Decontamination of settlements

1. Basic data for estimation of decontamination effectiveness

Decontamination of settlements was one of the main countermeasures during the initial stage of accidental response. The purpose of settlement decontamination after the Chernobyl accident was the removal of radiation source distributed in the urban environment inhabited by humans to isolated or at least remote places.

The decontamination efficiency may be determined by means of the following parameters:

- **(DF)** The efficiency of techniques in removing radioactivity from a surface. For example, a DF of 2 means that a reduction in contamination (alpha or beta/gamma activity) on the surface by a factor of 2 is seen following decontamination.
- **(DRF)** The reduction in gamma dose rate above a surface following decontamination. For example, a DRF of 5 means that, following decontamination, the dose rate 1 m above the surface is reduced by a factor of 5.
- **(DR)** The reduction in overall external exposure from deposited gamma-emitting material from all surfaces in the environment where an individual is located, taking into account any decontamination that has taken place. For example, a DF of 2 on roofs may result in a DR of 10% in the first year following deposition.

The information upon the effectiveness of different decontamination technologies accumulated by the present time could be chronologically and by subjects structured in the following way:

1. Results of laboratory and field investigations both before and after the Chernobyl accident, during which there have been determined the values of the DF and DRF factors for separate decontamination technologies conformably to different surfaces and objects in the anthropogenic environment [13, 15, 17].
2. Results of the carrying out large-scale measures upon the decontamination of settlements on the territories of Russia, Ukraine and Byelorussia radioactively contaminated after the accident at the Chernobyl NPP. After doing these actions, there were received for the first time the values of the DR factor based not on calculations, but on measurements of the dose reduction effect for the external exposure among different groups of population [21].
3. Results of a number of local field experiments (in 1989, 1990, 1995 and 1997) upon decontaminating small areas and buildings situated on them in the countryside of the Russia and Belarus [21, 22, 23].

The most interesting results appurtenant to the first group has been published as Riso report [24]. It constitutes a catalogue of achievable 'local' dose reduction factors or decontamination factors and other important parameters for different clean-up procedures in various types of environmental scenarios. The estimates were based on experimental work to assess the effect of dose reducing countermeasures in areas contaminated about 9 years ago by radioactive material released during the Chernobyl accident. However, it is very difficult on this background to get a clear view of the total dose-reducing effect (in terms of DR) in the antropogenic areas of carrying out a whole series of countermeasures on different surfaces, as it would be done in practice.

Large-scaled decontamination was performed in 1986-1989 in cities and villages of FSU most contaminated after the Chernobyl accident. This activity was performed usually by military personnel and included washing of building with water or special solutions, cleaning of residential areas, removal of contaminated soil, cleaning and washing of roads, and decontamination of open water supplies. Special attention was paid to kindergartens, schools, hospitals, and other buildings frequently visited by large numbers of persons. During large-scaled decontamination campaign in 1986-1989 about one thousand of settlements were treated, tens of thousand inhabited and social buildings, more than thousand of agricultural farms. Depending of decontamination technologies the dose rate over different visited plots was decreased by a factor of 1.5 to 15. But high cost of this activity hindered to clean totally the whole settlement territory and especially its vicinity, fields, meadows, forests where significant part of population spends a lot of time. Due to these conditions actual effectiveness of the annual external dose decrease after upper soil layer removal around houses, social and production buildings usually was 10 to 20% for average population ranging from about 30% for children visiting kindergarten and schools to less than 10% for outdoor workers (herders, foresters, etc.). These data were confirmed by individual external dose measurements [21]. The averted collective external dose in 90 thousand of inhabitants of 93 most contaminated settlements of the Brynsk region in Russia due to large-scaled decontamination in 1989 was estimated to be about 1 thousand man-Sv [21].

In the early period of the accident inhalation of resuspended radioactive particles of soil and nuclear fuel could significantly contribute in the internal dose. To suppress dust formation the method of dispersion of organic solution over contaminated plots was chosen which created invisible polymer film after natural drying. This method was implemented on the Chernobyl NPP and in 30-km zone during Spring - Summer 1986. Streets in cities were watered to prevent dust formation and to remove radionuclides in the seewerage system. The effectiveness of early decontamination efforts in 1986 still remains to be quantified. However, daily washing of streets in Kiev decreased collective external dose to its 3 million inhabitants by 3000 man-Sv and decontamination of schools and school areas saved 600 man-Sv.

The most interesting from the point of planning the decontamination strategy in a remote period after radioactive fall-outs is the third data group. These data are received in the course of carrying out a local decontamination of 3-5 houses and the surrounding territory in a rural areas of the Bryansk region (Russia) and Belarus 3 – 14 years after the radioactive fall-outs [22,23]. The analysis of the results of this work permits to come to the following conclusions that have practical importance for choosing decontamination strategy and methods:

- 10 years after the radioactive fall-outs, the main sources that define the external radiation dose rate outdoors are the contaminated areas of soil. The dose rate contribution from roads and trees practically disappear within the first five years.
- The main contributor to the dose rate inside the one-story houses was the contaminated soil around houses but roofs also made a significant contribution, whereas radiation from the walls was comparatively insignificant.
- More than 90% of the activity in soil is accumulated in the upper 10-cm layer.

2. List of recommended decontamination technologies

Planning the decontamination activity it is important to take into account contribution of the external dose in the total dose. In the areas with dominating soil type reach with clay, low transfer of cesium radionuclides along the food chain and consequently low internal dose relative decrease of total dose is close to decontamination effectiveness. In contrary, in the peaty soil areas where long-term internal exposure dominates relative decrease of the total dose due to village decontamination is expected to be insignificant.

Following dry deposition, street cleaning, removal of trees and shrubs and digging the garden are efficient and inexpensive means of achieving very significant reductions in dose and would rate highly in a list of priorities. Roofs are important contributors to dose but the cost of cleaning roofs is high and this would not rank highly in a list of priorities. Walls contribute little to dose, are expensive and difficult to decontaminate and would therefore carry a very low rating in a list of priorities.

In the case of wet deposition the garden will be given first priority since a considerable reduction in dose (~60%) can be achieved at relatively low cost. Street cleaning would also be useful.

The priorities that different procedures would be given in a decontamination strategy would be greatly environment-specific. Nevertheless, basing on the accumulated experience of the study upon this problem, the following set of the major decontamination procedures could be recommended:

1. Removal of the upper 5-10 cm layer of soil (it depends on the activity distribution in depth) in courtyards in front of residential buildings, around public buildings, schools and kindergartens, from roadsides inside a settlement. The removed most contaminated layer of soil gets placed into the holes specially dug on the territory of a private homestead land or on the territory of a settlement when decontaminating the settlement as a whole. At that the clean soil (sand) from the dug holes gets used for covering decontaminated areas. Such technology excludes the formation of special burials of radioactive waste.
2. Deep ploughing of private fruit gardens' territories (if they hadn't been ploughed up by this time), or removal of the upper 5-10 cm layer of the soil. By this time vegetable gardens have been ploughed up many times, and in this case the activity distribution in soil will be uniform in the layer 20-30 cm deep (it might be different in the abandoned area).
3. Covering the decontaminated parts with a layer of «clean sand», or, where possible, with a layer of gravel to attenuate residual radiation (see item 1).
4. Cleaning the roofs or their replacement (the roof decontamination should be done before decontaminating the under spread surface).

The list of these procedures can be applied both for decontaminating single private homestead lands and houses, and also for decontaminating settlements as a whole. It is evident that in the latter case the influence of the decontamination upon the further external radiation dose reduction will be greater. Achievable decontamination factors for various urban surfaces are presented in the Table 1.Detailed data on the efficiency, realisation technology, necessary equipment, cost and time expenses, quantity of radioactive waste, and other parameters of separate decontamination procedures are contained in the report [24].

Table 1. Achievable Decontamination Factors for Various Urban Surfaces.

Surface	Decontaminated Method	Achievable Decontamination Factor
Windows	Washing	10
Walls	Sandblasting	10 - 100
Roofs	Hosing and/or sandblasting	1 - 100
Gardens	Digging	6
Gardens	Removal of surface	4 - 10
Trees and Shrubs	Cut back or remove	~10
Streets	Sweeping and vacuum cleaning	1 - 50
Streets (asphalt)	Planing	>100

2.3. Justification and Optimisation

In accordance with the present methodology of radiation protection, a decision on intervention (decontamination) and selection of an optimal decontamination technology should be taken with calculating costs of all the actions and social factors. Calculated cost of actions relates to various decontamination technologies for which the assessment of the averted dose has been made. Benefit (averted collective effective dose) and detriment (expenses, collective dose of decontamination workers) are also compared for each decontamination technology with the accepted cost of one Man-Sv (ICRP Publ.37) or by means of multi-factorial analysis (ICRP Publ.55). If prognostic value of net effects of decontamination for all the considered technologies is positive, the application of these protection measures should be considered founded.

The list of decontamination procedures submitted below basically was prepared by J. Roed (Risø, Denmark) within IAEA TC Project RER/9/059 «Reducing External Exposure Doses in Contaminated Villages»

Name of countermeasure	Topsoil removal by machines (e.g., 'bobcat')
Countermeasure description	It is generally expected that much of an airborne Caesium deposition to soil will throughout several years remain distributed in the upper few centimetres of the soil profile. Gamma spectrometric analysis of soil core sample sections shows how deep a layer should be removed to maximise dose reduction with minimal impact on soil fertility and create minimum amount of waste. The removal may be carried out by 'bobcat' mini-bulldozers (easy to manoeuvre in small areas) or similar available equipment.
Targeted surface type / scale of application	Grassed areas and other areas of soil. The effect is highest if the soil have not been tilled since contamination. Can be carried out in large scale where equipment is available.

Time of application (number of days after deposition, season, etc.)	Can still after a decade save a significant fraction of the 70 y dose.
Practicability:	
• Required equipment and remedies	'Bobcat' or bulldozer. Also waste transport truck to repository and machinery for constructing repository, dependent on waste action scheme.
• Required consumables and other infrastructural elements	Petrol, roads to repository.
• Required man-power skills	Local entrepreneurs or municipal workers who have the required skills/ routine, and could, if necessary, instruct others. Care must be taken to remove soil to the optimal depth and not 'plough' the contamination into the clean surface.
• Required operator safety precautions	Under dusty conditions respiratory protection and protective clothes may be recommended.
• Other potential restrictions on practicability	In some cases frost may be restrictions.
Costs (excl. waste):	
• Costs of equipment and remedies	'Bobcat' (ca. 40,000 EURO), larger bulldozer (ca. 90,000 EURO) or Belarusian front loader (22,000 EURO).
• Costs of consumables	Ca. 0.04 l m^{-2} of petrol (excl. waste transport) at current cost per litre.
• Operator time consumption	Typically some 5-10 man-days per ha, excl. waste transport and work at repository.
• Factors influencing costs	Depth of soil layer to be removed. Distance to equipment, consumables and repository. Soil type and conditions, area size, shape, topography, vegetation, operator skills.
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	DF: ca. 10-30 if optimised according to contaminant distribution in soil. Corresponding to DRF: > 10-30
• Factors influencing effectiveness	Optimisation of thickness of removed soil layer (operator skills). Evenness of ground surface. Vertical Cs distribution homogeneity. Soil texture. Time (downward migration of Cs in soil).
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter

• Extra dose/risk	Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as greater as that to individuals living in the contaminated area. The collective dose to the operators however is much lower than that to the population.
• Factors influencing averted dose	Consistency in carrying out the procedure over a large area.
Waste:	
• Amount and type	If 5 cm topsoil is removed, this produces a waste corresponding to some 70 kg m^{-2}.
• Possible transport, treatment and storage routes.	See separate Chapter
• Specific waste problems	Transport and deposit of large amounts.
• Waste scheme cost estimate	See separate Chapter
Environmental impact	Possible (partial) loss of soil fertility and bio-diversity. Soil erosion. May in some soils remove the entire fertile layer. Requires fertilisation / replanting. Adverse esthetical effect of treatment.
Other side effects, pos. or neg.	-
State of testing/acceptability	Tested in semi-large scale (ca. 2000 m^2) on several occasions in the CIS.
Key references	Roed et al.: Risø-R-1029; Andersson: NKS/EKO-5(96)18; Roed et al.: Risø-R-828; Fogh et al.: Health Physics, 1999.

Name of countermeasure	High pressure water hosing of walls
Countermeasure description	Using pressure-washing equipment, water may be applied to a wall at a pressure of some 150 bar. This will loosen contamination from the wall and wash it off. A continuous water flow should be applied on the wall to transport contamination to the ground. The washing must start at the top of the wall. Alternatively, fire-hosing at hydrant pressure may be applied instead, with considerable less effect.
Targeted surface type / scale of application	Highly contaminated outer walls of buildings.
Time of application (number of days after deposition, season, etc.)	The immediate effect (DF) may decrease with time of application.
Practicability:	
• Required equipment and remedies	Hose pipe, turbo nozzle, mobile pressure washer (typical weight ca. 80 kg), and transport vehicle. Scaffolds or mobile lifts for tall buildings.

• Required consumables and other infrastructural elements	Water supply (water may be pumped from a lake or a stream if tap/hydrant is not available). Power supply (petrol-driven mobile generator may be applied if power is not available). Petrol for equipment transport vehicle.
• Required man-power skills	Special firms dealing with decontamination normally have the skill. The experience of the local fire brigade may also be exploited, but also less skilled personnel (e.g., house owners) can carry out the job with only little instruction.
• Required operator safety precautions	For tall buildings: lifeline. Water proof safety clothing recommended. Due to the water there will be only very little dust.
• Other potential restrictions on practicability	Walls must be water-resistant.
Costs (excl. waste):	
• Costs of equipment and remedies	Cost of mobile pressure washer with turbo nozzle: typically ca. 3000 EURO. (Or fire-hosing equipment ca. 1000 EURO). Variable costs for scaffolding/lifts according to need.
• Costs of consumables	Ca. 20 l per m^2 of water for mobile pressure washing or fire-hosing; power: typically 380 V at 12 A (with petrol-driven generator: ca. 4 l of petrol per hour) and petrol for equipment transport; at current prices.
• Operator time consumption	Pressure washing: Ca. 1-2 min. per m^2 (fire-hosing: 0.1-0.2 min. per m^2) plus variable time for setting up scaffolds/transport.
• Factors influencing costs	Need for scaffolds /mobile lifts, operator skills.
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	Expected DF: 1.5 - 4. The lower values relate to fire-hosing, the higher to high pressure washing.
• Factors influencing effectiveness	The procedure followed. Amount of water/time used and pressure. Increased water temperature (60-80 °C) increases the effect especially on painted or dirty surfaces. Somewhat higher effect on painted walls, but otherwise, wall material generally has little influence.
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter

• Extra dose/risk	The operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area. Collective dose to the operators however is low compared to the collective dose to the affected population.
• Factors influencing averted dose	Consistency in procedure application, care taken to wash contamination to the ground and not just translocate on the wall. The horizontal surface below the wall should ideally be treated *afterwards*.
Waste:	
• Amount and type	Generates some 20 l m^{-2} of liquid waste, and ca. 0.4 kg m^{-2} of solid waste containing nearly all contamination.
• Possible transport, treatment and storage routes.	None possible.
• Specific waste problems	Waste is in practise impossible to collect.
• Waste scheme cost estimate	Costs of contamination of underlying horizontal surface (incorporated in strategy).
Environmental impact	If no drain the water may damage basements
Other side effects, pos. or neg.	Cleaning of buildings.
State of testing/acceptability	Tested on a number of single house walls in CIS and Sweden.
Key references	Roed & Andersson: J. Environ. Rad. vol. 33, no.2; Andersson: NKS/EKO-5(96)18; Roed et al.: Risø-R-828; Hubert et al.: EUR 16530.

Name of countermeasure	Road planing
Countermeasure description	Road planing, using machines applied by the asphalt industry, removes a thin top layer (ca. 1 cm) of an asphalted road surface in ca. 2 m wide 'tracks'. The grinding is usually accomplished by a rotating 'drum' with grinding picks. Machines are often equipped with a rotating brush device for debris collection to a truck. If not, machine or manual sweeping must be added. As penetration of contaminants in asphalt will be negligible, nearly all contamination can be removed in this way. Similar effect on concrete roads.
Targeted surface type / scale of application	Contaminated asphalt (or concrete) roads.

Time of application (number of days after deposition, season, etc.)	As the decontamination effect of traffic can be substantial. (Decrease in contamination level by factor of 3 over first year for heavy trafficked roads have been observed). The method have only effect 15 years after the accident on lightly trafficked roads
Practicability:	
• Required equipment and remedies	'Professional' road planer (alternatively, small planers may be used, e.g., mounted on a mini-bulldozer, though these are much more time consuming). Also waste transport truck and machinery for constructing repository must be available.
• Required consumables and other infrastructural elements	Diesel. Roads to repository.
• Required man-power skills	4 operators (skilled workers from a contractor company).
• Required operator safety precautions	Casing protects operators against loosened debris. In strongly contaminated areas respiratory protection may be recommended.
• Other potential restrictions on practicability	If the road surface is very arched the grinding depth may have to be great.
Costs (excl. waste):	
• Costs of equipment and remedies	'Professional' road planer (ca. 70,000 EURO)
• Costs of consumables	Ca. 8 $l\ h^{-1}$ of diesel (excl. waste transport) at current cost per litre.
• Operator time consumption	Typically the procedure is carried out at a speed of 1000 $m^2\ h^{-1}$, and requires 4 workers. In addition: time consumption for waste collection/transport and work at repository.
• Factors influencing costs	Evenness and condition of roads (required grinding depth), planer size, sweeping device, distance to equipment and consumables, topography, operator skills, resurfacing (normally not necessary).
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	DF: 5-10 expectable (if loose debris is carefully removed).
• Factors influencing effectiveness	Homogeneity of treatment, evenness and condition of roads in relation to grinding depth, operator skills.
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter.

• Extra dose/risk	Depends on short-lived radionuclides (time). Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area (see also separate Chapter).
• Factors influencing averted dose	Time of application after accident. Consistency in carrying out the procedure over a large area. Measures taken to protect operators against inhalation, where required.
Waste:	
• Amount and type	If a 1 cm deep layer is removed, this produces some 15 kg m^{-2} of solid waste.
• Possible transport, treatment and storage routes.	See separate Chapter.
• Specific waste problems	Collection, transport and deposit of large amounts of solid waste.
• Waste scheme cost estimate	See separate Chapter.
Environmental impact	Toxicity of waste to be considered at repository.
Other side effects, pos. or neg.	The road surface is planed.
State of testing/acceptability	Tested in small scale in the CIS, pre-Chernobyl tests in USA.
Key references	Roed et al.: Risø-R-1029; Roed et al.: Risø-R-828; Roed: NKA 1990; Barbier & Chester, PNL, 1980.

Name of countermeasure	Triple digging
Countermeasure description	It is generally expected that much of an airborne Cs deposition to soil will throughout several years remain distributed in the upper few centimetres of the soil profile. The order of three vertical layers of soil is changed manually (by spade). The thin top layer (ca. 5-10 cm -optimised according to contamination depth) carrying nearly all contamination is buried in the bottom, with the vegetation (turf) facing down. The bottom layer (ca. 15-20 cm) is placed on top of this, and the intermediate layer (ca. 15-20 cm), which should not be inverted, is placed at the top. Thereby the contamination is shielded against, and impact on fertility is minimised.
Targeted surface type / scale of application	Grassed areas and other areas of soil. The effect is higher if the soil has not been tilledn tilled since contamination. Can be carried out in garden areas by house owners.

Time of application (number of days after deposition, season, etc.)	Can still after a decade save a significant fraction of the 70 y dose. Not possible during periods of frost.
Practicability:	
• Required equipment and remedies	Spades and in some cases shovels (with very loose soil /sand digging would partly be carried out from the side of the trench). Readily available in many households.
• Required consumables and other infrastructural elements	-
• Required man-power skills	Can be carried out by local inhabitants given instruction.
• Required operator safety precautions	None
• Other potential restrictions on practicability	High groundwater level. The method involves 'hard' work, not all can carry out.
Costs (excl. waste):	
• Costs of equipment and remedies	Spades: ca. 15 EURO.
• Costs of consumables	-
• Operator time consumption	Ca. ½ hour per m^2.
• Factors influencing costs	Individual work rates, soil type and conditions (e.g., moisture, season), vegetation, topography.
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	'Surface' DRF: ca. 5-10, if optimised according to contaminant distribution in soil.
• Factors influencing effectiveness	Soil type and conditions ('Loose' soil will be more difficult to treat optimally). Optimisation of layer depths. Vertical Cs distribution homogeneity. Time (downward Cs migration in soil).
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter
• Extra dose/risk	The operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area. Collective dose to the operators however is low compared to the collective dose to the affected population.
• Factors influencing averted dose	Consistency in carrying out the procedure over a large area.
Waste:	
• Amount and type	None
• Possible transport, treatment and storage routes.	-
• Specific waste problems	None

• Waste scheme cost estimate	-
Environmental impact	The procedure brings contamination closer to the groundwater. Caesiums will however normally be very strongly bound. Possible (partial) loss of soil fertility and bio-diversity. Soil erosion risk. Adverse esthetical effect of treatment.
Other side effects, pos. or neg.	Severely complicates subsequent *removal* of the contamination.
State of testing/acceptability	Tested several times after the Chernobyl accident, in ca.100-200 m^2 plots in CIS.
Key references	Roed et al.: J. Environ. Rad. vol. 45; Hubert et al.: EUR 16530; Andersson: NKS/EKO-5(96)18; Roed et al: Risø-R-828.

Name of countermeasure	Roof cleaning by cleaning device
Countermeasure description	Rotating brush driven by pressurised air at 700 l min^{-1} (water at ordinary mains pressure). Cleaning is performed in a closed (shielded) 'box' system. The device is mounted with an extendible rod that allows operation from the top of the roof or from the ground below single-storey buildings.
Targeted surface type / scale of application	Contaminated roof. Applicable at large scale, if device is available.
Time of application (number of days after deposition, season, etc.)	May still after a decade save a significant fraction of the 70 y dose, depending on roof type (material).
Practicability:	
• Required equipment and remedies	Roof cleaning device (+mobile air compressor for generating pressurised air, if not locally readily available), scaffolds or mobile lifts for operation from the roof. Also waste transport truck to repository and machinery for constructing repository must be available.
• Required consumables and other infrastructural elements	Water (and e.g., petrol for portable compressor if required). Petrol for equipment/ waste transport, roads to repository.
• Required man-power skills	Can be carried out by one (but more easily by two) unskilled workers given little instruction. Workers could be from specialised firms, but also e.g., house owners, fire brigade, or civil defence.

• Required operator safety precautions	Lifeline. Water proof safety clothing recommended. As the cleaning is carried out in wet medium the dust (inhalation) hazard is negligible.
• Other potential restrictions on practicability	-
Costs (excl. waste):	
• Costs of equipment and remedies	Roof cleaning device (ca. 6,000 EURO), (+ 1-2,000 EURO for mobile compressor if required and variable costs for scaffolding/lifts according to need).
• Costs of consumables	13 l m^{-2} of water (and e.g., 5 l petrol per hour for mobile compressor), at current prices.
• Operator time consumption	Estimated to ca. 4-8 minutes per m^2 depending on number of operators (1 or 2), excl. waste transport and work at repository.
• Factors influencing costs	Need for scaffolds /mobile lifts, need for mobile compressor, operator skills.
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	DF of 2-10 expectable (lowest value for eternite, clay and concrete roofs, highest value for silicon-treated eternite, and possibly even higher for aluminium/ iron).
• Factors influencing effectiveness	Contaminant aerosol type (size, solubility). Amount of water/time used. Increased water temperature (60-80 °C) may increase effect slightly on dirty surfaces. Roof material (see above), operator skills. The contamination will become somewhat more fixed after some months.
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter.
• Extra dose/risk	Depends on short-lived radionuclides (time). Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area (see also separate Chapter).
• Factors influencing averted dose	That also *neighbouring* roofs in the area are treated. Special care must be taken to clean roof gutters and drain pipes well.
Waste:	
• Amount and type	Typically some 0.2 kg m^{-2} of solid waste in 13 l m^{-2} of water.
• Possible transport, treatment and storage routes.	After filtration in a simple filter the water can be recycled on the roof. See also separate Chapter.

• Specific waste problems	Solid waste can not be avoided. Waste is impossible to collect without roof gutters - then ground below roof should be treated *after* the roof.
• Waste scheme cost estimate	See separate Chapter
Environmental impact	Solid waste toxicity problem if asbestos roof.
Other side effects, pos. or neg.	Moss, algae and dirt are removed from roof.
State of testing/acceptability	Tested on several roofs in the CIS contaminated by the Chernobyl accident.
Key references	Fogh et al: Health Physics 76(4); Roed et al: Risø-R-870; Roed et al: Risø-R-828; Hubert et al: EUR 16530.

Name of countermeasure	Skim-and-burial ploughing
Countermeasure description	It is generally expected that much of an airborne Cs deposition to soil will throughout several years remain distributed in the upper few centimetres of the soil profile. A skim coulter on the plough first places the upper 5 cm of soil in a trench made by the main ploughshare. In one movement, the main ploughshare then digs a new trench and places the lifted subsoil on top of the thin layer of topsoil in the bottom of the trench of the previous run. The skim coulter simultaneously places the top layer from the next furrow in the new trench, etc. Thereby the contamination is shielded against, and impact on fertility is minimised.
Targeted surface type / scale of application	Grassed areas and other areas of soil, which have not been tilled since contamination. Ploughs are not readily available, but can be supplied over a period of a few years.
Time of application (number of days after deposition, season, etc.)	Can still after a decade save a significant fraction of the 70 y dose. Not possible during periods of frost.
Practicability:	
• Required equipment and remedies	Tractor and skim-and-burial plough
• Required consumables and other infrastructural elements	Petrol.
• Required man-power skills	Can be carried out by farmers who are experienced with ploughing, but the objective must be carefully explained.
• Required operator safety precautions	Under very dusty conditions respiratory protection and protective clothes may be recommended.

• Other potential restrictions on practicability	High groundwater level. In sandy soil the performance of the plough may be less ideal. Application of fertilisers may be called for.
Costs (excl. waste):	
• Costs of equipment and remedies	European tractor: ca. 50,000 EURO. Tractor produced in Belarus named “Belarus” 15,000; Plough: ca. 4,000 EURO.
• Costs of consumables	Petrol: ca. 15 l ha^{-1}.
• Operator time consumption	Ca. 3 h per ha^{-1} (one operator).
• Factors influencing costs	Individual work rates, soil type and conditions (e.g., moisture, season), vegetation, topography.
Effectiveness (DF or 'surface' DRF):	
• Countermeasure effectiveness	Surface DRF: ca. 6-15, if optimised according to contaminant distribution in soil.
• Factors influencing effectiveness	Soil type and conditions ('Loose' soil will be more difficult to treat optimally). Optimisation of layer depths. Vertical Cs distribution homogeneity. Time (downward Cs migration in soil).
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter
• Extra dose/risk	Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area.
• Factors influencing averted dose	Consistency in carrying out the procedure over a large area. Measures taken to protect operators against e.g., inhalation, and contamination of skin/ clothes, where required.
Waste:	
• Amount and type	None
• Possible transport, treatment and storage routes.	-
• Specific waste problems	None
• Waste scheme cost estimate	-
Environmental impact	The procedure brings contamination closer to the groundwater. Cs will however normally be very strongly bound. Possible (partial) loss of soil fertility and bio-diversity. Soil erosion risk. Future restriction on land use: should not be deep-ploughed. Adverse aesthetical effect of treatment (e.g., in parks).
Other side effects, pos. or neg.	Severely complicates subsequent *removal* of the contamination.

State of testing/acceptability	Tested several times after the Chernobyl accident, in CIS and in Denmark (typically in 1000-2000 m^2 areas).
Key references	Roed et al.: J. Environ. Rad. vol. 33; Hubert et al.: EUR 16530; Andersson et al: NKS-16, ISBN 87-7893-066-9, 2000; Roed et al: Risø-R-828.

Name of countermeasure	Roof cleaning by roof cleaning trolley
Countermeasure description	Rotating nozzles are driven by hot water (ca. 65 °C) at high pressure (typically ca. 150 bar). Cleaning is performed in a closed (shielded) 'box' system. The device is mounted on a trolley that can be drawn up and down on a roof. Operated from the top of the roof - lowered using the pressure hose.
Targeted surface type / scale of application	Contaminated roof. Applicable at large scale, if device is available.
Time of application (number of days after deposition, season, etc.)	May still after a decade save a significant fraction of the 70 y dose, depending on roof type (material).
Practicability:	
• Required equipment and remedies	Roof cleaning trolley (+high pressure hot water generator), scaffolds or mobile lifts for operation from the roof. Also waste transport truck to repository and machinery for constructing repository must be available.
• Required consumables and other infrastructural elements	Water (and e.g., petrol for heating and generating pressurised water). Petrol for equipment/ waste transport, roads to repository.
• Required man-power skills	Carried out by two (unskilled) workers (one on the rooftop and one on the ground administrating supplies (given little instruction). Workers could be e.g., house owners, fire brigade, civil defence, or professional roof workers.
• Required operator safety precautions	Lifeline. Water proof safety clothing recommended. As the cleaning is carried out in wet medium the dust (inhalation) hazard is negligible.
• Other potential restrictions on practicability	-
Costs (excl. waste):	

• Costs of equipment and remedies	Roof cleaning trolley (ca. 500 EURO), (+ 37,500 EURO for hot water high pressure aggregate and variable costs for scaffolding/lifts according to need).
• Costs of consumables	30 l m^{-2} of water (and e.g., 8 l petrol per hour), at current prices.
• Operator time consumption	Estimated to ca. 10 minutes per m^2 for each of 2 workers, excl. waste transport and work at repository.
• Factors influencing costs	Need for scaffolds /mobile lifts, operator skills.
Effectiveness (DF or 'surface' DRF):	
• 'Likely' countermeasure effectiveness	DF of 3 expectable
• Factors influencing effectiveness	Contaminant aerosol type (size, solubility). Amount of water/time used. Roof material (see above), operator skills. The contamination will become somewhat more fixed after some months.
Doses:	
• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter.
• Extra dose/risk	Depends on short-lived radionuclides (time). Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area (see also separate Chapter).
• Factors influencing averted dose	That also *neighbouring* roofs in the area are treated. Special care must be taken to clean roof gutters and drain pipes well.
Waste:	
• Amount and type	Typically some 0.2 kg m^{-2} of solid waste in 30 l m^{-2} of water.
• Possible transport, treatment and storage routes.	After filtration in a simple filter the water can be disposed of.
• Specific waste problems	Solid waste can not be avoided. Waste is in practise impossible to collect without roof gutters - then ground below roof should be treated *after* the roof.
• Waste scheme cost estimate	See separate Chapter
Environmental impact	Solid waste toxicity problem if asbestos roof.
Other side effects, pos. or neg.	Moss, algae and dirt are removed from roof.
State of testing/acceptability	Tested on a roof in the CIS contaminated by the Chernobyl accident.
Key references	IAEA publication ???

Name of countermeasure	Normal digging to 30 cm (manual)
Countermeasure description	It is generally expected that much of an airborne Cs deposition to soil will throughout several years remain distributed in the upper few centimetres of the soil profile. Therefore, if the top layers of the soil are dug to a depth of 15-20 cm and it is attempted to bring the turf to the bottom of this vertical profile, a significant shielding against radiation from the contaminants is provided.
Targeted surface type / scale of application	Grassed areas and other areas of soil, which have not been tilled since contamination. Can be carried out in garden areas by house owners.
Time of application (number of days after deposition, season, etc.)	Should generally be carried out as early as possible, when the radiological situation is clear, but worker doses must be considered. Can still after a decade save a significant fraction of the 70 y dose. Not possible during periods of frost.
Practicability:	
• Required equipment and remedies	Spades. Readily available in many households.
• Required consumables and other infrastructural elements	-
• Required man-power skills	Can be carried out by local inhabitants given only little instruction.
• Required operator safety precautions	Under very dusty conditions respiratory protection and protective clothes may be recommended.
• Other potential restrictions on practicability	High groundwater level. The method involves 'hard' work, not all can carry out.
Costs (excl. waste):	
• Costs of equipment and remedies	Spades: ca. 15 EURO.
• Costs of consumables	-
• Operator time consumption	Ca. 15 minutes per m^2.
• Factors influencing costs	Individual work rates, soil type and conditions (e.g., moisture, season), vegetation, topography.
Effectiveness (DF or 'surface' DRF):	
• Likely countermeasure effectiveness	DRF: typically ca. 2-4.
• Factors influencing effectiveness	Soil type and conditions ('Loose' soil will be more difficult to treat optimally).
Doses:	

• Fractional averted dose in 'typical' environments (reference to report)	See separate Chapter
• Extra dose/risk	Depends on short-lived radionuclides (time). Over a limited period the operator dose contribution from external radiation could be up to 2-3 times as great as that to individuals living in the contaminated area (see also separate Chapter).
• Factors influencing averted dose	Consistency in carrying out the procedure over a large area. Measures taken to protect operators against e.g., inhalation, and contamination of skin/ clothes, where required.
Waste:	
• Amount and type	None
• Possible transport, treatment and storage routes.	-
• Specific waste problems	None
• Waste scheme cost estimate	-
Environmental impact	Adverse esthetical effect of treatment.
Other side effects, pos. or neg.	Severely complicates subsequent *removal* of the contamination and make a triple digging procedure considerable more difficult.
State of testing/acceptability	Tested in CIS after the Chernobyl accident.
Key references	Roed: NKA AKTU-245, 1990; Hubert et al.: EUR 16530; Roed et al: Risø-R-828.

The literature devoted to these questions:

1. Andersson, K.G., 1996. Evaluation of Early Phase Nuclear Accident Clean-up Procedures for Nordic Residential Areas, NKS Report NKS/EKO-5(96)18, ISBN 87-550-2250-2.

2. Andersson, K.G., 1996a. Modelling External Radiation Doses in Contaminated Urban Areas: Implications for Development of Decontamination Strategies, in proceedings of the IRPA9 International Congress on Radiation Protection, Vienna, ISBN 3-9500255-4-5, pp. 3-265 - 3-268.

3. Andersson, K.G. & Roed, J., 1994. The Behaviour of Chernobyl Cs-137, Cs-134 and Ru-106 in Undisturbed Soil: Implications for External Radiation, J. Environ. Radioactivity 22, pp. 183-196.

4. Andersson, K.G. & Roed, J., 1999. A Nordic Preparedness Guide for Early Clean-up in Radioactively Contaminated Residential Areas, J. Environmental Radioactivity vol. 46, no. 2, pp. 207-223.

5. Fogh, C.L., Andersson, K.G., Barkovsky, A.N., Mishine, A.S., Ponamarjov, A.V., Ramzaev, V.P. & Roed, J., 1999. Decontamination in a Russian Settlement, Health Physics 76(4), pp. 421-430.

6. Roed, J., Andersson, K.G. & Prip, H. (ed.), 1995. Practical Means for Decontamination 9 Years After a Nuclear Accident, Risø-R-828(EN), ISBN 87-550-2080-1, ISSN 0106-2840.

7. Roed, J., Andersson, K.G. & Togawa, O., 1996. Weathering of Radionuclides Deposited in Inhabited Areas, in proceedings of the IRPA9 International congress on radiation protection, Vienna, ISBN 3-9500255-4-5, pp. 3-167 - 3-169.

8. Roed, J., Lange, C., Andersson, K.G., Prip, H., Olsen, S., Ramzaev, V.P., Ponomarjov, A.V., Barkovsky, A.N., Mishine, A.S., Vorobiev, B.F., Chesnokov, A.V., Potapov, V.N. & Shcherbak, S.B., 1996a. Decontamination in a Russian Settlement, Risø-R-870, ISBN 87-550-2152-2.

9. Roed, J., Andersson, K.G., & Prip, H., 1996b. The Skim and Burial Plough: a New Implement for Reclamation of Radioactively Contaminated Land, J. Environmental Radioactivity vol.33, no.2 pp. 117-128.

10. Roed, J., Andersson, K.G., Barkovsky, A.N., Fogh, C.L., Mishine, A.S., Olsen, S.K., Ponomarjov, A.V., Prip, H., Ramzaev, V.P. & Vorobiev, B.F, 1998. Mechanical Decontamination Tests in Areas Affected by the Chernobyl Accident, Risø-R-1029, ISBN 87-550-2361-4.

11. Roed, J., Andersson, K.G., Fogh, C.L., Barkovski, A.N., Vorobiev, B.F., Potapov, V.N. & Chesnokov, A.V., 1999. Triple Digging - a Simple Method for Restoration of Radioactively Contaminated Urban Soil Areas, J. Environmental Radioactivity vol.45, no.2 pp. 173-183.

12. European Commission Belarus, the Russian Federation, and the Ukraine. Joint Study Project No.5; Pathway analysis and dose distributions. Final report. Luxembourg, EC, EUR 16541 $_{EN}$ (1996).

13. European Commission Belarus, the Russian Federation, and the Ukraine. Experimental Collaboration Project No.4; Evaluation and development of decontamination strategies for a range of environmental situations and evaluations of their efficacy and other impacts. Final report. Luxembourg, EC, EUR 16530 (1996).

14. Reclamation of contaminated urban and rural environments following a severe nuclear accident. Nordic Nuclear Safety Research, BER 6. Edited by: Per Strand, Lavrans Skuterud, Judith Mellin. NKS (97) 18 97-10-10, (1997).

15. J. Brown, J.R. Cooper, J.A. Jones, L. Flaws, R.McGeary, and J. Spooner Review of decontamination and clean-up techniques for use in the UK following accidental

releases of radioactivity to the environment. NRPB-R288 (DOE/RAS/96.009). Chilton, Didcot, Oxon OX11 0RQ (1996).

16. Warming L. Weathering and decontamination of radioactivity deposited on concrete surfaces. Roskilde, Riso National Laboratory, RISO-M-2473 (1984).

17. Sandalls F.J., Steward S.P., and Wilkins B.T. Natyral and forced decontamination of urban surfaces contaminated with radiocaesium. In Proceedings of the EC workshop on assessing off-site radiological consequences of nuclear accidents. Luxembourg, EC, EUR 10397, pp. 435-47 (1986).

18. Lehto J. (Ed.) Cleanup of large radioactive contaminated areas and disposal of generated waste. Final report of the KAN2 project, Roskilde, Nordic Committee for Nuclear Safety Research, TemaNord 1994:567 (1994).

19. Brown J., Haywoord S.M., and Roed J. The effectiveness and cost of decontamination in urban areas. In Proceedings of the international seminar on intervention levels and coutermeasures for nuclear accidents. Cadarache, October 1991. Luxembourg, EC, EUR 14469, pp. 511-32 (1992).

20. Sinnaeve J., and Olast M. (Eds.) Improvement of practical coutermeasures: the urban environment, post-Chernobyl action. Luxembourg, EC, EUR 12555 (1991).

21. Balonov M. I., Golikov V. Yu., Erkin V. G., Parchomenko V. I., Ponomarev A. V. Theory and practice of a large-scale programme for the decontamination of the settlement affected by the Chernobyl accident. In; International seminar on intervention levels and countermeasures for nuclear accident. Cadarache, 7-11 Oct. 1991.

22. J. Roed, C. Lange, K.G. Andersson, H. Prip, S. Olsen, V.P. Ramzaev, A.V. Ponomarjov, A.N. Barkovsky, A.S. Mishin, B.F. Vorobiev, A.V. Chesnokov, V.N. Potapov, S.B. Shcherbak Decontamination in a Russian settlement. Riso-R-870(EN). Riso National Laboratory, Roskilde, Denmark. March 1996.

23. J. Roed, K.G. Andersson, A.N. Barkovsky, C.E.Fogh, A.S. Mishine, S. Olsen, A.V. Ponomarjov, H. Prip, V.P. Ramzaev, , B.F. Vorobiev Mechanical Decontamination Tests in Areas Affected by the Chernobyl Accident Riso-R-1029(EN). Riso National Laboratory, Roskilde, Denmark. August 1998.

24. Practical Means for Decontamination 9 Years after a Nuclear Accident Editors J. Roed, K.G, Andersson, H. Prip Riso-R-828(EN), Riso National Laboratory, Roskilde, Denmark. December 1995.

25. IAEA (1983) IAEA Safety Guides. Safety Series no. 55, Planning for the off-site response to radiation accidents in nuclear facilities.