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Mechanical decontamination tests in areas affected by the Chernobyl accident

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Abstract Decontamination was carried out around three houses in Novo Bobovichi, Russia, in the summer of 1997. It was demonstrated that significant reductions in the dose rate both indoor (DRF = 0.27) and outdoor (DRF = 0.17) can be achieved when a careful cleaning is undertaken. This report describes the decontamination work carried out and the results obtained. The roof of one of the houses was replaced with a new roof. This reduced the Chernobyl related dose rate by 10 % at the ground floor and by 27 % at the first floor. The soil around the houses was removed by a bobcat, while carefully monitoring the ground for residual contamination with handheld dose meters. By monitoring the decline in the dose rate during the different stages of the work the dose reducing effect of each action has been estimated. This report also describes a test of a skim&burial plough developed especially for treatment of contaminated land. In the appendices of the report the measurement data is available for further analysis.

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Contents

Preface

In the south-west corner of the Briansk Region large areas were contaminated by the Chernobyl accident. The level of contamination exceeds 1.5 MBq m^{-2} in several villages and these have to some extent become deserted. There is a need for decontamination, both to prevent further depopulation and to stimulate the return of the population to the affected areas.

In 1995 a joint Russian-Danish field exercise sponsored by the Danish Emergency Management Agency under the Ministry of the Interior decontaminated the area around three houses in Novo Bobovichi 25 km north-north-west of Novozybkov. The work was carried out with hand tools, shovels and wheelbarrows, and monitored carefully with handheld dosimeters. Indoor dose rate reductions of 64 % and outdoor dose rate reductions of 78 % were achieved.

A second decontamination project was initiated in 1996 and in August 1997 a second field exercise was launched. Here the focus was on the application of heavy machinery in the decontamination work. An expedition from Risø National Laboratory went to the Novozybkov area in August 1997 with a bobcat (a mini bulldozer designed for work in gardens), an asphalt scraper and a skim and burial plough. An excavator and a tractor with a wagon were rented locally together with manual labour. The work was carried out in close collaboration between the Danish team and a team of five scientists from the Federal Radiological Center at the Institute of Radiation Hygiene in St. Petersburg.

It is our hope and belief that the results presented here, will form the basis for an increased interest in the possibilities provided by urban decontamination, especially in the light of the change in the Russian policy towards stopping the migration from the contaminated areas and instead remediate and resettle the areas.

This project was made possible by the funding provided by The Emergency Management Agency under the Danish Ministry of the Interior and all the participants would like to express their gratitude towards the Agency for the support, which has resulted in the most promising decontamination work in Russia so far.

1 Introduction

1.1 The Chernobyl Accident

As a consequence of the accident at the Chernobyl nuclear power plant in April 1986, large areas of primarily three republics of the former Soviet Union (Belarus, Russia and Ukraine) received high levels of surface contamination. In magnitude, the challenge in terms of measuring, monitoring and assessing the consequences of the accident are likely to have exceeded all previous efforts to deal with anthropogenic disasters. Over the first three years, various protective actions and restrictions were implemented in the affected areas. Among the actions were relocation, decontamination efforts in some of the most heavily contaminated settlements and control of locally produced foodstuffs. These countermeasures were aimed at reducing external and, particularly, internal dose rates from deposited ^{137}Cs in the areas. At a conference in Kiev in May 1988, the major short-term human, economic and environmental impacts of the accident were summarised as follows: 31 deaths, the evacuation of more than 100,000 persons from the 30 km zone surrounding the power plant, and the removal of a large number of livestock (several thousand), as well as a severe contamination of very large areas in cities, rural environments and forests. This contamination would inevitably have a long-termed effect, since two major dose contributors, ^{137}Cs and ^{90}Sr, both have radiological half-lives in the range of 30 years. From the limited applicable experience available from previous contamination events it was already known that the natural weathering processes would only very slowly reduce the radiation levels.

Over the following few years, an increasing amount of attention was paid to the long-term consequences, also for persons staying outside the early evacuation zone. Although some of the longer-termed effects could not be avoided at this point, e.g., thyroid cancers developing years after the early exposure to radioactive iodine in milk, it was clear that more guidance of the form of long-term radiation protection criteria would be required, to supplement, optimise and revise the relocation policies implemented over the first three years. At this point in 1989, the so-called 'safe-living concept' was introduced by the Soviet National Committee on Radiological Protection, defining an upper limit of equivalent dose rate of 350 mSv over a life-time, below which action in terms of countermeasures was deemed unnecessary.

A WHO founded group of experts soon after reached the conclusion that this upper limit was rather conservative and it was estimated that its implementation would imply the relocation of a further 100,000 persons. However, relocation was encouraged and over a period of some five years resulted in a degree of desertion of large areas. According to Hubert et al. (1996), a total of 260,000 people have been relocated. Only in recent years has the official policy changed, following the concept initiated by a group of experts of the USSR Academy of Sciences in 1991. Here, an increased interest was expressed for dose reducing measures to be implemented in the contaminated areas. The psychological factors in terms of stress, fear and anxiety were highlighted and were said to be in-line with typical post-accident syndrome effects, although special problems had arisen from misunderstanding and misinterpretation of the information given. It was stressed that an effort, both in terms of information and of dose reduction, would have to be made to end the mass relocations. After the separation of the different Soviet Republics in 1991, the Russian Federation introduced its own recommendations (Belyaev et al., 1996). In the 1993 recommendations the need was again stressed for '...effective measures for rehabilitation of the contaminated areas and restoration of normal life and economic activity'. The recommendation was to prepare a programme of rehabilitation to stop the degradation of residential, industrial and agricultural areas and stimulate the return of previously relocated persons.

To stimulate the rehabilitation process in the contaminated areas the Russian Federation has introduced a monthly payment to the population to compensate for the radiological risk of living or working in contaminated areas. The level of contamination by ^{137}Cs in open areas forms the basis for the magnitude of the payments. In the Novozybkov city area, where the contamination level is generally around 550 kBq/m^2, the monthly compensation to the locals in 1995 corresponded to 40 US$.

Also decontamination and reconstruction operations in settlements have now been resumed. So far, some old houses have been demolished, some new houses have been built, contaminated roads have been covered with new asphalt or clean gravel, which shields against the radiation and at the same time prevents resuspension in air of radioactive material. Further, new rain water drainage systems have been constructed.

The relocations have been stopped almost completely, since they are not cost-effective, and the remaining inhabitants mostly have a strong wish to stay in the local areas.

1.2 The Contamination of Novozybkov district

The news of the accident on April 26th 1986 at the Chernobyl nuclear power plant reached the population of the Novozybkov area of the Bryansk region in Russia on the 3rd of May (IAEA, 1991). Although some simple protective measures were soon after introduced in for instance kindergartens, it was not until the 9th of May that the authorities instructed the population to stay indoors, keep their windows closed and wash themselves thoroughly. However, at this point, the air concentrations of many of the most important radioisotopes had already decreased by several orders of magnitude (Kryshev, 1996), and the inhalation dose could thus not be reduced significantly by these countermeasures. Since the Novozybkov area received prolonged heavy rain soon after the Chernobyl accident, the air was, however, effectively cleaned by wash-out of the contaminants, and inhalation doses were not high in this area. The dry deposition processes are estimated to be responsible for only about 1 % of the ^{137}Cs contamination of the area (Roed et al., 1998). The wet deposition was, however, quite substantial in the Novozybkov area (as indicated by the red areas in plate 1, where the contamination level exceeds 1.5 MBq/m^2). Wet deposition, in general, leads to much greater deposition of pollutants per unit of time than does dry deposition. In the Bryansk region as a whole, 15 settlements with a total of about 22,000 people were contaminated with caesium of levels exceeding 1.5 MBq/m^2 (IAEA, 1991).

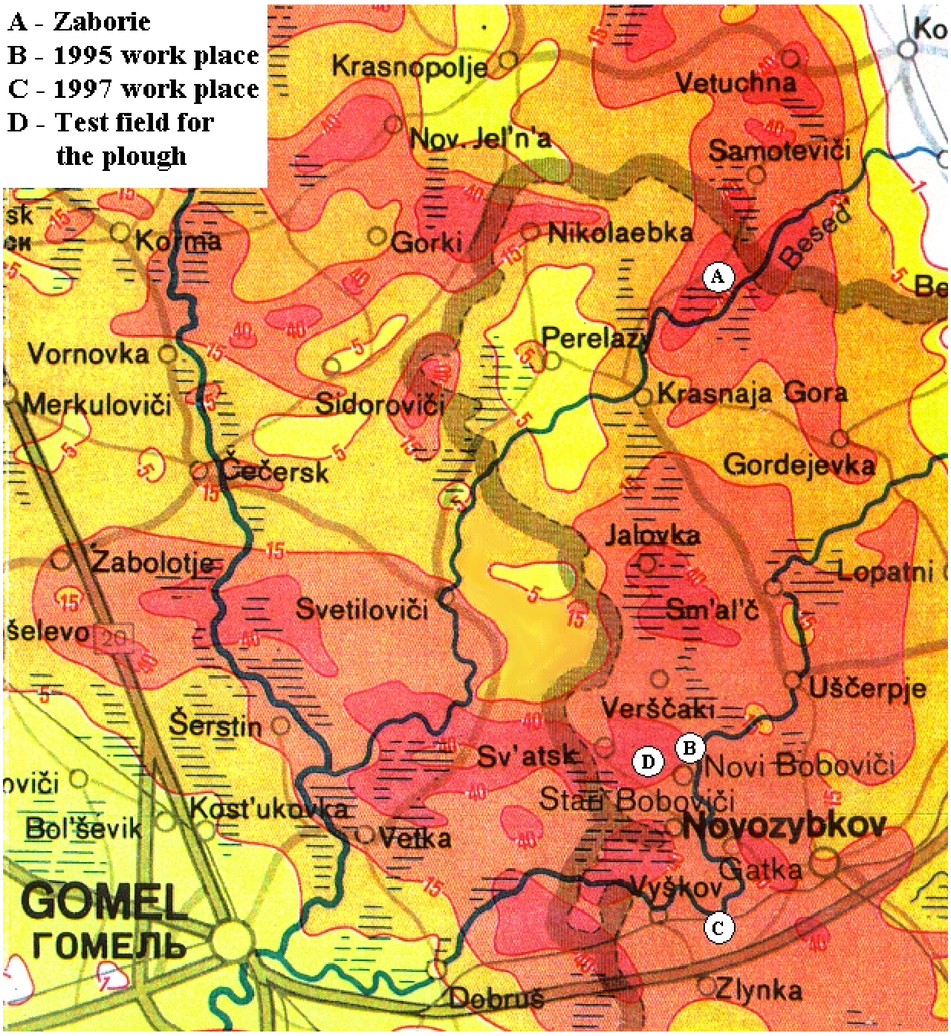


Plate 1.1 Initial^{137}Cs contamination levels in the Novozybkov area after the Chernobyl accident. Iso-lines are shown for contamination levels of 1 Ci/km^2, 5 Ci/km^2, 15 Ci/km^2 and 40 Ci/km^2 (corresponding to 37, 185, 555 and 1500 kBq/m^2).

Some three weeks after the accident had occurred, the town was supplied with powdered milk, which was free of ^{131}I. Potassium iodide tablets were at the same time distributed to children in the area, but as the introduction of this countermeasure was obviously too late, it was stopped again about a week later. Obviously, this sort of inconsistency increased the anxiety of the locals. In the time prior to this, however, particularly the children in the area received significant thyroid doses from the intake of ^{131}I. The thyroid doses to more than 17,000 inhabitants were estimated through a large-scaled measurement programme over the following weeks. About 7,000 of these were children. It was found that about 200 had received doses to the thyroid exceeding 0.75 Gy. According to ICRP publication 60 (1990), a dose of 0.75 Gy to the thyroid gives a fatal cancer risk of 6 10^{-4}. However, it must be stressed that risk coefficients vary greatly among different authors (Likhtarev et al., 1994). From the early phase, milk was imported from a radiologically clean area about 120 km away, and local food products checked regularly for the content of radioactive matter.

1.3 Experience from Previous Decontamination Efforts

Inhabited areas of the Bryansk region were subjected to decontamination during the summer of 1989. The decontamination work was carried out by units of the Soviet army, and covered 93 settlements with a total population of about 90,000 (Anisimova et al., 1994). At the time that the decontamination work was initiated the distribution of the contamination was described as rather heterogeneous. The mechanical impact of human activity on the contaminated surfaces was reported to be insignificant in some almost deserted areas, whereas it was highly significant in for instance working areas.

Essentially, the army units relatively consistently carried out only two procedures:

- A layer of topsoil was removed, which was supposed to include most of the contamination.
- A layer of clean sand or gravel was applied afterwards to shield against residual contamination in the soil.

Decontamination generally only took place in yards of private houses, around public buildings and along roads of a total length of about 190 km.

The St. Petersburg Institute of Radiation Hygiene carried out the dosimetric assessment of the effect of the work. The dose reducing effect was found to be disappointingly low. Decreases in dose rate by generally a factor of 1.1 to 1.5 were recorded. A similarly low efficiency was found to be the result when the same procedures were carried out in the Belarussian settlement Kirov. Here, the dose rate was reported to have been reduced by some 8 %.

The costs of the efforts in the Briansk region were in 1989 found to amount to 15,359 rubles per averted man-Sv, and since an averted man-Sv was then given the value of 5,000 rubles, the operation was clearly not cost-effective. Therefore, decontamination was not considered to be a realistic option in the following few years.

Very little is described about how the actions were carried out, but it is known that not all landowners allowed intervention on their ground. Therefore, coherent treated areas may not have been very large. As previously reported (Roed et al., 1996 a), the difference in dose rate reduction between treating only a 10 m by 10 m area and treating an extremely large area of land may in some cases be as much as a factor of 5. It is also evident that the planning of the operation and assessment of the local radiological conditions prior to treatment was insufficient. Any potentially effective countermeasure may fail to significantly reduce the dose rate if it is carried out regardless of the local contamination distribution. In some situations, the dose rate may even increase (Roed & Andersson, 1996). The thickness of the removed soil layer may not have been sufficient, and judging from radiological maps of the effect, the work was not carried out consistently, even over small garden areas. Further, it is unlikely that special care was taken to treat 'hot spot' areas, such as the soil immediately adjacent to buildings, soil under roof-gutters, etc. It has been established (Roed et al., 1996 a), that contamination on roofs may contribute significantly to the dose rate, but practically no efforts were made to treat these.

Four years later, an international effort supported by the Commission of the European Communities, was made to test a number of dose-reducing procedures, which were thought to be particularly promising for inhabited areas. The in situ tests, which took place in Russia and in the Ukraine in 1993-1994, indicated that it was indeed possible to reduce the dose rate significantly, although many years had already at that time passed since the Chernobyl accident, and it was certain that much of the contamination was strongly bound and much less accessible by the procedures than had previously been the case. Separate methods were tested and evaluated in a catalogue, which was published as a Risø report (Roed et al., 1995). However, the test areas were rather small and the dose-reducing effect of carrying out a complete clean-up strategy was never investigated.

Many different aspects need to be considered in the formation of a strategy. A procedure may be well suited for some types of environments, but may for specific reasons (e.g., soil texture, contamination distribution, time-period, season, etc.) be totally inapplicable in other environments. Further, the effect of carrying out a strategy can not be evaluated by merely adding up the effects of treating the individual surfaces. It might well be that in some cases, a decontamination procedure for one type of surface translocates the contamination from that surface onto a different area. In some cases, this may even lead to an increase in dose rate, and it is therefore important to carry out the different procedures of a strategy in the right sequential order.

Therefore, an expedition sponsored by the Danish Emergency Management Agency was launched in the autumn of 1995 to the contaminated Russian settlement Novo Bobovichi in the Briansk region, to which Chernobyl debris had descended in rain. The main objective was to prove that it was still possible by relatively simple and inexpensive means to carry out an effective dose reduction strategy in settlements contaminated by the Chernobyl accident.

The main contributor to radiation levels inside the wooden houses in the test area was found to be the contaminated soil but the roofs also made a significant contribution, whereas radiation from walls was comparatively insignificant. The many large pine trees in the area had shed their needles several times over since the accident and their contribution to radiation levels was very much less than that of the contamination in the soil. Contamination on roads was very small, and this was not surprising since earlier studies had shown that the levels on such surfaces usually decrease by at least one order of magnitude in the decade following wet deposition due to traffic and weathering. Clearly, decontamination of soil and roofs offered the greatest potential for reducing radiation levels in the settlement.

For logistical reasons, it would have been better to treat the roofs before the soil since there was a risk that contamination displaced from the roofs could land on the soil. However, for this demonstration it was decided to treat the soil first since this would facilitate a more accurate measurement of what can be achieved through roof-cleaning alone. The decontamination scheme was therefore as follows:

1. Removal of the topmost 5-10 cm of soil from an area of 20m by 20m around three wooden houses: only hand-tools (e.g. spades, shovels, wheelbarrows, etc.) were used in order to demonstrate what can be achieved by simple means.
2. Cleaning of the asbestos roofs of the three houses by first removing the loose litter (e.g. leaves and pine needles) and secondly by using a specially constructed scrubbing device.
3. Application of clean gravel to the decontaminated land to attenuate residual radiation.

This approach to decontamination enabled a calculation of the fraction by which the initial dose rate level was reduced by each of the decontamination steps. It was also possible to identify the likely sources of the residual contamination. The overall mean reduction in dose rate achieved as a result of the total operation was as much as 64%.

1.4 Objectives for the Expedition in 1997

The present report describes the results of a second field investigation campaign supported by the Danish Emergency Management Agency, in the late summer of 1997. Like in 1995, scientists from Risø and from the St. Petersburg Institute of Radiation Hygiene participated jointly in the experiments. This year, most of the assessments were made in the Guta Muravinka area of the Bryansk region.

One of the objectives for this year's work was to introduce in a clean-up strategy larger machines, which could carry out some of the tasks, which had in 1995 been accomplished by hand. For instance, the removal of soil was in 1995 carried out using spades and shovels. This could probably be accomplished at a much greater speed using a bobcat with a scraper. Due to the unevenness of the soil surface, the question remains as to whether this equipment would enable a homogeneous removal of a thin top layer. It might also prove difficult to manoeuvre around buildings and trees, and the dose rate contribution from the contaminated soil nearest to the house is often of great importance.

Essentially the same procedure that was in 1995 performed by triple digging was in 1997 accomplished using a specially constructed skim-and-burial plough. Hereby, the contaminated top soil layer is buried deep in the vertical profile, thus providing a good shielding against the radiation. Whereas it is estimated that one man can triple dig 2 m^2 of soil area per hour, the test showed that one plough can treat some 3,000 m^2 of land in an hour.

Some of the locations in which the dose rate measurements were carried out at Novo Bobovichi in 1995 were re-assessed in 1997. This would show if any re-contamination or other movement of the contamination had occurred.

One of the surprises from the 1995 measurements in Novo Bobovichi was the high level of contamination on roofs. The 1997 measurements at Guta Muravinka would show if this result could be verified, as a more general feature.

Also included in the 1997 measurement programme was an assessment of the dose rate in various locations at 1st floor level inside a building. Not only the total dose rate was observed, but also the decrease in dose rate by treatment of each surface. This type of measurements have to our knowledge never previously been made, although modelling has indicated the great significance of doses received indoors on various floors, due to the large fraction of time spent here.

In 1995 it was concluded, that a major contributor to dose rate after decontamination was the contaminated adjacent forest. Therefore, the forest contamination was further investigated in 1997, where dose rates were measured and samples brought to the laboratory for analysis. Forest decontamination has recently attracted great attention in Belarus and the Ukraine, since preliminary plans have been introduced for safe application of the removed contaminated bio-mass as fuel for specially designed power plants.

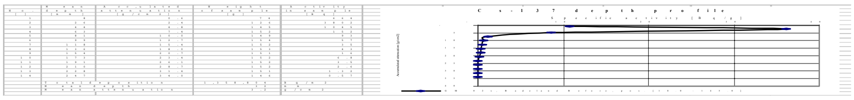
2 Units and Devices

2.1 Radiation Units

The results of the work carried out are explained by essentially three units:

Doses were measured in units of Sv (Sievert, 1 Sv = 1 J kg^{-1}), which is the SI unit for equivalent dose and is defined as the mean energy imparted by ionising radiation to matter of a given mass, multiplied by a factor indicating the biological effectiveness of the radiation. This latter factor is 1 for gamma radiation. Similarly, the term dose rate refers to the increment of the equivalent dose per unit of time, and is generally expressed in units of Sv h^{-1}. In some cases, the exposure rate has been measured in stead of the dose rate. Exposure is defined as the quotient by air mass of the absolute value of the total charge of ions of one sign produced in air when all electrons liberated by photons in air of the given mass have been stopped in air. The SI unit for exposure is C kg^{-1}. Often the unit Röntgen, R, is used instead (1R = 2.58 10^{-4} C kg^{-1} in air). The exposure rate is simply the increment of exposure per unit of time, here denoted as R h^{-1}. Although the relationship between the dose rate and the exposure rate is at low energies (less than 100 keV) greatly dependent on the tissue type (bone, muscle, fat, etc.), the major part of the doses received from ^{137}Cs radiation in the field is sufficiently high-energetic to justify the application of the general relationship of 100 R/h exposure rate corresponding to 1 Sv/h dose rate.

The dose reduction factor refers to the relationship between the dose rate after the introduction of a dose reductive measure and that, which was recorded initially. The dose rates applied here are not including the 'background' contributions from natural terrestrial radiation and cosmic radiation. Thus, the formula for the dose reduction factor can be expressed as:



The decontamination factor DF refers to the relationship between the contaminant concentration on a surface prior to decontamination and the concentration after the surface has been treated:

$$\mathrm{DF} = \frac{\text{surface concentration before decontamination}}{\text{surface concentration after decontamination}}$$

Using this factor, the effect of an effort to decontaminate a specific contaminated surface (such as a grassed field, a house roof, a road paving, etc.) can be described. The two surface concentrations, through which the DF is defined, have in this report predominantly been assessed by gamma spectrometric analysis using germanium or sodium iodide detectors. For in situ applications in a geometrically complex inhabited area, it is often necessary to collimate the detector in order to view defined areas of horizontal or vertical surfaces. Collimation of the detector was achieved with lead shielding blocks assembled on an adjustable steel table. Another option for determination of the DF is, where possible, to take samples of the treated and untreated surface for gamma spectrometric analysis in the laboratory.

2.2 Measurement of Dose Rates

Measurement of dose rate in the investigated areas was accomplished using various different devices. One of these is a Reuter Stokes ion-chamber (model RSS-112). The active volume of this device is 7.9 litres in magnitude and is filled with ultra-high purity argon at a pressure of 25 atmospheres. Radiation incident to the chamber produces ion-pairs, which are swept to the electrodes due to an electrical potential. The resulting current can be related directly to the exposure rate in air, which is then again related to a dose rate. The sensitivity response energy function is relatively flat between ca. 100 keV and ca. 10 MeV, but the chamber inevitably has a higher sensitivity towards scattered (low energy) radiation. The dose can be assumed to be a linear function of the detector response in the area up to 1 mSv/h. If the chamber is moved from one position to another, the corresponding time constant of the change of the signal has been found to be about 5 seconds. At the dose rate levels for which the device was applied in the contaminated areas around Novo Bobovichi and Guta Muravinka, the standard deviation of the result of a 5 seconds measurement was found to be about 1 %, whereas the uncertainty including systematic errors introduced through, for instance, the calibration and the atmospheric pressure was found to amount to about 5 %. Since a measurement with a low standard deviation only took 5 seconds to produce, a series of measurements over at least a minute was generally recorded to determine the deviations of the individual measurements. If this standard deviation exceeded 1%, it was concluded that the signal was not stable and the procedure was repeated.

As much of the ^{137}Cs has penetrated several centimetres into the ground, the dose rate in air will depend on the attenuation of the photons in the ground. The attenuation will depend on the varying moisture content in the ground. In Figure 2.1 the dose rate measured at a reference point is presented. It can be seen that the dose rate increases by about 5 % from the start of the measurements in Guta Muravinka to the end. It rained the night before the work started, but the following weeks the weather was dry. Throughout the first week the topsoil dried out and the dose rate increased. After about one week with dry weather the dose rate remained stable.

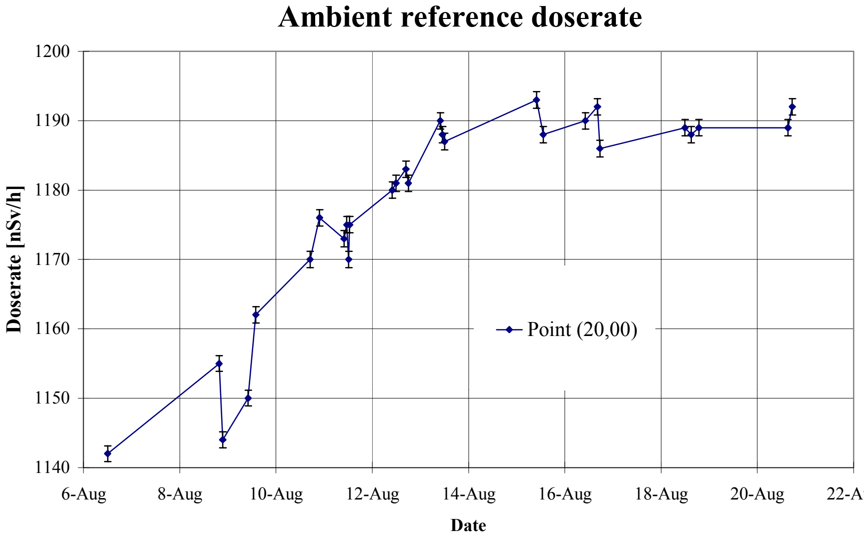


Figure 2.1. Total dose rate measured in Guta Muravinka at location (20, 00).

Also an easily portable instrument called EL 1101 was applied for dose rate assessment. The EL 1101 was produced by the Belarussian Company Atomteh and is based on a NaI crystal with a diameter of 16 mm and a length of 25 mm. This instrument measures the energy spectrum of the γ-photons in the energy range between 0.04 and 3 MeV. This spectrum is converted to a dose rate reading by a special algorithm. The El-1101 was used for the measurement of exposure rates and dose rates.

In Figure 2.2 a comparison between El-1101 and the Reuter Stokes ion chamber is shown. The measurements were made in different locations in Novo Bobovichi in August 1997. It can be seen that there is a good linear agreement between the two data sets.

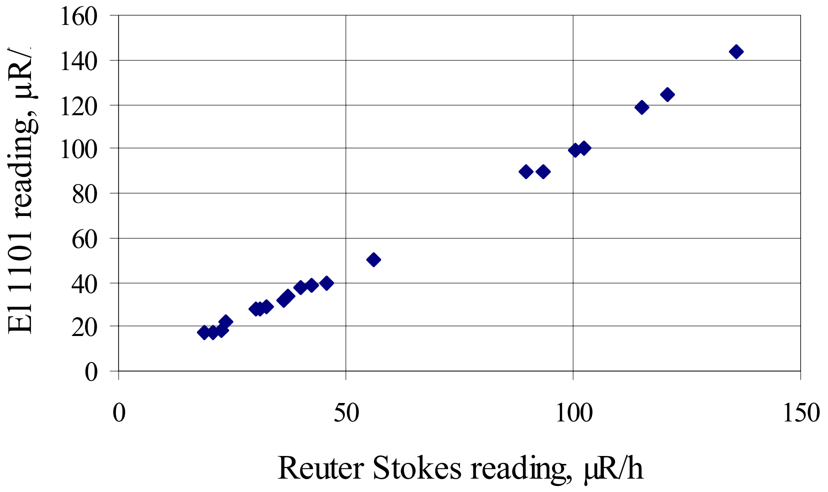


Figure 2.2. Exposure rates measured with an EL 1101 device plotted against exposure rates measured at the same locations using a Reuter Stokes RSS-112 ion chamber.

Another device that was less frequently applied to measure dose rates is the DRG-001. This instrument was constructed at the Institute of Radiation Hygiene in St. Petersburg and is based on Geiger-Müller tubes. The device, which was calibrated with the principal isotope in these investigations (^{137}Cs) actually measures the exposure rate.

A hand-held device, also developed at the Institute of Radiation Hygiene, with the name of DRG-01-T1 was applied more frequently. Also this instrument was based on Geiger-Müller tubes.

By calibration measurements in the Finnish Gulf the combined value of the noise and cosmic radiation response were found for the instruments:

- for DRG-01-T1	8.5 µR h^{-1}
- for DRG-001	4.5 µR h^{-1}
- for El-1101	1.5 µR h^{-1}

As can be seen there is a good correlation between the results of the two devices, with the measured dose rates ranging from 20 to 130 µRem/hour = 0.2 - 1.3 µSv/h.

The natural background was determined from measurements in 1995 to be 60 nSv h^{-1} in Novo Bobovichi (Roed *et. al*, 1996a). Here, the 'cosmic' dose rate contribution due to primarily high energy muons, photons and electrons, was estimated to be 35 nSv/h. This corresponds well with the exposure rate figure of 3.59 μR/h, which is stated in the RSS-112 operation manual for sea level altitude.

The terrestrial background contribution to dose rate was in 1995 estimated to be 25 nSv/h. This estimate was based on measurements of the soil contents of the naturally occurring radionuclides ^{40}K, ^{226}Ra and ^{232}Th, made both in situ and in the laboratory for soil samples, with the normally valid assumption that the isotopes are homogeneously distributed over the relevant vertical and horizontal distances. Measurements made in 1997 on soil samples from Guta Muravinka showed a similar content of these three radionuclides and the 'natural' dose rate contribution in Guta Muravinka can therefore be assumed to be similar to that found in Novo Bobovichi.

2.3 Other Contamination Assessment Methods

An other technique that was applied to investigate the distribution of the contamination and the effect of dose-reducing countermeasures was sampling for further analysis in the laboratory.

From spectrometric measurements at the surface, an equivalent 'average depth' of the contamination in soil may be estimated. However, the vertical distribution was previously erroneously considered to be adequately described by an exponential function of the depth. Recent investigations have shown that the Chernobyl radiocaesium depth distribution in soil is often better described by a Lorenz function. The exact vertical distribution of the contaminants in the soil, both before and after the introduction of a dose-reducing countermeasure, can be obtained only through soil sampling.

It is essential to know the distribution of the contamination in soil, both vertically and horizontally, before attempts are made to reduce the dose. If the depth distribution is not known, for instance, a too thin soil layer may be removed and the dose-reductive effect may be much less than what could have been achieved. This is one explanation for the low efficiency of the decontamination work that was first carried out by the authorities in the areas affected by the Chernobyl accident. Indeed, the result may be a rise in dose rate. On the other hand, if a too thick layer of soil is removed, it may severely affect the soil fertility and it will generate large volumes of waste.

The soil sampling was accomplished by driving polyethylene tubes measuring 81.0 mm in diameter and 4.5 mm in wall thickness into the ground. Tubes measuring about 30 cm in length were applied to investigate the vertical ^{137}Cs distribution in the soil prior to any dose-reductive treatment, whereas longer tubes measuring more than 50 cm were applied to determine the vertical distribution after digging or ploughing, which are procedures that affect the contaminant distribution throughout the uppermost half metre soil layer. When the full length of the tube had penetrated the ground, it was withdrawn together with a soil core. The withdrawal was performed with special care to prevent loose material from falling out. Therefore, the soil surrounding the outer surface of the tube was first excavated. The sample cores, which were still in plastic tubes, were then wrapped in a thin plastic film to prevent them from drying out and falling apart.

When the sample cores had reached the laboratory, 200 ml of distilled water was added to each tube, which was subsequently transferred to a deep freezer (at -20°C), where it was left for two days.

The tubes containing the samples were then sliced with a diamond saw. The blade of the saw is 2.57 mm thick. Consequently, by this slicing procedure, a corresponding layer of the soil core was lost by each sectioning. A spacing device on the diamond saw made it possible to accurately adjust the thickness of the slices. The saw blade usually has to be cooled with water, but at this point the samples contained sufficient amounts of water to grease/cool during the slicing process. As the samples were deep frozen the slices kept their parallel-side circular disc shape and even stones in the samples were cut through.

The reproducibility of this 'precision engineered' technique has been evaluated through an examination of a series of sectioned core samples, which showed that the variations in thickness have a standard deviation of about 1 %.

Since the samples stayed in the plastic tube during the slicing process, the sliced tube sections formed rings around the sample slices. These rings supported the samples during the different analysis sequences (drying, weighing and γ-measurement). Further, a removal of the whole soil core from the tube would have introduced an unnecessary cross-contamination hazard.

The samples were then dried in 3 days at 60°C. After drying, the density of the samples was established through a weighing, where the mass of the plastic ring was subtracted. Stones and grass roots were not removed. This enabled a determination of the bulk soil density and the attenuation as a function of depth. The density of the sample was also used to allow for the attenuation of gamma-rays through the soil slice while measuring the gamma-activity.

The photopeak count rate of ^{137}Cs (661.6 keV) in each sample was measured in a lead shielded gamma spectrometer which includes a 15.6 % efficiency Ge(Li) detector. In this calibrated detector system the sample was placed directly on top of the upward facing detector end cap.

Finally, the photopeak net count rate was converted to a contamination level (Bq cm^{-3} of ^{137}Cs) in the sample, taking into account differences in slice thickness and densities relative to the calibration standard.

In Appendix A, the vertical distribution of the contamination is shown both before and after dose-reductive countermeasures had been carried out. The mean depth in centimetres of each slice of the cylinder is given, allowing for the thickness of material removed by the saw blade. More importantly, depths are given in units of accumulated mass of soil per area above the given depth (g cm^{-2}). This figure is indicative of the attenuation that the soil provides against the radiation at the different depths, as it incorporates the soil density. It is evident that the soil density will be small in the top layers, which contain much organic material and has larger pores. The content of radioactivity is expressed in units of Bq per gramme of soil sample mass. This figure is a good measure of the amount of contamination associated with each amount of soil in the vertical profile.

In other cases, soil samples were taken using a specially constructed excavation device made out of steel. The samples that were produced in this way measured 20 cm in length, and 5 cm in diameter. These samples were sectioned in the field at 5 cm ± 10 % intervals, using a knife. The slices were placed in cylindrical metal containers and the content of ^{137}Cs was measured in a lead shielded spectrometer based on a NaI(Tl) detector (measuring 3 inches in both length and diameter) and a portable 480 channel analyser. The measurement time for the samples in the field was in all cases 120 seconds.

In some cases, another detector system was applied in the field - the CORAD developed by RECOM Ltd., Moscow, which is based on a lead collimated cylindrical NaI(Tl) detector crystal with both diameter and length of 50 mm operated with a photo multiplier. This system, which measures the contamination levels rather than dose rates, was here primarily applied to investigate the effect of decontamination trials on impermeable surfaces, particularly to scrape off a thin contaminated surface layer of asphalt. However, the system can also, through analysis of the detector response in different energy windows, be applied to estimate the average depth of a contamination distribution in for instance soil. A detailed description of this feature is given by Roed et al. (1996a), together with an account of how the calibration procedure is accomplished.

3 Guta Muravinka

The main effort of the 1997 expedition to Russia was the decontamination of the recreational zone in Guta Muravinka. The area was closed to the public after the Chernobyl accident, as it is situated in an area that has received a ^{137}Cs contamination of about1.5 MBq m^{-2}. Therefore, no decontamination had been carried out in the area. Three years ago the area was again opened to the public and now there is a steady stream of visitors, especially in the week-ends. Some come for the day and use the smaller cabins, others stay overnight in the houses. The average dose rate outdoors is about 1 µSv h^{-1}.

Two areas were selected for decontamination. A grassed area by the 'beach' and a larger area around the houses. These two areas represented the locations where people spend most time. The cleaning of the grassed area was a relatively simple task and it was done to get some experience in working with the bobcat. The cleaning around the houses was a greater task, which also gave more useful information about the obtainable effect of application of decontamination measures in urban areas.

The main innovation compared to earlier decontamination exercises was the use of heavy machinery for the soil removal. Here a bobcat was used. The bobcat is a 'mini-bulldozer' suitable for work in gardens and around houses. An excavator was used to dig pits for some of the waste and tractors with trailers were used to transport a part of the waste to remote depositories.

The work progressed according to the following schedule:

1. Mapping of the dimensions of the site.
2. Mapping of the ^{137}Cs pollution.
3. Test cleaning in the green area.
4. Removal of the soil
5. Measurements of the effect
6. Renewal of one roof
7. Final mapping of the contamination situation

The combined Russian-Danish team worked along this schedule for 3 weeks.

3.1 Description of the Site

The recreational area is located in a picturesque part of the east bank of the river Iput. It is a very attractive place, especially in good weather. The water in the river is clean and transparent, and the sandy shore makes it an excellent site for bathing. The shape of the riverbank area is shown in **Figure 3.1**. After a steep rise from the shoreline, the landscape becomes plane and forested. On this plane surface the recreational resort had been founded. A map of the part of the area that was selected for cleaning is shown in **Figure 3.2**. It includes five identical houses, in this study referred to as **Houses 1** through **5**. The houses were 1½ stories high, as can be seen in the sketch of the floors in **Figure 3.3**, and were intended for people staying for more than one day in the area. A series of smaller houses located to the left of the shown area were intended for one-day visitors. Below the area shown in **Figure 3.2** there were a large and a small kitchen building for cooking.

The shown area measured 60 by 150 meters, as indicated in the scales at the bottom and left sides of **Figure 3.2**. The entire area was marked with a 10 by 10 metres grid by setting a yellow wooden stick for each ten metres. In this way all measuring locations could be easily positioned by measuring the distance to the nearest sticks. All points could thus be referenced by a (x, y) co-ordinate, where x was the position along the bottom axis and y was the position along the left axis in **Figure 3.2**.

Prior to the Chernobyl accident this area was full of people on vacation in the houses or one day 'beach'-visits. The area is very easy to reach from Novozybkov – the trip takes a mere 15 minutes by train, and the train calls directly at the entrance of the recreational area. Now the number of visitors has declined considerably, as the recreational area lies in a zone where the contamination level exceeds 1.5 MBq m^{-2}, the Russian limit for areas that should be evacuated.

Houses 1 through 5 are identical, constructed as standard houses. Most likely, they were built out of prefabricated Finnish materials, since the size of the houses is very uniform. The main materials are wood and asbestos sheets. These houses were selected for decontamination as they had a good size, with a total ground area of 120 m^2, making them representable for typical family houses both in Russia and in western countries. The fact that they had first floors made them particularly interesting, as no measurement data are available on the dose composition and decontamination effect at first floor level of a building. Whereas first floors are unusual in Russia they are very widespread in most western countries and the experience gained would be very useful for verification of modelling results.

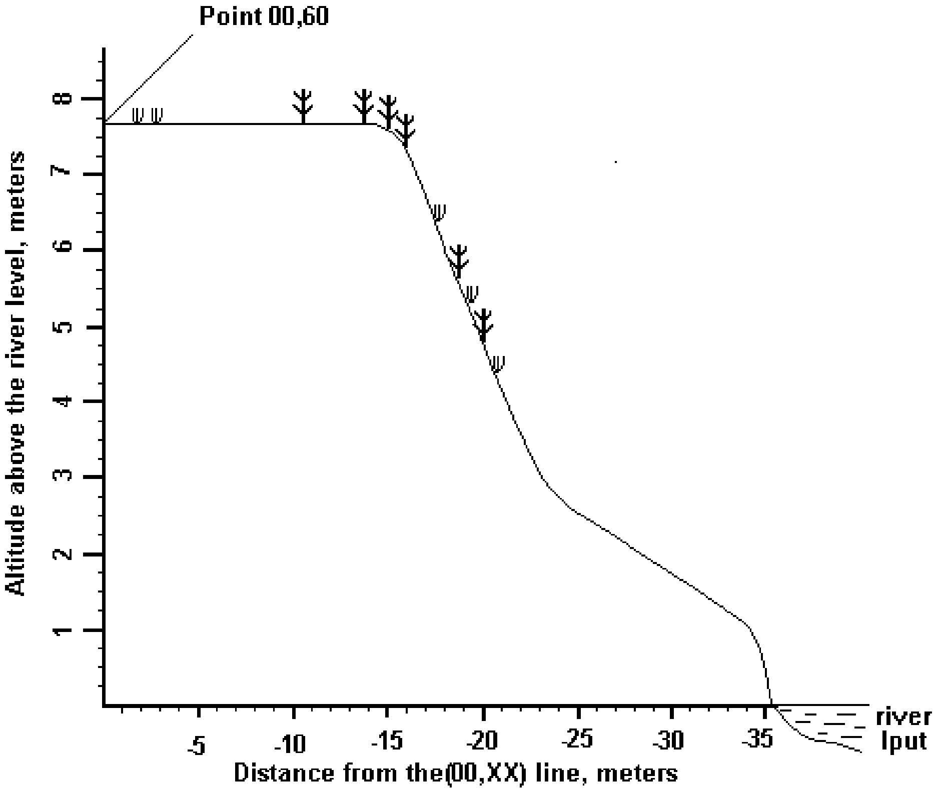


Figure 3.1. The river bank profile from the recreational site to the Iput river.

Plate 3.1. View of the houses before the decontamination. From the right to the left houses 1, 2 and 3 can be seen.

Plate 3.2. The first exercise with the Bobcat cleaning a grassed area close to the river bank.

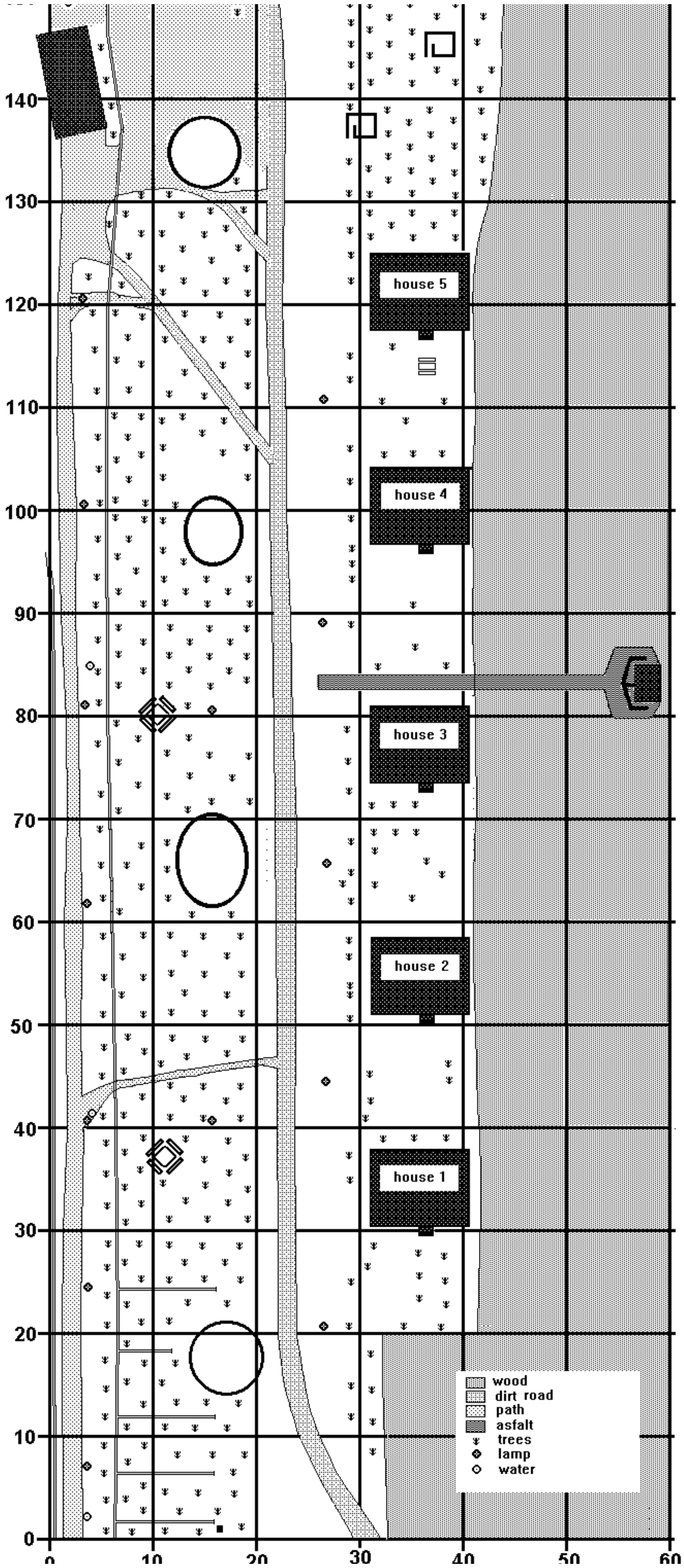


Figure 3.2. The recreational area seen from above

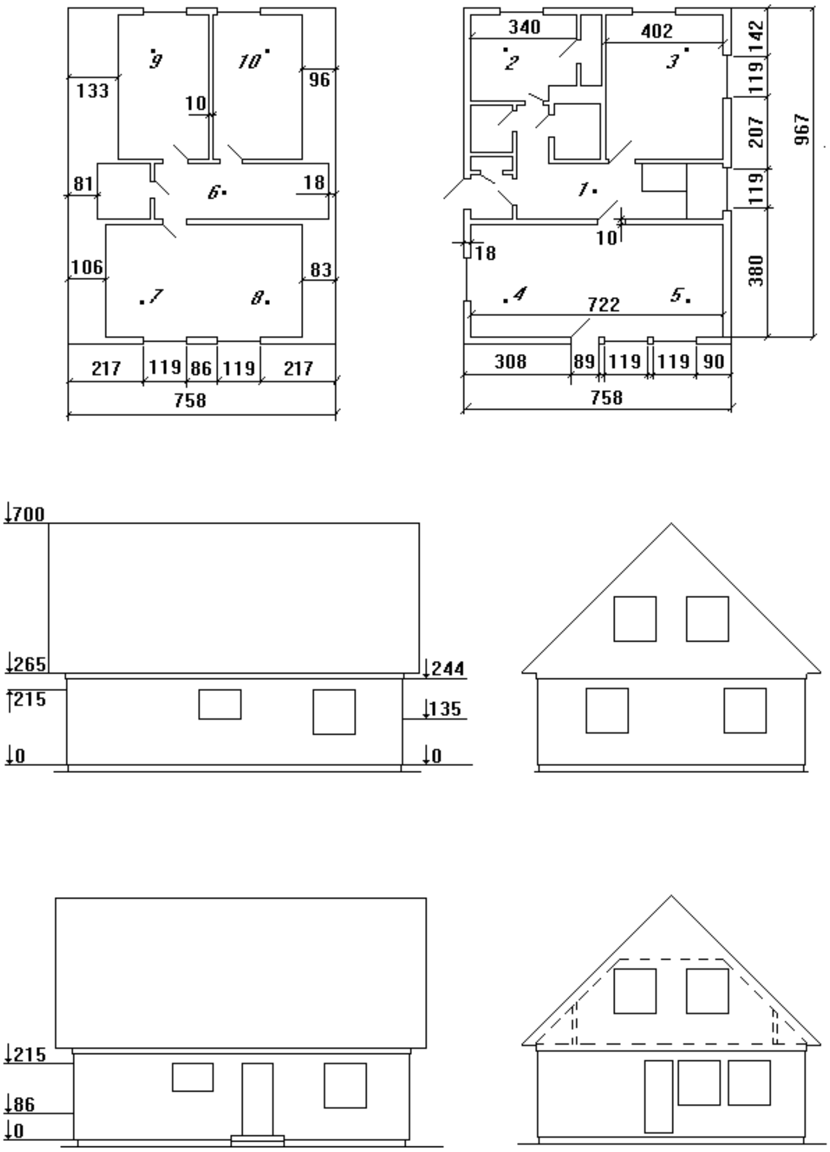


Figure 3.3. Diagram of houses 1 through 5.

3.2 Mapping of the ^{137}Cs Pollution in the Area

As shown in Figure 3.2 the area was mapped in a 10 by 10 metre grid. The dose rate was measured in all grid points with the Reuter Stokes ion chamber. Further, the dose rate was measured in 5 locations at a height of 1 metre above the ground level floor and in three locations 1 metre above the first floor inside the 5 houses. Measurements were also made around houses 1 and 2 and at the riverbank. In Table 3.1 a summary of the dose rate measurements is given for the 112 grid intersection points distributed along 7 lines with a constant x-coordinate. It can be seen that the dose rate is relatively constant in the area. The lowest values were generally obtained close to the river, as the river represents a radiologically ‘clean’ area. At greater distances from the river the average dose rate was found to be 1.1 ± 0.1 µSv h^{-1}. Inside the houses the radiation levels were very similar. At the ground floor level the dose rate was 509 ± 25 nSv h^{-1}, and at the first floor level it was 528 ± 8 nSv h^{-1}. This increase in dose rate with height was also observed in the houses in Novo Bobovichi in 1995 (Roed *et al.* 1996 a). Three reasons can be given for this:

- the soil surfaces are seen at a less flat angle, reducing the attenuation in the ground.
- The roof has a lower shielding effect than the walls.
- The roof contamination itself gives a higher contribution at first floor level.

In the centre of the houses the dose rate was only 340 ± 11 nSv h^{-1} - or 30 % lower than the average value of all the measurements made in the 5 houses (in the 4 corners and the centre).

Table 3.1. Review table of dose rates in Guta Muravinka measured with the Reuter Stokes ion-chamber.

Type of location	Number of points	Dose rate [nSv h^{-1}]	s. d. [nSv h^{-1}]
Line 0, near river	16	896	76
Line 10, central green area	16	1074	62
Line 20, along road	16	1115	47
Line 30, along houses	16	1022	153
Line 40, between houses	13	1213	200
Line 50, in forest 9 m from houses	16	1086	49
Line 60, in forest	16	1103	80
Ground floor house 1	5	484	109
Ground floor house 2	5	502	107
Ground floor house 3	5	501	102
Ground floor house 4	5	503	88
Ground floor house 5	5	552	130
Average of 5 houses	5x5	509	25
Centre of houses	5	340	11
2nd floor house 1	3	536	61
2nd floor house 2	3	529	60
2nd floor house 3	3	520	67

The contamination in the area was also measured with the CORAD device described in chapter two. Every other grid point was measured. The CORAD measurements showed some variation in the contamination inside the area, between 1.1 and 1.4 MBq m^{-2}. In contrast, a more uniform contaminant distribution was found in the forest, ~1.34 MBq m^{-2} (see Table 3.2). The CORAD measurements confirmed the results of the soil sampling (see below), namely that the contamination was situated in upper 2 – 3 cm of the soil .

Table 3.2. CORAD measurements of the surface contamination in the area.

	Number of measurement locations	Surface contamination [MBq m^{-2}]	Standard deviation [%]
Line 0	6	1.07	17
Line 1	5	1.14	9
Line 2	6	1.36	15
Line 3	5	1.06	26
Line 4	6	1.36	24
Line 5	5	1.32	17
Line 6	6	1.33	38

Depth Distribution of ^{137}Cs in the Soil.

The depth distribution of ^{137}Cs was measured by analysis of a series of soil cores in a provisional detector system on the site. Detailed knowledge on the depth distribution of the ^{137}Cs contamination is necessary for the planning of decontamination work, as the thickness of the soil layer that needs to be removed is dependent on the penetration of the contaminant. For this purpose 63 soil cores were sampled on the territory of the recreational area. On the basis of the analysis of the soil samples, it was possible to evaluate the spatial variation in the depth distribution of ^{137}Cs and from this estimate the quantity of contaminated soil that should be removed and disposed of. Besides helping in the planning of the work, both these soil samples and additional soil samples obtained for analysis in the laboratory were intended for a continued investigation of the migration of radioactive substances in soil.

A special sampler, consisting of a tube inserted into a cylindrical casing, was used to sample soil cores. To facilitate the penetration into the ground, the bottom end of the tube was sharpened. The sampler was driven 20 cm into the ground, and subsequently excavated using a shovel, and the tube was dismounted. A cylindrical sample, 20 cm long and with a cross sectional area of 21 cm^2, was obtained and cut into 5 cm thick slices, beginning from the deepest layer, in order to avoid cross-contamination from the more active top part. Thus, four samples were obtained, representing 0-5, 5-10, 10-15 and 15-20 cm depth. The volume of one soil sample was about 100 cm^3.

In order to characterise typical areas, soil was sampled from 9 different types of sites, each with homogeneous morphology. In order to have a statistically acceptable amount of information 5 to 10 soil samples were collected from each site. The characteristics of these sites are presented in Table 3.3. The tenth site in Novo Bobovichi was the place at which testing of the skim and burial plough was to take place.

Table 3.3. Description and location of the areas of soil sampling

Type of site	**Visual characteristic of the surface**	**Co-ordinates**
Strip of grass between houses and the road.	Very similar to virgin land	x=27 line
The track of the road	the Left track the Right track	x =22 and x=24
Roadside	Left roadside. Same altitude as the road	Line 21;YY
Middle of the road	The grassed area between tracks of the road	Line 23;YY
Forest	Natural forest between recreational area and railway	The area beyond line 45; YY in the direction of the X-axis.
Area between houses	Area between houses, covered by grass	Between lines 30;YY and 40;YY
Trampled-down plots between houses	Areas of no vegetation.	Between lines 30;YY and 40;YY
Area between pathways	Plot of virgin land, similar to the forest. Even mushrooms grow there	Between lines 05;YY and 20;YY
Flower-bed	Small hill with a diameter of about 7 metres in the virgin land area between roads. Before the Chernobyl accident this was a flower-bed.	In the map the beds are designated by white ellipses. The centres are located on line16;YY

The ^{137}Cs measurements were carried out using a spectrometer, which was set-up in one of the houses. A portable 480-channel analyser and a NaI(Tl) detector (80 by 80 mm) were placed in lead shielding with 50-100 mm wall thickness. The shielding was effected with 23 lead bricks 5*10*20 cm. A holder made out of a tin coffee can and an aluminium wire ensures that the sample is in the same position, on the detector axis, for each measurement. The measurement time for all samples was 120 seconds. Hereby, the sensitivity of the determination of the ^{137}Cs soil surface contamination became 20 kBq m^{-2} with a 50% uncertainty of measurement. Due to lack of standard sources of volume activity in the recreational area, calibration of the spectrometer was made in relative units.

When the full-energy peak of ^{137}Cs is measured in this lead-shielded NaI(Tl) counter, it is necessary to allow for the contributions from natural gamma emitters to the count rate in the ^{137}Cs energy window. This particularly concerns contributions from the photo peak of ^{226}Ra at 609 keV and from scattered radiation emitted by ^{40}K. For this purpose, it was assumed that the vertical distribution of ^{137}Cs was exponential:

$$C(x) = C_0 \cdot e^{-\alpha \cdot x} \tag{1}$$

where C_0 is the activity concentration of ^{137}Cs at the surface, Bq kg^{-1};
$C(x)$ is the activity concentration of ^{137}Cs at depth x, Bq kg^{-1};
α is the reciprocal relaxation length of the soil, cm^{-1}.

The mean $\alpha = 0.58\ \text{cm}^{-1}$ was determined after statistical analysis of all the measured samples from the recreational area.

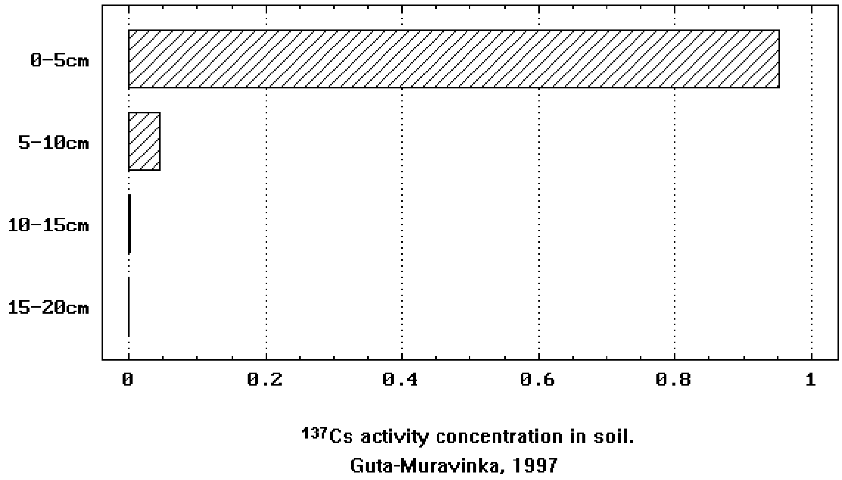


Figure 3.4. Average relative depth distribution of ^{137}Cs on the territory of the test site. Fractions of total activity, based on the analysis of 86 soil samples.

The results of measurements of the ^{137}Cs activity concentration in the soil samples are shown in the Table below. Here, the averages of the measurements in areas of different types are shown.

Table 3.4. ^{137}Cs depth distribution for each type of sample area.

Type	Surface ^{137}Cs contamination of ground [MBq m^{-2}]				
of site	0-5 cm	5-10 cm	10-15 cm	15-20 cm	Total
Strip of grass between houses and the road.	1.5±0.4	0.02±0.014	-0.001±0.005	-0.014±0.006	1.5±0.4
The dirt road	0.4±0.15	0.01±0.01	-0.003±0.009	-0.014±0.008	0.4±0.16
Roadside	2.5±0.4	0.10±0.02	0.015±0.015	-0.001±0.004	2.6±0.4
Middle of the road	1.2±0.3	0.04±0.02	-0.007±0.007	-0.014±0.004	1.2±0.32
Forest	1.7±0.4	0.11±0.06	0.015±0.017	0.020±0.02	1.8±0.4
Virgin land between houses	1.8±0.5	0.06±0.03	0.007±0.010	-0.001±0.004	1.9±0.6
Trampled down plots around the porch	1.3±0.5	0.14±0.26	0.008±0.006	0.007±0.02	1.4±0.7
Virgin soil between pathways	1.3±0.5	0.06±0.05	0.010±0.006	0.014±0.003	1.4±0.5
Flower-bed	1.4±0.4	0.05±0.01	0.007±0.01	0.004±0.01	1.5±0.4

As shown in the table, although the absolute level of caesium contamination may vary (0.4 MBq m^{-2} on a road and 2.5 by the road side), the relative ^{137}Cs depth distribution varies little over the whole area.

The average value of the reciprocal relaxation length, α, over the whole test area in Guta Muravinka, assuming an exponential depth distribution, was found to be $\alpha=0.58\ \text{cm}^{-1}$. In Novo Bobovichi the average reciprocal relaxation length was found to be $\alpha=0.24\ \text{cm}^{-1}$ (averaged over all samples) and $\alpha=0.49\ \text{cm}^{-1}$ excluding samples taken in areas where the soil was may have been disturbed after the Chernobyl accident. Compared with the published data (Golikov et al,

1991) the value of α=0.49-0.58 cm^{-1} corresponds to ^{137}Cs depth distribution for 1988, whereas α=0.24 cm^{-1} is closer to the present time value.

Another interesting point is that the caesium depth distribution under the drain of a roof can also be adequately described as exponentially decreasing. Here, the reciprocal relaxation length was found to be α=0.28 cm^{-1}, which does not differ significantly from what is generally observed, although the level of ^{137}Cs at that point exceeds the average value in the area by a factor of approximately 20.

The observed shape of the vertical contamination profiles and the similarities of the different profiles despite widely varying absolute levels of contamination is believed to have a simple explanation. Immediately after the deposition from the Chernobyl accident had occurred, ^{137}Cs ions dissolved in rainwater penetrated into ground and generated the initial exponential depth distribution of the activity. The ^{137}Cs ions were fixed, mainly by micaceous mineral particles in the soil, so strongly that it can be assumed that no further migration of ^{137}Cs in simple form has occurred. The micaceous particles that are most efficient in fixing the radiocaesium are the illites. Compared with other soil substances, these are very small particles, which are normally mixed in a 'random-like' stacking together with for instance organic matter. The organic matter will degenerate with time, releasing the caesium-containing illite particles, which may be transferred to deeper layers with the water flow through natural cracks in the ground.

In previous investigations of soil contamination, the diameter of the sample core was greater (about 100 cm^2). The samples selected from these rather large areas contained several large pores or cracks, through which surface water runs. Using this method which averages the contamination levels out over a large area, less variation was recorded within a lawn, compared with the smaller diameter cores, that were sampled for these investigations, which may by coincidence contain several large pores or no macro-pores at all. Therefore, the absolute contamination levels will vary greatly between small-diameter samples. Due to frost during winters or water flow, new cracks will appear in the ground, through which the small particles (and thereby the radiocaesium) will migrate to greater depth. Hereby, the reciprocal relaxation length slowly decreases.

It might have been expected that since the pores in the soil under a roof drain would be very well developed, due to the water flow, and would have a greater capacity to retain the contaminated water than in other parts of a lawn, the radiocaesium would have penetrated deeper under the roof drain. After all, the absolute level of contamination under the roof drain is about 20 times as high as that of the rest of the area. However, the soil is a very efficient filter, which removes the contaminants from the water flow, and there have not been recorded great differences between the shapes of the contaminant depth profiles under a roof drain and averaged over the whole area.

After returning from Guta Muravinka a number soil cores were analysed in the Laboratory. These results are presented in Appendix A. The 10 profiles from the open areas in the settlement showed an average contamination of 1.25 ± 0.36 MBq m^{-2}. This in good agreement with the CORAD results, but somewhat smaller then the average results obtained from the in situ soil sample measurements. The average attenuation depth was 2.6 ± 1.3 g cm^{-3}. This is in good agreement with the in situ observations that the ^{137}Cs contamination was situated very near the soil surface.

Summary of Soil Contamination

- As was found from the soil sample analysis, the ^{137}Cs contamination of visually different sites within the recreational area is practically identical. Very nearly all the contamination is concentrated in the top 5-centimeter layer.
- One exception is a road, where the level of contamination is, due to weathering, only 30 % of the average value for the recreational area and another exception is a road gutter, where the contamination is twice the average level in the area. This is in-line with the observations reported in Chapter 5, which show that the contamination on a road is usually attached to road dust particles that are now very strongly bound to the road and can rather easily be translocated by mechanical impact.
- The contamination in flowerbeds is a bit lower (80 %) than the average contamination. This could be explained as follows: during deposition in rain, the water ran down from the higher positioned beds to the surroundings. Practically all the activity is concentrated in the top 5-centimeter soil layer.
- The surface contamination of the ground below the drain of the roofs is 20 times higher than the average value over the recreational area.
- the sensitivity of the portable spectrometer, was sufficient both for planning the decontamination exercise and for scientific applications.
- Caesium migration in the soil is so slow that buried activity will remain fixed in the soil and not penetrate into the ground water.

Roof Contamination

The roof contamination was measured in two ways: with the portable SKIF 3 gamma analyser with a collimated NaI crystal and with the El-1117 β-detector.

The SKIF-3 gamma-analyser was used for gamma measurements of 16 asbestos sheets, taken from House 1. The total sheets were measured. For calibration of the instrument parts of 5 sheets were granulated and analysed in the laboratory. The surface activity was calculated on the basis of obtained results. The sheets with known ^{137}Cs activity were measured with a collimated SKIF-3. Results of the roof measurements are presented in Table 3.5.

The average contamination of the asbestos sheets with ^{137}Cs was 144 kBq m^{-2} (12 % of the soil surface contamination level). It should be mentioned that significant differences between individual sheets were observed. For reference, contamination levels of asbestos sheet contamination from Zaborie and Novo Bobovichi are also shown in Table 3.5.

Beta measurements of roof contamination were done after the soil decontamination. 14 sheets from House 1 and 12 sheets from House 2 were analysed. The east side of the roof of House 1 was more contaminated compared to the west side. For House 2 the opposite relationship was found. The average level of the contamination of the roof of House 1 was found with the beta counter to be 59 kBq m^{-2}, which was 2.4 times lower, than the values obtained by gamma measurements. A laboratory experiment was made with separate sheets, to determine this discrepancy between γ and β measurements. The slight penetration of ^{137}Cs into the asbestos-cement matrix is believed to be the cause for the twice as high gamma as beta results. This shows the weakness of β-measurements for estimation of contamination of roofs. Results of the β-measurements are presented in Appendix C.

Table 3.5. Measurements of the ^{137}Cs roof contamination of House 1 in Guta Muravinka. 16 old sheets were counted after the replacement of the roof. The measurements were made with the collimated NaI detector, SKIF. Averages are compared with measurement results from Zaborie and Novo Bobovichi.

N of sheet	Detector signal Count/sec	Surface contamination [kBq m^{-2}]
1	0.73	152
2	0.63	130
3	0.75	156
4	0.8	168
5	0.67	139
6	0.52	108
7	0.84	175
8	0.41	85
9	0.84	176
10	0.79	166
11	0.65	136
12	0.77	160
13	1.02	214
14	0.6	125
15	0.7	146
16	0.33	67
Average	0.69±0.17	144±36
Zabor 1	0.73	154
N.Bob 2	0.39	69
N.Bob 3	0.16	36
Zabor 5	0.33	68
Zabor 6	0.19	38

3.3 Decontamination Test at the Grassed Area

An area close to the riverbank, where many visitors were sunbathing, was selected for decontamination. It was the wish of the owner of the place that such an area should be cleaned, as well as an area around the houses. The riverbank area provided an excellent opportunity to test the Bobcat before beginning the work around the houses. The test area was a 10 by 10 m plot at the riverbank between co-ordinates y=140 and y=150 and x=10 and X=20 in Figure 3.2. In Plate 3.2 the Bobcat can be seen working at this plot.

The crucial experience to be gained from this work was the determination of the thickness of the soil layer that should be removed and a routine in manoeuvring with the bobcat so that exactly this amount was scraped off. For about two hours a man with a handheld dosimeter measured the surface dose rate after each scraping and reported the results to the bobcat operator. Also, while the bobcat was scraping a man reported back to the operator on the exact performance of the scraper. After this exercise the team was reassured that it would be possible to scrape-off a surface soil layer of a well-controlled thickness, around the houses.

The removed soil was placed in a trailer and in a pile north of the cleaned area. After the area had been scraped the bobcat was used to make a hole as indicated in Figure 3.5. This hole was filled with the contaminated topsoil. The sand from the excavation was placed in a pile south of the hole and used to cover the hole and an area with clean sand in the end. In this way the original contours of the landscape were maintained. A similar method was used for the waste from the decontamination around the houses, but here an excavator was used to dig the holes, and this speeded up the work process considerably.

The decontamination at the riverbank took about 6 hours, and 100 m^2 were treated. This corresponds to about 16 $m^2\ h^{-1}$, including a slow start where the driver of the bobcat was practising. The bobcat was also used to dig the hole for the waste in the centre. A task it is not very well suited for.

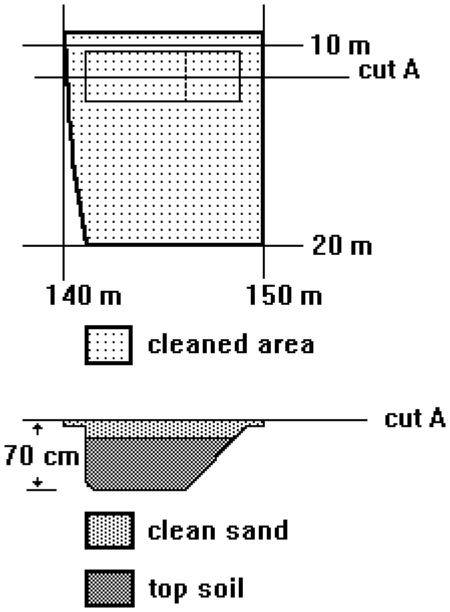


Figure 3.5, Diagram of the decontamination at the riverbank. The lower part shows how the removed topsoil was placed in a hole and covered with clean sand.

The dose rate was measured over the area both before and after decontamination along the line y=145. The result is shown in Figure 3.6. A background dose rate contribution of about 60 nSv/h should be subtracted to determine the effect of the work carried out. As can be seen, over the treated area, the dose rate was reduced by some 60 %. This figure would inevitably have been greater if the procedure had been carried out over a larger area, as a large contribution to the residual dose rate in the treated area comes from scattered radiation from contamination at rather large distances from the treated spot.

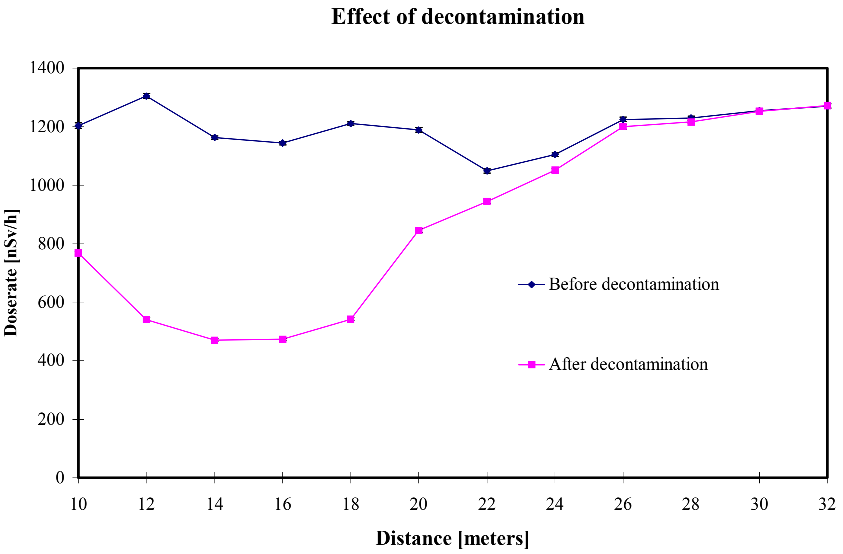


Figure 3.6. Dose rate profile over the green area at the 'beach'. The 'Distance' is the x co-ordinate along the y = 145 metres line.

Also 4 soil cores were obtained: two before (GM01 and GM02) and two after the decontamination work (GM03 and GM03). These profiles can be seen in Appendix A. The two first profiles confirm the previous result that 95 % of the activity was located in the top 5 cm of the soil. The profiles taken after the decontamination show that about 90 % of the contamination had been removed and that the top 5 to 7 centimetres consist of clean sand. The GM04 profile was taken over the buried waste, and at 30 cm depth some activity can be seen. This may be the start of the 'waste zone'.

In conclusion, the soil profiles analysed in the laboratory confirmed the first impression, that the exercise at the 'beach' plot was successful in removing 5 to 7 centimetres of the topsoil containing more than 90 % of the contamination.

3.4 Decontamination Around the Houses

After the decontamination at the riverbank the work was started around the houses. It was decided to begin the work around house 1 and move down towards house 5. The objective was to clean around at least three houses so that the house in the middle would have 'clean' houses to both sides and thus a maximum reduction in the radiation level.

The work was carried out through the following stages:

1. The bobcat was used to move the topsoil into piles.
2. A team with dose meters and shovels checked the area and removed 'hot spots', especially around trees and other difficult accessible places.
3. An excavator moved into the cleaned area and dug a number of pits for the waste.
4. The bobcat was used to move the waste into the pits.
5. The bobcat distributed the clean sand from the pits over the cleaned area, restoring the previous level of the surface.

The first scraping with the bobcat moved the topsoil into piles about 10 meters apart. The narrow width of the scraper enables the bobcat to move freely even in relatively densely overgrown areas. In the beginning, smaller bushes were removed manually, but as it was established that these could easily be removed by the bobcat, this was stopped and after that, the bobcat was applied without pre-treatment. Another problem was the roots from larger trees. Typically the bobcat could not work nearer than 0.5 meters to large trees. Here the soil had to be removed by hand.

Whenever an area had been treated, either by the bobcat or by hand, it was checked with handheld dosimeters and additional soil was removed if necessary. The procedure was followed that if the dosimeters read more than 300 nSv h^{-1} then an extra effort was required. Levels lower than 300 nSv h^{-1} were difficult to obtain without treating large areas, due to the large amounts of scattered radiation.

As the bobcat is not suited for digging pits an excavator was used for this task. The excavator worked for about 4 hours over two days in order to dig 8 pits. Some soil was also removed on wagons towed by a tractor. Some 7 - 10 % of the waste was removed in this way. The main advantage of the pits was that waste buried within the area was not regarded as radioactive waste and therefore it was exempted from the strict rules applying for radioactive waste. Also, the clean sand from the pits was useful to cover possible remaining activity on the ground and restoring the previous level of the ground. In Plate 3.3 the excavator can be seen digging the pit between houses 2 and 3 around co-ordinate (45, 65). To the left the clean sand is dug up into a pile and to the right the contaminated soil is lying ready to be pushed into the pit. In the background the bobcat is filling another pit with contaminated soil. The excavator took about 30 minutes to dig a hole for 8 – 10 m^3 of waste.

In Figure 3.7 the decontaminated area is shown together with the position of the pits. As can be seen, the soil has been removed around three houses. In general, decontamination out to 10 metres from each house was desired. To the north (the left in Figure 3.7) the dirt road was used as a limit. The road was found to have considerably lower levels of contamination than had the surroundings (about 30 %, see Table 3.4) and it was for this reason decided not to treat the road. So in this direction the area was cleaned to distances of 8 meters from the houses. To the east of house 3 the soil was only removed between the house and the asphalted road to the toilets, due to time restraints. So in this direction the soil was only removed out to a distance of 2 metres from the house.

In total, the topsoil was removed from about 2000 m^2. This took about 35 hours with the bobcat, including filling the waste into pits and covering them with clean sand. Scraping of the topsoil was accomplished at a work rate of about 75 – 100 m^2 h^{-1}, depending on the number of obstacles in the area.

In Plate 3.4 the bobcat can be seen, applying clean sand from the pits to the decontaminated area. The application of sand took about 12 hours for the 2000 m^2, giving a work rate of 160 m^2 h^{-1}. In Plate 3.4 the bobcat is distributing sand at the south-east corner of house 1. Although the shape of the profile was not significantly different from that recorded in other places, the absolute amount of contamination which had penetrated deeply into the ground was some 20 times greater at the south corners of the houses, where the contaminated rainwater from the roof drains ended, than it was in the rest of the area. It was therefore necessary to dig deeper here. Soil samples showed contamination levels of up to 12 MBq m^{-2} (see GM09 and GM11 in appendix A) and CORAD measurements showed an average contamination level of 6 MBq m^{-2} at the south corners of the houses.

In Plate 3.5 the bobcat can be seen working behind house 1 around position number (55, 35). The topsoil has been removed from the area around house 1 and clean sand has been added. The bobcat is now distributing sand over the pit dug south of house 1. The picture gives an impression of the area after the decontamination.

At the end of the work the roof of house 1 was replaced with a new clean roof. Various methods for decontamination of roofs had already been examined during the previous work in Novo Bobovichi in 1995 (Roed *et al*. 1996 a) and by others (e.g., Andersson, 1991; Sandalls, 1987; Gjørup et al, 1985).

Measurements with handheld β-detectors had indicated that the roof carried a substantial amount of activity and the previous work in Novo Bobovichi had shown a significant influence from the activity deposited on the roof. Still there was a discussion as to whether there would also be a significant influence in houses as large as those in Guta Muravinka. But after measurements with a collimated NaI detector it became clear that the contamination on the roofs was a significant contributor to the total dose rate, especially in the first floor. This was confirmed by the measurements of the reduction in the dose rate after the soil removal, which showed that the dose rate in the first floor was reduced by only 32 %. After this, it was decided that the roof also needed to be replaced as it had a significant influence on the dose rate.

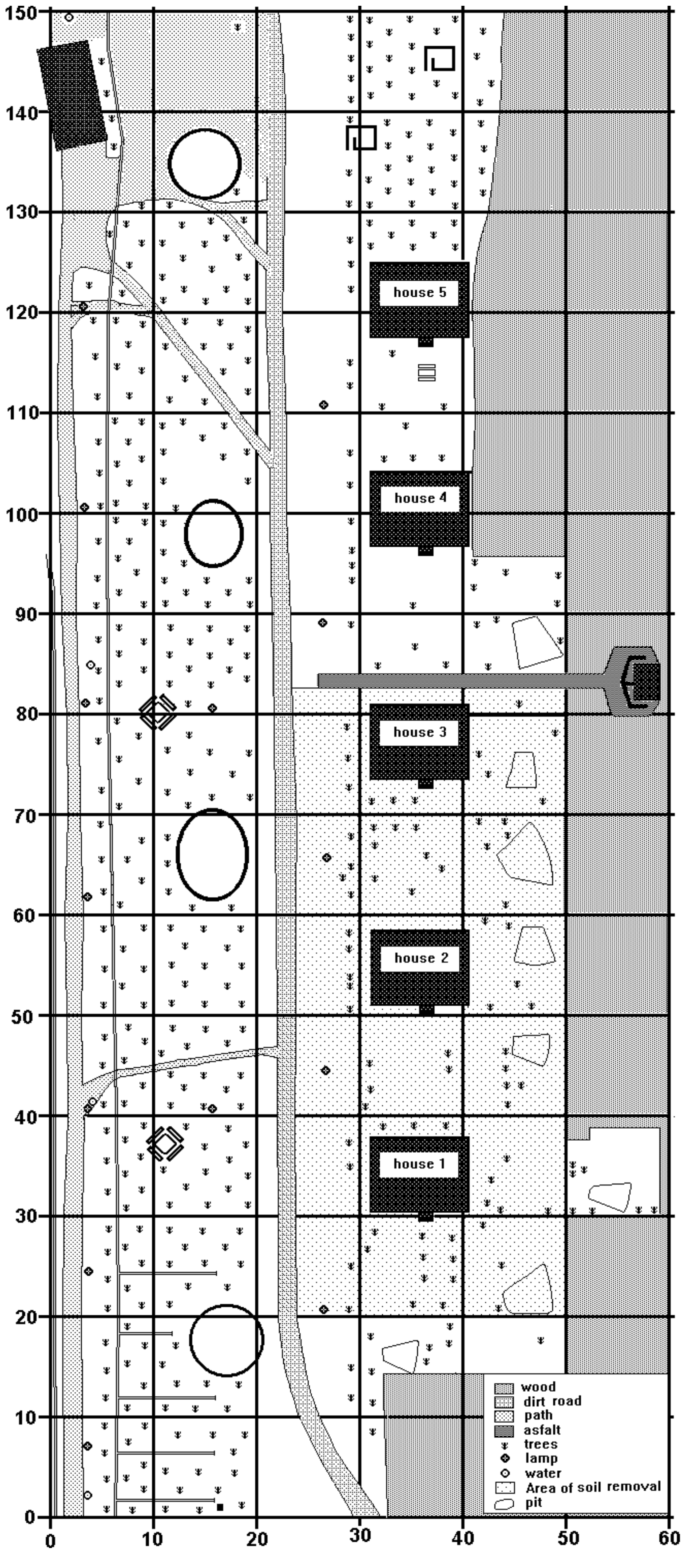


Figure 3.7. Plan of the recreational area with indications of the different types of surface. Grid co-ordinates are given in units of metres.

Plate 3.3. Excavator digging holes for waste burial in the forest. The sand is placed in a pile on the cleaned ground and the topsoil lies ready on the other side of the hole.

Plate 3.4. Application of clean sand at the corner of house number 1.

Plate 3.5 The Bobcat in the forest behind house 1. An area in the forest is cleaned to make room for an extra pit around (54, 32).

3.5 Results of the Decontamination Work

As described in section 3.2 the dose rate was measured at all grid points as shown in Figure 3.2 and at a number of locations inside the houses. During the work the reduction in the dose rate was measured after each stage of the work, as follows:

1. After the removal of the soil.
2. After the distribution of clean sand.
3. After the removal of the roof of house number 1.

Results of the Reuter Stokes Ion Chamber Dose Rate Measurements

During the decontamination work the dose rate was measured with the Reuter Stokes ion chamber inside houses 1 and 2 and along a line between houses 1 and 2. In Figure 3.8 the centreline data is presented for the four situations: initial value, the value after soil removal, the value after the sand has been applied and the value after the renewal of the roof of house 1. It can be seen that the dose rate changes very rapidly from the cleaned area to the contaminated area. In the centre of the cleaned area the dose rate is almost constant, as the remaining contamination and sky-shine dominates the dose rate here (as opposed to the border areas where direct radiation from the un-treated areas is the dominating source). Spectroscopy measurements inside the cleaned area confirmed that scattered radiation was at that point dominant in the spectrum.

Based on the average dose rate in the central area, at a distance of 34 to 38 metres in Figure 3.8, the dose reductions were calculated, and these are presented in Figure 3.9. It was found that the Chernobyl-related part of the dose rate (i.e. the dose rate excluding natural background and cosmic radiation contributions) was reduced by some 83 %. The removal of the soil gave the largest reduction, 79 %, whereas addition of sand and removal of the roof each gave 2 %. It is interesting to note that the application of clean sand only gave a further 1.8 % reduction. In 1995 in Novo Bobovichi, the application of clean sand gave a 7 % further dose rate reduction relative to the initial level. The thickness of the clean sand layer was about the same in these two situations and this difference clearly indicates that the bobcat was much more efficient in achieving a complete removal of the radiocaesium, than were the manual methods used in 1995. It is also interesting to note that the removal of the roof actually gave a measurable reduction in the dose rate level of 2.4 %. This effect was just for one roof. If a similar contribution is assumed from the roof of house number 2, it actually contributes about 15 % of the remaining dose rate in the area between the two houses.

In Figure 3.10 the dose reductions at ground floor level in house number 1 are shown, and Figure 3.11 shows the effect at first floor level in the same house.

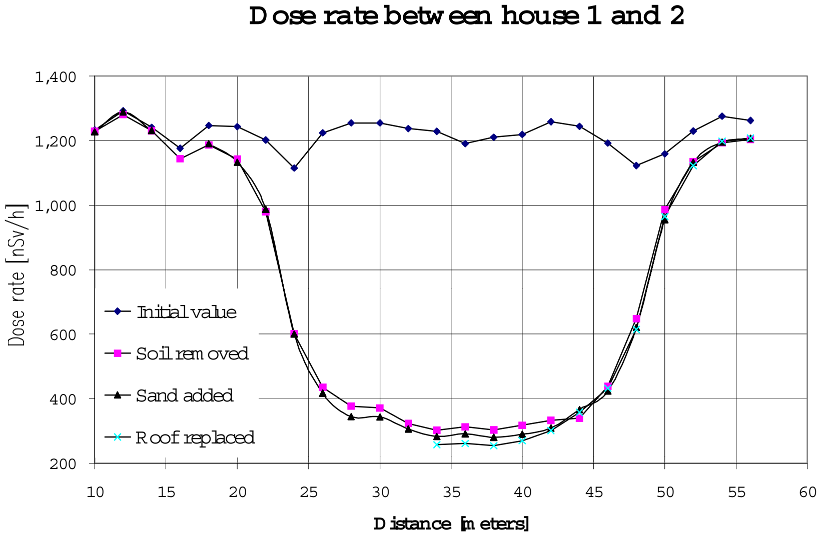


Figure 3.8. Dose rate along the centreline between houses 1 and 2 during different stages of the work.

El-1101 Dose Rate Measurements

The dose rate was measured diagonally across House 1 and House 2 with the El-1101 fixed on a tripod 1 meter above ground. The positions of the measuring locations are shown in Figure 3.12. The measurements in the corners were only made at the ground floor level. The rest of the measurements were made at ground floor and first floor level.

The curves of DR inside houses were asymmetrical. There was a strong influence of the 'hot spots' under the roof drainage (as marked in Figure 3.12), which can be seen at the ground floor even at the distance of 3.8 m from the centre (Figure 3.13, Figure 3.14 and Figure 3.15). The average dose rate at the first floor level was significantly higher than that at the ground floor level; the influence of 'hot' corners by the drains could also be seen here (Figure 3.16). Removal of the topsoil around the houses led to a significant decrease in the dose rate (Figure 3.14, Figure 3.15 and Figure 3.16). After decontamination the dose rate profile became more flat. The highest reductions were observed at the ground floor. At the ground floor level the Chernobyl component of the dose rate was reduced by 58 % when the topsoil was scraped off. At the first floor level the reduction was only 35%. The application of clean sand over the ground did not have a measurable effect on the dose rate. The roof removal showed that 9% of Chernobyl contribution to the dose rate at the ground floor level and 27 % of the dose rate at the first floor level were caused by radiocaesium in the asbestos roofing sheets. In this particular case a contamination level of 144 kBq m^{-2} ^{137}Cs on the roof caused an exposure rate of 3.5 μR/h at the ground floor and 13.6 μR/h at the first floor level (see Table B2 in appendix B).

The contribution of the roof contamination to the total value of the outdoor dose rate was investigated on the line, which crossed the middle of House 1a from west to east (see Table B3). The distance between individual measurements was 1 m. The dose rate profile across the area shows the clear influence of radiocaesium roof contamination on the dose formation at distances of up to 10 m from the outer walls of the house. A contamination level of 144 kBq m^{-2} of ^{137}Cs on the roof gave an exposure rate of approximately 3 μR h^{-1} outdoors at a distance of 5 m from the outer wall of House 1.

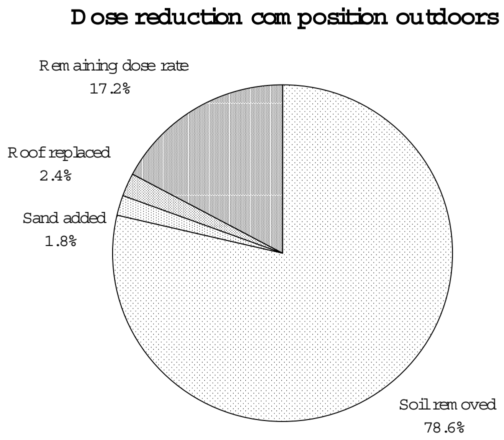


Figure 3.9. Reduction of the Chernobyl related dose rate contribution outdoors between houses 1 and 2, obtained from the dose rate data presented in Figure 3.8.

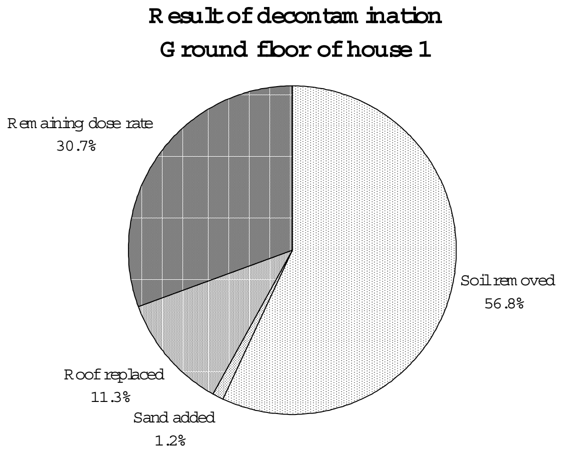


Figure 3.10. The effect on the Chernobyl-related dose rate of the various steps of the decontamination work on the ground floor of house 1.

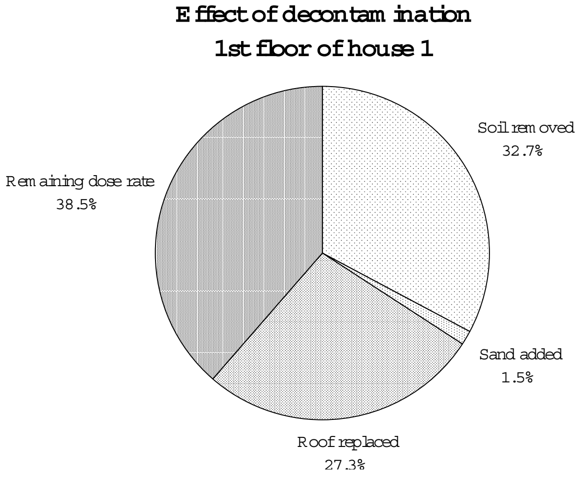


Figure 3.11. The effect on the Chernobyl-related dose rate of the various steps of the decontamination work on the first floor of house 1.

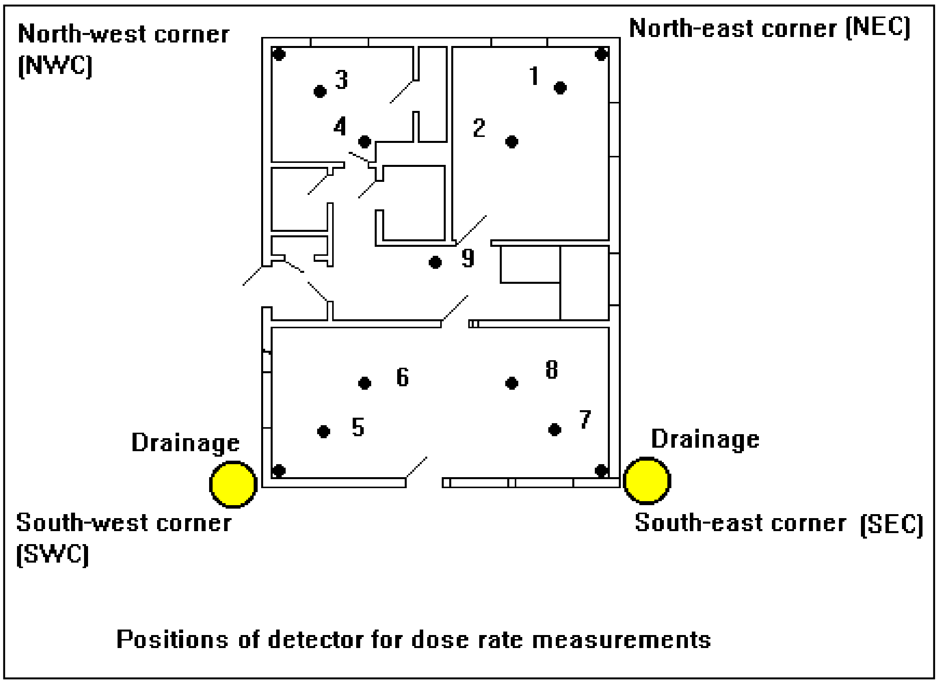


Figure 3.12. Positions of the measurement locations on the ground floor of House 1 and House 2

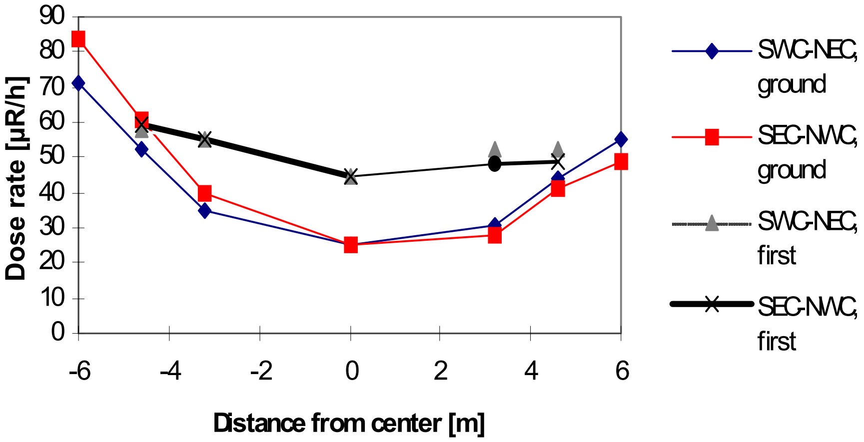


Figure 3.13. Dose rate profile at ground and first floor level inside house one measured with EL-1101.. South-west corner to north-east corner and south-east corner to north-west corner.

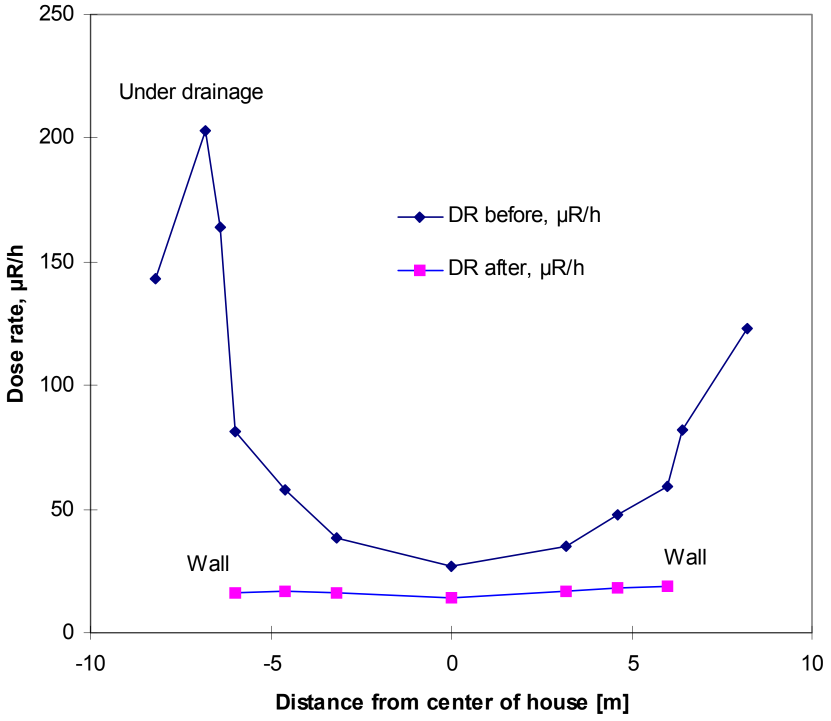


Figure 3.14. Chernobyl component of dose rate inside (ground floor) and outside House 2 before and after intervention, east-west corner direction measured with El-1101.

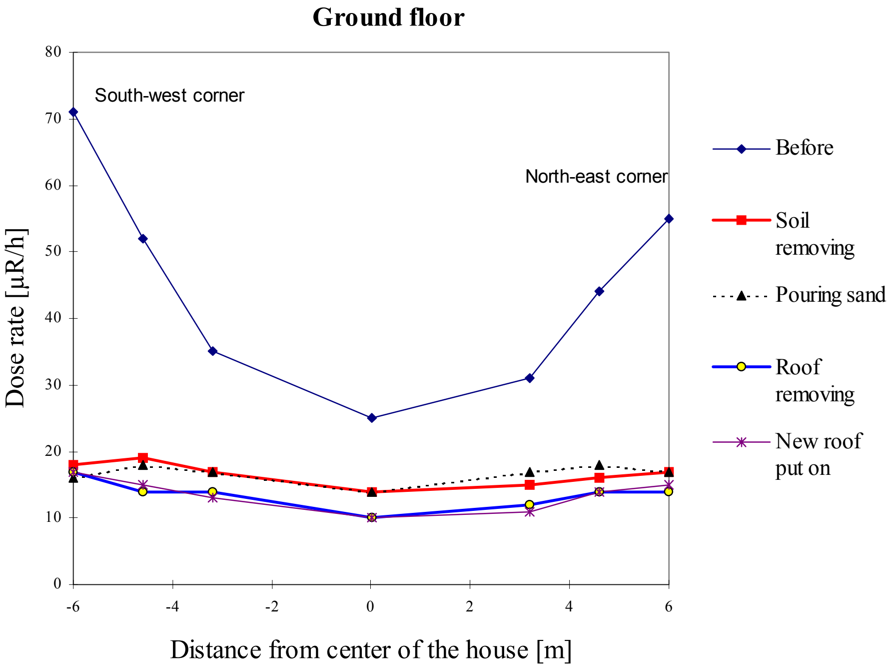


Figure 3.15. Dose rate at ground level in house 1 at different stages of intervention, Chernobyl component, measured with El-1101.

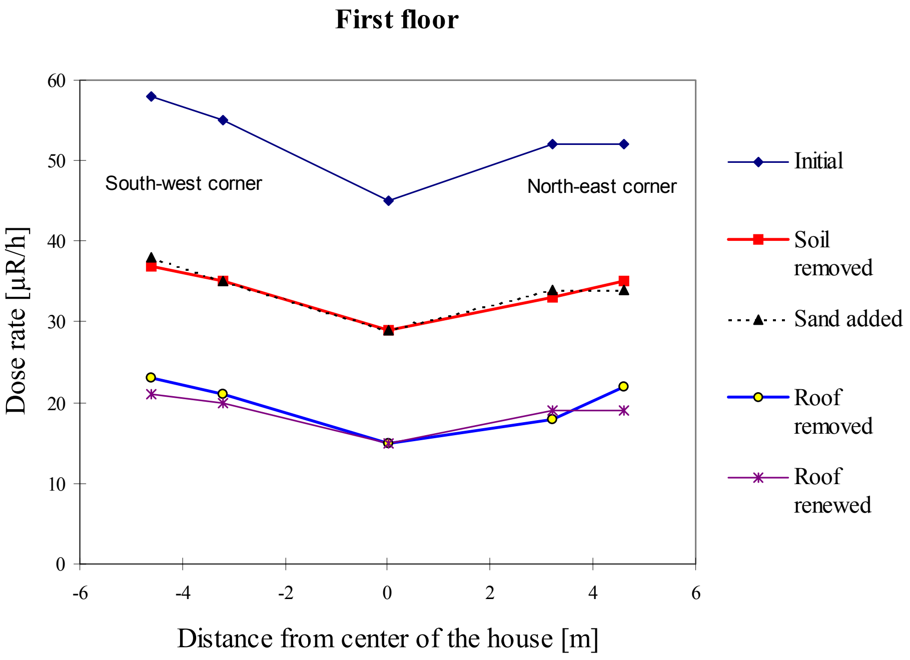


Figure 3.16. Dose rate in House 1 at different stages of intervention, Chernobyl component, first floor, measured with El-1101.

Unscattered ^{137}Cs Photons from Different Directions in House 1

A portable gamma-analyser, SKIF-3 (Sinco, Russia), based on a 25*25 mm sodium iodide detector crystal, was used for a series of angular in situ gamma spectrometric measurements. The detector was placed in a lead collimator on a tripod (minimum lead wall thickness: 5 cm). The construction of the tripod and lead shielding made it possible to point the collimator opening (with a 45 degrees spatial angle) in any direction and thereby to assess the angular distribution of the gamma flux.

Only the unscattered part of the ^{137}Cs gamma radiation was measured. In Table 3.6 the results of these measurements, made before and after the total dose reduction strategy was carried out, are presented. If it is assumed that the 6 measurements pointing in different directions adequately represent the contributions from all angles, the results of the directional measurements express the fractions of the total unscattered radiation (shown as percentages in Table 3.6). The collimated sodium iodide detector measurements show that the roof contamination was a significant contributor to the unscattered part of the gamma flux, and thereby to the dose rate. This conclusion was confirmed by the dose rate reductions obtained through replacement of the roof.

Table 3.6. Angular distribution of the flux of gamma photons with energy 661.6 keV in the middle of house 1 before and after the dose reduction strategy was carried out. The measurement results are also expressed as percentages of the total (sum of measurements) before action. The uncertainty of each measurement was about 15 %.

Direction	Peak area, counts/sec		Fraction of total	Fraction of initial total
	Before action	After action	[%]	[%]
roof	0.38	0.05	15%	2%
floor	0	0	0%	0%
south wall (forest)	0.59	0.24	23%	9%
west wall (gate)	0.80	0.22	32%	9%
north wall (road)	0.23	0.17	9%	7%
east wall (House 2)	0.53	0.20	21%	8%
Sum	2.53	0.88	100%	35%

The results from Table 3.6 are also visualised in Figure 3.17.

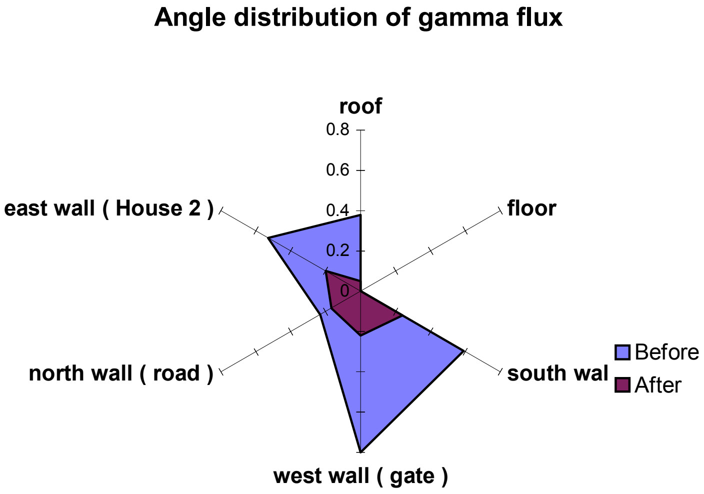


Figure 3.17. Unscattered gamma flux from different directions in house 1, ground floor, before and after dose reductive action.

3.6 Cost Analysis of the Results

As hired local workers carried out most of the actual decontamination work, it is possible to estimate the costs of an implementation of the strategy in Russia. The following example refers to a single house with a 1000 m^2 garden. If more houses were treated in the same area the work could have a greater effect, due to the removal of contamination at large distances, and a lower cost per house. In 1997 skilled workers were paid 20 $ per day, whereas unskilled workers were paid 10 $ per day.

First a survey of the area should be made in order to estimate the depth distribution of the contamination, the influence of the roof, etc. This can be done in two days by a skilled technician. One day would be required for measuring and sampling, and one day for analysis.

A new Bobcat (mini-bulldozer) would cost about 30,000 $. If it is assumed that this is written off over 6 years and that it is used for 25 weeks per year the weekly cost is 200 $. An additional ca. 100 $ per week would be required for gasoline (diesel) and maintenance, giving a total cost of the Bobcat of 300 $ for one week's work (5 days). The bobcat driver must be a skilled worker, and would earn 20 $ per day, corresponding to 100 $ per week. Two workers with shovels should assist the driver in areas that are difficult to access. This would cost another 100 $ over a week.

Three options may be considered for the roof: no action, cleaning the roof or replacing it. Cleaning the roof would require that two men work for three days with high pressure water hosing equipment. The costs for changing the roof can be based on the actual costs in 1997 (334 $ for new sheets and 80 $ for labour).

The averted dose is calculated from an assumption of the occupancy pattern, as follows: 10 % of the time spent in the garden, 20 % down stairs, 30 % upstairs (sleeping, etc.) and 40 % outside the area (possibly working). Cleaning the roof would reduce the dose rate by half as much as would be achieved by replacing the roof (Roed *et al.* 1996 a). In the collective dose calculation it is assumed that 6 people live the house over the next 50 years.

A summary list of the costs and the calculated averted doses is shown in Table 3.7.

Table 3.7. Cost and averted doses when a single house is decontaminated. The averted dose for the first year refers to individual doses, whereas the averted collective dose is based on the assumption that six people live in the house.

Item	Untreated roof	Cleaning roof	Replacing roof
Initial survey	40 \$	40 \$	40
Bobcat	300 \$	300 \$	300
Driver	100 \$	100 \$	100
Excavator	50 \$	50 \$	50
Manual assistance	100 \$	100 \$	100
Roof	0 \$	90 \$	414
Sum	590 \$	680 \$	1004
Averted dose 1st year	1.8 mSv	2.0 mSv	2.2 mS
Averted collective dose	0.30 manSv	0.34 manSv	0.37 manS
Cost per averted Sv	$1967\ \$\ \text{manSv}^{-1}$	$2015\ \$\ \text{manSv}^{-1}$	2713 \$ manSv

The IAEA (1983) recommend a minimum value of $3000\ \$\ \text{manSv}^{-1}$, while IRCP (1989) recommend a value of 20,000 $ for most developed countries. The cost of the dose reductions obtained through this work are well below these values and it seems that the methods would be useful in the areas affected by the Chernobyl accident also seen from a pure cost benefit view.

Another consideration that could be made is the comparison between the cost of decontamination of a house and the cost of Chernobyl compensation for the residents. Four adult people in a house in the most contaminated zones receive about 160 $ per month in Chernobyl compensation. By for instance reducing this amount by 25 % for people living in decontaminated houses, the Russian government would have a profit after 1 or 2 years.

While the option including replacement of the roof has the highest cost per averted Sv it should be noted that this option has the additional benefit of having a new roof.

It must be stressed that the figures presented in Table 3.7 are connected with large uncertainties. Wages are at the moment low in Russia and they must be expected to rise over the coming years, making a decontamination more expensive.

Even larger uncertainties are associated with the dose calculations. The dose reductions obtained will vary from house to house, and the collective dose will vary with the number of people living in the house and their behaviour patterns.

4 Skim and Burial Ploughing

4.1 The Radiological Purpose

Numerous different countermeasures were considered and applied to reduce external as well as internal doses due to contamination of large open (rural) land areas after the Chernobyl accident. In the early phase after the accident no clear contingency strategy had been formulated, and as a consequence, the introduced operations (listed below) were of a hit or miss nature.

- harvesting and disposal of surface-contaminated crops (leaving the land relatively clean).
- spraying plastic or rubber-based fixatives on soil and dust to suppress resuspension.
- application of lime and inorganic fertilisers to soils to reduce root uptake of certain radioelements.
- removal of surface soil, and thereby removal of most of the contamination from the land.
- normal mouldboard ploughing (to 20-30 cm depth) to suppress resuspension, dilute the contamination and disperse it from the surface of the ground.

Some of these countermeasures were ineffective and others had adverse side effects. For instance, there was no means of predicting in advance the optimum amounts of lime and fertilisers to be added to achieve a known reduction in soil-to-plant transfer of the relevant radioelements (Desmet, 1991). The process was therefore not as cost-effective as it might have been.

The application of fixatives in the contaminated land areas has been limited to suppression of resuspension. Fixatives have, however, also been considered for decontamination operations in smaller land areas (Andersson & Roed, 1994 a).

Scraping off a 10 cm layer of surface soil from an area of 1 km^2 by bulldozers generated about 50,000 metric tonnes of radioactive waste for disposal. In shallow virgin soils of the former Soviet Union this type of operation would often remove the entire fertile soil layer. Melin et al. (1991) reported difficulties in scraping off thinner layers with a bulldozer.

An external dose reduction factor of about 15 was obtained by ploughing to a depth of 30 cm in a ^{86}Rb contaminated field (gamma photon energy 1.078 MeV) with an ordinary mouldboard plough (Roed et al., 1996 b).

One advantage of ploughing procedures as large scale dose reducing measures is that they can be carried out by local agricultural workers. The local groundwater conditions should, however, be considered prior to any ploughing procedure to ensure that the contamination is not brought too close to the groundwater level. In the Chernobyl case, a fine mist of water has often been applied immediately before ploughing, in order to reduce resuspension.

In terms of cost and availability, normal ploughing is an attractive countermeasure, but it is of limited effectiveness since the normal mouldboard plough operates down to a depth of only about 25 cm and much of the contamination remains accessible to plant roots. Further ploughing may not improve the situation since much of the buried contamination would then be returned to the surface.

By deep-ploughing, to 45 cm instead, contaminants such as radiocaesium are placed beyond the root-zone of many crops and will remain in a thin layer deep in the soil profile without further intervention, due to the strong soil fixation (Andersson & Roed, 1994 b).

Experiments by Menzel et al. (1968) demonstrated an effectiveness of more than 90 % in reducing radiostrontium uptake by various subsequently grown crops by deep-ploughing. The effectiveness was substantially increased by addition of sodium carbonate to the soil. Since sodium carbonate is a root inhibitor rather than a chemical, which affects strontium availability, the results should also apply to other radioisotopes.

The reduction of the external radiation in the area will also be larger than by conventional ploughing. Also, the radioactive matter will have been placed sufficiently deep in the soil profile that subsequent ploughing does not redistribute it.

The main disadvantage of deep- ploughing is that poorer quality soil is brought to the surface.

In order to overcome the problems associated with both normal ploughing and deep-ploughing, a new type of plough has been developed jointly by Risø National Laboratory and Bovlund Agricultural Engineers Denmark. This plough ideally skims off the topmost layer of soil (about 5 cm) and buries it at a depth of some 40-50 cm without inverting the intermediate layer. Hence the name 'skim and burial plough'. The removal of only about a 5 cm layer of topsoil is a minimising of the effect on the fertility of the land.

Overall, the skim and burial plough greatly reduces radiation levels at the ground surface, the resuspension hazard is eliminated, most of the contamination is made inaccessible to plant roots and the effect on soil quality is relatively small, but the procedure should not be applied in very shallow virgin soils. The plough would only have little beneficial effect in areas, which have been cultivated after the contamination took place.

4.2 Plough Design and Construction

Examination of various types of common ploughs and attachments showed that nothing was readily available which could be easily modified to achieve the desired objective. A machine which lifts a 50 cm layer of soil to a height of about 60 cm while simultaneously placing the topmost 5 cm layer in the bottom of the trench was considered but this was rejected on account of its excessive power requirements making it unsuitable for use with normal-sized tractors. It was therefore decided to design and build an entirely new type of plough and this has been done.

A skim coulter first places the upper 5 cm layer 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. In this way, the 5-50 cm soil layer is lifted only about 10-15 cm and the power requirements are minimised. However, the possibility exists that the 5-50 cm layer will be partially inverted and that not all of the contaminated top layer will be placed in the bottom of the trench.

Initially, a 1/10 scale model of the skim and burial plough was constructed and tested. After various adjustments and modifications, a full-sized version was constructed. As a result of further attempts to improve performance subsequent to testing, various modifications were made to the original design.

Based on the much modified full-sized model, a prototype full-scale plough was constructed and tested on a soil consisting of a 30 cm layer of light soil overlaying a sandy soil. This field was specially selected for a rigorous test of the performance of the plough on a light soil. The tests showed that it was necessary to build a higher and broader shield in order to prevent the sandy soil from falling into the furrow before the top layer had been placed in the bottom of the furrow.

Further testing and modifications resulted in a plough considered to be worthy of extended and intensive field trials. The plough is shown in Figure 4-1.

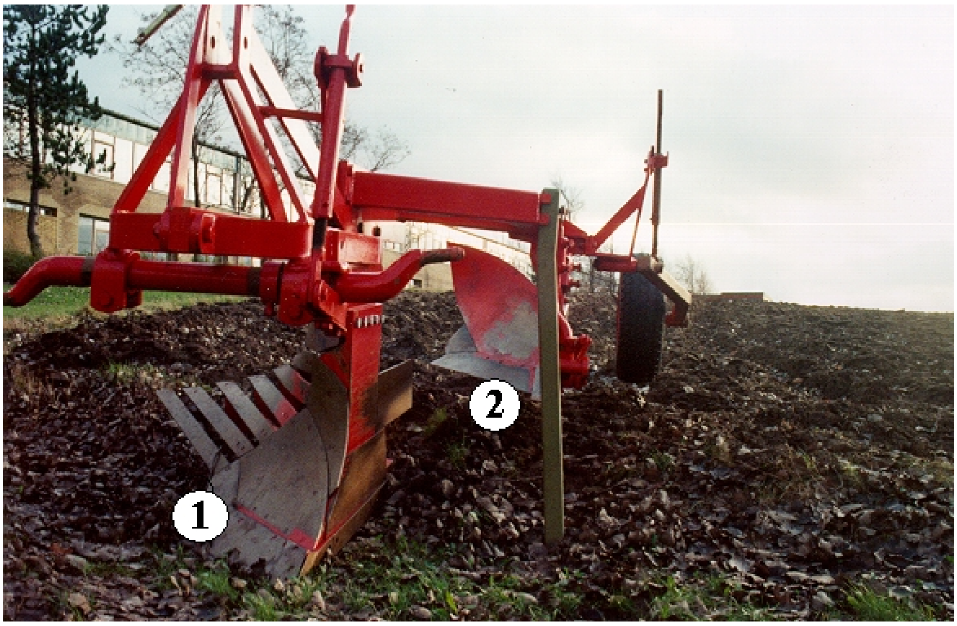


Figure 4.1. The Skim and Burial Plough showing the positions of the main ploughshare (1) and the skim coulter (2).

4.3 Field Trials and Discussion

The plough was tested in a field near Novo Bobovichi in August 1997. The test field was one of only few pastures in the area, which had not been cultivated since the Chernobyl accident occurred. The area which was skim-and-burial ploughed measured 20 m by 50 m. The soil type was characterised as a sandy loam horizon grading into sand below about 10 cm depth. The plough, which weighs about 880 kg, was drawn by a normal Russian four wheel driven farm tractor. The power requirement of the plough is some 90 kW (120 hp). The plough produced a furrow about 60 cm wide and 50 cm deep. The skim coulter, which is adjustable, was set to skim off the contaminated topmost 5 cm soil horizon, but often went a few cm deeper and occasionally did not remove anything.

The soil measurement data for samples NB21-24 (in Appendix A) show the vertical distribution profile of the ^{137}Cs contamination in the test field prior to ploughing. All these profiles have sharp ^{137}Cs peaks, which supports the hypothesis that the area is pasture land. Distribution profiles NB21 and NB23 show that by far the most of the radiocaesium is located at a depth of only a few centimetres in the soil. Contrary to this, distribution profiles NB22 and, particularly, NB24 have shapes which could be indicative of a much deeper migration. However, it became apparent after the soil had been ploughed that a part of the test area had been in use after the Chernobyl accident to store large amounts of lime, which had possibly been applied to farmland to reduce the radiostrontium uptake by plants. The small increase in the contamination in the very topmost few mm of these vertical profiles must be ascribed to either smearing of contamination during mechanical removal of the chalk or possibly resuspension, although the latter process is reported to have had little impact in recent years.

Plate 4.1 shows the ploughing process. This picture shows that the unskilled local operator was going so fast that the shield did not properly prevent the soil from falling into the furrow before the top layer had been placed in the bottom of the furrow. Further, the ploughing depth was often not properly adjusted and this greatly affected the performance of the skim coulter. In the picture, the skim coulter goes too deep, and due to the high speed the skimmed-off layer is dislocated horizontally and not falling into the bottom of the trench. This stresses the importance of experience with ploughing (at a suitable velocity), and in particular, understanding of the objective to be achieved. Compared with previous trials of the plough the latter problem was in this case complicated since instructions were given through a local instructor, as it would often occur in reality.

Plate 4.2 shows the furrows after a ploughing. The furrow produced by the skim coulter is seen to the right in the picture. It is seen that the furrow produced by the main coulter (immediately to the left of the skim coulter furrow) has to some extent collapsed. The reason for this was that the ploughing was carried out in the late summer, following a very warm and dry period. The soil therefore contained very little moisture and the subsoil crumbled and fell to the bottom of the trench. Consequently, the skimmed-off layer containing the contamination was not buried sufficiently deep. As the soil had not been cultivated in many years the thick top soil horizon was held together by the mature turf mat. Layers removed by the skim coulter and in some cases even layers under that contained so much organic material that they were held together and were in some cases stacked vertically because of the high velocity (sometimes broken at the middle) and only partially tilted. Therefore, several contamination peaks are in some cases seen at different depths in the vertical profiles after ploughing (see sample profiles NB25-28 in Appendix A. Bits of grass turf and chalk in the left part of the picture show that the skimmed-off top layer was, due to too high speed, in some cases slung far away from the furrow in which it should have been placed.

Plate 4.3 shows the area during the ploughing process. The white colour of lime is here clearly seen in the track produced by the skim-coulter. This picture also shows that due to the mature grass cover the large amounts of lime were not visible before the ploughing. The thickness of the lime layer (partly mixed with the topsoil) corresponded well with the ca. 2-4 cm increased contamination depth in profiles NB22 and NB24.

Monte Carlo calculations of gamma radiation transport have shown that in a large area where the contamination lies about 4 cm deep ca. 50 % of the dose rate is due to contamination at distances greater than 10 m. Also by Monte Carlo calculations, it was found that the dose rate from within an area of radius 10 m is reduced to about 50 % if a contamination at a depth of ca. 4-5 cm is transferred to a depth of ca. 8 cm. This means that a 2-4 cm lime top layer in an area with a radius of 10 m would be expected to reduce the dose rate at the centre by some 25 %.

Figure 4-2 shows the measured dose rate on a horizontal line across the ploughed area. The area that was ploughed is that from -10 m to 10 m from the centre. In the area where the samples with the deepest contamination peak were taken the initial dose rate was found to be the lowest. It is seen that the dose rate level after action is as expected slightly lower in the area with the more shallow contamination, since the skimmed-off layer is (ideally) positioned with the turf facing down. As can be seen, the shielding effect of the lime layer in the central area is in good agreement with the results of the Monte Carlo calculations, assuming that the dimensions of the lime-covered area has approximately the same dimensions as the test area. The 'level' lines in Figure 4-2 indicate the dose rate levels in areas that were least affected by the lime. From these two lines together with the natural background line (this was measured in 1995 in the area and was assumed to be practically constant), the dose reduction factor, R could be found as:

$$R=(D'_a - D'_b) / (D'_i - D'_b),$$

where D'_i and D'_a are the dose rates 1 m above the surface, respectively before and after skim-and-burial ploughing, whereas D'_b is the dose rate contribution from the background radiation.

In this case R was found to be 2.2. The rather limited effect compared with previously recorded results is partly due to the rather small size of the treated area, since much of the dose rate is caused by contamination at great distances. If very large areas were treated it has been found by the Monte Carlo method (Roed *et al*., 1996 a) that this treatment would result in a dose rate reduction by a factor of 6-7. Previous trials in a Danish pasture (Roed et al., 1996 b) as well as in a pasture in the Ukrainian part of the 30 km zone around the Chernobyl power plant (Hubert et al., 1996) dose reduction factors as high as 15-20 were in some cases reported to be expectable for very large areas, where the conditions were most favourable.

Plate 4.1. The plough in use in the Novo Bobovic area. The skim furrow is made on the left by the skim coulter while the m coulter simultaneously creates the deeper trenc in which the top layer is buried. The plough is he going too deep and the person behind it is trying to adjust the ploughing depth.

Plate 4.2. This picture shows the furrows after a ploughing. Traces of lime are clearly seen, both in the furrow produced by the skim coulter and in the treated land to the left, where soil from lower layers covers most of the area. Note that also bits of grass turf thrown to rather large distances are visible in the left part of the picture.

Plate 4.3. The tractor and plough are here about to start a new furrow. Note t white colour of lime in the skim furrow created by th previous run and that bits turf have not been remove at the centre of the skim furrow.

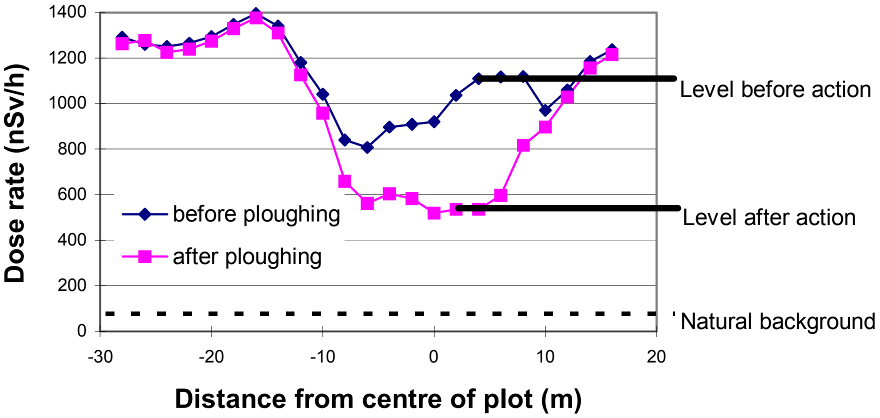


Figure 4.2. Dose rate [nSv/h] traverse (east to west) the 20 m by 50 m skim-and-burial ploughed area before and after ploughing, as measured with a Reuter Stokes ion chamber at a height of 1 m above the ground. The natural background contribution is indicated by a dotted line. The lines shown for the levels before and after treatment refer to those parts of the treated plot, which were least affected by a lime top layer.

The potential reducing effect of the procedure on the internal dose received from crops grown and consumed through the foodchain was not assessed in the area. Naturally, this would greatly depend on the local farming practice and type of crops applied (e.g., shallow or deep rooted), and also on the preparation/refining of the food products prior to consumption. Finally, the local traditional diet is an important factor. The internal doses might well be dominated by the digested highly contaminated mushrooms collected in forest areas rather than by agricultural products as such.

An important feature concerning application of the skim-and-burial plough in agricultural practice is the limited effect on soil fertility. In some virgin land areas of the former Soviet Union, however, the fertile layer is not much thicker than that which is skimmed off by this plough. In a virgin land area near Novo Bobovichi, very near the ploughing test area, effectively the same procedure was in 1995 carried out manually by triple digging (Roed et al, 1996 a). Although the treatment by skim-and-burial ploughing of such shallow soils can be problematic, the triple digging test plot is now completely overgrown, indicating that the procedure has not had a devastating effect on the fertility. Reductions in plant radiocaesium uptake by as much as a factor of 10 may under favourable conditions be expected (Roed et al., 1995).

The cost of a skim and burial plough is at present about 4000 ECU, which is approximately twice the cost of an ordinary plough in Western Europe. However, the annual discount will be dominated by the much more expensive, though often readily available, ordinary farming tractor that is required.

With the skim and burial plough an area of about 3000 m^2 can be treated per hour, corresponding to 3 10^6 m^2/year. The total costs per unit of area treated will therefore be low.

5 Asphalt Scraper Experiment

5.1 Asphalted Roads in Novo Bobovichi

In 1995 it was established that some of the asphalted areas in Novo Bobovichi carried considerable amounts of ^{137}Cs. After completion of the decontamination strategy which was carried out in 1995, the contamination of the area was reassessed. It was found that there was a marked increase in the dose rate at 1 m above the roads leading to the houses. This is clearly seen in **Figure 5.1**, which shows a series of measurements of the dose rate across the treated area. It was mainly on the pavements and walkways around the houses that dose rates were elevated. The paved areas used for heavy traffic had at some point after the Chernobyl accident been treated with a layer of new asphalt. In any case, the mechanical removal of the contamination by heavy traffic would have substantially reduced the dose-rate contribution from these surfaces over almost a decade. Due to the close proximity to the houses the contamination on the walkways would give a significant dose rate contribution to people staying in the houses. It was therefore decided to investigate the dose reducing effect of treating an asphalted area with a commercial road scraper, and already in 1995 an area in Novo Bobovichi behind the treated houses was reserved for the experiment, which was carried out in 1997.

5.2 Contamination of Asphalt Surfaces in General

Throughout the years, many investigations have been made in attempt to remove radioactive contamination bound to dust particles of different sizes on roads. These were performed by various means including sweeping (Clark and Cobbins, 1964; Sartor et al., 1974, Calvert et al., 1984, Andersson, 1991), water hosing (Roed and Andersson, 1994; Warming , 1984) or other means (e.g., ‘shot-blasting’, Warming, 1987). Although only few of these methods could be applied successfully after the Chernobyl accident, they generally demonstrated that much of the radioactive material deposited on a road will remain attached to a thin superficial dust layer or adsorbed directly on the surface. After deposition, the level of contamination will decrease depending on the amount of mechanical impact, surface water flow, etc.

An experiment was carried out with the objective to give a relative measure of the retention of radiocaesium in the bitumen fraction of asphalt coatings. The surface of roofing-felt covered with stone chippings has approximately the same roughness as an asphalt surface. A surface of 46 cm by 53 cm of this material was covered with bitumen, which had been heated to 150 ºC for 4 hours. When the surface had dried, 1.09 litres of water, corresponding to 4.5 mm of water over the total area, containing 1061 Bq/l of 137Cs was slowly and evenly applied by spraying homogeneously over a period of 45 minutes. The surface was placed horizontally, but at the middle of one side, wherefrom the exceeding water was to run off, the surface was held 8 mm down. 0.99 l of the water was found to run off. This corresponds to 90.8 % of the water. A measurement on a Ge(Li) detector of the activity in the run off water revealed that only 7.3 % of the activity was intercepted by the surface. The fact that very little activity was left on the surface corresponds well with the visual impression that the bitumen surface repelled the water. As very little contamination was intercepted by the bitumen fraction of asphalt, the contaminants on such surfaces must be associated with exposed pebbles and street dust.

An experiment has been carried out in order to establish that the low porosity of an asphalt surface will permit virtually no downward migration through the surface. Here, an asphalt core with a diameter of 72 mm, corresponding to a road surface area of 0.0041 m^2 had been taken from a trafficked area in Sweden which had been contaminated by the Chernobyl accident several years earlier. The ‘hot spots’ on the asphalt surface were delineated with white chalk marks. These spots were then carefully ground-off using a steel chisel and weighed. Knowing the area of sample removed and the mass, the approximate thickness was calculated. Following each grinding-off of high spots, the radiocaesium content of the samples was measured. The first grinding removed 10.0 g, corresponding to 1.23 mm and took with it 78 % of the caesium contamination. The second grinding removed a further 9 % in 9.4 g, while the third grounding removed 10 % in 15.4 g. The conclusion drawn from this experiment was therefore that several years after deposition the upper 1 mm containing small, more or less firmly fixed dust particles holds practically all the deposited radiocaesium in the asphalt profile. As the method applied may have given rise to some cross-contamination of the sample, it is likely that en even greater fraction was held in the upper 1 mm layer. This finding is in-line with the results of in situ measurements over longer time-periods after the Chernobyl accident, which showed that in trafficked areas the mechanical wearing of asphalt surfaces often reduced contamination levels by more than a factor of 20 over a decade.

Further experiments (Andersson, 1991) have shown that the effect of sweeping roads and thereby also of natural weathering processes on road surfaces, which have received a radiocaesium deposition, will strongly depend on the surface dust loading.

5.3 Experiments in Novo Bobovichi

The size of the test area in Novo Bobovichi was app. 8 by 10 meters and the asphalt had remained undisturbed since the Chernobyl accident. The scraper, which was brought from Denmark, weighed about 100 kg. The grinding device of the scraper consisted of four cross-shaped grinders mounted at the ends of two perpendicular rods, rotating around a common, central axis. A shield prevents the loosened material from being spread over a large area.

The test area was covered by considerable amounts of organic litter. The organic cover consisted of partly mouldered leaves and needles from the surrounding trees as well as of moss and lichens, indicating that the mechanical impact in the area since the Chernobyl accident had been very limited. The ^{137}Cs contamination level before decontamination was measured by in-situ gamma spectrometry and using the CORAD device. Throughout the exercise CORAD measurements were performed in the four different points indicated in Figure 5.2, and at the centre of the circular test area. In situ gamma spectrometric measurements were made only at the centre of the area. These measurement series were repeated after each treatment of the asphalt area. Further, the dose-rate was measured with the Reuter Stokes ion chamber to investigate the total dose reducing effect in the area of the treatment.

First, the organic matter was removed from an area with a diameter of 2 metres (see Figure 5.2), by thorough sweeping using an ordinary broom. The organic material was collected and it was found to amount to 7.5 kg m^{-2}, containing 255 kBq m^{-2} of ^{137}Cs contamination. The initial level of ^{137}Cs contamination was found by both in situ spectrometry and by the CORAD method to be of the order of 630 kBq m^{-2}. The residual contamination level would therefore be expected to amount to about 375 kBq m^{-2}, which was verified by in situ measurements (as shown in Table 5.1). After this organic ‘litter’ sample had been taken, a larger area with a diameter of 6 metres was swept in preparation for the application of the scraper. The height of the scraping device was set so that it would remove a ca. 1 cm surface layer of the asphalt. The specific height of the grinding device was set relative to the height of the wheel-pairs of the scraper, and since the asphalt surface was not plane, it was soon found that the method removed more than 1 cm in some places and practically nothing in others. It was therefore decided to give the test area a second treatment with the scraper. However, this time, the grinding depth was not pre-set, but continuously manually adjusted, so that a layer of a more homogeneous thickness was removed. The slight colour changes in the treated areas gave a good indication of the homogeneity. After each scraping, the loosened material was swept away with a broom. The results of these two successive scrapings are also shown in Table 5.1. An analysis of the removed material from the first scraping showed the content of ^{137}Cs to be 21.8 kBq kg^{-1}, corresponding to a surface contamination of 195 kBq m^{-2}. Subtracting this from the ca. 380 kBq m^{-2} before the treatment, the residual contamination level would be about 185 kBq m^{-2}, and this was again verified by the in situ measurements (as shown in Table 5.1). The second scraping was found to remove less contamination per unit of mass (13.2 kBq kg^{-1}), and reduced the contamination level by a further ca. 100 kBq m^{-2} to about 85 kBq m^{-2}. After the second scraping treatment, the effect of running over the area with a municipal vacuum sweeping device was simulated by ordinary vacuuming, to remove any residual loose contamination which had not been removed by the broom. This would particularly affect the small particles. The vacuuming removed 2.7 kg per m^{2}, corresponding to a surface contamination of 36 kBq m^{-2}, so that the residual contamination on the surface was at the end of the order of 50 kBq m^{-2}. The average decontamination factor for the scraping procedure was found by the in situ measurements to be about 5. As shown in Table 5.1, the corresponding reduction in dose- rate at a height of 1 m above the treated surface was from 656 nSv/h to 517 nSv/h (about 20 %). As the dose profile in **Figure 5.1** indicates the dose rate is dominated by contributions from a large area.

The first of the two plates below shows the CORAD device in operation in the test area, and the second plate shows the asphalt scraper in action.

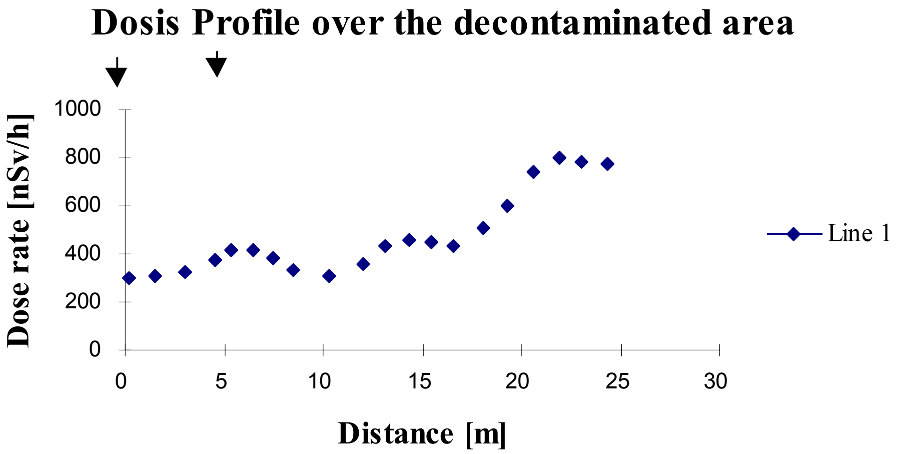


Figure 5.1. Dose profile across the decontaminated area in Novo Bobovichi in 1995, as measured with the Reuter Stokes ion chamber. The arrows show the positions of the roads leading to the houses.

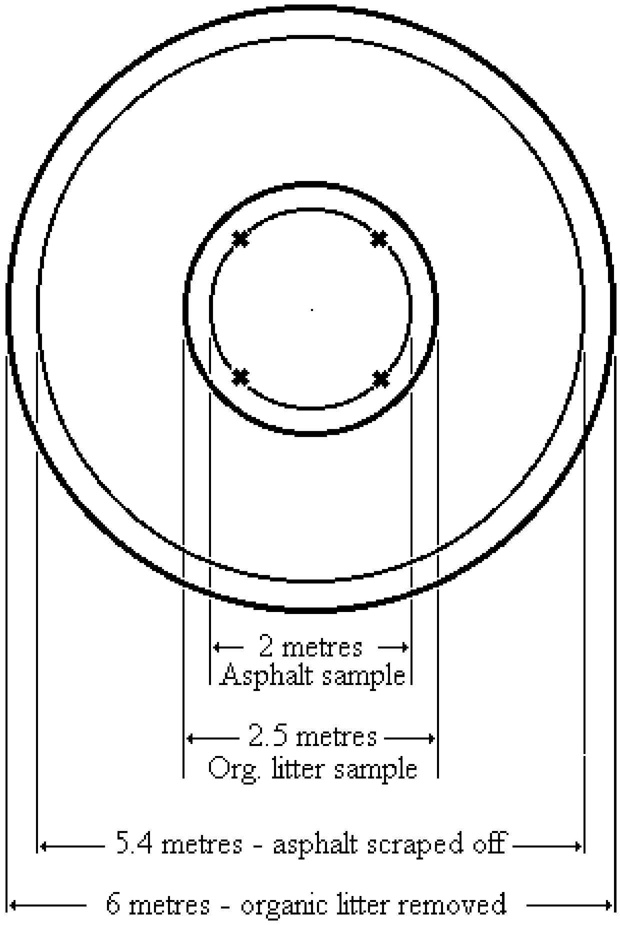


Figure 5.2. Plan of the asphalt scraping test area. The four dots on the inner circle indicate points of CORAD measurements. CORAD, dose rate and in situ gamma spectrometric measurements were also performed at the centre of the area.

Plate 5.1. The CORAD device measuring the contamination of the asphalted area after removal of the organic cover. The picture shows that the photomultiplier of the NaI crystal based system is facing down. This is the only opening in the lead collimator surrounding the crystal. The box with the electronics for data collection and treatment is seen to the left in the picture. The measurements are made at a height of 1 m above ground level.

Plate 5.2. The asphalt scraper working on the contaminated pavement. As can be faintly seen from the picture, the road is covered with a powder of loosened asphalt particles after the operation.

Table 5.1. Measurement results from the dose reduction exercise. Contamination level measurements obtained with CORAD (number of measurements in parentheses) and gamma spectrometer and dose rates measured with the Reuter Stokes ion chamber.

Description	CORAD [kBq/m^2]	Reuter Stokes [nSv h^{-1}]	In-situ Ge [kBq/m^2]
Initial value	629 ± 4 (2)	826	
After litter removal	381 ± 20 (10)	656	370
After 1st scraping	192 ± 28 (6)		
After 2nd scraping	85 ± 40 (3)		
After vacuuming	78 ± 30 (6)	517	83
Total DF	5.0		

6 Monitoring of the 1995 Site

The results of the investigations in 1995 are described in detail in an earlier report by Roed et al. (1996 a). This Chapter reports work carried out to examine the changes in dose rate levels that have occurred in the period 1995-1997.

The Decontaminated Test Area Near Novo Bobovichi

In 1995 decontamination tests took place in a Russian settlement near the village of Novo Bobovichi (ca. 25 km north-north-east of Novozybkov). In this area, where deposition of contaminants occurred in rainfall, the ^{137}Cs level was originally close to the threshold value for resettlement, and the outdoor dose rate was in 1995 found to exceed 1 µSv/h in parts of the test area. Overall, the area was forested, but an area measuring about 100 m by 100 m had partially been cleared of trees to make room for the settlement. The dose rate was found to be particularly high in places in or adjacent to the large contaminated forest.

The main objective of the decontamination work in 1995 was to reduce the dose rates in and around three selected houses. In an area measuring about 20 m by 20 m around the houses, a top soil layer of about 5-10 cm in thickness, containing much of the contamination, was skimmed off. Subsequently roofs of the houses were either cleaned or completely renewed, and finally, a ca. 5 cm layer of clean sand was added to provide shielding against residual contamination in the areas where soil had been removed. Excluding the contributions from cosmic radiation and from naturally abundant radionuclides, the dose rate inside the houses was found to have been reduced by up to two thirds. Although this result gave the clear indication that it is still possible to significantly reduce dose rates in areas heavily contaminated by the Chernobyl accident, some scepticism was expressed as to whether the dose reduction would be permanent or deposition of resuspended soil from the surrounding untreated areas would re-contaminate the decontaminated test plot. Therefore, dose rates were re-measured in 1997 in the same positions as in 1995. Table 6.1 shows the results of the new measurements in comparison with those of 1995. The measurement standard deviations of the individual results were generally less than 1 %.

In 1995, the positions of the measurement points had been marked with wooden sticks. In 1997 most of these sticks were impossible to retrieve, and the positions outside the houses were therefore only approximately the same as the original (within one meter). However, Table 6.1 shows that the standard deviations of the relationship between the dose rate contributions of the contaminants measured in 1997 and 1995 in the different types of area are rather limited. It is also seen that the standard deviations do not appear to change with increased number of measurements points nor with the size or location of the area, suggesting that the deviations relate to the difficulties to find the exact same positions, rather than to changes in the contamination distribution pattern. Further, it is seen that there is no significant difference between the average relationships (nor standard deviations) of those areas that were treated and those that were not. This also indicates that no significant re-contamination of the treated areas has occurred over the two years.

From all the measurements of contamination levels of ^{134}Cs and ^{137}Cs in samples in the area in September 1995 it was found that there was 36 times more ^{137}Cs than ^{134}Cs, with a standard deviation of only a few percent.

The exposure rate coefficients for the two isotopes are respectively:

$$\Gamma(^{137}\mathrm{Cs}) = 0.3224\ \mathrm{R^*m^2/h/Ci}$$

$$\Gamma(^{134}\mathrm{Cs}) = 0.8820\ \mathrm{R^*m^2/h/Ci}$$

This, in turn, implies that in September 1995, the fraction of the dose rate caused by ^{134}Cs could be found as:

$$D'_{rel}(^{134}\mathrm{Cs}, 1995) = 1{*}0.8820/(1{*}0.8820+36{*}0.3224) = 0.071,$$

whereas the fraction of the dose rate due to ^{137}Cs contamination was at the same time

$$D'_{rel}(^{137}\mathrm{Cs}, 1995) = 36{*}0.3224/(1{*}0.8820+36{*}0.3224) = 0.929.$$

Over the 23 months that passed between the measurement series in 1995 and that in 1997, radioactive decay was responsible for a reduction of the contribution of ^{137}Cs to dose rate by a factor of 0.957, and for a reduction of the ^{134}Cs dose rate contribution by a factor of 0.525. Thereby, the reduction in dose rate could be found as:

$$D'_{97}/D'_{95} = 0.071 * 0.525 + 0.929 * 0.957 = 0.037 + 0.889 = 0.926,$$

which corresponds well with the observed reductions for the caesium isotopes (see Table 1). This means that the only measurable change in dose rate level over the two years is that from radioactive decay. In other words: no significant traces of any re-distribution, vertical or horizontal, were detectable in any of the measurement plots.

The 1:36 relationship between contamination levels of ^{134}Cs and ^{137}Cs in 1995 was verified in the following way: From calculations of natural decay it is easily found that the total amount of ^{134}Cs was immediately after the Chernobyl accident in 1986 about 23 times as great as that which was observed during the field campaign in 1995. Similarly, the total amount of ^{137}Cs is found to have been 1.2 times greater in 1986 than in 1995. As the two isotopes are chemically identical and follow the same distribution pattern and further emit gamma radiation of on average almost the same energy, it follows that the dose rate relationship $D'(^{134}\mathrm{Cs})$ / $D'(^{137}\mathrm{Cs})$ should have been

1*23*0.8820/36*1.2*0.3224 = 1.45

in 1986, which agrees very well with the value given in the report of the International Chernobyl Project (IAEA, 1991).

The International Chernobyl Project also states that the relationship between the amounts of ^{137}Cs and ^{134}Cs released by the Chernobyl accident was very close to 2. From this it follows that the total dose rate contribution of the two radiocaesium isotopes had in 1997 decreased by a factor of 3 since the deposition took place in 1986. However, in the early phase (first few months) after the Chernobyl accident the external dose rate in the test area was dominated by contributions of relatively short-lived isotopes of for instance iodine and ruthenium (Kelly, 1987).

The Triple Digging Test Area

In a 10 m by 10 m plot on the banks of the river Iput, the triple digging procedure was tested in 1995. By triple digging, the order of three vertical layers of soil is changed (initially: the top ca. 5 cm, the middle ca. 15 cm and the bottom ca. 15 cm), whereby a shielding against the radioactive matter is achieved. The top soil layer, which contains practically all the radioactive caesium, is placed in the bottom of the vertical profile, with the turf facing down. Soil from the bottom is placed immediately on top of this, while the intermediate layer, which must not be inverted, is placed at the top, ensuring the optimal effect with the least impact on the fertility of the area.

The procedure was found to be effective (dose rate reduction of the order of a factor of 10 if a large open area is treated), and the effect has a permanent character unless the soil is subsequently deep-cultivated. The area was initially overgrown with a mixture of different grass types, ranging from rye grasses (*Lolium*), orchard grasses (*Dactylis*) and meadow grasses (*Poa*) to fescue grasses (*Festuca*). However, when we visited the area which was triple dug in 1995 it was apparent that the vegetation in the test spot was different from that of the surrounding area. A resistant fescue grass (*Festuca Rubra*), which was at the time seminiferous and was seen to have a thinner straw and a more reddish/brownish colour, had taken over (see Plate 4), presumably due to the changes in fertility in this shallow type of soil.

Table 6.1. Dose rates (nSv/h) in the test area of Novo Bobovichi. Measurements made in the autumn of 1995 and 1997. Also given are the relationships between dose rate contributions from contamination in 1997/1995 (background/cosmic contribution of 60 nSv/h excluded). Averages and standard deviations are given for assessments of this relationship in different areas.

Point reference number	Measurement area	D' (nSv/h), 1997	D' (nSv/h), 1995	D'(1997) / D'(1995) corr	Relationship statistics
19	Forest	1057	1198	0.876	Average:
20	Forest	1108	1201	0.918	0.90
25	Forest	995	1237	0.794	Standard d.:
26	Forest	1038	1086	0.953	0.06
71	Forest	1055	1126	0.933	
42	Treated soil	280	302	0.909	Average:
44	Treated soil	258	281	0.895	0.91
46	Treated soil	228	245	0.908	Standard d.:
47	Treated soil	253	284	0.861	0.06
49	Treated soil	277	266	1.053	
51	Treated soil	288	339	0.817	
52	Treated soil	208	223	0.908	
53	Treated soil	296	310	0.944	
23	untreated soil	863	982	0.871	Average:
24	untreated soil	755	814	0.921	0.92
39	untreated soil	941	1015	0.923	Standard d.:
40	untreated soil	858	947	0.900	0.04
41	untreated soil	796	807	0.985	
78	House no. 6	172	185	0.896	Average:
79	House no. 4	216	235	0.891	0.91
80	House no. 3	334	357	0.923	Standard d.:
81	House no. 1	420	439	0.950	0.03
85	House no. 5	191	204	0.910	
86	House no. 2	343	386	0.868	

Plate 6.1. The 10 m by 10 m plot that was triple dug in September 1995, photographed in August 1997. The test area is shown in the centre of the picture. The colour difference indicates that a new type of vegetation (a fescue grass - Festuca Rubra) now dominates in the treated area.

7 Contamination of the Forested Area

Both of the settlements subjected to decontamination in 1995 and 1997 were situated in forested areas. After the field tests in 1995 it was discussed whether contamination present in the trees would give a substantial contribution to the dose rate or if the trees would act as a shield against irradiation from distant areas. McGee et al. reported that 7 % of the total ^{137}Cs Chernobyl deposition to a Swedish spruce forest was present in the above ground part of the trees. This amount of activity would give rise to a measurable dose rate in the houses as the radiation from the trees will have high probability of entering the houses through the roof, that has a lower shielding factor. But the trees will also lower the dose in the houses as they shield for photons coming from more distant areas.

Trees have also received an increasing attention over the latest years, as one of the major economic penalties of the Chernobyl accident is the contamination of large forested areas.

7.1 Sampling and Analysis

In 1997 a sampling programme was planned, aimed at obtaining a preliminary picture of the contamination situation in the forested areas around Novozybkov. Three areas were selected for sampling. One near each of the two settlements, Guta Muravinka and Novo Bobovichi, where decontamination work was carried out, and a third area close to the village of Zaborie. This village received a very high level of contamination from the Chernobyl accident – about 4 MBq m^{-2} on average. In Zaborie both trees planted before and after the Chernobyl accident were sampled. The new trees were planted in an area that had been deep ploughed. This area was only about 200 metres from the ‘old’ forest where a pine was also sampled. The soil was in all sampling areas sandy with a thin organic horizon.

The result of soil sampling in the four locations is shown in Table 7.1. Four soil samples were taken at each location and analysed in the laboratory. In two locations only two soil profiles have been analysed so far.

It can be seen that the variability of the results is very high in the area in Zaborie where there had been deep ploughed, whereas it is low in the three other locations where we have undisturbed soil profiles. The locations with undisturbed soil had very similar mean attenuation depth, about 1.7 g cm^{-2}, with low variability. Overall, the surface contamination was three times higher in Zaborie than in the two other places and the attenuation depth was three times greater in the place in Zaborie that had been deep ploughed.

Table 7.1. Review of soil samples taken at the wood sample sites.

Location	Number of samples analysed	Mean surface contamination [MBq m^{-2}]	Mean depth [mm]	Mean attenuation [g cm^{-2}]
Zaborie Young	4	4.2 ± 2.2	48 ± 12	5.4 ± 1.1
Zaborie Old	2	2.95 ± 0.06	35 ± 3	1.8 ± 0.6
Novo Bobovichi	2	1.041 ± 0.004	38 ± 2	1.7 ± 0.2
Guta Muravinka	4	1.2 ± 0.3	27 ± 8	1.6 ± 0.3

Pine, Birch and Oak trees were sampled. In total, seven trees were cut, as presented in Table 7.2. As pine is the most common tree in the Russian forests special focus was put on this species. A mature pine tree was sampled from all locations as well as a younger pine tree from one site. Birch is also very common and was sampled in two locations. Oak was only found in Guta Muravinka.

Sections of the trunks of the trees were sampled at a height of 1 metre above ground. For the pine tree additional pieces of the trunk were sampled at intervals corresponding to 5 years' growth in Zaborie and Novo Bobovichi and with 2 year growth intervals in Guta Muravinka. Branches were sampled with leaves or needles. On location, the leaves and needles were separated from the twigs. For the pine trees the needles and branches were divided according to the year of growth, which easily can be identified on a pine tree.

After returning to the laboratory the bio-material samples were dried to constant weight at 80 °C, except for the trunk sections, which were dried at room temperature.

The bio-material samples were homogenised and measured by gamma spectrometry in standard containers, and the results were expressed in relation to the dry mass. The piece from 1 metre's height above ground and the 5 year old piece from the top of the tree were cut into discs and separated according to year rings.

Table 7.2. Trees sampled during the 1997 campaign

Location	Description	Species	Sample description
Zaborie	Young birch	*Betula pubescens*	10 year old and 3.5 meter high birch tree.
Zaborie	Young pine	*Pinus sylvestris*	10 year old
Zaborie	Old pine	*Pinus sylvestris*	~ 45 year old 15 meter high pine split in two at 5 metres' height
Novo Bobovichi	Old pine	*Pinus sylvestris*	21 year old pine tree. 21 m high and 76 cm Ø at 1 m height
Guta Muravinka	Birch	*Betula pubescens*	Birch
Guta Muravinka	Oak	*Quercus robur*	13 year old Oak tree
Guta Muravinka	Pine	*Pinus sylvestris*	Pine

The obtained samples varied some in both amount and density of the wood chips. The chips were filled into a plastic container with a diameter of 50 mm and a height of 56 mm. The sample was pressed in a hydraulic press according to weight, until the height of the sample corresponded to a uniform density of 0.22 g cm^{-3}. The detectors used for the analysis were efficiency calibrated with 4 standards consisting of standard containers 10, 33, 66 and 100 % filled with an isotope mix absorbed on a material of a suitable density. Figure 7.1 shows the efficiency calibration for the three detectors used in the study

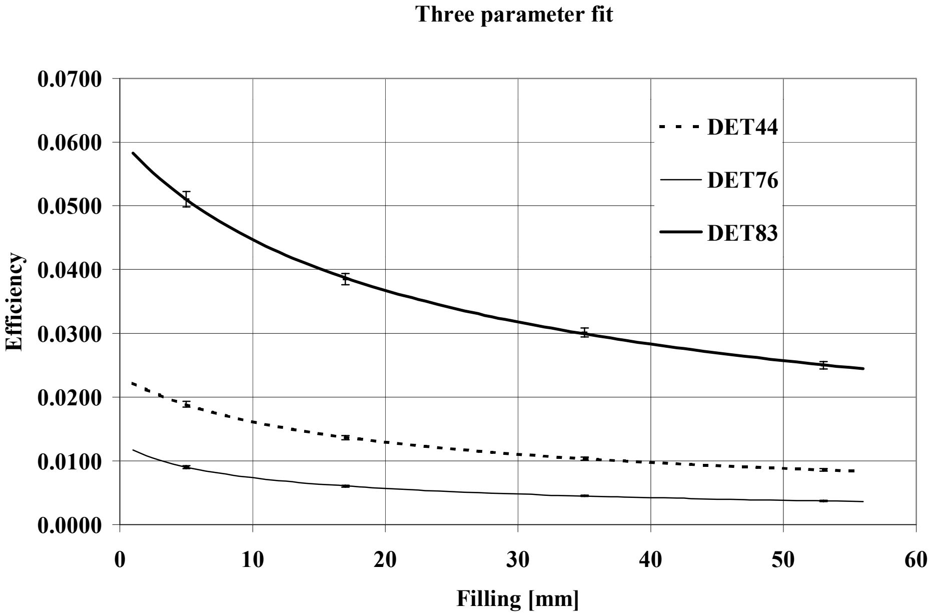


Figure 7.1. Efficiencies of the three detectors (DET44, DET76 and DET83) used for the analysis of the wood samples as a function of the filling of the sample container.

The efficiency factors obtained from the four standards were fitted with an analytical expression for the efficiency (*Eff*) as follows:

$$Eff = A(f + B)^{C},$$

where A, B and C are empirical constants and f is the filling height in the container.

7.2 Results and Discussion

Samples have been analysed for their mean content of ^{137}Cs activity. Seven wood samples have been divided into year rings. In **Table 7.3** the specific activities in Bq per gram of dry matter are shown for the samples. The corresponding transfer factors, TF, were calculated by dividing the specific activities by the contamination level in **Table 7.1**. The TFs are presented in Table 7.4.

Table 7.3. Specific activities in different parts of the sampled species. The results are for mixed samples including bark for the wood and twig samples. The 'New needles' column refers to needles or leaves from the current year, whereas '3 year needles' refers to needles from 1995. Similarly the 1 and 3 year twig columns refer to twigs from the current year and from 1995.

Sample	Root [Bq g^{-1}]	Wood 1 m. [Bq g^{-1}]	Wood 5 y. [Bq g^{-1}]	New needles [Bq g^{-1}]	3 year needles [Bq g^{-1}]	1 year twigs [Bq g^{-1}]	3 year twigs [Bq g^{-1}]	Bark 1 m. [Bq g^{-1}]
Pine Za-old	7.7	5.7	4.9	56.5	12.4	58.7	14.6	6.78
Pine Za-yng	1.76	0.31	0.41	4.9	-	4.64	-	1.46
Pine NB	0.40	0.78	0.23	1.17	0.25	1.17	0.38	-
Pine GM	-	0.81	0.82	9.1	2.01	5.69	1.48	-
Birch Za	-	0.044	0.052	0.25	-	0.176	-	0.089
Birch GM	-	1.11	0.83	2.6	-	1.13	0.67	-
Oak GM	-	1.83	-	12.9	-	3.13	2.71	9.39

Table 7.4. ^{137}Cs transfer factors from soil to wood matter. The specific activities shown in Table 7.3 were divided by the surface contamination obtained from analysis of soil samples. The TF's are expressed in units of 10^{-3} m^2 kg^{-1}.

Sample	Root	Wood 1 m.	Wood 5 y.	New needles	3 year needles	1 year twigs	3 year twigs	Bark 1 m.
Pine Za-old	2.6	1.95	1.65	19.2	4.2	19.9	4.95	-
Pine Za-yo.	0.60	0.11	0.14	1.7	-	1.57	-	-
Pine NB	0.38	0.75	0.22	1.1	0.24	1.15	0.37	-
Pine GM	-	0.68	0.68	7.6	1.68	4.7	1.23	-
Birch Za	-	0.015	0.018	0.08	-	0.06	-	-
Birch GM	-	-	-	2.1	-	0.94	0.56	-
Oak GM	-	1.53	-	10.8	-	2.6	2.3	-

The specific activity was highest in the cambium parts of the trees. For pine trees the specific activity was highest for fresh needles and twigs, followed by 2 and 3 year old needles and twigs, roots, bark and finally wood. In Zaborie the specific activity in the old pine was about 10 times higher than that in the young pine tree. This must indicate that either the surface contamination on the tree is absorbed into the old pine tree or uptake from a ploughed soil is considerably smaller than that from a virgin soil.

The Birch trees had higher specific activities than had the pine trees, both in Zaborie and in Guta Muravinka. This is in good agreement with the results presented by Tikhomirov *et al.* (1993). On the contrary, the other deciduous tree (the oak in Guta Muravinka) had the highest specific activity in the sampled trees from this site.

When comparing the transfer factors for the pine trees from different sites it can be seen that the three older trees have similar TFs, 0.7 – 2.0 10^{-3} m^2 kg^{-1}, whereas the young pine from Zaborie has a considerable smaller TF, 0.1 10^{-3} m^2 kg^{-1}. The observed TFs for pine are in good agreement with the numbers reported by Belli *et al.* (1996).

The results of the analysis of the seven samples divided into year rings are presented in Figure 7.2. The results from analysis of the old pine from 1997 to 1958 show that the ^{137}Cs is mobile in the tree trunk, as presented by others (e.g. Kohno *et al.* (1988) and Momoshima and Bondietti (1994)). No peak can be seen in the year ring corresponding to 1986, where the Chernobyl accident occurred. The activity is almost homogeneously distributed over the year rings, all the way back to the 1958 ring. The concentration seems to decline towards an equilibrium level in the centre of the tree.

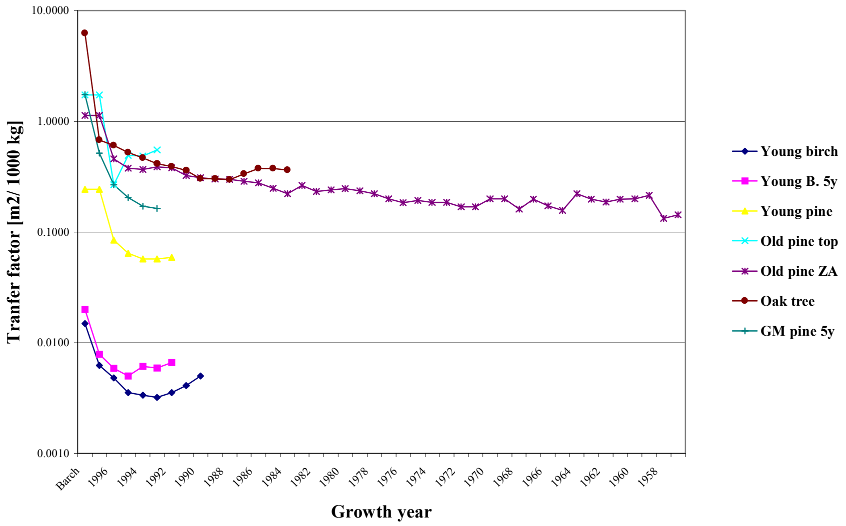


Figure 7.2. Transfer factors for the analysed samples as a function the growth year

8 Conclusion

The experimental campaign in Novo Bobovichi gave new experience to all participants regarding the applied equipment, methods, measurement devices and the obtained decontamination results. The work has demonstrated that a significant dose reduction can be achieved in the urban area with relatively simple methods. Compared to the results obtained in 1995, significantly higher dose reduction factors were achieved. A reason for this may be that the soil contamination in the test area in Guta Muravinka appeared to be confined to a thinner layer, wherefore a greater part was removed with the topsoil. In our opinion the most important reason for the good results, both in 1995 and in 1997, was the careful monitoring during the dose reduction process. For instance, each plot was re-measured for activity and subsequently treated until all ‘hot spots’ had been removed.

Some scepticism has been expressed as to whether resuspended contaminated soil from areas outside the cleaned location might rapidly lead to a re-contamination. Re-measurements of the area that was decontaminated in 1995 clearly show that this is not the case.

Over the latest few years the Russian policy in the contaminated areas has changed. Until recently relocation was encouraged and many have left the areas. Today, however, the Russian authorities wish to reclaim the land and the relocation has been stopped. Remediation methods that would lower the dose to people living in the area have received new attention. Reductions of a scale as those described in this report would in practically all contaminated areas bring the annual doses down below the 1 mSv/year limit recommended by the IAEA.

8.1 Equipment and Methods

Three machines were tested in the contaminated areas in 1997. The Bobcat proved to be an excellent tool for decontamination around houses. Large areas could be treated in reasonable time. At the same time, the manoeuvrability of the bobcat's shovel ensured that relative small amounts of waste were generated.

The asphalt scraper demonstrated that smaller asphalted areas can easily be cleaned. It is a relatively simple machine and easy to operate.

The skim and burial plough was tested in a field northwest of Novo Bobovichi. This test only gave a dose rate reduction by a factor of 2.2. However, the test area had rather limited dimensions, and if a much larger area had been treated the DRF would have been around 6-7. It should be stressed that the test field conditions were far from the optimal. For instance, the ploughing was carried out in the late summer, following a very warm and dry period, wherefore the soil contained very little moisture and the subsoil crumbled and fell to the bottom of the trench.

Concerning measuring equipment a good correlation was found between the results obtained with the hand-held Russian DRG-01-T instrument and with the Reuter Stokes ion chamber. Another easily portable dose rate measurement device made in Belarus, the El-1101, was applied frequently, and also the results obtained with this instrument were at both high and low dose rates found to correlate very well with those obtained with the Reuter Stokes ion chamber.

A portable Russian gamma-analyser, SKIF-3, was used in a specially designed lead collimator arrangement for series of angular in situ gamma spectrometric measurements. This made it possible to qualitatively assess the effect of the decontamination operation on the gamma signal from different surfaces.

8.2 Decontamination Results

The strategy for decontamination around the houses in the village of Guta Muravinka consisted of removal of topsoil, which was replaced with radiologically 'clean' sand, and removal of the roof of one of the houses. The soil removal accomplished with a mini-bulldozer gave a reduction of the dose rate contribution from the contamination in the area by almost 79 % outdoors in the treated area between two houses. The corresponding effect on the contaminant dose rate contribution inside the houses was somewhat smaller, since the contamination on the house is here of more importance. At ground floor level the dose rate reduction was by 57 %, whereas it was 33 % at the 1st floor level, where much of the dose rate is due to contamination at greater distances than the dimensions of the cleaned area. Since the soil contamination lay in a thinner area in Guta Muravinka than it did in Novo Bobovichi, where the 1995 measurements were conducted, a considerably larger fraction of the contamination could be removed with a thin topsoil layer. Therefore, contrary to what had been observed in Novo Bobovichi, the subsequent application of a thin layer of 'clean' sand had in Guta Muravinka practically no additional effect. One of the surprising findings of the experimental work in 1995 was that the dose rate contribution from contamination on the roofs of houses was highly significant. The roof again proved to be an important contributor to the dose rate inside houses, especially at first floor level. Here, the dose rate was reduced by 27 % when the roof was replaced. Since only the roof of one house was replaced, an even greater effect could be expected if the roofs of neighbouring buildings had also been changed. The overall result of the strategy was a reduction of the dose rate outdoors in the treated area by almost a factor of 6, and indoors by generally about a factor of 3. If larger areas were treated, as would be the case if the strategy were to be implemented in a full-scale operation, the dose rate contribution from the far away areas could have been reduced considerably, and the total effect would have been even better.

The results of the measurements carried out both in 1995 and in 1997 clearly indicate that a large fraction of the residual dose rate in the area after decontamination is caused by the contaminated forested areas in the vicinity of the test plot. The contamination descended in rain on the test plot. It should be stressed that in areas that received a dry deposition, the relative contamination level in a forest will be substantially greater, making the forest an even more important dose contributor than in this case study. A preliminary investigation of the distribution of the distribution of the contamination in the forest indicates that most of the contamination in the trunk of a tree lies in the cambium. This seems to be the case both for old trees and for young trees planted after the Chernobyl accident occurred in 1986. In the deeper layers of the tree trunk the contamination appears to distribute rather homogeneously. However, further work should be carried out to establish this important point.

8.3 Future Work

Now decontamination has been tested at two sites with manual methods and with machines. The next step would be to do decontamination work around populated houses in some of the more contaminated villages. This can hopefully be achieved through a continuation of this project or through funding IAEA that have approval from UN of a project involving decontamination work in Belarussian settlements.

Some improvements in the instrumentation could also be wished for. The El-1101 was an improvement compared to the instruments used for monitoring the work in 1995, but testing of instruments based β-detectors would still be interesting. Improvement in measuring time and precision could hopefully be obtained.

A collimated NaI based monitor could be installed on the back edge of the bobcats' shovel, monitoring the contamination of the soil after scraping. A display could then be placed in front of the driver so he could follow the results of his work "on-line". Such a construction would make driver more independent of the continuous evaluation of his work by people with handheld instruments.

A more extensive analysis of the contamination in the forest and its implications for dose is required to fully account for the effect that may be obtained by implementation of a clean-up strategy in the contaminated areas. Since a large dose contribution from the forested area can be ascribed to contamination in the forest floor duff layers, it is not known whether the most important effect of the trees as such is the shielding or the dose contribution due to their contamination. Therefore it is not known if it would be beneficial from a pure dose point of view to remove the trees. This question could be answered by Monte Carlo photon transport modelling. However, this would require a greater and more general knowledge of the contaminant distribution. For instance, if small diameter samples were taken throughout the trunks of a great number of trees in the specific area, these could be sectioned according to year rings, which could be bulked from different trees for the contamination analysis, in order to examine the general contamination distribution in the area.

Investigations of dose rate contributions inside houses from indoor contamination, and more generally, investigations to identify the important sources to the residual dose rate in the treated areas.

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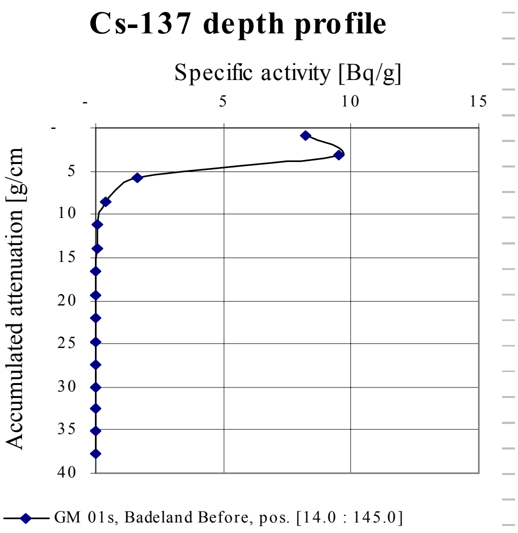
Appendix A. Soil Samples

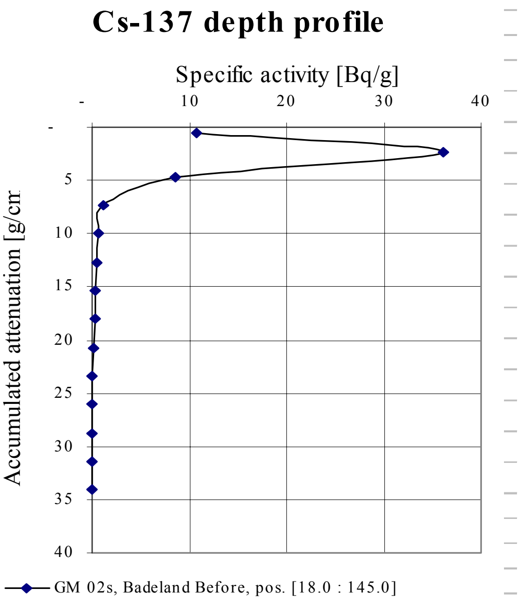
Table A.1. Review of soil samples analysed in the laboratory.

Sample ID		Total deposition [kBq/m^2]	Mean depth [mm]	Mean attenuation [g/cm^2]
GM01	Beach site - before	506	23.3	2.84
GM02	Beach site - before	1,359	31.7	3.23
GM03	Beach site - after	104	80.3	11.43
GM04	Beach site - after	104	160.1	22.56
GM05	Around house 2 (40, 59)	10,629	84.0	3.57
GM06	Around house 2 (40.4, 50.5)	7,962	64.6	7.69
GM07	Around house 2 (31.8, 50.5)	1,194	41.5	3.66
GM08	Around house 2 (31.8, 58.6)	497	31.4	2.33
GM09	Center line (12, 44.5)	1,180	25.2	2.96
GM10	Center line (16, 44.5)	1,479	26.7	2.46
GM11	Center line (32, 44.5)	1,669	31.2	2.90
GM12	Center line (36, 44.5)	1,516	51.4	5.65
GM13	Center line (46, 44.5)	929	22.0	1.67
GM14	Center line (56, 44.5)	1,145	22.6	1.92
GM15	Forest A	1,083	23.8	1.16
GM16	Forest B	1,645	37.8	1.56
GM19	Center line - after (33, 44.5)	44	89.3	12.54
GM20	Center line - after (35, 44.5)	219	69.3	9.48
GM21	Center line - after (37, 44.5)	83	102.4	14.14
NB03	Triple digging site A	1,085	239.5	25.58
NB04	Triple digging site B	1,170	200.1	21.74
NB06	Forest 0.5 m North of pine	1,044	39.5	1.61
NB07	Forest 0.5 m North of pine	1,038	36.4	1.89
NB21	S&B experiment - before SW	1,500	58.5	3.86
NB22	S&B experiment - before NE	1,551	56.3	4.80
NB23	S&B experiment - before NW	1,610	26.6	1.37
NB24	S&B experiment - before SE	1,156	102.2	10.66
NB25	S&B experiment - after A	470	223.4	29.80
NB26	S&B experiment - after B	200	195.6	26.72
NB27	S&B experiment - after C	1,122	162.0	20.95
NB28	S&B experiment - after D	1,065	158.4	14.90
NB29	S&B experiment - after E	1,668	176.6	17.17
ZA01	Young forest	2,196	46.5	4.87
ZA02	Young forest	7,055	64.1	6.92
ZA03	Young forest	2,751	34.7	4.52
ZA04	Young forest	4,726	46.3	5.09
ZA12	Old forest	2,990	37.0	2.26
ZA13	Old forest	2,903	33.0	1.35

No.	Mean depth	Acculated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.8	104	719
2	26	3.1	151	1203
3	44	5.8	153	212
4	63	8.5	155	55
5	81	11.2	155	6.6
6	99	13.9	153	4.2
7	117	16.6	156	3.1
8	136	19.4	153	1.65
9	154	22.1	153	0.51
10	172	24.7	152	0.31
11	191	27.4	149	0.20
12	209	30.0	145	0.20
13	227	32.5	149	0.16
14	246	35.2	148	0.10
15	264	37.8	151	0.12
	Total deposition		505,753	Bq/m2
	Mean depth		23	mm
	Mean attenuation		2.8	g/cm2

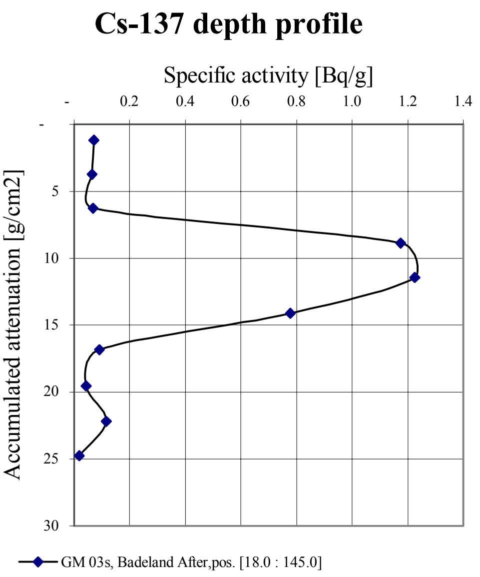


No.	Mean depth	Acculated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.6	74	664
2	26	2.4	126	3802
3	44	4.8	145	1045
4	63	7.4	152	152
5	81	10.0	149	93
6	99	12.7	154	57
7	118	15.4	152	35
8	136	18.0	153	43
9	154	20.7	151	16
10	173	23.4	152	6.8
11	191	26.1	152	3.5
12	210	28.7	152	2.6
13	228	31.4	151	1.32
14	247	34.0	146	0.57
	Total deposition		1,358,804	Bq/m2
	Mean depth		32	mm
	Mean attenuation		3.2	g/cm2

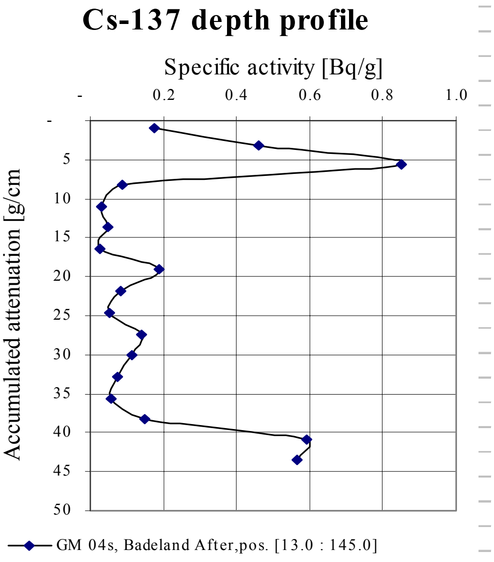


No. []	Mean depth [mm]	Accumulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	1.2	148	8.9
2	26	3.7	141	7.5
3	44	6.3	148	8.5
4	62	8.9	146	143
5	81	11.4	147	151
6	99	14.1	154	100
7	118	16.8	155	12
8	136	19.5	153	5.4
9	155	22.2	149	14
10	173	24.8	143	2.2

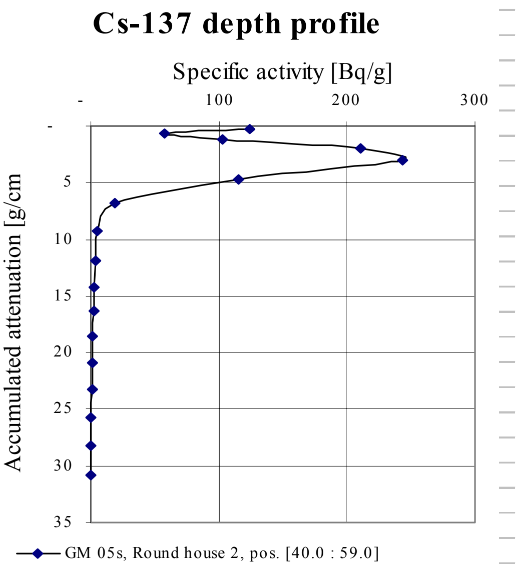
Total deposition	103,898	Bq/m2
Mean depth	80	mm
Mean attenuation	11.4	g/cm2



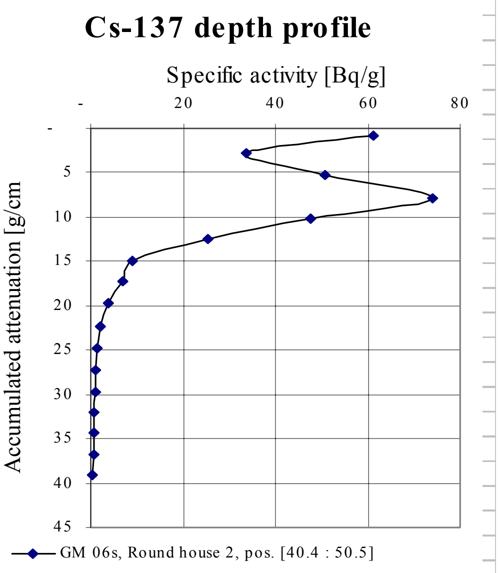
No. []	Mean depth [mm]	Accumulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.9	112	17
2	26	3.1	138	53
3	45	5.6	144	103
4	63	8.2	152	11
5	82	10.9	156	4.0
6	101	13.7	156	6.2
7	119	16.4	154	3.6
8	138	19.1	155	25
9	156	21.9	157	11
10	175	24.6	157	6.9
11	193	27.4	156	18
12	211	30.1	156	15
13	230	32.9	156	10
14	248	35.6	156	7.3
15	267	38.3	150	19
16	285	40.9	147	73
17	304	43.5	149	71
	Total deposition		103,515	Bq/m2
	Mean depth		160	mm
	Mean attenuation		22.6	g/cm2



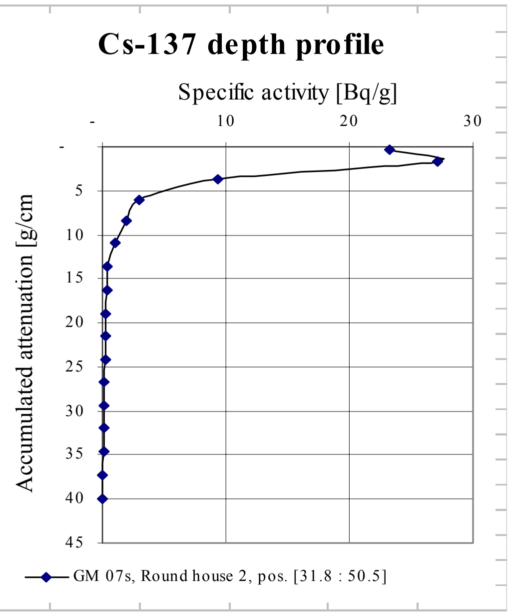
No.	Mean depth	Accumulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.2	24	2530
2	27	0.6	27	1296
3	46	1.2	33	2900
4	66	1.9	50	8889
5	85	3.1	80	16342
6	104	4.7	109	10607
7	124	6.8	132	2115
8	143	9.3	146	641
9	163	11.9	145	400
10	182	14.3	125	290
11	202	16.4	113	188
12	222	18.6	135	204
13	241	20.9	134	191
14	261	23.3	133	101
15	280	25.7	142	65
16	300	28.3	145	35
17	319	30.8	145	12
	Total deposition		10,628,649	Bq/m2
	Mean depth		84	mm
	Mean attenuation		3.6	g/cm2



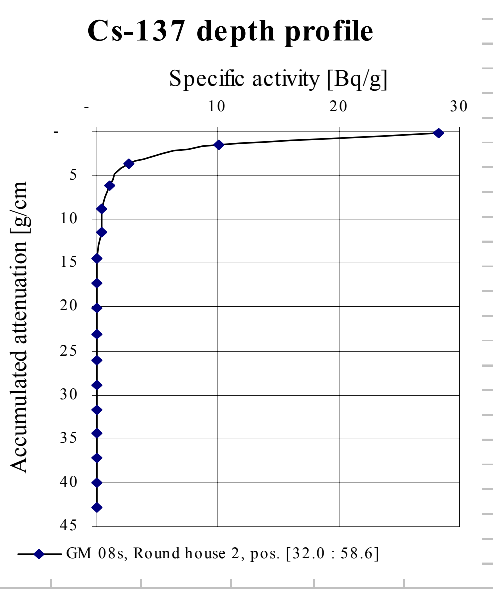
No.	Mean depth	Accumulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.7	92	4730
2	26	2.8	139	3964
3	46	5.3	146	6284
4	65	7.8	141	8842
5	85	10.2	131	5245
6	104	12.5	131	2803
7	124	14.9	133	1002
8	143	17.3	139	802
9	162	19.8	143	468
10	182	22.3	140	241
11	202	24.8	142	160
12	221	27.3	140	120
13	240	29.6	128	104
14	260	32.0	133	88
15	279	34.3	136	88
16	299	36.8	138	63
17	318	39.1	128	50
	Total deposition		7,961,866	Bq/m2
	Mean depth		65	mm
	Mean attenuation		7.7	g/cm2



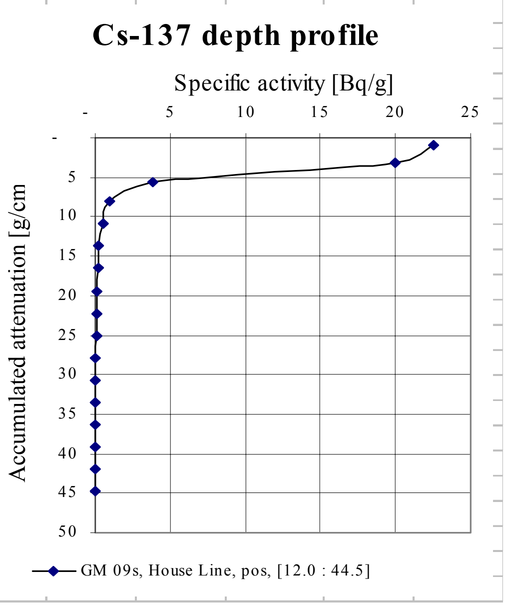
	Mean	Acculated	Weight	Activity
No.	depth	attenuation	of sample	in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.4	51	993
2	27	1.8	101	2318
3	46	3.8	126	986
4	65	6.1	136	341
5	84	8.5	135	214
6	103	11.0	149	128
7	122	13.6	153	57
8	142	16.3	151	46
9	161	19.0	149	36
10	180	21.6	141	31
11	200	24.1	147	38
12	219	26.7	153	13
13	238	29.4	146	16
14	257	32.0	145	15
15	277	34.6	150	10
16	296	37.3	155	4.6
17	316	39.9	147	4.2
	Total deposition		1,194,366	Bq/m2
	Mean depth		42	mm
	Mean attenuation		3.7	g/cm2



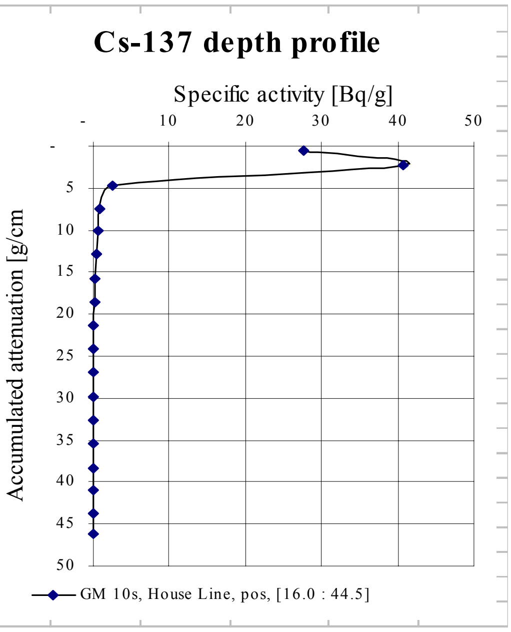
	Mean	Acculated	Weight	Activity
No.	depth	attenuation	of sample	in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.2	28	654
2	27	1.5	114	978
3	47	3.7	135	297
4	66	6.1	143	133
5	86	8.7	148	43
6	105	11.5	163	57
7	124	14.4	166	7.4
8	143	17.3	164	3.7
9	163	20.2	161	2.5
10	182	23.1	166	1.9
11	201	26.0	166	1.3
12	221	28.9	163	1.3
13	240	31.7	153	2.0
14	260	34.4	156	1.5
15	280	37.2	158	1.4
16	299	40.0	157	0.9
17	319	42.8	163	0.6
	Total deposition		496,551	Bq/m2
	Mean depth		31	mm
	Mean attenuation		2.3	g/cm2



No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.9	111	2106
2	27	3.1	138	2343
3	47	5.5	139	447
4	66	8.1	154	123
5	86	10.9	157	77
6	105	13.7	161	33
7	125	16.5	161	23
8	144	19.4	161	14
9	163	22.3	164	9.5
10	183	25.1	157	10.0
11	203	27.9	158	3.7
12	222	30.7	160	1.15
13	242	33.5	160	1.86
14	261	36.4	161	1.13
15	281	39.2	158	0.81
16	300	42.0	158	1.21
17	320	44.8	158	1.13
	Total deposition		1,180,057	Bq/m2
	Mean depth		25	mm
	Mean attenuation		3.0	g/cm2

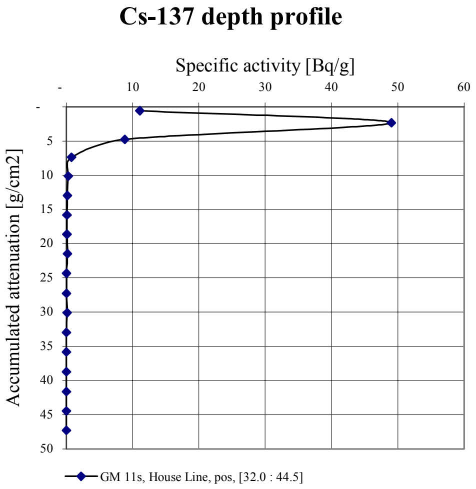


No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.5	64	1477
2	26	2.2	126	4338
3	45	4.7	155	344
4	65	7.4	154	108
5	84	10.1	148	92
6	103	12.8	165	55
7	123	15.7	161	14.9
8	142	18.5	157	17.4
9	162	21.4	163	10.2
10	181	24.2	156	7.1
11	200	27.0	160	11.7
12	220	29.8	159	3.6
13	239	32.6	161	1.34
14	258	35.5	158	2.01
15	278	38.3	163	2.21
16	297	41.0	148	1.04
17	316	43.7	152	0.48
18	335	46.2	132	0.59
	Total deposition		1,479,398	Bq/m2
	Mean depth		27	mm
	Mean attenuation		2.5	g/cm2



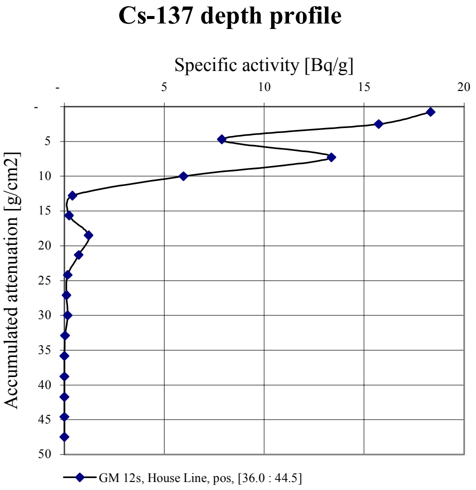
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.6	70	659
2	27	2.3	130	5391
3	47	4.8	142	1061
4	66	7.4	154	101
5	85	10.1	157	39
6	105	13.0	165	22
7	124	15.8	156	13
8	143	18.6	162	13
9	163	21.5	159	25
10	182	24.3	165	4.6
11	201	27.2	164	2.2
12	220	30.1	159	13.9
13	240	33.0	163	1.95
14	259	35.8	163	1.23
15	278	38.7	164	0.45
16	298	41.6	165	0.49
17	317	44.5	157	0.41
18	335	47.3	159	1.22

Total deposition	1.668.711	Bq/m2
Mean depth	31	mm
Mean attenuation	2.9	g/cm2



No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.8	93	1448
2	28	2.5	103	1375
3	48	4.7	145	960
4	67	7.3	149	1687
5	86	10.0	157	791
6	106	12.8	160	56
7	125	15.6	161	33
8	145	18.5	160	165
9	164	21.3	160	98
10	184	24.2	164	23
11	203	27.1	165	17
12	223	30.0	164	24
13	242	32.9	165	4.8
14	262	35.8	166	1.41
15	281	38.8	169	1.22
16	301	41.7	164	1.12
17	320	44.6	159	1.09
18	340	47.5	167	1.19

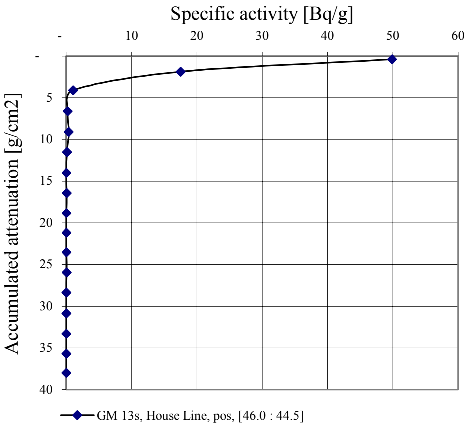
Total deposition	1.515.771	Bq/m2
Mean depth	51	mm
Mean attenuation	5.6	g/cm2



No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.4	49	2063
2	27	1.9	118	1757
3	47	4.1	135	119
4	67	6.6	149	30
5	86	9.1	131	44
6	105	11.5	144	16.3
7	125	14.0	136	5.7
8	144	16.4	138	10.3
9	164	18.8	133	5.9
10	183	21.2	132	5.8
11	202	23.5	135	5.2
12	221	25.9	135	11.4
13	241	28.4	141	5.2
14	260	30.8	139	3.6
15	280	33.3	139	2.7
16	299	35.7	130	3.0
17	318	38.0	133	2.6

Total deposition 928.852 Bq/m2
Mean depth 22 mm
Mean attenuation 1.7 g/cm2

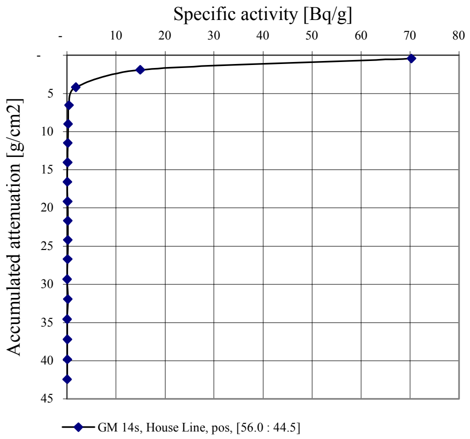
Cs-137 depth profile



No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm2]	[g]	[Bq]
1	8	0.4	52	3087
2	27	1.9	118	1496
3	47	4.2	136	210
4	66	6.5	132	44
5	85	9.0	143	29
6	105	11.5	140	19.4
7	124	14.0	145	12.4
8	144	16.6	145	10.3
9	164	19.1	144	15.0
10	184	21.7	141	20.7
11	203	24.2	141	20.2
12	222	26.7	146	14.5
13	242	29.3	149	6.0
14	261	31.9	147	19.7
15	280	34.6	149	5.4
16	300	37.2	149	8.9
17	319	39.8	148	8.3
18	337	42.4	146	5.5

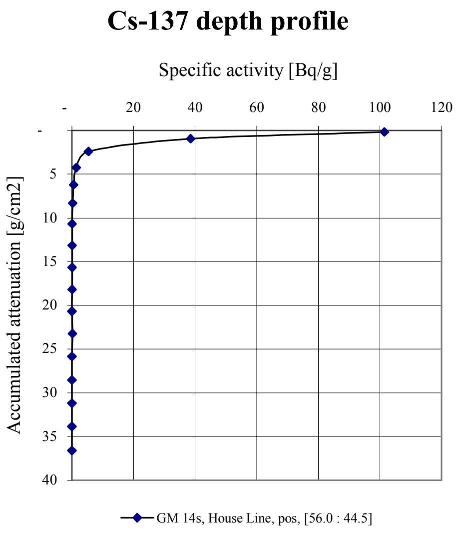
Total deposition 1.145.458 Bq/m2
Mean depth 23 mm
Mean attenuation 1.9 g/cm2

Cs-137 depth profile



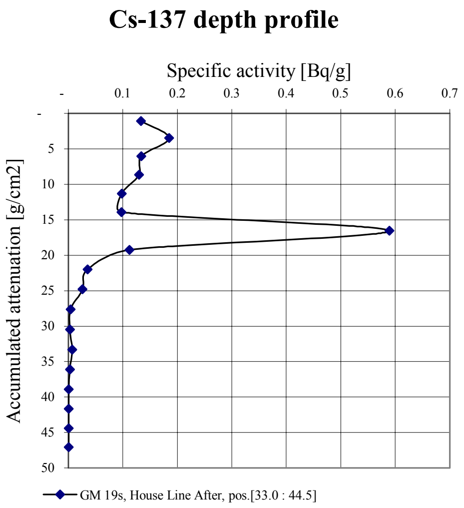
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.2	23	1970
2	26	0.9	63	2023
3	44	2.4	102	458
4	62	4.2	110	131
5	81	6.2	113	51
6	99	8.3	126	26
7	118	10.7	140	10
8	136	13.1	143	5.1
9	155	15.7	144	7.0
10	173	18.2	139	5.0
11	192	20.7	146	3.7
12	210	23.2	146	21.0
13	229	25.9	151	2.8
14	247	28.5	153	0.24
15	265	31.2	151	0.120
16	284	33.9	152	0.000
17	302	36.6	160	0.096

Total deposition 1.082.517 Bq/m2
Mean depth 24 mm
Mean attenuation 1.2 g/cm2



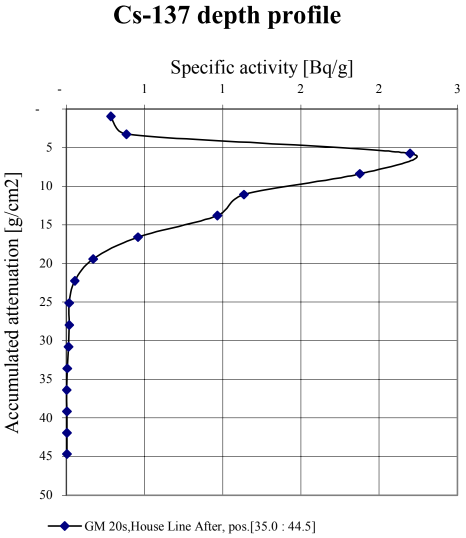
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	1.1	132	14.8
2	26	3.5	142	22
3	44	6.0	148	16.6
4	63	8.6	150	16.3
5	81	11.3	150	12.4
6	99	13.9	150	12.2
7	118	16.6	148	73
8	136	19.2	157	14.7
9	154	22.0	158	4.6
10	173	24.8	159	3.5
11	191	27.6	162	0.60
12	210	30.5	161	0.40
13	228	33.3	160	0.97
14	247	36.1	158	0.39
15	265	38.9	159	0.116
16	284	41.7	157	0.136
17	302	44.4	154	0.112
18	320	47.1	146	0.118

Total deposition 44.259 Bq/m2
Mean depth 89 mm
Mean attenuation 12.5 g/cm2



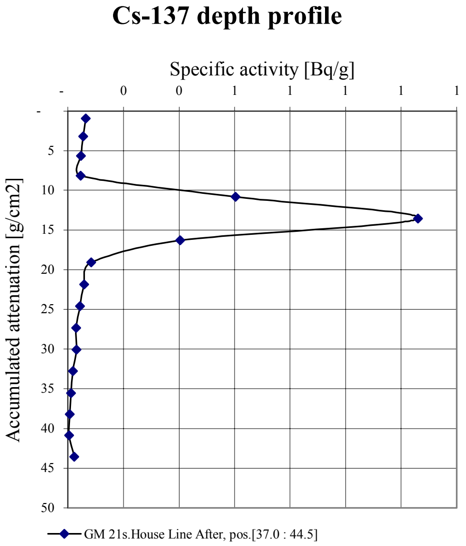
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.9	119	28
2	26	3.2	142	46
3	44	5.8	146	268
4	62	8.4	151	238
5	81	11.1	154	146
6	99	13.8	156	126
7	117	16.6	160	61
8	136	19.4	161	23
9	154	22.3	163	7.4
10	172	25.1	162	2.5
11	191	28.0	162	2.6
12	209	30.8	159	2.1
13	227	33.6	159	1.01
14	246	36.4	158	0.55
15	264	39.1	157	0.67
16	283	41.9	157	0.73
17	301	44.7	157	0.64

Total deposition	218.948	Bq/m2
Mean depth	69	mm
Mean attenuation	9.5	g/cm2



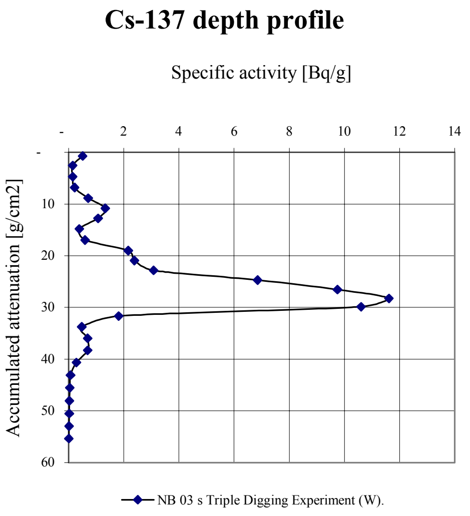
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	7	0.9	119	6.3
2	25	3.2	137	6.3
3	44	5.6	142	5.6
4	62	8.2	144	5.5
5	80	10.8	156	79
6	99	13.6	156	164
7	117	16.3	158	53
8	136	19.1	158	11.0
9	154	21.8	156	7.6
10	172	24.6	156	5.6
11	190	27.3	156	3.9
12	209	30.1	154	3.9
13	227	32.8	156	2.4
14	246	35.5	154	1.41
15	264	38.2	150	0.84
16	283	40.9	153	0.44
17	301	43.5	151	2.9

Total deposition	82.509	Bq/m2
Mean depth	102	mm
Mean attenuation	14.1	g/cm2



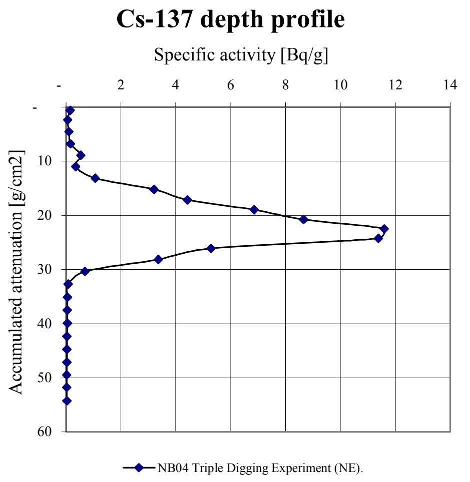
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm 2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.7	88	37
2	27	2.6	123	15
3	45	4.7	121	15
4	64	6.8	119	22
5	82	8.9	113	66
6	100	10.8	108	120
7	118	12.8	115	103
8	137	14.8	121	39
9	155	17.0	120	60
10	174	19.0	111	201
11	192	20.9	108	215
12	210	22.8	107	276
13	229	24.7	107	612
14	247	26.5	101	826
15	266	28.3	96	928
16	284	29.9	87	768
17	302	31.7	117	179
18	321	33.8	120	48
19	339	36.0	130	75
20	358	38.3	135	77
21	376	40.7	135	31
22	394	43.1	140	8.2
23	413	45.6	142	4.7
24	431	48.1	142	3.1
25	449	50.5	139	2.5
26	468	53.0	137	1.4
27	486	55.3	134	0.9

Total deposition	1.085.223	Bq/m 2
Mean depth	239	mm
Mean attenuation	25.6	g/cm 2



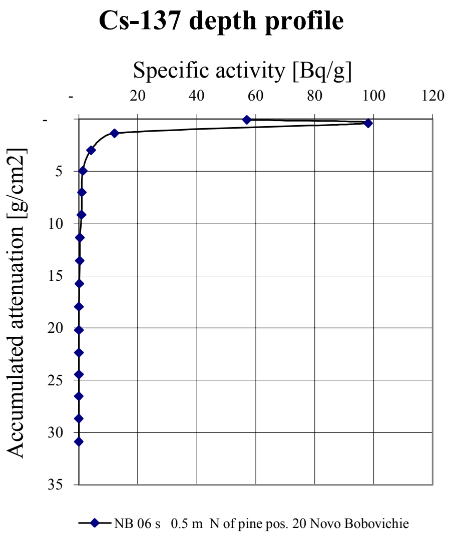
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm 2]	Weight of sample [g]	Activity in sample [Bq]
1	7	0.6	78	9.1
2	25	2.4	121	5.8
3	44	4.6	128	11
4	62	6.8	125	17
5	80	8.9	116	52
6	99	11.0	124	36
7	117	13.1	120	106
8	135	15.2	114	305
9	153	17.1	106	392
10	171	19.0	103	588
11	190	20.8	99	717
12	208	22.5	99	962
13	226	24.3	100	954
14	244	26.1	111	490
15	263	28.1	119	334
16	281	30.3	132	76
17	299	32.7	136	8.8
18	318	35.1	137	5.2
19	336	37.5	137	4.4
20	355	39.9	138	5.5
21	373	42.3	137	3.0
22	391	44.7	137	3.2
23	409	47.1	137	3.5
24	428	49.4	123	2.2
25	446	51.8	141	2.5
26	465	54.2	138	2.8

Total deposition	1.169.715	Bq/m 2
Mean depth	200	mm
Mean attenuation	21.7	g/cm 2



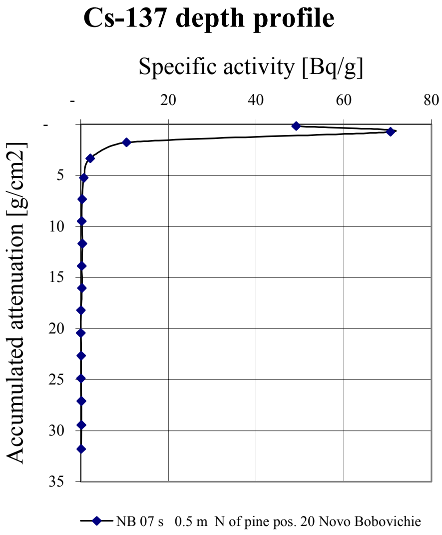
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	7	0.1	7	314
2	26	0.4	32	2627
3	44	1.4	77	784
4	62	3.0	106	372
5	81	4.9	118	136
6	99	7.0	118	103
7	118	9.1	124	94
8	136	11.3	127	41
9	154	13.5	123	30
10	173	15.7	126	23
11	191	17.9	126	9.4
12	210	20.2	127	4.3
13	228	22.4	120	4.4
14	247	24.4	116	4.3
15	266	26.5	121	2.7
16	284	28.7	123	1.6
17	303	30.9	128	2.3

Total deposition	1.043.643	Bq/m2
Mean depth	40	mm
Mean attenuation	1.6	g/cm2



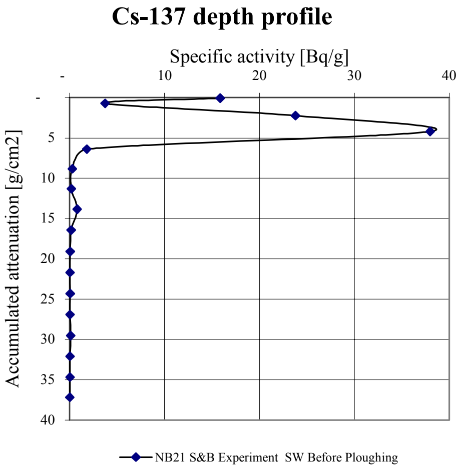
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.2	22	884
2	26	0.7	42	2458
3	44	1.8	77	670
4	63	3.3	101	186
5	81	5.2	117	72
6	100	7.3	120	34
7	118	9.5	125	28
8	137	11.7	125	40
9	155	13.9	124	29
10	173	16.0	122	31
11	192	18.2	126	7.8
12	210	20.4	125	5.8
13	229	22.7	128	14.1
14	248	24.9	124	9.8
15	266	27.1	129	21
16	285	29.4	135	21
17	304	31.8	131	16.9

Total deposition	1.037.804	Bq/m2
Mean depth	36	mm
Mean attenuation	1.9	g/cm2



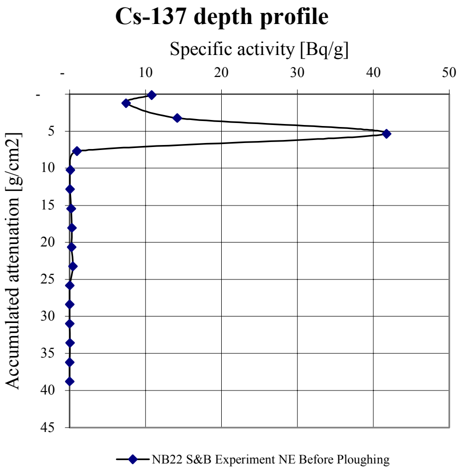
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.1	8	111
2	26	0.7	66	207
3	45	2.2	106	2117
4	63	4.2	116	3680
5	81	6.4	132	198
6	99	8.8	145	34
7	118	11.3	139	21
8	136	13.8	147	96
9	154	16.5	150	21
10	173	19.1	149	8.3
11	191	21.7	147	6.1
12	210	24.3	149	6.8
13	228	26.9	148	5.2
14	247	29.5	147	12.7
15	265	32.1	147	4.9
16	283	34.7	144	4.1
17	302	37.2	143	2.1

Total deposition	1.499.660	Bq/m2
Mean depth	58	mm
Mean attenuation	3.9	g/cm2



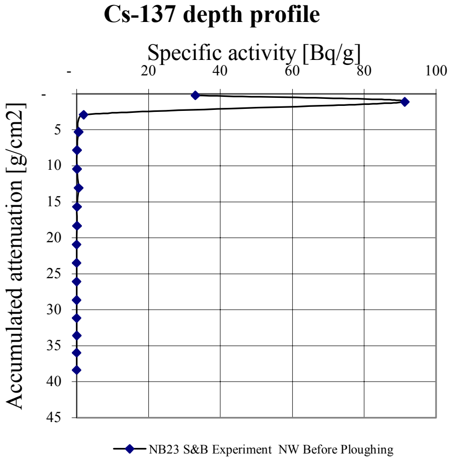
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	7	0.1	17	151
2	25	1.2	105	653
3	44	3.2	123	1456
4	62	5.4	120	4196
5	80	7.7	143	117
6	99	10.2	148	13
7	117	12.8	148	7.2
8	135	15.4	148	25
9	154	18.0	148	39
10	172	20.6	148	31
11	190	23.2	146	51
12	209	25.8	146	4.2
13	227	28.4	147	0.84
14	246	31.0	148	0.96
15	264	33.6	148	7.0
16	282	36.2	149	0.45
17	301	38.8	144	0.28

Total deposition	1.550.698	Bq/m2
Mean depth	56	mm
Mean attenuation	4.8	g/cm2



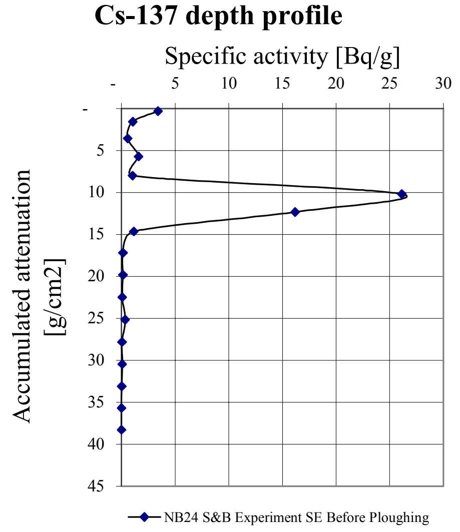
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.2	26	708
2	26	1.1	78	5905
3	44	2.9	127	201
4	62	5.3	143	62
5	80	7.8	148	10.9
6	99	10.4	150	11.1
7	117	13.1	149	66
8	136	15.7	150	10.5
9	154	18.3	149	11.5
10	172	20.9	145	1.87
11	191	23.5	147	1.58
12	209	26.1	145	2.2
13	227	28.6	147	1.43
14	246	31.2	141	1.52
15	263	33.6	135	3.4
16	282	36.0	135	2.8
17	300	38.4	138	2.2

Total deposition	1.609.659	Bq/m2
Mean depth	27	mm
Mean attenuation	1.4	g/cm2



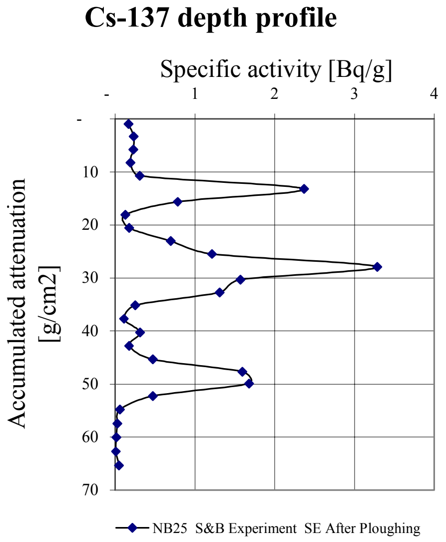
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.3	40	115
2	26	1.6	104	92
3	44	3.6	121	58
4	62	5.7	126	168
5	80	8.0	132	113
6	99	10.2	119	2591
7	117	12.3	123	1663
8	135	14.6	139	133
9	154	17.2	150	18.3
10	172	19.8	150	18.4
11	190	22.5	151	8.5
12	209	25.2	152	44
13	227	27.8	151	6.3
14	246	30.5	150	8.6
15	264	33.1	148	1.51
16	283	35.7	148	0.77
17	301	38.3	145	0.93

Total deposition	1.155.861	Bq/m2
Mean depth	102	mm
Mean attenuation	10.7	g/cm2



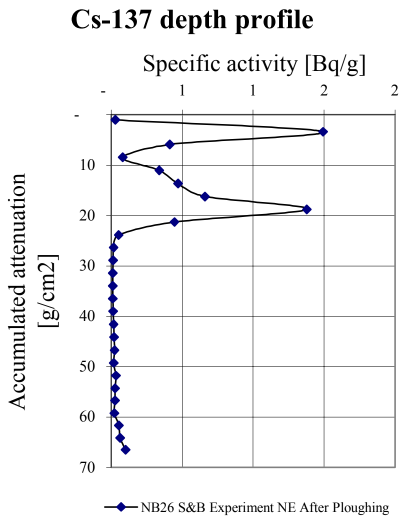
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	1.0	121	16.8
2	26	3.3	142	28
3	44	5.8	141	27
4	63	8.3	141	23
5	81	10.7	140	36
6	99	13.2	139	275
7	118	15.6	139	91
8	136	18.1	140	14.8
9	154	20.6	142	21
10	173	23.0	138	81
11	191	25.5	139	141
12	209	27.9	138	379
13	227	30.3	136	179
14	246	32.7	135	148
15	264	35.1	143	30
16	282	37.7	147	13.7
17	301	40.3	145	38
18	319	42.8	146	21
19	338	45.3	140	55
20	356	47.7	125	167
21	374	49.9	127	177
22	393	52.3	142	56
23	411	54.8	149	7.6
24	429	57.4	151	3.4
25	448	60.1	147	1.86
26	466	62.7	152	1.23
27	484	65.3	147	6.1
28	503	67.9	149	9.1
29	521	70.5	147	0.56
30	540	73.2	150	0.38
31	558	75.8	145	0.30
32	577	78.3	149	0.32

Total deposition	469.954	Bq/m2
Mean depth	223	mm
Mean attenuation	29.8	g/cm2



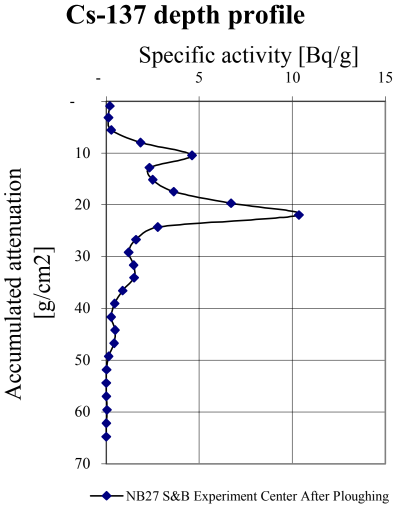
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	1.0	128	3.0
2	26	3.4	143	178.1
3	44	5.9	143	49.2
4	62	8.5	148	10.0
5	81	11.1	149	42.2
6	99	13.7	147	57.9
7	117	16.2	145	79.7
8	135	18.8	143	165.5
9	154	21.3	144	53.8
10	172	23.8	144	6.3
11	191	26.4	143	2.0
12	209	28.9	144	1.42
13	228	31.4	143	1.25
14	246	33.9	144	1.34
15	264	36.5	144	1.30
16	283	39.0	145	1.70
17	301	41.6	145	2.0
18	319	44.1	147	2.4
19	338	46.7	147	2.9
20	356	49.3	143	2.1
21	374	51.8	141	3.9
22	393	54.3	142	3.3
23	411	56.7	140	3.1
24	429	59.2	141	2.6
25	448	61.7	140	6.2
26	466	64.1	138	7.2
27	484	66.5	135	11.3
28	503	68.8	130	18.1
29	522	71.1	121	62.0
30	541	73.2	123	49.2
31	560	75.3	118	41.6

Total deposition	200.052	Bq/m2
Mean depth	196	mm
Mean attenuation	26.7	g/cm2



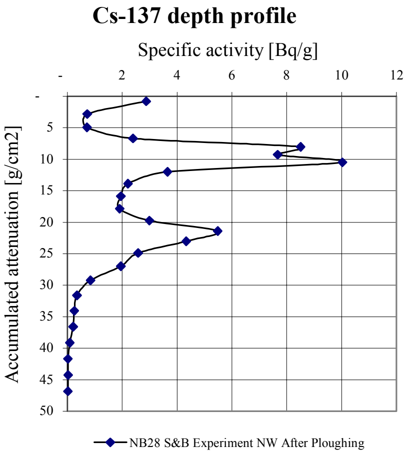
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm 2]	Weight of sample [g]	Activity in sample [Bq]
1	7	0.9	116	19.5
2	25	3.2	138	14.6
3	43	5.6	137	30
4	62	8.0	139	215
5	80	10.4	138	533
6	98	12.8	134	261
7	116	15.2	130	272
8	135	17.5	130	394
9	153	19.7	126	710
10	171	22.0	130	1126
11	190	24.3	136	314
12	208	26.7	138	184
13	226	29.2	140	141
14	244	31.6	140	172
15	262	34.1	140	174
16	281	36.6	142	105
17	299	39.1	144	55
18	317	41.6	146	33
19	335	44.2	143	57
20	353	46.7	146	51
21	372	49.3	145	16.6
22	390	51.8	149	2.5
23	408	54.4	145	0.58
24	426	57.0	147	1.21
25	444	59.6	147	5.1
26	462	62.2	147	0.93
27	481	64.8	149	0.06
28	499	67.4	152	0.87
29	518	70.1	155	0.03
30	536	72.8	154	0.20
31	554	75.5	150	0.29

Total deposition	1.121.982	Bq/m 2
Mean depth	162	mm
Mean attenuation	20.9	g/cm 2



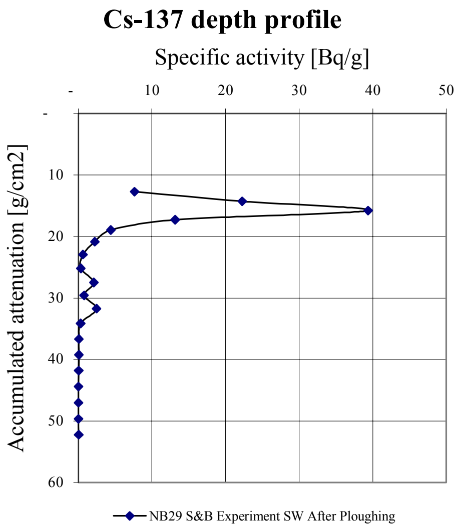
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm 2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.8	99	237
2	26	2.8	132	80
3	44	5.0	111	67
4	63	6.7	85	170
5	81	8.0	70	500
6	99	9.3	69	440
7	118	10.5	72	608
8	136	12.0	99	302
9	155	13.9	112	207
10	173	15.9	114	187
11	191	17.9	114	182
12	209	19.7	98	245
13	228	21.4	89	407
14	246	23.0	98	356
15	265	24.9	112	242
16	283	27.0	125	204
17	301	29.2	132	94
18	320	31.6	137	41
19	338	34.1	142	30
20	357	36.6	144	25
21	375	39.1	145	11.5
22	394	41.7	146	3.0
23	412	44.3	146	3.4
24	431	46.8	147	2.2

Total deposition	1.064.952	Bq/m 2
Mean depth	158	mm
Mean attenuation	14.9	g/cm 2



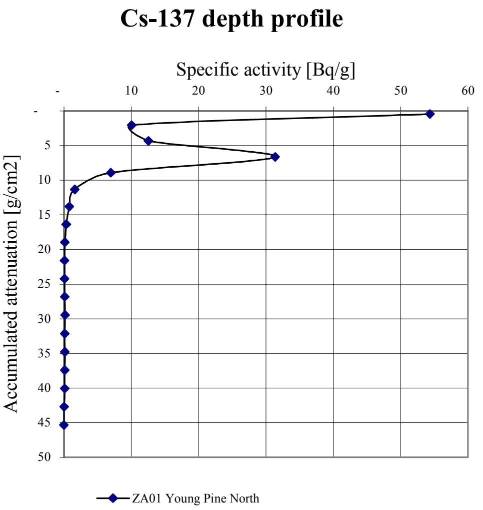
No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm 2]	[g]	[Bq]
1	128	12.7	90	573
2	146	14.3	87	1623
3	164	15.8	85	2789
4	183	17.3	85	939
5	201	18.9	104	382
6	219	20.9	113	211
7	238	22.9	126	65
8	256	25.2	131	39
9	274	27.5	129	228
10	293	29.6	109	73
11	311	31.7	134	278
12	329	34.2	143	36
13	348	36.7	145	10.1
14	366	39.2	146	9.6
15	384	41.8	146	7.0
16	403	44.4	149	2.1
17	421	47.0	149	1.9
18	439	49.6	148	2.2
19	458	52.2	145	5.2

Total deposition	1.668.499	Bq/m 2
Mean depth	177	mm
Mean attenuation	17.2	g/cm 2



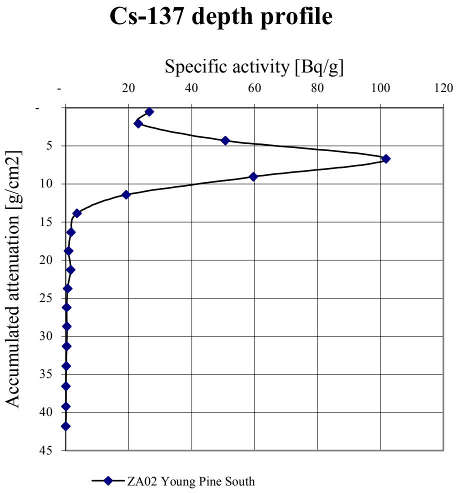
No.	Mean depth	Acc,ulated attenuation	Weight of sample	Activity in sample
[]	[mm]	[g/cm 2]	[g]	[Bq]
1	8	0.4	56	2536
2	26	2.1	128	1071
3	44	4.3	132	1384
4	62	6.6	127	3333
5	81	8.9	134	782
6	99	11.3	139	185
7	117	13.8	143	96
8	136	16.4	148	44
9	154	19.0	148	19
10	173	21.6	151	9.1
11	191	24.2	149	9.0
12	209	26.8	146	15
13	227	29.5	155	22
14	246	32.1	150	14
15	264	34.8	149	17
16	283	37.4	149	15
17	301	40.0	150	13
18	320	42.7	153	2.6
19	338	45.3	146	1.7

Total deposition	2.195.580	Bq/m 2
Mean depth	47	mm
Mean attenuation	4.9	g/cm 2



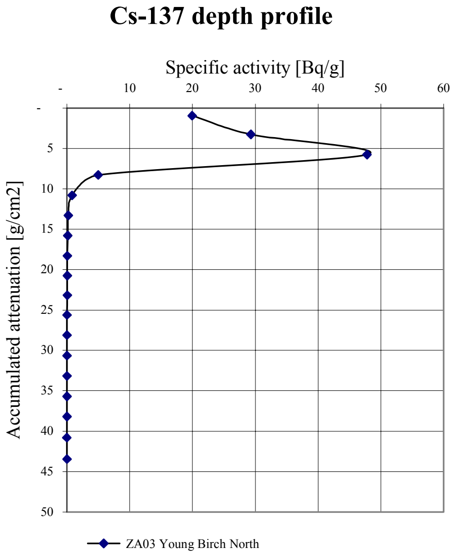
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.5	62	1370
2	26	2.1	117	2248
3	44	4.3	138	5857
4	63	6.7	132	11257
5	81	9.0	134	6701
6	99	11.4	137	2187
7	118	13.8	140	420
8	136	16.3	141	203
9	154	18.8	140	109
10	173	21.3	140	186
11	191	23.7	140	69
12	209	26.2	140	33
13	227	28.7	145	42
14	246	31.3	148	39
15	264	33.9	150	26
16	282	36.6	151	8.3
17	300	39.2	151	9.1
18	318	41.8	147	3.6

Total deposition	7.055.167	Bq/m2
Mean depth	64	mm
Mean attenuation	6.9	g/cm2



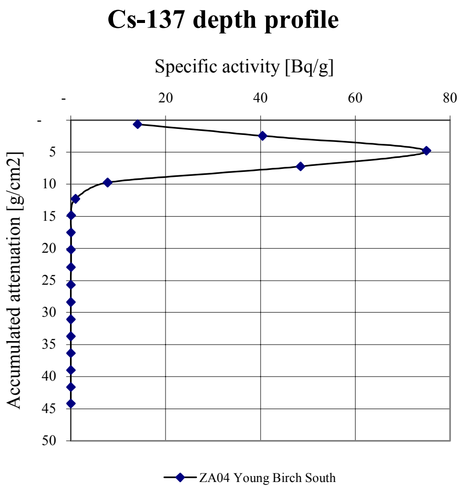
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	1.0	119	1988
2	26	3.3	143	3486
3	44	5.8	143	5720
4	62	8.3	144	600
5	81	10.8	141	100
6	99	13.3	142	29
7	117	15.8	142	17
8	136	18.3	142	11
9	154	20.7	138	9.3
10	172	23.2	138	9.1
11	191	25.6	140	3.1
12	209	28.1	142	2.6
13	228	30.6	144	1.9
14	246	33.2	143	1.9
15	265	35.7	143	2.2
16	283	38.2	143	2.0
17	302	40.8	152	1.9
18	321	43.5	150	2.0

Total deposition	2.751.201	Bq/m2
Mean depth	35	mm
Mean attenuation	4.5	g/cm2



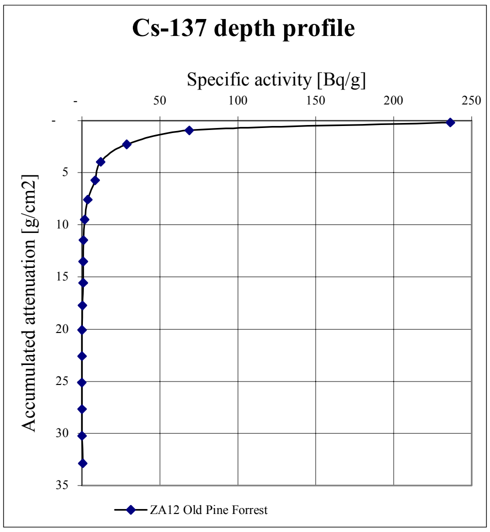
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.7	81	958
2	26	2.5	125	4222
3	44	4.8	137	8575
4	63	7.2	143	5789
5	81	9.7	144	932
6	100	12.3	146	117
7	118	14.9	147	9.3
8	137	17.5	152	4.9
9	155	20.2	153	2.6
10	173	22.9	157	3.0
11	192	25.7	154	1.77
12	210	28.4	153	1.62
13	228	31.1	154	2.0
14	247	33.7	148	1.75
15	265	36.3	150	0.65
16	284	39.0	151	0.98
17	302	41.6	147	0.35
18	320	44.2	145	0.78

Total deposition	4.726.118	Bq/m2
Mean depth	46	mm
Mean attenuation	5.1	g/cm2



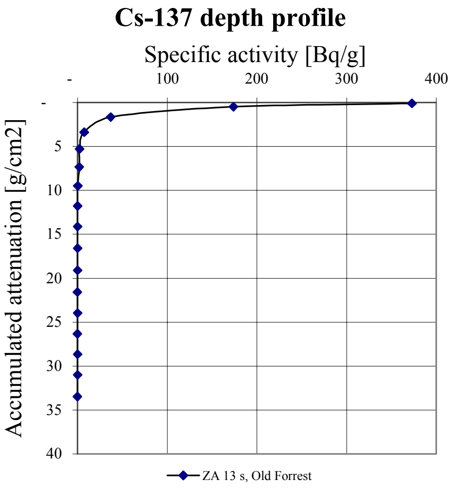
No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.2	23	4581
2	26	0.9	62	3591
3	44	2.3	91	2201
4	63	4.0	99	997
5	81	5.7	102	722
6	100	7.6	109	343
7	118	9.5	109	166
8	136	11.5	116	99
9	155	13.5	116	88
10	173	15.6	116	82
11	191	17.7	129	37
12	210	20.1	140	18
13	228	22.6	144	9.2
14	247	25.1	144	5.1
15	265	27.7	145	10
16	284	30.2	146	10
17	303	32.9	153	74

Total deposition	2.989.622	Bq/m2
Mean depth	37	mm
Mean attenuation	2.3	g/cm2



No. []	Mean depth [mm]	Acc,ulated attenuation [g/cm2]	Weight of sample [g]	Activity in sample [Bq]
1	8	0.1	10	2996
2	26	0.5	37	5431
3	44	1.7	95	2938
4	63	3.4	101	626
5	81	5.3	116	227
6	100	7.3	119	215
7	118	9.5	126	40
8	136	11.8	132	32
9	155	14.1	135	31
10	173	16.6	143	21
11	192	19.1	144	13
12	210	21.6	137	11
13	229	23.9	134	14
14	247	26.3	135	12
15	266	28.6	130	35
16	284	31.0	136	20
17	303	33.5	144	5.6

Total deposition	2.902.804	Bq/m2
Mean depth	33	mm
Mean attenuation	1.4	g/cm2



Appendix B. Dose Rate Measurements

Table B.1. Dose rate measurements with the Reuter Stokes ion-chamber.

			Pre doserate			18/8 1997	20/8 1997
X-pos	Y-pos	Describtion	nSv/h	nSv/h	nSv/h	nSv/h	nSv/h
0	0		855			1189	
0	10		808			877	
0	20		873			836	
0	30		916			892	
0	40		1012			1046	
0	50		901			910	
0	60		876			892	
0	70		941			966	
0	80		937			956	
0	90		795			823	
0	100		907			931	
0	110		913			946	
0	120		914			945	
0	130		1060	1073		1090	
0	140		880	886		899	
0	150		751	769		771	
10	0		1151			1181	
10	10		1068			1087	
10	20		1108			1129	
10	30		1018			1041	
10	40		1016			1024	
10	50		1050			1068	
10	60		1001			1000	
10	70		1048			1065	
10	80		1028			1043	
10	90		1026			1079	
10	100		1057			1092	
10	110		1123			1162	
10	120		1067			1103	
10	130		1183	1197		1198	
10	140		1204	981		999	
10	150		1036	752		756	
20	0		1142			1189	
20	10		1140			1164	
20	20		1112			1101	
20	30		1020			981	
20	40		1096			1040	
20	50		1151			1090	
20	60		1148			1081	
20	70		1185			1117	
20	80		1148			1110	
20	90		1127			1156	
20	100		1133			1173	
20	110		1109			1153	
20	120		1161			1189	

20	130		1082	1126	1133
20	140		1042	972	980
20	150		1048	869	874
30	0	ditch	961		988
30	10		1097		1025
30	20		1116		478
30	30		852		300
30	40		1066		280
30	50		917		284
30	60		1108		276
30	70		1132		313
30	80		820		340
30	90		1057		1050
30	100		709		725
30	110		1118		1145
30	120		847		851
30	130		1086	1109	1121
30	140		1227	1247	1259
30	150		1232	1247	1264
40	0		908		923
40	10		1214		1129
40	20		1215		388
40	30		1326		258
40	40		1383		264
40	50	Gutter	1693		263
40	60		1361		266
40	70		1128		304
40	80				
40	90		1000		921
40	100				
40	110		1025		1060
40	120				
40	130		1185		1232
40	140		1152		1191
40	150		1184		1225
50	0		1009		1044
50	10		1111		1120
50	20		1135		1071
50	30		1042		816
50	40		1048		856
50	50		1092		876
50	60		1007		772
50	70		1090		822
50	80		1028		692
50	90		1099		986
50	100		1099		1113
50	110		1100		1140
50	120		1080		1128
50	130		1094		1143
50	140		1174		1234
50	150		1163		1220
60	0		1086		1124
60	10		1095		1135
60	20		1185		1217
60	30		1079		1036

60	40		1023			1021	
60	50		1082			1098	
60	60		1056			1164	
60	70		1136			1158	
60	80		892			899	
60	90		1023			1048	
60	100		1166			1203	
60	110		1121			1164	
60	120		1205			1269	
60	130		1170			1223	
60	140		1163			1217	
60	150		1171				
32.2	31.2	house 1 NW gnd	449	298	246	254	212
32.2	36.5	house 1 NE gnd	465		250	243	199
35.9	33.8	house 1 C gnd	332	221	213	213	157
39.6	31.3	house 1 SW gnd	560	264	259	254	204
39.6	36.5	house 1 SE gnd	615	275	263	243	196
		house 1 S 1st	588	407	401	392	265
		house 1 C 1st	468	362	350	347	212
		house 1 N 1st	551	422	401	393	265
32.2	52.2	house 2 NW gnd	479	365	258	237	
32.2	57.4	house 2 NE gnd	511	450	253	236	
35.9	54.8	house 2 C gnd	334	259	209		
39.6	52.2	house 2 SW gnd	608	275	252	236	
39.6	57.4	house 2 SE gnd	580	326	269	230	
		house 2 S 1st	598	422	387	372	
		house 2 C 1st	494	386	331	322	
		house 2 N 1st	494	424	361	358	
32.2	74.3	house 3 NW gnd	495				
32.2	79.2	house 3 NE gnd	483				
35.9	76.9	house 3 C gnd	344				
39.6	74.3	house 3 SW gnd	579				
39.6	79.5	house 3 SE gnd	605				
		house 3 S 1st	563				
		house 3 C 1st	473				
		house 3 N 1st	524				
35.9	27.9	2 m west of h 1	789				
29	34	2 m north of h 1	923				
35.9	39.8	2 m east of h 1	1061				
42.75	34	2 m south of h 1	1054				
35.6	49	2 m west of h 2	941				
28.8	54.85	2 m north of h 2	914				
35.6	60.6	2 m east of h 2	1169				
42.53	54.85	2 m south of h 2	1017				
35.6	71.1	2 m west of h 3	872				
28.8	76.95	2 m north of h 3	922				
35.6	82.7	2 m east of h 3	972				
42.5	76.95	2 m south of h 3	1009				
32.2	97.3	house 4 NW gnd	519				
32.2	102.5	house 4 NE gnd	540				
35.9	99.9	house 4 C gnd	349				
39.6	97.3	house 4 SW gnd	538				
39.6	102.5	house 4 SE gnd	570				
32.2	118.6	house 5 NW gnd	529				
32.2	123.8	house 5 NE gnd	525				

35.9	121.2	house 5 C gnd	359				
39.6	118.6	house 5 SW gnd	667				
39.6	123.8	house 5 SE gnd	679	15/8 97	16/8 97	18/8 97	20/8 97
10	44.5	line h1 - h2	1192	1200	1183	1179	
12	44.5	line h1 - h2	1249	1249	1233	1239	
14	44.5	line h1 - h2	1200	1203	1185	1184	
16	44.5	line h1 - h2	1137	1133	1101		
18	44.5	line h1 - h2	1206	1199	1142	1144	
20	44.5	line h1 - h2	1202	1181	1100	1089	
22	44.5	line h1 - h2	1162		943	949	
24	44.5	line h1 - h2	1078		579	577	
26	44.5	line h1 - h2	1183	1103	419	401	
28	44.5	line h1 - h2	1213	1094	363	331	
30	44.5	line h1 - h2	1213	1000	358	330	
32	44.5	line h1 - h2	1196	625	312	294	
34	44.5	line h1 - h2	1188	394	291	272	247
36	44.5	line h1 - h2	1151	361	301	280	251
38	44.5	line h1 - h2	1170	331	292	270	244
40	44.5	line h1 - h2	1179	351	306	279	259
42	44.5	line h1 - h2	1217	398	321	297	289
44	44.5	line h1 - h2	1203	357	327	352	343
46	44.5	line h1 - h2	1153	442	422	408	415
48	44.5	line h1 - h2	1085	646	624	597	590
50	44.5	line h1 - h2	1120	952	950	918	925
52	44.5	line h1 - h2	1189	1094	1093	1089	1077
54	44.5	line h1 - h2	1233	1149	1149	1149	1149
56	44.5	line h1 - h2	1220	1155	1159	1160	1158
10	145	Green plot at river	1204	768			
12	145	Green plot at river	1305	541			
14	145	Green plot at river	1163	470			
16	145	Green plot at river	1144	473			
18	145	Green plot at river	1211	542			
20	145	Green plot at river	1189	845			
22	145	Green plot at river	1049	945			
24	145	Green plot at river	1105	1051			
26	145	Green plot at river	1225	1200			
28	145	Green plot at river	1230	1216			
30	145	Green plot at river	1255	1253			
32	145	Green plot at river	1270	1272			
		House 1 2-m East				236	
		House 1 2-m South				290	
		House 1 2-m West				255	
		House 1 2-m North				305	
		House 2 2-m North				294	
		House 2 2-m East				254	
		House 2 2-m South				296	
		House 2 2-m West				260	

Table B.2. Exposure rate inside house 1, ground floor at different stages of intervention measured with El-1101 (μR h^{-1}).

Point N	Floor	Before	Soil removing	Pouring sand	Roof removing	New roof put on
C1	ground	60	22	22	19	20
C2	ground	54	26	24	21	22
C3	ground	76	23	21	22	22
C4	ground	89	24	22	18	20
1	ground	49	21	23	19	19
2	ground	36	20	22	17	16
3	ground	46	24	25	21	21
4	ground	33	21	20	18	18
5	ground	57	24	23	19	20
6	ground	40	22	22	19	18
7	ground	66	23	23	20	20
8	ground	45	22	21	18	17
9	ground	30	19	19	15	15
Average	ground	52.4	22.4	22.1	18.9	19.1
1	first	57	40	39	27	24
2	first	57	38	39	23	24
3	first	54	40	39	28	26
4	first	53	39	39	27	25
5	first	63	42	43	28	26
6	first	60	40	40	26	25
7	first	64	39	39	25	25
8	first	60	38	38	25	23
9	first	50	34	34	20	20
Average	first	57.6	38.9	38.9	25.4	24.2

Table B.3. Exposure rate inside (ground floor) and outside House 2 before and after intervention, East corner - west corner direction

Distance from centre of house	DR before, μR/h	DR after, μR/h
-8.2	143	
-6.8	203	
-6.4	164	
-6	81	16
-4.6	58	17
-3.2	38	16
0	27	14
3.2	35	17
4.6	48	18
6	59	19
6.4	82	
8.2	123	

Table B.4. Influence of roof contamination on exposure rate formation around House 1, Chernobyl component.

Distance from the centre of House 1 [m]	After soil removal [μR h^{-1}]	After roof removing [μR h^{-1}]	
-15.8	21	18	Direction
-14.8	21	18	to House 2(east)
-13.8	20	19	
-12.8	18	19	
-11.8	19	19	
-10.8	18	19	
-9.8	22	18	
-8.8	21	18	
-7.8	21	17	
-6.8	21	16	
-5.8	17	16	
-4.8	18	15	
-3.8	15	14	
0	15	10	
3.8	19	17	
4.8	21	19	
5.8	21	19	
6.8	21	18	
7.8	21	20	
8.8	24	21	
9.8	25	21	Direction
10.8	25	23	to gate(west)

Appendix C. Miscellaneous Measurements

Table C.1. β-Measurement results of roof contamination of House 1 after covering with clean sand. In this table gamma refers to the background response of the β-detector caused by γ-rays.

N of sheet	East side			West side		
	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]
1	10.5	4.0	6.5	7.2	2.9	4.3
2	7.8	2.8	5.1	7.1	3.5	3.5
3	12.8	3.4	9.4	5.6	2.9	2.7
4	8.9	3.2	5.7	7.7	2.7	5.1
5	10.1	2.5	7.5	9.3	3.2	6.1
6	10.7	3.2	7.5	11.0	4.0	7.0
7	10.1	3.3	6.8	9.4	3.8	5.6
Average	10.1	3.2	6.9	8.2	3.3	4.9

Table C.2. β-Measurement results of roof contamination of House 2 after covering with clean sand. In this table gamma refers to the background response of the β-detector caused by γ-rays.

N of sheet	East side			West side		
	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]
1	10.7	4.0	6.6	10.6	3.7	6.9
2	6.5	3.7	2.9	10.6	3.9	6.7
3	3.8	2.3	1.6	11.3	4.0	7.3
4	5.1	1.7	3.5	9.6	4.5	5.1
5	11.1	4.6	6.5	11.7	4.1	7.6
6	4.5	2.0	2.5	11.1	3.8	7.3
Average	7.0	3.0	3.9	10.8	4.0	6.8

Table C.3. Decontamination experiment on one roof sheet from house 1. A 50 % reduction was obtained by scraping with a simple steel instrument. In this table gamma refers to the background response of the β-detector caused by γ-rays.

Sheet 5	Before scraping			After scraping		
Measuring point	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]	ß+gamma [Bq cm^{-2}]	gamma [Bq cm^{-2}]	ß [Bq cm^{-2}]
1	10.46	2.96	7.5	6.29	2.45	3.84
2	9.35	2.87	6.48	5.35	2.46	2.89
3	8.83	2.5	6.33	5.04	2.27	2.77
4	11.41	3.24	8.17	7.09	2.27	4.82
5	10.6	2.88	7.72	6.21	2.25	3.96
6	10.3	2.63	7.67	5.84	2.46	3.38
Average	10.2	2.8	7.3	6.0	2.4	3.6

Table C.4. Decontamination of two roof sheets determined by ß- and γ-measurements of the ^{137}Cs contamination. The β-measurements were done in situ, 50 cm from the edge of the lowest sheets

	ß-measurements [kBq m^{-2}]		γ-measurements [kBq m^{-2}]	
Object	Average	SD	Average	SD
Sheet 21, before scraping	91	11	196	18
Sheet 21, after scraping	60	11	152	11

Table C.5. Angle distribution of flux of gamma quanta with energy 661 keV in the middle of house 1. Shielded measurements.

Direction	Before intervention	After soil removing and sanding	After roof removing	Total reduction factor
roof	0.38	0.38	0.05	7.6
floor	0	0	0	0
south wall	0.59	0.34	0.24	2.5
west wall	0.8	0.23	0.22	3.6
north wall	0.23	0.17	0.17	1.4
east wall	0.53	0.12	0.2	2.7
Sum	**2**	**1.24**	**0.68**	**2.9**
40° up west			0.01	
40° up east			0.16	
No shielding	**4.27**	**2.27**	**1.5**	**2.8**

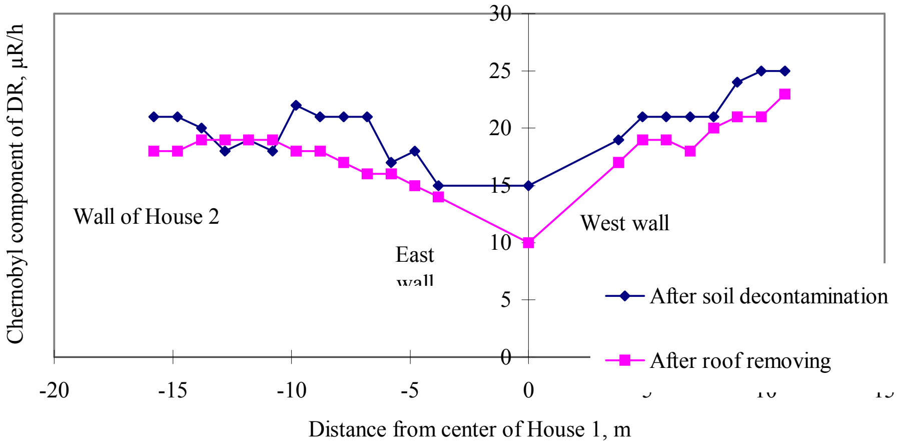


Figure C.1. Exposure rate from house 2 through house 1.

Table C.6. CORAD measurements 1997, Guta Muravinka, Briansk Region.

x-coordinate [m]	y-coordinate [m]	Equivalent deposition [μCi m^{-2}]	Total deposition [μCi m^{-2}]	Ratio
0	0	24.5	35.2	1.30
0	20	16.2	21.8	0.81
0	40	22	30.9	1.14
0	60	18.7	23.4	0.87
0	80	19.2	28.8	1.07
0	80	19.2	28.8	1.07
0	100	26.1	33.5	1.24
10	10	26.7	33.4	1.24
10	30	23.5	31.6	1.17
10	50	23.7	28.2	1.04
10	70	25.6	33.6	1.24
10	90	22.9	27.2	1.01
20	0	30.1	44.2	1.64
20	20	24.2	40.9	1.51
20	40	24.7	34.8	1.29
20	60	31.7	38.6	1.43
20	100	32.6	38.7	1.43
30	10	22.9	27.2	1.01
30	30	19.8	29	1.07
30	50	14.9	17.7	0.65
30	70	29.5	36	1.33
30	90	25.9	34	1.26
40	0	17	31.9	1.18
40	20	31.7	39.6	1.47
40	40	28.7	40.4	1.49
40	60	39	52.4	1.94
40	70	23.2	35.5	1.31
40	90	16.8	24.1	0.89
50	10	30.3	39.7	1.47
50	30	24.4	34.4	1.27
50	50	28	35	1.30
50	70	30	39.4	1.46
50	90	26	30	1.11
60	0	24.6	31.5	1.17
60	20	31.7	41.6	1.54
60	40	18.1	60.3	2.23
60	60	26.8	31.9	1.18
60	80	11.2	15.8	0.58
60	100	29.1	41	1.52
40.4	50.6	137	179	6.62
60	80	12.3	19.2	0.71
10	145	25.5	34.2	1.27
12	145	38.3	56.3	2.08
14	145	14	26.3	0.97
16	145	26.9	34.5	1.28
18	145	33.6	49.4	1.83
20	145	39.4	66.4	2.46
10	145	11.2	22.5	0.83
12	145	1.87	7.14	0.26
14	145	0	0	0.00
16	145	0	0	0.00
18	145	2.15	7.2	0.27
20	145	17.7	35	1.30

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Title and authors

Mechanical decontamination tests in areas affected by the Chernobyl accident

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Abstract (max. 2000 characters)

Decontamination was carried out around three houses in Novo Bobovichi, Russia, in the summer of 1997. It was demonstrated that significant reductions in the dose rate both indoor (DRF = 0.27) and outdoor (DRF = 0.17) can be achieved when a careful cleaning is undertaken. This report describes the decontamination work carried out and the results obtained. The roof of one of the houses was replaced with a new roof. This reduced the Chernobyl related dose rate by 10 % at the ground floor and by 27 % at the first floor. The soil around the houses was removed by a bobcat, while carefully monitoring the ground for residual contamination with handheld dose meters. By monitoring the decline in the dose rate during the different stages of the work the dose reducing effect of each action has been estimated. This report also describes a test of a skim&burial plough developed especially for treatment of contaminated land. In the appendices of the report the measurement data is available for further analysis.

Descriptors INIS/EDB

CESIUM 137; CHERNOBYL; DECONTAMINATION; DOSE RATES; HOUSES; INTERNATIONAL CO-OPERATION; RADIATION DOSE DISTRIBUTIONS; REACTOR ACCIDENTS; RURAL AREAS; RUSSIAN FEDERATION; SOILS; SURFACE CONTAMINATION; SKIM-AND-BURIAL PLOUGHING; ASPHALT SCRAPING; FOREST ECOLOGY; DOSE RATE REDUCTIONS; BOBCAT; SOIL REMOVAL

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