資料４－３

Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience （2006,IAEA）（抜粋）

and soil treatment and cultivation. Their implementation on more than three billion hectares of agricultural land has made it possible to minimize the amount of products with radionuclide activity concentrations above the action levels in all three countries.

1.3.1.4. Forest countermeasures

The principal forest related countermeasures applied after the Chernobyl accident were management based countermeasures (restrictions of various activities normally carried out in forests) and technology based countermeasures.

Restrictions widely applied in the three most affected countries, and partially in Scandinavia, included the following actions that have reduced human exposure due to residence in radioactively contaminated forests and the use of forest products:

(a) Restrictions on public and forest worker access, as a countermeasure against external exposure.
(a) Restrictions on the harvesting of food products such as game, berries and mushrooms. In the three most affected countries mushrooms are widely consumed, and therefore this restriction has been particularly important.
(b) Restrictions on the collection of firewood by the public, in order to prevent external exposures in the home and garden when the wood is burned and the ash is disposed of or used as a fertilizer.
(c) Alteration of hunting practices, aimed at avoiding the consumption of meat with high seasonal levels of radiocaesium.
(d) Fire prevention, especially in areas with large scale radionuclide deposition, aimed at the avoidance of secondary contamination of the environment.

However, experience in the three most affected countries has shown that such restrictions can also result in significant negative social consequences, and advice from the authorities to the general public may be ignored as a result. This situation can be offset by the provision of suitable educational programmes targeted at the local scale to emphasize the relevance of suggested changes in the use of some forest areas.

It is unlikely that any technology based forest countermeasures (i.e. the use of machinery and/or chemical treatments to alter the distribution or transfer of radiocaesium in the forest) will be practicable on a large scale.

1.3.1.5. Aquatic countermeasures

Numerous countermeasures were put in place in the months and years after the accident to protect water systems from the transfer of radionuclides from contaminated soils. In general, these measures were ineffective and expensive and led to relatively high exposures of the workers implementing the countermeasures.

The most effective countermeasure was the early restriction of drinking water abstraction and the change to alternative supplies. Restrictions on the consumption of freshwater fish have proved effective in Scandinavia and Germany; however, in Belarus, the Russian Federation and Ukraine such restrictions may not always have been adhered to.

It is unlikely that any future countermeasures to protect surface waters would be justifiable in terms of economic cost per unit of dose reduction. It is expected that restrictions on the consumption of fish will remain in a few cases (in closed lakes) for several more decades.

Future efforts in this area should be focused on public information, because there are still public misconceptions concerning the perceived health risks due to radioactively contaminated waters and fish.

1.3.2. Recommendations

1.3.2.1. Countries affected by the Chernobyl accident

Long term remediation measures and countermeasures should be applied in the areas contaminated with radionuclides if they are radiologically justified and optimized.

Members of the general public should be informed, along with the authorities, about the existing radiation risk factors and the technological possibilities to reduce them in the long term via remediation and countermeasures, and be involved in discussions and decision making.

In the long term, remediation measures and countermeasures remain efficient and justified — mainly in the agricultural areas with poor (sandy and peaty) soils, where high radionuclide transfer from soil to plants can occur.

respectively, 15 years after the accident. Levels of milk contamination higher than 500 Bq/L occur in six Ukrainian, five Belarusian and five Russian settlements (in 2001).

The concentrations and transfer coefficients shown in the above mentioned figures and tables show that there has been only a slow decrease in radiocaesium activity concentrations in most plant and animal foodstuffs during the past decade. This indicates that radionuclides must be close to equilibrium within the agricultural ecosystems, although continued reductions with time are expected, due to continuing radionuclide migration down the soil profile and to radioactive decay (even if there was an equilibrium established between ^{137}Cs in the labile and non-labile pools of soil). Given the slow current rates of decline, and the difficulties in quantifying long term effective half-lives from currently available data because of high uncertainties, it is not possible to conclude that there will be any further substantial decrease over the next decades, except due to the radioactive decay of both ^{137}Cs and ^{90}Sr, which have half-lives of about 30 years.

Radionuclide activity concentrations in foodstuffs can increase through fuel particle dissolution, changes in the water table as a consequence of change of management of currently abandoned land or cessation of the application of countermeasures.

3.4. FOREST ENVIRONMENT

3.4.1. Radionuclides in European forests

Forest ecosystems were one of the major seminatural ecosystems contaminated as a result of fallout from the Chernobyl plume. The primary concern from a radiological perspective is the long term contamination of the forest environment and its products with ^{137}Cs, owing to its 30 year half-life. In the years immediately following contamination, the shorter lived ^{134}Cs isotope was also significant. In forests, other radionuclides such as ^{90}Sr and the plutonium isotopes are of limited significance for humans, except in relatively small areas in and around the CEZ. As a result, most of the available environmental data concern ^{137}Cs behaviour and the associated radiation doses.

Forests provide economic, nutritional and recreational resources in many countries.

TABLE 3.6. MEAN AND RANGE OF CURRENT CAESIUM-137 ACTIVITY CONCENTRATIONS IN AGRICULTURAL PRODUCTS ACROSS CONTAMINATED AREAS OF BELARUS [3.49], THE RUSSIAN FEDERATION [3.55] AND UKRAINE [3.63]
(data are in Bq/kg fresh weight for grain, potato and meat and in Bq/L for milk)

Caesium-137 soil deposition range	Grain	Potato	Milk	Meat
Belarus				
>185 kBq/m^2 (contaminated districts of the Gomel region)	30 (8–80)	10 (6–20)	80 (40–220)	220 (80–550)
37–185 kBq/m^2 (contaminated districts of the Mogilev region)	10 (4–30)	6 (3–12)	30 (10–110)	100 (40–300)
Russian Federation				
>185 kBq/m^2 (contaminated districts of the Bryansk region)	26 (11–45)	13 (9–19)	110 (70–150)	240 (110–300)
37–185 kBq/m^2 (contaminated districts of the Kaluga, Tula and Orel regions)	12 (8–19)	9 (5–14)	20 (4–40)	42 (12–78)
Ukraine				
>185 kBq/m^2 (contaminated districts of the Zhytomyr and Rovno regions)	32 (12–75)	14 (10–28)	160 (45–350)	400 (100–700)
37–185 kBq/m^2 (contaminated districts of the Zhytomyr and Rovno regions)	14 (9–24)	8 (4–18)	90 (15–240)	200 (40–500)

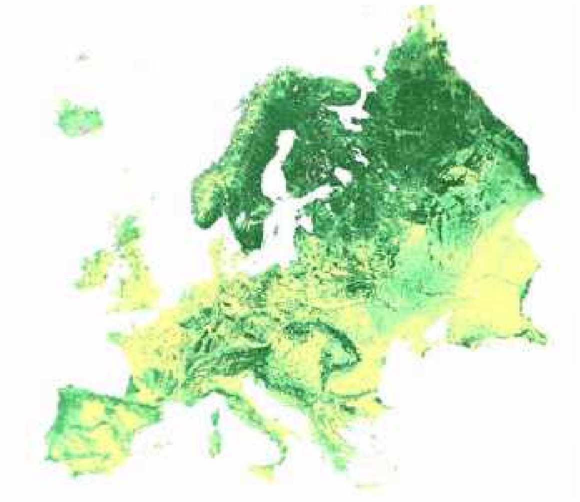

FIG. 3.34. Forest map of Europe. The darkest colour, green, indicates a proportion of 88% forest in the area, while yellow indicates less than 10% [3.69].

Figure 3.34 shows the wide distribution of forests across the European continent. Following the Chernobyl accident, substantial radioactive contamination of forests occurred in Belarus, the Russian Federation and Ukraine, and in countries beyond the borders of the former USSR, notably Finland, Sweden and Austria (see Fig. 3.5). The degree of forest contamination with ^{137}Cs in these countries ranged from >10 MBq/m^2 in some locations to between 10 and 50 kBq/m^2, the latter range being typical of ^{137}Cs deposition in several countries of western Europe.

Since the Chernobyl accident it has become apparent that the natural decontamination of forests is proceeding extremely slowly. The net export of ^{137}Cs from forest ecosystems was less than 1%/a [3.66, 3.67], so it is likely that, without artificial intervention, it is the physical decay rate of ^{137}Cs that will largely influence the duration over which forests continue to be affected by the Chernobyl fallout. Despite the fact that the absolute natural losses of ^{137}Cs from forests are small, recycling of radiocaesium within forests is a dynamic process in which reciprocal transfers occur on a seasonal, or longer term, basis between biotic and abiotic components of the ecosystem. To facilitate appropriate long term management of forests, a reliable understanding of these exchange processes is required. Much information on such processes has been obtained from experiments and field measurements, and many of these data have been used to develop predictive mathematical models [3.68].

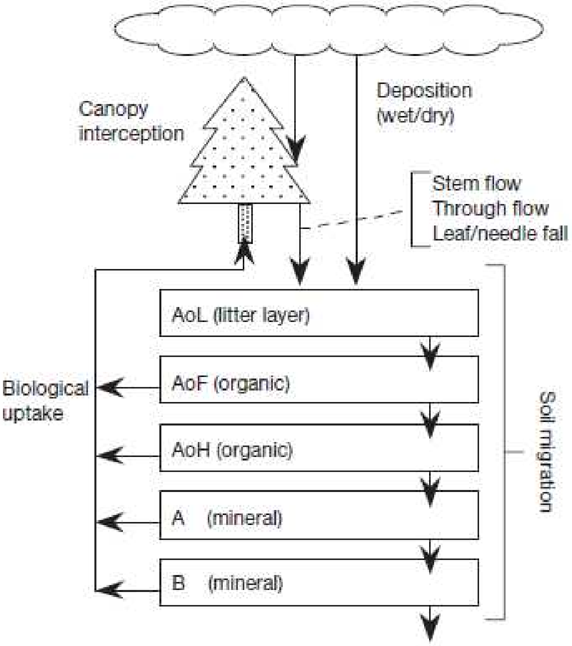

FIG. 3.35. Major storages and fluxes in radionuclides of contaminated forest ecosystems [3.70].

3.4.2. Dynamics of contamination during the early phase

Forests in the USSR located along the trajectory of the first radioactive plume were contaminated primarily as a result of dry deposition, while further away, in countries such as Austria and Sweden, wet deposition occurred and resulted in significant hot spots of contamination. Other areas in the USSR, such as the Mogilev region in Belarus and Bryansk and some other regions in the Russian Federation, were also contaminated by deposition with rain.

Tree canopies, particularly at forest edges, are efficient filters of atmospheric pollutants of all kinds. The primary mechanism of tree contamination after the Chernobyl accident was direct interception of radiocaesium by the tree canopy, which intercepted between 60% and 90% of the initial deposition [3.66]. Within a 7 km radius of the reactor this led to very high levels of contamination on the canopies of pine trees, which, as a consequence, received lethal doses of radiation from the complex mixture of short and long lived radionuclides released in the accident. Gamma dose rates in the days and weeks immediately following the accident were in excess of 5 mGy/h in the area close

Depending on the decontamination technologies used, the dose rate over different measured plots was reduced by a factor of 1.5–15. However, the high cost of these activities hindered their comprehensive application on contaminated areas. Due to these limitations, the actual effectiveness of the decrease in annual external dose was 10–20% for the average population and ranged from about 30% for children visiting kindergartens and schools to less than 10% for outdoor workers (herders, foresters, etc.). These data were confirmed by individual external dose measurements conducted before and after large scale decontamination campaigns in 1989 in the Bryansk region of the Russian Federation [4.18].

Regular monitoring of decontaminated plots in settlements over five years showed that after 1986 there was no significant recontamination and that the exposure rate was decreasing over the long term, as described in Section 5.1 of this report. The averted collective external dose to 90 000 inhabitants of the 93 most contaminated settlements of the Bryansk region was estimated to be about 1000 man Sv [4.18].

Since 1990 large scale decontamination in the countries of the former USSR has been stopped, but particular contaminated plots and buildings with measured high contamination levels have been specifically cleaned. Some decontamination activities still continue in Belarus, aimed mostly at public buildings and areas: hospitals, schools, recreation areas, etc. However, in some contaminated Belarusian villages, cleanup of dwellings and farms has also been performed [4.22].

Another area of continuing decontamination activity is the cleanup of industrial equipment and premises contaminated as a result of ventilation systems being operated during the release/deposition period in 1986 and immediately afterwards. Some 20 to 30 industrial buildings and ventilation systems have been decontaminated annually in Belarus [4.22].

4.2.3. Recommended decontamination technologies

In accordance with present radiation protection methodology, a decision on intervention (decontamination) and selection of optimal decontamination technologies should be made giving consideration to the costs of all actions and to social factors. The calculated cost should address the various decontamination technologies for which an assessment of the averted dose has been made. The benefit (averted collective effective dose) and detriment (expenses, collective dose to decontamination workers) are to be compared for each decontamination technology by means of a cost–benefit analysis [4.9] or multiattribute analysis [4.24], which may include qualitative social factors.

The priorities that different procedures would be given in a decontamination strategy should be environment specific. Nevertheless, based on accumulated experience and research, the following generic set of the major simple decontamination procedures can be recommended for the long term:

(a) Removal of the upper 5–10 cm layer (depending on the activity–depth distribution) of soil in courtyards in front of residential buildings, around public buildings, schools and kindergartens, and from roadsides inside a settlement. The removed, most contaminated, layer of soil should be placed into holes specially dug on the territory of a private homestead or on the territory of a settlement. The clean soil from the holes should be used to cover the decontaminated areas. Such a technology excludes the formation of special burial sites for radioactive waste.

(b) Private fruit gardens should be treated by deep ploughing or removal of the upper 5–10 cm layer of soil. By now, vegetable gardens have been ploughed many times, and the activity distribution in soil will be uniform in a layer 20–30 cm deep.

(c) Covering the decontaminated parts of courtyards, etc., with a layer of clean sand, or, where possible, with a layer of gravel to attenuate residual radiation (see item (a)).

(d) Cleaning or replacement of roofs.

These procedures can be applied both for decontaminating single private gardens and houses and for decontaminating settlements as a whole. It is evident that, in the latter case, the influence of the decontamination on further reduction in external radiation dose will be greater. Achievable decontamination factors for various urban surfaces are presented in Table 4.4. Detailed data on the efficiency, technology, necessary equipment, cost and time expenses, quantity of radioactive waste, and other parameters of decontamination procedures are contained in Ref. [4.25].

Radioactive waste generated from urban decontamination should be disposed of in