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Cleanup techniques for Finnish urban environments and external doses from ^{137}Cs — modelling and calculations

M. Moring and M.–L. Markkula

FINNISH CENTRE FOR RADIATION
AND NUCLEAR SAFETY
P.O.BOX 14 FIN–00881 HELSINKI
Finland
Tel. +358 9 759 881

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ABSTRACT

After radioactive deposition it is important to take as effective countermeasures as possible, with the resources given, to decrease the radiation doses received by people. We assessed external doses under various deposition conditions and compared efficiencies of some simple decontamination techniques (grass cutting, vacuum sweeping, hosing of paved surfaces and roofs and felling trees). The present model was constructed for Finnish conditions and housing areas, using ^{137}Cs transfer data from Nordic and Central European studies and models. This compartment model concerns behaviour and decontamination of ^{137}Cs in the urban environment under summer conditions. Doses to man have been calculated for wet (light rain) and dry deposition in four typical Finnish building areas: single-family wooden houses, brick terraced-houses, blocks of flats and urban office buildings.

The external doses from ^{137}Cs received over 50 years from the activity deposited on grassy areas vary 65-80% of the total external dose, except with in the office environment. Cutting and removal of grass is the most effective of the decontamination techniques studied here. As long as it is performed very shortly after fallout grass cutting can reduce the external lifetime dose to man by about 40% in the event of dry deposition and about 20% in wet deposition with light rain. The activity deposited on roofs also results in a significant contribution to the dose. People living in small wooden houses will receive a total 50-year external dose of 30-40 μSv kBq^{-1} m^{-2}. This is twice as much as those living in brick terraced-houses and three to four times more than those living in blocks of flats.

CONTENTS

1 INTRODUCTION

Following a radioactive fallout, the external radiation doses received by people in urban areas are in general lower than in rural areas. Initial retention of deposition on urban surface structures is in general lower than on natural surfaces and removal of contaminants is thus more effective. About 80% of the Finnish population lives in urban environments (Statistics Finland 1994), thus rendering an important fraction of the collective dose received.

Here we describe the distribution of wet and dry fallout and weathering processes in urban areas. A calculation model is applied to four types of urban building area according to Finnish housing statistics. We have considered simple decontamination techniques, that can be applied with normally existing resources and no significant waste problems. These include cutting and removal of grass, vacuum cleaning of streets, hosing down streets and roofs and felling trees. We did not consider sandblasting, removal of road surfaces, soil ploughing or removal of the surface layer of soil, although they are efficient decontamination techniques, because they are labour intensive or lead to waste problems. Resuspension, foggy weather and calculation of dose from indoor sources are not considered in this model.

The structure of the model and the transfer rates describing weathering are very similar to those in the EXPURT model (Crick and Brown 1990). The deposition and decontamination data were applied mostly following the works of Roed (1990) and Brown *et al.* (1996). The effects on the dose resulting from caesium migration into soil were calculated according to measurements performed in Finland (Rantavaara *et al.* 1996). Average doses to people are calculated as functions of time, taking into account the shielding effects of the various building types and the average time people spend outdoors and indoors.

Early application of countermeasures in a fallout situation is important, thus decision makers need prior knowledge of the expected doses and the effectiveness of various countermeasures. The calculations aid in estimating the external radiation doses to the population and the effectiveness of decontamination processes after a deposition event. Our goal has been to make use of published modelling studies and to apply these to Finnish housing conditions. We constructed a dynamic calculation model for estimation of external doses from ^{137}Cs to the Finnish urban population and comparison of simple decontamination techniques. For the estimation of area specific collective doses the residential areas modelled were chosen in a manner that makes linking of our results with data on habitats and regional deposition possible.

2 STRUCTURE AND PARAMETERS OF THE TRANSFER MODEL

The calculation model (Figure I) is based on linear compartment model theory. The calculations were performed for unit deposition onto grass occurring under summer conditions. We used grass as a reference surface to which deposition onto other surfaces is related. If fallout occurs in the winter, snow and ice will change the situation drastically.

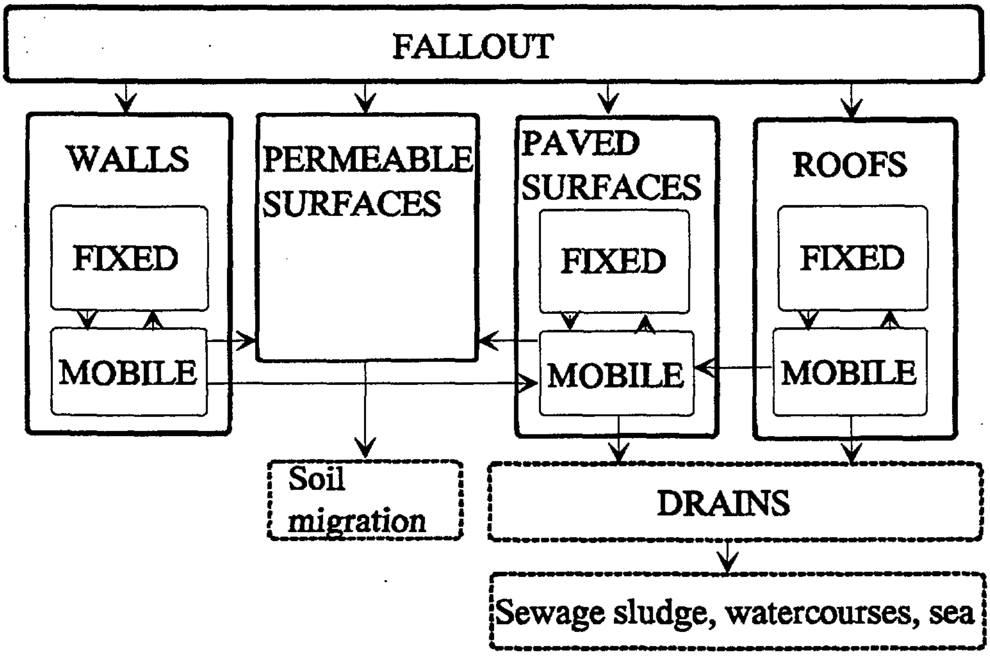

Figure 1. Model structure. Dash line marked compartments represent sinks.

The transfer rate for radioactive material following deposition on a given type of surface can be defined as (Andersson *et al.* 1995)

$$\frac{dX_m}{dt} = \sum S_{nm} X_n - (\sum S_{mn}) X_m - L_m X_m + F_m \qquad (1)$$

X_m, X_n = the radioactive matter in compartments m and n at time t
S_{nm}, S_{mn}= the transfer coefficient from compartment n to m and vice versa.
L_m = the transfer coefficient for flow of radioactivity out of the system (e.g., loss by radioactive decay).
F_m = the activity deposited on the surface at time t.

2.1 Urban environments

Calculations were performed for inhabitants of detached houses, terraced-houses, blocks of flats and urban office buildings. The dwellings were chosen to represent the main dwelling types in Finland. The following assumptions were made for the four urban environments: detached houses are wooden, one fifth of their street areas are paved and the rest covered with sand. Terraced-houses are constructed of bricks and they have paved street areas. Blocks of flats and urban office buildings are made of concrete, and their street areas are paved. All gardens are covered with grass (Table I).

Table I. Urban surfaces (m^2) related to various types of building area. Estimated by Sinkko and Ikäheimonen (1996)[a].

	Roof	*Walls*	*Garden grass*	*Streets*	
				paved	*sand*
Detached house	120	150	1050	100	400
Terraced-house	300	400	1050	700	–
Block of flats	450	1000	3400	2000	–
Urban office building	450	1000	20	2000	–

[a] Sinkko K, Ikäheimonen T. Finnish Centre for Radiation and Nuclear Safety. Personal communication, 1996.

2.2 Deposition

The surfaces in an urban environment include lawns, roofs, walls, streets, paved areas and trees. The distribution patterns of deposition are dependent on the weather conditions under which they occur. Various surface characteristics greatly impact the deposition; under dry conditions the amounts of activity depositing on rough permeable surfaces (e.g. lawns) can be about one order of magnitude higher than that depositing on smooth impermeable surfaces (e.g. asphalt, concrete). Deposition velocities for grass vary, depending on the biomass of the grass. The dry deposition velocity for short grass is about the same as that for roofs, but for long, dense grass the values can be more than six times greater (Roed 1987a).

Table II. *Ratio of deposition velocities on various surfaces related to that on grass (Roed 1990). The estimates for wet deposition assume a total of 5 mm of rain.*

Surface	*Dry deposition*	*Wet deposition*	
			Range
Grass	1	1	
Sand and hard, impermeable ground surfaces	0.16	0.4	0.4–0.8
Roofs	0.65	0.6	0.3–0.9
Walls	0.023	0.02	0.01–0.03
Trees	1.63	1[a]	

[a] Estimate by authors, based on the assumption that light rain is effectively intercepted by the tree canopy.

Dry deposition consists of radioactive fallout without precipitation. The deposition velocity definition used is the ratio of deposition rate per unit area to air concentration per unit volume (Brown *et al.* 1995). Wet deposition includes gases and particles that form deposits with precipitation. The deposition rate is usually modelled using the washout coefficient, which describes the scavenging of gases and particles from a radioactive cloud by rain. The washout coefficient is dependent mostly on the size distributions of the aerosols and water drops. Wet deposition by light rain is different from wet deposition by heavy rain due to the difference in amount of surface runoff water. We have chosen light rain (5 mm) because in that event very little surface runoff is present, and most of the deposited material is retained on the surfaces. Wet deposition on walls is dependent on the wind speed and direction. The parameter values for dry and wet deposition on urban surfaces are presented in this model relative to the deposition on grass (Table II, p. 9, Tschiersch *et al.* 1995, Brown *et al.* 1995, Roed 1990).

The amounts of wet-deposited ^{137}Cs on various surfaces were estimated for light rain (Table II, p. 9). The estimates were based on measurements by Roed, Sandalls and Karlberg in Denmark and Sweden (Roed 1987a, Roed and Sandalls 1989, Karlberg 1990 as cited by Roed 1990). If the amount of rain were higher, more radiocaesium would be transported away from hard surfaces with runoff, and the doses would be smaller. According to Roed the relatively high deposition velocity on roof materials is probably due to the corrugated nature of the roofs measured, combined with the higher wind speed at roof level. The amount of ^{137}Cs retained varies highly with roof material (Roed 1987b). The parameters we have used are best applicable to porous roof materials (e.g. red tile).

Under dry conditions the deposition on trees can increase the total deposition in urban areas, because trees capture the aerosol particles more efficiently than the other actual surfaces (Jacob and Meckbach 1987). Nearby trees could thus be a significant source of external radiation for people outdoors immediately after the deposition. Trees would also increase the dose indoors, if the tree canopies are at the height of windows, the shielding effect of which is less than that of the walls. The amount of material deposited on trees is dependent on the season. The deposition on deciduous trees during winter will be small compared with that in summer. Activity fixed on leaves is removed by leaf fall during the first autumn after the fallout. The activity also transfers from trees to the underlying surfaces due to the effects of wind and rain. Wet deposition on trees will not increase the total amount of deposited material per unit surface area (Brown *et al.* 1995). Deposition velocities for trees and bushes in a suburban area are of the same magnitude as for trees in a forest.

2.3 Weathering

Typical weathering processes include rain, wind, frost, mechanical influence (street cleaning, traffic), resuspension and downward migration into soil. The velocity at which radiocaesium is removed by weathering processes varies, depending on the surface type, mode of deposition and the weather conditions. Rain is the primary weathering process. Some of the radiocaesium will be removed from hard surfaces, such as roofs, walls, and paved areas, by water flowing over these surfaces. It is assumed that for paved areas the runoff will be 100% after an initially accumulated 3 mm of rain (Richie *et al.* 1976). We have used 650 mm as yearly rainfall, which is the mean for the period 1961–1975 in the vicinity of Helsinki (National Board of Waters, Finland 1980). From drains radiocaesium ends up in sewage sludge and watercourses and might still be harmful.

In weathering measurements performed in Germany by Jacob *et al.* in the first few days after the Chernobyl accident about 50–70% of the ^{137}Cs was removed by runoff with rain and by street cleaning. The differences between asphalt, concrete and granite paving were not significant, while cobblestone paving retained the radionuclides more effectively (Jacob *et al.* 1987). According to Wilkins the first precipitation after dry deposition controls the removal of activity and the decontamination efficiency of the rainfall is dependent more on the total amount of rainfall than on the rate of it (Wilkins 1987).

After dry deposition material on the surface becomes more strongly fixed with time. This is probably due to the impact of moisture (light rain, mist or dew), and after several days the material will be as fixed as if it were wet-deposited (Sandalls *et al.* 1986). Weathering of strongly fixed material is a slow process. Fixation and remobilization of ^{137}Cs was modelled similarly as in the EXPURT model (Table III), and the flow of rainwater between various compartments was estimated by the authors (Table IV, p.12).

Table III. Model parameters for translocation of ^{137}Cs (Crick and Brown 1990).

Description	*Value*
Fraction of mobile component that is fixed per hour (h^{-1})	0.0583
Mobile fraction of dry deposition on roofs, walls and hard surfaces	0.1
Fixed fraction of dry deposition on roofs, walls and hard surfaces	0.9
Fraction of the fixed component on roofs, removed per mm of rainfall (mm^{-1})	3×10^{-4}
Fraction of the fixed component on external walls, removed per mm of rainfall (mm^{-1})	10^{-6}
Fraction of the fixed component on hard surfaces, removed per mm of rainfall (mm^{-1})	10^{-3}
First rain after deposition (d)	2
Yearly rainfall (mm^{-1})	650[a]

[a] National Board of Waters, Finland 1980.

Table IV. Estimated fraction of water running from one surface to another.

From \ to	*Drains*	*Grass*	*Hard surfaces*
Roofs	0.75	–	0.25
Walls	–[a]	0.5	0.5
Hard surfaces	0.75	0.25	–
Grass	–	–	–
Sand	–	–	–

[a]Negligible

2.4 Migration into soil

Radiocaesium will migrate more deeply into permeable surfaces, mainly due to transport with water; however, most soil materials bind radiocaesium strongly and therefore migration is a slow process. In most undisturbed soil types found in Finnish environments, over 90% of ^{137}Cs will be found in the surface vegetation and top 5 cm of mineral soil, about ten years after the deposition (Rantavaara 1996)[a]. The migration of radiocaesium will lead to shielding of external radiation in the soil itself and surface roughness will also provide some shielding. The effect of penetration of ^{137}Cs in permeable surfaces is accounted for in the dose rate calculations explained in Chapter 4.

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[a] Rantavaara A, Finnish Centre for Radiation and Nuclear Safety, Personal communication, 1996.

3 DECONTAMINATION TECHNIQUES

The efficiency of a decontamination technique is dependent on the deposition conditions and on the type of contaminated surface, particle size and solubility of the contaminant. Due to fixation and weathering processes it is important that the techniques are applied soon after the fallout, for the decontamination to be effective. In the event of dry deposition decontamination is usually more effective than with wet deposition. In the present work the following decontamination techniques are considered: vacuum sweeping, hosing, flushing and grass cutting. These are relatively effective, easy to carry out and inexpensive techniques that can be used both on a large and small scale (e.g. by the home owner). We have also with a simple example considered felling trees. In the literature the range of effectiveness of the various decontamination techniques is notable (Table V, p. 14).

To obtain the decrease in dose rates calculated here all cleanup actions should be applied as early as possible after the fallout. In our calculations grass cutting, sweeping, hosing and tree felling were performed on the day following fallout. French *et al.* described the techniques more thoroughly (French *et al.* 1996). The fraction of radioactivity removed is dependent on the biomass of the grass at the time of deposition. The environmental half-life of radiocaesium deposited on grass is of the magnitude of 20 days (Miller and Hoffman 1983), which suggests that the effectiveness of grass cutting is greatly reduced within the first days after deposition. In our calculations grass cutting was assumed to be performed with a cutter that collected all the cut grass.

Sweeping and vacuum sweeping are regular street-cleaning techniques whose efficiency is greatly dependent on the original dust load, size of the particles and the time elapsed before the techniques are applied. The more dust at the time of deposition the greater the efficiency, since mere sweeping without vacuuming is very ineffective for small particles when the dust load on the surface is low. In the model sweeping of paved surfaces was assumed to be performed with a vacuum street sweeper.

Hosing can be efficient if it is done reasonably soon after deposition, especially after dry deposition, although hosing often merely relocates the contamination to an other place from where it might be even more difficult to remove. From roofs the contamination runs mainly into drains with the hosing water. In the model hosing of roofs and paved surfaces was assumed to be performed with a regular waterhose, although a more efficient hosing method would be with a high–pressure waterhose.

Felling trees produces much waste and leads to problems with resuspension. To obtain a reduction of 90% of the radiocaesium on a tree one should use a cover on the ground, when trees are felled.

The efficiencies of decontamination techniques in this model are conservative estimates from Table V (Table VI, p. 15).

Table V. *Range of decontamination efficiencies of some techniques according to the literature (Roed 1990, Brown 1996).*

Decontamination technique	*Surface*	*Activity removed (%)*
Sweeping and vacuum sweeping		
	Paved surfaces	20–90
	Permeable surface	67–90
Hosing and flushing		
	Paved surfaces	45–95
	Roofs	25–90
	Walls	0
Removal of surfaces		
	Topsoil	75–90
	Road surface removed	98–100
	Replacing roofs	100
Grass cutting		25–90
Felling trees		90–98
Other techniques		
Ploughing (15–30 cm)	Parks	25–98
Digging	Gardens	83
Sandblasting	Buildings	40–100

Table VI. *Decontamination efficiencies (%) used for early actions after deposition. Conservative estimates based on Table V.*

Decontamination technique (Day 2)	*Dry deposition*	*Wet deposition*
Grass cutting[a]	50	25
Vacuum sweeping paved surfaces	50	–[b]
Hosing paved surfaces	80	45
Hosing roofs	30	25
Felling trees	90	90

[a] Grass cutting performed with a cutter and collector

[b] Negligible

4 DOSE CALCULATION METHODS

People living in urban environments spend an approximated 90% of their time inside buildings, therefore the shielding characteristics of houses play a very important role in the dose calculations. Finck measured and calculated the shielding effects of five Swedish building types, and these calculations are also applicable in Finland. The shielding factor is defined as the ratio of the dose inside the building to the dose one meter above an infinite plane source. For shielding of external radiation from the ground provided by houses this factor varies from about 0.4 for small wooden houses to almost 0.02 for thick-walled multistorey blocks of flats (Finck 1991, Table VII p. 17).

Lawn and sand are permeable surfaces into which water can penetrate. Radiocaesium thus migrates more deeply into the soil, which leads to a reduction in dose rate due to shielding by the soil. The migration was assumed to lead to a reduction in dose rate outdoors, according to the formula (Gale *et al.* 1964):

$$D(t) = D(0) \times (a_1 e^{-\frac{\ln(2)}{T_1}t} + a_2 e^{-\frac{\ln(2)}{T_2}t}) \qquad (2)$$

$D(t)$	= dose rate at time t	
$D(0)$	= dose rate at time 0	1.3×10^{-12} (Sv m^2 h^{-1} Bq^{-1})
a_1	= fraction of rapid removal	0.62
a_2	= fraction of slow removal	0.38
T_1	= half-life of rapid removal	1.15 (a)
T_2	= half-life of slow removal	18.8 (a)

The values for parameters a and T were estimated for Finnish conditions (Rantavaara *et al.* 1996) and the dose conversion factor D(0) was from Jacob *et al.* (1988).

For impermeable ground surfaces, the dose rates were calculated from the modelled activity levels, using the dose rate constant for ^{137}Cs in fresh fallout. This implies the presence of some surface roughness, but no migration into the surface. Indoor dose rates were calculated with the shielding factors for the houses in Table VII (p 17).

Table VII. Shielding factors for various houses, calculated by Finck and used in the present study (Finck 1991).

Type of house	*Shielding factor used*	*Range*
Detached wooden house	0.37	0.2 –1.0
Terraced–house with brick walls	0.15	0.04–0.4
Block of flats with concrete walls	0.017	0.001–0.1
Urban office building with concrete walls	0.017	0.001–0.1

Doses from the surfaces of a house (e.g. roofs and walls) and from trees were calculated from the modelled activity levels with the computer program MATERIA (Markkanen 1995). This program allows calculation of doses with a shielding layer between the contaminated layer and the point at which exposure occurs. In all calculations we assumed that the person is situated in the centre of the middle floor of the house. This results in a good approximation for the dose from the walls, because moving towards one wall will always imply moving away from another, which results in a smaller difference in dose between different points within the house. For doses from roofs, the calculated value will represent a mean.

For trees we calculated the dose from one small–sized tree 8 m in height with a canopy 2 m in diameter. The activity in the tree canopy is assumed to decrease with a half time of 20 days (Miller and Hoffman 1983) until it has attained equilibrium, which is assumed to be 10% of the activity in the soil area covered by the canopy (Rantavaara and Raitio 1996)[a] . The dose is calculated assuming that the tree is 5 m away when a person is outdoors, and 8 m away from a person indoors exposed through the wall.

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[a] Rantavaara A, Raitio H. Personal communication, September 1996.

5 RESULTS

The time-integrated effective doses were calculated for adult individuals for the first month, the first year, 3 years, 10 years and 50 years. The doses were calculated for the four types of residential areas: detached wooden house and brick terraced-house in a suburban area, 3-storey block of flats in a suburban area and office building in the centre of a big city. Calculations are made both for dry deposition and deposition with light rain (5 mm), equivalent to 1 kBq m^{-2} on grass.

5.1 Doses without countermeasures

Individual doses will be highest for persons living in small houses. This is partly due not only to the lower shielding factor for these buildings, but also to the large amount of grass and permeable surfaces in their surroundings (Table I, p. 8). Under dry-deposition conditions, the amount of activity deposited on grass will be about six times higher than that deposited on paved surfaces. The differing relations between depositions on and initial runoff from various surfaces is the main reason for differences between the doses from dry and wet deposition. The calculated differences in doses after dry and wet deposition were small in the present study, due to the assumption of wet deposition with light rain when surface runoff is almost negligible. In the event of dry deposition the 50-year dose for a person living in a small wooden house will be three times and for a person living in a brick terraced-house two times the dose of one living in a flat (Table VIII p. 20).

Contamination on permeable surfaces is the predominant source and contributes to over 50% of the dose in all environments, except the urban office building (Table VIII, p. 20). The removal of radiocaesium from permeable surfaces, and the migration downwards are very slow processes, which makes the exposure from these surfaces even more dominant in the long run. The next most significant surfaces in all environments are the roofs (except with office buildings, where they are the most significant). Radiocaesium deposits readily onto roof materials, and once deposited is not very mobile. Furthermore, roofs are close to the persons indoors, and the shielding provided by roof materials does not reduce the dose effectively. Typically, the deposition on roofs will contribute 20–40% of the total dose.

The amount of radiocaesium depositing onto walls is very small; thus walls are not significant contributors to the short-term dose, except in the office environment. The weathering of radiocaesium deposited on walls is extremely slow, and the contribution from radiocaesium on walls to the dose becomes significant for long time periods. In the event of dry deposition, paved surfaces will not contribute much to the dose, except in the urban office environment. If the deposition is wet the paved surfaces are normally significant in the beginning, or even dominant as in the office environment. Since transport through weathering is effective from these surfaces their relative importance as a source of radiation diminishes with time.

A single contaminated tree is not a significant contributor to the dose, even if it is situated near the exposed person at all times. In an area with many trees the effect of a single tree should be multiplied by the number of trees within about 10 m from the person to estimate the total effect which could yield significant doses.

Table VIII. Time integrated external doses for an adult Finn (μSv) from a ^{137}Cs deposition equivalent to 1 kBq m^{-2} on grass, originating from various surfaces (%).

Type of House	*Dry deposition*					*Wet deposition*				
Surface	*1 mo*	*1 yr*	*3 yr*	*10 yr*	*50 yr*	*1 mo*	*1 yr*	*3 yr*	*10 yr*	*50 yr*
Detached house										
Dose (μSv)	**0.4**	**4**	**9**	**20**	**30**	**0.4**	**5**	**10**	**20**	**40**
Permeable[a] (%)	73	71	70	72	78	75	74	73	76	82
Hard paving (%)	1	1	1	0	0	3	3	2	1	1
Roof (%)	25	27	28	26	18	21	22	23	22	15
Wall (%)	0.8	0.9	1.1	2	4	0.6	0.7	0.9	1.4	3
Tree (%)	0.3	0.1	0.1	0.1	0.2	0.3	0.1	0.1	0.1	0.2
Terraced house										
Dose (μSv)	**0.2**	**2**	**6**	**10**	**20**	**0.3**	**3**	**6**	**10**	**20**
Permeable (%)	57	56	56	59	68	50	52	54	60	70
Hard paving (%)	6	5	4	2	1	20	17	13	8	5
Roof (%)	36	37	39	37	26	29	30	32	31	22
Wall (%)	0.9	1.1	1.3	2	4	0.7	0.8	1.0	2	3
Tree (%)	0.5	0.1	0.1	0.2	0.4	0.5	0.1	0.1	0.2	0.4
Block of flats										
Dose (μSv)	**0.1**	**1**	**3**	**6**	**10**	**0.1**	**1**	**3**	**7**	**10**
Permeable (%)	59	57	56	58	64	52	54	55	60	67
Hard paving (%)	5	5	4	2	1	18	16	12	7	4
Roof (%)	32	35	36	33	22	27	28	30	28	19
Wall (%)	3	3	4	6	12	2	2	3	5	9
Tree (%)	1.0	0.3	0.3	0.4	0.7	0.9	0.2	0.2	0.3	0.7
Office building										
Dose (μSv)	**0.1**	**0.6**	**1**	**3**	**4**	**0.1**	**1**	**2**	**3**	**5**
Permeable (%)	2	2	2	3	3	1	2	2	3	5
Hard paving (%)	28	25	19	12	8	62	57	48	35	27
Roof (%)	63	67	71	72	56	34	38	45	52	45
Wall (%)	5	6	8	13	30	3	3	5	9	22
Tree (%)	1.9	0.5	0.5	0.8	1.8	1.1	0.3	0.4	0.6	1.5

[a] Grassland and sand

5.2 Effects of cleanup

The effect of all cleanup techniques will be higher for dry than for wet deposition, assuming that they are applied before the first rain arrives. The total achievable lifetime dose reduction with the light decontamination techniques modelled here is about 40% if the deposition is dry, and more than 20% in the case of wet deposition (Table IX, p. 22). Cleanup is naturally most effective when applied to those surfaces that contribute most to the dose, therefore cutting and removal of grass, if done soon after deposition before the deposited material has been washed off the grass into the ground, is the most effective countermeasure in most cases. For grass cutting to have any beneficial effects the cut grass must be removed to a place where it will cause little or no dose to people. If this is not done sufficiently soon, other more laborious and costly techniques will possibly be needed.

Hosing of roofs is also an effective countermeasure in most cases and should if possible be done such a way that the water runs directly into drains, and not through permeable surfaces from which the removal of activity would then be difficult. Hosing and, in the event of dry deposition, vacuum sweeping of paved areas results in significant dose reductions only in the urban office environment. The actual dose reduction at the individual level will be low because the doses in this environment are in general low. Due to the high population density, road cleaning could still be cost-effective in city centres. Felling trees will result in only a small overall dose reduction, and the cost in labour and the impact on scenery would be very high.

Table IX. External dose reduction (%) achieved by applying simple decontamination techniques.

Type of house		*Dry deposition*					*Wet deposition*				
Surface	*Action*	*1 mo*	*1 yr*	*3 yr*	*10 yr*	*50 yr*	*1 mo*	*1 yr*	*3 yr*	*10 yr*	*50 yr*
Detached house											
Grassland	Cutting	32	33	33	34	37	14	15	15	15	17
Hard	Vacuum sweeping	0.5	0.4	0.3	0.2	0.1	0	0	0	0	0
Hard	Hosing	1	1	1	0	0	1	1	1	1	0
Roofs	Hosing	7	8	8	8	5	5	5	6	5	4
Trees	Felling	0.3	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2
All	**Total**[a]	**40**	**42**	**42**	**42**	**43**	**21**	**22**	**22**	**22**	**21**
Terraced house											
Grassland	Cutting	27	28	28	29	34	12	13	13	15	17
Hard	Vacuum sweeping	3	3	2	1	0.7	0	0	0	0	0
Hard	Hosing	4	4	3	2	1	8	8	6	3	2
Roofs	Hosing	10	11	12	11	8	7	8	8	8	5
Trees	Felling	0.5	0.1	0.1	0.2	0.4	0.4	0.1	0.1	0.2	0.4
All	**Total**[a]	**41**	**43**	**43**	**42**	**43**	**27**	**28**	**27**	**26**	**25**
Block of flats											
Grassland	Cutting	27	28	28	29	32	12	13	14	15	17
Hard	Vacuum sweeping	3	3	2	1	0.6	0	0	0	0	0
Hard	Hosing	4	4	3	2	1	8	7	5	3	2
Roofs	Hosing	9	10	11	10	6	6	7	7	7	5
Trees	Felling	0.9	0.3	0.3	0.4	0.7	0.8	0.2	0.2	0.3	0.6
All	**Total**[a]	**41**	**43**	**42**	**41**	**40**	**27**	**27**	**27**	**25**	**24**
Office building											
Grassland	Cutting	1	1	1	1	2	0	0	1	1	1
Hard	Vacuum sweeping	13	12	9	6	4	0	0	0	0	0
Hard	Hosing	21	19	15	9	7	26	25	22	16	12
Roofs	Hosing	18	20	21	22	17	8	9	11	13	11
Trees	Felling	1.7	0.5	0.5	0.8	1.8	1.0	0.3	0.4	0.6	1.5
All	**Total**[a]	**41**	**41**	**38**	**33**	**27**	**35**	**36**	**34**	**30**	**26**

[a] Total of the four most effective techniques

6 DISCUSSION

The processes governing dry deposition in urban areas are not very well understood. We have used a simplistic approach of calculating the total deposition to urban areas by summing the deposition to different surfaces. This does not account for possible large scale distribution patterns in an urban area, which has been criticised (Underwood 1987). The effects of weathering and cleaning actions may be somewhat better understood, but also here is a field with much room for experimental and theoretical work.

Starting from a point at which the deposition to grass is equal to unity, the mean short–term doses from permeable surfaces in any type of region were estimated to be accurate within a factor of two while the 50–year doses may differ more from the estimated. Doses from paved surfaces could be a factor of five higher in the acute phase than as modelled here. The amount of activity dry–deposited on trees has been suggested to be a factor of six higher than as modelled here (Jacob and Meckbach 1987) which would affect the short–term doses from trees. One should also remember that this model is concerned only with ^{137}Cs, and the acute case would be very different if the effect of large amounts of short–lived nuclides would be accounted for.

Roofs are constructed of many different materials, and these differ widely in how they interact with radiocaesium; thus the average cases modelled here cannot be generalized to be accurate for any particular house. In addition to the above uncertainties, the effects of the countermeasures can be a factor of two higher or lower than the ones used in this model, without going to any extremes. The effectiveness of decontamination techniques is also dependent on how carefully and how soon they are performed.

Grass cutting should be done before the first rain, because the rain will transfer significant amounts of radiocaesium to the soil below. One would then have to apply much more elaborate schemes, such as ploughing or removal of surface soil to obtain similar dose reductions. The reductions achievable with these costlier techniques might be higher than those for grass cutting by a factor of two for dry deposition or even five for wet deposition, assuming that one can remove almost all activity from these surfaces by removing the topsoil which would be a very extreme measure. On hard surfaces the first heavy rain will act in a manner similar to the cleanup techniques described here. Light rain will not lead to much runoff but might fix the radiocaesium to the surfaces. For comparison, calculations with the EXPURT model for "a typical urban area" with 65% paved areas and 35% soil and grass areas (Brown *et al.* 1996) also pointed out that the permeable surfaces are the predominate sources of dose. In these calculations the contribution to the overall dose from roofs was small (< 10% during 1 year, 4% during lifetime) and walls became an important contributor (12%) to the lifetime dose in the event of dry deposition.

The present study was focused on deposition under summer conditions and on several simple decontamination techniques, most of the results are also applicable during spring and autumn. Further work should be done especially regarding northern winter conditions with snow and ice. The model results are useful for estimating doses and for ranking the effectiveness of countermeasures in a fallout situation, but one should be careful not to trust the figures too heavily, without other sources of confirmation.

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