Dose rate mapping and quantitative analysis of radioactive deposition with simple monitoring instruments in Finland after the Chernobyl accident

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This article reviews the Finnish dose-rate mapping equipment and the system to process the obtained results, which were used immediately after the 1986 Chernobyl accident. We present the results of the external gamma-radiation monitoring carried out with simple civil-defence gamma monitoring instruments and compare them with the subsequent deposition mapping performed with research-grade instruments. The analysis shows that the quality of radiation mapping is good enough for decision makers to direct protective measures to the right areas. This review also demonstrates that a simple stationary external gamma radiation monitoring network can be effectively used for early warning in radiation emergency situations.

Introduction

The intense nuclear weapons testing in the atmosphere in the 1950s and the beginning of the 1960s led many countries to initiate environmental-radiactivity surveillance programmes (UNSCEAR 2000). In Finland, the arrangements for a countrywide radioactivity monitoring programme were initiated in 1956 by the Finnish Meteorological Office (currently the Finnish Meteorological Institute), the Defence Forces, the Finnish Marine Research Institute and the University of Helsinki (Mattsson 2005). In 1958, the Institute of Radiation Physics (current name STUK — Radiation and Nuclear and Safety Authority, henceforth STUK) was established to study, among other things, the environmental behaviour and human health risks of artificial radioactivity (Hoffman 2008). The first monitoring programmes began in Finland in the late 1950s. Radiation monitoring devices and procedures were developed within separate projects by several authorities but also as a result of joint efforts. Finnish manufacturers of monitoring devices also participated in the development work.

In Finland, measurements of external dose rate have continued regularly since the early 1960s. The countrywide radiation monitoring network was built by the Ministry of the Interior and the Defence Forces for the purpose of civil defence, as well as military nuclear, biological and chemical (NBC) protection (Blomqvist 1981). The stationary external dose rate monitoring network was planned to comprise about
500 stations: one station in every 40 × 40 km² in northern Finland, and one station in every 20 × 20 km² in southern Finland (Blomqvist 1981). With this network, the fallout from the series of atmospheric nuclear weapons tests at Novaya Zemlya in 1961 and 1962 was registered. In 1986, when the Chernobyl nuclear power plant accident took place, over 400 stations were in operation. Already before the Chernobyl accident, there were plans to develop the monitoring network to give more accurate and more real-time information on external radiation. In addition to this network, the Finnish Meteorological Institute and STUK operated a few stations for monitoring external dose rate.

The monitoring networks and instruments

In 1986, the Ministry of the Interior operated Finland’s largest countrywide external radiation monitoring network (Fig. 1). It was administered by the 12 state provincial offices. The monitoring was carried out by e.g. municipal fire departments, the Public Roads and Waterways Board and civil aviation authorities at the airports. The Defence Forces had an external radiation monitoring network of its own, with some of the monitoring stations located at the premises of the Frontier Guard Authority. In 1986, altogether 320 stations were maintained by the Ministry of the Interior and 85 by the Defence Forces.

The instruments used by the Ministry of the Interior’s stationary external gamma monitoring stations were Wallac/Alnor RDA-31 (Fig. 2), and RDA-4 and RD-120/1200 (Fig. 3) radiation monitors. The two measurement ranges for these instruments were 0.05–400 mR h⁻¹ and 0.05–400 R h⁻¹. The energy dependence for gamma radiation was ±20% in the photon energy range from 60 keV to 3 MeV. These were used to measure gamma radiation dose rates at a height of 1.5 m above the ground level. The detectors of the monitors consisted of two energy-compensated Geiger-Müller (GM) tubes.

The accuracy of the measurements was not the best possible because:

1. The dose rates were below the calibrated range of the radiation monitors (minimum 10 µSv h⁻¹). For this reason, at some mon-
Monitoring stations pulses from the GM-tube were counted by an operator during a 3-min period. This method of data collection causes a systematic error, an underestimate of 30% (Blomqvist 1981). Only 21 of the stations in Finland were equipped with an automatic digital pulse register unit (DPR-82), which counted the pulses into a register during an hour, thus reducing this error.

2. Different GM-tubes gave slightly different count rates for equal dose rates at low radiation levels.

3. GM tubes have an internal background “noise” count rate.

The estimated overall accuracy of each measurement was ±50%, because the measured magnitudes of dose rates were near the minimum detectable value. The accuracy of the stations equipped with a DPR-82 unit was ±10%–20% (Blomqvist 1988) depending on the monitor and location-specific differences.

**Fig. 2.** Alnor RDA-31 Radiation monitor.

**Fig. 3.** Wallac RD-1200 Radiation monitor.
For backup purposes, there was a portable radiation monitor at every station. If an alarm occurred at a monitoring station, the result was ensured with a portable monitor (Alnor/Wallac RD-6/7/8/10; Figs. 4–6). The two measurement ranges of these instruments were 0.01–300 mR h⁻¹ and 0.01–300 R h⁻¹. The energy dependence was ±20% in the range 45 keV to 2 MeV.

All the measured values were stored in the database in counts per hour (cph) and converted to μR h⁻¹. The conversions from cph to μR h⁻¹ for the Wallac RD-6 and RD-7 radiation monitors were made using the following equation (Blomqvist 1981):

\[ D = 0.265 \times n - 7.5 \]  

(1)
and for the Wallac/Alnor RD-8, RD-10 and RDA-31 monitors, the conversions were done as follows (Ministry of the Interior, calibration test 1986):

\[
D = 0.78 \times n - 3, D < 0.1 \text{ mR h}^{-1} \quad (2)
\]
\[
D = 0.00086 \times n, D \geq 0.1 \text{ mR h}^{-1} \quad (3)
\]

where \(n\) is the number of counts in units counts per minute (cpm) and \(D\) is the dose rate (µR h\(^{-1}\)). Note that \(R = 0.01\) Sv.

Of the 320 stations operating under the Ministry of the Interior, 260 stations were measuring normally once a week on Tuesdays. Sixty stations were monitoring the dose rate continuously. At 20 of these continuously monitoring stations, there was an auxiliary unit DPR-82 which digitally counted the pulses from a GM-tube and displayed the result on a digital display. In Rovaniemi, there was one additional station with a DPR-unit. This station delivered results directly to STUK (Blomqvist 1986). Twenty-seven stations plotted the dose rate continuously on a monthly chart. Other stations recorded their results once a week. On a specific request from the Ministry of the Interior or from the state provincial office, there was a possibility to intensify the monitoring.

In 1986, the responses to measured external gamma dose rates were as follows:

- at 0.7 µSv h\(^{-1}\): notify radiation monitoring authorities;
- at 10 µSv h\(^{-1}\): intensify measurement intervals and alert authorities;
- at 200 µSv h\(^{-1}\): warn the population;
- at 2 mSv h\(^{-1}\): commence population protection.

To minimize equipment-related false alarms, it was required to verify the dose rate measurement with another instrument, and take into account the natural background dose rate, which in Finland varies between 0.04 and 0.3 µSv h\(^{-1}\) (Mustonen 2000).

In radiation emergency situations, it was possible to establish 2000 additional measuring points and send out patrols, which used portable radiation monitors. In 1986, there were 4942 universal radiation dose rate instruments in authority use in the Finnish municipalities (Sisä-asianministeriö 1989).

The monitoring network was based upon manual data transmission. For data processing of the measurement results, the Ministry of the Interior had a computer-based radiation control system. The system performed the following tasks (Niemen 1984):

- recording of data on nuclear explosions and radiation measurements, and transmitting them to all system users;
- defining the areas where warning or alarm is to be given to the public;
- compiling prognoses based on nuclear explosion and wind data or on measuring data;
- follow-up of the radiation situation and its development; and
- transmitting information.

The data used in this review consists of the monitoring results from the Ministry of the Interior’s radiation monitoring network, which were stored in an unpublished database during the management of the consequences of the Chernobyl nuclear accident. In this review we present the radiation situation pictures produced in 1986 and new analyses of the same data produced with new means in 2011. The main emphasis is on the quality of the situation pictures used in 1986.

**The Chernobyl accident**

**Atmospheric transport**

The Chernobyl nuclear accident took place in the former Soviet Union on 26 April 1986 at 01:23 Local Time (LT) (IAEA 1992). Two explosions occurred in the accident (Arvela et al. 1987). The accident destroyed one of the four RBMK-1000 type reactors and released significant radioactive contamination into the environment.

The first emissions were transported north-westwards over Poland, the Baltic States, Finland, Sweden and Norway. On 27 April 1986, emissions were spreading to eastern central Europe, southern Germany, Italy and former Yugoslavia. Within the next week, the plume was transported southwards from Chernobyl to
Romania, Bulgaria, the Balkans, the Black Sea and Turkey. After that, the emissions arrived again over central Europe and Scandinavia (Persson et al. 1987). Finally, the plume was distributed practically throughout the northern hemisphere. Most of the radioactivity that originated from Chernobyl remained in the troposphere, but it could be detected also in the stratosphere (Jaworowski and Kownacka 1988).

The calculated air mass trajectories originating from Chernobyl at the time of the accident show that the radioactive plume moved first northwestwards (Valkama et al. 1995). At the altitudes of 1500–2500 m, the plume continued to southwestern Finland and once over Finland the plume turned to northeast and continued over the Soviet Union to the White Sea. The arrival time in southwestern Finland for a release height of 2000 m was 27 April 1986 at 12:00 Coordinated Universal Time (UTC). The plume was hindered by a frontal zone from the north and did not reach northern Finland (Paatero et al. 2010).

Precipitation efficiently scavenges airborne contaminants to the ground. Thus precipitation governed in many cases how the Chernobyl plume was deposited in Finland. On 27 April 1986, when the first release plume from Chernobyl passed over Finland there was no or very light rain in southern Finland (Paatero et al. 2010). A slightly larger amount of precipitation (< 3 mm) occurred in a zone from southwestern Finland towards the northeast. On 28 April 1986, the weather in southern Finland was quite dry except that some rain 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 southeastwards towards the Kotka region. After that, there was a dryer period from 1 May 1986 (Finnish Centre for Radiation and Nuclear Safety 1986a, Finnish Centre for Radiation and Nuclear Safety 1986b, Nordlund 1986, Savolainen et al. 1986, Arvela et al. 1987).

Management of the radiation situation in 1986

The first official notification of the accident that was received from the Soviet Union’s official news office was released by the TV news of Finland’s national public service broadcasting company (YLE) on Monday 28 April 1986 at 20:30 LT. Before that, there were several observations of increased external dose rates in both Sweden and Finland. In Sweden, the observations were made at the Forsmark nuclear power plant. In Finland, the first observations were made in Kajaani on Sunday 27 April 1986 at 20:40 LT at a radiation monitoring station operated by the Defence Forces (STUK press release 28 April 1986 16:00 LT). In addition some observations were made at other monitoring stations but those were not made available at that time to the decision makers. Later these recordings were restored and used in the situation analysis (Paatero et al. 2010).

When the Ministry of the Interior received the information regarding abnormal radiation monitoring results on 28 April 1986 at 14:30 LT, it contacted STUK, and some more information was exchanged. STUK reported about observations made in Sweden at the Forsmark nuclear power plant. The headquarters of the Finnish Defence Forces reported the above-mentioned Kajaani abnormal measurement to the Ministry of the Interior on 28 April shortly after 14:30 LT.

STUK requested the Ministry of the Interior to check the monitoring data at the external gamma radiation monitoring stations equipped with DPR-82 units, which was done on the same day at around 15:30 LT (Fig. 7). The dose rates at some stations in southern Finland were 1.5–2 times higher than the normal dose rate of 0.05–0.15 µSv h⁻¹. This is not exceptional as the snow cover attenuates the gamma radiation emitted by the natural radionuclides in the ground and northern Finland was still covered with snow at the time of the Chernobyl accident (Fig. 8). At 21:00 LT, the Ministry of the Interior ordered intensified monitoring at the monitoring stations equipped with DPR-82 units. The stations should log the monitoring result once every hour into a logbook and report the results on demand.

On Tuesday 29 April 1986, the measurement results from regions with precipitation showed 5–30 times higher dose rate values than normal. The Ministry of the Interior ordered intensified monitoring at all continuously monitoring sta-
The monitoring results should be logged into a logbook at 7:00, 15:00 and 23:00 LT, and reported to the Ministry every morning at 9:00 LT by fax or telex. The results of the intensified measurements were received for the first time soon after 15:00 LT on 29 April. The highest dose rate, 4 µSv h⁻¹, was measured in Uusikaupunki (Fig. 9).

The Ministry of the Interior and STUK decided to extend the intensified monitoring to all Ministry of the Interior monitoring stations from 2 May 1986 12:00 LT. The radiation monitoring data system developed for civil defence purposes was modified so as to enable the measurement records to be stored in a database, and subsequently used to draw radiation maps with a data plotter. The first map was drawn on 2 May 1986 at 12:12 LT (Fig. 10). The dose rates from external gamma radiation decreased gradually. The area with increased dose rates extended from southern Finland to the Kokkola–Kajaani line.

On 5 May 1986, the Ministry of the Interior prepared a composite radiation map for Finland. Increased dose rates were registered south from the Kokkola–Kajaani line. The values were about twice the normal values, but only at locations with heavy rain (e.g., Uusikaupunki [see Fig. 11], Hämeenlinna, Lahti, Tampere, Jyväskylä,
On 6 May 1986, the Ministry of the Interior changed the routine for intensified measurements at Viitasaari, they were about 10 times higher than normal (Fig. 12).

On 6 May 1986, the Ministry of the Interior changed the routine for intensified measurements...
at the continuously monitoring stations: henceforth, the data should be entered into the logbook once every three hours starting at 9:00 LT, and the results should be delivered to the Ministry the following morning after 9:00 LT. The other stations should register the results once a day at 8:00 LT, and deliver them to the state provincial offices immediately after each measurement. The offices should deliver the combined list of the results from their regions to the Ministry by telex or fax. However, upon a marked rise in dose rates, the Ministry should be notified immediately.

To establish the normal background external gamma radiation dose rate at each station, on 7 May 1986 the Ministry of the Interior collected the 22 April and 29 April radiation data from the State provincial offices’ emergency response centres. On 17 May 1986, the Ministry ordered the monitoring at the stations back to normal routine.

**Analysis of the monitoring data**

Based on the monitoring results, the Ministry of the Interior compiled rough maps of the radiation and presented them each day, usually in the early afternoon. The radiation monitoring data

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**Fig. 11.** Dose rates in Uusikaupunki (southwestern Finland), after the Chernobyl accident in spring 1986.

**Fig. 12.** External gamma dose rates on 5 May 1986 at 15:00 LT. (a) original map, and (b) the current MapInfo version.
system plotted isocurves of the radiation dose rates. The grid for the calculation was based on the Triangulated Irregular Network (TIN) method. The interpolation of the results was done so that every station within a 50-km radius had an effect on the result calculated for the grid. The results were weighted with the distance. The values of the isocurves were about 2, 5 and 10 times the normal background dose rate level, i.e. 0.2, 0.5 and 1.0 µSv h⁻¹, respectively.

We redrew the map of the dose rates with the MapInfo Professional 10.0 software. The used method was Inverse Distance Weighting (IDW) (Shepard 1968). The IDW interpolator calculates the values of grid cells that cover the mapping area. Each data point value that is considered in the calculation for a cell value is weighted by its distance from the centre of the cell. Because the interpolation is an inverse distance weighting calculation, the farther a point is from the cell, the less influence its value will have on the resulting cell value. According to the MapInfo user guide, this method of interpolation works well for sparse data and for arbitrary data. The used values were: grid size 10 km, exponent 5 and radius 100 km. The exponent determines how much influence each point will have on the result. The higher the exponent the greater the influence closer points will have on the cell value.

The original radiation situation maps (Figs. 10a and 12a) — also used by the decision makers and to inform the media — were plotted with a plotter and the raster was added manually. The new maps (Figs. 10b and 12b) were based on those maps. Because of the different interpolation method, smaller anomalies are shown on the new maps, and the resolution of the results is better. However, the resolution of the maps in 1986 was good enough for identification of the most contaminated areas.

In the original maps, the missing values for stations were extra- and interpolated. For the extrapolation the modified Way-Wigner formula (Way and Wigner 1948) was used for the fallout:

\[
D_t = D_{\text{ref}} t^{-0.9} \quad (4)
\]

where \(D_t\) is the dose rate at time \(t\) (in hours) and \(D_{\text{ref}}\) is the reference dose rate (here 298 µSv h⁻¹).

The exponent (−0.9) was calculated from the Uusikaupunki measurement results, and it was used for all stations.

When comparing the map of the original gamma radiation two weeks after the accident with the caesium deposition map created by STUK in 1986–1987 based on sensitive Geiger counter and mobile gamma spectrometer measurements (from Arvela et al. 1990), similarities are evident (see Fig. 13; the lines have been drawn to help comparisons). Linear correlations between dose rates calculated from caesium deposition and external dose rate rise caused by the deposition were also calculated for three regional levels: 12 provincial office regions \(r = 0.98\), 21 counties \(r = 0.77\) (Fig. 14); and 209 municipalities \(r = 0.66\). There are some differences in low dose rates, which can be explained by differences in accuracy of the monitoring instruments and the reference time. The Ministry of the Interior’s monitoring network results are from the 16th day after the accident, and they include also gamma radiation from short-lived gamma-emitting isotopes. In the comparison map (Fig. 13a), only gamma radiation emitted from \(^{137}\text{Cs}\) and \(^{134}\text{Cs}\) is shown.

After the peak of external radiation — 4 µSv h⁻¹ in Uusikaupunki on 29 April 1986 at 20:00 LT (Fig. 11) — the dose rate started to decrease with a half-life of 4.8 days (Paatero et al. 2010). This suggests that much of the external radiation was due to \(^{131}\text{I}\) (half-life 8.0 days) and \(^{132}\text{Te}^{132}\text{I}\). The half-lives of \(^{132}\text{Te}\) and \(^{132}\text{I}\) are 3.2 days and 2.3 hours, respectively.

When the external dose rate is plotted against the \(^{131}\text{I}\) deposition in southern Finland reported by Jantunen et al. (1987) (see Fig. 15), the points are scattered, and no correlation exists \((r^2 = 0.1229)\). This can be related to the poor quality of the measurements, or the distance between the dose rate monitoring points and the \(^{131}\text{I}\) deposition measurement sites. The deposition was very unevenly distributed even within a few kilometres especially in southwestern Finland (Raunemaa et al. 1987). There can also be human errors involved because many measurements as well as data transfer and processing was done manually. Due to the \(^{131}\text{I}\) deposition of about 75 kBq m⁻², the measured dose rates approached or exceeded 0.4 µSv h⁻¹ in every case but one.
Dose rate mapping and analysis of radioactive deposition

Fig. 13. (a) Dose rates calculated from Arvela et al. (1990), and (b) differences between external dose rates on 15 May 1986 and station’s background levels on 22 April 1986. The lines have been drawn to help comparisons.

Fig. 14. Correlation between external dose rates on 15 May 1986 minus each station’s background level on 22 April 1986, and dose rates calculated from Cs deposition (Arvela et al. 1990) for the counties.

Fig. 15. Dose rate on 3 May 1986 vs. $^{131}$I deposition in southern and central Finland (data from Jantunen et al. 1987). The dashed line indicates the theoretical dose rate of 0.0013 $\mu$Sv h$^{-1}$ due to the $^{131}$I deposition only (Health Canada 1999), and the dotted line the dose rate of 0.4 $\mu$Sv h$^{-1}$, i.e., the current inter-agency warning level.
The external gamma radiation monitoring network was useful in the initial management of the consequences of the Chernobyl accident. The first three weeks after the accident, higher external dose rates were detected by the monitoring network. After two months, the dose rates decreased to levels difficult to detect. The reasons for that were the decay of the radioactive deposition, the washout of deposition from the ground surface, and the vertical migration of deposition to the ground. The partial snow coverage and frozen ground in Finland in early May 1986 may also have caused a more rapid transfer of deposited radionuclides from the ground surface to water systems, and subsequently into the Baltic Sea.

Discussion and conclusions

In most cases a dense network of gamma radiation monitoring stations will satisfy the requirement of detecting serious threats from a radioactive plume. A simple Geiger counter can be used for radiation mapping if dose rates are within the detection range of the counter. When counting the pulses manually (audible or light pulses) from the GM tube, the overall accuracy is ±50%. Studies after the Chernobyl accident showed that the alarm level with a digital counter could be set to 0.4 μSv h⁻¹ with a 1-hour counting time, but with a 3-minute counting time the alarm level should be 1 μSv h⁻¹. Correlation show that the measurements correlate better within larger areas.

This review shows that a quite simple stationary external gamma radiation monitoring network can provide reliable radiation mapping after a release from a nuclear power plant. The requirements for such a network should be:

1. The measurement range for the monitoring instruments should detect significant changes in external gamma radiation: a ±30% change in background radiation must be detected.
2. The network grid density determines the resolution of the radiation mapping. The denser the grid the better the resolution. At least one monitoring station should be in each grid cell.
3. The location and time of the measurement must be recorded.
4. The measuring procedure should be standardized for all stations. The measurement time, height from ground level and the free area around the detector should be standard for all recorded results.

For early warning purposes there are additional requirements:

1. To minimize false alarms, there should be a predefined, customized alarm level for each station: a level that is generated from earlier recorded results at the station and depends on the measurement capabilities of the station.
2. The alarm and measurement must be confirmed by independent means. There should be a local operator measure the surroundings of the detector.
3. The alarm should be delivered to on duty personnel automatically.

To study and analyze the measurements there are further requirements:

1. The meteorological data should be available. The minimum needed are the existence of precipitation at the station and the prevailing wind speed and direction.
2. There should be data processing capacity so that the data can be presented in an easy-to-understand visual format.

These requirements are well met in the current Finnish inter-agency radiation monitoring and analysis system called USVA (Devell and Lauritzen 2001), which has been in operation since the year 1999.

References

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