6. RADIOLOGICAL EFFECTS ON THE PUBLIC

6.1 Introduction

161. This section describes the radiological impact on members of the public, in terms of critical group doses and collective doses (see Chapter 2), of each component of the nuclear fuel cycle. In this generic study, a set of common standard assumptions for habits, etc., has been used for each phase of the fuel cycle with the exception of one difference for mining and milling. The methodology adopted in this approach is given in Chapter 4.

162. Site specific calculations, when available, provide an indication of the sensitivity of the results to assumptions about locations and habits, *etc.* as well as providing further insights into the distributions of doses amongst individuals.

163. The results are presented in terms of collective doses to the regional population (in all cases except mining and milling, this is the population of Europe) summed up to 500 years. The reasons for summing up to 500 years are given in Chapter 2. Critical group doses are also estimated in the generic assessment whereas the site-specific calculations provide information on the collective dose up to 500 years to the local population, which is defined as being within 100 km of the site, and on the dose to average individuals in the surrounding population. The collective doses are normalised to the electricity produced in GWa.

164. Results are summarised below for each category of facility. Detailed results for the generic calculations are given in Annex B and are summarised in Table 20.

6.2 Mining and Milling

165. Only generic calculations were done for uranium mining and milling. The main sources of exposure are releases of radon-222 to atmosphere and leaching of radium-226 and daughter radionuclides[5] into local water bodies. Radon-222 gives rise to doses by inhalation and also, in some circumstances, to doses from consumption of foodstuffs following the deposition of daughter radionuclides (in this case mainly polonium-210 and lead-210). Releases of radionuclides to freshwater systems give rise to doses from the consumption of freshwater fish and from drinking the water.

[5] Radon-222 is a member of a decay chain of radionuclides (see Fig ?). It is itself produced from the decay of radium-226 and it decays via a number of short half-life radionuclides to the longer **lived lead-210 (half life** 22 y) and polonium-210 (half-life 138 days). The final produce of the decay chain is a stable isotope of lead (lead-206).

166. The critical group for discharges to atmosphere is assumed to reside one km away from the mining and milling tailings heap. In the calculations described in Annex B, the heap is assumed to have an area of 100 hectares and to release radon-222 at a rate of 3 Bq m^{-2} s^{-1}. The resultant annual dose from inhalation is estimated to be about 160 μSv. This dose is proportional to the assumed radon release rate and the area of the tailings; the value chosen for the radon release rate is appropriate for abandoned mill tailings where there is some form of cover reducing radon egress. The exhalation rate for bare tailings can be higher at up to 300 Bq m^{-2} s^{-1}. Some fraction of the tailings would be exposed during the operational phase of the mine but it could be assumed for a well-managed operation that radon-222 exhalation rates averaged over the area of the tailings are unlikely to be more than a factor of two higher than those assumed here. This leads to an estimated critical group dose from radon-222 releases of up to around 300 μSv per year.

167. The majority of large uranium production facilities are situated in areas of very low agricultural productivity and so doses from terrestrial foodchain pathways were not considered in assessing critical group doses. However, some radionuclides could be leached from the tailings heap and could contaminate nearby freshwater systems. Therefore, doses via consumption of freshwater and of freshwater fish were evaluated. Typical concentrations of radionuclides measured in freshwater from near to uranium mining facilities were taken. Concentrations of radionuclides in freshwater fish were estimated using standard concentration factors. The estimated dose via these two exposure pathways is, in total, around 190 μSv y^{-1} for an adult and about 250 , μSv y^{-1} for an infant. In the case of the infant, the majority of the dose arises from the drinking water pathway, whereas for the adult, the consumption of fish is the more important pathway.

168. It is possible that individuals living near to uranium mining and milling facilities could receive doses via both inhalation of radon and freshwater pathways. Therefore, annual doses to the critical group from uranium mining and milling are likely to be in the range 300 , μSv - 500 μSv.

169. Collective doses from the releases of radon-222 were estimated. Two calculations were undertaken. The first calculation was of the collective dose from inhalation. This is proportional to the number of people exposed. Data on population distributions around uranium mining and milling facilities were not available to this study and so a generic assumption of a population density of 1 person per km^2 out to a distance of 2000 km was made. Calculations were done for two distance bands, from 0 to 100 km and from 100 to 2000 km. The affect of different population densities on the estimate of collective dose can be made by simple scaling.

170. Radon-222 is a member of a decay chain *[add figure]* and, as such, it decays to produce other radionuclides. Two of these radionuclides (polonium-210 and lead-210) can give rise to doses via foodchain pathways. In order to calculate the contribution from these pathways to the collective dose, data on agricultural production in the affected area is required. These data were not available to this study. Therefore, an upper estimate of the collective dose from foodchain pathways was obtained assuming European agricultural production data. In order to undertake this calculation, it also had to be assumed that the uranium mine was located somewhere and for the purpose of the calculation it was arbitrarily assumed to be in the UK.

171. The collective dose summed up to 500 years to the population within 2000 km of the mine from inhalation from releases of radon-222 in one year is 0.132 manSv; the vast majority of which is delivered to the population within 100 km. Assuming that the tailings from uranium produced for one GW y are distributed over one hectare (UNSCEAR, 1993), this gives a normalised collective dose of 1.32 10^{-3} manSv $(GW\ y)^{-1}$. The corresponding estimate for terrestrial foodchain production is about

6.7 10^{-2} manSv (GW y)$^{-1}$ Thus, an upper estimate of the collective dose for releases from a tailings heap over one year is about 7 10^{-2} manSv (GW y)$^{-1}$ Tailings, however, contain very long-lived radionuclides including thorium-230 (half-life 80,000 years) and radium-226 (half-life 1,600 years), the immediate precursor of radon-222, and so radon-222 releases could continue for many thousands of years. Nevertheless, the tailings arising from uranium production for one GW y will eventually be covered by other tailings and the heap would eventually be capped by an inert layer of material reducing radon emissions. Thus, it is reasonable to assume that the tailings associated with one GW y of electricity production would release radon-222 for a period of 10-15 years giving an estimated collective dose of about 1 manSv (GW y)$^{-1}$. Taking account of the uncertainties in the calculation, the value could lie in the 0.1 manSv (GW y)$^{-1}$ to perhaps a little above 1 manSv (GW y)$^{-1}$. However, the possibility of protracted releases due to poor maintenance of the tailings cannot be entirely discounted and it is possible that collective doses of tens of manSv could be incurred over 500 years.

6.3 Fuel Fabrication

172. The generic calculations were undertaken for summed discharges from fuel conversion, enrichment and fabrication from sites in the UK. The main contribution to the discharges was from the conversion of uranium ore concentrate to uranium hexafluoride. The estimated doses are very small. Estimated critical group doses from atmospheric discharges were less than 1 μSv y^{-1} for both adults and infants; the estimates for discharges to the aquatic environment were higher at around 20 μSv y^{-1} for adults and 4 μSv y^{-1} for infants.

173. The collective doses per GW y of electricity to the European population were also very small. Collective doses summed to 500 years to the population of Europe were 6.29 10^{-4} manSv (GW y)$^{-1}$ from discharges to atmosphere and 2.8 10^{-4} manSv (GW y)$^{-1}$ for releases to the aquatic environment.

174. Specific calculations were undertaken for two sites in France. These sites are the uranium oxide fuel fabrication plant at Romans and the mixed oxide fuel fabrication plant, MELOX, at Marcoule. The calculated collective doses to the population of Europe summed over 500 years for the Romans plant were 3.0 10^{-4} manSv (GW y)$^{-1}$ for liquid releases and 2.1 10^{-5} manSv (GW y)$^{-1}$ for releases to atmosphere. The corresponding figures for the MELOX facility were 2.5 10^{-3} manSv (GW y)$^{-1}$ and 1.3 10^{-5} manSv (GW y)$^{-1}$ respectively. These values, although differing by up to around an order of magnitude from the generic calculations, confirm the low overall radiological impact from this phase of the fuel cycle. The detailed calculations show that the majority of the collective dose is delivered to the local population. The average annual doses to individuals in the local population was estimated to be around a few nSv (10^{-9} Sv) for liquid discharges from both sites with even lower doses from discharges to atmosphere.

6.4 Power Production

175. Because the radiological impact can depend on the local environment, the generic calculations considered two locations for a typical PWR: one on the River Loire at Dampierre and the other on the north coast of France at Flamanville. The same discharges were assumed for each site.

176. For discharges to atmosphere, the critical group doses were similar for both sites at around 0.5 μSv y^{-1} for both adults and infants. For liquid discharges, the critical group dose for adults for the coastal site was around an order of magnitude higher, 0.33 μSv y^{-1}, than for the inland site,

0.044 μSv y^{-1}. The critical group doses for infants were similar in both cases at around 0.03 μSv y^{-1}. These doses are very small.

177. Collective doses summed over 500 years to the population of Europe were, in both cases, dominated by the contribution from releases to atmosphere. For the coastal site, discharges to atmosphere give rise to about 0.53 manSv (GW y)$^{-1}$; the corresponding figure for the inland site is about 0.63 manSv (GW y)$^{-1}$. Liquid releases give rise to a collective dose of 0.014 manSv (GW y)$^{-1}$ for the coastal site and 0.02 manSv (GW y)$^{-1}$ for the inland site. The dominant contributor to the total collective dose is carbon-14.

178. Site-specific calculations were not undertaken for power generation.

179. On the basis of limited data it is concluded that there is no difference in discharges between MOX and UO_2 fuel (see Chapter 3 and Annex A).

6.5 Reprocessing, Vitrification and Interim Storage

180. The generic calculations indicate that the highest critical group doses are received by adults from discharges to the marine environment. This dose is estimated at around 290 μSv y^{-1}. About 50% is from the consumption of fish with another 35% from consumption of molluscs. The dominant radionuclide is carbon-14 which accounts for around 70% of the total dose. Due to the fact that infants are assumed to eat little seafood, the assessed dose to an infant is much lower at about 20 μSV y^{-1}.

181. Critical group doses from releases to atmosphere are about 110 , μSv y^{-1} to adults and 130 μSv y^{-1} to infants. Carbon-14 and iodine-129 are the main contributors in both cases. Consumption of grain is the main contributing pathway for adults with consumption of milk being the main one for infants.

182. Collective doses are dominated by the contribution from atmospheric releases. The collective dose to the population of Europe summed over 500 years from releases to atmosphere is about 1.3 manSv (GW y)$^{-1}$. Discharges of carbon-14 contribute about 75% with krypton-85 contributing about another 17%. The corresponding collective doses from discharges to the marine environment are lower at about 0.234 manSv (GWy)$^{-1}$; the main contribution again coming from carbon-14 (around 80%).

183. The generic calculations assume a standard set of habits which may not be applicable to all sites. Calculations using habit data specific to the environment surrounding the La Hague site were also undertaken. Thus estimated, the maximum critical group dose from a combination of discharges to atmosphere and to the marine environment is around 12 μSv to an inhabitant of a nearby village. Average doses to individuals within 100 km of the site were estimated at a few nanoSieverts (nSv) from liquid releases and around 0.5 μSv from releases to atmosphere. Estimated collective doses were similar to those from the generic calculations and can be explained by different assumptions including the fact that the site specific calculations calculated the collective dose to the population of the European community as it was in 1990, whereas the generic calculations considered Europe as a whole. Discharges to atmosphere contribute about 0.55 manSv (GW y)$^{-1}$ to the population of Europe summed over 500 years with liquid releases contributing around 0.22 manSv (GW y)$^{-1}$. Carbon-14 was again among the important radionuclides.

6.6 Solid Waste Disposal

184. Radiological protection strategies for two options are based on different approaches: do not separate radioactive components and dispose them at once; and separate different radioactive components and manage them in accordance with their radiological characteristics. Both approaches have different characteristics but can satisfy radiological protection objectives when properly implemented.

Table 19. **Characteristics of Solid Waste Generation and Disposal**

	No-reprocessing Option	Reprocessing Option
Mining and Milling	- U contaminated - low radioactive but long life - very large volume	Same as no-reprocessing but approximately 20% less
Conversion	- U contaminated - low radioactive but long life - small volume	Same as no-reprocessing but approximately 20% less
Enrichment	- U contaminated - low radioactive but long life - small volume - (depleted UF6)	Same as no-reprocessing but approximately 20% less
Fuel Fabrication	- U contaminated - low radioactive but long life - small volume	Same for U contaminated waste but approximately 20% less - Pu contaminated waste: small volume
Nuclear Power Plant	- FP and AP contaminated - LLW and ILW - spent fuel	- Waste: same as no-reprocessing - MOX spent fuel: approximately 25% of no-reprocessing
Reprocessing	No waste	- vitrified HLW - Pu contaminated LLW and ILW: small volume - (recovered uranium oxide)
Decommissioning and Dismantling	- U, FP and AP contaminated - mainly low active - very large volume	- U, FP and AP contaminated waste: same as no-reprocessing - low level Pu contaminated waste: small volume
Characteristics	- large volume from mining and milling - Spent fuel - single disposal option for spent fuel	- 20% less volume - MOX spent fuel and HLW - Pu contaminated waste - customised disposal options for long lived waste

LLW: low-level waste
ILW: intermediate-level waste
HLW: high-level waste
FP: fission product
AP: activation product

185. Radioactive inventories and composition in two options are significantly different and those to be disposed of also. In case of the no-reprocessing option, all radioactive materials in spent fuel are to be disposed of in deep geological repository. Accordingly, certain long-lived radionuclides, which are separated and released in the environment during reprocessing, remain inside the spent fuel. In case of reprocessing options, recovered Plutonium is recycled and recovered Uranium will be temporally stored awaiting for future use either for feed material for enrichment or fuel fabrication. Thus their total quantity to be disposed of is significantly less than in the case of no-reprocessing option.

186. Although no release from repository is assumed for this study, it is worthwhile reviewing progress in safety assessment of deep geological disposal concept, which is a favoured option in the OECD Member counties. A number of safety analyses or performance assessment of deep repositories have been carried out to study the safety and feasibility of disposing either spent fuel or vitrified high level waste into repositories in different geological media. The level of details in these assessments varies and is dependent on the overall progress of waste management programmes in different countries. The main objective of these studies has neither been the direct comparison of host media nor the different main categories of waste (spent fuel or high level waste). Rather the intention or objective has been to demonstrate on the one hand the applicability of performance assessment methodologies and on the other hand the feasibility to achieve the required high safety level of waste disposal.

187. All the results show that it is possible to design the engineered safety features and to locate sites in different host media in such a way that the radiological consequences to hypothetical critical groups in the vicinity of the repositories do not exceed the regulatory limits. The average does to larger population groups are much lower.

188. Nevertheless, as a result of differences in the radioactive inventories in spent fuel and in spent MOX fuel and vitrified waste, particularly of very long-lived radionuclides such as Te-99, I-129, Cs-135 and actinides, results of performance assessments have significantly different implications from radiation protection viewpoint. Some of them are soluble to groundwater and have a potential to return to the environment.

189. The inventory of radionuclides in wastes requiring deep geological disposal includes for the recycle option the high-level waste from reprocessing and the spent MOX fuel and correspondingly for the once-through option the spent uranium oxide fuel. There are certain differences in the radionuclide inventories, but the natural and engineered barriers of the disposal system in combination effectively inhibit or retard the releases of radionuclides to the biosphere. Consequently the radiation exposures remain very small and the differences between the main fuel cycle options remain small as compared to the uncertainty interval caused by the assumptions and also small compared to the variation interval between different host rock formations. In the case of hypothetical human intrusion deep into the repository the technical and natural release barriers could be bypassed. In that improbable case the exposures to a small group of persons could be higher and the relative differences larger between the main options. However, for larger population groups even these improbable intrusion scenarios are unlikely to show any marked differences between the main fuel cycle options.

6.7 Summary of Results

190. In the generic calculations, the fuel cycle was divided into four stages: uranium mining and milling; fuel fabrication, including enrichment and uranium conversion; power production; and reprocessing. The results, Table 20, show that the highest radiological impacts come from two of these stages, uranium mining and milling, and reprocessing. Power production gives rise to similar collective doses to these two stages but the critical group doses are very much lower.

191. For both uranium mining and milling and reprocessing, the assessed critical group doses were in the range 300 μSv y~1 to 500 μSv y^{-1} For reasons outlined in the introduction, actual critical group doses at specific sites will be different and may be significantly so, due to differences in the habits of local populations, *etc.* However, the results show that the potential to expose local individuals is similar for these two stages of the fuel cycle.

192. The assessed collective doses are also of a similar order for these two fuel cycle stages. The collective dose summed over 500 years to the regional population *(ie,* within around 2,000 km) is up to around 1 manSv $(GW\ y)^{-1}$ for uranium mining and milling and about 1.5 manSv $(GW\ y)^{-1}$ for reprocessing. However, there are a number of uncertainties surrounding these numbers: population characteristics are assumed to remain unchanged over the time period and, in the case of uranium mining and milling, radon-222 emanation rates could be significantly different from those assumed in this study leading to higher or lower collective doses. Indeed, if the tailings piles were partially uncovered following a period of poor maintenance, collective doses of up to a few tens of man.Sv could be received. Thus, differences between the two assessed collective doses do not provide a meaningful basis for distinguishing between these two processes.

193. Site specific calculations were not undertaken for uranium mining and milling but were done so for the other three stages. In general, these calculations support the conclusions from the generic study in that the assessed collective doses from reprocessing, totalling about 0.8 manSv $(GW\ y)^{-1}$, and the critical group doses are higher than for the other two stages of the fuel cycle that were considered. Furthermore, fuel fabrication gave rise to the lowest collective doses, which is the same conclusion as from the generic study.

194. Collective doses have been summed up to 500 years into the future in this study. It is possible to sum these doses for longer time periods, including infinity. As the collective doses from the major components of the fuel cycles (mining and milling, power production and reprocessing) involve long-lived radionuclides, such an approach would lead to larger collective doses per GWa of electricity. However, this is unlikely to affect the conclusions of the study for the following reasons. The majority of the collective dose summed over 500 years from both power production and reprocessing arises from the relatively long-lived, mobile radionuclide carbon-14 (half-life 5500 years *[check]).* Thus extension of the time period considered is not likely to alter the relative contributions of these two processes. Furthermore, the production of radon-222 in tailings will continue for of the order of hundreds of thousands of years because it is supported by the very long-lived radionuclide thorium-230 (half-life 80000 years). Thus collective doses from this part of the fuel cycle could be considerable if estimated over very long time periods but would also be subject to the uncertainties mentioned above.

Table 20. **Summary of doses from generic calculations**

Stage of fuel Cycle	**Critical group dose** ($\mu Sv\ y^{-1}$)	**Collective dose up to 500 years** ($manSv\ (GW\ y)^{-1}$)	
		Liquid	**Atmosphere**
Uranium mining and milling	300 – 500	-	0.1 – 1.0 (could be up to tens of manSv)
Fuel fabrication	20	$3\ 10^{-4}$	$6\ 10^{-4}$
Power production	0.5 – 0.8	$1\ 10^{-2} - 2\ 10^{-2}$	0.5 – 0.6
Reprocessing	300 – 400	0.23	1.3