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Airborne and deposited radioactivity from the Chernobyl accident — a review of investigations in Finland

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The Chernobyl nuclear accident happened in the former Soviet Union on 26 April 1986. The accident destroyed one of the RBMK-1000 type reactors and released significant radioactive contamination into the environment. At first the emissions were transported north-westwards over Poland, the Baltic States, Finland, Sweden and Norway. During 27 April 1986 emissions were spreading to eastern-central Europe, southern Germany, Italy and Yugoslavia. Radioactivity mapping over Finland between 29 April and 16 May 1986 showed that the ground deposition in Finland covered southern and central parts of the country but had an irregular distribution. The highest (over 100 μR h^{-1} [1 μSv h^{-1}]) contamination disclosed by the mapping was around the city of Uusikaupunki in western Finland and the city of Kotka in southeastern Finland. The Uusikaupunki region was an area of heavy fallout associated with the air mass that was located in the Chernobyl area at the time of the accident. The fallout pattern of reftractory nuclides, e.g. plutonium isotopes, had their spatial maximum in this region. Medical consequences in Finland were luckily mild, the most important symptoms being psychological ones. No increase in thyroid cancer or birth defect occurrence has been observed. The Chernobyl accident boosted the radioecological research which had already been calming down after the last atmospheric nuclear test in China in October 1980. Important new results concerning e.g. hot particles have been achieved. The most important effects of the accident in Finland were, however, the increase of public awareness of environmental issues in general and especially of nuclear energy. In Finland, the nuclear energy programme was halted until 2002 when the Parliament of Finland granted a licence to build the fifth nuclear reactor in Finland.

Introduction

The Chernobyl nuclear accident happened in the former Soviet Union 26 April 1986. The Chernobyl nuclear power plant is situated in Ukraine 130 km north of the capital Kiev. The reactors at

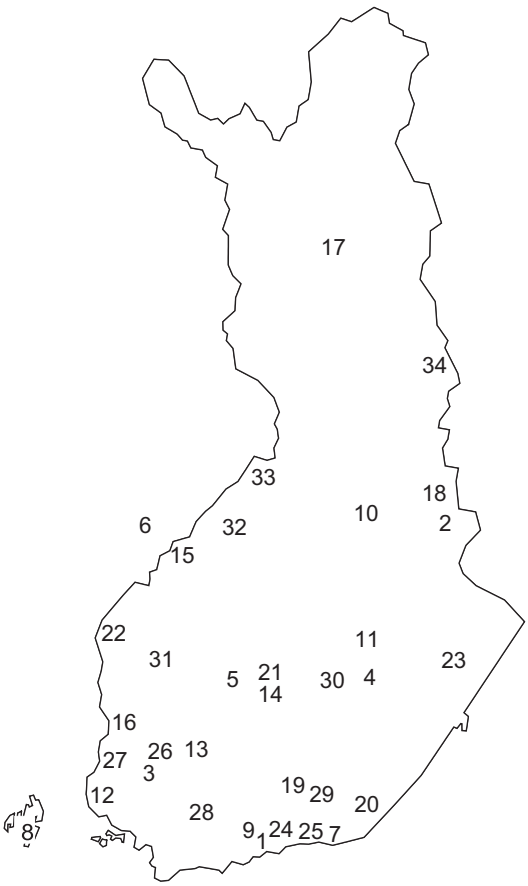

Fig. 1. Locations mentioned in the text. 1 = Helsinki, 2 = Kuhmo, 3 = Huittinen, 4 = Varkaus, 5 = Multia, 6 = Gulf of Bothnia, 7 = Kotka, 8 = Mariehamn, 9 = Nurmijärvi, 10 = Kajaani, 11 = Kuopio, 12 = Uusikaupunki, 13 = Tampere, 14 = Jyväskylä, 15 = Kokkola, 16 = Pori, 17 = Sodankylä, 18 = Halla, 19 = Lake Päijänne, 20 = Lappeenranta, 21 = Tikkakoski, 22 = Vaasa, 23 = Joensuu, 24 = Kerava, 25 = Loviisa, 26 = Vammala, 27 = Rauma, 28 = Forssa, 29 = Heinola, 30 = Pieksämäki, 31 = Seinäjoki, 32 = Ylivieska, 33 = Raahe, and 34 = Kuusamo.

Chernobyl were of the type RBMK-1000 which is a graphite-moderated design using light water for cooling. The nuclear fuel of the reactor consists of 180 tonnes of relatively lightly enriched uranium dioxide. The thermal output of the reactor model is 3200 MW with an electrical output of 1000 MW. The accident destroyed one of the reactors and released a significant amount of radioactivity into the environment (International Atomic Energy Agency 1986).

The fourth reactor was scheduled for a regular maintenance shutdown on 25 April 1986. During the shutdown, a test programme was planned to be conducted to assess how long the kinetic energy of the steam turbines could deliver power for a safe operation of the power plant in case of an emergency shutdown without external power. To perform the test, several reactor safety systems had to be switched off. The staff of the plant started the experiment on 26 April 1986 at 01:22:30 local time (21:22:30 UTC on 25 April 1986), ignoring the process control computer's recommendation for an immediate reactor shutdown. A minute later a power surge in the reactor caused two subsequent explosions. The graphite moderator caught fire and was burning for at least a week, thus prolonging the emissions of radioactivity into the atmosphere. The fire was extinguished and the emissions halted by dropping 4000 tonnes of sand, clay, boron and lead over the reactor ruins from helicopters (International Atomic Energy Agency 1986).

According to the Soviet estimates, all the radioactive noble gases of the core inventory were liberated during the accident. 10%–20% of the volatile nuclides, e.g. ^{131}I and ^{137}Cs, were distributed into the environment. A 2%–6% fraction of the refractory nuclides, such as ^{95}Zr, fuel uranium isotopes and transuranium elements, was released as well (International Atomic Energy Agency 1986).

This article summarizes the meteorology associated with the atmospheric dispersion of radioactivity from Chernobyl to Finland, and observations of external radiation and airborne and deposited radioactivity in Finland. An emphasis is put on the investigations during the acute phase of the fallout situation and on studies published so far only in institutional report series and conference proceedings. Locations mentioned in the text are indicated in Fig. 1.

Meteorological situation and dispersion of the emissions

During the night of Saturday, 26 April 1986, a strong high pressure was centred over the northwestern Russia and a weaker high pressure over the Adrian Sea (Fig. 2). A strong low pressure area was situated around Iceland and weaker lows in southern France and on the northern coast

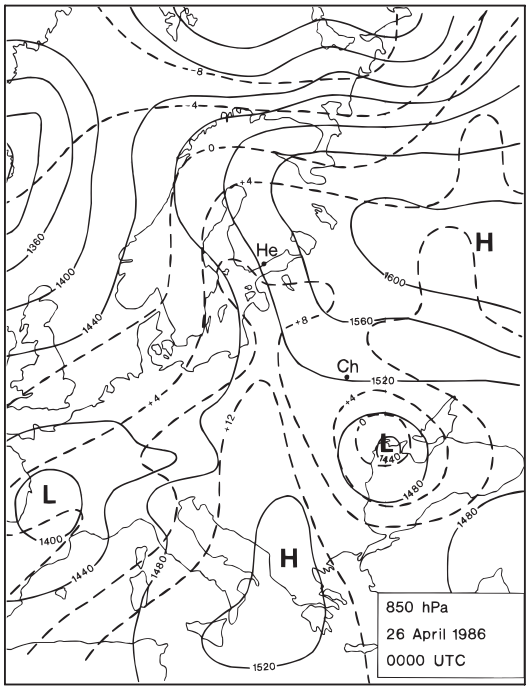

Fig. 2. Weather situation over Europe on Saturday, 26 April 1986 at 00:00 UTC. Ch = Chernobyl, He = Helsinki. Solid lines: Isohypses (gpm) of the 850 hPa pressure level. Dotted lines: Isotherms (°C) of the 850 hPa pressure level (Puhakka *et al.* 1988, courtesy of the Department of Physics, University of Helsinki).

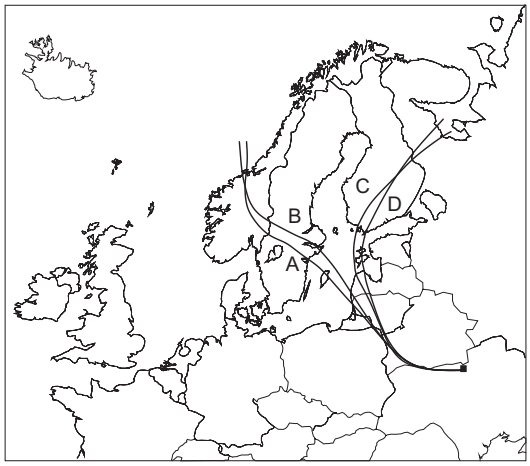

Fig. 3. Air mass trajectories from Chernobyl on 25 April 1986 at 21:00 UTC calculated with the TRADOS computer code (Redrawn from Valkama *et al.* 1995). Effective release heights: A = 750 m, B = 1000 m, C = 1500 m, and D = 2500 m.

of the Black Sea. The isohypse of the 850 hPa (mb) pressure level extended from Chernobyl all the way to the Helsinki region (*see* Fig. 2).

In the area around Chernobyl the winds close to the ground were very weak, the sky was clear and there were occurrences of mist. A temperature inversion reached from the surface up to about 400 m with the ambient temperature increasing by 2–4 °C within the inversion layer. Above the inversion layer the airstream was much stronger with the wind speeds of 8–14 m s^{-1}. The airflow above the inversion was towards northwest, anti-cyclonally around the high pressure area in Russia. This air stream brought, taking into consideration the season, exceptionally warm weather to Finland.

The energy released during the accident caused the radioactive plume to break through the inversion layer to the free troposphere where the high wind speeds quickly spread the radioactive contamination. At first the emissions were transported north-westwards over Poland, the Baltic States, Finland and Sweden. During 27 April 1986 emissions were spreading to eastern central Europe, southern Germany, Italy and Yugoslavia. Within the next week the plume was transported southwards from Chernobyl to Rumania, Bulgaria, the Balkans, the Black Sea and Turkey. After that the emissions arrived again over central Europe, Scandinavia and Finland (Persson *et al*. 1987). Finally the plume was distributed practically all over the northern hemisphere. Most of the Chernobyl-originated activity remained in the troposphere but it could be detected also in the stratosphere (Jaworowski and Kownacka 1988).

The air parcel trajectories originating from Chernobyl at the time of the accident show that the radioactive plume moved first northwestwards (Fig. 3; Valkama *et al*. 1995). Over Lithuania the plume separated to two main paths. At lower altitudes (750–1000 m) the plume continued towards Sweden and Norway (Liljenzin *et al*. 1988). At higher altitudes (1500–2500 m) the plume turned towards the north. The plume arrived in Finland from the south-west. According to these calculations the arrival time in south-western Finland was 27 April 1986 at 12:00 UTC for a release height of 2000 m. Then the plume went across the country north-

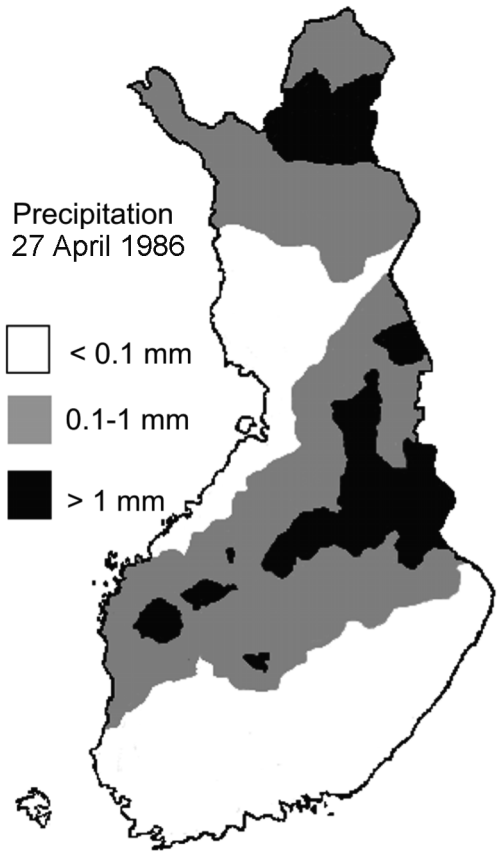

Fig. 4. Precipitation (mm) on 27 April 1986 in Finland (Data: Finnish Meteorological Institute).

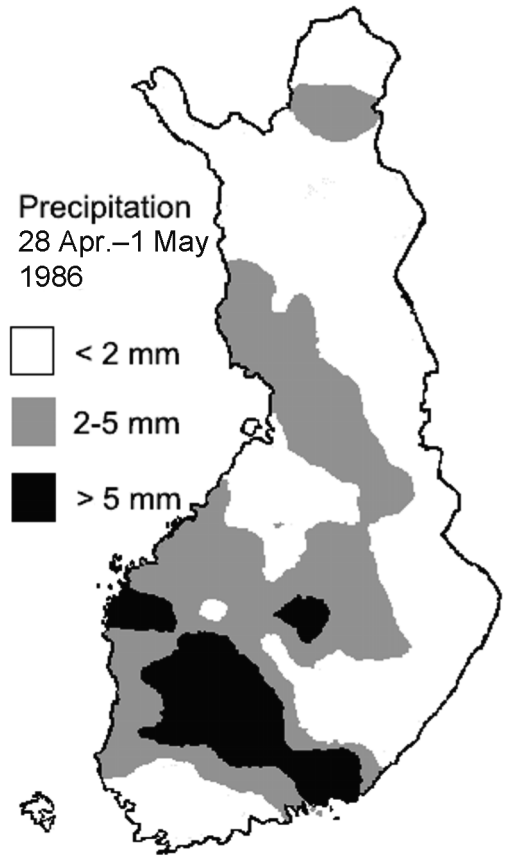

Fig. 5. Precipitation (mm) between 28 April and 1 May 1986 in Finland (Data: Finnish Meteorological Institute).

eastwards to the Kuhmo region and then back to Soviet Union and towards the southern shore of the White Sea. A frontal zone north of this route hindered the plume to reach northern Finland which could have resulted in catastrophic socio-economical effects on the reindeer husbandry in northern Finland.

Precipitation scavenges efficiently airborne contaminants to the ground. As a rule of thumb one milliliter of precipitation contains as much contaminants, whether radioactive or chemical, as one cubic metre of air (Paatero *et al*. 1994, Paatero 2000). Thus the amount of precipitation governed in many cases how the Chernobyl plume was deposited in Finland. During 27 April 1986, when the passage of the plume associated with the initial explosion occurred, there was no or very light rain in southern Finland. Slightly larger amount of precipitation (< 3 mm) occurred along the previously mentioned frontal zone from south-western Finland north-eastwards (Fig. 4). During 28 April 1986, the weather was also quite dry in southern Finland except that some rain (< 5 mm) was observed in the regions of Huittinen, Varkaus, and Multia, and along the coast of the Gulf of Bothnia. During the next three days there was heavy precipitation (up to 10 mm per day) along a zone from the coast of the Gulf of Bothnia south-eastwards towards the Kotka region (Fig. 5). A dryer period started on 2 May 1986 (Finnish Centre for Radiation and Nuclear Safety 1986a, Nordlund 1986, Savolainen *et al*. 1986, Arvela *et al*. 1987).

First observations in Finland

In Finland, many of the radioactivity and weather observations as well as dispersion estimates were not available during the acute phase

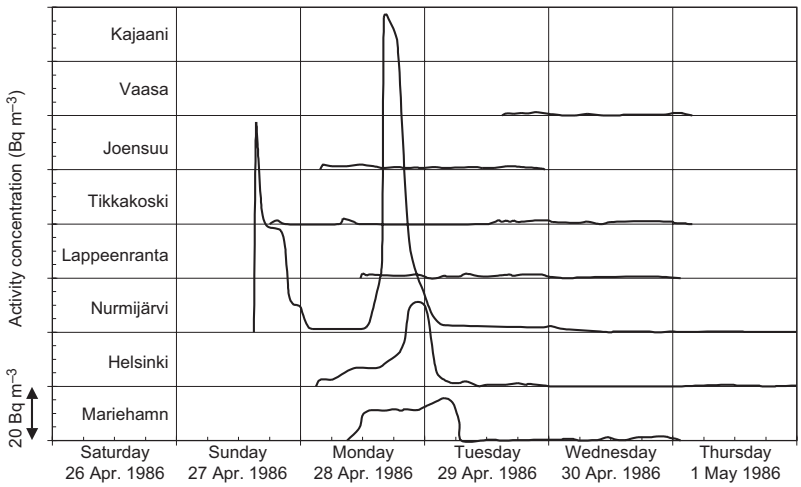

Fig. 6. Artificial aerosol beta activity in ground-level air (Bq m^{-3}) in Finland during 26 April–1 May 1986 (Redrawn from Mattsson and Hatakka 1986).

of the fallout situation because of a government employees' strike. In many cases weather and radioactivity observations were made but they were stored only in stations' logbooks and not transmitted to the Finnish Meteorological Institute's (FMI) or internationally. Later many observations were restored from logbooks, strip-chart recordings, etc. In certain cases even radiation alarms were ignored.

Retroactively it has been noticed that the Chernobyl plume did not reach the ground-level air in the archipelago of Ahvenanmaa south-west of Finnish mainland during 27 April 1986 except that two hot particles, i.e. highly radioactive agglomerates discussed in more detail below, were observed with the aerosol beta activity monitors of the FMI at the Mariehamn airport (Fig. 6; Mattsson and Hatakka 1986). The particles were large enough to settle by gravitation through a clean layer of air beneath the plume. On the afternoon of 27 April 1986, an aerosol beta activity monitor reacted to the artificial radioactivity at Nurmijärvi but not in Helsinki despite the short (about 40 km) distance between the monitoring stations. This was probably due to the convection over inland Nurmijärvi while the lower troposphere was stratified in Helsinki due to the cold sea surface. Unfortunately the alarm at the Nurmijärvi monitoring station did not cause any action due to the civil servants' strike. Most of the FMI's aerosol beta activity monitors in southern and central Finland detected artificial radioactivity on 28 April 1986, especially in the afternoon owing to the increased vertical mixing of the troposphere.

The external dose rate was not significantly affected by the radioactivity in the ground-level air. The first alarm leading to a nation-wide alert occurred at Kajaani, north-eastern Finland, in the evening of 27 April 1986. A monitoring station of the Ministry of the Interior measured an increased exposure rate value of 0.1 mR h^{-1} ($\approx$ 1 μSv h^{-1}) in connection with a rain shower (Finnish Centre for Radiation and Nuclear Safety 1986a). However, at the time, the ground-level air there, as well as in most of Finland, was still quite free from artificial activity excluding above mentioned Nurmijärvi (Mattsson and Hatakka 1986). On 29 April 1986, the rain area moved from the west coast of Finland in an easterly direction. The rain scavenged the activity to the ground causing notable increases in the external dose rate at several monitoring stations (Fig. 7; Koivukoski 1986).

The Finnish Centre for Radiation and Nuclear Safety [currently STUK — Radiation and Nuclear Safety Authority], found fresh fission products from aerosol, snow and lichen samples collected from 28 April 1986 onwards (Finnish Centre for Radiation and Nuclear Safety 1986b). After the first few days no significant amounts of radioactivity were deposited in Finland, although somewhat elevated values were observed on 11 and 13 May 1986 in southern Finland. In the rapid surveys carried out by researchers from the Universities of Helsinki and Kuopio, the

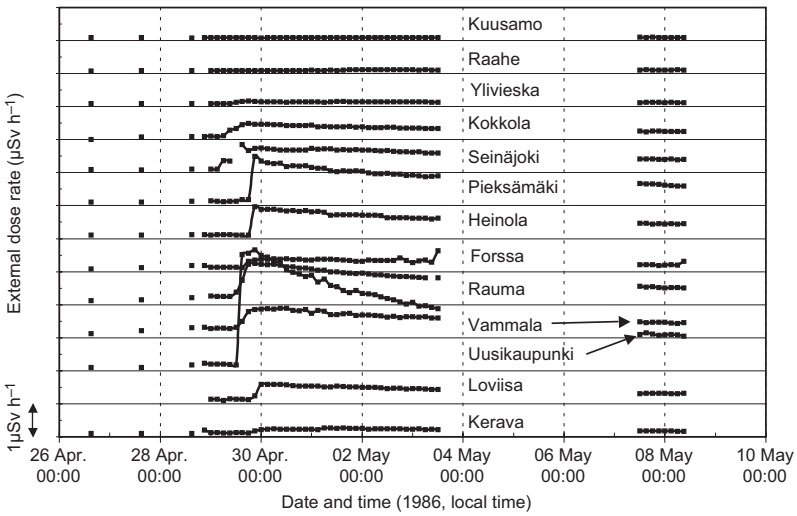

Fig. 7. External dose rate (μSv h^{-1}) in monitoring stations around Finland during 26 April–8 May 1986 (Koivukoski 1986).

National Public Health Institute (KTL), the FMI and the State Technical Research Centre (VTT), radioactive substances were detected in samples taken from living trees, needle fall, traffic signs, rain water, ventilation filters and numerous other places (Suutarinen 1986, Anttila *et al*. 1987, Raunemaa *et al*. 1987, Sinkko *et al*. 1987, Jantunen *et al*. 1991).

External radiation and air electricity

In Finland, the Ministry of Interior is responsible for the civil defence. As a response to the imminent threat of a global nuclear war the Finnish Ministry of Interior established a nation-wide monitoring network for external radiation in the early 1960s. Most of the stations with a 24/7 working scheme were set up in places such as airports, fire stations, and national road authority's road maintenance bases. Most of the stations were equipped only with hand-held geiger counters, only some of them were furnished also with pulse registration units. The monitors were originally meant for civil defence purposes and thus their sensitivities and calibrations were not ideal for the relatively small dose rates measured after the Chernobyl accident. But the large number of the stations, several hundreds, provided important information about the behaviour of the external radiation in Finland. Some of the data has been previously reported, e.g. in Puhakka *et al*. (1990). However, this summary is based on the original radiation situation reports that the regional rescue services sent to the Ministry of Interior in April–May 1986 (Koivukoski 1986). The original units of exposure rate (μR h^{-1}) have been converted here to dose rate units (μSv h^{-1}) by dividing them by 100.

The recording of the external radiation in the city of Uusikaupunki is depicted in Fig. 8. On 2 May 1986, the rescue chief of Uusikaupunki reported that the rain on 29 April 1986 started at 12:30 (Koivukoski 1986). Within three hours there was a 20-fold increase in the external dose rate. After its maximum, 3.7 μSv h^{-1} at 20:00 of 29 April 1986, the dose rate started to decrease with a half-time of 4.8 days. This suggests that much of the external radiation was due to ^{131}I (half-life 8.0 days) and ^{132}Te/^{132}I. The half-lives of ^{132}Te and ^{132}I are 3.2 days and 2.3 hours, respectively.

The highest dose rates were observed in the south-western part of Finland (Fig. 9). The pattern has several similar features to the precipitation between 28 April and 1 May 1986 in the area between Tampere and Kotka, Jyväskylä region, and Kokkola region (*see* Fig. 5). This demonstrates the importance of precipitation scavenging airborne radioactivity down to the surface.

First surveys of radiation in the upper atmosphere were performed by aircrafts of the Finnish Air Force responding to the news about a suspected radioactive plume (Sinkko *et al*. 1987).

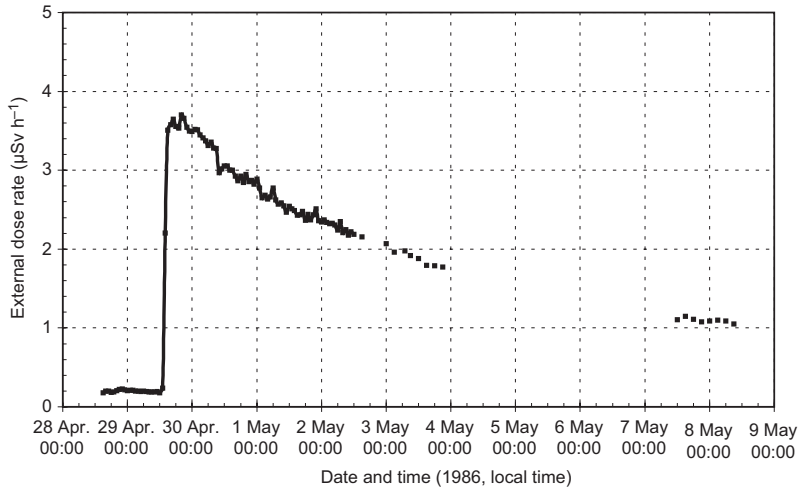

Fig. 8. External dose rate (μSv h^{-1}) in Uusikaupunki during 28 April–8 May 1986 (Koivukoski 1986).

Vertical profiles of gamma radiation values at airport regions in Helsinki, Tampere and Pori before noon of 29 April 1986 showed that the external radiation was at its maximum between 1000 and 2000 m above the ground (Sinkko *et al*. 1987). The gamma dose rate levels were between 0.1 and 0.8 μSv h^{-1}.

A need for a fast tool to warn about an approaching radioactive plume became apparent when a special research going on at the time of the accident in the FMI became public. As a part of its geophysical research programme the FMI had been monitoring electrical parameters of the atmosphere for several years. Radioactive substances in the air can affect the electrical conductivity of the air. A tenfold increase in the conductivity was observed in Helsinki-Vantaa airport in April–May 1986. Between 30 April and 1 May 1986, the conductivity meter went over scale but from the recordings of potential gradient it was estimated that the conductivity had been 150–200 fS m^{-1} (Tuomi 1988, 1989). The normal level was reached again by the end of summer 1986. However, later it became apparent that if the conductivity was to be used for radioactivity monitoring it would require a simultaneous aerosol particle size distribution measurement. The conductivity depends not only on the amount of ions and charged particles in the air but also on the size of the charged particles. The larger the particles are the smaller is their mobility and consequently their contribution to the conductivity. Similar conductivity

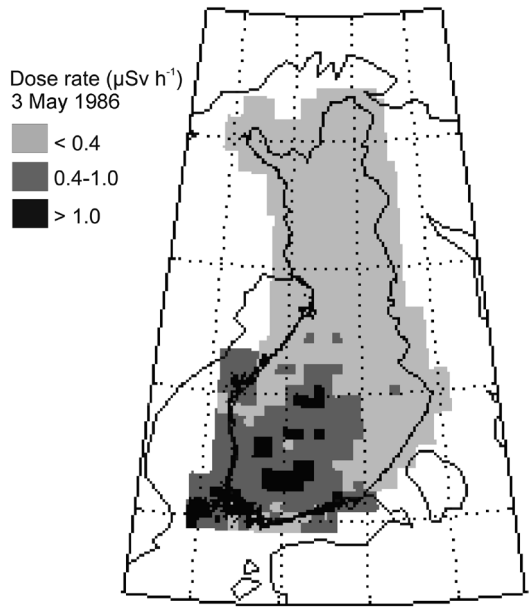

Fig. 9. External dose rate (μSv h^{-1}) in Finland on 3 May 1986 during 7:00–15:00 local time (Koivukoski 1986).

observations were made in Sweden. In Uppsala, north-west of Stockholm, the electrical conductivity of the air increased from 20 fS m^{-1} to 220 fS m^{-1} after a rainfall on 29 April 1986 (Israelsson and Knudsen 1986).

Radionuclides in the air

The FMI has collected daily aerosol samples

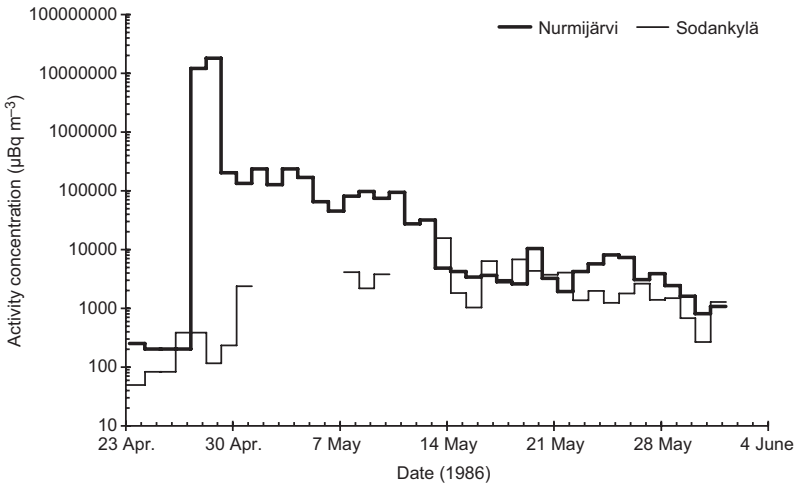

Fig. 10. Total beta activity concentration in ground-level air (μBq m^{-3}) at Nurmijärvi and Sodankylä during 23 April–31 May 1986 (Paatero *et al.* 1994).

with a high-volume filter sampler at Nurmijärvi since 1962. The filter samples have been measured for total beta activity. The measurements were carried out five days after the end of sampling when the short-lived daughter nuclides of radon-222 had decayed to lead-210 (^{210}Pb) and the radon-220 progeny had decayed to stable lead (Mattsson *et al*. 1996). The measured activity consists of ^{210}Pb and possible artificial beta-emitting fission products. The monthly mean total beta activity concentration in April 1986 was the highest ever recorded, 1 Bq m^{-3} (Paatero *et al*. 1994). However, the time-integrated activity concentration was significantly higher in the early 1960s due to the Soviet and U.S. atmospheric nuclear tests. The total beta activity concentration decreased five orders of magnitude at Nurmijärvi from 27–28 April to 31 May 1986 (Fig. 10). Simultaneous data from Sodankylä showed that the daily activity concentrations were 1–4 orders of magnitude lower in northern Finland as compared with those at Nurmijärvi during the first two weeks after the plume arrival.

Between 28 April and 16 May 1986, the concentration of ^{137}Cs in ground-level air at Nurmijärvi decreased by four orders of magnitude, starting from 10^4 mBq m^{-3} (Finnish Centre for Radiation and Nuclear Safety 1986b). On 28 April 1986, the ground-level air at Nurmijärvi contained 32 μBq m^{-3} of ^{239,240}Pu and 506 μBq m^{-3} of ^{242}Cm (Jaakkola *et al*. 1986). For comparison, the annual mean ^{239,240}Pu concentration in the air in Helsinki varied between 7 and 26 μBq m^{-3} in 1962–1964 due to the atmospheric nuclear tests (Jaakkola *et al*. 1979). Carbon-14 and tritium could be observed in the air in Helsinki only during the first three days after the arrival of the Chernobyl plume (Salonen 1987). The maximum carbon-14 activity concentration was 30 times higher and tritium activity concentration 100 times higher than the background level.

From an analysis of a filter sample taken at 1500 m height in Finland at noon of 29 April 1986 the most dominant radionuclides were ^{131}I, ^{132}Te and ^{137}Cs, and also ^{103}Ru activity was observed. In the ground level air in Helsinki the concentrations were at that time about 1/200 of the plume activity (Sinkko *et al*. 1987). Just by coincidence, a geological survey aircraft equiped with a NaI(Tl) spectrometer flew through the Chernobyl plume on 29 April 1986. From the analysed gamma spectra ^{131}I, ^{132}I, ^{134}Cs, ^{137}Cs and ^{140}La could be found (Grasty *et al*. 1997).

The characteristics of radioactive aerosols in ambient air in Finland were measured by Kauppinen *et al*. (1986). Iodine, whose isotopes are short-lived, was transported mainly in the gaseous phase and was partly adsorbed on local aerosol during travel. Geometric mean diameter of the aerosol particles carrying ^{131}I as measured 7–9 May was in the range 0.33–0.57 μm. Iodine was bound to smaller particles than the nuclides ^{103}Ru, ^{132}Te and ^{137}Cs. These were bound to particles having a geometric mean diameter between 0.63 and 0.93 μm. The values deter-

mined with the aid of an 11-stage Berner low-pressure impactor were similar to those observed by Reineking *et al*. (1987) in Germany.

Deposition

Regional variation of deposition

In striking contrast to the 1960s nuclear weapons test fallout, the Chernobyl fallout was very unevenly distributed in Sweden and Finland. In Finland, the regional deposition pattern of different nuclides has been studied by carborne and airborne *in-situ* gamma spectrometric measurements and by collecting lichen, peat, soil and precipitation samples followed by laboratory analysis (Saxén *et al*. 1987a, Arvela *et al*. 1990, Jantunen *et al*. 1991, Reponen 1992, Reponen *et al*. 1993, Paatero *et al*. 2002, Kettunen 2006, Paatero *et al*. 2007, Ylipieti *et al*. 2008). A fraction of the radionuclides were associated with hot particles. In addition, the nuclide ratios showed large and apparently random variations even between close locations. For example, ^{95}Zr was mainly deposited on a relatively narrow band from south-western Finland towards the north-east. ^{137}Cs, on the other hand, was deposited to larger areas in south-western, central and south-eastern Finland. The reason for these variations was that the composition of the emissions varied as a function of time. The first release from the reactor explosion contained debris of the reactor fuel including refractory nuclides, for example, ^{95}Zr, ^{90}Sr, and plutonium isotopes, while later during the subsequent fire the volatility of the nuclides affected the composition of the emissions (Fig. 11; Saxén *et al*. 1987a). In addition there might have been short-term criticality events that might have produced new fission products to the remains of the reactor core. The Finnish Defence Forces later surveyed the regional distribution of ^{137}Cs in southern and central Finland using airborne gamma spectrometry (Kettunen 2006).

Two consistencies with the activity ratios, however, soon emerged: the ^{95}Zr:^{141}Ce activity ratio was constant, 1.04, and the ^{134}Cs:^{137}Cs activity ratio was also constant, 0.549, corresponding to a fuel burn-up of 9 GWd (tU)$^{-1}$ (Anttila 1986). Kirchner and Noack (1988) reported a ^{134}Cs:^{137}Cs

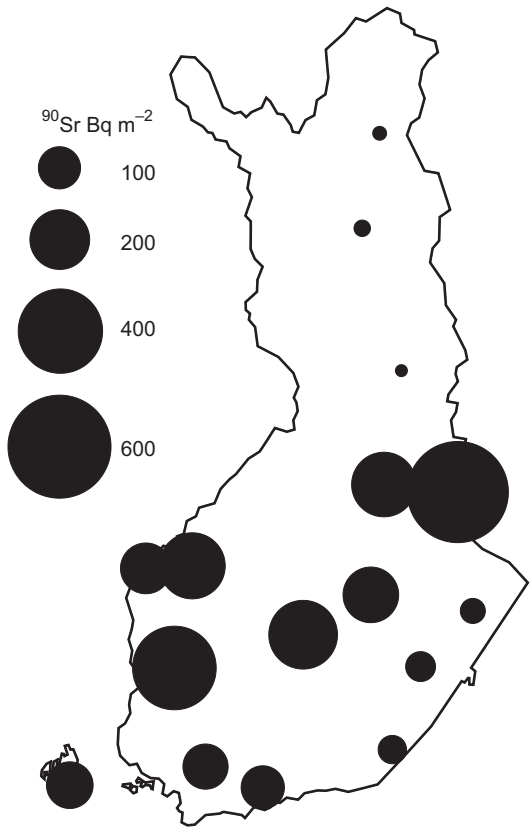

Fig. 11. Deposition of ^{90}Sr (Bq m^{-2}) in Finland in April–September 1986 (Saxén *et al.* 1987).

ratio of 0.528, and a corresponding fuel burn-up of 12.85 GWd (tU)$^{-1}$. These logical and consistent results indicated that there were logical explanations to be searched for also for the other, apparently illogical, results dealing with e.g. the high temperature behaviour of ruthenium isotopes (Jantunen *et al*. 1991).

Based mainly on lichen (*Hypogymnia physodes*, *Cladonia* sp.) and pine-needle (*Pinus sylvestris*) sample analyses it was found out that the deposition could vary significantly even within a few kilometres. These unsystematic high-deposition spots of about 5 km radius were identified in three to four locations, the highest ^{95}Nb activity being in some areas about 40 kBq kg^{-1} of sample mass. In these hot spots, the activities of the refractory nuclides ^{95}Zr, ^{95}Nb and ^{144}Ce had a relatively higher contribution to total activity as compared with that in other areas (Luokkanen *et al*. 1988a).

The caesium isotopes 134 and 137 appeared in particles with the size range below 1 micrometer and deposited mainly by rain scavenging which was also identified in aerial fallout mappings (Arvela *et al*. 1987, Luokkanen *et al*. 1988b, Lang *et al*. 1988, Arvela *et al*. 1989, Jantunen *et al*. 1991). The highest aerial deposition values obtained in the analyses were 70 kBq m^{-2} for ^{137}Cs and 420 kBq m^{-2} for ^{131}I (Jantunen *et al*. 1991) and about 30 kBq m^{-2} for ^{95}Zr (Arvela *et al*. 1990). The Finnish Centre for Radiation and Nuclear Safety divided the country into five deposition categories according to ^{137}Cs fallout, the highest being 10–67 kBq m^{-2} (Arvela *et al*. 1987, Rantavaara 1988). In the cluster analysis of 257 samples (Lang *et al*. 1988) the non-volatile elements Zr, Nb and Ce coupled properly together and ruthenium was observed to follow the more volatile cesium.

Radioecological studies

The Department of Radiochemistry of the University of Helsinki has a long tradition in studying the deposition of fission products and transuranium elements and their transfer along especially terrestrial food chains (Jaakkola *et al*. 1981). Also after the Chernobyl accident these research themes were thoroughly investigated (Paatero *et al*. 1998, Paatero and Jaakkola 1998, Paatero 2000, Paatero *et al*. 2002, Salminen *et al*. 2005, Lehto *et al*. 2008). Suutarinen (1986) reported already on 15 May 1986 contents of transuranium nuclides in precipitation samples collected in April 1986. The clear difference compared with the global fallout of the weapons testing was the high amount of ^{242}Cm present in the samples. Only minute amounts of ^{242}Cm were produced in the weapons testing (Holm and Persson 1978). The depositions of $^{239,240}Pu$, ^{241}Am and ^{244}Cm in most of the reindeer husbandry area were < 0.25 Bq m^{-2}, < 0.036 Bq m^{-2}, and < 0.023 Bq m^{-2}, respectively. For comparison, the $^{239,240}Pu$ deposition from the weapons testing has been estimated to be some 50 Bq m^{-2} between the 60° and 70° northern latitudes (Hardy *et al*. 1973). Only in the southernmost reindeer herding district of Halla the deposition values were about three times higher. Pilviö (1998) studied the transfer of deposited transuranium elements and Saxén *et al*. (1987b) the transfer of ^{137}Cs, ^{134}Cs, ^{131}I, ^{89}Sr, ^{90}Sr and ^{3}H in lake Päijänne in central Finland because this lake is the drinking water source for most of the Helsinki metropolitan area.

Effective decay rate studies

Radioactive fallout may also cause external dose on people. The level of this radiation is changing with time due to physical decay, but also due to removal from the surfaces that the people are exposed to by rain washing, migration into the soil, leaching from organic material, and removal or covering of the surface soil in the various urban development processes. The effective decay rate was investigated by repeated measurements from the same locations on hard (asphalt), porous (sand) and natural (grass, forest) surfaces for about 900 days after 1 May 1986 (Reponen and Jantunen 1991, Reponen 1992). The radiation level in 1986 was observed to decrease very fast in summer but considerably slower in fall. As expected, the decay was fastest from the hard artificial urban surfaces, such as stone, concrete and asphalt, as well as worked on surfaces, gravel and sand, and slowest — essentially identical to physical decay — from grass and forest surfaces in the parks. The effective half-life for the 1986 decay of ^{137}Cs (physical half-life 30 years) was 80–200 days for hard and 150–400 d for sand surfaces. For the 1987–1988 decay period, the respective values were slowed down to 330–720 d and 1200–4200 d. These numbers mean that removal of the fallout radionuclides from many typical urban surfaces — with the exception of parks — is relatively fast, and that the external radiation in the cities is therefore reduced more rapidly than the physical decay of the nuclides alone would indicate. This finding is of importance for estimating the external radiation from those fallout radionuclides with a half life of years or more.

The highest specific concentrations in the soil were usually below rain channels of dwellings. For ^{131}I the 42 kBq kg^{-1} concentration observed on 18 May 1986 decayed to 6 kBq kg^{-1} in a month and a respective decrease was obtained

also for ^{103}Ru activity (Raunemaa 1986). Precipitation scavenging was studied by Jylhä (1991) using Chernobyl fallout and weather radar data to obtain empirical value for the scavenging coefficient from the radioactive plume approaching Finland at the height of 1500 m. Coefficients could be determined for ten radionuclides including iodine by taking into consideration the in-cloud and below-cloud wet removal effect caused mostly by liquid-phase micrometeors. The average scavenging coefficient, incorporating both the rainout and washout effects, was $\Lambda = 10^{-4}R^{0.64}$ (s^{-1}), where R is the rain intensity. Radar weather data give a three dimensional picture of precipitation in real time and can thus give a qualitative fast fallout estimate.

Hot particles

The existence of radioactive hot particles in the Chernobyl plume was a specific feature during the early stages of emissions. These particles were highly radioactive agglomerates, being either fragments of the nuclear fuel or particles formed by interactions between condensed radionuclides, nuclear fuel and structural materials of the reactor (Devell *et al*. 1986, Raunemaa *et al*. 1987, Lancsarics *et al*. 1988).

The appearance of hot particles was not a unique event. They were often observed with autoradiography in the 1960s and 1970s as a result of the atmospheric nuclear tests (Sisefsky 1964, Sisefsky and Persson 1970, Moore *et al*. 1973). The aerodynamic diameter of the Chernobyl-originated hot particles varied from one to several hundred micrometres; gravitational settling thus had to be taken into account when assessing their transport behaviour in the atmosphere (Pöllänen *et al*. 1997).

Once it was observed that the Chernobyl fallout contained hot particles, several studies to detect and characterise these particles were started immediately in the Universities of Helsinki and Kuopio and in the laboratories of the FMI and STUK (Mattsson and Hatakka 1987, Raunemaa *et al*. 1987, Saari 1987, Jantunen *et al*. 1988, Saari *et al*. 1989, Ikäheimonen 2003). Ventilation filters, needle and lichen materials, solid surfaces, etc. were intensively searched by research groups to detect hot particles. The size of transported high-radioactive hot particles was deduced to be below 20 μm with residence time estimations (Nordlund 1986). The equivalent diameter in the range of 2.7–5.6 μm with the mean aerodynamic diameter of 10 μm was later analyzed from the particles isolated and pictured in the University of Helsinki by using autoradiography and scanning electron microscopy (Luokkanen *et al*. 1988b, Saari *et al*. 1989). Rytömaa *et al*. (1986) found airborne hot particles with a size ranging from 3 to 7 μm. One of the first summary reports, with a strong Finnish contribution, concerning the Chernobyl hot particles was presented in 1987 at the Theuern meeting (von Philipsborn and Steinhäusler 1988).

Dozens of hot particles having an activity of over 50 Bq were detected from daily aerosol samples collected at Nurmijärvi between 27 and 30 April 1986 (Fig. 12). The air volume of these samples was about 3500 m^3. The number of particles with the activity ranging from 0.05 to 50 Bq in these filters varied between several hundreds and over ten thousand during these first days. Starting from 1 May 1986 only a few occasional hot particles were found as the scavenging rain of 29 April 1986 had cleared the air and the plume transport direction had changed (Mattsson and Hatakka 1986). If a person spent eight hours per day outdoors every day between 27 April and 31 May 1986, he/she would have inhaled about 40 of these particles assuming a breathing air consumption of 10 m^3 per 8 h. The number of particles actually reaching the lungs would obviously be smaller.

One of the important outcomes of the appearance of radioactive hot particles was the intensification of the studies on their health effects. A particle causes local non-stochastic damages in its closest location and may introduce possible long-term effects. Studies on these were initiated after Chernobyl e.g. in Finland (Rytömaa *et al*. 1986, Lang and Raunemaa 1991, Pöllänen 2002).

Conclusions

The Chernobyl accident showed how a released radioactive or otherwise hazardous plume can,

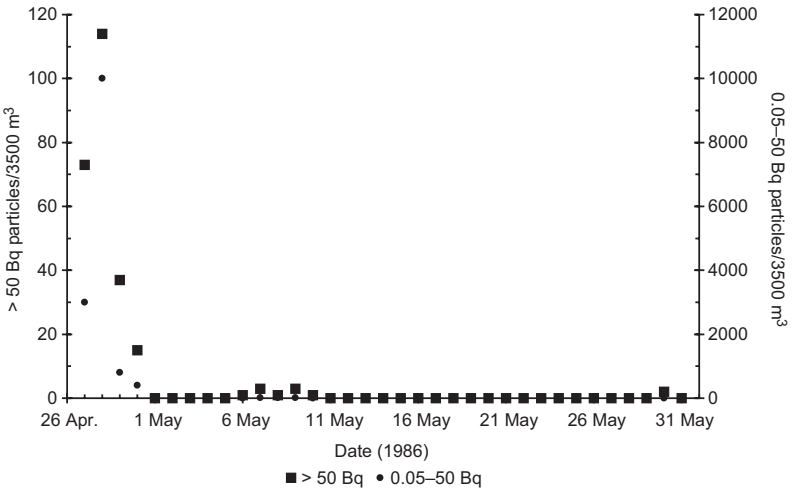

Fig. 12. Hot particles in the ground-level air at Nurmijärvi during 27 April–31 May 1986 (Mattsson and Hatakka 1986).

under certain meteorological conditions, rapidly move over long distances. A similar case was observed in December 1966 when radioactivity from a leaking underground nuclear test in Semipalatinsk, Kazakhstan (then USSR), was transported to Finland in three days (Kauranen *et al*. 1967). In the case of the Chernobyl accident, Finland was spared from serious consequences with a narrow margin. Had the accident taken place only a day before, heavy fallout would have been deposited in northern Finland according to the dispersion model calculations by Siljamo and Lahtinen (2006). This would have ruined the reindeer husbandry business for decades resulting in serious economical, social and cultural damages especially within the indigenous Sami population.

Certain consequences did, however, result from the Chernobyl accident in Finland. Medical consequences were luckily mild, the most important symptoms being psychological ones. No increase in birth defects or thyroid cancer occurrence has been observed in Finland (Harjulehto-Mervaala *et al*. 1992, Auvinen *et al*. 2001, Ikäheimonen 2006).

Based on the lessons learnt after the accident, a lot of efforts have been aimed to the improvement of information dissemination including international and interagency communication and responding to the information demands of the mass media and the general public. The authorities participating in the national radiation surveillance programme were able to obtain a variety of new radiation measurement equipment during the months and years following the accident (Paatero *et al*. 1994). The accident again showed the importance of real-time aerosol beta activity monitoring in addition to the dose rate measurements. Depending on the geographical area in Finland the beta activity monitors reacted to the Chernobyl debris even two days earlier than did the dose-rate meters. The need for existing continuous sampling programmes of surface air and ground deposition was also emphasized because these programmes provide samples for analyses of radionuclides which need to be separated radiochemically. An important lesson was also that the proper functioning of the operational weather service, including weather observations, numerical weather prediction models and dispersion models utilising the previous two, has to be secured in all circumstances.

The Chernobyl accident boosted the radioecological research which had already been calming down after the last atmospheric nuclear test in China in October 1980. Important new results concerning e.g. hot particles and transfer of rafionuclides along several food-chains have been achieved. The Chernobyl signal can be used for a long time in, for example, dating sediment cores. The observations of airborne radioactivity are still used in the validation of atmospheric dispersion models. Finnish authorities and university researchers managed, thanks to the experience gained since the late 1950s and the very rapid organisation of a coordinated research

programme and funding by the Academy of Finland, to produce a huge amount of data in a very short time after the accident covering a large variety of radiation protection aspects. Much of the information was gathered by research teams outside of the actual radiation protection authorities. A possibility for such an *ad hoc* cooperation is important in a small country like Finland with limited human, economical and technological resources.

The most important effects of the accident in Finland were societal and political ones. The public awareness of environmental issues in general and especially of nuclear energy were increased. The nuclear energy programme was halted until May 2002, when the Parliament of Finland granted a licence to build the fifth nuclear power reactor in Finland.

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