can be reduced to ambient levels and the contribution to dose commitment is essentially zero; similarly downwards migration of uranium and thorium with a rate of $2\ 10^{-3}$ m a^{-1} would lead to a normalized collective effective dose equivalent commitment of the order of 30 man Sv [GW(e) a]$^{-1}$. Assuming that the tailings are eroded into the aquatic environment, leads to a normalized collective effective dose equivalent commitment of 460 man Sv [GW(e) a]$^{-1}$, of which 76% is contributed by ^{210}Po. The results will be highly dependent upon the local site characteristics and the answer given here must be uncertain by at least an order of magnitude. Finally, it must be recognized that any decision to use fast-breeder reactors, by more efficient utilization of uranium resources, could reduce the normalized collective effective dose equivalent commitment from tailings by two orders of magnitude.

210. In order to estimate the maximum per caput annual effective dose equivalent in the future as a result of nuclear power production, an incomplete collective effective dose equivalent commitment truncated over the expected duration of the practice of generation of electricity by fission power, taken here as 500 a, must be used. The releases during the operational stage of the nuclear fuel cycle lead to a local and regional normalized collective effective dose equivalent commitment of 5.7 man Sv [GW(e) a]$^{-1}$ of which 98% is received in the first few years after discharge. For those nuclides which become globally dispersed, the incomplete normalized collective effective dose equivalent commitment to 500 a is about 18 man Sv [GW(e) a]$^{-1}$. The choice of 500 a as a mean duration of the practice of producing power by nuclear fission implies the use of breeder reactors and the rate of mining would decrease. The normalized incomplete collective effective dose equivalent commitment from mining and milling, based on the present fuel cycle, is therefore to 100 a and is likely to be due mainly to radon releases giving 2.5 man Sv [GW(e) a]$^{-1}$. Thus, on the pessimistic assumption that no technological improvements are made and current levels of discharge continue for 500 a, the maximum annual collective effective dose equivalent would be about 25 man Sv [GW(e) a]$^{-1}$. The annual collective and per caput effective dose equivalents for a notional nuclear programme to the year 2500 are shown in Table 53, again assuming that present release levels are not reduced and that the annual generation of electric energy reaches 1 kW a per caput, i.e., some 10^4 GW(e) a in 2500. It can be seen that even with the maximizing assumptions made here, the level of annual per caput effective dose equivalent rises to the equivalent of 1% of natural background radiation. The annual per caput effective dose equivalent would reduce after the end of the practice, to about 1% of the final values after 100 a.

211. Normalized collective effective dose equivalent commitments from mill tailings, waste disposal and the global dispersion of the long-lived nuclides ^{14}C and ^{129}I must be uncertain because of difficulties in predicting future practices, population sizes and habits, environmental pathways and human metabolism. At present the estimate is of the order of $4\ 10^3$ man Sv [GW(e) a]$^{-1}$, mainly delivered in the time period starting 10^5 years from now. Such figures should not be relied upon for decision-making purposes and the Committee therefore recommends that little significance be attached to these complete collective effective dose equivalent commitment estimates. The Committee however recommends that more research be undertaken in order to better quantify the incomplete collective effective dose equivalent commitments.

Table 1

Attainable production capability of uranium in 1979 and estimated reserves [113]

Country or area	Production capability in 1979 (t)	Estimated reserves a/ (t)
Argentina	135	37000
Australia	600	354000
Brazil	103	164000
Canada	6900	1,029000
France	2950	100000
Gabon	1000	35000
India	200	13000
Namibia	3700	175000
Niger	3350	210000
South Africa	5240	525000
Spain	339	19000
Sweden	0	304000
United States	19000	1,831000

a/ Reasonably assured reserves, assuming a price of US$ 130 per kilogram of uranium.

Table 2

Estimated radioactive airborne effluents from the model mine and operations at the model mill

Radionuclide	Normalized release from mine [GBq (GW[e] a)$^{-1}$]	Normalized release from milling [GBq (GW[e] a)$^{-1}$]	Normalized annual release from tailings area [GBq (GW[e] a)$^{-1}$]
^{238}U	-	0.66	0.0007
^{234}U	-	0.66	0.0007
^{230}Th	-	0.074	0.015
^{226}Ra	-	0.04	0.015
^{210}Pb	-	0.04	0.015
^{210}Po	-	0.04	0.015
^{222}Rn	20000	880	1000

Table 3

Population and atmospheric dispersion parameters at the model mine and mill site a/

	Pasquill category						
	A	B	C	D	E	F	D + rain
Frequency (%)	3.8	5.1	6.5	25.5	22.6	36.2	0.3
Height of atmospheric mixing depth (m)	2000	2000	1000	1000	200	200	1000
Wind speed (m s^{-1})	1	2	5	5	3	2	5

a/ The effective height of release is 10 m. The population density is 3 km^{-2} for 0-100 km and 25 km^{-2} for 100-200 km.

Table 4

Estimated normalized collective absorbed dose commitments from particulate airborne releases from uranium milling

	Normalized collective absorbed dose commitment [10^{-5} man Gy (GW[e] a)$^{-1}$]								
	Gonads	Breast	Lungs	Red bone marrow	Bone lining cells	Thyroid	Kidneys	Liver	Remainder tissues
Cloud passage: Inhalation									
^{238}U	-	-	210	0.2	2	-	0.9	0.006	-
^{234}U	-	-	250	0.2	3	-	1	0.006	-
^{230}Th	-	-	26	15	200	-	0.04	0.3	-
^{226}Ra	-	-	0.9	0.03	0.4	-	0.006	0.006	-
^{210}Pb	-	-	0.5	0.2	2	-	0.4	0.8	-
^{210}Po	-	-	1.2	0.02	0.02	-	0.6	0.2	-
Total (rounded) (α)	-	-	490	16	210	-	3	1	-
Activity deposited: Internal irradiation									
^{238}U	2	2	2	5	29	2	17	2	2
^{234}U	2	2	2	3	26	2	16	2	2
^{230}Th	0.01	0.01	0.7	0.8	11	0.01	0.4	0.01	0.01
^{226}Ra	0.1	0.1	0.1	0.4	4	0.1	0.1	0.1	0.1
^{210}Pb-^{210}Po	4	4	2	4	26	4	4	4	4
Total (rounded) (α)	8	8	7	13	96	9	37	8	8
Activity deposited: External irradiation (γ)	23 to all organs and tissues								

Table 5

Normalized collective effective dose equivalent commitments from particulate and gaseous airborne releases from mining and milling

	Collective effective dose equivalent commitment (10^{-2} man Sv [GW(e) a]$^{-1}$)			
	Inhalation during the passage of the cloud	Internal irradiation due to the activity deposited	External irradiation due to the activity deposited	Total
Milling				
Particulates	1.3	0.2	0.02	1.5
Gaseous radon-222 and daughters	2.3	0.1		2.4
Mining				
Gaseous radon-222 and daughters	50	-	-	50
Total				54

Table 6

Normalized collective effective dose equivalent commitment to the local and regional population from tailings at the model mine and mill

(a) Atmospheric releases of radon and airborne particulates as a function of the time for which the erosion continues

	Normalized collective effective dose equivalent commitment (man Sv [GW(e) a]$^{-1}$)		
Release duration (a)	1	10^3	10^5
^{238}U	0.000005	0.005	0.5
^{234}U	0.000006	0.006	0.6
^{230}Th	0.0004	0.44	44
^{226}Ra	0.000009	0.009	0.9
^{210}Pb	0.00002	0.02	2
^{210}Po	0.00002	0.02	2
^{222}Rn	0.025	25	2500
Total (rounded)	0.026	26	2600

(b) Releases of tailings into the marine environment

	Normalized collective effective dose equivalent commitment (man Sv [GW(e) a]$^{-1}$)
^{238}U	0.15
^{234}Th	8.8
^{234}U	0.17
^{230}Th	0.54
^{226}Ra	18.6
^{210}Pb	79.7
^{210}Po	350
Total	460

Table 7

Normalized effluent discharges from the model fuel conversion, enrichment and fabrication facilities

(MBq [GW(e) a]$^{-1}$)
[E1, B2, B22, P1, S6]

Isotope	Atmospheric			Aquatic		
	Con-version	En-richment	Fabri-cation	Con-version	En-richment	Fabri-cation
^{238}U	74	3.7	0.74	814	370	370
^{235}U	2.0	0.07	0.22	20	7.4	7.4
^{234}U	74	3.7	7.4	814	370	370
^{234}Th	74	3.7	0.74	-	-	370
^{230}Th	0.74	-	-	56	-	-
^{226}Ra	0.07	-	-	126	-	-
^{222}Rn	8140	-	-	-	-	-

Table 8

Meteorological characteristics and population distribution around the model fuel fabrication facility used for assessing radon releases a/

Quantity	Pasquill weather category							
	Dry						Rain	
	A	B	C	D	E	F	C	D
Frequency (%)	0.3	4.5	12.1	63	5	4.6	1.7	8.4
Wind speed ($m\ s^{-1}$)	1	2	5	5	3	2	5	5
Depth of mixing layer (m)	2000	2000	1000	1000	200	200	1000	1000

a/ The assumed stack height is 60 m.
The assumed population distribution is uniform at 25 km^{-2}.

Table 9

Normalized collective absorbed dose commitments by inhalation for airborne releases from fuel fabrication

	Normalized collective absorbed dose commitment [10^{-6} man Gy $(GW[e]\ a)^{-1}$]								
	Gonads	Breast	Lungs	Red bone marrow	Bone lining cells	Thyroid	Kidneys	Liver	Remainder tissues
Cloud passage: Inhalation									
^{238}U	-	-	250	0.2	3	-	1	-	-
^{234}U	-	-	320	0.2	3	-	1	-	-
^{230}Th	-	-	3	2	20	-	0.004	-	-
^{226}Ra	-	-	0.02	-	0.007	-	-	-	-
Total (rounded) (α)	-	-	570	2	30	-	2	-	-
Activity deposited: Internal irradiation									
^{238}U	2	2	2	6	35	2	20	2	2
^{234}U	2	2	2	4	34	2	20	2	2
^{230}Th	0.001	0.001	0.07	0.08	1	0.001	4	0.001	0.001
^{226}Ra	0.002	0.002	0.002	0.008	0.08	0.002	0.002	0.002	0.002
Total (rounded) (α)	4	4	4	10	70	4	40	4	4
Activity deposited: External irradiation (γ)	0.4 to all organs and tissues								

Table 10

Normalized collective effective dose equivalent commitment from the model fuel fabrication facility

Radionuclide	Normalized collective effective dose equivalent commitment [10^{-4} man Sv (GW[e] a)$^{-1}$]		
	Cloud passage: Inhalation	Activity deposited: Internal irradiation	Activity deposited: External irradiation
^{238}U	6	0.7	0.004
^{234}U	7	0.9	
^{230}Th	0.2	0.01	
^{226}Ra	0.0004	0.001	
^{222}Rn	4	0.02	
Total (rounded)	20	2	0.004

Table 11

World nuclear generating capacity in 1979
[Net values in GW(e) and numbers of units in parentheses]
[I1, K12]

Country or area	Reactor type: PWR	BWR	GCR	HWR	LWGR	FBR	Total capacity	kW(e) per caput
Argentina				0.34 (1)			0.34	0.015
Belgium	1.66 (3)						1.66	0.17
Bulgaria	0.82 (2)						0.82	0.10
Canada				5.49 (11)			5.49	0.25
Czechoslovakia	0.38 (1)						0.38	0.024
Finland	0.42 (1)	0.66 (1)					1.08	0.23
France	5.71 (7)		2.13 (7)	0.07 (1)		0.25 (1)	8.16	0.15
German Dem. Rep.	1.29 (4)						1.29	0.074
Germany, Fed.Rep.of	5.37 (6)	3.16 (5)	0.01 (1)	0.05 (1)		0.02 (1)	8.61	0.14
India		0.40 (2)		0.20 (1)			0.60	0.001
Italy	0.24 (1)	0.15 (1)	0.15 (1)				0.54	0.01
Japan	6.44 (9)	7.72 (12)	0.16 (1)	0.15 (1)			14.47	0.16
Republic of Korea	0.56 (1)						0.56	0.17
Netherlands	0.45 (1)	0.05 (1)					0.50	0.038
Pakistan				0.13 (1)			0.13	0.002
Spain	0.15 (1)	0.44 (1)	0.48 (1)				1.07	0.031
Sweden	0.80 (1)	2.90 (5)					3.70	0.46
Switzerland	1.62 (3)	0.32 (1)					1.94	0.31
USSR	2.49 (7)	0.09 (5)			7.89 (16)	0.15 (2)	10.62	0.043
United Kingdom			6.75 (32)			0.23 (1)	6.98	0.13
United States	31.88 (42)	17.78 (26)	0.33 (1)				49.99	0.24
Other Asia	1.21 (2)						1.21	0.084
Total	61.49 (92)	33.67 (60)	10.01 (44)	6.43 (17)	7.89 (16)	0.65 (6)	120.14	0.07

Table 12

Noble gases discharged in airborne effluents from PWRs in various countries 1975-1979
[B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]

Country and reactor	Startup year	Electrical capacity [GW(e)]	Release (TBq)				
			1975	1976	1977	1978	1979
Belgium							
Doel 1,2	1974/75	0.79	7.7	30	28	17	44
Tihange	1975	0.87	17	170	55	58	14
Finland							
Loviisa	1977	0.42	-	-	2.2	1.4	1.6
France							
Fessenheim	1977	1.78	-	-	70	73	
Chooz	1967	0.30	100	183	103	120	
Bugey 2,3	1978	1.85	-	-	-	4.1	
Germany, Fed. Rep. of							
Obrigheim	1968	0.33	296	12	14	17	3.8
Stade	1972	0.63	47	389	132	18	8.5
Biblis A,B	1974/76	2.39	62	54	156	79	43
Neckarwestheim	1976	0.81	-	19	70	4.3	12
Unterweser	1978	1.23	-	-	-	1.9	38
Italy							
Trino	1964	0.25	17	6.6	2.2	20	
Japan							
Mihama 1	1970	0.34	2.7	2.1	2.7	1.7	2727
Mihama 2	1972	0.50	7.0	30	14	6.7	0.59
Mihama 3	1976	0.83	-	10	6.3	0.9	0.26
Takahama 1	1974	0.83	4.8	3.6	4.4	3.1	3.0
Takahama 2	1975	0.83	3.0	3.3	2.3	2.1	2.4
Ohi 1	1977	1.17	-	-	0.4	9.3	3.0
Ohi 2	1978	1.17	-	-	-	0.33	2.3
Ikata 1	1977	0.57	-	-	2.2	3.0	3.4
Genkai 1	1975	0.57	1.5	1.8	2.0	1.6	1.0
Netherlands							
Borssele	1973	0.45	97	144	37	15	8
Sweden							
Ringhals 2	1975	0.80	-	8.5	11	5.4	22
United States							
Arkansas 1	1974	0.84	38	210	514	277	315
Arkansas 2	1979	0.95	-	-	-	-	168
Beaver Valley	1976	0.80	-	-	2	14	65
Calvert Cliffs 1,2	1974	1.62	3.2	286	825	1020	378
Cook 1,2	1975	2.14	-	36	141	1795	403
Crystal River	1977	0.80	-	-	112	254	2802
Davis Besse	1977	0.92	-	-	47	77	62
Farley	1978	0.83	-	-	-	131	118
Fort Calhoun	1973	0.46	16	80	141	50	26
R.E. Ginna	1969	0.47	389	204	118	36	28
Haddam Neck	1968	0.55	18	18	115	79	204
Indian Point	1973/76	1.77	303	392	592	551	343
Kewaunee	1974	0.52	91	59	90	16	5.6
Maine Yankee	1972	0.77	152	48	11	53	73
Millstone Point 2	1975	0.80	-	57	84	28	13
North Anna	1978	0.90	-	-	-	559	232
Oconee	1973/74	2.64	562	1628	1317	1612	1772
Palisades	1971	0.64	97	1.1	2.2	12	2.5
Point Beach 1,2	1970/72	0.99	1676	74	42	19	36
Prairie Island	1973/74	1.01	81	64	25	47	26
Rancho Seco	1974	0.87	4.4	4.7	74	263	326
H.B. Robinson	1970	0.66	43	29	18	33	56
St. Lucie	1976	0.78	-	-	940	1084	570
Salem 1	1976	1.08	-	-	7.3	0.38	9.2
San Onofre	1967	0.44	66	15	5.6	67	24
Surry 1,2	1972/73	0.55	298	710	703	161	66
Three Mile Island 1	1974	0.79	134	102	614	581	83
Trojan	1975	1.08	-	-	113	11	34

Table 12, continued

Country and reactor	Startup year	Electrical capacity [GW(e)]	Release (TBq) 1975	1976	1977	1978	1979
Turkey Point	1972/73	1.32	496	577	862	870	392
Yankee Rowe	1960	0.17	1	1	4.6	24	6.7
Zion 1,2	1973/74	2.08	1676	5254	1191	2505	1262
Total annual energy generated [GW(e) a]			16.9	19.2	23.8	29.4	27.5
Normalized release [TBq (GW[e] a)$^{-1}$]			402	570	388	432	370
		Average 1975-1979			430 TBq [GW(e) a]$^{-1}$		

Table 13

Isotopic composition of noble gases discharged from PWRs in the United States during 1979 [B23]

Reactor	Startup year	Energy generated [GW(e) a]	Release (TBq) ^{41}Ar	^{85m}Kr	^{85}Kr	^{87}Kr	^{88}Kr	^{131m}Xe	^{133m}Xe	^{133}Xe	^{135m}Xe	^{135}Xe	^{138}Xe
Arkansas 1	1974	0.397	0.30	3.2	0.20	0.49	1.7	0.11	2.8	289	-	24	-
Arkansas 2	1979	0.916	5.3	-	-	-	-	0.001	-	143	-	19	-
Beaver Valley	1976	0.221	-	-	0.52	-	0	18	1.6	45	-	0.027	-
Calvert Cliffs 1,2	1975/77	1.161	0.005	1.3	0.036	-	0.045	0.048	0.14	363	-	13	-
Cook 1,2	1975/78	1.373	0.019	0.007	326	-	-	-	0.88	70	-	7.8	-
Crystal River	1977	0.453	17	25	-	7.8	19	36	49	2290	21	212	125
Davis Besse	1977	0.381	0.02	0.26	56	0.61	0.43	0.019	0.023	3.3	0.51	0.24	1.2
Joseph M. Farley	1978	0.211	11	0.001	0.78	0.062	0.007	3.5	1.4	95	-	5.1	0.01
Fort Calhoun	1973	0.440	0.078	0.01	0.48	0.004	0.016	-	0.19	25	-	0.24	-
R.E. Ginna	1969	0.355	0.033	0.11	0.74	-	-	0.036	0.018	25	-	1.9	-
Haddam Neck	1967	0.493	-	0.051	37	0.13	0.12	1.5	0.29	155	0.027	1.1	0.13
Indian Point	1973	1.142	-	0.92	24	0.29	1.0	3.8	3.6	297	0.38	11	0.84
Kewaunee	1974	0.412	0.31	0.016	1.0	-	0.013	-	0.007	1.1	-	0.41	-
Maine Yankee	1972	0.537	-	-	1.0	-	-	2.4	-	67	-	1.4	-
Millstone Point 2	1975	0.520	0.068	-	0.36	-	-	-	-	648	-	0.64	-
North Anna	1978	0.507	0.007	0.67	0.05	0.01	0.02	0.12	0.58	224	0.02	7.3	0.01
Oconee 1,2,3	1973/74	1.708	1.0	3.4	40	0.26	1.1	14	27	1646	1.4	29	0.15
Palisades	1971	0.415	-	-	0.090	-	-	0.021	0.002	2.4	-	0.007	-
Point Beach 1,2	1970/72	0.808	2.1	2.3	1.2	1.2	3.6	-	0.11	11.3	0.78	12	1.2
Prairie Island 1,2	1973/74	0.865	0.1	0.03	0.048	0.09	-	-	0.068	25	-	0.71	-
Rancho Seco	1974	0.687	0.06	0.52	0.27	0.007	0.041	0.085	0.92	300	-	24	-
H.B. Robinson	1970	0.482	0.05	-	-	-	-	-	-	56	-	0.87	-
Salem	1976	0.250	0.011	0.043	0.050	-	0.04	-	0.12	8.4	-	0.56	-
St. Lucie	1976	0.592	0.92	4.9	2.9	5.0	10	31	4.9	492	0.41	9.4	4.7
San Onofre	1967	0.401	0.40	0.08	2.3	0.019	0.084	0.10	0.073	19	-	0.53	-
Surry 1,2	1972/73	0.343	0.083	0.029	0.013	0.041	0.02	-	0.36	63	-	2.5	-
Three Mile Island 1	1974	0.266	0.67	-	0.007	-	0.007	0.093	0.26	81	-	0.95	-
Trojan	1975	0.631	0.016	0.042	0.038	0.034	0.058	0.092	0.28	32	0.13	1.4	0.016
Turkey Point	1972/73	0.811	2.0	0.050	0.035	0.0099	0.036	0.075	0.25	389	0.068	1.1	0.026
Yankee Rowe	1960	0.149	0.062	0.060	0.060	0.050	0.093	0.012	0.069	4.3	0.82	0.94	0.028
Zion	1973	1.238	0.28	0.062	0.097	-	1.5	8.8	0.63	1132	-	118	-
Total annual energy generated [GW(e) a]		19.165											
Normalized release [TBq (GW[e] a)$^{-1}$]			2.1	2.2	25	0.84	2.0	6.3	5.0	469	1.3	26	6.9

Table 14

Noble gases discharged in airborne effluents from BWRs in various countries 1975-1979
[B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]

Country and reactor	Startup year	Electrical capacity [GW(e)]	Release (TBq) 1975	1976	1977	1978	1979
Finland							
Olkiluoto	1978	0.660	-	-	-	0.25	0.014
Germany, Fed. Rep.of							
Gundremmingen	1966	0.237	274	195	9.2	8.5	-
Lingen	1968	0.182	1295	237	4.9	-	-
Würgassen	1971	0.640	4.5	18	29	121	159
Brunsbüttel	1976	0.770	-	36	116	280	46
Isar	1977	0.870	-	-	0.9	40	85
Italy							
Garigliano	1964	0.152	8456	8861	3328	2886	
Caorso	1978	0.548	-	-	-	-	
Japan							
Tsuruga	1970	0.357	85	70	23	16	8.1
Tokai 2	1978	1.100	-	-	-	-	-
Fukushima 1	1971	0.460	196	1070	17	740	133
Fukushima 2	1974	0.784					
Fukushima 3	1976	0.784	0.63	0.25	1.1	0.77	0.67
Fukushima 4	1978	0.784					
Fukushima 5	1978	0.784	-	-	0.0026	0.024	0.0025
Hamaoka 1	1976	0.540	-	-	-	-	-
Hamaoka 2	1978	0.840	-	-	-	-	-
Shimane	1974	0.460	-	-	-	-	-
Netherlands							
Dodewaard	1968	0.052	78	230	481	159	119
Sweden							
Oskarshamn 1	1970	0.460	-	5402	5217	4613	4700
Oskarshamn 2	1974	0.590	-	1.4	31	44	290
Ringhals 1	1974	0.780	-	1712	78	2900	19300
Barsebäck 1	1975	0.590	-	0.78	3	2.9	0.97
Barsebäck 2	1976	0.590	-	-	0.37	2.0	3.3
United States							
Big Rock Point	1963	0.075	1872	562	496	699	323
Browns Ferry	1973/77	3.195	932	2974	6142	5809	10027
Brunswick	1975/76	1.580	6.8	685	9102	3381	3184
Cooper	1974	0.764	729	1420	47	151	1125
Dresden 1	1960	0.200	19240	17020	19240	31450	6.8
Dresden 2,3	1971/72	1.545	13653	1199	11581	1502	2557
Duane Arnold	1975	0.515	57	195	143	58	342
J.A. Fitzpatrick	1975	0.300	151	1709	862	218	125
Edwin I. Hatch	1975	0.717	57	115	70	60	142
Humboldt Bay	1963	0.065	10952	3441	-	-	-
Lacrosse	1969	0.048	2109	4588	1573	312	385
Millstone Point 1	1971	0.652	109890	18759	22940	20942	762
Monticello	1971	0.536	5735	422	254	238	149
Nine Mile Point	1969	0.610	48100	6512	131	112	38
Oyster Creek	1969	0.520	7622	6142	6549	36926	37470
Peach Bottom	1974	2.086	480	7730	2631	1425	4592
Pilgrim	1972	0.664	3885	6771	15281	1210	514
Quad Cities	1973	1.538	4070	1166	947	1199	1644
Vermont Yankee	1972	0.514	124	106	131	183	299
Total annual energy generated [GW(e) a]			9.53	13.04	13.24	18.1	20.0
Normalized release [TBq (GW[e] a)$^{-1}$]			25447	7104	8103	6500	4407

Average 1975-1979 8800 TBq [GW(e) a]$^{-1}$

Table 15

Isotopic composition of noble gases discharged from BWRs in the United States during 1979 [B23]

Reactor	Startup year	Energy generated [GW(e) a]	Release (TBq)							
			^{41}Ar	^{83m}Kr	^{85m}Kr	^{85}Kr	^{87}Kr	^{88}Kr	^{89}Kr	^{90}Kr
Big Rock Point 1	1962	0.013	-	9.9	12	0.037	31	17	24	26
Browns Ferry 1,2,3	1973/77	2.393	44	-	50	8140	73	101	-	-
Brunswick 1,2	1975/77	0.810	41	-	88	-	316	281	-	-
Cooper	1974	0.591	-	25	74	3.9	100	188	-	-
Dresden 1	1959	1.013	-	-	-	-	-	-	-	-
Dresden 2,3	1970/71		-	54	-	-	69	136	-	-
Duane Arnold	1974	0.352	3.8	-	32	13	3.2	21	-	-
J.A. Fitzpatrick	1974	0.349	1.5	-	4.7	0.13	2.4	4.1	-	-
Edwin I Hatch	1974	0.401	2.0	-	5.8	-	0.37	2.8	0.06	-
Lacrosse	1967	0.024	-	-	6.8	0.36	41	25	0.49	-
Millstone Point 1	1970	0.505	-	-	14.	-	8.4	2.2	-	-
Monticello	1970	0.522	-	0.37	0.31	0.74	1.9	1.0	36	1.2
Nine Mile Point	1969	0.354	-	-	-	-	-	16	-	-
Oyster Creek	1969	0.541	-	-	1613	-	5217	5032	1.1	-
Peach Bottom 2,3	1973/74	1.740	-	-	16	-	4.1	3.1	-	-
Pilgrim	1972	0.574	-	-	96	0.002	83	204	-	-
Quad Cities 1,2	1971/72	1.075	-	-	121	-	488	190	-	-
Vermont Yankee	1972	0.414	-	-	1.3	-	3.8	3.2	-	-
Total annual energy generated [GW(e) a]		11.670								
Normalized release [TBq (GW[e] a)$^{-1}$]			7.9	7.6	180	690	550	530	5.2	2.3

Reactor	Startup year	Energy generated [GW(e) a]	Release (TBq)							
			^{131m}Xe	^{133m}Xe	^{133}Xe	^{135m}Xe	^{135}Xe	^{137}Xe	^{138}Xe	^{139}Xe
Big Rock Point 1	1962	0.013	0.11	0.32	5.8	40	20	38	64	35
Browns Ferry 1,2,3	1973/77	2.393	-	-	319	121	38	-	610	-
Brunswick 1,2	1975/77	0.810	-	29	84	888	1217	-	240	-
Cooper	1974	0.591	1.7	11	310	9.4	358	0.23	45	-
Dresden 1	1959	1.013	-	-	6.8	-	-	-	-	-
Dresden 2,3	1970/71		-	-	219	250	466	-	1365	-
Duane Arnold	1974	0.352	-	-	212	9.4	42	-	5.1	-
J.A. Fitzpatrick	1974	0.349	4.6	1.2	70	0.6	29	-	3.3	-
Edwin I Hatch	1974	0.401	14	1.2	110	0.74	2.1	-	2.4	-
Lacrosse	1967	0.024	0.35	3.0	27	33	120	2.9	120	-
Millstone Point 1	1970	0.505	81	-	12	119	74	269	182	-
Monticello	1970	0.522	0.07	0.02	10	2.8	2.1	47	41	3.7
Nine Mile Point	1969	0.354	-	-	-	6.0	5.1	-	12	-
Oyster Creek	1969	0.541	-	-	1298	3648	8362	23	12284	-
Peach Bottom 2,3	1973/74	1.740	5.0	72	3922	3.2	566	-	0.97	-
Pilgrim	1972	0.574	-	-	71	7.6	19	-	32	-
Quad Cities 1,2	1971/72	1.075	-	-	481	33	97	-	235	-
Vermont Yankee	1972	0.414	-	-	164	36	8.1	-	81	-
Total annual energy generated [GW(e) a]		11.670								
Normalized release [TBq (GW[e] a^{-1}]			9.1	10	630	450	980	33	1300	3.3

Table 16

Noble gases discharged in airborne effluents from HWRs in various countries 1975-1979 [B21, M10]

Country and reactor	Startup year	Electrical capacity [GW(e)]	Release (TBq) 1975	1976	1977	1978	1979
Argentina							
Atucha	1974	0.320	9.3	160	71	311	252
Canada							
Bruce A	1976/79	4 x 0.755	-	-	1254	1550	3084
Pickering A	1971/73	4 x 0.514	162	104	159	152	218
Total annual energy generated [GW(e) a]			2.2	2.6	3.2	4.1	4.3
Normalized release [TBq (GW[e] a)$^{-1}$]			86	102	464	491	827

Average 1975-1979: 460 TBq [GW(e) a]$^{-1}$

Table 17

Activation gases released from GCRs in various countries 1975-1979

Country and reactor	Startup year	Electrical capacity [GW(e)]	Release (TBq) 1975	1976	1977	1978	1979
France							
Chinon 1	1963	0.070					
Chinon 2	1965	0.210	224	182	145	94	
Chinon 3	1966	0.400					
St. Laurent des Eaux 1	1969	0.460	129	107	155	250	
St. Laurent des Eaux 2	1971	0.515					
Bugey 1	1972	0.540	195	114	89	107	
Italy							
Latina	1963	0.153	96	92	89	97	
Japan							
Tokai	1966	0.166	207	229	289	307	333
United Kingdom							
Calder	1956	0.200		548	962	1073	1100
Chapelcross	1959	0.192		1184	1184	1184	1200
Berkeley	1962	0.276		592	555	444	444
Bradwell	1962	0.250		555	666	592	555
Hunterston A	1964	0.300			555	740	
Hunterston B	1976	1.240		74			
Trawsfynydd	1964	0.390		5550	5550	4810	5180
Hinkley Point A	1965	0.460		2960	2960	2960	2590
Hinkley Point B	1976	1.240					
Dungeness A	1965	0.410		1110	1110	1110	444
Sizewell	1965	0.420		2220	2220	2220	2220
Oldbury	1967	0.416					
Wylfa	1971	0.840					
Total annual energy generated [GW(e) a]			4.42	4.59	5.10	5.07	4.4
Normalized release [TBq (GW[e] a)$^{-1}$]				3381	3241	3153	3194

Average 1976-1979: 3240 TBq [GW(e) a]$^{-1}$

Table 18

Tritium discharged in airborne effluents from reactors 1975-1979
[B21, B23, D6, D8, E9, G3, K4, L1, L6, M10, N19, P2, S14]

Country and reactor	Release (TBq)				
	1975	1976	1977	1978	1979
P W R					
France					
Bugey 2,3	-	-	-	44	
Chooz	-	-	-	-	
Fessenheim	-	-	-	-	
Germany, Fed.Rep.of					
Obrigheim	0.99	2.3	0.85	0.96	0.63
Stade	0.56	0.78	0.59	0.99	1.2
Biblis, A,B	0.48	0.48	1.26	2.29	2.4
Neckarswestheim		0.074	0.92	1.04	1.1
Unterweser		-	-	-	0.21
Italy					
Trino	0.14	0.60			
Netherlands					
Borssele	0.44	0.33	0.37	0.93	0.9
United States					
Arkansas 1	0.019	0.25	7.0	0.22	0.47
Arkansas 2	-	-	-	-	0.15
Beaver Valley		138	7.9	14	0.82
Calvert Cliffs	0.046		4.3	0.06	0.19
Cook 1	0.0007	0.004	0.007	0.72	0.5P
Crystal River	-	-	4.5	0.96	1.1
Davis Besse	-	-	0.0014	1.2	0.4
Joseph M. Farley	-	-	-	2.9	0.54
Fort Calhoun	0.088	0.093	0.11	0.14	0.054
R.E. Ginna	0.21	0.89	1.90	1.6	3.6
Haddam Neck	2.59	27	0.0004	2.5	6.4
Indian Point	0.48	0.89	0.44	0.38	0.48
Kewaunee	1.37	0.026	0.14	0.46	0.26
Maine Yankee	0.17	0.14	0.078	0.041	0.11
Millstone Point II	0.063	0.56	0.070	1.5	3.8
North Anna	-	-	-	0.66	0.070
Oconee	62.9	18.5	2.31	2.5	0.98
Point Beach	15.5	14.8	7.22	6.3	29.7
Prairie Island	0.37	1.22	3.24	5.3	5.8
Rancho Seco		0.34	0.78	8.9	5.3
H.B. Robinson	7.14	5.85	2.26	1.6	0.38
Salem	-	-	1.9	5.3	108
St. Lucia		0.074	11.8	19.8	12.6
San Onofre	1.26	1.74	2.81	1.1	1.0
Surry	1.18	13.7	32.5	8.1	3.0
Three Mile Island	1.48	26.6	4.77	7.9	2.4
Trojan	-	0.056	0.11	0.15	0.39
Turkey Point	0.13	0.19	0.14	0.13	0.035
Yankee Rowe	0.074	0.074	0.12	0.11	0.13
Total annual energy generated [GW(e) a]	15.7	16.8	21.3	24.4	22.8
Normalized release [TBq (GW[e] a)$^{-1}$]	6.2	15.2	4.5	5.9	8.5
	Average 1975-1979		7.8 TBq [GW(e) a]$^{-1}$		
B W R					
Germany, Fed. Rep.of					
Gundremmingen	3.7	1.0	0.26	0.037	0.014
Lingen	1.1	0.22	0.20	0.078	-
Würgassen	0.07		0.89	0.28	0.33
Brunsbüttel		0.0074	0.18	0.24	0.34
Isar				0.056	0.25
Italy					
Garigliano	0.026	0.55			
Netherlands					
Dosewaard	-	-	-	-	-
United States					
Big Rock Point	0.27	0.31	0.40	0.31	0.12
Browns Ferry	0.19	0.021	0.87	1.1	1.3
Brunswick	0.07	0.81	0.052	0.37	0.88
Cooper	1.6	2.5	1.9	0.21	0.92
Dresden 1	1.3	2.3	0.56	3.3	0.25
Dresden 2,3	8.1	5.2	18	12	6.8

Table 18, continued

Country and reactor	Release (TBq)				
	1975	1976	1977	1978	1979
Duane Arnold	0.70	0.59	0.56	0.22	0.33
J.A. Fitzpatrick	0.011	0.56	0.26	0.28	0.24
Edwin I. Hatch	0.066	0.052	0.085	0.22	0.54
Humboldt Bay	0.093	0.048	0.0024	0.0015	0.002
Lacrosse	0.63	0.48	0.32	0.29	0.17
Millstone Point I	0.63	1.1	2.4	1.8	2.2
Monticello		2.8	5.1	8.7	8.1
Nine Mile Point	3.4	0.70	1.7	3.2	1.5
Oyster Creek	0.10	0.041	0.044	1.4	1.4
Peach Bottom	0.011	1.0	3.7	0.74	1.0
Pilgrim	2.7	1.4	0.023	3.5	5.8
Quad Cities	1.4	11.0	1.5	3.7	5.4
Vermont Yankee	0.26	0.52	0.85	0.45	0.61
Total annual energy generated [GW(e) a]	7.1	9.6	10.6	13.1	13.2
Normalized release [TBq (GW[e] a)$^{-1}$]	3.8	3.5	3.8	3.2	2.9
	Average 1975-1979		3.4 TBq [GW(e) a]$^{-1}$		
H W R					
Argentina					
Atucha	38	220	224	222	237
Canada					
Bruce	-	-	315	481	1399
Pickering	918	891	1628	962	1147
Total annual energy generated [GW(e) a]	2.0	2.6	3.2	4.1	4.3
Normalized release [TBq (GW[e] a)$^{-1}$]	478	427	677	406	647
	Average 1975-1979		540 TBq [GW(e) a]$^{-1}$		

Table 19

Tritium discharged in liquid effluents from reactors 1975-1979
[B21, B23, D6, D8, E9, G3, G4, K4, L1, L6, M10, N19, P2, S14]

Country and reactor	Release (TBq)				
	1975	1976	1977	1978	1979
P W R					
Finland					
Loviisa	-	-	1.2	5.0	
France					
Bugey 2,3	-	-	-	3.3	
Chooz	92	71	96	65	
Fessenheim	-	-	3.1	31	
Germany, Fed. Rep.of					
Obrigheim	6.2	4.7	5.5	4.8	5.0
Stade	3.9	1.6	4.8	4.9	5.4
Biblis A,B	4.1	13	13	28	18
Neckarwestheim	-	0.19	3.1	5.0	3.8
Unterweser	-	-	-	0.0081	4.0
Italy					
Trino	44	27	64	77	
Japan					
Mihama 1,2	2.4	5.2	4.1	8.1	7.4
Mihama 3	-	1.7	3.7	5.2	3.6
Takahama 1,2	13	13	11	17	8.5
Ohi 1,2	-	-	0.014	4.4	16
Ikata 1	-	-	3.3	11	4.1
Genkai	2.3	1.1	11	6.7	11

Table 19, continued

Country and reactor	Release (TBq) 1975	1976	1977	1978	1979
Netherlands					
Borssele	2.1	1.5	1.5	8.4	8.3
Sweden					
Ringhals 2	-	10	8.8	11	8.9
United States					
Arkansas 1	17	7.8	9.1	10.8	6.2
Arkansas 2	-	-	-	-	1.95
Beaver Valley	-	0.32	4.0	12.9	3.5
Calvert Cliffs	9.7	10	21	16.8	19
Cook 1	2.1	7.1	11	23	45
Crystal River	-	-	6.1	5.7	6.1
Davis Besse	-	-	0.33	8.0	9.1
Joseph M. Farley	-	-	-	2.2	3.5
Fort Calhoun	4.1	4.5	5.8	5.6	9.5
R.E. Ginna	9.6	8.9	4.4	8.9	8.9
Haddam Neck	210	179	247	146	131
Indian Point	2.9	12	14	28.4	18.2
Kewaunee	10	6.7	11	10.9	9.2
Maine Yankee	6.5	14	5.7	11.7	7.5
Millstone Point 2	0.28	10	7.8	7.4	9.4
North Anna	-	-	-	10.4	11.6
Oconee	131	81	71	43	33
Palisades	1.5	0.36	2.1	3.7	4.7
Point Beach	33	27	37	48	33
Prairie Island	0.017	0.0037	50	20	23.3
Rancho Seco	4.9	0	0.0031	-	-
H.B. Robinson	23	36	25	17.5	15.9
Salem	-	0.0015	11	16.5	86
St. Lucie	-	0.49	9.0	4.7	4.7
San Onofre 1	148	125	66	92.5	85.8
Surry	16	29	15	27.6	13.2
Three Mile Island 1	17	7.0	7.1	5.7	2.1
Trojan	-	1.3	12	5.9	2.5
Turkey Point	29	29	34	43	35
Yankee Rowe	9.1	5.8	5.1	7.2	6.5
Zion	38	28	27	27	22
Total annual energy generated [GW(e) a)]	16.9	19.2	23.8	29.4	25.8
Normalized release, [TBq (GW[e] a)$^{-1}$]	52.9	38.7	40.0	33.0	30.0
	Average 1975-1979 38 TBq [GW(e) a]$^{-1}$				
B W R					
Finland					
Olkiluoto	-	-	-	0.0086	0.46
Germany, Fed.Rep.of					
Gundremmingen	4.7	1.9	0.81	0.093	0.026
Lingen	0.63	0.56	0.092	0.070	0.028
Würgassen	0.15	1.1	1.3	2.0	1.5
Brunsbüttel	-	-	0.34	0.70	0.085
Isar	-	-	0.0015	0.17	0.80
Italy					
Garigliano	0.19	0.67	0.56	0.37	
Japan					
Tsuruga	1.5	1.9	1.0	0.78	1.4
Tokai 2	-	-	-	0.14	0.31
Fukushima 1	-	-	0.14	0.067	0.13
Fukushima 2	-	-	0.0017	0.13	0.16
Fukushima 3	-	-	0.13	0.19	0.0052
Fukushima 4	-	-	-	0.034	0.000027
Fukushima 5	-	-	0.0073	0.10	0.078
Hamaoka 1	-	-	0.24	0.037]	0.63
Hamaoka 2	-	-	-	0.085]	
Shimane	0.14	0.24	0.18	0.19	0.16
Sweden					
Oskarshamn		1.3	1.3	1.6	2.7
Ringhals 1		0.85	0.56	0.32	1.7
Barsebäck		0.52	0.74	1.3	1.1
United States					
Big Rock Point	0.22	0.074	0.33	0.15	0.20
Browns Ferry	0.37	0.15	0.89	1.1	0.49
Brunswick	0.11	0.22	0.33	0.52	1.1

Table 19, continued

Country and reactor	Release (TBq)				
	1975	1976	1977	1978	1979
Cooper	0.30	0.30	0.33	0.28	0.25
Dresden 1	0.01	0.0007	0.0033	0.49	0.056
Dresden 2,3	2.0	0.74	0.19	0.71	0.71
Duane Arnold	0.012	0.013	0.0078	4.4	0.010
J.A. Fitzpatrick	0.18	0.16	0.12	0.070	0.056
Edwin I. Hatch	0.22	0.33	0.44	0.33	0.46
Humboldt Bay	0.74	0.48	0.020	0.001	0.002
Lacrosse	4.7	1.5	1.8	1.7	1.3
Millstone Point 1	3.0	0.74	0.16	0.12	0.29
Monticello	-	-	-	-	-
Nine Mile Point	1.0	0.093	0.092	-	0.25
Oyster Creek	0.67	1.4	0.70	0.73	0.052
Peach Bottom	1.1	2.7	2.6	1.2	1.6
Pilgrim	0.67	1.7	1.2	0.11	0.50
Quad Cities	2.0	1.8	0.98	0.64	0.63
Vermont Yankee	-	0.059	0.031	-	0.15
Total annual energy generated [GW(e) a]	9.53	13.04	13.24	18.1	20.0
Normalized release, [TBq (GW[e] a)$^{-1}$]	2.6	1.6	1.3	1.1	1.0
	Average 1975-1979		1.4 TBq [GW(e) a]$^{-1}$		
G C R					
France					
Chinon	-	3.9	4.1	4.8	
St. Laurent	-	19	13	25	
Bugey 1	9.0	7.2	8.9	14	
Japan					
Tokai	-	-	-	0.0006	0.033
United Kingdom					
Calder	-	-	-	-	-
Chapelcross	0.26	0.33	0.074	1.2	2.8
Bradwell	3.3	11	7.4	3.8	4.4
Berkeley	2.6	1.1	1.9	0.59	1.6
Hunterston A	2.0	2.4	2.0	2.0	
Hunterston B		1.6	2.0	85	
Trawsfynydd	3.3	0.59	0.48	0.56	2.1
Hinkley Point A	2.0	0.89	1.2	2.0	3.6
Hinkley Point B		0.11	27	59	160
Dungeness A	0.93	1.3	0.96	1.2	0.78
Sizewell	1.8	2.3	1.6	1.1	1.6
Oldbury	0.52	0.70	0.56	0.27	0.22
Wylfa	4.8	7.3	11	39	4.6
Total annual energy generated [GW(e) a]	4.42	4.59	5.10	5.07	4.4
Normalized release, [TBq (GW[e] a)$^{-1}$]	6.91	13.0	16.0	47.2	41.0
	Average 1975-1979		25 TBq [GW(e) a]$^{-1}$		
H W R					
Argentina					
Atucha	31	76	218	229	259
Canada					
Bruce	-	-	36	152	546
Pickering	540	224	703	1188	1421
Total annual energy generated [GW(e) a]	2.0	2.6	3.2	4.1	4.3
Normalized release, [TBq (GW[e] a)$^{-1}$]	286	115	299	383	518
	Average 1975-1979		350 TBq [GW(e) a]$^{-1}$		

Table 20

Carbon-14 discharges from LWRs
in the Federal Republic of Germany 1976-1978
[R1, S15]

Reactor	Release (GBq)		
	1976	1977	1978
PWR a/			
Obrigheim		111 (15)	33 (19)
Stade		111(111)	55 (55)
Biblis A		178 (15)	78 (22)
Biblis B		181 (4.4)	168 (15)
Neckarwestheim		148 (4.1)	144 (6)
Normalized release [GBq (GW[e] a)$^{-1}$]			222
BWR b/			
Gundremmingen	137	37	3.7
Lingen	42	7.4	-
Würgassen	-	229	229
Brunsbüttel		159	167
Normalized release [GBq (GW[e] a)$^{-1}$]			518

a/ CO_2 bound values in parentheses.
b/ CO_2 values only.

Table 21

Iodine releases to atmosphere from reactors 1975-1979
[B21, B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]

Country and reactor	Release (GBq)				
	1975	1976	1977	1978	1979
PWR					
Belgium					
Doel	0.089	0.19	0.089	-	0.33
Tihange	0.021	0.74	0.081	0.37	0.11
Finland					
Loviisa	-	-	0.04	-	0.0021
Germany, Fed. Rep. of					
Obrigheim	0.41	0.074	0.022	0.026	0.03
Stade	0.37	0.74	0.96	0.14	0.086
Biblis A,B	0.19	0.37	0.15	0.59	0.68
Unterweser	-	-	-	0.00074	0.045
Neckarwestheim	-	0.074	1.7	0.26	0.032
Italy					
Trino	0.0017	0.00003	0.0033		
Japan					
Mihama 1	-	0.012	0.014	0.0089	0.0048
Mihama 2	-	0.18	0.078	0.093	0.037
Mihama 3	-	0.0052	0.0082	0.010	0.0078
Takahama 1,2	0.048	0.0074	0.070	0.010	0.014
Ohoi 1	-	-	0.00067	0.078	0.041
Ohoi 2	-	-	-	0.0022	0.089
Ikata 1	-	-	-	0.00056	0.028
Netherlands					
Borssele	0.52	0.31	0.13	0.0078	-
Sweden					
Ringhals 2	-	0.27	0.81	0.69	0.27
United States					
Arkansas 1	0.81	1.5	0.41	0.11	0.16
Arkansas 2	-	-	-	-	0.17
Beaver Valley	-	0.0081	0.0056	0.63	0.015
Calvert Cliffs	1.3	18.0	14.0	7.4	15.5
Cook 1	0.0063	0.052	3.7	0.48	0.55
Fort Calhoun	0.26	27.0	4.8	0.30	0.47
Crystal River	-	-	0.058	31.0	58.0
Davis Besse	-	-	0.0041	0.11	0.20

Table 21, continued

Country and reactor	Release (GBq)				
	1975	1976	1977	1978	1979
Joseph M. Farley	-	-	-	0.0017	0.0005
R.E. Ginna	2.4	1.3	0.96	0.32	0.71
Haddam Neck	0.033	0.027	0.030	0.11	1.8
Indian Point	15.0	10.0	5.2	3.0	6.1
Kewaunee	0.74	0.12	0.76	0.15	0.043
Maine Yankee	0.22	0.059	0.21	0.074	4.8
Millstone Point 2	0.0017	1.8	0.22	0.53	0.62
North Anna	-	-	-	1.1	1.4
Oconee	0.41	5.9	14.0	6.3	7.4
Palisades	16.0	1.1	0.89	1.6	1.0
Point Beach	7.0	0.23	0.23	0.56	0.78
Prairie Island	0.78	0.93	0.30	0.74	0.16
Rancho Seco	0.007	0.04	0.096	18	0.20
H.B. Robinson	0.85	9.3	0.44	0.070	0.006
Salem	-	-	-	0.20	0.30
St. Lucie	-	0.074	3.0	38	7.4
San Onofre	9.3	0.17	0.0066	0.0078	0.0045
Surry	4.8	20.0	18.0	2.2	0.23
Three Mile Island 1	0.035	0.32	0.78	0.96	0.41
Trojan	-	-	0.97	0.89	1.7
Turkey Point	17.0	19.0	52.0	18.0	1.7
Yankee Rowe	0.1	0.048	0.0085	0.014	0.014
Zion	-	3.3	1.6	2.6	0.45
Total annual energy generated [GW(e) a]	16.9	19.2	23.8	29.4	27.5
Normalized release [GBq (GW[e] a)$^{-1}$]	4.70	6.41	5.32	4.68	4.18
	Average 1975-1979 5.0 GBq [GW(e) a]$^{-1}$				
B W R					
Finland					
Olkiluoto	-	-	-	0.017	0.023
Germany, Fed.Rep. of					
Gundremmingen	9.3	13	0.19	0.0028	-
Lingen	48	1.9	0.052	0.00074	-
Würgassen	0.052	1.7	1.0	4.1	2.5
Brunsbüttel	-	0.00074	0.56	1.8	0.018
Isar	-	-	-	-	0.003
Italy					
Garigliano	0.59	1.3	0.56		
Japan					
Tsuruga	1.2	1.0	0.37	0.19	0.17
Tokai 2	-	-	-	0.012	0.028
Fukushima 1,2	0.48	8.9	1.0	32.0	5.9
Fukushima 3,4	-	0.0037	0.18	0.048	0.096
Fukushima 5					-
Hamaoka 1,2					0.0052
Shimane					-
Sweden					
Ringhals 1		0.67	0.32	1.2	23
Oskarshamn		2.7	8.9	5.5	5.0
Barsebäck		0.070	0.031	0.089	0.10
United States					
Big Point Rock	10.0	5.9	7.4	5.4	0.24
Browns Ferry	22.0	22.0	5.9	14.4	5.8
Brunswick	0.10	17.0	78.0	38.0	28.0
Cooper	16.0	3.3	1.7	5.4	8.0
Dresden 1	211.0	85.0	2020.0	997.0	0.12
Dresden 2,3	4.1	4.8	4.8	2110.0	1298.0
Duane Arnold	15.0	4.1	4.1	1583.0	569.0
J.A. Fitzpatrick	0.67	215.0	7.0	9.4	0.86
Edwin I. Hatch	0.24	0.13	0.27	0.084	0.92
Humboldt Bay	41.0	14.0	0.00044	-	-
Lacrosse	4.8	3.7	9.3	1.5	0.82
Millstone Point 1	2331.0	1332.0	2257.0	1417.0	141.0
Monticello	555.0	37.0	20.0	15.0	10.3
Nine Mile Point	222.0	318.0	52.0	44.0	5.8
Oyster Creek	1517.0	1702.0	1517.0	2294.0	2868.0
Peach Bottom	1.3	70.0	63.0	52.0	49.0

Table 21, continued

Country and reactor	Release (GBq)				
	1975	1976	1977	1978	1979
Pilgrim	229.0	74.0	126.0	61.0	52.0
Quad Cities	107.0	159.0	222.0	407.0	523.0
Vermont Yankee	15.0	2.6	0.81	11.0	21.0
Total annual energy generated [GW(e) a]	9.53	13.04	13.24	18.1	20.0
Normalized release [GBq (GW[e] a)$^{-1}$]	561	314	484	501	280
	Average 1975-1979 410 GBq [GW(e) a]$^{-1}$				
G C R					
France					
Chinon	0.78	0.081			
Bugey	0.81	0.070			
St. Laurent	0.59	0.41			
Japan					
Tokai				0.0041	0.0030
H W R					
Argentina					
Atucha [GBq (GW[e] a)$^{-1}$]	0.16	1.2	0.24	5.4	8.7
	Average 1975-1979 3.1 GBq [GW(e) a]$^{-1}$				

Table 22

Isotopic composition of iodine releases from reactors in the United States in 1979 [B23]

Reactor	Release (GBq)				
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I
P W R					
Arkansas 1	0.16	-	0.0067	-	-
Arkansas 2	0.17	-	0.0003	-	-
Beaver Valley	0.015	-	0.0015	-	0.0018
Calvert Cliffs	11.1	0.28	4.0	-	0.14
Cook 1	0.53	-	0.026	-	-
Crystal River	0.69	-	0.15	-	58.0
Davis Besse	0.18	-	0.023	-	0.0041
Fort Calhoun	0.048	-	0.067	0	0.35
Joseph M. Farley	0.0005	-	-	-	-
R.E. Ginna	0.35	0.044	0.32	-	-
Haddam Neck	1.7	-	0.093	-	0.14
Indian Point	4.3	-	0.46	-	1.3
Kewaunee	0.020	0.0078	0.011	0.00035	0.0039
Maine Yankee	2.0	-	2.6	-	0.23
Millstone Point 2	0.53	-	0.036	-	0.059
North Anna	1.3	-	0.052	-	-
Oconee	5.1	0.10	1.8	0.033	0.37
Palisades	0.70	-	0.31	-	0.083
Point Beach	0.16	0.36	0.26	0.008	0.0029
Prairie Island	0.14	-	0.023	-	-
Rancho Seco	0.17	-	0.030	-	-
H.B. Robinson	0.0014	-	0.0021	-	0.004
St. Lucie	3.7	-	3.7	-	0.004
Salem	0.20	-	0.10	-	-
San Onofre	0.045	-	-	-	-
Surry 1,2	0.23	0.0044	0.0029	-	-
Three Mile Island 1	0.41	-	-	-	-
Trojan	0.53	0.001	0.47	-	0.70

Table 22, continued

Reactor	Release (GBq)				
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I
Turkey Point	1.2	-	0.58	-	0.065
Yankee Row	0.0067	-	0.0028	-	0.0048
Zion 1,2	0.23	-	0.22	-	-
Total annual energy generated [GW(e) a]	19.165				
Normalized release, [GBq (GW[e] a)$^{-1}$]	1.9	0.042	0.78	0.0017	3.2
B W R					
Big Rock Point	0.011	-	0.11	-	0.13
Browns Ferry 1,2,3	1.0	-	1.1		3.7
Brunswick 1,2	4.7	1.3	17,8	-	4.2
Cooper	2.5	-	0.76	-	4.7
Dresden 1	0.12	-	-	-	-
Dresden 2,3	75	-	390	-	834
Duane Arnold	0.35	-	2.7	-	566
J.A. Fitzpatrick	0.21	-	0.44	-	0.21
Edwin I. Hatch	0.88	-	0.043	-	-
Lacrosse	0.41	0.011	0.28	0.030	0.088
Millstone Point	15	-	59	-	67
Monticello	0.89	-	3.4	-	6.0
Nine Mile Point	1.0	-	1.5	-	3.3
Oyster Creek	326	-	1095	-	1447
Peach Bottom 2,3	9.5	-	23	-	16
Pilgrim	3.7	-	5.7	-	43
Quad Cities 1,2	35	-	210		278
Vermont Yankee	15	-	4.4	-	1.8
Total annual energy generated [GW(e) a]	11.670				
Normalized release, [GBq (GW[e] a)$^{-1}$]	42	0.11	155	0.0026	281

Table 23

Particulate releases from reactors in various countries 1975-1979
[B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]

Country and reactor	Release (GBq)				
	1975	1976	1977	1978	1979
P W R					
Belgium					
Doel	6.7	7.8	6.3	6.7	
Tihange	-	0.0018	1.1	3.2	
Finland					
Loviisa	-	-	-	0.042	0.037
France					
Chooz	0.089	0.063	3.4	0.44	
Fessenheim	-	-	-	0.67	
Bugey 2,3	-	-	-	0.059	
Germany, Fed. Rep.of					
Obrigheim	0.93	0.30	0.24	0.16	0.075
Stade	1.1	0.26	0.33	0.37	0.025
Biblis A,B	0.22	0.11	0.20	0.0013	0.016
Neckarwestheim	-	0.019	0.45	0.19	0.025
Italy					
Trino	-	-	0.0037		
Netherlands					
Borssele	0.67	0.052	0.025	0.00052	0.004
Sweden					
Ringhals 2	-	0.30	0.26	0.083	0.009
United States					
Arkansas 1	0.41	0.63	0.0044	0.044	0.00074
Arkansas 2	-	-	-	-	0.0074
Beaver Valley	-	0.00005	0.0002	0.00074	0.00059
Calvert Cliffs	0.41	0.59	5.2	0.50	0.18

Table 23, continued

Country and reactor	Release (GBq)				
	1975	1976	1977	1978	1979
Cook 1,2	-	0.0002	0.52	3.6	2.2
Crystal River	-	-	0.037	0.0006	0.16
Davis Besse	-	-	0.0088	0.0083	0.033
Joseph M. Farley	-	-	-	1.5	0.81
Fort Calhoun	0.0041	0.01	0.0027	0.0045	0.0059
R.E. Ginna	0.0016	0.001	0.0026	0.0048	0.34
Haddam Neck	0.078	0.0063	0.036	0.081	0.11
Indian Point	46	1.0	0.56	6.9	12
Kewaunee	24	0.012	0.021	0.059	0.003
Maine Yankee	0.0093	0.078	0.012	0.0081	0.037
Millstone Point 2	0.0004	0.11	0.014	0.029	3.0
North Anna	-	-	-	0.036	0.81
Oconee	0.010	3.7	7.8	1.9	3.7
Palisades	0.022	0.56	0.041	0.15	0.059
Point Beach	3.5	0.59	0.067	0.37	0.35
Prairie Island	0.13	0.0089	0.041	0.0015	0.003
Rancho Seco	0.0029	0.002	0.093	0.52	0.048
H.B. Robinson	0.050	0.021	0.093	0.013	0.015
St. Lucie	-	0.00056	2.8	10	3.7
Salem	-	-	0.00001	1.3	0.081
San Onofre	1.3	0.00067	0.00018	0.093	0.00074
Surry	2.9	3.0	0.56	0.13	0.052
Three Mile Island 1	0.0037	0.16	0.44	3.7	0.04
Trojan	-	0.37	0.95	0.24	0.74
Turkey Point	2.2	2.8	1.9	2.9	1.7
Yankee Rowe	0.30	0.00081	0.0012	0.0002	0.003
Total annual energy generated [GW(e) a]	15.7	17.3	21.8	24.8	23.6
Normalized release, [GBq (GW(e) a)$^{-1}$]	5.77	1.27	1.54	1.85	1.28
	Average 1975-1979 2.15 GBq [GW(e) a]$^{-1}$				
B W R					
Finland					
Olkiluoto	-	-	-	0.0059	0.33
Germany, Fed.Rep.of					
Gundremmingen	0.30	0.19	0.27	0.15	0.004
Lingen	3.7	0.019	0.070	0.056	0.0013
Würgassen	4.0	0.63	1.4	2.1	1.4
Brunsbüttel	-	0.26	2.7	1.4	7.4
Isar	-	-	0.0011	0.16	0.79
Italy					
Garigliano		1.2	0.74		
Netherlands					
Dodewaard	0.22	0.12	0.11	0.035	
Sweden					
Oskarshamm	-	15	8.3	1.2	1.6
Ringhals 1	-	4.9	20	11	94
Barsebäck	-	0.096	0.72	1.6	0.30
United States					
Big Rock Point	3.6	1.5	0.32	0.22	0.059
Browns Ferry	2.2	2.0	2.4	3.7	4.8
Brunswick	0.14	0.70	5.2	4.1	25
Cooper	1.1	0.41	0.17	0.081	0.11
Dresden 1	13.0	17.0	22.0	41	0.77
Dresden 2,3	153.0	167.0	1561.0	89.0	185.0
Duane Arnold	0.33	0.25	0.27	0.85	0.89
J.A. Fitzpatrick	0.67	0.70	1.1	2.0	0.32
Edwin I. Hatch	0.01	0.017	0.031	0.085	0.078
Humboldt Bay	31.0	1.0	0.015	0.026	0.004
Lacrosse	0.48	0.85	0.41	0.12	0.48
Millstone Point 1	7.0	5.6	7.4	50	7.0
Monticello	24.0	1.9	0.74	0.50	0.37
Nine Mile Point	16.0	3.7	1.8	1.0	0.74
Oyster Creek	6.7	8.1	48.0	296.0	19.0
Peach Bottom	0.14	1.4	1.0	0.46	0.30
Pilgrim	24.0	12.0	7.8	2.1	2.0

Table 23, continued

Country and reactor	Release (GBq) 1975	1976	1977	1978	1979
Quad Cities	15.0	20.0	27.0	41.0	23.0
Vermont Yankee	0.074	0.21	0.28	0.20	1.1
Total annual energy generated [GW(e) a]	7.1	10.9	11.9	15.5	15.5
Normalized release [GBq (GW[e] a)$^{-1}$]	43.0	24.4	144.0	35.5	24.2
	Average 1975-1979 52.7 GBq [GW(e) a]$^{-1}$				
G C R					
France					
Chinon	0.37	0.67	0.48	0.48	
Bugey	0.063	0.30	0.28	0.67	
St. Laurent	0.048	0.070	0.23	0.16	
Japan					
Tokai	-	-	-		
United Kingdom					
Bradwell	0.11	0.096	0.11	0.15	0.15
Berkeley	0.14	0.11	0.11	0.074	0.15
Hunterston A	-	-	0.37	0.37	-
Hunterston B	-	0.27	0.26	0.019	-
Trawsfynydd	0.41	0.48	0.67	0.37	0.41
Hinkley Point A	0.41	0.48	0.37	0.41	0.74
Hinkley Point B	-	0.70	0.67	1.1	1.1
Dungeness A	2.0	0.70	0.41	0.52	0.33
Sizewell	0.37	0.41	0.56	0.48	0.45
Oldbury	1.3	0.067	0.11	0.074	0.10
Wylfa	0.15	0.31	0.37	0.37	0.26
Total annual energy generated [GW(e) a]	4.42	4.59	5.10	5.07	4.3
Normalized release [GBq (GW[e] a)$^{-1}$]	1.19	1.02	0.98	1.03	0.86
	Average 1975-1979 1.0 GBq [GW(e) a]$^{-1}$				
H W R					
Argentina					
Atucha [GBq (GW[e] a)$^{-1}$]	0.018	0.037	0.028	0.060	0.078
	Average 1975-1979 0.044 GBq [GW(e) a]$^{-1}$				

Table 24

Liquid effluent discharges other than tritium from reactors 1975-1979
[B23, D6, D8, E9, G3, K4, L1, L6, N19, P2, S14]

Country and reactor	Release (GBq) 1975	1976	1977	1978	1979
P W R					
Belgium					
Doel	381	1840	625	696	
Tihange	14	31	132	72	
Finland					
Loviisa	-	-	4	18	15
France					
Chooz	318	95	4.1		
Fessenheim	-	-	256	174	
Bugey 2,3	-	-	-	364	
Germany, Fed. Rep.of					
Obrigheim	64	36	9.6	6.3	6.3
Stade	10	12	14	3.7	9.7
Biblis A	27	8.1	3.8	4.7	1.9

Table 24, continued

Country and reactor	Release (GBq) 1975	1976	1977	1978	1979
Biblis B	-	11	1.1	4.4	7.8
Neckarswestheim	-	8.9	5.6	1.1	2.1
Unterweser	-	-	-	-	0.07
Italy					
Trino	54	100	52	48	
Japan					
Mihama 1	0.74	0.22	0.28	0.32	0.34
Mihama 2					
Mihama 3		0.01	0.044	0.048	0.078
Takahama 1	0.16	0.14	0.31	0.074	0.063
Takahama 2					
Ohi 1		0.0014	0.041	0.06	
Ohi 2					
Ikata 1		0.037	0.048	0.007	
Genkai 1	0.033	-	-	-	-
Netherlands					
Borssele	60	31	16	11	11
Sweden					
Ringhals	-	225	427	209	115
United States					
Arkansas 1	115	485	167	223	114
Arkansas 2	-	-	-	-	48
Beaver Valley 1	-	6.3	24	9.7	4.5
Calvert Cliffs 1	53	44	129	227	289
Cook 1	9.6	69	56	55	95
Crystal River	-	-	0.57	1.1	15
Davis Besse	-	-	0.96	3.3	1.6
Joseph M. Farley	-	-	-	3.7	2.2
Fort Calhoun	13	20	13	22	9.0
R.E. Ginna	16	26	2.4	2.2	3.2
Haddam Neck	44	4.8	63	35	32
Indian Point	182	184	112	111	87
Kawaunee	27	105	47	26	33
Maine Yankee	119	105	16	3.8	17
Millstone Point 2	0.74	9.6	57	103	180
North Anna	-	-	-	9.9	22
Oconee 1,2,3	187	293	1340	241	34
Palisades	128	16	3.4	3.6	4.7
Point Beach 1,2	87	120	56	25	27
Prairie Island 1,2	17	3.7	0.49	0.18	0.33
Rancho Seco	0.37	-	-	-	-
H.B. Robinson	17	14	12	6.6	11
St. Lucie	-	3.0	215	104	99
Salem 1	-	0.37	107	148	147
San Onofre 1	45	275	364	437	407
Surry 1,2	343	1246	2424	89	94
Three Mile Island 1	2.6	3.7	7.2	23	18
Trojan	-	102	155	26	21
Turkey Pt. 3,4	114	320	329	123	15
Yankee Rowe	0.74	0.37	0.67	3.0	0.43
Zion 1,2	0.37	5.9	35	35	26
Total annual energy generated [GW(e) a]	16.9	19.2	23.8	29.4	27.5
Normalized release, [GBq (GW!e] a)$^{-1}$]	145	310	306	126	74
	Average 1975-1979 184 GBq [GW(e) a]$^{-1}$				
B W R					
Finland					
Olkiluoto	-	-	-	1.2	7.7
Germany, Fed. Rep.of					
Gundremmingen	47	43	64	20	8.3
Lingen	1.5	9.6	0.37	0.37	0.93
Würgassen	69	41	58	20	16
Brunsbüttel	-	83	61	52	17
Isar	-	-	1.5	7.8	9.7
Italy					
Garigliano	116	139	152	111	
Japan					
Tsuruga	1.5	1.9	1.0	0.78	1.4
Tokai 2	-	-	-	0.14	0.31
Fukushima 1	-	-	0.14	0.067	0.13

Table 24. continued

Country and reactor	Release (GBq) 1975	1976	1977	1978	1979
Fukushima 2	-	-	0.017	0.13	0.16
Fukushima 3	-	-	0.13	0.19	0.0052
Fukushima 4	-	-	-	0.034	0.000027
Fukushima 5	-	-	0.0073	0.10	0.078
Hamaoka 1	-	-	0.24	0.037	0.63
Hamaoka 2	-	-	-	0.085	
Shimane	0.14	0.24	0.18	0.19	0.16
Sweden					
Oskarshamn 1,2		903	485	158	155
Ringhals 1		232	249	148	223
Barsebäck 1,2		64	68	140	58
United States					
Big Rock Point 1	74	28	14	10	33
Browns Ferry 1,2,3	100	146	44	488	66
Brunswick 1,2	70	122	230	129	189
Cooper	64	2.6	28	113	92
Dresden 1	31	13	22	12	0.98
Dresden 1,2	30	45	16	15	9.8
Duane Arnold	3.7	3.7	0.085	10	0.02
J.A. Fitzpatrick	197	222	33	58	24
Edwin I. Hatch	2.2	1.5	925	1.5	1.8
Humboldt Bay	140	37	34	7.2	3.5
Lacrosse	525	214	788	328	124.7
Millstone Point 1	7360	357	19	6.5	7.8
Monticello	-	-	-	-	-
Nine Mile Point	780	79	11	-	70
Oyster Creek	15	8.1	3.6	0.55	0.25
Peach Bottom 2,3	34	125	83	189	722
Pilgrim	296	86	126	65	19
Quad Cities	633	258	50	83	48
Vermont Yankee	0.37	0.37	5.7	-	0.01
Total annual energy generated [GW(e) a]	9.53	13.04	13.24	18.1	20.0
Normalized release, [GBq (GW[e] a)$^{-1}$]	1100	251	273	121	96
	Average 1975-1979	290 GBq [GW(e)a]$^{-1}$			
G C R					
France					
Chinon	24	21	8.5	13	
Bugey 1	511	133	144	401	
St. Laurent	174	110	181	300	
Japan					
Tokai					
United Kingdom					
Chapelcross	640	1200	337	2830	9100
Bradwell	4400	2420	2450	2000	1576
Berkeley	2000	4140	5480	1180	1687
Hunterston A	4260	5880	5440	2220	-
Hunterston B	-	22	44	220	-
Trawsfynydd	629	740	500	648	289
Hinkley Point A	5880	5110	4440	4070	2812
Hinkley Point B	-	41	44	189	600
Dungeness	2940	1710	1680	1410	1110
Sizewell	740	1090	1590	910	1420
Oldbury	1010	1860	2440	1120	706
Wylfa	125	241	688	977	600
Total annual energy generated [GW(e) a]	4.42	4.59	5.10	5.07	4.3
Normalized release, [GBq (GW[e] a)$^{-1}$]	5280	5390	4990	3650	4628
	Average 1975-1979	4767 GBq [GW(e) a]$^{-1}$			
H W R					
Argentina					
Atucha [GBq (GW[e] a)$^{-1}$]	520	750	530	230	390
	Average 1975-1979	473 GBq [GW(e) a]$^{-1}$			

Table 25

Radionuclide composition of liquid discharges other than tritium from reactors in the United States in 1979

Reactor	Release (GBq)									
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{24}Na	^{51}Cr	^{54}Mn	^{56}Mn	^{57}Co
P W R										
Arkansas 1	10	0.0004	0.012	-	-	0.002	11	1.5	-	0.11
Arkansas 2	8.9	0.0033	1.7	0.0037	0.19	2.5	0.67	1.4	0.0037	0.12
Beaver Valley 1	0.032	-	0.030	-	-	-	0.048	0.27	-	-
Calvert Cliffs 1	24	0.46	14	-	1.3	-	24	4.1	0.024	0.24
Cook 1	0.44	-	0.024	-	-	0.52	5.2	2.9	-	0.085
Crystal River	2.2	0.0063	0.070	-	0.0056	0.0033	0.63	0.20	-	-
Davis Besse	0.13	-	0.0074	-	-	0.0037	0.034	0.24	-	-
Joseph M. Farley	0.049	0.0048	0.0037	-	0.00026	0.056	0.093	0.11	-	0.0036
Fort Calhoun	0.78	-	0.10	-	-	-	0.57	0.13	-	0.089
R.E. Ginna	0.34	-	-	-	-	-	0.13	0.048	-	-
Haddam Neck	2.5	-	-	-	-	-	0.31	0.093	-	0.00015
Indian Point	5.1	0.00096	0.0037	-	-	-	2.9	1.3	-	0.0002
Kawaunee	0.022	-	-	-	-	0.052	1.9	0.63	-	0.0018
Maine Yankee	15	-	0.21	-	-	-	0.0023	0.014	-	0.0023
Millstone Point 2	4.4	0.0059	0.19	-	-	3.0	8.2	5.9	0.0016	-
North Anna	5.9	-	0.89	-	-	0.012	0.033	0.048	-	0.74
Oconee 1,2,3	5.3	0.019	0.36	0.074	0.096	0.0096	0.36	0.27	0.0017	0.018
Palisades	0.014	-	-	-	-	-	0.47	0.46	-	0.00019
Point Beach 1,2	0.33	0.36	6.3	0.78	3.1	-	0.020	0.27	-	0.0059
Prairie Island 1,2	0.028	-	-	-	-	-	0.016	0.0013	-	-
Rancho Seco	-	-	-	-	-	-	-	-	-	-
H.B. Robinson	0.14	-	-	-	-	-	-	1.1	-	0.0042
St. Lucie	1.8	0.0057	0.35	0.0037	0.091	0.0032	5.2	2.1	1.6	0.054
Salem 1	0.70	-	0.11	-	-	0.16	3.5	15	-	-
San Onofre 1	0.93	-	-	-	-	-	8.3	0.28	-	-
Surry 1,2	2.4	5.2	4.9	4.3	7.1	8.9	7.4	1.5	-	0.074
Three Mile Island 1	5.3	-	-	-	-	-	0.25	0.054	-	-
Trojan	0.47	-	0.071	0.0037	0.026	0.0067	2.7	1.3	-	0.048
Turkey Pt. 3,4	0.74	0.49	2.1	0.11	1.2	0.19	0.18	0.041	-	0.005
Yankee Rowe	0.15	-	0.015	-	-	-	0.015	0.004	-	-
Zion 1,2	0.43	-	0.00057	-	-	0.39	2.2	0.61	-	0.024
Total annual energy generated [GW(e) a]	19.165									
Normalized release [GBq (GW[e] a)$^{-1}$]	4.6	0.31	1.7	0.24	0.68	1.1	4.6	2.2	0.085	0.084

Table 25, continued

Reactor	Release (GBq)										
	^{58}Co	^{59}Fe	^{60}Co	^{65}Zn	^{89}Sr	^{90}Sr	^{95}Zr	^{97}Zr	^{95}Nb	^{97}Nb	^{99}Mo
P W R											
Arkansas 1	58	0.74	17	0.013	0.11	0.015	1.1	0.01	2.0	0.16	0.11
Arkansas 2	30	0.56	0.81	0.0013	0.24	-	0.031	-	0.047	0.022	0.031
Beaver Valley 1	1.6	0.033	2.3	-	0.0007	0.0016	0.0033	-	-	-	-
Calvert Cliffs 1	141	1.1	12	-	0.085	0.096	5.6	0.019	0.59	-	0.45
Cook 1	33	0.70	20	0.21	0.0096	0.0044	3.0	0.11	3.0	-	-
Crystal River	4.3	0.093	1.3	0.034	1.8	0.26	0.26	-	-	-	0.52
Davis Besse	0.85	0.0093	0.093	0.01	0.0014	0.0017	0.012	-	-	-	0.036
Joseph M. Farley	0.96	0.019	0.81	0.0011	-	0.00074	0.0074	-	0.023	-	0.0013
Fort Calhoun	0.41	0.074	0.15	0.089	0.018	0.0048	0.079	-	0.046	-	0.032
R.E. Ginna	0.081	0.0074	1.5	-	-	-	0.033	-	0.024	-	0.041
Haddam Neck	0.52	0.00015	3.6	0.00015	0.25	0.13	5.4	-	-	-	0.00015
Indian Point	11	0.56	5.9	1.8	0.18	0.33	0.52	-	-	-	6.3
Kawaunee	11	0.085	6.7	-	0.030	0.0063	0.11	-	0.13	-	-
Maine Yankee	0.67	-	0.052	-	-	0.0017	-	-	-	-	0.0024
Millstone Point 2	60	0.67	58	0.0044	0.048	0.0063	1.1	0.0015	2.6	3.3	0.037
North Anna	4.8	0.0033	0.47	-	0.18	0.13	0.033	-	-	-	-
Oconee 1,2,3	6.7	0.019	1.8	-	3.0	0.27	0.37	0.011	0.15	1.0	0.059
Palisades	2.4	0.047	0.46	-	-	-	0.021	-	0.054	-	-
Point Beach 1,2	1.8	0.0033	0.59	-	0.0026	0.00063	0.081	-	0.046	-	0.070
Prairie Island 1,2	0.11	0.015	0.035	-	-	-	0.00034	-	-	-	0.0025
Rancho Seco	-	-	-	-	-	-	-	-	-	-	-
H.B. Robinson	3.7	0.085	2.9	-	-	-	-	-	-	-	-
St. Lucie	37	0.37	7.0	0.12	0.028	0.00004	0.67	0.0095	-	-	0.0074
Salem 1	52	0.98	70	-	-	-	0.37	-	-	-	-
San Onofre 1	343	7.3	25	-	0.60	0.025	-	-	0.59	-	-
Surry 1,2	67	0.0060	61	-	0.052	0.016	-	-	0.71	-	-
Three Mile Island 1	2.3	0.0049	0.54	0.015	3.4	0.27	0.0011	-	0.34	-	0.00032
Trojan	5.2	0.15	6.4	0.0097	0.065	0.0037	0.48	-	0.78	-	0.00078
Turkey Pt. 3,4	1.8	0.0063	3.1	-	0.29	0.048	0.029	-	0.012	-	0.0044
Yankee Rowe	0.015	-	0.0069	0.0036	0.0006	0.0021	-	-	-	-	0.0083
Zion 1,2	5.2	0.041	7.1	-	0.021	0.016	0.14	-	0.50	-	-
Total annual energy generated [GW(e) a]	19,165										
Normalized release, [GBq (GW(e) a)$^{-1}$]	46	0.71	17	0.12	0.54	0.086	1.0	0.0084	0.60	0.23	0.38

Table 25, continued

Reactor	Release (GBq)											
	^{99m}Tc	^{103}Ru	^{106}Ru	^{110m}Ag	^{124}Sb	^{125}Sb	^{134}Cs	^{136}Cs	^{137}Cs	$^{140}Ba/La$	^{141}Ce	^{144}Ce
P W R												
Arkansas 1	-	0.12	0.040	1.1	-	-	3.6	-	5.6	0.25	-	0.037
Arkansas 2	-	0.0051	-	0.061	-	-	0.057	0.0081	0.95	0.018	-	-
Beaver Valley 1	-	-	-	-	-	-	0.023	-	0.10	-	0.0090	-
Calvert Cliffs 1	-	0.93	0.47	3.5	1.0	10	14	0.12	21	0.70	0.21	-
Cook 1	-	-	-	-	-	-	0.048	-	0.15	0.016	-	-
Crystal River	0.014	-	-	0.0074	-	-	1.7	-	2.5	0.013	0.022	0.17
Davis Besse	0.0033	-	-	-	-	-	0.048	-	0.12	0.016	0.0074	-
Joseph M. Farley	0.00004	-	0.0013	0.0063	-	-	0.0052	0.00019	0.016	0.0037	0.00019	0.0033
Fort Calhoun	0.016	0.059	-	-	0.070	-	2.3	0.070	0.37	0.14	0.12	-
R.E. Ginna	-	0.011	0.05	0.028	-	-	0.12	0.049	0.48	0.013	0.0025	0.0070
Haddam Neck	0.00015	2.4	1.4	0.002	-	0.00015	1.5	-	1.8	0.017	2.0	10
Indian Point	0.22	0.0004	-	-	0.0074	0.011	5.2	-	16	1.7	0.50	0.0096
Kawaunee	-	-	-	1.2	2.1	2.4	2.9	-	3.2	0.059	-	-
Maine Yankee	-	-	-	-	-	-	0.12	-	0.78	-	-	-
Millstone Point 2	-	-	-	2.4	-	-	12	1.6	14	0.035	0.018	0.13
North Anna	0.0028	0	0	0	0	-	3.3	-	4.6	-	-	-
Oconee 1,2,3	0.036	0.0020	0.25	0.37	-	0.061	4.6	0.37	8.9	0.12	-	0.17
Palisades	-	-	-	-	-	-	0.074	-	0.29	-	-	-
Point Beach 1,2	-	0.081	-	-	0.0085	0.019	0.56	0.00048	2.0	1.1	-	0.074
Prairie Island 1,2	0.0034	-	-	-	0.027	-	-	-	-	-	-	-
Rancho Seco	-	-	-	-	-	-	-	-	-	-	-	-
H.B. Robinson	-	-	-	-	0.031	0.041	0.13	1.7	1.1	-	0.00070	0.019
St. Lucie	0.036	0.027	-	1.2	1.5	1.0	10	0.12	14	0.013	0.030	0.11
Salem 1	-	-	-	-	0.45	-	2.1	0.019	1.6	-	-	-
San Onofre 1	1.2	0.50	-	1.1	-	-	0.87	-	1.7	-	-	-
Surry 1,2	-	-	-	-	-	-	16	0.0042	36	0.015	0.0060	0.12
Three Mile Island 1	-	0.011	-	0.057	0.016	0.098	0.86	0.058	3.7	0.84	0.0019	0.0013
Trojan	0.008	0.22	-	0.63	0.16	0.37	0.078	0.0032	0.19	0.54	0.074	0.14
Turkey Pt. 3,4	0.0044	0.010	-	0.12	0.58	0.63	1.1	-	1.8	-	-	-
Yankee Rowe	0.0013	-	-	0.0011	0.0016	-	0.075	-	0.098	0.0061	0.0021	0.0083
Zion 1,2	0.029	-	-	0.24	0.80	-	4.4	-	5.3	0.070	-	-
Total annual energy generated [GW(e) a]	19.165											
Normalized release, [GBq (GW[e] a)$^{-1}$]	0.087	0.23	0.12	0.63	0.35	0.76	4.4	0.21	7.7	0.29	0.16	0.57

Reactor	Release (GBq)									
	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{24}Na	^{51}Cr	^{54}Mn	^{56}Mn	^{57}Co
B W R										
Big Rock Point	-	-	0.010	-	-	0.0014	0.21	2.2	-	-
Browns Ferry 1,2,3	1.4	-	0.78	-	-	10	17	3.7	0.10	-
Brunswick 1,2	8.0	0	0.65	-	-	60	13	18	0.024	-
Cooper	3.4	-	-	-	-	0.046	2.1	5.5	0.0053	-
Dresden 1	-	-	-	-	-	-	-	0.037	-	-
Dresden 2,3	0.18	-	-	-	-	-	0.012	1.1	-	-
Duane Arnold	-	-	-	-	-	-	-	0.0037	-	-
J.A. Fitzpatrick	0.023	-	0.010	-	0.0023	1.8	0.14	5.3	-	-
Edwin I. Hatch	0.18	0.0002	0.0019	-	0.0007	0.11	0.12	0.035	0.00037	-
Humboldt Bay	-	-	-	-	-	-	-	0.18	-	-
Lacrosse	1.8	0.17	0.94	0.009	0.33	-	0.16	2.4	0.0037	2.5
Millstone Point 1	0.20	0.0004	0.028	0.0008	0.014	-	0.29	1.0	0.0006	-
Monticello	-	-	-	-	-	-	-	-	-	-
Nine Mile Point	-	-	-	-	-	-	-	0.81	-	-
Oyster Creek	0.052	-	0.027	-	0.023	0.0009	0.096	0.0024	-	0.00015
Peach Bottom 2,3	36	0.12	17	-	4.4	343	2.4	0.27	-	-
Pilgrim	0.0007	-	0.005	-	-	-	0.25	0.48	-	-
Quad Cities	4.2	-	-	-	-	-	-	0.26	-	-
Vermont Yankee	0.0002	-	-	-	-	-	0.0019	0.0022	-	-
Total annual energy generated [GW(e) a]	11.670									
Normalized release, [GBq (MW[e] a)$^{-1}$]	4.7	0.025	1.7	0.0008	0.41	36	3.1	3.5	0.011	0.22

Table 25, continued

Reactor	Release (GBq)										
	^{58}Co	^{59}Fe	^{60}Co	^{65}Zn	^{89}Sr	^{90}Sr	^{95}Zr	^{97}Zr	^{95}Nb	^{97}Nb	^{99}Mo
B W R											
Big Rock Point 1	0.063	0.19	4.8	0.034	0.016	0.042	-	-	-	-	-
Browns Ferry 1,2,3	0.85	0.47	7.9	11	0.32	0.14	4.9	-	-	-	0.35
Brunswick 1,2	3.6	1.1	18	0.68	0.014	0.008	-	0.17	-	0.035	0.11
Cooper	1.3	0.37	11	6.5	3.6	0.27	0.21	-	0.18	-	0.21
Dresden 1	0.051	0.0037	0.46	-	0.072	0.0074	0.011	-	0.013	-	-
Dresden 1,2	0.24	0.012	5.7	-	0.30	0.07	0.07	-	0.17	-	-
Duane Arnold	-	-	0.0096	-	0.0021	0.0021	-	-	-	-	-
J.A. Fitzpatrick	2.1	0.061	8.9	0.25	0.0074	0.0056	0.0024	-	-	-	0.019
Edwin I. Hatch	0.089	0.0052	0.29	0.30	0.012	0.0031	0.0013	0.00015	0.0033	0.0011	0.0025
Humboldt Bay 3	-	-	0.44	-	-	0.078	-	-	-	-	-
Lacrosse	18	0.061	33	1.1	11	0.43	3.7	-	6.0	0.19	0.062
Millstone Point 1	0.15	0.070	3.6	0.006	0.032	0.0067	0.016	0.0003	0.067	0.002	0.0009
Monticello	-	-	-	-	-	-	-	-	-	-	-
Nine Mile Point	0.22	-	17	-	0.037	0.12	-	-	-	-	-
Oyster Creek	-	-	0.012	-	0.0011	0.00012	-	-	-	-	-
Peach Bottom 2,3	2.9	-	6.0	17	0.74	0.030	-	-	0.017	-	0.0059
Pilgrim	0.059	0.013	3.1	0.025	0.078	0.019	0.0052	-	-	-	0.0074
Quad Cities	0.089	-	7.0	0.17	19	0.20	-	-	-	-	-
Vermont Yankee	0.0004	0.001	0.00056	0.0011	0.0002	0.0001	0.00085	-	-	-	0.00011
Total annual energy generated [GW(e) a]	11.670										
Normalized release [GBq (GW[e] a)$^{-1}$]	2.5	0.20	11	3.2	3.0	0.12	0.76	0.015	0.023	0.019	0.066

Reactor	Release (GBq)									
	^{99m}Tc	^{103}Ru	^{110m}Ag	^{124}Sb	^{134}Cs	^{136}Cs	^{137}Cs	$^{140}Ba/La$	^{144}Ce	^{239}Np
B W R										
Big Rock Point 1	-	-	-	0.16	1.9	-	18	0.059	-	0.047
Browns Ferry 1,2,3	0.35	-	-	0.41	1.9	0.43	2.8	0.19	-	0.41
Brunswick 1,2	0.41	-	0.052	0.003	12	0.014	21	-	-	-
Cooper	0.19	-	0.60	0.11	11	0.042	14	0.70	-	-
Dresden 1	-	0.0037	-	-	0.076	-	0.21	-	0.037	-
Dresden 2,3	-	0.069	0.23	0.0015	0.41	-	1.1	-	0.033	-
Duane Arnold	-	-	0.0003	-	0.0009	-	0.0003	-	-	-
J.A. Fitzpatrick	0.0013	-	0.0022	-	1.6	-	3.4	0.00059	0.0026	-
Edwin I. Hatch	0.0021	-	0.00052	-	0.20	0.01	0.22	0.001	0.0005	0.0022
Humboldt Bay 3	-	-	-	-	0.27	-	2.2	-	0.074	-
Lacrosse	1.3	1.1	-	0.0048	4.5	0.026	18	3.7	12	3.1
Millstone Point 1	-	-	0.0013	0.0048	0.037	-	0.17	0.12	0.026	-
Monticello	-	-	-	-	-	-	-	-	-	-
Nine Mile Point	-	-	-	-	13	-	37	0.023	-	0.059
Oyster Creek	0.014	-	-	-	0.0001	-	0.026	-	-	0.007
Peach Bottom 2,3	3.7	0.0067	0.0037	0.020	145	-	121	0.89	-	1.1
Pilgrim	0.0074	-	-	-	0.22	-	1.1	0.30	0.023	-
Quad Cities	-	-	0.027	-	7.4	0.37	12	6.1	-	-
Vermont Yankee	0.00011	-	-	-	0.00032	-	0.00041	0.0012	-	-
Total annual energy generated [GW(e) a]	11.670									
Normalized release [GBq (GW[e] a)$^{-1}$]	0.51	0.10	0.023	0.060	17	0.076	22	1.0	1.0	0.40

Table 26

Liquid effluents other than tritium discharged from GCRs in the United Kingdom in 1979 [H14]

Reactor	Release (GBq)									
	^{35}S	^{55}Fe	^{60}Co	^{89}Sr	^{90}Sr	^{106}Ru	^{125}Sb	^{134}Cs	^{137}Cs	^{144}Ce
Bradwell	250	79	14	14	150	2	2	120	670	17
Berkeley	350	2	2	2	78	2	30	190	860	15
Trawsfynydd	120	3	0.6	0.1	27	6	10	9	49	3
Hinkley A	210	8	1	11	350	67	140	150	1160	67
Dungeness	46	4	0.6	3	95	1	2	120	730	2
Sizewell	140	4	6	4	91	0.7	4	170	870	7
Oldbury	260	18	3	7	52	4	7	18	200	8
Wylfa	12	4	0.6	0.6	23	1	2	37	480	1
Total annual energy generated	4.3 GW(e) a									
Normalized release [GBq (GW[e] a)$^{-1}$]	320	28	6	10	200	19	46	190	1170	28

Table 27

Population distribution around the model reactor site and meteorological characteristics of its location

METEOROLOGICAL CHARACTERISTICS

Quantity	Pasquill weather category							
	Dry						Rain	
	A	B	C	D	E	F	C	D
Frequency (%)	1	11	19	32	16	18	1	25
Wind speed (m s^{-1})	1	2	5	5	3	1	5	5
Depth of mixing layer (m)	2000	2000	1000	1000	200	200	1000	1000

Distribution of wind direction frequencies (30° sectors)
0.079, 0.08, 0.1, 0.1, 0.044, 0.023, 0.024, 0.061, 0.12, 0.16, 0.13, 0.074

Stack height: 30 m

POPULATION DISTRIBUTION

Distance (km)	0 - 1	1 - 2	2 - 5	5 - 10	10 - 20	20 - 50
Population	1300	3000	26000	90000	430000	2800000
Cumulative	1300	4300	30000	120000	550000	3300000

Distance (km)	50-100	100-200	200-500	500-1000	1000-2000
Population	6100000	20000000	70000000	140000000	17000000
Cumulative	9400000	29000000	99000000	240000000	260000000

Table 28

Normalized local and regional collective dose commitments for noble gases from the model PWR

Radionuclide	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)									Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues	
^{41}Ar	4.3	5.3	5.7	5.0	4.8	5.7	5.0	9.8	5.3	5.1
^{85m}Kr	1.2	1.3	2.2	1.3	1.5	2.2	1.3	6.4	1.4	1.5
^{85}Kr	1.2	1.7	2.0	1.6	1.4	2.0	1.6	410	1.7	5.7
^{87}Kr	0.7	0.9	1.0	0.9	0.9	1.0	0.9	3.9	0.9	0.9
^{88}Kr	12	15	16	22	15	16	15	41	15	16
^{131m}Xe	0.8	0.8	1.2	0.6	0.7	1.2	0.6	47	0.9	1.3
^{133m}Xe	2.4	2.6	4.2	2.4	2.7	4.2	2.4	44	2.8	3.2
^{133}Xe	220	270	560	250	350	560	250	2700	310	340
^{135m}Xe	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.5	0.2	0.2
^{135}Xe	40	43	64	42	42	64	42	180	46	48
^{138}Xe	1.8	2.2	2.4	2.1	2.1	2.4	2.1	4.8	2.2	2.2
Total (rounded)	280	350	660	330	420	660	320	3450	380	420

Table 29

Normalized collective effective dose equivalent commitment for noble gases from the model PWR as a function of distance

Distance (km)	Normalized collective effective dose equivalent commitment [10^{-4} man Sv (GW[e] a)$^{-1}$]	Percentage distribution
0-2	5	1.2
2-5	12	2.9
5-10	18	4.2
10-20	27	6.5
20-50	40	9.6
50-100	55	13.2
100-200	114	27.2
200-500	122	29.0
500-1000	20	4.8
1000-2000	6.3	1.5
Total (rounded)	420	100

Table 30

Normalized local and regional collective dose commitments for noble gases from the model BWR

Radionuclide	Normalized collective absorbed dose commitment (man Gy [GW(e) a]$^{-1}$)									Normalized collective effective dose equivalent commitment (man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues	
^{41}Ar	0.003	0.004	0.005	0.004	0.004	0.005	0.004	0.008	0.004	0.004
^{85m}Kr	0.02	0.02	0.04	0.02	0.03	0.04	0.02	0.11	0.03	0.03
^{85}Kr	0.007	0.01	0.01	0.009	0.008	0.01	0.009	2.5	0.01	0.034
^{87}Kr	0.10	0.13	0.14	0.12	0.13	0.14	0.12	0.56	0.13	0.13
^{88}Kr	0.69	0.87	0.92	1.2	0.88	0.92.	0.83	2.3	0.87	0.90
^{131m}Xe	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.02	0.001	0.001
^{133}Xe	0.06	0.08	0.16	0.07	0.10	0.16	0.07	0.79	0.09	0.10
^{135m}Xe	0.13	0.02	0.02	0.02	0.01	0.02	0.02	0.04	0.02	0.02
^{135}Xe	0.32	0.35	0.52	0.34	0.34	0.52	0.34	1.5	0.37	0.39
^{138}Xe	0.21	0.26	0.28	0.35	0.25	0.28	0.25	0.55	0.26	0.26
Total (rounded)	1.4	1.7	2.2	2.2	1.8	2.1	1.7	9.1	1.8	1.9

Table 31

Normalized collective effective dose equivalent commitment for noble gases from the model BWR as a function of distance

Distance (km)	Normalized collective effective dose equivalent commitment [man Sv (GW[e] a)$^{-1}$]	Percentage distribution
0-2	0.19	10
2-5	0.27	14
5-10	0.30	16
10-20	0.34	18
20-50	0.46	24
50-100	0.18	9.3
100-200	0.10	5.4
200-500	0.04	2.2
500-1000	0.01	0.5
1000-2000	0.01	0.5
Total	1.9	100

Table 32

Normalized local and regional collective absorbed dose commitments from tritium in airborne discharges from the model reactor

Reactor	Normalized discharge [TBq (GW[e] a)$^{-1}$]	Normalized collective whole-body absorbed dose commitment [man Gy (GW[e] a)$^{-1}$]		
		Ingestion	Inhalation	Total
BWR	3.4	0.03	0.005	0.04
PWR	7.8	0.07	0.01	0.08
GCR	11	0.1	0.02	0.1
HWR	540	4.8	0.8	5.6

Table 33

Normalized local and regional collective absorbed dose commitments from carbon-14 releases to atmosphere

Reactor	Normalized discharge [TBq (GW[e] a)$^{-1}$]	Normalized collective whole-body absorbed dose commitment [man Gy (GW[e] a)$^{-1}$]		
		Ingestion	Inhalation	Total
BWR	0.5	0.92	0.001	0.92
PWR	0.2	0.39	0.00006	0.39
GCR	1.1	2.2	0.0003	2.2
HWR	17	30	0.005	30

Table 34

Normalized local and regional collective dose commitments for iodine releases from the model PWR

Pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)									Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$) a/
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues	
Direct cloud irradiation	0.04	0.05	0.06	0.05	0.04	0.06	0.05	0.11	0.02	0.05
Inhalation	0.01	0.04	0.03	0.42	120	0.03	0.02	0.03	0.04	3.7
Ingestion b/	0.006	0.02	0.02	0.02	84	0.02	0.009	0.01	0.02	2.6
External dose from ground deposits	0.18	0.22	0.32	0.13	0.19	0.35	0.11	0.27	0.22	0.22
Resuspension	0.000005	0.00002	0.00001	0.0002	0.07	0.00001	0.000009	0.00001	0.00002	0.002
Total (rounded)	0.24	0.33	0.42	0.62	210	0.45	0.19	0.42	0.32	6.6

a/ Percentage contribution by iodine isotopes to collective effective dose equivalent commitment: ^{131}I 96 %; ^{133}I 2 %; ^{135}I 2 %.

b/ Percentage contribution of each pathway to ingestion doses: milk 90 %; beef 5 %, green vegetables 5 %.

Table 35

Normalized local and regional collective dose commitments for iodine releases from the model BWR

Pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)									Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$) a/
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues	
Direct cloud irradiation	3.5	4.4	5.1	4.2	3.8	5.1	4.2	9.8	4.4	4.2
Inhalation	0.91	1.7	1.5	32	3900	1.4	1.4	1.2	1.7	120
Ingestion b/	0.16	0.55	0.38	0.44	2000	0.36	0.22	0.35	0.50	62
External dose from ground deposits	7.2	9.0	12	6.8	7.8	13	5.9	11	8.7	8.7
Resuspension	0.0002	0.0005	0.0003	0.006	1.6	0.0003	0.0003	0.0003	0.0005	0.05
Total (rounded)	12	16	19	43	5900	20	12	22	15	190

a/ Percentage contribution by iodine isotopes to collective effective dose equivalent commitment: ^{131}I 78 %; ^{132}I 0.001 %; ^{133}I 17 %; ^{135}I 5 %.

b/ Percentage contribution of each pathway to ingestion doses: milk 90 %; beef 5 %, green vegetables 5 %.

Table 36

Normalized local and regional collective dose commitments for particulate releases from the model PWR and BWR

Pathway	Normalized collective absorbed dose commitment (10^{-3} man Gy [GW(e) a]$^{-1}$)									Normalized collective effective dose equivalent commitment (10^{-3} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues	
PWR										
Direct cloud irradiation	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.002
Inhalation	0.04	0.06	0.41	1.4	0.05	0.82	0.11	0.04	0.06	0.27
Ingestion a/	2.1	1.9	14	1.9	1.9	28	2	1.9	1.9	4.4
External dose from ground deposits	5.9	7.7	8.3	7.2	6.4	8.6	6.6	9.6	7.3	7.3
Resuspension	0.001	0.002	0.02	0.04	0.002	0.04	0.004	0.001	0.002	0.009
Total (rounded)	8.1	9.7	23	11	8.4	37	8.9	11	9.2	12
BWR										
Direct cloud irradiation	0.03	0.04	0.05	0.04	0.04	0.05	0.04	0.07	0.04	0.04
Inhalation	0.93	1.4	10	35	1.3	20	2.8	0.91	1.4	6.6
Ingestion a/	52	47	350	45	48	680	52	36	46	110
External dose from ground deposits	150	190	200	180	160	210	160	240	180	180
Resuspension	0.03	0.05	0.42	1.1	0.04	0.85	0.09	0.03	0.05	0.22
Total (rounded)	200	240	560	260	210	910	220	270	230	290

a/ The pathways contributing to the ingestion dose are: grain 30 %; green vegetables 25%; milk 15 %; milk products 10 %; root vegetables 10 %; beef 5 %; others 5 %.

Table 37

Radionuclides considered for liquid effluent calculations from the model reactor site, normalized releases and concentration factors for marine and freshwater media

Radionuclide	Normalized release [GBq/(GW[e] a)]			Marine concentration factor ($m^3\ t^{-1}$)					Freshwater concentration factor ($m^3\ t^{-1}$)	
	BWR	PWR	GCR	Fish	Crustacea	Molluscs	Sediments	Seaweed	Sediments	Fish
^{54}Mn	10	4.0	-	500	10000	10000	10000	10000	10000	300
^{58}Co	6.9	90		100	1000	1000	10000	1000	30000	300
^{60}Co	30	34	25	100	1000	1000	10000	1000	30000	300
^{65}Zn	8.8	-	-	2000	5000	100000	10000	1000	1000	1000
^{89}Sr	8.2	1.0	-	1	10	10	500	10	2000	30
^{90}Sr	0.33	0.2	420	1	10	10	500	10	2000	30
^{106}Ru	-	-	34	1	500	2000	10000	2000	40000	10
^{110m}Ag	-	1.2	-	1000	5000	50000	10000	1000	200	3
^{125}Sb	-	-	80	500	300	100	10000	100	300	1000
^{131}I	13	9	-	10	100	100	100	1000	200	30
^{134}Cs	46	9	392	50	30	30	500	30	30000	1000
^{137}Cs	60	16	2600	50	30	30	500	30	30000	1000
^{144}Ce	-	-	50	10	1000	1000	10000	1000	30000	1000

Table 38

Parameters for the river model used to assess reactor releases

Section	Water velocity ($m\ s^{-1}$)	Sediment velocity ($m\ s^{-1}$)	Suspended sediment load ($g\ m^{-3}$)	Drinking water extraction ($m^3\ a^{-1}$)	Fish production ($t\ a^{-1}$)
1	0.8	0.0002	40	100000	100
2	0.75	0.00015	45	140000	66
3	0.7	0.0001	50	31000	600

Table 39

Normalized collective dose commitments from liquid reactor effluents discharged into the model river

Reactor type and pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e)a]$^{-1}$)							Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Remainder tissues	
PWR								
Drinking water								
^{131}I	0.008	0.02	0.02	0.02	94	0.02	-	2.8
^{58}Co	0.58	0.33	0.39	0.29	0.27	0.29	0.79	0.53
^{60}Co	1.4	0.70	0.82	0.56	0.49	0.59	3.1	1.6
^{90}Sr	0.009	0.009	1.2	0.009	0.009	2.6	-	0.21
^{134}Cs	1.2	1.1	1.2	1.1	1.2	1.1	1.3	1.2
^{137}Cs	1.6	1.5	1.5	1.5	1.5	1.5	1.4	1.5
Total	4.8	3.7	5.1	3.5	97	6.1	6.5	7.8

Table 39, continued

Reactor type and pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e)a]$^{-1}$)							Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Remainder tissues	
Fish								
^{131}I	0.0006	0.002	0.001	0.002	6.7	0.001	-	0.20
^{58}Co	0.11	0.06	0.07	0.06	0.05	0.06	0.14	0.10
^{60}Co	0.26	0.13	0.15	0.11	0.09	0.11	0.59	0.30
^{90}Sr	0.0003	0.0003	0.05	0.0003	0.0003	0.10	-	0.008
^{134}Cs	0.76	0.68	0.76	0.68	0.72	0.68	0.81	0.75
^{137}Cs	1.0	0.93	0.93	0.93	0.93	0.93	0.91	0.94
Total	2.1	1.8	2.0	1.8	8.5	1.9	2.4	2.3
External								
^{58}Co	0.0014		to all organs and tissues					0.0014
^{60}Co	0.033		to all organs and tissues					0.033
^{134}Cs	0.0023		to all organs and tissues					0.0023
^{137}Cs	0.0079		to all organs and tissues					0.0079
Total	0.045		to all organs and tissues					0.045
B W R								
Drinking water								
^{131}I	0.01	0.03	0.02	0.03	130	0.02	-	4.0
^{60}Co	1.3	0.63	0.75	0.53	0.46	0.55	3.3	1.6
^{65}Zn	1.0	1.0	1.4	0.88	0.88	1.4	1.2	1.1
^{89}Sr	0.06	0.06	0.75	0.06	0.06	1.1	1.1	0.49
^{90}Sr	0.01	0.01	1.9	1.3	1.3	3.9	-	0.34
^{134}Cs	5.8	5.2	5.8	5.2	5.4	5.2	5.3	5.4
^{137}Cs	5.6	5.2	5.2	5.2	5.2	5.2	5.2	5.6
Total	14	12	16	12	140	18	18	19
Fish								
^{131}I	0.08	0.002	0.002	0.002	10	0.002	-	0.29
^{60}Co	0.24	0.12	0.14	0.10	0.10	0.10	0.62	0.30
^{65}Zn	1.2	1.2	1.7	1.2	1.1	1.7	1.6	1.4
^{89}Sr	0.002	0.002	0.03	0.002	0.002	0.04	0.05	0.02
^{90}Sr	0.0005	0.0005	0.07	0.0005	0.0005	0.15	-	0.01
^{134}Cs	3.6	3.2	3.6	3.2	3.4	3.2	4.7	3.8
^{137}Cs	3.5	3.3	3.3	3.3	3.3	3.2	3.8	3.5
Total	8.8	7.5	8.8	7.5	18	8.1	11	9.3
External								
^{60}Co	0.033		to all organs and tissues					0.033
^{134}Cs	0.012		to all organs and tissues					0.012
^{137}Cs	0.030		to all organs and tissues					0.030
Total	0.075		to all organs and tissues					0.075

Table 40

Normalized collective dose commitments for the model PWR, BWR and GCR on a notional site in the eastern English Channel

Reactor type and pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)								Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Upper large intestine	Lower large intestine	
PWR									
Fish									
^{54}Mn	0.29	0.14	0.25	0.11	0.06	0.30	0.72	1.1	0.37
^{58}Co	0.48	0.15	0.21	0.071	0.05	0.10	1.7	3.3	0.64
^{60}Co	4.0	2.0	2.4	1.6	1.4	1.7	11	20	4.9
^{110m}Ag	0.45	0.20	0.25	0.22	0.05	0.13	1.6	2.9	0.77
^{134}Cs	3.8	3.4	3.8	3.4	3.6	3.4	4.2	4.4	4.0
^{137}Cs	8.2	7.6	7.6	7.6	7.6	7.6	8.8	8.8	8.2
Total	17	13	15	13	13	13	28	41	19
Crustacea									
^{54}Mn	0.29	0.14	0.25	0.11	0.06	0.30	0.72	1.1	0.37
^{58}Co	0.28	8.6	0.12	0.04	0.03	0.06	0.96	1.9	0.37
^{60}Co	1.5	0.73	0.87	0.59	0.51	0.62	3.9	7.3	1.8
^{110m}Ag	0.11	0.05	0.06	0.05	0.01	0.03	0.37	0.68	0.18
^{134}Cs	0.09	0.08	0.09	0.08	0.09	0.08	0.10	0.10	9.5
^{137}Cs	0.17	0.16	0.16	0.16	0.15	0.16	0.18	0.18	0.17
Total	2.4	1.2	1.5	1.0	0.86	1.2	6.2	11	3.0
Molluscs									
^{54}Mn	2.5	1.2	2.1	0.98	0.49	2.6	6.2	9.8	3.2
^{58}Co	2.8	0.89	1.2	0.42	0.32	0.59	9.9	23	3.8
^{60}Co	11	5.3	6.3	4.3	3.7	4.5	28	53	13
^{110m}Ag	9.4	4.2	5.1	4.6	1.0	2.7	33	61	16
^{134}Cs	0.70	0.63	0.70	0.63	0.67	0.63	0.78	0.81	0.74
^{137}Cs	1.1	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.1
Total	28	13	16	12	7.2	12	79	150	38
Grand total	47	28	32	26	21	26	110	200	60

Table 40, continued

Reactor type and pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)								Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Upper large intestine	Lower large intestine	
B W R									
Fish									
^{54}Mn	0.62	0.30	0.54	0.25	0.12	0.65	1.6	2.5	0.81
^{60}Co	3.7	1.8	2.2	1.5	1.3	1.5	9.7	18	4.5
^{65}Zn	13	13	18	12	12	18	16	19	15
^{134}Cs	19	17	19	17	18	17	21	22	20
^{137}Cs	31	29	29	29	29	29	33	33	31
Total	67	61	69	60	60	66	81	95	71
Crustacea									
^{54}Mn	0.62	0.30	0.54	0.25	0.12	0.65	1.6	2.5	0.81
^{60}Co	1.3	0.65	0.77	0.53	0.46	0.55	3.4	6.5	1.6
^{65}Zn	1.1	1.2	1.6	1.0	1.0	1.6	1.4	1.6	1.3
^{134}Cs	0.47	0.42	0.47	0.42	0.44	0.42	0.51	0.54	0.49
^{137}Cs	0.64	0.59	0.59	0.59	0.59	0.59	0.69	0.69	0.64
Total	4.1	3.1	4.0	2.8	2.6	3.8	7.6	12	4.8
Molluscs									
^{54}Mn	5.4	2.6	4.7	2.1	1.1	5.6	13	21	7.0
^{60}Co	9.8	4.9	5.8	4.0	3.4	4.1	26	49	12
^{65}Zn	280	270	390	250	250	390	340	400	320
^{134}Cs	3.6	3.2	3.6	3.2	3.4	3.2	4.0	4.2	3.8
^{137}Cs	4.1	3.8	3.8	3.8	3.8	3.8	4.4	4.4	4.1
Total	300	280	410	260	260	410	390	480	350
Grand total	370	350	480	330	320	480	480	580	420

Table 40, continued

Reactor type and pathway	Normalized collective absorbed dose commitment (10^{-4} man Gy [GW(e) a]$^{-1}$)								Normalized collective effective dose equivalent commitment (10^{-4} man Sv [GW(e) a]$^{-1}$)
	Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Upper large intestine	Lower large intestine	
G C R									
Fish									
^{60}Co	3.0	1.5	1.8	1.2	1.1	1.3	7.9	15	3.7
^{90}Sr	0.39	0.39	55	0.39	0.39	120	1.7	6.1	10
^{106}Ru	0.02	0.01	0.01	0.01	0.01	0.01	0.23	0.66	5.4
^{125}Sb	6.1	2.1	4.6	1.3	0.96	20	48	130	14
^{134}Cs	160	140	160	140	150	140	180	190	170
^{137}Cs	1300	1200	1200	1200	1200	1200	1400	1400	1300
^{144}Ce	0.004	0.001	0.009	0.0006	0.0005	0.13	2.2	6.4	0.51
Total	1500	1300	1400	1300	1400	1500	1600	1700	1500
Crustacea									
^{60}Co	1.1	5.3	0.63	0.43	0.37	0.45	2.8	5.3	1.3
^{90}Sr	0.14	0.14	20	0.14	0.14	42	0.62	2.2	3.6
^{106}Ru	0.33	0.29	0.31	0.29	0.29	0.29	5.2	15	1.2
^{125}Sb	0.15	0.51	0.11	0.03	0.02	0.49	1.2	3.0	0.34
^{134}Cs	4.0	3.6	4.0	3.6	3.8	3.6	4.4	4.6	4.2
^{137}Cs	27	25	25	25	25	25	29	29	27
^{144}Ce	0.02	0.006	0.04	0.003	0.002	0.06	11	31	2.5
Total	33	34	50	29	30	72	54	90	39
Molluscs									
^{60}Co	8.1	4.1	4.8	3.3	2.9	3.4	0.00002	41	10
^{90}Sr	0.91	0.91	130	0.91	0.91	260	3.9	14	23
^{106}Ru	12	10	11	10	10	10	190	530	43
^{125}Sb	0.37	0.13	0.28	0.08	0.06	1.2	3.0	7.7	0.86
^{134}Cs	30	27	30	27	29	27	34	35	32
^{137}Cs	180	170	170	170	170	170	190	190	180
^{144}Ce	0.20	0.06	0.45	0.03	0.03	0.64	110	320	26
Total	230	210	350	210	210	470	530	1100	310
Grand total	1700	1600	1800	1600	1600	2000	2200	3000	1800

Table 41

Radionuclides discharged to the atmosphere from fuel reprocessing plants 1975-1979
[B2, B22, L1, L6]

Year	Energy [GW(e) a]	Activity released (TBq)									
					Particulate release		Isotopic composition of particulate release (total β)					
		^{3}H	^{14}C	^{85}Kr	Total α	Total β	^{90}Sr	^{106}Ru	^{129}I	^{131}I	^{134}Cs	^{134}Cs
						WINDSCALE (United Kingdom)						
1975	3.2	444		44000	0.0028	0.070						
1976	3.2	444		44000	0.0019	0.13						
1977	2.1	296		33000	0.0010	0.28	0.041		0.0059	0.0026		0.23
1978	1.8	222	4.1	26000	0.00089	0.34	0.048	0.0078	0.0026	0.015	0.027	0.24
1979	2.5	290	3.5	35000	0.0010	0.31	0.009	0.003	0.006	0.03	0.025	0.24
1975-1979 Normalized release [TBq (GW[e] a)$^{-1}$]		133	1.8	14000	0.0006	0.088						
						LA HAGUE (France)						
1975	1.6	3.3		24000	$5.9\ 10^{-10}$	0.0006						
1976	0.84	1.8		13000	$7.4\ 10^{-10}$	0.0003						
1977	1.8	11		25000	$1.1\ 10^{-7}$	0.0001						
1978	2.1	4.1		29000	$1.1\ 10^{-6}$	0.0001						
1975-1979 Normalized release [TBq (GW[e] a)$^{-1}$]		3.2		14000	$1.9\ 10^{-7}$	0.0002						
						MARCOULE (France)						
1975	0.24	4.4		3700	$8.1\ 10^{-7}$	0.001						
1976	0.22	4.4		3500	$6.7\ 10^{-7}$	0.001						
1977	0.32	2.8		4400	$3.2\ 10^{-6}$	0.0002						
1978	0.83	63		11000	$1.7\ 10^{-6}$	0.0003						
1975-1978 Normalized release [TBq (GW[e] a)$^{-1}$]		46		14000	$4.0\ 10^{-6}$	0.002						

Table 42

Radionuclides released to the aquatic environment from fuel reprocessing
[B2, B22, L1, L6]

Year	Activity released (TBq)				
	Total α	Total β (other than ^{3}H)	^{3}H	^{90}Sr	^{106}Ru
		WINDSCALE (United Kingdom)			
1975	85	9065	1400	466	762
1976	60	6771	1200	381	766
1977	46	7129	910	427	816
1978	68	7124	1050	597	810
1979	62	4100	1200	250	390
1975-1979 Normalized release [TBq (GW[e] a)$^{-1}$]	25	2671	450	166	277
		LA HAGUE (France)			
1975	0.49	1180		75	829
1976	0.37	714		40	555
1977	0.67	765	331	73	540
1978	0.51	1092	728	140	801
1975-1978 Normalized release [TBq (GW[e] a)$^{-1}$]	0.32	592	272	52	430
		MARCOULE (France)			
1975	0.019	42		0.93	33
1976	0.011	23		0.41	20
1977	0.013	30	117	0.37	27
1978	0.013	35	270	0.88	25
1975-1978 Normalized release [TBq (GW[e] a)$^{-1}$]	0.035	81	337	1.6	65

Table 43

Isotopic composition of liquid effluents from the Windscale reprocessing plant [D2, D22]

Radionuclide	Annual discharge (TBq)		
	1977	1978	1979
^{35}S		1.8	1.4
^{54}Mn		0.22	0.037
^{55}Fe		2.3	1.8
^{60}Co		1.0	0.52
^{63}Ni		1.5	0.18
^{65}Zn		0.037	0.022
^{89}Sr		9.9	7.5
^{90}Sr	427	597	250
^{95}Zr	92	82	60
^{95}Nb	203	148	98
^{99}Tc		179	43
^{103}Ru		8.5	5.8
^{106}Ru	816	810	390
^{110m}Ag		0.33	0.033
^{125}Sb		29	14
^{129}I	0.11	0.074	0.12
^{134}Cs	594	404	240
^{137}Cs	4480	4090	2600
^{144}Ce	152	104	83
^{152}Eu		10	3.7
^{154}Eu		38	1.9
^{155}Eu		7.8	4.0
Uranium		10936 (kg)	6000 (kg)
^{237}Np		0.60	0.33
^{238}Pu		12	12
$^{239+240}Pu$	36	46	37
^{241}Pu	981	1773	1500
^{241}Am	3.6	7.9	7.9
^{242}Cm		0.55	0.37
$^{243+244}Cm$		0.33	0.15
Electricity production from fuel reprocessed [GW(e) a]	2.1	1.8	2.5

Table 44

Population distribution around the Windscale reprocessing plant and meteorological characteristics of its location

METEOROLOGICAL CHARACTERISTICS

Quantity	Pasquill weather category							
	Dry						Rain	
	A	B	C	D	E	F	C	D
Frequency (%)	0.3	4.5	12.1	63	5	4.6	1.7	8.4
Wind speed ($m\ s^{-1}$)	1	2	5	5	3	1	5	5
Depth of mixing layer (m)	2000	2000	1000	1000	200	200	1000	1000

Distribution of wind direction frequencies (30^{o} sectors): 0.091, 0.089, 0.096, 0.11, 0.098, 0.069, 0.049, 0.034, 0.056, 0.10, 0.11, 0.094

Stack height: 100 m (effective)

POPULATION DISTRIBUTION

Distance (km)	0 - 1	1 - 2.5	2.5 - 6	6 - 12.5	12.5-17.5
Population	36	230	1100	12000	17000
Cumulative	35	220	1400	14000	31000

Distance (km)	17.5-60	60-150	150-375	375-900	900-2700
Population	71000	20000000	36000000	110000000	82000000
Cumulative	74000	21000000	57000000	170000000	260000000

Table 45

Averaged local and regional normalized whole-body absorbed dose commitments from tritium and carbon-14 discharges to the atmosphere from Windscale (United Kingdom)

Radio-nuclide	Normalized collective absorbed whole-body dose commitment [man Gy (GW[e] a)$^{-1}$]		
	Ingestion	Inhalation	Total
^{3}H	0.30	0.049	0.35
^{14}C	0.69	0.0001	0.69

Table 46

Collective dose commitments from atmospheric annual discharges from Windscale (United Kingdom) averaged between 1975 and 1979

Pathway	Collective effective dose equivalent commitment (man Sv)	Collective absorbed dose commitment (man Gy)								
		Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Skin	Remainder tissues
CLOUD										
^{85}Kr	0.26	0.058	0.078	0.095	0.074	0.065	0.095	0.074	19	0.078
DEPOSIT										
^{137}Cs	1.1	0.87	1.2	1.4	1.1	0.97	1.4	1.0	1.4	1.1
INHALATION										
^{3}H	0.3	0.13	0.3	0.13	0.13	0.13	0.13	0.13	0.13	0.13
^{239}Pu	0.11	0.00074	-	0.0043	0.02	-	0.059	0.012	-	-
^{240}Pu	0.10	0.00068	-	0.0044	0.018	-	0.054	0.011	-	-
^{241}Am	0.08	0.000095	-	0.0056	0.00052	-	0.075	0.016	-	-
^{238}Pu	0.04	0.00022	-	0.0015	0.0071	-	0.019	0.0041	-	-
^{129}I	0.007	-	-	-	-	0.24	-	-	-	-
^{137}Cs	0.006	0.006	0.005	0.006	0.0056	0.005	0.005	0.0054	0.0041	0.005
Total	0.47									
INGESTION										
^{3}H	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
^{134}Cs	0.13	0.13	0.11	0.13	0.11	0.11	0.11	0.13	0.11	0.086
^{137}Cs	1.1	1.1	0.98	0.98	0.98	0.98	0.98	1.1	0.98	0.76
^{14}C	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
^{90}Sr	0.24	-	-	1.3	-	-	2.8	0.0096	0.0096	0.0096
^{129}I	0.34	-	-	-	-	11	-	-	-	-
Total	4.4									
GRAND TOTAL	6.2									

Table 47

Collective absorbed dose commitments for average releases between 1975 and 1979 into the Eastern Irish Sea from Windscale (United Kingdom) and into the Eastern English Channel from La Hague (France)

Pathway		Collective absorbed dose commitment (man Gy)							
		Gonads	Breast	Red bone marrow	Lungs	Thyroid	Bone lining cells	Liver	Lower large intestine
		WINDSCALE (United Kingdom)							
Fish									
^{137}Cs		270	250	250	250	250	250	250	270
Mollusc and crustacea									
^{106}Ru		8.7	7.4	8.1	7.4	7.4	7.4	-	380
Fish, crustacea, mollusc									
^{90}Sr		-	-	25	-,	-	54	-	-
Mollusc									
^{239}Pu and ^{240}Pu		0.024	-	0.16	-	-	2	0.42	0.50
^{241}Pu		0.46	-	2.7	-	-	36	5.9	2.3
Total	βγ	280	260	290	260	260	350	260	650
	α	0.024	-	0.16	-	-	2	0.42	0.50
		Collective effective dose equivalent commitment: 311 man Sv							
		LA HAGUE (France)							
Fish									
^{137}Cs		9.5	8.8	8.8	8.8	8.8	8.8	8.8	9.5
Mollusc and crustacea									
^{106}Ru		20	17	19	17	17	17	-	880
Mollusc									
^{239}Pu and ^{240}Pu		0.005	-	0.036	-	-	0.42	0.09	0.11
^{241}Pu									
Total	βγ	30	26	28	26	26	26	11	890
	α	0.005	-	0.036	-	-	0.42	0.09	0.11
		Collective effective dose equivalent commitment: 84 man Sv							

Table 48

Local and regional collective effective dose equivalent commitments for normalized discharges from the model reprocessing facility to atmospheric and marine environments

Radionuclide	Normalized release [TBq (GW!e! a)$^{-1}$]	Normalized collective effective dose equivalent commitment [man Sv (GW!e! a)$^{-1}$]
ATMOSPHERIC		
^{3}H	60	0.1
^{14}C	0.4	0.2
^{85}Kr	10000	0.03
^{90}Sr	0.0007	0.006
^{129}I	0.0002	0.004
$^{238,239,240}Pu$	0.00001	0.002
	Total	0.3
AQUATIC		
^{137}Cs	7	0.4
^{106}Ru	10	0.3
^{90}Sr	2	0.02
^{129}I	0.04	0.008
$^{238,239,240}Pu$	0.5	0.0006
	Total	0.7

Table 49

Representative annual effective dose equivalents to most exposed individuals from reprocessing LWR fuel at the model facility

Radionuclide	Annual effective dose equivalent (μSv)
ATMOSPHERIC	
^{3}H	5
^{14}C	10
^{85}Kr	5
^{90}Sr	2
^{129}I	2
α emitters	1
Total	25
AQUATIC	
^{90}Sr	2
^{106}Ru	50
^{137}Cs	150
^{129}I	1
α emitters	0.5
Total (rounded)	200

Table 50

Summary of normalized releases of radionuclides of global significance and of the corresponding collective effective dose equivalent commitments

Radionuclide	Normalized release [TBq (GW[e] a)$^{-1}$]	Normalized collective effective dose equivalent commitment [man Sv (GW[e] a)$^{-1}$]				
		Integration time (a)				
		10^1	10^2	10^4	10^6	10^8
^{3}H	640	0.015	0.02	0.02	0.02	0.02
^{85}Kr	11000	0.9	1.9	1.9	1.9	1.9
^{14}C	17	3	10	70	110	110
^{129}I	0.04	-	0.02	0.2	28	560

Table 51

Collective effective dose equivalent commitments from high-level waste disposal per unit electrical energy generated for different fuel cycles [111]

	Normalized collective effective dose equivalent commitment [man Sv (GW[e] a)$^{-1}$]				
	LWR	HWR			
DISPOSAL OF UNREPROCESSED FUEL					
Uranium content of fuel					
Migration time 10^6 a	62	300			
Migration time 10^5 a	71	170			
All other elements					
Migration time 10^6 a	27	10			
Migration time 10^5 a	200	280			
Total (rounded) (10^6 a)	89	310			
(10^5 a)	270	450			
	LWR (Plutonium recycle)	FBR	HWR		HTR
			Uranium Plutonium	Uranium Thorium	Uranium Thorium
DISPOSAL OF REPROCESSING WASTES					
Uranium content of fuel					
Migration time 10^6 a	22	0.8	130	22	1.1
Migration time 10^5 a	23	1.1	72	120	6.0
All other elements					
Migration time 10^6 a	9	18	6	14	24
Migration time 10^5 a	27	51	45	140	110
Total (rounded) (10^6 a)	31	19	140	36	25
(10^5 a)	50	52	120	260	120

Table 52

Summary of normalized collective effective dose equivalent commitments to the public from nuclear power production

	Normalized collective effective dose equivalent commitment [man Sv (GW[e] a)$^{-1}$]		
LOCAL AND REGIONAL CONTRIBUTION			
Mining			
Radon	0.5	Total	0.5
Milling (excluding releases from tailings)			
Uranium, thorium, radium	0.015		
Radon	0.02		
		Total	0.04
Fuel fabrication			
Uranium	0.002	Total	0.002
Reactor releases			
Atmospheric			
- Noble gases	0.6		
- Tritium	0.5		
- Carbon-14	2.8		
- Iodines	0.06		
- Particulates (caesium, ruthenium, cobalt)	0.1		
		Total	4.1
Aquatic			
- Tritium	0.04		
- Other (caesium, ruthenium, cobalt)	0.02		
		Total	0.06
Fuel reprocessing			
Atmospheric			
- Tritium	0.1		
- Krypton-85	0.03		
- Carbon-14	0.2		
- α emitters	0.002		
		Total	0.3
Aquatic			
- Caesium 134, 137	0.4		
- Ruthenium-106	0.3		
- Strontium-90	0.02		
- α emitters	0.0006		
- Iodine-129	0.008		
		Total	0.7
Transportation	0.003	Total	0.003
TOTAL for operations in the nuclear fuel cycle		5.7 man Sv [GW(e) a]$^{-1}$	

	Complete and incomplete normalized collective effective dose equivalent commitment [man Sv (GW[e] a)$^{-1}$]				
	Integration period (a)				
	10^1	10^2	10^4	10^6	10^8
GLOBAL CONTRIBUTION FROM OPERATIONS IN THE NUCLEAR FUEL CYCLE					
Tritium	0.015	0.02	0.02	0.02	0.02
Krypton-85	0.9	1.9	1.9	1.9	1.9
Carbon-14	3	10	70	110	110
Iodine-129	-	0.02	0.2	28	560
TOTAL (rounded)	3.9	12	72	140	670
WASTE DISPOSAL (assuming LWR fuel reprocessed and plutonium utilization in LWRs and FBRs)					
Mill tailings (radon) a/	0.25	0.25	250	2800	2800
(uranium) b/			460	460	460
High-level wastes	-	-	-	30	30

a/ Assuming radon emanation continued at the same rate as at disposal with 2 m earth covering.

b/ Assuming that at 10^3 a the tailings are eroded into fresh water, then marine environments.

Table 53

Annual per caput doses from the continued generation of nuclear electric power to the year 2500

	Year			
	1980	2000	2100	2500
Annual projected nuclear generation [GW(e) a]	80	1000	10000	10000
Annual collective effective dose equivalent (man Sv)	500	10000	200000	250000
World population	$4\ 10^9$	10^{10}	10^{10}	10^{10}
Annual per caput effective dose equivalent (μSv)	0.1	1	20	25
Percentage of average exposure to natural sources of radiation (%)	0.005	0.05	1	1

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back to first page