

Radionuclide deposition in Finland 1961–2006

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Key words: deposition, ^{137}Cs , ^{90}Sr , tritium, fallout, resuspension, rainwater, Chernobyl, nuclear weapon tests

Abstract

The measurement of deposited radionuclides in Finland started in 1961. Atmospheric nuclear weapons tests worldwide in the 1950s and 1960s caused the stratospheric deposition of ^{137}Cs and ^{90}Sr . By 1986, the accumulated deposition of ^{90}Sr in Finland was estimated to be 1 100 Bq/m² and that of ^{137}Cs 1 790 Bq/m². The deposition of these radionuclides was relatively evenly distributed over the country. Tritium was also released in atmospheric nuclear weapons tests and the maximum tritium concentration in rainwater, 650 Bq/l, was detected in summer 1963. Since then, the tritium concentration in rainwater has gradually decreased and was around 2 Bq/l in 2006.

In 1986, an accident at the nuclear power plant in Chernobyl, Ukraine (then Ukrainian Soviet Socialist Republic, Soviet Union), resulted in a very uneven areal distribution of radionuclides in Finland. In addition to short-lived radionuclides, up to 30 000 Bq/m² of ^{137}Cs and 600 Bq/m² of ^{90}Sr was detected at sampling stations by the end of 1986. Based on the monitoring of external radiation, a study covering all municipalities in Finland reported even higher values of up to 78 000 Bq/m² for ^{137}Cs (Arvela et al., 1990). Following the accident, resuspension of the deposited ^{137}Cs and ^{90}Sr from the environments of the sample collectors was evident. Resuspension was highest immediately after the Chernobyl deposition, thereafter gradually decreasing. Dry and wet deposition have been separately studied since 1993.

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Avainsanat: radioaktiivinen laskeuma, ^{137}Cs , ^{90}Sr , tritium, resuspensio, sadevesi, Tshernobyl, ydinasekoheet

Tiivistelmä

Radioaktiivisen laskeuman määrittäminen aloitettiin Suomessa vuonna 1961. Ilmakehässä suoritetuissa ydinasekoeteissa 1950- ja 1960-luvuilla vapautui ^{137}Cs - ja ^{90}Sr -isotooppeja stratosfääriin, josta ne laskeutuivat vähitellen maahan. Vuoden 1985 loppuun mennessä oli Suomeen kertyneen ^{90}Sr -laskeuman määrä 1 100 Bq/m² ja ^{137}Cs -laskeuman 1 790 Bq/m². Nämä radionuklidit olivat jakautuneet melko tasaisesti koko maahan. Myös tritiumia vapautui ydinasekoeteista, ja suurimmat tritiumpitoisuudet sadevedessä, 650 Bq/l, mitattiin kesällä 1963. Tämän jälkeen sadeveden tritiumpitoisuudet ovat asteittain pienentyneet ja olivat vuonna 2006 noin 2 Bq/l.

Vuonna 1986 Tshernobylin ydinvoimalaitosonnettomuus Ukrainassa (silloisen Neuvostoliiton Ukrainan sosialistisessa neuvostotasavallassa) aiheutti puolestaan hyvin epätasaisen radioaktiivisten aineiden jakautumisen Suomessa. Lyhytikäisten radionuklidien lisäksi näytteenkeräysasemilla havaittiin ^{137}Cs -laskeumaa jopa 30 000 Bq/m² ja ^{90}Sr -laskeumaa 600 Bq/m². Tutkimuksessa, jossa määritettiin kaikkien kuntien keskimääräinen ^{137}Cs -laskeuma ulkoisen säteilyn mittausten perusteella, on raportoitu vielä tätäkin korkeampia ^{137}Cs -laskeumia, 78 000 Bq/m² (Arvela ym., 1990). Onnettomuuden jälkeen laskeumanäytteiden keräyspaikoilla havaittiin, että merkittävä osa maahan tulleista radioaktiivisista aineista siirtyi takaisin ilmaan. Tämä resuspensio oli suurinta heti Tshernobylin onnettomuuden tapahduttua, minkä jälkeen se vähitellen pieneni. Kuivalaskeuman ja märkälasseuman osuutta laskeumassa on myös tutkittu vuodesta 1993 eteenpäin.

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1 Introduction

Radioactive substances can be deposited as dry or as wet deposition with rain or snow. The analysis of deposition samples provides information on the distribution and levels of deposited radionuclides and forms the basis for research concerning the transfer of radionuclides in terrestrial and aquatic environments. The analysis of deposited radionuclides is an important part of environmental monitoring program. The results of the analysis provide continuous information on the amounts of deposited radioactivity. Due to the passive nature of sampling, only minimal actions are required by people. Although deposition samples have some limitations with regard to regional representation, information about the concentration of radioactive substances per unit surface area (Bq/m^2), obtained from the analysis of deposition samples, can be utilized in environmental modelling applications. Deposition samples can also be archived after gamma-spectrometric measurement and additional radionuclides can later be analysed from the archived samples if desired.

STUK has been continuously monitoring deposited radionuclides since the 1960s. The monitoring programme consists of a network of stations that has evolved from 17 stations (including 5 stations collecting tritium) when the programme started in 1961 to the current 9 stations. The objective of this report is to gather and analyze the historical data pertaining to the deposition of radioactive isotopes in Finland mainly originating from the global fallout from nuclear weapons tests in the 1950s and 1960s and from the Chernobyl accident in 1986. The total annual amounts of the radionuclides deposited in Finland and their long-term temporal changes are presented and discussed. Resuspension of ^{137}Cs and ^{90}Sr after the Chernobyl deposition as well as the contribution of wet and dry deposition to total deposition of radionuclides are also discussed.

2 Materials and methods

2.1 Deposition data

The data presented in this report have been compiled from the following STUK annual reports: Salo (1966, 1967, 1968, 1971, 1982a, 1982b, 1983, 1984), Salo and Koivulehto (1977), Koivulehto et al. (1979, 1980, 1981), Paakkola (1987), Saxén et al. (1987), Aaltonen et al. (1990), Saxén et al. (1994), Mustonen (2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007) and from STUK's unpublished records.

2.2 Sampling sites

The sampling network for deposition samples has evolved since 1961 when the operation of the network began with 17 stations in Finland continuously collecting wet and dry deposition samples that were analyzed monthly. During the study period, 1961–2006, samples were collected at several sites (Fig. 1a). The maximum number of sampling sites in the network was 18 after the Chernobyl accident in 1986. The current sampling network consists of 9 stations (Fig. 1b). The sampling network for tritium in rainwater has also varied. The sampling started at 5 stations in the early 1960s and the network increased to 7 stations in 1968. In 1977, the number of stations was reduced to 4. Since 1995, rainwater for tritium determination has been collected from two stations: in Rovaniemi and Helsinki. A list of all stations and their operational years are presented in Table 1.

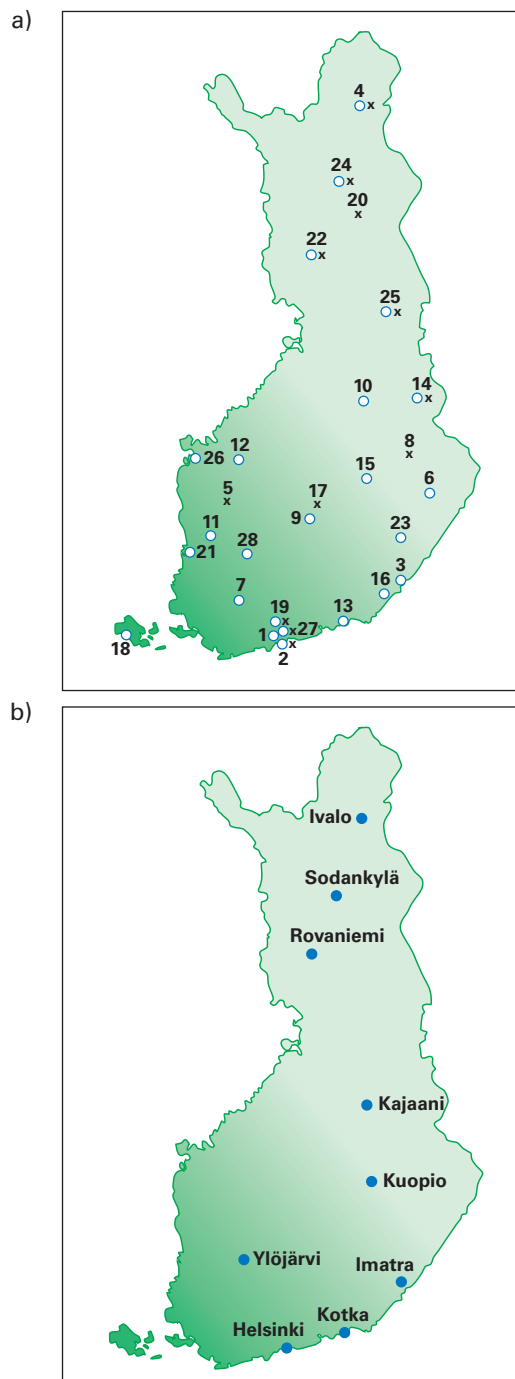


Table 1. Sampling sites and operational years. Sites that are currently in use are bolded.

Number on map (Fig.1)	Sampling Site	⁹⁰ Sr and ¹³⁷ Cs in deposition samples	³ H in rain ¹	New deposition sampler (0.07m ²) installed
1	Espoo (Otaniemi) ²	1961–1970		
2	Helsinki Harakka ² Konala ¹¹ Roihupelto	1961–1970 1986 1994–	1995–	1.1.2004
3	Imatra	1995–		1.11.1999
4	Inari Ivalo ^{2,7,9} Nellimö	1961–	1961–1963, 1968–1994	1.5.1996
5	Jalasjärvi		1961–1963, 1968–1970	
6	Joensuu ^{2,10}	1961–1999		
7	Jokioinen ²	1961–2006		
8	Juuka		1968–1977	
9	Jyväskylä ²	1961–2004		1.9.1999
10	Kajaani ²	1961–		1.1.2000
11	Kankaanpää, (Niinisalo)	1986–2006		
12	Kauhava ²	1961–1994		
13	Kotka	1999–		1.10.1999
14	Kuhmo	1970–1994	1967–1994	
15	Kuopio ^{2,10}	1961–1994, 2005–		1.4.2005
16	Lappeenranta ^{2,3,4}	1961–1994		
17	Laukaa		1961–1963, 1968–1977	
18	Mariehamn ²	1961–2006		3.4.1996
19	Nurmijärvi ^{2,3,5,11}	1961–1994	1977–1994	
20	Pelkosenniemi		1961–1977	
21	Pori ²	1961–1985		
22	Rovaniemi Apukka ⁶ Korkalovaara ⁹	1972–1983, 1986– 1999–	1973–	1996
23	Savonlinna ^{2,10}	1961–1994		
24	Sodankylä ^{2,7,8,9}	1961–	1962–1964	1.5.1996
25	Taivalkoski ^{2,7,8}	1961–2006		
26	Vaasa ²	1961–2006		1.5.1996
27	Vantaa	1970–1976	1967–1976	
28	Ylöjärvi	1999–		2.9.1999

¹ Tritium samples were collected irregularly during 1961–1963.² During 1961–1962 and 1966–1985 deposition samples from several stations were pooled for ⁹⁰Sr and ¹³⁷Cs analysis.

- ³ Two deposition collectors in place during 1976–1985.
⁴ Station-specific ¹³⁷Cs determination during 1976–1985.
⁵ Station-specific ⁹⁰Sr and ¹³⁷Cs determination during 1976–1985.
⁶ No ⁹⁰Sr determination during 1986–1998.
⁷ During 1.4.1989–30.9.1994 deposition samples from Ivalo, Sodankylä and Taivalkoski were pooled together.
⁸ During 1.10.1994–30.12.1994 deposition samples from Sodankylä and Taivalkoski were pooled together.
⁹ During 1.5.1996–30.3.1999 samples from Ivalo, Sodankylä and Rovaniemi (Korkalovaara) were pooled together.
¹⁰ During 1.4.1989–30.9.1994 deposition samples from Kuopio, Joensuu and Savonlinna were pooled together.
¹¹ Daily deposition measurements of gamma nuclides in 1986 in part of the year.

2.3 Sampling and sample treatment

Until the end of 1963 the deposition samples were collected with stainless steel funnels (diameter 30 cm) into ion-exchange columns. The columns were placed in thermostat-controlled boxes and the funnels were heated in the winter. From 1964 onwards the samples were collected directly into polythene bottles. The samplers were normal rate meters, made of stainless steel or brass, with surface areas of 0.05 or 0.07 m² and located at a height of about one metre above the ground. Samples from the steel collectors were used to analyze gamma-emitting radionuclides, strontium and transuranic isotopes, and those from the brass collectors were used for tritium determination. Each sampler was surrounded by a wind shelter. During winter the samplers were taken inside to melt the frozen sample and a new sampler was placed inside the wind shelter to guarantee continuous sampling. Collectors were usually emptied monthly and the stainless steel collectors were rinsed with dilute nitric acid and distilled water after every emptying to prevent the adsorption of radionuclides onto their walls. The rinsing solutions were added to the sample. The brass samplers used for tritium were only rinsed with distilled water.

After 1996 new samplers with surface areas of 0.07 m² developed by STUK were installed (Fig. 2). They have a light heating resistor inside the funnel to melt the snow and ice collected in the funnel and to thus make sampling more reliable in the winter. Deposition collectors currently in use (Figs 2 and 3) are described in more detail by Ilus et al. (2008). In 1993 a deposition collector that separates wet and dry deposition from each other was introduced in Helsinki (Fig. 4). The collector has two separate vessels to collect wet and dry deposition and a mobile lid. The collector is equipped with a sensor that moves the lid to cover the dry deposition vessel when exposed to rain. When the rain ceases, the lid automatically moves to cover the wet deposition vessel respectively. The surface area of both wet and dry deposition collector is 0.5 m², larger than the surface area of a regular collector (0.07 m²), to better detect low concentrations of radionuclides. The collection period is one month for the wet and dry deposition collector.

During 1961–1962 and 1966–1985, the samples from different stations were pooled and analysed as one sample, representing the fallout level for the whole country. Additional collectors with surface areas of 1 m² were located at two sampling stations (Lappeenranta and Nurmijärvi) and samples from these stations were analyzed separately, as were the samples from stations in Kuhmo and Rovaniemi, to compare the deposition between the various parts of Finland. After the Chernobyl accident in 1986, the samples were separately analyzed for each station with a few exceptions where samples collected at certain stations were pooled together as noted in Table 1. The total amounts of radionuclides in the samplers were established by analysing the samples monthly for gamma-emitting radionuclides and usually monthly or quarterly for radiostrontium, with the exception of the short period after the Chernobyl accident from May until July 1986 when the samples were analyzed more frequently at stations Nurmijärvi, Helsinki and Rovaniemi. The collection period for tritium was one month.

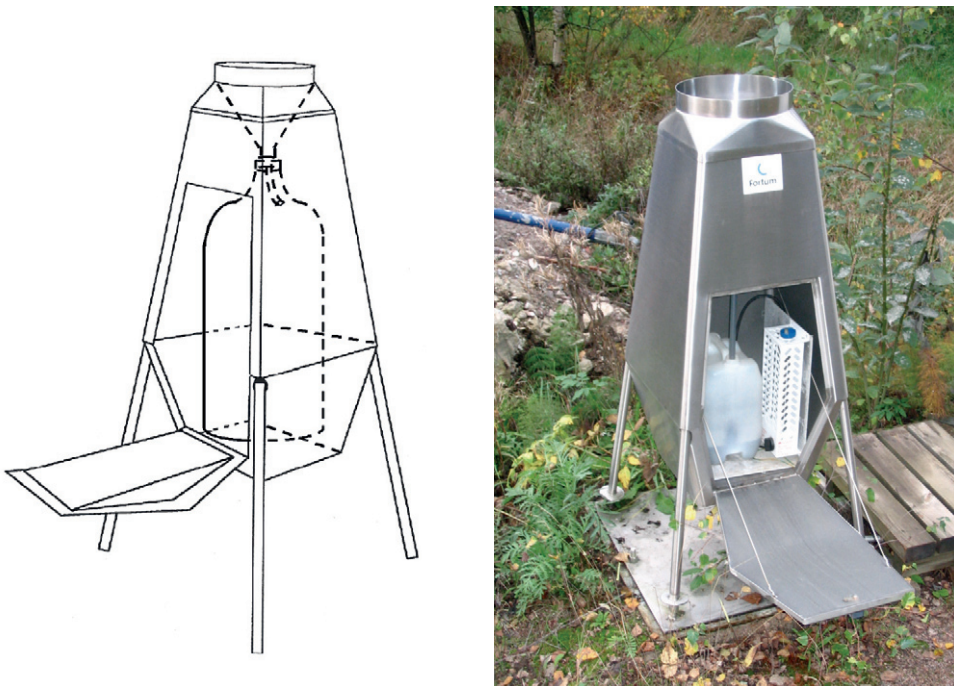


Fig. 2. The deposition collector 'Ritva' developed at STUK.



Fig. 3. The collector for tritium in rainwater.

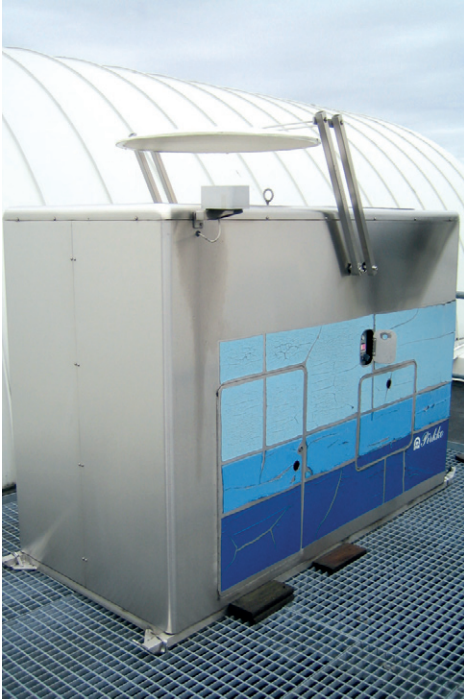


Fig. 4. The wet and dry deposition collector 'Pirkko' with a rain sensor and a mobile lid developed at STUK.

2.4 Analytical methods

Gamma-emitting radionuclides

In the early years of sampling, ^{137}Cs was analyzed through radiochemical separation according to Osmond et al. (1959). Later, it was analyzed by gamma-ray spectrometry after the samples from the fallout collectors had been concentrated by evaporation and the solid material ashed. After the Chernobyl accident, the deposition samples were analysed by gamma-ray spectrometry without any concentration for a few months. Analytical methods for gamma-emitting nuclides are described in detail by Koivulehto et al. (1979), Saxén et al. (1987) and Aaltonen et al. (1990).

^{89}Sr and ^{90}Sr

The analytical method used for the determination of ^{89}Sr and ^{90}Sr was based on the method of Osmond et al. (1959) with some modifications. After radiochemical separation, strontium isotopes were measured as strontium carbonate with a low-background gas-flow beta counter. After a two-week ingrowth period, ^{90}Y , the daughter of ^{90}Sr , was precipitated as yttrium oxalate and measured twice to check the purity of the ^{90}Y samples (Saxén et al., 1987). Over the years, the method has been improved to allow more rapid separation of strontium. The currently used method is based on the use of extraction chromatography resins and consecutive measurements of strontium isotopes. ^{89}Sr is first measured through Cerenkov radiation and then, after the addition of scintillation cocktail, ^{90}Sr is measured with a low background liquid scintillation counter (Saxén, 2007). The improved calibration of the liquid scintillation counter allows the measurement of ^{90}Sr at any time during the ingrowth of ^{90}Y after the chemical separation of Sr.

Tritium

Until the early 1990s the samples were distilled to dryness and tritium in water was determined with electrolytic enrichment according to the method of Östlund and Werner (1962) with a slight modification, followed by a liquid scintillation measurement. A Packard liquid scintillation counter (detection limit 12 Bq/l) was used until 1976 (Salo and Koivulehto, 1977), when it was replaced by an LKB-Wallac Ultrabeta 1210 liquid scintillation counter with a detection limit of 0.9 Bq/l (Koivulehto et al., 1979). Since the early 1990s, the measurements were carried out with a Quantulus low background liquid scintillation spectrometer. This resulted in the same detection limit (0.9 Bq/l) as the earlier instrument but without the need for electrolytic enrichment of the samples.

3 Results and discussion

3.1 ^{90}Sr and ^{137}Cs fallout from nuclear weapons tests

STUK has continuously monitored deposited radionuclides in Finland since the 1960s. The average annual and accumulated depositions in Finland, representing the fallout level for the whole country until 1985, are given in Table 2 and illustrated in Figures 5 and 6. The annual depositions of ^{137}Cs and ^{90}Sr at individual stations during 1961–2006 are presented in Tables 3 and 4 and illustrated in Figure 10.

Before 1986 the radionuclides in deposition mainly originated from the stratospheric deposition caused by 542 nuclear weapons tests conducted in the atmosphere by the United States, the former USSR, France, the UK and China (UNSCEAR, 2000). The majority of these tests were conducted in the 1950s and 1960s and long-lived radionuclides released into the atmosphere included ^{90}Sr and ^{137}Cs with physical half-lives of 29 and 30 years, respectively. Depositions of these radionuclides gradually decreased after 1963, the year of maximum deposition, when more than 400 Bq/m² of both ^{90}Sr and ^{137}Cs was deposited in Finland (Fig. 5). The preceding year, 1962, was the year when the largest number of nuclear weapons tests were conducted. After the nuclear test ban treaty was signed in 1963, only a limited number of atmospheric nuclear weapons tests were carried out by China and France.

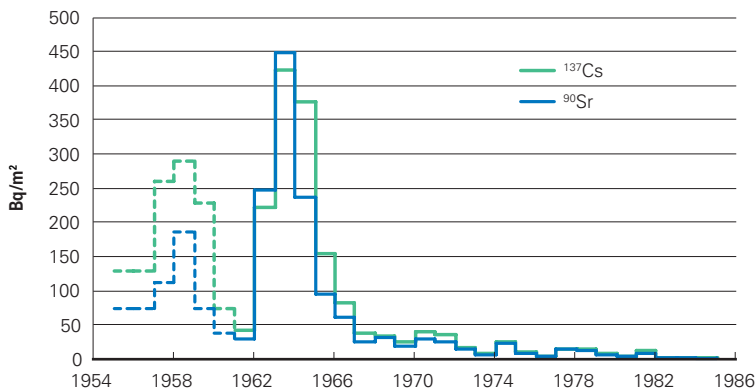


Fig. 5. Annual deposition of ^{137}Cs and ^{90}Sr in Finland during 1961–1985. The results prior to 1961 (dashed) are values from Leningrad, USSR (Salo et al., 1984).

After the last Chinese atmospheric nuclear weapons test in 1980, both ^{90}Sr and ^{137}Cs had a residence time of 2 years (calculated for 1982–1985) in stratosphere in Finland. A somewhat shorter residence time of one year was calculated for the period 1962–1967. These residence times are based on the following equation: $\lambda_{\text{strat}} = \lambda_{\text{eff}} - \lambda_r$, where λ_{strat} is the stratospheric decay constant, and λ_{eff} is the effective (observed) decay constant and λ_r the physical decay constant of the radionuclide. Katsuragi (1982) estimated the residence time of nuclear debris in the atmosphere to be 30–50 days in the troposphere and 1.0–1.2 years in the stratosphere on the basis of $^{89}\text{Sr}/^{90}\text{Sr}$ ratios of the fallout data during 1973–1981 in Japan.

The accumulated depositions of the long-lived radionuclides ^{137}Cs and ^{90}Sr gradually decreased after 1966, the year of maximum accumulated deposition (Fig. 6, Table 2). In 1985 the accumulated deposition of ^{90}Sr in Finland was estimated to be 1 100 Bq/m² and that of ^{137}Cs 1 790 Bq/m². The deposition from nuclear weapons tests was relatively evenly distributed over the whole country (Salo et al., 1984). The average ^{137}Cs to ^{90}Sr ratio in the deposition from the global fallout was 1.4 ± 0.2 . Paatero et al. (2010a) studied the regional variation of ^{90}Sr deposition from the atmospheric weapons tests and found that highest cumulative ^{90}Sr deposition values occurred in southern and eastern Finland while the lowest values were observed in western and northern Finland reflecting the spatial variability of the precipitation amounts in Finland.

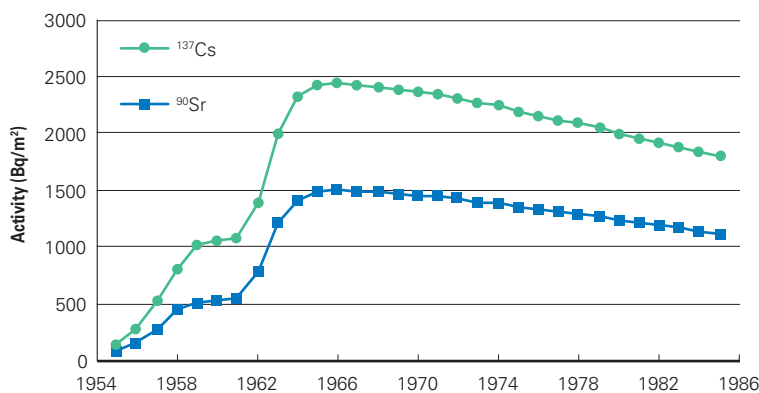


Fig. 6. Accumulated deposition (decay corrected) of ^{137}Cs and ^{90}Sr (Bq/m²) in Finland 1955–1985.

The ^{137}Cs and ^{90}Sr deposition from the global fallout (prior to 1986) exhibited seasonal variation as demonstrated in Figure 7. Both ^{137}Cs and ^{90}Sr displayed identical seasonal cycling with the maximum deposition detected in summer, from June to July, and the minimum in winter. This was caused by the mixing of stratospheric and tropospheric air masses through the seasonal thinning of the tropopause, which takes place in the spring. Because of the limited exchange of air masses, the fallout continued for many years after termination of the nuclear weapons tests, with a continuously decreasing trend. A spring-summer maximum in deposition samples has also been detected in other places at similar latitudes (Bunzl et al., 1995; Hötzl et al., 1992; Kulan, 2006).

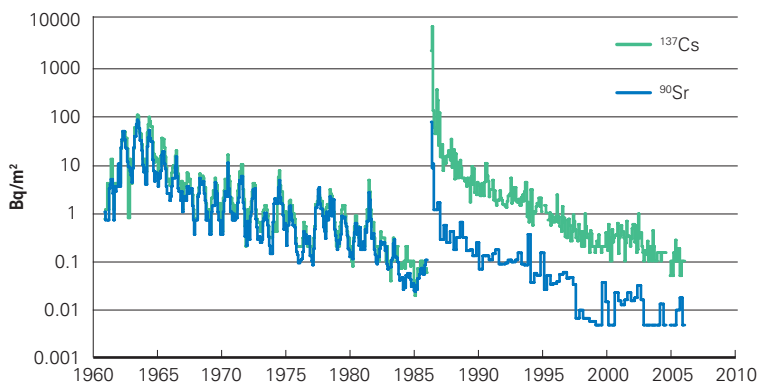


Fig. 7. The monthly ^{90}Sr and ^{137}Cs deposition in Southern Finland.

3.2 Deposition from the Chernobyl accident in 1986

After the Chernobyl accident on 26 April 1986, more than 25 different radioisotopes were detected in deposition samples (Saxén et al., 1987). The deposition collectors at three stations (Helsinki, Nurmijärvi, Rovaniemi) were emptied more frequently than normally and the deposited radionuclides were even measured and reported for daily samples (Saxén et al., 1987). The period of radionuclide release from Chernobyl was short. The deposition continued for a few weeks, and had more or less ceased by the end of June. According to Cambray et al. (1987), over 90% of the deposition occurred before mid-May 1986. The deposition of short-lived ^{131}I at two stations, in Nurmijärvi and Helsinki, showed maximum values on 30 April 1986 (Fig. 8). Most of the iodine was transported in the gaseous form and was partly adsorbed on local aerosols during travel

(Paatero et al., 2010b). Iodine measurements in air showed that 85–95% of iodine penetrated through the glass fibre filter to the carbon bed (Sinkko et al., 1987). Based on the STUK data, Anttila et al. (1987) determined that the dry deposition velocity of iodine was smaller than velocity of the other isotopes at the same size range indicating that the deposition of the gaseous iodine was small in the collector used. The deposition of iodine gradually decreased, and in early June no more iodine was detected. The half-life of ^{131}I is only 8 days and it decayed away within a few months. Other short-lived radioisotopes that were detected included ^{99}Mo , ^{133}I , ^{134}Cs , ^{136}Cs , ^{140}Ba , ^{89}Sr , ^{144}Ce , ^{141}Ce , ^{106}Ru , ^{103}Ru , ^{95}Zr , ^{125}Sb , $^{110\text{m}}\text{Ag}$, $^{129\text{m}}\text{Te}$, ^{125}Sb and ^{127}Sb (Saxén et al., 1987).

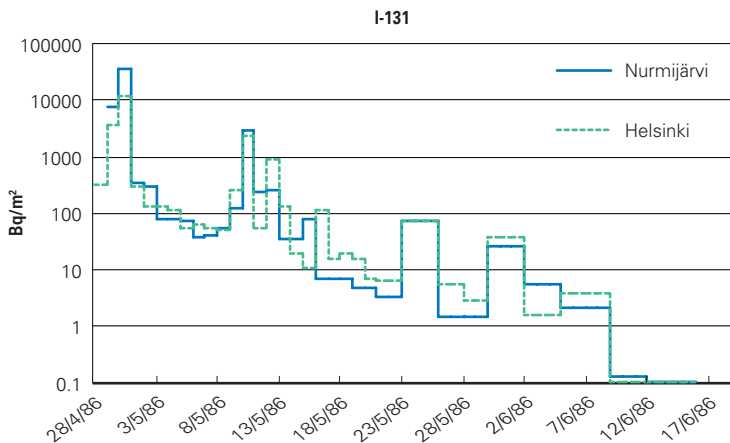


Fig. 8. Deposition of iodine from the Chernobyl accident at Nurmijärvi and Helsinki stations during April to June 1986.

The most prominent radionuclide in the Chernobyl deposition was the long-lived ^{137}Cs , with a physical half-life of 30 years. The regional distribution of the Chernobyl deposition in Finland was very uneven for ^{137}Cs and ^{90}Sr , the other long-lived isotope (Fig. 9, Tables 3 and 4). The accumulated depositions of ^{137}Cs and ^{90}Sr at various sampling stations at the end of 1986 are presented in Table 5. The uneven distribution of deposited radionuclides was a result of local rain showers that effectively washed out the radioactivity to the ground and the fact that the radioactive substances were released from the reactor at different stages of the accident. The highest ^{137}Cs deposition was detected in southern and central Finland, where up to 30 kBq/m² of ^{137}Cs was deposited by the end of 1986 at the sampling stations of this study. Better coverage of the ^{137}Cs distribution from the Chernobyl accident is given by Arvela et al. (1990),

who determined the average values for all the municipalities in Finland by means of external radiation measurements. Municipal averages up to 78 kBq/m² of ¹³⁷Cs were recorded.

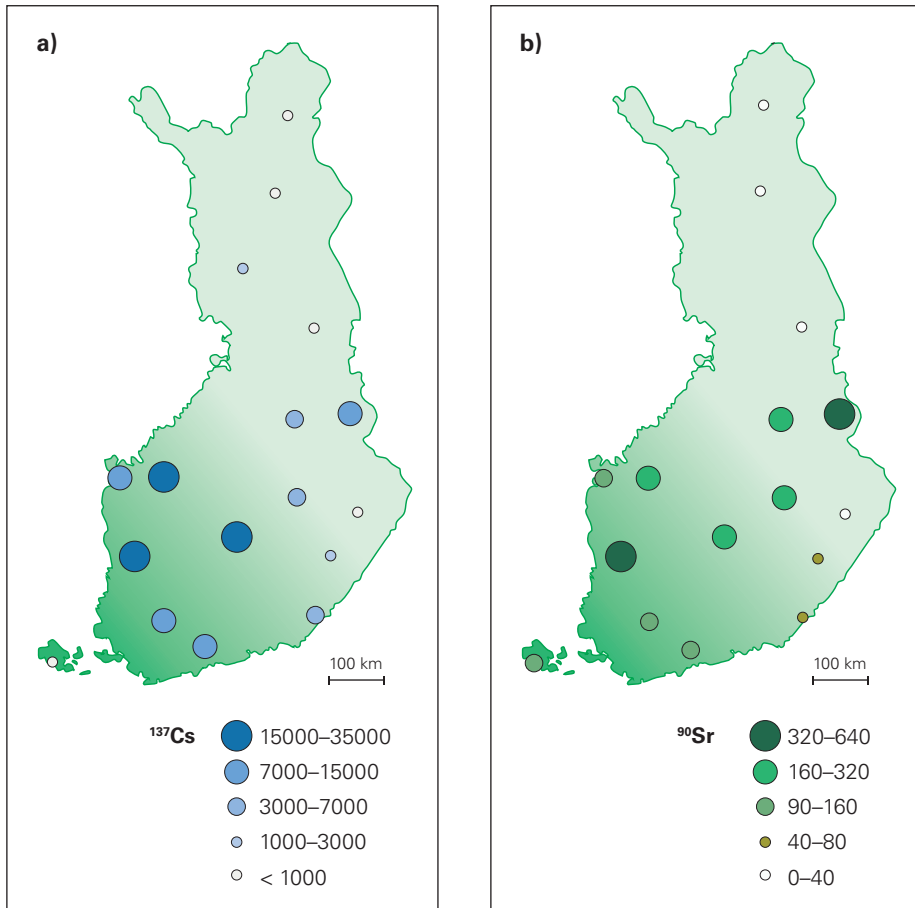


Fig. 9. Deposition of a) ¹³⁷Cs and b) ⁹⁰Sr (Bq/m²) in Finland during 1986.

The distribution of ⁹⁰Sr, a non-volatile element, differed markedly from that of the volatile nuclide ¹³⁷Cs, being highest in the north-eastern part of the main deposition area, where up to 0.6 kBq/m² of ⁹⁰Sr was deposited in 1986 in Kuhmo. The areal distribution of ⁹⁰Sr deposition in Finland correlated well with the distribution of precipitation and followed the distribution of another non-volatile nuclide, ⁹⁵Zr (Arvela et al., 1990). The distribution pattern for ⁹⁰Sr was also very similar to that for ²⁴¹Pu (Paatero et al., 1994a). In April 1986, the ratio of ¹³⁷Cs to ⁹⁰Sr varied from 12 to 86, whereas the ratio of these isotopes in depo-

sition originating from the nuclear weapons test period was almost constant, being 1.4 on average.

Transuranic elements were also detected in the deposition at low concentrations (Saxén et al., 1987; Aaltonen et al., 1990). In the most contaminated areas, the amount of transuranic elements deposited was only 10% of the amount deposited during the nuclear weapons tests. Up to 0.8 Bq/m² of ^{239,240}Pu was detected by early May 1986 in Kuhmo, where ²³⁸Pu (0.5 Bq/m²) and ^{243,244}Cm (0.1 Bq/m²) were also detected. The highest ²⁴¹Am deposition, 0.2 Bq/m², was measured in Niinisalo in April 1986. Short-lived ²⁴²Cm was also detected with levels of up to 14 Bq/m² by early May 1986 in Kuhmo.

3.3 Deposition of radionuclides after 1986

Since the short Chernobyl deposition period, the deposition of radionuclides has continuously decreased in Finland (Fig. 10). In the 1990s the deposition samples from Northern Finland (Ivalo, Taivalkoski, Sodankylä, Korkalovaara) were pooled together for measurement. When the pooling procedure was changed in the mid 1990s, a sudden decrease in ¹³⁷Cs deposition, by a factor of ten, was detected in Ivalo and Sodankylä (Fig. 10). This reflected the higher ¹³⁷Cs deposition levels detected in Taivalkoski than at the other northern stations. The lower ¹³⁷Cs levels detected in Ivalo and Sodankylä may also be influenced by the new deposition samplers that were installed to these stations in the mid 1990s.

The seasonal behaviour of ⁹⁰Sr and ¹³⁷Cs deposition after the Chernobyl accident was different from that in the nuclear weapons test period, and no seasonal patterns were evident after 1986 (Fig. 7). Radionuclides from nuclear weapons tests in the 1950s and 60s were injected into the stratosphere, from where they were transferred into the troposphere in the spring, whereas the radionuclides from Chernobyl were mostly only injected into the troposphere. Changes in the seasonal behaviour of deposited ⁹⁰Sr and ¹³⁷Cs can be attributed to the decreased stratospheric contribution and increased dominance of Chernobyl-produced regional resuspension (Kulan, 2006). The differences between the sampling stations have gradually decreased, but the annual deposited amounts of ¹³⁷Cs have still differed between stations by a factor of 60 in the 2000s due to local resuspension which is discussed in more detail in chapter 3.4.

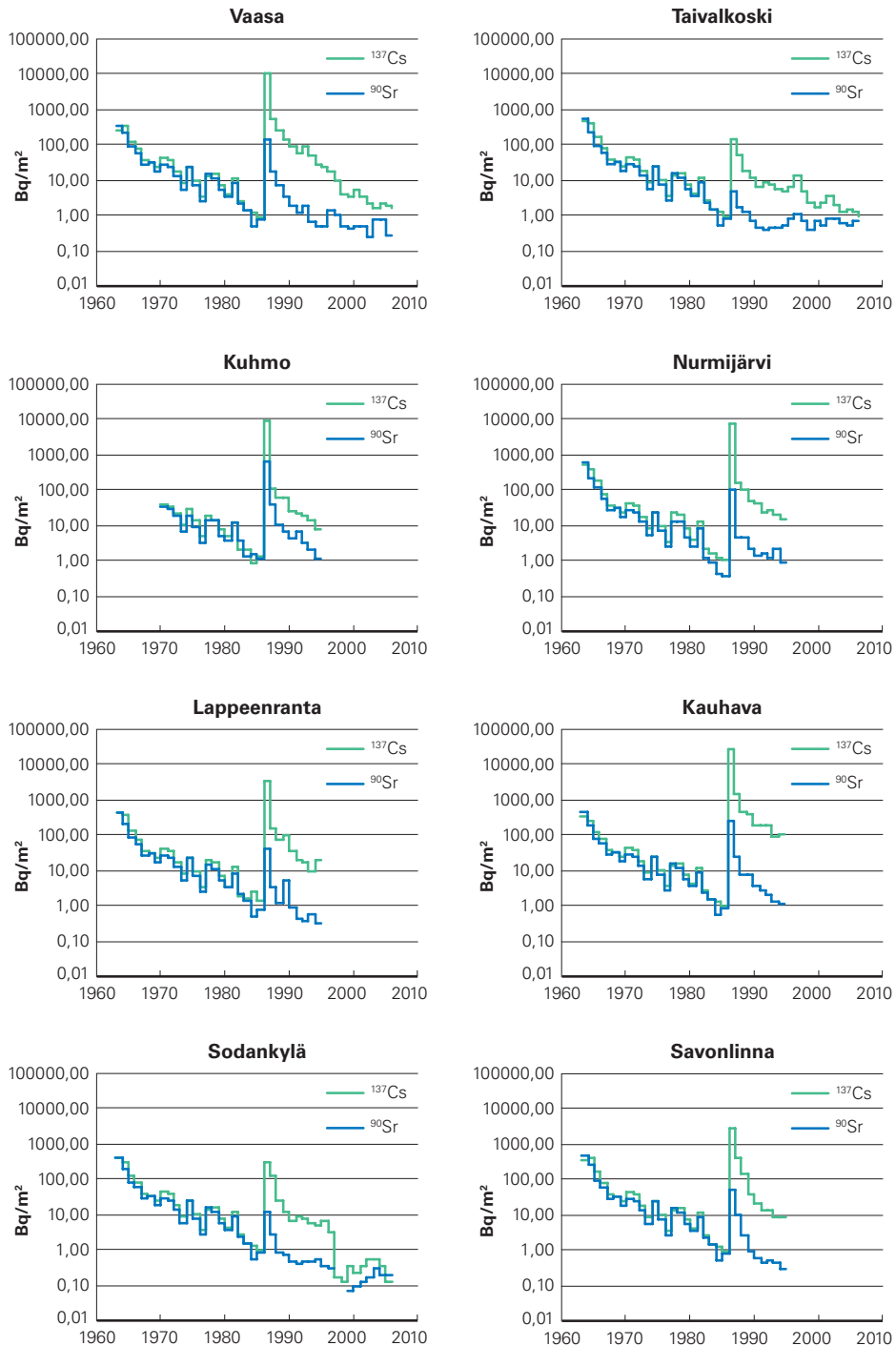


Fig. 10. Annual depositions of ^{137}Cs and ^{90}Sr (Bq/m^2) at various sampling stations in 1963–2006 (pages 21–22).

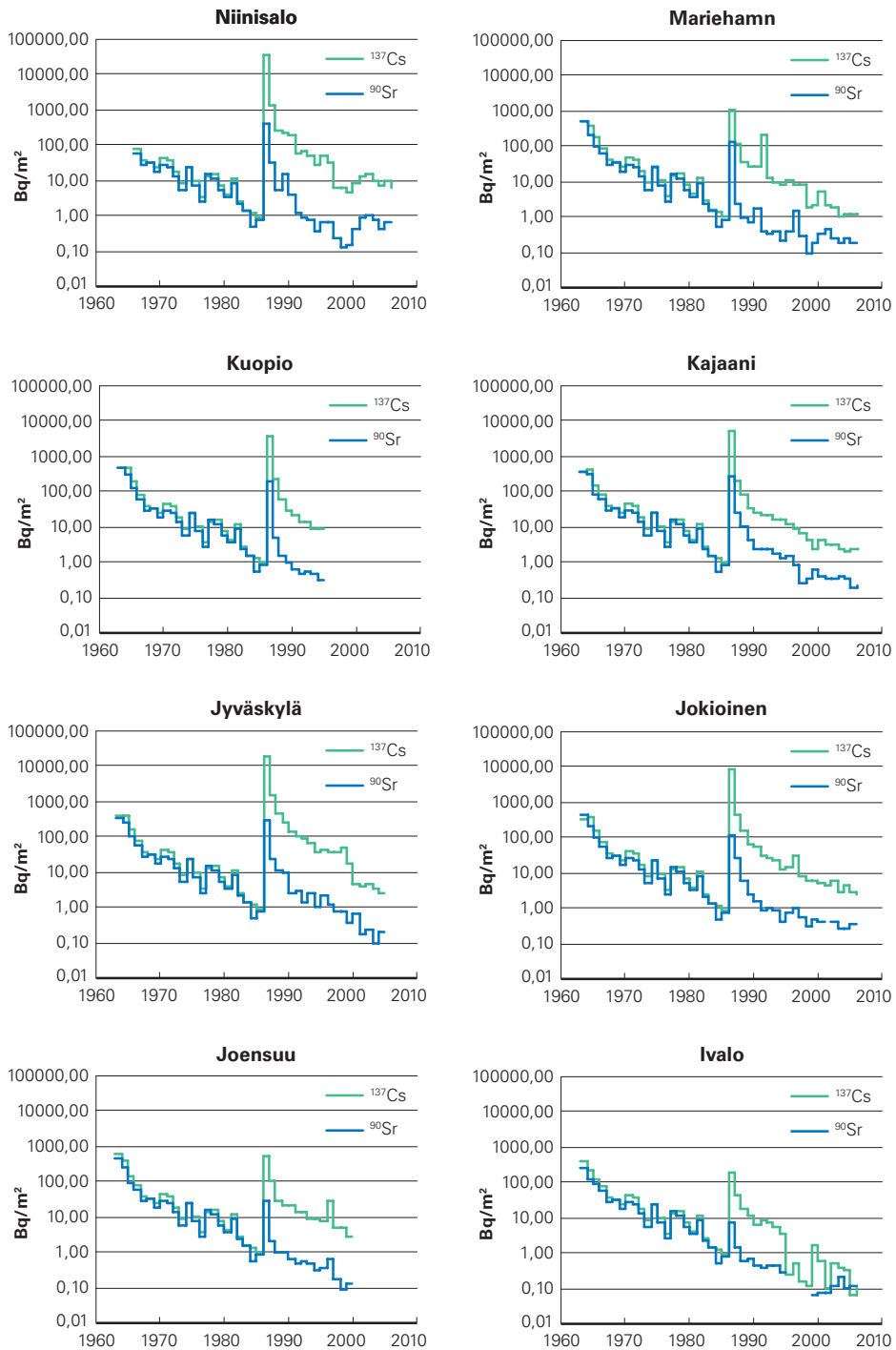


Fig. 10 continued. Annual depositions of ^{137}Cs and ^{90}Sr (Bq/m²) at various sampling stations in 1963–2006 (pages 21–22).

3.4 Resuspension

Local resuspension

The first indication of resuspension in Finnish deposition data was the observation where ^{137}Cs deposited in 1987 seemed to follow the same distribution pattern as in 1986 (Aaltonen et al., 1990), a tendency that continued in the following years. For both radiocaesium and radiostrontium, relatively strong correlations were recorded between the amounts of deposited radionuclides during the discharge period in 1986 and in the following years (Fig. 11). This suggests that the main source of the radionuclides deposited since 1987 has been local resuspension from the area around the sampling sites. If radiocaesium and radiostrontium were mainly of stratospheric origin, the correlation with the original Chernobyl deposition at the stations would not have been so strong, but would have been almost the same at all stations. Moreover, the summer maxima, which are characteristic of stratospheric deposition and were clearly detected before the Chernobyl accident, could not indisputably be detected after 1986 (Fig. 7). Resuspension from farther away at a longer distance as a major source is also out of the question, because it would not have resulted in the detected correlation.

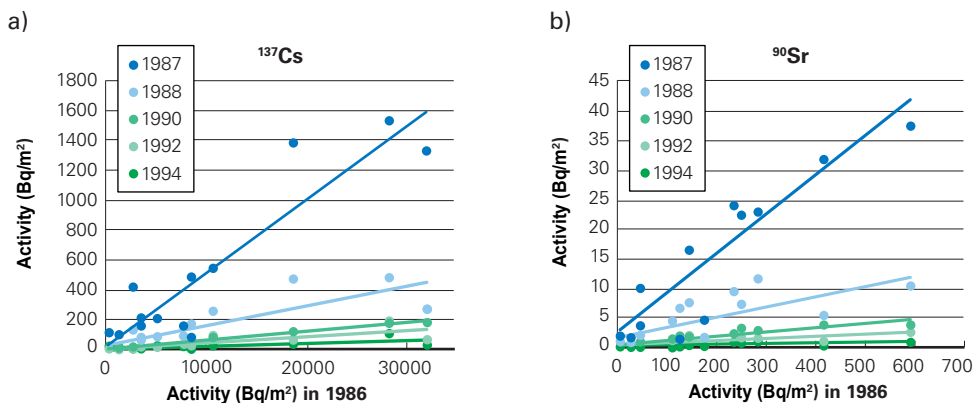


Fig. 11. Correlation of a) ^{137}Cs and b) ^{90}Sr in deposition between samples collected in 1986 and in subsequent years from various stations.

Long-term resuspension

Resuspension of Chernobyl-derived, long-lived nuclides ^{90}Sr and ^{137}Cs , appears to slowly decrease under Finnish environmental and climatic conditions. At most stations, two, or at certain stations even three components can be distinguished

in the decline of ^{137}Cs (Fig. 12) and ^{90}Sr depositions. The estimations were carried out using the total annual amounts of ^{137}Cs and ^{90}Sr detected in deposition samplers at various stations. Resuspension was strongest immediately after the Chernobyl deposition and initially decreased with a half-life of 2 to 14 months for ^{137}Cs and 2 to 7 months for ^{90}Sr . For ^{137}Cs , this component typically lasted until the beginning of 1987, and at certain stations in northern or eastern Finland even until the first months of 1989. For ^{90}Sr , the first component typically lasted until the beginning of 1987. The second component of the decrease had a half-life of 20 to 60 months for both ^{137}Cs and ^{90}Sr . When there was a third component to the decrease in ^{137}Cs and ^{90}Sr , the half-lives of the second component ranged from 10 to 20 months for ^{137}Cs and from 12 to 34 months for ^{90}Sr . When present, the third component had a much longer half-life, invariably exceeding 3 years. The decrease in ^{137}Cs and ^{90}Sr was slower ($T_{1/2}$ longer) at the stations in northern and eastern Finland than at the other stations. This was possibly due to the lower contribution of the Chernobyl accident and therefore the higher contribution of stratospheric fallout to the deposited radionuclides in these areas.

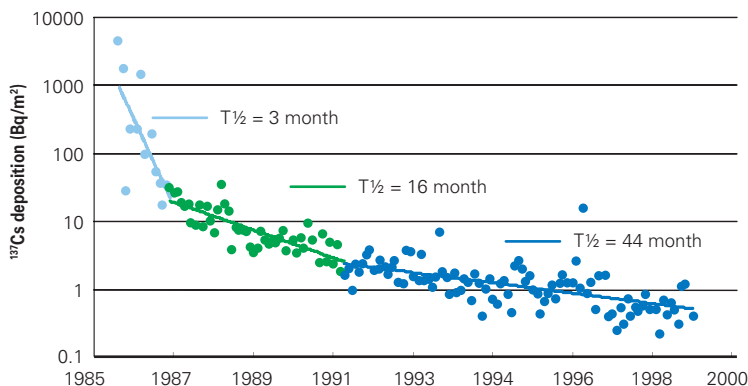


Fig. 12. Deposition of ^{137}Cs at one of the stations (Jokioinen). Three components in the decline are shown with different colours and associated half-lives are also given.

Environmental factors

To examine whether the differences in resuspension were due to differences in the environments of the samplers, the type of land in the immediate vicinity of the samplers was defined. Six of the stations situated in natural forest (Kajaani, Kauhava, Niinisalo, Nurmijärvi, Sodankylä, Taivalkoski), while the others situated in an at least partly cultivated environments, with grass or asphalt and sand or gravel, and also trees and other vegetation nearby. Despite these differences, no connections between environmental factors and resuspension

could be found. Weather conditions, especially wind speed, certainly contributed to the high variation in the amounts of total resuspension at various stations. A twofold increase in wind speed has found to lead to a much greater increase in resuspension, and a single high wind speed event can therefore dominate long-term average flux estimates (Howard and Desmet, 1998).

Proportions of stratospheric deposition and resuspension

After the Chernobyl accident, small amounts of deposited ^{137}Cs and ^{90}Sr originated from the 'old' stratospheric deposition, which was fairly evenly distributed throughout the country. However, the contribution of the 'old' stratospheric deposition of ^{137}Cs was negligible compared with that of the Chernobyl deposition. According to the study of Kownacka and Jaworowski (1994), the Chernobyl deposition also had a stratospheric component, as shown by the spring peaks they detected each year between 1987 and 1991. They assumed that radiocaesium resuspended from the soil was also uplifted to high altitudes and trapped in the lower stratosphere. Our results favour local resuspension as the main source, as do those of Aarkrog et al. (1989, 1991). Had large amounts of radiocaesium entered the stratosphere, the correlation between the original deposited amounts at the various stations and the amounts detected in later years at the same stations would not have been as strong as recorded in our study. Moreover, our samples did not display clear summer peaks.

The stratospheric component of deposition (including long-distance resuspension) can be derived from Figure 9, where the curves approach the value of the stratospheric component of deposition, i.e. the point where the lines intersect the y axis (= A). The proportion of the 'old' stratospheric deposition of nuclides (= B) in a particular year can be roughly estimated with the pre-Chernobyl deposition values for 1985 and the assumed annual decrease in the rate of deposition of 30% detected in the 1980s in Finland. The stratospheric fraction of the Chernobyl deposition is then A minus B. If the average value of the nuclides detected in deposition samples at all stations in a particular year is given by C, the proportion of resuspension in deposition in that year is C minus A. Calculations reveal that between 1987 and 1994, 86% of ^{137}Cs and 92% of the ^{90}Sr detected in deposition samples was resuspended, and the rest was of stratospheric origin or long-distance resuspension. For ^{137}Cs , the 'old' stratospheric deposition was estimated to account for 0.2% of the total amounts detected during 1987–1994, while stratospheric Chernobyl deposition or long-distance resuspension accounted for 14%. For ^{90}Sr , the respective proportions were estimated to be around 3% for the 'old' stratospheric deposition and 5% for the stratospheric Chernobyl deposition or long-distance resuspension. According to Hirose et al. (1989), 80% of ^{137}Cs and 40% of ^{90}Sr detected in Japan in 1987

originated from the stratospheric component of the Chernobyl deposition. The larger share of stratospheric component in Japan is due to longer distance from the Chernobyl and therefore resulting in smaller deposition.

3.5 Wet and dry deposition

Wet deposition occurs via falling precipitation (rain, sleet, snow, hail) whereas dry deposition occurs by the direct interaction of a material with a surface. Precipitation scavenges efficiently airborne contaminant to the ground. According to Paatero et al. (1994b) one millilitre of precipitation contains as much contaminants as one cubic metre of air. In dry deposition sedimentation effects dominate for larger particles. However, for smaller particles the interaction is complex in the outdoor environment because of the wide range of environmental conditions and the wide range of surface types and orientations.

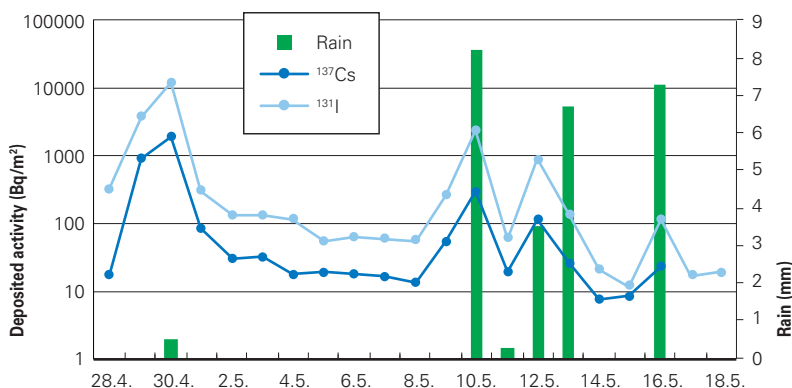


Fig. 13. Deposited ^{137}Cs and ^{131}I from the Chernobyl accident and the amount of precipitation during April 28 – May 19, 1986 in Helsinki. The precipitation values were obtained from the Finnish Meteorological Institute.

3.5.1 Wet and dry deposition from the Chernobyl accident in Helsinki

The amount of precipitation governed largely how the Chernobyl plume was deposited to Finland (Paatero et al., 2010b). Relationship between the precipitation and deposited amounts of radionuclides in Helsinki is demonstrated in Fig. 13. To estimate the share of wet and dry deposition to total ^{137}Cs deposition, the daily ^{137}Cs deposition values from Konala station, Helsinki (Saxen et al., 1987) were used as well as the precipitation information from Kaisaniemi station, Helsinki obtained from the Finnish Meteorological Institute. It was calculated that 34% of the ^{137}Cs was deposited in days with no rain and 66% was deposited in rainy days during the three week period (April 28–May, 1986) in Helsinki.

Anttila et al. (1998) evaluated the dry deposition velocities and washout concentration ratios for several radionuclides in the Chernobyl deposition. They calculated the amount of ^{137}Cs in dry deposition, for days with no precipitation, using the total inner surface area of the collector instead of the surface area that is used as an area for the deposited nuclides at STUK. The total inner surface area of the collector was about 7 times larger than the surface area. Using total inner surface area for the deposition area and taking into consideration the amount of dry deposition in rainy days and using the dry deposition velocities that Anttila et al. (1998) determined, we calculated that the dry deposition would account approximately 10% of the total ^{137}Cs deposition during the three-week period in Helsinki. However, this value is probably an underestimation as the deposition of radionuclides on a smooth surface of the collector is presumably smaller than it is on diverse surfaces occurring in natural and urban environments. Additionally, the larger particles (hot particles) known to be present in the early days of Chernobyl accident deposit through gravitational settling supporting the use of surface area instead of total inner surface of the collector.

In conclusion, dry deposition from the Chernobyl accident accounted 10–34% of the total deposition in Helsinki. The dry and wet deposition estimates for the Chernobyl accident in this chapter are merely ballpark estimates.

3.5.2 Wet and dry deposition in 1993–2006

The wet and dry deposition samples have been separately collected with a deposition collector 'Pirkko' (Fig. 4) since 1993 in Helsinki, Roihupelto. The wet and dry deposition of ^{137}Cs and ^7Be are given in Table 6 and illustrated in Fig. 14. ^7Be is a naturally occurring radionuclide that is of cosmogenic origin and formed in the upper troposphere and lower stratosphere. The sampling area of the wet and dry deposition samplers was 0.5 m² for each. The results in Table 6 have been calculated using the sampling area of 0.5 m² for both dry and wet deposition. In average, 11% (median 8.0%) of ^7Be and 31% (median 29%) of ^{137}Cs was detected in dry deposition, respectively. When the ^{137}Cs was below the detection limit in dry deposition samples, the value MDA/2 (where MDA= minimum detectable activity) was used to derive the average wet and dry deposition values of ^{137}Cs .

The dry-to-total deposition ratio of ^7Be agrees well with the ratios reported in literature. Ioannidou et al. (2006) determined that the dry deposition of ^7Be was less than 9.4% of the total deposition based on few measurements. Rosner et al. (1996) reported a mean value of 12% for the dry deposition during 1991–1995. Rosner et al. (1996) found the dry-to-total deposition ratio of ^{137}Cs to be 5 times higher than that of ^7Be . Ioannidou (2006) also measured 3–4 times higher dry-to-total deposition ratio for ^{137}Cs than for ^7Be and attributed this to the higher

resuspension factor of ^{137}Cs . In our samples the dry-to-total ratio of ^{137}Cs was about 3 times higher than that of ^7Be and the local resuspension was determined to be the dominating source for the deposited ^{137}Cs in 1990s (chapter 3.4).

To get an alternative estimation for the magnitude of dry deposition the results were also calculated using the total inner surface area of the dry collector (1.57 m^2) instead of the sampling area of 0.5 m^2 . With this approach, the dry deposition of ^{137}Cs would account 17% and that of ^7Be 4% of the total amounts deposited for these two nuclides. However, these values may be underestimations as the deposition to the smooth surface of the collector is probably less than on the various types of surfaces in the nature. Based on the above mentioned calculations it can be concluded that the dry deposition of ^{137}Cs is between 17% and 30% of the total ^{137}Cs deposition during 1993–2006.

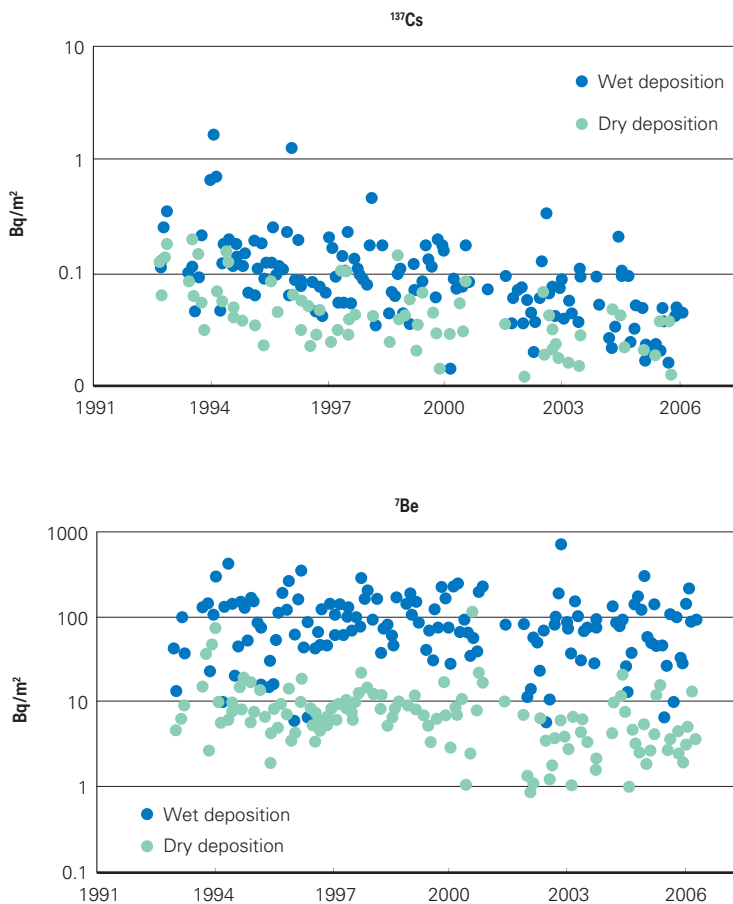


Fig. 14. Dry and wet deposited ^{137}Cs and ^7Be in Helsinki (with logarithmic scale).

The ^{137}Cs results from the dry and wet deposition samples that were analyzed separately were summed together for each month and compared with the ^{137}Cs results from the monthly deposition samples that were determined with the regular ‘Ritva’ deposition collector (0.05 m²) located at the same site in Helsinki (Table 3). It was noticed that the summed wet and dry ^{137}Cs deposition was 40% smaller than the ^{137}Cs deposition obtained by the ‘Ritva’ collector. The difference between the two collectors reflects the influence of properties of the collectors on the deposition results.

3.6 Tritium in rainwater

The average annual activity concentrations of ^3H in rainwater from various stations are presented in Table 7 and the respective results as deposited amounts of ^3H in Table 8. Tritium has a physical half-life of 12.3 years. It is produced naturally by the interaction of cosmic radiation with atmospheric components in the upper troposphere and lower stratosphere with a ratio of 1:2 (Araguas et al., 1996). From the early 1950s, tritium was also produced in nuclear weapons tests in the atmosphere that overshadowed the natural production by two to three orders of magnitude over many years (Araguas et al., 1996). After 1963, only limited nuclear weapons tests were carried out in the atmosphere. Tritium is also released into the environment from nuclear power production.

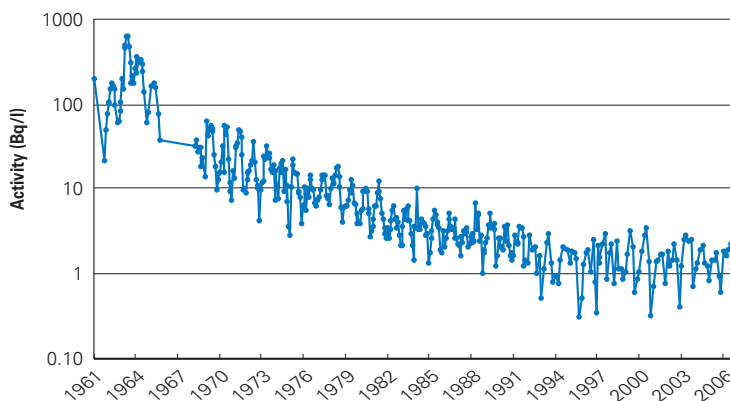


Fig. 15. Tritium activity (Bq/l) in rainwater in North Finland.

Prior to the nuclear weapons tests, the tritium concentration in rainwater was estimated to be about 0.6 Bq/l (Gat et al., 2001). In 1961, STUK started to monitor tritium in rainwater in northern Finland, and few years later monitoring

was also started in southern Finland. The maximum tritium concentration in rainwater, 650 Bq/l, was detected in Rovaniemi in summer 1963 (Fig. 15). This is in agreement with the measurements in Vienna, where the ^3H peak in rainwater was about 600 Bq/l during spring 1963 (Gat et al., 2001). Since then, ^3H concentrations in rainwater have decreased (Fig. 15). No considerable differences can be seen in tritium concentration in rain between the North and South Finland with the exception of the period 1993–2002 (Fig 16), when significantly higher concentrations were detected in South Finland due to treatment of tritium waste in a basement of a building where the sampler was located on the roof. However, the annual tritium depositions (Table 8) were slightly lower in North Finland than in South Finland due to lower precipitation in North Finland as compared to South Finland. Currently, the average tritium concentration in rainwater is around 2 Bq/l in Finland.

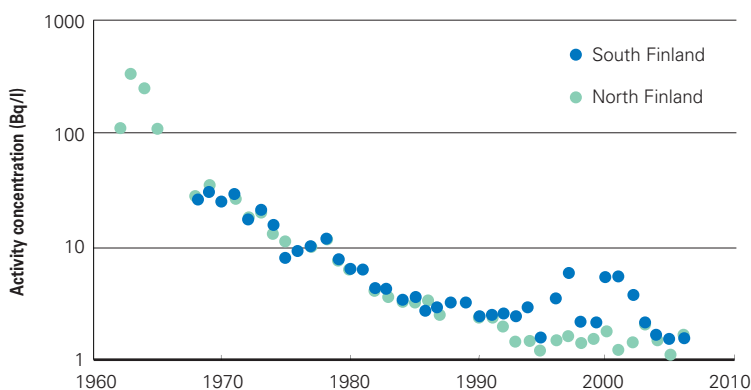


Fig. 16. Average annual tritium concentration (Bq/l) in North and South Finland. In the 1990s, tritium waste was handled in a basement of a building in South Finland where the sampling station was located on the roof.

The tritium concentration in rainwater follows a seasonal pattern that is influenced by the timing, location and intensity of exchange of tropospheric and stratospheric air masses, as well as the tritium concentration in the stratosphere. The seasonal pattern in Figure 17 demonstrates the annual cycle, with maximum concentrations in summer, from June to July, and the minimum in winter, similarly for ^{90}Sr and ^{137}Cs , as discussed above. A seasonal pattern in tritium concentrations has also been detected at other stations in the northern hemisphere with slightly varying amplitudes and phase shifts (Gat et al., 2001, Araguas et al., 1996). Globally, the highest tritium levels have been recorded north of the 30th latitude where the concentrations were 5 times

higher than those at lower latitudes and tropical stations, and also higher than in the southern hemisphere at comparable latitudes, reflecting the predominant northern hemispheric location of the weapons testing sites (Gat et al., 2001).

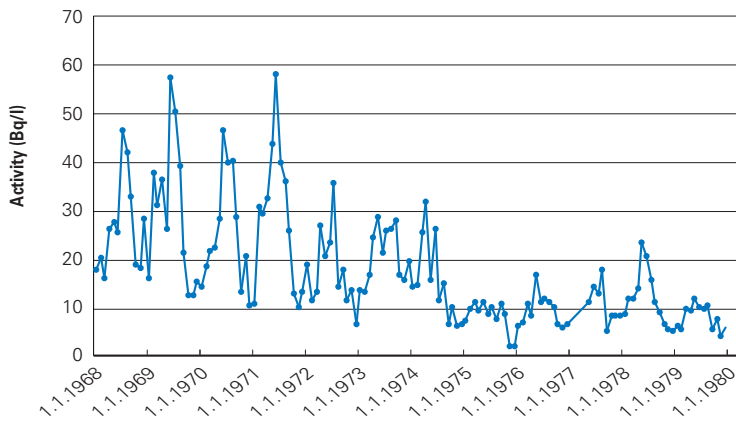


Fig. 17. Seasonal pattern of tritium activity in rainwater in Southern Finland during 1960s and 1970s.

4 Conclusions

Most man-made radionuclides in the Finnish environment are derived from the atmospheric nuclear weapons tests that were mainly conducted in the 1950s and 1960s and from the Chernobyl accident in 1986. The deposition from the Chernobyl accident was marked by an uneven areal distribution of radionuclides, in contrast to the stratospheric deposition of the nuclear weapons test period which was relatively evenly distributed in Finland. The activity concentration of tritium, which is also naturally present in the environment, increased by a few orders of magnitude in the 1960s due to the nuclear weapons tests that peaked in 1963. Since then, its concentration has decreased close to the levels found prior to the atmospheric weapons tests.

Radionuclides from the Chernobyl accident were deposited within a few weeks after the accident, but measurable concentrations of the long-lived nuclides (^{137}Cs and ^{90}Sr) were detected for several years following the deposition due to local resuspension. Our measurements show that under Finnish climatic conditions about 90% of the detected radioactivity in deposited samples was due to local resuspension in the absence of ongoing radioactive releases. The rest of the detected radioactivity was of stratospheric origin or due to long-distance resuspension. Since 1993, wet and dry deposition have been measured separately and the results indicate that the dry deposition of ^{137}Cs account 17–30% of its total deposition.

Information obtained from the deposition samples has proved useful in radioecological studies, for example, in those evaluating the transfer of radionuclides in the environment. Despite the limited regional coverage of the current network (9 stations), long-term monitoring of deposited radionuclides provides essential information about the changes in and the distribution and levels of radionuclides which can be utilized in environmental modelling. Continuous sampling and analysis of deposition is a simple and economical way to remain aware of the prevailing radiation situation and to gain essential information in the case of a radiation incident.

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APPENDIX 1.

Tables of deposition of ^{137}Cs , ^{90}Sr and ^3H

Table 2.

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Table 2. Annual and accumulated deposition (decay corrected) of ^{90}Sr and ^{137}Cs (Bq/m^2) in Finland during 1961–1985. Results prior to 1961 (*in italics*) are values for Leningrad (Salo et al., 1984).

Year	Annual deposition (Bq/m^2)		Accumulated deposition (Bq/m^2)	
	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
1955	<i>129.5</i>	<i>74</i>	<i>130</i>	<i>70</i>
1956	<i>129.5</i>	<i>74</i>	<i>260</i>	<i>150</i>
1957	<i>259</i>	<i>110</i>	<i>510</i>	<i>260</i>
1958	<i>289</i>	<i>190</i>	<i>790</i>	<i>430</i>
1959	<i>229</i>	<i>74</i>	<i>1000</i>	<i>500</i>
1960	<i>74</i>	<i>37</i>	<i>1050</i>	<i>520</i>
1961	41	30	1070	540
1962	223	246	1390	770
1963	422	448	1980	1200
1964	377	237	2320	1410
1965	155	95	2420	1470
1966	83	61	2450	1490
1967	37	26	2430	1480
1968	34	31	2410	1480
1969	24	18	2380	1460
1970	40	28	2360	1450
1971	36	25	2340	1440
1972	17	14	2310	1420
1973	8.0	5.6	2260	1390
1974	24	22	2240	1380
1975	10	7.6	2190	1350
1976	3.4	2.7	2150	1320
1977	14	15	2110	1300
1978	14	12	2080	1280
1979	7.7	5.6	2040	1260
1980	4.0	3.6	1990	1230
1981	12	8.5	1960	1210
1982	2.6	2.1	1920	1180
1983	1.5*	1.4	1880	1160
1984	1.2	0.51	1840	1130
1985	0.85	0.78	1790	1100

* Data from part of the year are missing.

Table 3a. Annual deposition of ^{137}Cs (Bq/m^2) at various sampling stations. Results prior to 1961 (*in italics*) are values for Leningrad (Salo et al., 1984).

Year	Ivalo ^{a,c}	Jokioinen	Jyväskylä	Kajaani	Mariehamn	Kankaanpää (Niinisalo)	Sodankylä ^{a,b,c}	Taivalkoski ^{a,b}
1963	<i>385</i>	<i>358</i>	<i>364</i>	<i>329</i>	<i>459</i>		<i>406</i>	<i>444</i>
1964	<i>225</i>	<i>366</i>	<i>383</i>	<i>418</i>	<i>319</i>		<i>283</i>	<i>387</i>
1965	<i>126</i>	<i>159</i>	<i>156</i>	<i>135</i>	<i>152</i>		<i>128</i>	<i>169</i>
1986	185*	8380	18600	5080	975	32000	306	142*
1987	45.3	482	1380	198	106	1360	115	46.8
1988	18.2	166	470	80.8	30.0	268	22.9	16.9
1989	11.3	68.3	248	33.4	22.7	211	10.7	11.1
1990	6.7	54.3	129.3	23.0	24.5	178	6.7	6.7
1991	9.0	31.5	102	20.3	186	53.7	9.0	9.0
1992	7.5	29.0	90.6	19.0	11.3	67.1	7.5	7.5
1993	5.1	24.9	68.5	15.1	8.7	46.4	5.1	5.1
1994	3.3	12.4	39.4	15.0	6.9	28.0	4.5	4.5
1995	0.3	16.0	45.7	11.5	9.7	51.1	6.1	6.2
1996	0.5	29.4	38.5	8.8	7.4	31.1	3.1	12.9
1997	0.2	8.7	37.7	6.0	7.3	6.5	0.2	4.5
1998	0.1	6.5	47.0	3.8	1.7	6.2	0.1	2.3
1999	1.7	6.5	16.3	2.1	2.0	4.7	0.3	1.6
2000	0.6	5.3	4.6	3.9	4.7	8.6	0.3	2.3
2001	0.1	4.5	3.8	3.0	1.8	13.4	0.2	3.3
2002	0.5	5.8	5.0	3.0	1.8	14.1	0.3	1.8
2003	0.4	2.8	3.4	2.1	1.0	9.7	0.5	1.1
2004	0.3	4.3	2.6	1.8	1.0	6.8	0.5	1.5
2005	0.1	2.8		2.1	1.1	9.2	0.3	1.2
2006	0.2	2.4		2.1	1.0	6.4	0.1	0.9

^a Samples from Ivalo, Sodankylä and Taivalkoski were pooled together during 1.4.1989–15.9.1994.

^b Samples from Sodankylä and Taivalkoski were pooled together during 15.10.1994–15.12.1994.

^c Samples from Ivalo, Sodankylä and Rovaniemi (Korkalovaara) were pooled together during 15.5.1996–15.3.1999.

* Deposition data missing for part of the year.

Table 3b. Annual deposition of ¹³⁷Cs (Bq/m²) at various sampling stations. Results prior to 1961 (*in italics*) are values for Leningrad (Salo et al., 1984).

Year	Vaasa	Imatra	Kotka	Ylöjärvi (Lakiala)	Helsinki (Harakka)	Espoo	Pori	Rovaniemi ^c (Korkalovaara)	Helsinki (Roihupelto)
1963	<i>252</i>				<i>492</i>	<i>522</i>	<i>477</i>		
1964	<i>326</i>				<i>362</i>	<i>466</i>	<i>398</i>		
1965	<i>125</i>				<i>178</i>	<i>164</i>	<i>217</i>		
1986	10700*								
1987	546								
1988	251								
1989	139								
1990	95								
1991	61								
1992	89								
1993	46								
1994	26								
1995	22	4.8							9.3
1996	17	7.1							9.0
1997	10	3.6							5.2
1998	3.7	3.7							4.1
1999	3.4	2.5						0.5	2.7
2000	5.1	2.8	4.9	8.1				0.6	3.9
2001	3.6	3.4	5.0	5.8				0.4	4.3
2002	2.3	3.0	4.4	5.3				0.6	3.4
2003	1.7	2.4	3.1	5.0				0.7	2.0
2004	2.3	1.9	3.0	3.9				0.6	1.1
2005	1.9	1.7	3.3	4.5				0.1	1.4
2006	1.6	1.4	3.6	4.2				0.1	1.2

^c Samples from Ivalo, Sodankylä and Rovaniemi (Korkalovaara) were pooled together during 15.5.1996–15.3.1999.

* Deposition data missing for part of the year.

Table 3c. Annual deposition of ^{137}Cs (Bq/m^2) at various sampling stations. Results prior to 1961 (*in italics*) are values for Leningrad (Salo et al., 1984).

Year	Joensuu ^a	Kauhava	Kuhmo	Kuopio ^a	Lappeenranta	Nurmi-järvi	Rovaniemi (Apuikka)	Vantaa	Savonlinna ^a
<i>1963</i>	<i>615</i>	<i>340</i>		<i>433</i>	<i>422</i>	<i>507</i>			<i>329</i>
<i>1964</i>	<i>419</i>	<i>268</i>		<i>446</i>	<i>369</i>	<i>415</i>			<i>381</i>
<i>1965</i>	<i>134</i>	<i>122</i>		<i>174</i>	<i>132</i>	<i>197</i>			<i>160</i>
1970			39					50	
1971			34					40	
1972			19.3					22	
1973			9.2				8.0	8.6	
1974			27				31	26	
1975			12				11.2	17	
1976			4.9				3.3	4.1	
1977			17		22	22	18		
1978			13		18	19	18		
1979			7.1		7.5	8.5	7.4		
1980			4.7		3.2	4.2	3.0		
1981			11.2		13.8	12.8	14.4		
1982			1.9		1.8	2.3	2.3		
1983			2.0		1.8	1.6	7.3		
1984			0.8		2.4	1.2			
1985			1.3		1.3	1.1			
1986	547	28200	8220	3520	3410	7790	1220		2680
1987	104	1530	98.8	214	163	165	7.5		417
1988	26.8	477	53.8	57.2	74.4	97.8	4.4		130
1989	21.6	399	57.3	28.6	99.0	48.5	5.5		36.7
1990	19.6	185	24.4	19.6	35.2	43.7	2.4		19.6
1991	13.0	195	20.8	13.0	21.0	23.8	1.8		13.0
1992	12.9	191	18.8	12.9	17.7	25.5	1.7		12.9
1993	8.8	93.2	13.8	8.8	9.5	20.8	1.6		8.8
1994	8.8	103	7.5	8.8	21.6	14.8	0.8		8.8
1995	7.7						1.0		
1996	28						0.5		
1997	4.3						0.5		
1998	4.3						0.8		
1999	2.6								
2000							0.6		
2001							0.9		
2002							1.0		
2003							1.2		
2005				1.3*			0.5		
2006				2.3			0.6		

^a During 1.4.1989–15.9.1994 deposition samples from Kuopio, Joensuu and Savonlinna were pooled together.

* Deposition data missing for part of the year.

Table 4a. Annual deposition of ⁹⁰Sr (Bq/m²) at various sampling stations.

Year	Ivalo ^{a,c}	Jokioinen	Jyväskylä	Kajaani	Mariehamn	Kankaanpää (Niinisalo)	Sodankylä ^{a,b,c}	Taivalkoski ^{a,b}
1963	258	462	316	345	483		410	519
1964	111	218	240	285	192		197	225
1965	90	100	97	77	94		75	91
1986	7.7*	126	281	234	117	415	10.6*	4.7
1987	1.4	27.2	23.1	24.2	2.2	31.8	2.6	1.6
1988	0.6	6.7*	11.4	9.4	0.9	5.3	0.8	1.2
1989	0.7	2.8	9.3	4.2	0.6	14.4	0.7	0.7
1990	0.4	1.7*	2.7	2.1	1.6	4.0*	0.4	0.4
1991	0.4	1.0	3.0	2.3	0.4	1.2	0.4	0.4
1992	0.5	1.0	1.5	2.1	0.3	1.0	0.5	0.5
1993	0.4	0.8	2.7	1.6	0.4	0.8	0.4	0.4
1994	0.3	0.4	1.1	1.2	0.2	0.4	0.5	0.5
1995		0.8	2.2	1.4	0.4	0.6	0.3	0.8
1996		1.1	1.3	0.8	1.5	0.7	0.3	1.1
1997		0.6	0.8	0.3	0.3	0.2		0.6
1998		0.3	0.8	0.3	0.1	0.1		0.4
1999	0.1	0.5	0.4	0.6	0.2	0.2	0.1	0.6
2000	0.1	0.4	0.7	0.4	0.3	0.4	0.1	0.5
2001	0.1		0.2	0.3	0.4	0.9	0.1	0.8
2002	0.1	0.4	0.2	0.3	0.2	1.1	0.2	0.8
2003	0.2	0.3	0.1	0.4	0.2	0.8	0.3	0.6
2004	0.1	0.3	0.2	0.3	0.2	0.4	0.2	0.5
2005	0.1	0.4		0.2	0.2	0.7	0.2	0.6
2006	<0.2			0.2			<0.2	

^a Samples from Ivalo, Sodankylä and Taivalkoski were combined during 15.1.1989–15.9.1994.

^b Samples from Sodankylä and Taivalkoski were combined during 15.10.1994–15.12.1994.

^c Samples from Ivalo, Sodankylä and Rovaniemi (Korkalovaara) were combined during 15.5.1996–15.3.1999.

* Deposition data missing for part of the year.

Table 4b. Annual deposition of ^{90}Sr (Bq/m^2) at various sampling stations.

Year	Vaasa	Imatra	Kotka	Ylöjärvi (Lakiala)	Helsinki (Harakka)	Espoo	Pori	Rovaniemi ^c (Korkalovaara)	Helsinki (Roihupelto)
1963	340				527	553	558		
1964	208				269	298	248		
1965	91				109	104	108		
1986	143*								
1987	16.5								
1988	7.5								
1989	3.3								
1990	1.8*								
1991	1.1								
1992	1.9								
1993	0.7								
1994	0.5								
1995	0.5	0.6							0.5
1996	1.3	0.6							0.6
1997	1.0	0.3							0.3
1998	0.5	0.1							0.1
1999	0.4	0.2					0.1		0.2
2000	0.5	0.1	0.2	0.2			0.1		0.1
2001	0.5	0.2	0.3	0.2					0.2
2002	0.3	0.3	0.3	0.2			0.2		0.2
2003	0.8	0.1	0.1	0.2			0.4		0.1
2004	0.8	0.2	0.2	0.1			0.2		0.1
2005	0.3	0.1	0.3	0.1			0.5		0.1
2006		<0.1	0.3	0.1			0.2		<0.1

^a Samples from Ivalo, Sodankylä and Taivalkoski were combined during 15.1.1989–15.9.1994.

^b Samples from Sodankylä and Taivalkoski were combined during 15.10.1994–15.12.1994.

^c Samples from Ivalo, Sodankylä and Rovaniemi (Korkalovaara) were combined during 15.5.1996–15.3.1999.

* Deposition data missing for part of the year.

Table 4c. Annual deposition of ^{90}Sr (Bq/m^2) at various sampling stations.

Year	Joensuu ^a	Kauhava	Kuhmo	Kuopio ^a	Lappeenranta	Nurmi-järvi	Rovaniemi (Apukka)	Savonlinna ^a	Vantaa
1963	439	422		451	452	601		450	
1964	270	188		287	218	226		238	
1965	90	75		112	88	113		92	
1970			33						41
1971			29						33
1972			18						17
1973			6.5				7.7		7.1
1974			18				21.5*		18
1975			8.3				8.4		8.9
1976			3.0				7.3		4.0
1977			13			13.3*	26.1		
1978			12			12.3	11.7		
1979			4.7			4.7	7.6		
1980			3.3			2.5	3.5*		
1981			11.3*			8.7	9.2		
1982			3.3			1.2	2.3		
1983			1.3			0.9	2.1		
1984			1.3			0.4	1.5		
1985			1.1			0.4	1.4		
1986	29.1	247	589	176	43.8	108	8.8	46.7*	
1987	1.9	22.5	37.6	4.8	3.6	4.6	4.9	10.0	
1988	0.9	7.5	10.3	1.5	1.3	4.5	2.4	2.4	
1989	0.9	7.8	6.5	0.9	5.7	2.2	4.8	0.9	
1990	0.6	3.3	4.1*	0.6	0.9	1.4	1.6	0.6	
1991	0.4	2.7	6.2	0.4	0.4	1.5	1.5	0.4	
1992	0.5	2.0	2.8	0.5	0.4	1.3	0.6	0.5	
1993	0.5	1.2	1.9	0.5	0.6	2.1	1.0	0.5	
1994	0.3	1.1	1.0	0.3	0.3	0.9	0.8	0.3	
1995	0.3						0.3		
1996	0.6						0.2		
1997	0.2						0.3		
1998	0.1						0.1*		
1999	0.1								
2005				0.1*					
2006				<0.1					

^a During 15.1.1989–15.9.1994 deposition samples from Kuopio, Joensuu and Savonlinna were pooled together.

* Deposition data missing for part of the year.

Table 5. Accumulated deposition (decay corrected) of ^{137}Cs and ^{90}Sr (Bq/m^2) at various sampling stations at the end of 1986.

Sampling Station	^{137}Cs	^{90}Sr
Ivalo	1900	1100
Joensuu	2300	1100
Jokioinen	10000	1200
Jyväskylä	21000	1400
Kauhava	30000	1300
Kajaani	6800	1300
Kuhmo	10000	1700
Kuopio	5200	1200
Lappeenranta	5100	1100
Nurmijärvi	9500	1200
Mariehamn	2700	1200
Kankaanpää	34000	1500
Rovaniemi	3000	
Savonlinna	4400	1100
Sodankylä	2100	1100
Taivalkoski	1900	1100
Vaasa	13000	1200

Table 6. Wet and dry ^{137}Cs and ^7Be deposition (Bq/m^2) in Helsinki 1993–2006 collected with the 0.5 m^2 deposition collector 'Pirkko'.

Collection started	Collection ended	^{137}Cs (Bq/m^2) in dry deposition	^{137}Cs (Bq/m^2) in wet deposition	^7Be (Bq/m^2) in dry deposition	^7Be (Bq/m^2) in wet deposition
24.8.1993	10.9.1993	0.0642	0.113	4.60	43.6
10.9.1993	1.10.1993	0.130	0.126	5.16	13.2
1.10.1993	1.11.1993	0.134	0.262	6.79	99.4
1.11.1993	30.11.1993	0.180	0.356	9.37	39.3
29.4.1994	1.6.1994	0.0849	0.107	15.9	135
1.6.1994	1.7.1994	0.202	0.117	38.8	146
1.7.1994	2.8.1994	0.0613	0.0475	2.70	23.2
2.8.1994	31.8.1994	0.140	0.0947	51.3	111
31.8.1994	4.10.1994	0.0538	0.219	72.4	302
4.10.1994	31.10.1994	0.0330	< 0.03	9.83	9.85
31.10.1994	1.12.1994			5.79	
1.12.1994	31.12.1994		0.684		134
1.12.1994	2.1.1995			8.77	
2.1.1995	1.2.1995	< 0.05	1.67	6.17	436
1.2.1995	2.3.1995	0.0719	0.690	9.81	141
2.3.1995	31.3.1995	0.0618	0.0467	9.75	20.3
31.3.1995	3.5.1995	0.0561	0.121	8.37	46.3
3.5.1995	31.5.1995	0.155	0.182	15.0	156
31.5.1995	3.7.1995	0.125	0.193	18.7	135
3.7.1995	1.8.1995	0.0501	0.115	7.515	52.4
1.8.1995	31.8.1995	0.0391	0.186	6.36	166
31.8.1995	2.10.1995	< 0.03	0.141	17.0	152
2.10.1995	1.11.1995	0.0387	0.116	8.52	90.6
1.11.1995	30.11.1995	< 0.05	0.152	13.4	74.5
30.11.1995	29.12.1995	<	0.0689	6.89	6.0
29.12.1995	1.2.1996	< 0.06	0.0636	7.99	31.6
1.2.1996	20.2.1996	0.0339	0.192	1.91	15.7
20.2.1996	1.3.1996	<	0.108	4.30	16.4
1.3.1996	1.4.1996	<	0.191	4.97	53.2
1.4.1996	30.4.1996	0.0249	0.0899	8.87	118
30.4.1996	31.5.1996	< 0.1	0.123	10.3	186
31.5.1996	1.7.1996	0.08582	0.121	7.94	124
1.7.1996	1.8.1996	< 0.05	0.252	14.0	269
1.8.1996	2.9.1996	0.0451	0.101	3.68	608
2.9.1996	1.10.1996	< 0.07	0.114	4.47	60.7
1.10.1996	30.10.1996	< 0.06	0.112	10.2	169
30.10.1996	2.12.1996	< 0.07	0.232	18.7	352
2.12.1996	31.12.1996	< 0.04	0.0650	10.0	44.4
31.12.1996	31.1.1997	0.0612	1.29	9.09	87.3
31.1.1997	28.2.1997	0.0629	0.0902	5.73	6.65
28.2.1997	1.4.1997	< 0.1	0.193	3.53	4 4.6

Table 6 continued.

Collection started	Collection ended	¹³⁷ Cs (Bq/m ²) in dry deposition	¹³⁷ Cs (Bq/m ²) in wet deposition	⁷ Be (Bq/m ²) in dry deposition	⁷ Be (Bq/m ²) in wet deposition
1.4.1997	2.5.1997	0.0301	0.0801	8.36	64.8
2.5.1997	2.6.1997	0.0537	0.0838	4.60	48.2
2.6.1997	1.7.1997	0.0511	0.0849	6.49	126
1.7.1997	1.8.1997	0.0240	0.0852	5.55	47.5
1.8.1997	1.9.1997	0.0296	0.0481	8.02	149
1.9.1997	1.10.1997	0.0478	0.0755	8.75	121
1.10.1997	31.10.1997	< 0.03	0.0412	6.44	61.4
31.10.1997	1.12.1997	< 0.05	0.0688	8.22	144
1.12.1997	1.1.1998	0.0245		10.3	
1.12.1997	2.1.1998		0.208		62.5
2.1.1998	2.2.1998	< 0.07	0.1667	11.0	139
2.2.1998	28.2.1998	< 0.07	0.0942	8.29	98.8
28.2.1998	1.4.1998	0.0313	0.0550	6.74	69.7
1.4.1998	30.4.1998	0.105	0.143	9.87	103
30.4.1998	2.6.1998	0.106	0.106	12.3	77.4
2.6.1998	1.7.1998	0.0290	0.231	21.2	290
1.7.1998	30.7.1998	0.0395	0.0561	15.7	163
30.7.1998	31.8.1998	0.0425	0.133	14.8	208
31.8.1998	1.10.1998	< 0.05	0.107	14.2	93.7
1.10.1998	2.11.1998	< 0.07	0.0971	12.1	171
2.11.1998	30.11.1998	< 0.06	0.0877	8.41	38.9
30.11.1998	31.12.1998	< 0.03	0.0798	12.1	75.9
31.12.1998	1.2.1999	< 0.03	0.178	4.52	82.8
1.2.1999	1.3.1999	0.0420	0.471	7.90	63.8
1.3.1999	1.4.1999	< 0.06	0.0339	6.90	47.2
1.4.1999	3.5.1999	< 0.03	0.178	10.2	173
1.6.1999	2.7.1999	< 0.05	0.0434	8.32	173
2.7.1999	2.8.1999	0.0244	0.0698	9.61	141
2.8.1999	31.8.1999	< 0.05	0.0635	9.19	1 84.2
31.8.1999	4.10.1999	0.1467	0.0987	8.16	108
4.10.1999	1.11.1999	0.0408	0.111	11.6	159
1.11.1999	1.12.1999	0.0415	0.0435	8.52	90.0
3.1.2000	1.2.2000	0.0595	0.0362	6.61	42.4
1.2.2000	29.2.2000	< 0.07	0.125	5.34	71.8
29.2.2000	31.3.2000	0.0210	0.0707	3.33	30.9
31.3.2000	2.5.2000	0.0359	0.0729	5.93	127
2.5.2000	31.5.2000	0.0676	0.0843	6.24	78.4
31.5.2000	30.6.2000		0.177		241
8.6.2000	30.6.2000	< 0.05		7.01	
30.6.2000	1.8.2000	< 0.05	0.133	17.6	163
1.8.2000	1.9.2000	0.0436	0.116	6.55	76.9

Table 6 continued.

Collection started	Collection ended	¹³⁷ Cs (Bq/m ²) in dry deposition	¹³⁷ Cs (Bq/m ²) in wet deposition	⁷ Be (Bq/m ²) in dry deposition	⁷ Be (Bq/m ²) in wet deposition
1.9.2000	2.10.2000	< 0.1	0.0609	2.99	29.2
2.10.2000	2.11.2000	0.0287	0.630	8.59	236
2.11.2000	1.12.2000	0.0144	0.179	10.2	259
1.12.2000	29.12.2000	< 0.07	0.161	7.40	67.3
29.12.2000	1.2.2001	0.0286	0.0147	10.3	95.8
31.1.2001	28.2.2001	< 0.03	0.09232	1.111	64.621
28.2.2001	2.4.2001	< 0.03	0.07334	2.464	34.786
2.4.2001	2.5.2001	0.0547	0.0770	118	56.2
2.5.2001	1.6.2001	0.0312	0.0770	8.07	39.6
1.6.2001	2.7.2001	0.0856	0.174	21.3	199
2.7.2001	1.8.2001	< 0.08	0.0846	17.5	236
2.1.2002	1.2.2002	< 0.09	0.0726	10.2	81.3
1.7.2002	2.8.2002	0.0361	0.0918	7.32	79.5
2.8.2002	2.9.2002	< 0.06	0.061	1.38	11.5
2.9.2002	30.9.2002	< 0.06	0.0360	0.875	14.4
30.9.2002	1.11.2002	< 0.05	0.0703	1.12	57.9
1.11.2002	2.12.2002	< 0.04	0.0737		51.2
2.12.2002	2.1.2003	0.0122	0.0368	6.48	23.8
2.1.2003	31.1.2003	< 0.04	0.0592		70.9
31.1.2003	28.2.2003	< 0.06	0.0444	3.52	5.85
28.2.2003	1.4.2003	< 0.06	0.0203	1.28	11.2
1.4.2003	2.5.2003	< 0.04	0.0373	1.75	80.6
2.5.2003	2.6.2003	< 0.05	0.0612	3.90	103
2.6.2003	1.7.2003	0.0669	0.122	6.02	187
1.7.2003	1.8.2003	0.0194	0.332	3.81	706
1.8.2003	1.9.2003	0.0411	0.0671	3.90	91.1
1.9.2003	1.10.2003	0.0323	0.0774	2.89	78.0
1.10.2003	31.10.2003	0.0236	0.0421	1.10	37.98
31.10.2003	1.12.2003	0.0184	0.0762	6.59	150
1.12.2003	31.12.2003	< 0.04	0.0880	6.05	102
31.12.2003	30.1.2004	< 0.04	0.0391	4.50	31.8
30.1.2004	2.3.2004	0.0162	0.0577	6.27	70.3
2.3.2004	31.3.2004	< 0.04	0.0439	3.46	75.9
31.3.2004	4.5.2004	0.0156	0.0387	1.91	28.7
4.5.2004	2.6.2004	< 0.06	0.0917	2.24	76.5
2.6.2004	21.6.2004	0.0277	0.107	1.70	95.0
1.10.2004	2.11.2004	< 0.07	0.0912	4.48	1396
2.11.2004	1.12.2004	< 0.07	0.05104	10.1	88.9
1.12.2004	3.1.2005	< 0.03	< 0.05	11.5	83.2
3.1.2005	1.2.2005	< 0.03	< 0.04	21.6	96.8
1.2.2005	1.3.2005	< 0.03	0.0277	7.77	27.6

Table 6 continued.

Collection started	Collection ended	¹³⁷ Cs (Bq/m ²) in dry deposition	¹³⁷ Cs (Bq/m ²) in wet deposition	⁷ Be (Bq/m ²) in dry deposition	⁷ Be (Bq/m ²) in wet deposition
1.3.2005	1.4.2005	< 0.03	0.0224	1.02	13.0
1.4.2005	3.5.2005	< 0.05	0.0349	4.82	39.3
3.5.2005	31.5.2005	< 0.03	0.212	3.42	142
31.5.2005	1.7.2005	0.433	0.103	2.78	175
1.7.2005	31.7.2005	0.0223	0.0924	2.72	128
31.7.2005	1.9.2005	< 0.06	0.0949	5.37	306
1.9.2005	30.9.2005	< 0.02	0.0244	1.85	57.9
30.9.2005	1.11.2005	< 0.06	0.0319	2.74	50.7
1.11.2005	2.12.2005	< 0.03	0.0528	4.22	146
2.12.2005	3.1.2006	0.0209	0.0489	12.9	48.7
3.1.2006	2.2.2006	< 0.03	0.0172	15.1	46.1
2.2.2006	1.3.2006	< 0.02	0.0238	2.607	6.49
1.3.2006	31.3.2006	< 0.03	0.0207	3.34	26.1
31.3.2006	2.5.2006	0.0195	0.0238	3.71	109
2.5.2006	1.6.2006	< 0.07	0.0211	3.19	10.1
1.6.2006	30.6.2006	0.0375	0.0497	4.46	103
30.6.2006	1.8.2006	< 0.05	0.0377	2.49	33.1
1.8.2006	31.8.2006	0.0388	0.0159	2.10	28.4
31.8.2006	2.10.2006	0.0134	< 0.04	5.17	143
2.10.2006	1.11.2006	< 0.04	0.0423	3.36	215
1.11.2006	1.12.2006	< 0.03	0.0491	13.5	88.9
1.12.2006	29.12.2006	< 0.03	0.0455	3.51	92.3

Table 7. Average tritium concentration in rain (Bq/l) at various sampling stations.

Year	Vantaa/ Nurmijärvi/ Helsinki	Rovaniemi	Pelkosenniemi	Kuhmo	Inari, Nellimö	Juuka	Laukaa	Jalasjärvi
1962			114		120		120	101
1963			342		291			
1964			261					
1965			116					
1968	27		28	32	30	34	30	28
1969	30		36	34	28	31	30	28
1970	25		25	26	25	28	23	24
1971	29		27	27	29	26	26	
1972	18		17	18	14	17	17	
1973	21	20	25	23	23	26	23	
1974	15	13	12	15	13	13	11	
1975	8.2	11	13	10	9.7	13	13	
1976	9.2	9.0	8.4	9.4	6.9	10	11	
1977	11	9.8	11	11	8.9	11	11	
1978	12	12		11	11			
1979	7.9	7.5		8.3	7.7			
1980	6.5	6.1		6.0	5.3			
1981	6.1	6.2		7.0	6.4			
1982	4.3	3.9		4.4	3.3			
1983	4.3	3.7		3.7	3.2			
1984	3.5	4.0		3.7	3.1			
1985	3.7	3.2		3.4	3.0			
1986	2.7	3.4		3.2	2.7			
1987	3.0	2.5		3.0	2.9			
1988	3.3	3.2		3.2	3.0			
1989	3.2	3.0		3.2	2.4			
1990	2.6	2.4		2.9	2.3			
1991	2.5	2.4		2.3	2.3			
1992	2.6	1.8		2.6	1.9			
1993	2.5	1.5		2.6	1.9			
1994	3.0	1.5		2.1	2.3			
1995	1.6	1.2						
1996	3.4	1.5						
1997	5.7	1.6						
1998	2.2	1.4						
1999	2.2	1.6						
2000	5.6	1.8						
2001	5.6	1.3						
2002	3.8	1.4						
2003	2.2	2.0						
2004	1.7	1.5						
2005	1.5	1.1						
2006	1.6	1.6						

Table 8. Annual tritium deposition (kBq/m²) at various sampling stations.

Year	Vantaa/ Nurmijärvi/ Helsinki	Rovaniemi	Pelkosenniemi	Kuhmo	Inari	Juuka
1962			59*		60*	
1963			182		196*	
1964			117			
1965			71**			
1968	18			19		
1969	15		13*	18	11*	13*
1970	17		13	15	10	18
1971	11		11	15	15	14*
1972	11		8.4	11	5.7*	9.5
1973	11	9.1	12	12	9.4	16
1974	9.1	9.5	9.2	12	6.9	11*
1975	3.9	6.7	7.4	6.3	5.9	7.4
1976	3.9	3.8	3.5	4.5*	2.6	5.3
1977		5.5	6.5	6.6	4.6	6.0
1978	5.9	4.8		4.4	4.4	
1979	5.2	4.1		5.6	3.1	
1980	3.9	2.6		2.9	1.7	
1981	5.9	4.6		5.3	4.0	
1982	2.7	2.1		2.5	2.1	
1983	2.5	2.6		2.9	1.7	
1984	3.0	2.2		2.3	1.8	
1985	2.8	1.9		2.0	1.6	
1986	1.9	1.7		2.2	1.4	
1987	1.8	1.3		2.0	1.7	
1988	2.3	1.8		2.3	1.8	
1989	2.1	2		1.8	1.6	
1990	1.8	1.3		1.6	0.9	
1991	1.7	1.5				
1992	1.8**	1.5**				
1993	1.4**	0.79**				
1994	1.8**	0.81**				
1995	0.83**	0.63**				
1996	2.2**	0.78**				
1997	2.0	0.78**				
1998	1.6	1.17**				
1999	1.2	1.02**				
2000	2.6*	1.43**				
2001	3.6	0.97**				
2002	1.6	0.84**				
2003	1.1	1.22**				
2004	0.72*	1.18**				
2005	1.1	0.88**				
2006	0.74	0.64**				

* Deposition data missing for part of the year.

** Tritium has been analyzed only for every second month. To estimate the annual deposition the measured tritium concentration values from the preceding month have been used for the missing months.

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