Review

Decontamination Tests in the Recreational Areas Affected by the Chernobyl Accident: Efficiency of Decontamination and Long-term Stability of the Effects

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Summary

The paper provides a review of the decontamination tests and the follow up monitoring program conducted by the Russian and Danish researchers in two recreational areas in the period 1995–2003. The recreational areas Novie Bobovichi and Muravinka consisted of sets of wooden and brick summer houses in forest-grassland surroundings. The sites are located on the territory of the Bryansk region (Russia) at a distance of about 180 km north-east of the Chernobyl Nuclear Power Plant. Before intervention began, the inventory of ^{137}Cs in soil was determined at a level of 1000 kBq m^{-2}. The collaborative research project showed that use of simple countermeasures involving hand-tools and light machinery could reduce the external dose rate considerably, even though 10 years had passed since fallout of the Chernobyl radiocesium. The long-term monitoring of the recreational areas did not demonstrate significant re-contamination of cleaned ground plots within the time period of 15–17 years after intervention. The technologies and the methods implemented to clean up the recreational areas may be recommended for restoration of some Japanese sites that were strongly contaminated in 2011 as a result of the Fukushima accident.

Key words: Chernobyl, nuclear accident, radiocesium, decontamination, external exposure, monitoring.

INTRODUCTION

The accident at the Chernobyl Nuclear Power Plant (ChNPP) in 1986 resulted in widespread radioactive contamination of the European part of Russia. For many settlements from the Bryansk region (population number in 1989: 1.47 million), the initial ground deposition (inventory) of ^{137}Cs exceeded 0.55 MBq m^{-2} or 15 Ci km^{-2} [1, 2], that was established as a threshold for permanent relocation or resettlement [3]. According to Belyaev [3], the zone in the Bryansk region with ^{137}Cs ground contamination exceeding 15 Ci km^{-2} included 206 settlements with a total population of 82,000. The maximum ^{137}Cs inventory of 3.8 MBq m^{-2} was reported for the Zaborye settlement (the western part of the Bryansk region), which is located at a distance of about 220 km from the damaged ChNPP [4]. For the first post-accidental year (1986), the external and total annual effective

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doses for the residents of Zaborye were estimated at 36 mSv and 45 mSv, respectively [4]. To speed up the decline of the external and internal exposure from the Chernobyl fallout, various countermeasures had been implemented in residential areas of the Bryansk region during the first 3–4 years after the accident [5, 6]. The averted collective external dose for the residents of 93 most contaminated settlements of the Bryansk region due to decontamination in 1989 was calculated to be about 1000 man-Sv [5]. Nonetheless the decontamination campaign was not considered fully successful. For example, in Novozybkov city (180 km north-east from ChNPP) with an initial ^{137}Cs ground contamination of 0.7 MBq m^{-2} and population of about 43,600 [7], the 1986–1989 decontamination activities reduced external effective dose by a factor of only 1.1–1.2 (or by 10–20%). As a result, since 1989, a large scale resettlement of the population from the radioactively contaminated areas was initiated. It should be stressed that many local citizens were unhappy to leave their homes and start a new life in the so called “clean areas” [8]. These people preferred to have some monetary compensation (e.g., about 160 US$ per month in the most contaminated zone in 1997 [9]) and early retirement age because of the permanent stay inside the radioactively contaminated zone. Therefore research studies and practical steps to increase the efficiency (including cost-efficiency) of decontamination or “rehabilitation” [6] continued to be of high priority for the Russian officials in the early 1990’s.

In 1991–1992, the European Union (EU) in collaboration with the governments of Belarus, Russia and Ukraine had launched an ambitious research program that included 16 projects dealing with Chernobyl problems. Experimental collaboration project No 4 “Strategies of decontamination” from this program had the objective of developing decontamination strategies and methods suitable for the areas affected by the Chernobyl fallout [10, 11].

Along with the EU-Belarus-Russia-Ukraine initiative, different national and international research projects started. One of such bilateral projects was carried out by the RISØ National Laboratory, Roskilde, Denmark (RISØ; now: Center for Nuclear Technologies, Technical University of Denmark) and the Research Institute of Radiation Hygiene, St.-Petersburg, Russia (RIRH) in the territory of the Bryansk region in the period 1995–2003. It was the main objective of that work to examine the possibilities for reducing the external doses by decontamination of housing areas in the remote period (~10 years) after the accident. A study of the long-term stability of the applied clean-up procedures was another task of the project. To achieve this goal, a program of complex monitoring of the treated areas and untreated (control) areas has been carried out. The paper provides a review of the decontamination tests and the follow up monitoring program conducted in two heavily contaminated forested sites. The review is mainly based on papers published in peer-reviewed scientific journals [9, 12, 13, 14, 15]. Details (including photographic illustrations) of the sites description, radiation conditions before and after decontamination, and the clean up methods can be found in two scientific reports issued by RISØ [16, 17].

Sites description

The decontamination tests were performed in the territories of the so-called ‘recreational areas’ Muravinka (52.48° N 31.78° E) and Novie Bobovichi (52.65° N 31.75° E) which belonged to enterprises in the town of Novozybkov. The sites are located at a distance of about 180 km north-east of the ChNPP. The recreational areas consisted of sets of wooden and brick summer houses in forest-grassland surroundings. The areas are located on the flat banks of the Iput river. Figures 1 and 2 show typical houses from the sites. The ground area of the houses was 10.0 m × 7.5 m and 5.0 m × 4.5 m in Muravinka and Novie Bobovichi, respectively. All the buildings had roofs made of asbestos-cement sheets. A thick layer of organic matter (litter, mosses) was found on the roofs in Novie Bobovichi. The houses were built in the 1970’s in Muravinka, and in the beginning of the 1980’s in Novie Bobovichi, i.e. before the Chernobyl accident. In Novie Bobovichi, there were several asphalted paths and two large plots covered with asphalt. No decontamination had been carried out in the areas before the RISØ-RIRH experiments [9].

Fig. 1　Typical one-storey wooden houses and an asphalted area from untreated part of Novie Bobovichi
Pine (*Pinus sylvestris*) is the dominant species of the trees, 1998.

Fig. 2　A typical two-storey house from untreated part of Muravinka
The house is surrounded by pine-trees and leafy plants, 1998.

The study areas geographically belong to the Belarus-Bryansk Polessie with the prevalence of sandy and sandy-loam types of sod-podzol soil [7]. The soil types are characterized by relatively high soil-to-plant (soil-to-fungi) transfer factors with respect to cesium radionuclides [18]. The average annual temperature is circa +6.5 °C. In Novozybkov, the first snow usually appears at the end of November; in March the snow melts away. The total amount of annual precipitation is about 585 mm [7].

Radiation conditions before intervention

Instruments and methods

The following radiometric and dosimetric parameters were studied before, during and after decontamination [15, 16, 17]:

a) gamma-ray dose rate in air in terms of exposure dose rate (R h^{-1}), absorbed dose rate (Gy h^{-1}), or ambient dose equivalent rate (Sv h^{-1}), depending on the instrument calibrations;
b) fluences of the primary and scattered photons in air;
c) fluences of beta-rays from the roof surface;
d) activities of the man-made and natural radionuclides in soil, plants and building materials.

The gamma-ray dose rate was determined with a detector placed at a height of 1 m (the standard geometry) or 5–10 cm (the “near” geometry) above the ground (outdoor locations) or above the floor (indoor locations). High pressure ionizing chamber, Geiger-Muller counters, scintillating plastic with heavy metals admixtures, and NaI(Tl) crystals were used as detectors in the instruments for registration of γ-rays.

For in situ γ-ray spectroscopy, high purity semiconductor germanium detectors and NaI(Tl) scintillation detectors were employed. Usually the detector was mounted on a tripod at a height of 1 m above the ground (Figure 3) with the crystal faced down. Collimated detectors and different distances from the surface of interest were also used (Figure 4). In situ γ-ray spectroscopy allowed to: 1) estimate contribution of the primary and scattered photons to the total dose in air; 2) measure activity concentrations of natural radionuclides in soil; 3) evaluate inventory of radiocesium in soil and roofs.

Soil cores were collected with a steel dismountable sampler (Figures 12 and 13; see also Figure 3 in ref. [19]) or a section of plastic tube, which was driven into the ground to a depth of 20–30 cm. The soil cores collected with the steel sampler were sliced on site into horizontal 2–5 cm thick layers. For preparation of the samples obtained with a plastic pipe, a technology based on slicing the deep frozen materials with a diamond saw was implemented [16]. Roof materials, as well as grass and fungi were also collected. The activities of ^{137}Cs, ^{134}Cs, ^{40}K, ^{226}Ra and ^{232}Th in samples were determined in the laboratories of RISØ

Fig. 3 A scintillation portable gamma-ray spectrometer mounted on a tripod

The NaI(Tl) detector is set up at a height of 1 m above the ground. The untreated plot in the forest near Muravinka was selected for regular monitoring measurements, 2002.

Fig. 4 A scintillation portable gamma-ray spectrometer mounted on a tripod

The NaI(Tl) detector is set up at a height of 10 cm above the ground. The central dirty road in the middle of the Muravinka recreational area, 2002.

and RIRH using semiconductor and scintillation gamma-ray spectrometry. Because one of the RIRH laboratories had been installed in Novozybkov city [20], results of the gamma-spectroscopic measurements could be obtained very quickly, i.e. within a day or two.

Results of measurements and estimations

Before intervention began [16, 17], the inventory of ^{137}Cs in soil was determined at a level of 1000 kBq m^{-2} (Table 1). This figure is comparable with values of the ^{137}Cs deposition density for the most highly contaminated areas located to the north-west of the Fukushima Dai-ichi Nuclear Power Plant in Japan [21, 22]. The average $^{134}Cs/^{137}Cs$ activities ratio (corrected to April 26 1986) for the soil samples was calculated as 0.54 for Muravinka and 0.55 for Novie Bobovichi [14]. This corresponds to the average ratio of 0.55 derived by Mück et al. [23] for the so called "consistent radionuclide vector" after the Chernobyl accident.

The ^{137}Cs activity vertical distribution in soil (in %) before intervention is shown in Figure 5. For Muravinka, about 95% of the total radiocesium inventory was associated with the top 0–5 cm soil layer (including forest litter). In the Novie Bobovichi area, the contaminant had penetrated somewhat deeper in the soil, and the corresponding top soil layer,

Table 1 ^{137}Cs inventory (kBq m^{-2}) in soil and on/in roofs in Novie Bobovichi (1995) and Muravinka (1997) before intervention

Area	^{137}Cs inventory, kBq m^{-2}	
	Soil	Roof (asbestos-cement sheets)
N. Bobovichi	990 ± 320 (10)	153 ± 74 (3)
Muravinka	1250 ± 360 (10)	144 ± 36 (16)

Note: The number of samples is given in brackets. Ref. 9, 15, 16, 17.

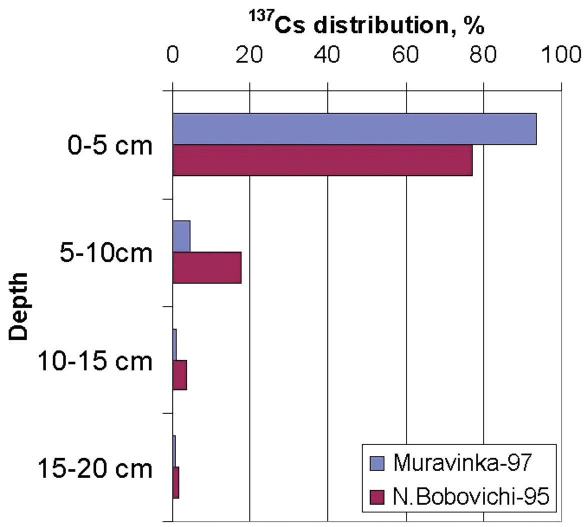

Fig. 5 The ^{137}Cs activity vertical distribution (in percentage of total inventory) in soil at the housing areas in Muravinka and Novie Bobovichi before intervention (based on ref. [16, 17])

including forest litter, contained about 75% of the total activity. The recorded distributions of contamination led to the assumption that removal of a 5–7 cm layer of topsoil would give a profound reduction of the γ-ray dose in air for the outdoor locations.

The average contamination level of asbestos-cement sheets taken from the roofs (Table 1) was found to be approximately 150 kBq m^{-2}, corresponding to ca. 10–15% of the soil contamination level. The organic matter collected from the roofs in Novie Bobovichi was also heavily contaminated with radiocesium – up to 140 kBq kg^{-1}, dry weight [16]. The organic matter contributed about 70% to the total inventory of 170 kBq m^{-2} for the roof of house 5 in Novie Bobovichi [16]. Based on these data it was concluded that the contamination on the roofs would be a significant source for external exposure indoors [9]. The roofs were selected as obligatory targets for decontamination.

The ^{137}Cs inventory for a small asphalted plot (area approximately 10 m × 8 m), which had been selected in Novie Bobovichi in 1997 for testing a portable mechanical scraper, was measured as 630 kBq m^{-2}. Interestingly, about 45% of the activity was associated with the organic materials, i.e. the leaves, pine needles, mosses, lichens and decomposed organic matter, that covered the asphalt surface. The asphalt plot had remained undisturbed since the Chernobyl accident [17].

Additionally to the housing areas located in forest surroundings, a grassland site near Novie Bobovichi was chosen for a test of a special digging method ('triple digging' [13]), whereby a contaminated topsoil layer is buried deep in the ground, thus greatly reducing external exposure, with minimal adverse effect on soil fertility (which can otherwise be a considerable risk when digging or ploughing shallow soils typical of the test areas). The plot is located on the grassland floodplain area of the Iput river. The area had been used as a pasture for cattle for many years before and after the accident. In September 1995, the ^{137}Cs inventory on the tested grass-covered plot was ca. 1020 kBq m^{-2}. Here, the upper 0–5 cm soil layer contained only 36% of the total inventory, which indicated a much faster vertical migration of the Chernobyl radiocesium in grasslands compared to forests.

Before the intervention began (September 1995), the average absorbed gamma-dose rates in air in the Novie Bobovichi area were 850 nGy h^{-1} (outdoor) and 390 nGy h^{-1} (indoor, wooden houses). In Muravinka before the tests started (August 1997), those were 1000 nGy h^{-1} (outdoor), 490 nGy h^{-1} (indoor, first floor) and 430 nGy h^{-1} (indoor, ground floor). In the center of the asphalted area and on the 'triple dug' ground plot, gamma-ray dose rate was measured as ca. 830 nGy h^{-1} (in August 1997) and 830 nGy h^{-1} (in September 1995), respectively [15, 16, 17].

By chance, the decontamination tests were conducted in that part of the Bryansk region where the background γ-ray dose rate due to the terrestrial radionuclides of ^{40}K, and ^{226}Ra and ^{232}Th series was comparatively low, of about 16–30 nGy h^{-1} [15]. This made it possible to study the Chernobyl component with higher accuracy. The contribution from the natural terrestrial radiation (including radon progeny) and cosmic radiation, as well as the intrinsic noise of a dosimeter (a total value of 60 nGy h^{-1}) had been subtracted from the dosimeter reading prior to calculation of the dose reducing efficiency of decontamination.

Description of decontamination activities

The decontamination activities included

[15, 16, 17]:

a) Removal of a topsoil layer (5–10 cm) around three houses at each place (270 m^2 in Novie Bobovichi and 2000 m^2 in Muravinka). Only hand-tools (e.g., spades, shovels, wheelbarrows) were used in Novie Bobovichi, while in Muravinka, common contractor machinery (a ‘Bobcat’ mini-bulldozer) was used as the main device (Figure 6A). Special attention was paid to avoid significant mechanical damage of major roots of the trees during soil treatment.

b) Addition of uncontaminated sand (a layer thickness of about 7–10 cm). The sand was obtained from the nearest sand pit (the Novie Bobovichi test) or from the holes dug on site by an excavator (the Muravinka test).

c) Total renewal of the roof cover of a house at each site (Figure 6B). The old asbestos-cement sheets were replaced by the new sheets.

d) Decontamination of roofs of two houses in Novie Bobovichi using a mechanical brush and high pressure water hosing (turbo nozzle). A metal scraper (a hand tool) was tested to decontaminate a small area of the roof of a house in Muravinka.

e) Decontamination of an asphalted area with a broom, mechanical scraper and vacuum sweeping device (Figure 7A). A circular area of about 6 m in diameter (28 m^2) was treated. An approximately 2 cm deep layer of asphalt and all organic matter was removed from the central part of the plot (area ca. 23 m^2), and additionally the organic matter was scraped from the surrounding ring (about 0.5 m wide).

f) Triple digging of a grass-covered ground plot (Figure 7B). The ‘triple digging’ procedure [13] was performed on an area of 10 m × 10 m. The top 5–7 cm of soil was buried at a depth of 20– 30 cm.

Fig. 6 “Bobcat” minibulldozer is ready to start top-soil removal around house No. 1 in Muravinka (A). Roof replacement on house No. 1 in Muravinka after top-soil removal and application of clean sand (B).

Fig. 7 A small road scraper on the treated asphalt area in Novie Bobovichi (A). Triple digging of a grassed area (B).

In Novie Bobovichi, the generated wastes (around 26 m^3) were collected for permanent storage in unfinished foundations of two houses located near the decontaminated plot. No additional protection against disturbing the waste depositories by natural processes or humans was made. In Muravinka, the wastes were buried in eight holes (volume of 8–10 m^3 each) dug by an excavator in the ground of those plots, which had already been decontaminated. An advantage of the latter approach for the wastes disposal is that the clean sand from the holes can be immediately applied over the treated plots to shield against residual radioactivity and to cover the roots of trees. After filling with wastes, the holes were covered by a 15–20 cm layer of clean sand.

The efficiency of each technological stage was carefully monitored with gamma-dose rate meters. The dose rate value of 300 nSv h^{-1} at a height of 5–10 cm above the ground was selected as a threshold for stopping soil removal around houses. Without treatment of larger areas, it was difficult to achieve levels lower than 300 nSv h^{-1} due to strong scattered radiation from the surrounding untreated environment [9].

Results of decontamination activities

Reduction of contamination

Table 2 summarizes the results of the decontamination tests in terms of the contamination reduction. The calculated values of the decontamination factor (DF: level of surface contamination prior to the treatment relative to that after the treatment) varied very widely depending on the treated surface and method of clean up. The treatment of asbestos-cement sheets with a turbo-nozzle, roof washer or metal scrapper resulted in reduction of the ^{137}Cs contamination by a factor of only 1.5–2.0. The tests indicated a rather strong fixation of the contaminant on the inorganic roof material 9–11 years after deposition. Essentially, complete renewal of the asbestos-cement sheets gave nearly 100% removal of the contaminant from the roof of house No 6 in Novie Bobovichi and house No 1 in Muravinka.

A considerable efficiency of decontamination was achieved by the mechanical treatment of an asphalted surface with a scraper [17]: the inventory of ^{137}Cs on the surface was reduced by a factor of 5 (i.e. 80% of activity was removed). If one includes into the assessment the removal of the radioactivity associated

Table 2 Reduction of the ^{137}Cs inventory for selected surfaces due to decontamination carried out in Novie Bobovichi (1995) and Muravinka (1997)

Site	Location	Target surface	Reduction of the ^{137}Cs inventory	
			Decontamination factor	%
N. Bobovichi	Around houses	Soil[a,b]	4.1	76
N. Bobovichi	Houses Nos. 4, 5 & 6	Roof[b]	3.3 - (~ infinity)	70 - (~ 100)
N. Bobovichi	House No. 4	Roof (asbestos-cement sheets)[c]	2.0	51
N. Bobovichi	House No. 5	Roof (asbestos-cement sheets)[d]	1.6	36
N. Bobovichi	River bank	Soil[a,b]	4.6	78
N. Bobovichi	In the forest	Asphalt[b]	8.0	88
N. Bobovichi	In the forest	Asphalt	5.0	80
Muravinka	Around houses	Soil[a,b]	8.0	88
Muravinka	House No. 1	Roof[b]	~ infinity	~ 100
Muravinka	House No. 1	Roof (asbestos-cement sheets)[e]	2.0	51

Note: Evaluation of the activity reduction is based on results of *in situ* measurements and laboratory gamma-ray spectrometry; a- the top 20 cm soil layer; b - decontamination procedure included removal of organic matter from the surface; c - decontamination with turbo nozzle; d - decontamination with a mechanical brush; e - decontamination with a metal scraper.

Ref. 12, 13, 14, 15, 16, 17.

Table 3 Reduction of the Chernobyl relating γ-ray dose rate for selected locations due to decontamination carried out in Novie Bobovichi (1995) and Muravinka (1997)

Site	Location	Position of detector	Reduction of dose rate	
			Dose rate factor	%
N. Bobovichi	Housing area, soil	1 m above the ground	5.0	80
N. Bobovichi	Houses Nos. 4, 5 & 6, ground floor	1 m above the floor	2.9	66
N. Bobovichi	River bank, triple digging plot	1 m above the ground	2.1	52
N. Bobovichi	Asphalt area in the forest	1 m above the asphalt	1.7	40
Muravinka	Housing area, soil	1 m above the ground	5.9	83
Muravinka	House No. 1, ground floor	1 m above the floor	3.2	69
Muravinka	House No. 1, first floor	1 m above the floor	2.6	61

Ref. 12, 13, 14, 15, 16, 17.

with the organic matter, which had covered the area before decontamination, a value of DF would be equal to 8.

The inventory of ^{137}Cs in soil around houses was reduced by a factor of about 8 in Muavinka and 4 in Novie Bobovichi. The difference between two sites is attributable to the vertical distributions of the contaminant in the soil. Figure 5 demonstrates that in Novie Bobovichi, a significant proportion of the ^{137}Cs inventory has migrated deeper than 5 cm.

A triple digging procedure resulted in a four- or fivefold decrease in the ^{137}Cs inventory in the top 20 cm of soil profile [13].

Dose rate reduction

Table 3 summarizes results of the decontamination tests in terms of the Chernobyl related γ-ray dose reduction. The values of dose rate reduction factor (DRF) given in the table are calculated for the center area of a treated plot or a house. Usually the maximum dose reductive effect was observed here; the dose rate along the centreline of a decontaminated plot had an inverse bell-shaped (or hat-shaped) profile [9, 13, 14, 16, 17]. The decontamination in the housing areas resulted in a DR reduction by a factor of around 5–6 for outdoor locations and by generally a factor of 3 for indoor locations. On the treated grassland (a river bank) and asphalted plot, the dose rate decreased by a factor of only around two. The reason for this difference between housing and other areas is believed to be related to sizes of the treated plots. For example, a very similar value (around 4.3) of the DF was deduced for the housing area and the 'triple dug' plot in Novie Bobovichi, while the DRF was estimated for the housing area as 4.1 (treated area ~ 270 m^2) and for the triple dug plot as only 2.1 (treated area ~ 100 m^2). With a Monte-Carlo simulation code it was demonstrated that if a larger area had been treated with the triple digging procedure, the dose rate reduction would have been much greater. Specifically, for an area of 40,000 m^2, a reduction of dose rate by approximately 80% (DRF=5) is expected [13]. Such model calculations also indicate that a significant component of the residual dose rate on the dug area is associated with the contaminated (untreated) areas surrounding the treated plot.

A detailed monitoring of radiation conditions during the intervention in housing areas allowed the Danish-Russian researchers to estimate the contribution of each technological step (operation) to the dose rate reduction [9, 12]. The results of these estimations are summarized in Table 4. A removal of the top soil layer gave the major contribution to the DR reduction for outdoor locations. Further application of clean sand had some easily measurable effect (about 15%) in Novie Bobovichi, whereas in Muravinka this procedure gave only about 2% to the total DR reduction outdoors. The thickness of clean sand layer was approximately the same for both test sites [9]. Therefore, the difference in the shielding effect of sand between the sites may be (to some extent) attributable to the fact that the residual radioactivity on the ground after top soil removal was measured for Muravinka as 12% relative to the initial

Table 4 Contribution (%) of the various operations of decontamination to the reduction of the Chernobyl related dose rate (DR) indoor and outdoor in Novie Bobovichi and Muravinka

Site	Location	Contribution of the operations into DR reduction, %			
		Soil clean up		Roof clean up	
		Soil removal	Application of clean sand	Litter removal	Asbesto-cement sheets cleaning or renewing
N. Bobovichi	Soil, housing area	84.4	15.6	n.e.	n.e.
N. Bobovichi	House 4	58.5	13.2	11.3	17.0
N. Bobovichi	House 5	55.4	14.3	12.5	17.9
N. Bobovichi	House 6	50.0	10.9	12.5	26.6
Muravinka	Soil between houses 1 and 2	94.9	2.2	0.0	2.9
Muravinka	House 1, ground floor	82.0	1.7	0.0	16.3
Muravinka	House 1, first floor	53.2	2.4	0.0	44.4

Note: n.e. – not estimated. Based on ref. [9, 12].

level, while for Novie Bobovichi this was much greater, around 24% (Table 2).

By using a very precise instrument, a Reuter Stokes ion chamber, it was possible to measure the contribution of the roof contamination to the total Chernobyl-related DR outdoor in Muravinka. A standard deviation for a single measurement did not exceed 1% [9]. In the middle of the centreline between houses 1 and 2, i.e. at a distance of about 7 m from each house (see Figure 1 in ref. [9]), a renewal of the roof on house No 1 resulted in about 3% reduction of the DR. A much higher DR reduction due to the roof decontamination was found for indoor locations, especially for the points located near the roof (Table 4). Thus, for the first floor of house No 1 in Muravinka, a renewal of the roof and a removal of the top-soil had approximately the same DR reducing effect.

Cost-benefit analysis of the intervention in Muravinka

After intervention in Muravinka, calculations were made to estimate the cost (on a monetary basis) of the implemented countermeasures and their efficiency in terms of the averted external dose [9]. It was assumed that: a) a single house with a 1000 m^2 grassland area is decontaminated, and 2) six people live in the house during the next 50 years. Three options related to the roof treatment were considered: 1) roof untreated, 2) roof cleaned, and 3) roof replaced. At the time of intervention (1997), the locally hired skilled workers and unskilled workers were paid 20 US$ per day and 10 US$ per day, respectively. In 1997, the cost per an averted man-Sv was calculated as 1967 US$ (treated soil+untreated roof), 2017 US$ (treated soil+cleaned roof) and 2715 US$ (treated soil+replaced roof). A minimum value of 3000 US$ per man-Sv was recommended by ICRP [24] for developing countries. That time, Russia belonged to such countries. Therefore, the calculations show that the decontamination in Muravinka was a cost-effective operation, although more than 11 years had passed since the accident. It worth noting, however, that direct application of such simple methodology of cost-benefit analysis to different countries and scenarios of radioactive contamination might lead to non-robust conclusions because many factors should be taken into account for evaluation of remediation and decontamination actions [9, 10, 25]. Below, we list some of those factors. First of all, these quite cost effective options were available in Muravinka due to the fact that there were no previous countermeasures and that the contaminant had not penetrated deeply into the soil profile. Secondly, the easiest way of waste disposal on site was selected and implemented. This approach may not be complied with legislation in the countries other than Russia. Third, top-soil removal at the garden or kitchen garden areas would lead to reducing the soil fertility, and it, in turn, would require application of clean fertile soil. On the 'benefit' side, very important factors include the social and economical benefits to the population of being able to stay in an area that might otherwise become deserted. As mentioned in current ICRP recommendations (e.g., [26]), the optimum protection option is not *necessarily* the option that results in the lowest residual annual doses. Some options could result in a lower residual annual dose but give a smaller net benefit than the optimum option. Whether stigmatization of the contaminated areas in the eyes of the world may to some extent be avoided by reducing contamination levels is another question.

Long-term monitoring of the decontaminated sites

Goals of the post-interventional monitoring program

There are three main tasks of the post-interventional monitoring program that is going on in the areas studied [14, 15]:

1) to estimate a capacity of the disturbed semi-natural ecosystems to recover after the mechanical impact;

2) to examine the long-term stability (over decades) of the achieved efficiency with respect to external exposure;

3) to study accumulation of radiocesium by plants and fungi from the treated and control areas.

In 1995–2004, the program was conducted very intensively. The activities included repeated large-scale measurements on a grid, repeated small scale linear measurements, regular measurements at reference points 1–3 times per year, and periodical collection of environmental samples (soil, forest litter, grass, fungi). In 2005, several reference points were selected in each area for further periodical (once per year) measurements of gamma-dose rate and fluences of nonscattered photons in air. It was also decided to perform collection of environmental samples once per 3–5 years. The monitoring program is still on going.

General state of the treated areas

Immediately after intervention, the area around treated houses looked like a sand beach (Figure 8). After 2–5 years, formation of new grass cover was observed on some opened plots (Figure 9) and at the sites of waste burial. Young trees (e.g. *Betula* sp., *Pinus sylvestris*), grown after intervention, have been also found in the treated housing areas. At the same time, development of typical forest litter was registered under old pine trees (Figure 10). Accumulation of organic matter (needles, leaves, moss) was found on the treated asphalt plot and on decontaminated roofs in Novie Bobovichi. Since 2000–2002 [14], fruit bodies of various fungi species (*Russula* sp., *Suillus* sp., *Tricholoma* sp., *Collybia* sp, *Amanita muscaria)* could be collected on decontaminated plots in the housing areas (Figure 11). Unfortunately, in 2003–2004 all wooden houses from the recreational areas of Novie Bobovichi and Muravinka were dismantled due to economical problems. The building materials, except some brick foundations, were removed from the areas for further reuse. The flooded plain pasture, a section of which was selected for the 'triple digging' test in 1995, is now in a process of natural reforestation because local farmers have stopped to use it for cattle grazing.

Fig. 8 A view at the house 1 after intervention in Muravinka. The area around the house is covered with clean sand, and the roof is renewed, May 1998.

Fig. 9 Formation of new grass cover on an opened part of the decontaminated plot in Novie Bobovichi, June 2001.

Fig. 10　Formation of new forest litter under pine trees on the decontaminated plot in Novie Bobovichi, April 2002.

Fig. 11　Fruiting bodies of edible fungi (*Suillus* sp., to the left; *Russula* sp., to the right) and forest litter from treated plot in Novie Bobovichi, October 2002.

Dynamic of γ-ray dose rate in air

The first series of repeated measurements of DR in air was made in the decontaminated test area at Novie Bovovichi in August 1997, i.e. 23 months after intervention. The average values of DR reduction over this period were calculated as 10%, 8%, 9%, 9% and 10%, respectively for the background forest (5 points), untreated soil (5 points), treated soil (8 points), untreated houses (3 points) and treated houses (3 points). For all locations, the decline in DR was mostly attributable to radioactive decay of ^{137}Cs and ^{134}Cs, which accounted for reduction of the Chernobyl-related DR by 7.4% [17]. Results of the first repeated measurements indicated stability of the dose reduction effect achieved by the decontamination. This has reduced the level of concern about the issue of re-contamination of the treated areas by resuspended soil and other radioactive materials from the surrounding untreated areas [17]. The monitoring measurements conducted in the period 1995–2003 (and further on) confirmed the long-term effect of decontamination. Reduction in DR at all sites has been attributable mostly to physical decay of cesium radioisotopes ($T_{1/2(phys)}$=2.06 y for ^{134}Cs and $T_{1/2(phys)}$ =30 y for ^{137}Cs). The time-dependence of the dose rate due to environmental mobility of the contaminant since the first measurements in 1995 (Novie Bobovichi) or in 1997 (Muravinka) could be described well by an exponential function [14]. Mean values of the ecological half-time ($T_{1/2(eco)}$) were found to be 52±26 y, 57±23 y, 43±21 y, 46±15 y, 66 y, and 80±56 y for the following locations: untreated outdoors (5 points), treated outdoors (5), untreated indoors (5), treated indoors (4), waste container (1) and undisturbed forest-grassland plots outside the recreational areas (12), respectively. These data, as well as results from other studies, e.g. [20, 27], indicate a strong fixation of ^{137}Cs in the environment several years after the Chernobyl accident. The trends observed for the outdoor sites and waste container for the period 1995–2003 have been confirmed by monitoring of the recreational areas and reference forest-grassland plots outside these areas during 2004–2012 (unpublished data).

Radiocesium in soil, grass and fungi

Analysis of the soil cores sampled in 2002 from treated and untreated areas demonstrated no clear evidences of any significant horizontal or vertical radiocaesium migration. On the contrary, a tendency towards a decrease of the total ^{137}Cs inventory in treated ground plots was observed in both recreational areas following the intervention [14]. It is interesting to note that a clear borderline between added yellow sand and dark maternal soil could be distinguished in all collected soil cores (see an example in Figure 12). A peak of ^{137}Cs activity concentration was found just below the borderline between the maternal soil and added sand (Figure 12). For the undisturbed plots sampled in 2002, the maximum activity concentration of radiocesium was associated with the top 0–2 cm (or 0–4 cm) soil layer (Figure 13; see also Figure 2 in ref. [14]). Repeated sampling (2004–2009) did not reveal any significant re-contamination of the treated plots (unpublished data).

In 2000–2002, the activity concentrations of ^{137}Cs in fungi (five species) collected at the untreated forested areas in Novie Bobovichi and Muravinka ranged from 3000 Bq kg^{-1} to 340000 Bq kg^{-1} (on dry weight) [14]. The levels of contamination for the same species from treated plots appeared to be approximately one order of magnitude lower, varying from 280 Bq kg^{-1} to 19000 Bq kg^{-1}. Still larger differences (up to two orders of magnitude) were found between the treated and untreated plots with respect to the activity concentrations of ^{137}Cs in grasses [14]. It is believed that the lower level of residual ground contamination by ^{137}Cs and its deep position in the soil profile (Figures 12 and 13) are responsible for the profound differences between activity concentrations in the biota samples from treated and untreated plots.

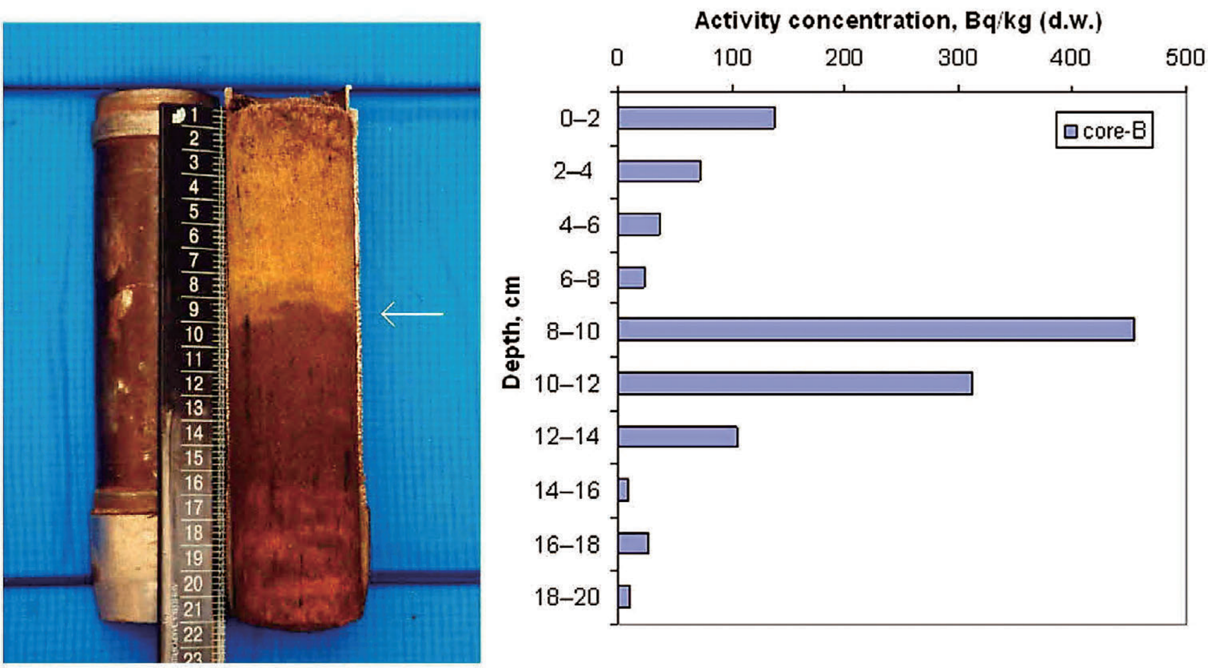

Fig. 12 Vertical distribution of the activity concentration of ^{137}Cs (to the right) in a soil core (to the left) sampled on treated plot in Muravinka in 2002

White arrow indicates a borderline between the maternal soil and added sand. The distribution of activity concentration is constructed based on ref. [14].

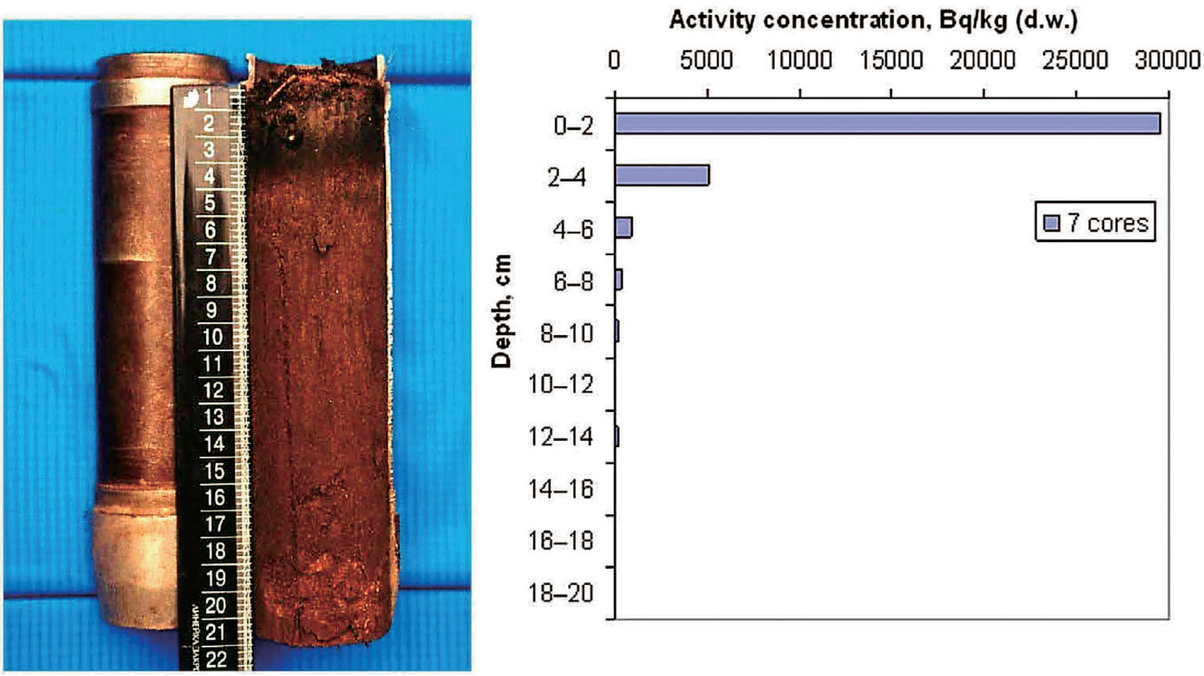

Fig. 13 Vertical distribution of activity concentration (dry weight) of ^{137}Cs at an untreated plot in Muravinka in 2002 (to the right) and a soil core sampled on the plot (to the left)
The distribution of activity concentration is constructed based on ref. [14].

Conclusions

The collaborative RISØ–RIRH research project conducted on the radioactively contaminated territories of the Bryansk region (Russia) in 1995–2003 showed that optimised implementation of simple countermeasures involving hand-tools and light machinery could reduce the external dose rate considerably, even though 10 years had passed since the fallout of radiocesium. The countermeasures were found to be cost-effective. The long-term monitoring of the treated recreational areas Novie Bobovichi and Muravinka did not demonstrate significant re-contamination of cleaned ground plots within the time period of 15–17 years after intervention. The technologies and methods implemented for clean up of the recreational areas may be recommended for restoration of other radioactively contaminated housing areas located in undisturbed forest-meadow surroundings. Specifically, some areas, which had been heavily contaminated in 2011 as a result of the Fukushima accident in Japan, could be a target for such intervention.

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