5 Pathways for Internal and External Exposure

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5.1 INTERNAL EXPOSURE PATHWAYS

5.1.1 Introduction

The main pathways leading to intake of radionuclides by humans following a nuclear explosion are inhalation of contaminated aerosols or gases and ingestion of contaminated water or foodstuffs as discussed below. Radioisotopes of iodine, strontium and caesium are of most interest in this respect because they are both released in considerable quantities during nuclear explosions (Chapter 4) and are readily transferred to humans by foodchain pathways and then subsequently absorbed through the gastro-intestinal tract.

5.1.2 Inhalation

Inhalation of radioactive gases and aerosols may occur during the initial passage of the radioactive cloud and at later times as a consequence of resuspension of material previously deposited on vegetation and other surfaces. In this respect, it is necessary to consider both humans and grazing animals, where inhaled material may either be absorbed via the lungs or removed from the lungs to the gastro-intestinal tract for subsequent absorption. For humans, there are internationally accepted models such as those developed by ICRP (1980) for calculating absorption of radionuclides following inhalation, taking into account factors such as particle size and radionuclide composition. Such models are based on ICRP 'reference man' (1975) and therefore may not be entirely appropriate to the populations surrounding nuclear test sites at the time and conditions in which the most significant explosions occurred. Analysis of exposure pathways during the passage of a radioactive cloud is relatively straightforward. It involves application of ICRP models with appropriate modification of parameters to

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take into account factors such as the distribution of particle sizes within the cloud and the physical and chemical form of radionuclides within such particles.

Models for application to grazing animals that form a potential pathway for transfer are not as well developed as are those for humans. According to conditions during the passage of the cloud, it is quite possible that inhalation could contribute to concentrations of radionuclides in animal products. This was demonstrated clearly after the Chernobyl accident where ^{131}I exposure of housed animals via inhalation resulted in contamination of milk, although at much lower concentrations than were observed for animals exposed to similar air concentrations but in free-grazing conditions (Coughtrey *et al.*, 1990).

Analysis of inhalation pathways following a nuclear explosion requires consideration of the extent of ground contamination and the degree to which deposits are resuspended to the atmosphere at various times after the depositional event. Resuspension varies as a function of the nature of the ground surface (e.g. urban or rural conditions), meteorological conditions (e.g. wind speed, rainfall) and physical disturbance, such as that created by agricultural activities (ploughing, rainfall) and urban activities (e.g. street sweeping, spraying with water to reduce dust, etc.). It is particularly sensitive to local climate and environmental conditions.

The importance of the inhalation pathway for an individual member of a potentially exposed population will depend on the following factors.

1. The time of year at which the event occurred (affecting both ground conditions and the person's habits).
2. Location and activity during the passage of the cloud, i.e. whether indoors or outdoors, whether at work or at rest, and the nature and pattern of work.
3. Nature of place of residence following the passage of the cloud, i.e. whether rural or urban.
4. Occupation following the passage of the cloud, i.e. whether working indoors or outdoors and, if the latter, whether involved in activities which result in, or are related to, higher-than-average resuspension.

For grazing animals a further set of factors apply, i.e. their location at the time of passage of the cloud, and their subsequent husbandry and feeding behaviour following passage of the cloud.

Such factors have to be taken into account when estimating exposure to radionuclides that have been released from nuclear explosions. Their nature and relative importance will have differed between test sites, and according to the year in which the most significant event(s) occurred (due to societal changes) and the season of the year in which those tests occurred. Their contribution to uncertainties in estimated doses cannot be ignored.

5.1.3 Ingestion

Ingestion of radionuclides by humans following nuclear explosions can occur from consumption of contaminated vegetable and animal products, water and, in some cases, soil. The latter can be quite important for children. The main pathways that require consideration whilst estimating doses are summarized in Figure 4.1.

Plant products may be contaminated directly as a consequence of deposition of particles, in which case radionuclide intake by humans will depend to a large extent on the manner in which plant-based foodstuffs are prepared prior to consumption. Plant products may also become contaminated indirectly as a consequence of the translocation of radionuclides from foliage or from the soil to the harvested product. In this case the intake by humans is less sensitive to the method of food preparation. For short-lived radionuclides such as ^{131}I, direct contamination tends to dominate over indirect contamination. The opposite applies to longer-lived radionuclides such as ^{90}Sr and ^{137}Cs.

Radionuclides can be transferred to products derived from grazing animals as a consequence of ingestion of contaminated plants, water and soil. Meat and milk are by far the most important pathways in this respect. Radionuclides such as ^{131}I and ^{137}Cs are transferred relatively effectively to both meat and milk, with transfer to milk of goats and sheep more effective than that for cattle. Contamination of meat with ^{131}I is of little significance apart from the thyroid, which is generally not consumed by humans. In contrast, ^{137}Cs is relatively uniformly distributed throughout the body of most grazing animals and is retained with a biological half-life ranging from several days to a few tens of days (Coughtrey *et al.*, 1983–86). Contamination of meat with radiocaesium can therefore provide a pathway for protracted exposure of humans according to the extent to which it remains available to the animal via consumption of plants or soil. Radiostrontium tends to be accumulated in the skeletal parts of most animals and therefore is not of relevance for meat products.

The transfer of radionuclides to animal products is sensitive to both diet and animal husbandry. In general, free-ranging animals show higher transfers of radionuclides than do those which are kept in more intensive systems. This is the effect of a combination of factors, such as the areas available for grazing, selectivity during grazing, and the quantity of soil in the diet.

There are wide ranges in reported feed-to-meat and feed-to-milk transfer factors for radionuclides such as ^{90}Sr, ^{131}I and ^{137}Cs. If specific data are not available for specific assessments it is important to select parameter values which relate as much as possible to the particular conditions of the assessment. The use of generic or average values could, in many cases, result in an underestimate of the actual transfer.

The behaviour of radionuclides in aquatic ecosystems can be very complex according to the mechanism of entry, i.e. direct deposition or transfer from the surrounding watershed, initial physical and chemical form of the radionuclide, and the physical, chemical, hydrological and biological characteristics of the ecosystem. Nevertheless, the potential contamination of aquatic organisms, especially fish, with radiocaesium should not be ignored, especially as concentrations can be maintained for prolonged periods where potassium concentrations of the ecosystem are low or where the potential for fixation in mineral sediments is limited.

The transfer of ^{90}Sr, ^{131}I and ^{137}Cs to humans via the foodchain is also dependent on chemical factors such as the background stable iodine content of soils, plants and animals, and nutrient status (potassium in the case of radiocaesium and calcium in the case of radiostrontium). Where concentrations of stable iodine are low, intakes of ^{131}I may be transferred more effectively to milk and blocked less readily by the thyroid. The behaviour of ^{90}Sr in the environment is related to that of calcium. There is good evidence to indicate that its transfer through soil–plant–animal foodchains is related to that of calcium. The link between potassium and radiocaesium is not as clear as is that between calcium and radiostrontium. The long-term availability of ^{137}Cs for uptake by plants is related to the quantity of available potassium in soil as well as to the quantity of specific minerals which can result in adsorption or fixation of the radionuclide. The discrimination between Cs and K is much greater than is that between Sr and Ca.

5.1.4 Ingestion pathways for populations close to test sites

At the time of the most important explosions at different test sites, there were specific environmental and population conditions which were very different from those that are experienced in equivalent populations at the present time. Such conditions could, potentially, have important consequences when reconstructing past exposures. The following sections summarize those factors that are known to have been relevant for specific populations and test sites.

5.1.4.1 Nevada

The main radioecological impact of explosions at the Nevada Test Site (NTS) has been demonstrated to be contamination of milk with ^{131}I. Analysis of radioiodine concentrations in milk has indicated more than an order of magnitude variation in transfer to individual cattle within a herd (Appleby, 1998). As a consequence it was necessary to consider bulk milk and milk from farmyard cattle separately. Additionally, because there are differences between the transfer of radioiodine to goats milk compared with cows milk it was necessary to consider separately the consequences of testing for consumers of goats milk.

During reconstructions of the consequences of testing at NTS, assumptions concerning agricultural practice have proved to be very important, as have assumptions about the distribution of contaminated products, such as milk, to populations outside the area immediately affected by the explosions (Church *et al.*, 1998).

Dose reconstructions at NTS identified the need for application of site-specific data for interception fractions of fallout. Information derived from studies in 1953 indicated interception fractions that were ten times lower than values which would otherwise have been derived from the literature (Appleby, 1998). For wet deposition, experimental studies were required to derive appropriate parameters (Bouville *et al.*, 1998) and it was recognized that local enhanced levels of fallout could be related to thundershower activity (Church *et al.*, 1998).

Mathematical models such as PATHWAY have been applied during reconstructions of doses from testing at NTS. This has required a major investment in analysing data and in selecting parameters which are appropriate to agricultural and other conditions which existed at the time of the tests (Appleby, 1998; Bouville *et al.*, 1998; Church *et al.*, 1998; Coughtrey *et al.*, 1998).

Assessments of the potential impacts of contamination of groundwaters as a consequence of testing at NTS have involved extremely conservative assumptions, for example abstraction of drinking water from wells driven into the contaminated aquifer (Anspaugh, 1995).

5.1.4.2 Semipalatinsk

As at NTS, assumptions concerning interception have proved to be important in dose reconstructions for tests at Semipalatinsk. Data from the 1962 explosion indicate that only particles $< 75\ \mu m$ would have contaminated grass and that the availability of young, growing, grass was a major factor in uptake of radionuclides by cattle. Assumptions about changes in solubility with distance also proved to be very important (Gordeev *et al.*, 1998).

Gordeev *et al.* (1998) also reported the results of investigations on a herd of 100 dairy cows located 105 km from the site of test explosions. These investigations were used to derive time-dependent parameters for the uptake of a range of radionuclides to cows milk. They also demonstrated the marked effects of time of year on rate of decline of radionuclide concentration in cows milk, as well as the effects of rainfall following periods of drought.

For bread products, Gordeev *et al.* (1998) reported that the ratio of specific activity in fresh grain to that in grass was 0.22 and provided relationships for estimating specific activity of radionuclides in bread products. In this respect it was noted that there were differences between bread that was produced from 'highest grade' and 'second rate' flour.

Vlasov (cited by Coughtrey, 1998) reported that variability in external dose was only a factor of 0.2 whereas for ingestion doses it was a factor of 1.7. Ingestion doses from agricultural products were between 0.2 and 1.2 times external doses (Shoiket, cited by Coughtrey, 1998). It is not clear why this ratio was higher for Semipalatinsk tests than for NTS tests (Anspaugh, 1995). One factor could be the large differences that existed between diet and lifestyle of the two populations.

Fallout from Semipalatinsk was distributed over large distances and in different directions. Significant differences in deposition and environmental behaviour were observed at different distances from the source, reflecting partially the nature of the affected ecosystem. Some information exists on site-specific transfer factors for Semipalatinsk fallout but such information appears to be far from complete (Coughtrey, 1998).

Studies following excavation of Lake Chagan have demonstrated higher concentrations of radionuclides in horse meat relative to that from cattle. This is thought to reflect differences in grazing habits; horses grazed feather grass and wormwood near to Lake Chagan whereas cattle grazed cultivated pastures (Akhmetov *et al.*, 1994). Additionally, fish and water birds may have provided a possible route for ingestion of radionuclides by the local population. Such pathways have been reported not to provide any danger to human health (Akhmetov *et al.*, 1994).

In a recent study (IAEA, 1997), data on local dietary habits were obtained by talking to local inhabitants. The information obtained indicated that most of the foodstuffs used in settlements close to the test site were locally produced. The principal exceptions were flour, rice and sugar. The diet appeared to be dominated by animal products and bread or other flour-based foodstuffs. Fruit and vegetable production was stated to be variable but generally low and some individuals claimed to eat no fruit or vegetables. Table 5.1 provides a summary of dietary information provided to the IAEA mission. It is not clear to what extent the lifestyles and habits observed in 1994 reflected those that would have pertained during the period of testing at Semipalatinsk. However, the observations that milk and milk products formed a significant contribution to diet, that drinking water was mostly provided from wells, and that fruit and vegetables appeared to be grown in small plots adjacent to houses and farms, are not untypical of what might be expected for the rural populations present in the 1950s and 1960s. If anything, it can be assumed that locally grown or produced foodstuffs would have formed an even greater proportion of diet at that time.

5.1.4.3 Novaya Zemlya

The main radioecological impact of explosions at Novaya Zemlya has been via the lichen–reindeer–human foodchain (Ramzaev *et al.*, 1993). Radionuclide

Table 5.1 Summary of dietary information provided by inhabitants of settlements near the Semipalatinsk site in 1994 (IAEA, 1997).

Location	Source of foodstuff	Foodstuff	Details
Dolon	Home produced	Meat	Beef, mutton, poultry
		Vegetables	Carrots, tomatoes, cabbage, potatoes, cucumbers
		Fruit	Plums, melons
		Milk	Mostly turned into milk products
		Eggs	
	Brought in from elsewhere	Bread	
		Flour	
		Sugar	
		Rice	
		Animal feed	Hay, wheat, barley and millet
Beriozka Farm	Home produced	Meat	
		Milk	No vegetables, no fruit
		Eggs	
	Brought in from elsewhere	Flour	Bread is made at the farm
Akzhar	Home produced	Meat	Beef, mutton, poultry
		Vegetables	Carrots, tomatoes, cabbage, potatoes, cucumbers
		Fruit	Blackcurrants, strawberries
		Milk	Mostly turned into milk products
		Mushrooms	From the woods
	Brought in from elsewhere	Bread	
		Flour	

transfer through this foodchain was approximately 10–100 times more effective than for the grass–cow–human foodchain, and the absorbed doses for radiocaesium and radiostrontium in reindeer were quite close to limits that had been established for persons who worked with radiation. The highest contamination of reindeer occurred in the Kola peninsular (Murmansk Province), some 500–600 km from Novaya Zemlya. Here the transfers appeared to be more efficient than for other areas such as Yakutia.

The critical group for Novaya Zemlya has been established as the aboriginal dwellers of the extreme North who were employed in reindeer breeding operations, herdsmen, reindeer breeders and their family members (Ramzaev *et al.*, 1993). This reflects their consumption of contaminated meat, use of melted snow for drinking and cooking, consumption of freshwater fish, and consumption of partridge meat. The size of the group was estimated at 30 000 persons. A further 300 000 persons (mostly small-city dwellers) also consumed reindeer meat but at much lower rates. Alaskan natives were less at risk due to different practices in herding and the time of slaughtering reindeer.

5.1.4.4 Pacific

The key factor in Pacific tests is whether they occurred over water or land and whether or not the population had been evacuated (Doury, 1996). For the Marshall Islands the main problem was radiocaesium and the terrestrial foodchain (Kirchmann *et al.*, 1993). Assumptions concerning lifestyle proved to be critical in estimating doses due to very specific practices, such as the collection of sap from trees, the drying of fish on roofs, cooking outdoors, and the methods used for collection and storage of water for drinking and washing (Simon, cited by Coughtrey, 1998). Dose estimates proved to be very sensitive to assumptions about the environmental half-life of radiocaesium in contaminated ecosystems.

The behaviour of radiocaesium in tropical ecosystems is very different from that in temperate environments (Kirchmann *et al.*, 1993). This needs to be taken into account when estimating doses and when considering issues such as the migration of radiocaesium to groundwaters.

An IAEA Advisory Group (IAEA, 1998) reviewed the two independent assessments that had been performed to evaluate the potential doses to a population that might live on Bikini Island in the future, and provided the data given in Table 5.2. This serves to demonstrate the great range in food items currently consumed in the region. There is no reason to believe that a similar variety in diet would not have existed at the time of testing of nuclear devices. Table 5.2 emphasizes the importance of breadfruit and coconut in the diet. Coconut appears to have a particularly high uptake of radiocaesium. Little is known of the uptake of radionuclides by many of the listed dietary components.

In 1994, Service Mixte de Surveillance Radiologique et Biologique de l'Homme et de l'Environment (SMSRB) investigated the levels of radioactivity in dietary components of inhabitants of French Polynesia. The study involved 171 samples and a breakdown of the various food types involved is given in Table 5.3 (SMSRB 1994). It emphasizes the diversity in diet of inhabitants of islands.

5.1.4.5 Lob Nor

Very little information has been obtained on the environmental and population characteristics of persons likely to have been affected by explosions at Lob Nor. It can be assumed that, at the time of the explosions, there would have been considerable variability in the environments that were affected and in the living and dietary habits of the affected population.

Liu Ying and Zhu Changshou (1996) commented that potentially critical groups living in the north of China and in Inner Mongolia had not been investigated. Zhu Changshou *et al.* (1996) provided estimates of doses for

Table 5.2 Diet models for adults potentially living on Bikini island (IAEA, 1998).

Food stuff	Local component of an 'imported' foods diet (g day $^{-1}$)	Local foods only diet (g day^{-1})
Reef fish	24.2	86.8
Tuna	13.9	72.0
Mahi mahi	3.56	21.4
Marine crabs	1.68	19.5
Lobster	3.88	35.2
Clams	4.56	58.1
Trochus	0.10	0.24
Tridacna muscle	1.67	11.4
Jedrul	3.08	19.4
Coconut crabs	3.13	24.9
Octopus	4.51	49.0
Turtle	4.34	17.8
Chicken muscle	8.36	31.2
Chicken liver	4.50	17.7
Chicken gizzard	1.66	3.32
Pork muscle	5.67	13.9
Pork liver	2.60	6.70
Pork heart	0.31	0.62
Bird muscle	2.71	26.4
Bird eggs	1.54	22.8
Chicken eggs	7.25	41.2
Turtle eggs	9.36	235
Pandanus fruit	8.66	63.0
Pandanus nuts	0.50	2.00
Breadfruit	27.2	186
Coconut juice	99.1	333
Coconut milk	51.9	122
Drinking coconut meat	31.7	181
Copra meat	12.2	71.3
Sprouting coconut	7.79	122
Marshalese cake	11.7	0
Papaya	6.59	27.0
Pumpkin	1.24	5.44
Banana	0.02	0.58
Arrowroot	3.93	94.9
Citrus	0.10	0.20
Rainwater	313	629
Well water	207	430
Malolo	199	0
Coffee/tea	228	0

Table 5.3 Produce harvested or fished locally or brought in from other islands in French Polynesia (SMSRB, 1994).

Main dietary component	Break down of component
Beverages	Local beer
	Pineapple juice
	Drinking water
	Local milk
Meat	Local goat meat
	Local dog meat
	Local beef
	Local eggs
	Local pork
	Local chicken
Fish	Big eye scad
	Skipjack meat
	Freshwater prawn
	Coral fish
	Yellowfin tuna meat
Sea foods	Clam
	Spiny lobster
	Octopus
	Brisley turban
Leafy vegetable	Cabbage
	Leek
	Lettuce
	Taro leaves
Fruit-type vegetable	Egg plant
	Cucumber
	French beans
	Tomato
	Breadfruit tree fruit
Root vegetables	Carrot
	Manioc
	Turnip
	Sweet potato
	Potato
	Taro roots
	White taro roots
Fruit	Pineapple
	Avocado
	Banana
	Lemon
	Coconut meat
	Mango
	Muskmelon
	Orange and tangerine
	Grape fruit
	Papaya
	Water melon

urban and rural communities and noted higher doses for rural populations compared with urban populations. This effect was attributed to the overall higher dietary intake of rural populations. Regional differences were attributed to differences in the content of cereals in the diet. Hou Jiele *et al.* (1996) noted the occurrence of hot particles at Wulumqi in Xinjiang Province following tests in 1962 and identified a critical group of herdsmen who may have consumed snow meltwater. Liu Ying and Zhu Changshou (1996) noted that milk was not a major dietary component for adults but that the dose to infants was higher than for adults due to intake of ^{131}I with contaminated milk. Zhu Changshou and Liu Ying (1996) noted that the main components of Chinese food are cereals and vegetables but that both milk and fish were significant due to radioecological transfer.

A further and potentially important factor may be dietary intakes of stable iodine. Some of the Chinese Provinces potentially affected by explosions at Lob Nor showed low dietary iodine intakes, in some cases to such an extent that measures were taken for human health purposes (Hou Jiele *et al.*, 1996).

5.1.4.6 Maralinga

Palmer and Brady (1988) provided a very detailed study on the diet and lifestyle of aborigines in the Maralinga area. Cooked meats consumed by aborigines include kangaroo, rabbits, turkey, edible grubs, lizards and goanna. The total bush meat consumed per person per year was approximately 221 kg (605 g day^{-1}). Kangaroo represented the most commonly consumed meat, followed by rabbits and then turkey. Grubs, lizards and goanna were consumed at a much lower rate. All cooked meats were considered to provide a potential for contamination because of preparation on leaves or a piece of cardboard on the ground, the use of earth ovens and the fact that rare meat is moist. Kangaroo was also stored for up to three days in trees during winter prior to consumption.

It was notable that the specific population studied by Palmer and Brady (1988) had not only a very high intake of meat but also of bread and flour. Additionally, relative to the Australian diet in general, the daily intake of eggs was high.

It is clear that the application of average statistics would not account for the likely impacts of past nuclear weapons testing on local aborigine populations that would have been particularly susceptible, both as a consequence of their particular diet and their habits.

5.1.5 CONCLUSIONS

The sites chosen for testing of nuclear devices in the 1950s and 1960s have a number of common factors relevant to pathways for radionuclide transfer.

First they were all in remote locations, i.e. surrounded by large land masses (NTS, Semipalatinsk, Lob Nor, Maralinga), or the sea (Marshall Islands, French Polynesia, Novaya Zemlya). Secondly, because of the location and often hostile environmental conditions, the local populations present at the time of the tests often lived very close to the land, obtaining much of their agricultural produce locally. Water would have been obtained from rainwater (e.g. Marshall Islands), local wells (Semipalatinsk) or melted snow (Novaya Zemlya). In several cases the basic foodstuffs would have represented locally produced meat often raised in semi-natural conditions (e.g. kangaroo at Maralinga, reindeer in areas affected by testing at Novaya Zemlya, and possibly horses at Semipalatinsk), or milk (either the household cow as at NTS or in areas of the Altai affected by testing at Semipalatinsk, or even goats and sheep). Basic diets would have been supplemented by smaller contributions of unusual foodstuffs such as mushrooms (in temperate climates), grubs and lizards (in Australia), and seafood (in island populations).

The environmental conditions associated with the test sites are not, in general, those for which the majority of radioecological information on radionuclide transfer applies. This factor, in conjunction with the specific dietary intakes of the affected populations needs to be taken into account in dose reconstruction studies. Whereas extensive information is available for populations affected by tests at NTS, and some information is available on potential dietary intakes for populations affected by testing in the Pacific, Maralinga and local populations at Semipalatinsk, much less information is available for more distant populations affected by testing at Novaya Zemlya, Semipalatinsk and Lob Nor. Careful consideration of basic radioecological information is required when performing dose reconstructions. The accuracy of such studies would be improved considerably by utilization of site-specific information.

5.2 EXTERNAL EXPOSURE PATHWAYS

5.2.1 Natural radiation sources

5.2.1.1 Cosmic Radiation

Cosmic rays, which originate in space, and solar particles enter the Earth's atmosphere and begin a cascade of secondary interactions and decays. The resultant ionization is a function of both altitude and latitude. The ionizing component of cosmic rays produces, on average, an absorbed dose rate in air of 32 nGy h^{-1} at sea level in the mid-latitudes, corresponding to an effective dose rate of 32 nSv h^{-1}. The neutron component of cosmic rays results in an effective dose rate of 3.6 nSv h^{-1}. The intensities of both components increase with altitude, more so for the neutron component.

Taking into account shielding by buildings for the ionizing component and the distribution of world population with altitude, the population-weighted average annual effective dose from cosmic rays is 380 μSv. The effective dose rate received during a commercial flight is about 3 $\mu Sv\ h^{-1}$; the per caput annual effective dose for the world population due to air travel is 2 μSv.

5.2.1.2 Terrestrial Radiation

Exposure to gamma rays from natural radionuclides occurs outdoors and indoors. Surveys by direct measurements of dose rates have been conducted during the last few decades in many countries. National averages range from 24 to 160 $nGy\ h^{-1}$

The dose rate in air *outdoors* from terrestrial gamma rays in normal circumstances is around 57 $nGy\ h^{-1}$. National averages range from 24 to 160 $nGy\ h^{-1}$. Soil and survey data yield similar values. Communities living on mineral sands may well be exposed at two orders of magnitude more.

The gamma-ray dose rate *indoors* is estimated to be 80 $nGy\ h^{-1}$, the population-weighted mean of measured values world-wide, and the range of reported national averages is 20–190 $nGy\ h^{-1}$. These results are in accordance with values inferred from outdoor measurements and the concentrations of radionuclides in building materials. Applying a coefficient of 0.7 $Sv\ Gy^{-1}$ to convert absorbed dose rate in air to effective dose and using an indoor occupancy factor of 0.8, the world-wide average annual effective dose from external exposure to terrestrial radionuclides is 0.46 mSv.

In comparing the *indoor* and *outdoor* averages, it is seen that the overall effect of surrounding building materials is to increase the dose rate 40–50%.

The ratio of indoor to outdoor dose rates varies from 0.8 to 2.0. In only two countries, Iceland and the USA, are average absorbed dose rates indoors judged to be less than outdoors. This ratio is sensitive to the structural properties of dwellings (materials, thicknesses and dispositions) and is of limited utility for estimating exposures in particular cases from outdoor data. However, the relatively narrow range of the indoor–outdoor ratio reflects the fact that building materials are usually of local origin and that their radionuclide concentrations are similar to those in local soil. The building materials act as sources of radiation and also as shields against outdoor radiation. In wooden and lightweight houses, the source effect is negligible and the walls are an inefficient shield with respect to the outdoor sources of radiation, so that the absorbed dose rate in air could be expected to be somewhat lower indoors than outdoors. In contrast, in massive houses made of brick, concrete or stone, the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials.

5.2.2 Artificial environmental radiation

5.2.2.1 Deposition

Mechanisms of deposition were discussed in some detail in the UNSCEAR Committee's 1964 report. After entering the troposphere from above, fission products are transported down to the level of the rain-bearing clouds, mainly by turbulent mixing. This downward movement is enhanced over anticyclonic systems and restricted over cyclonic systems. Below this level, the radioactive particles are rapidly washed out by precipitation and deposited upon the surface. In addition, dry removal of fission products takes place through several mechanisms. Dry removal by sedimentation requires particles to be larger than about 5 μm and is important only in local fall-out. Dry deposition of world-wide fallout makes an important contribution to the total fallout only in areas of low rainfall.

Fission products can enter rainwater by processes within the cloud, the so-called rain-out, or can be picked up by raindrops below the cloud, the so-called wash-out. For aerosols of small particle size the wash-out is relatively quite slow so that rain-out is probably the most important wet-deposition process. The small contribution of wash-out processes to total deposition probably accounts for the fact that the activity of fission products in ground-level air does not seem to be greatly influenced by precipitation rates.

5.2.2.2 External irradiation

Several of the artificial radionuclides that are present in fallout emit gamma rays and thereby give rise to an external radiation dose. In addition to various short-lived radionuclides, the most important of which are ^{95}Zr and ^{95}Nb, the main contributor to external gamma radiation is ^{137}Cs, which has a physical half-life of 30 years.

In principle it should be possible to calculate the external doses from the short-lived radionuclides using the deposition data for each radionuclide and appropriate dose-rate conversion factors. For ^{137}Cs the distribution has been assumed to be exponential with a mean depth in the soil of 3 cm. For the short-lived fission products a linear distribution was assumed.

For the short-lived fission products, there is little leaching into the soil before they decay, but for ^{137}Cs, Gale *et al.* (1964) found there was a rapid movement into the soil during the first few years and henceforth the distribution remained fairly static. The amount of penetration depended upon the soil type, but in all cases most of the ^{137}Cs remained in the top 10 cm of soil.

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