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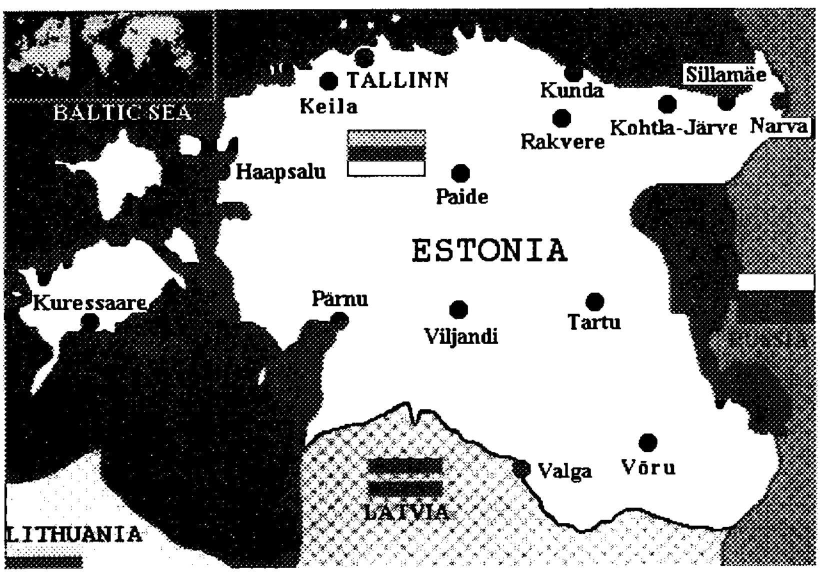
Dose-Rate Mapping and Search of Radioactive Sources in Estonia

S. Ylätalo, J. Karvonen, T. Honkamaa, T. Ilander, H. Toivonen



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PREFACE

We thank Professor Antti Vuorinen, Director of the Finnish Centre for Radiation and Nuclear Safety, for launching the environmental monitoring programme and for placing the facilities of STUK to our disposal. We are also grateful to Mr Jaan Saar, Estonian Ministry of Environment, for co-operation and help during the project. The enthusiastic support from local authorities was crucial for the success of the measurements.

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ABSTRACT

The Estonian Ministry of Environment and the Finnish Centre for Radiation and Nuclear Safety agreed in 1995 on a radiation mapping project in Estonia. The country was searched to find potential man-made radioactive sources. Another goal of the project was to produce a background dose-rate map over the whole country. The measurements provided an excellent opportunity to test new in-field measuring systems that are useful in a nuclear disaster.

The basic idea was to monitor road sides, cities, domestic waste storage places and former military or rocket bases from a moving vehicle by measuring gamma spectrum and dose rate. The measurements were carried out using vehicle installed systems consisting of a pressurised ionisation chamber (PIC) in 1995 and a combination of a scintillation spectrometer (NaI(Tl)) and Geiger-Müller-counter (GM) in 1996. All systems utilised GPS-satellite navigation signals to relate the measured dose rates and gamma-spectra to current geographical location. The data were recorded for further computer analysis.

The dose rate varied usually between 0.03-0.17 μSv/h in the whole country, excluding a few nuclear material storage places (in Saku and in Sillamäe). Enhanced dose rates of natural origin (0.17-0.5 μSv/h) were measured near granite statues, buildings and bridges. No radioactive sources were found on road sides or in towns or villages.

CONTENTS

1 INTRODUCTION

The Estonian authorities have expressed several times their concern about radioactive material dispersed into the environment. Some findings of very active sources (beside the Narva Road and in Kiisa, Lindholm et al. 1996) gave additional impulse to a meeting in 1995 in Tallinn between the Estonian and Nordic authorities. A joint project was planned for monitoring Estonian road sides, cities, domestic waste storage places, military or missile bases or other possible locations where radioactive material may have been stored or handled. An extensive environmental radiation monitoring project was started in 1995 between the Estonian Ministry of Environment and the Finnish Centre for Radiation and Nuclear Safety. The measurements were finished during the summer 1996.

The aim of the project was to produce a background dose-rate map over the Estonian cities and road sides, and to find hazardous radioactive sources. The project was a good opportunity to test apparatus performance in real conditions.

Radiation monitoring was performed by a system installed in a moving vehicle for natural background dose-rate measurement (PIC and GM, pressurised ionisation chamber and Geiger-Müller-counter, respectively) and for radioactive nuclide identification (scintillation spectrometer, NaI(Tl) crystal). Geographical location was determined by a GPS-navigation system. The spectra and the dose rate were recorded together with co-ordinates by a computer for further analysis and utilisation.

To find radioactive sources in Estonia, the measurement routes of the vehicle were chosen in respect to human activities. Cities, domestic waste disposal places, military and old Russian rocket bases as well as metal storage and customs places near the border side were studied.

In principle, all roads broader than 4 m were included in the study plan. If no habitation was on the area, some smaller roads were omitted because of lack of time. Large cities and villages were thoroughly screened.

The background dose rate was recorded partly by random choice of the measurement patrol and partly by local interests. Domestic waste storage places, rocket and military bases were shown to the measurement patrol by a guide present.

2 EQUIPMENT AND SOFTWARE

2.1 Apparatus

The measurement apparatus was installed inside a Toyota Land Cruiser jeep. Detailed specifications of the equipment are given in appendices A1-A4. The operation of mapping software and in-field monitoring techniques are dealt by Ilander et al (1996), and Toivonen et al (1994), respectively.

In dose-rate measurements, in 1995, a pressurised ionisation chamber (PIC) was used. The device is a spherical vessel of ultra high purity argon in 25 bar pressure, equipped with collection electrodes for the ions produced by the entering radiation. In electric field, these ions form a current, which is detected by an electrometer. The signals are further processed for recording by a computer. The spectral sensitivity of ionisation chamber is nearly linear in energy range from 0.07 MeV-10 MeV (Reuter-Stokes, 1993).

In 1996 the PIC was replaced by a Geiger-Müller-counter, which operates as a pulse counter. The detector is a large combined sensor (RD-02L) of two Geiger-Müller tubes (Mullard ZP 1221, Philips 1304). This set-up is designed for maximum sensitivity for both low and high dose rates. For the sensor tube, the ambient dose equivalent energy response is flat within 30 % over the range from 0.05 MeV to 3 MeV (^{137}Cs) (Appendix A2). The applicable absorbed dose rate

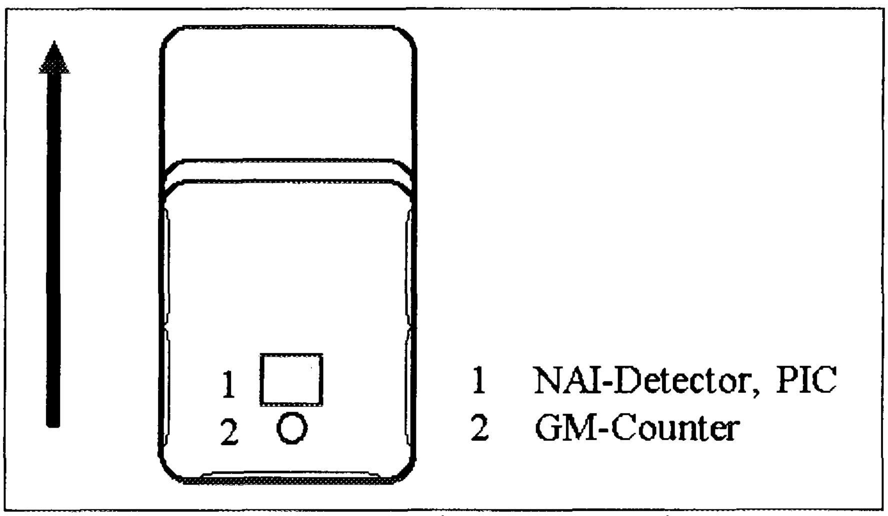


Figure 1. *Apparatus installation in the measurement vehicle.*

ranges from 0.03 μSv /h to 10 Sv/h. Further technical specifications are given in more detail in appendix A2.

Since both dose-rate measurement instruments (PIC and GM) operate on different principle, there is a need to compare their performance. Therefore, a calibration was made with a ^{137}Cs source. Both sensors and the source were put 1m above the ground level on a flat surface in outdoor conditions. The dose rate was measured during a 5 min period at four locations. The distances were chosen as shown in Fig. 2, which describes the correlation between these two data sets. Table I shows characteristic coefficients, which are used in data presentation to convert dose rates from one instrument to the other. Due to very good correlation, the results from GM measurements are presented as such and a conversion factor is applied to PIC results (Table I).

The pressurised ionisation chamber measures constant weak current due to radiation induced ionisation's. The instrument records exposure rate. Dose rate and exposure rate can be changed from one to another by a transformation constant 10.5 mSv/R (Ambient dose equivalent, H*(10), ICRU-report 47, 1992). However, in the measurements in 1995, a factor of 8.69 mSv/R was used for the

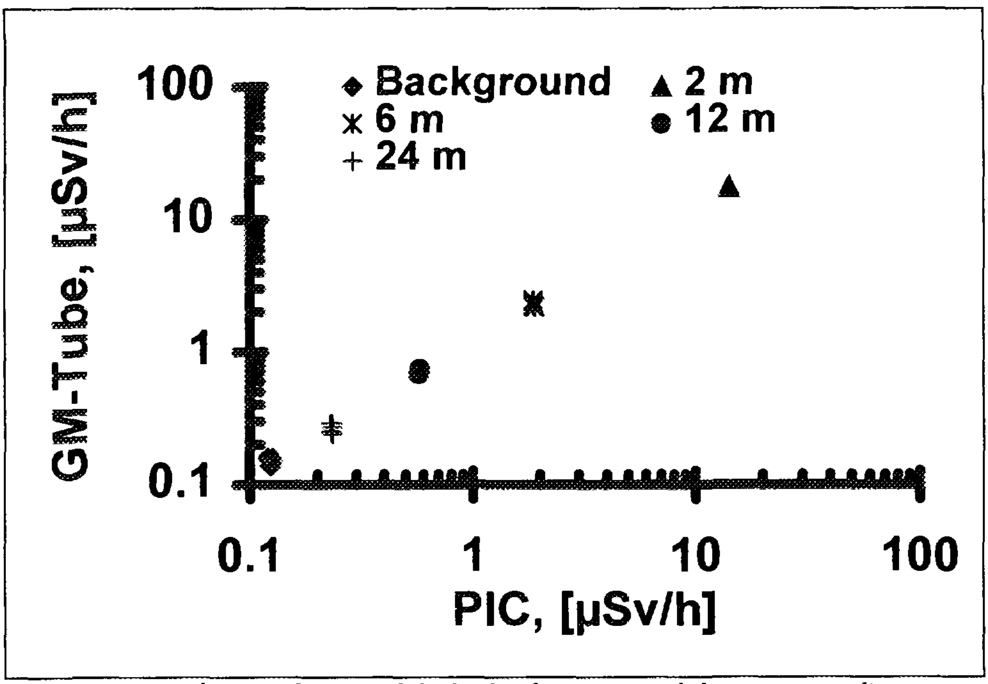


Figure 2. *Correlation of PIC and GM-tube data in semi-laboratory conditions.*

Table I. *Statistical results of regression analysis of the dose rate comparison of PIC and GM (c.f. Fig. 2).*

Correlation Coefficient	0.9999
Average Ratio, $\dot{H}_{PIC}/\dot{H}_{GM}$	0.8282
Standard Deviation	0.05
Number of Data Points	25

transformation constant to replace the exposure rate by dose rate. The ratio of the correction factors (8.69/10.5) gives 0.8276. This is in excellent agreement with the experimental average ratio (Table I).

In 1996, a scintillator spectrometer apparatus was included in the field measurements for radionuclide identification. The device has a 5"× 5" tallium doped NaI crystal as a sensor and suitable pulse counting electronics (NOMAD, model 92X-P). The hardware was operated via SAMPO-code in real-time mode during the monitoring of the background and radioactive source chase. In addition to total count window, three ROI windows were defined, for ^{137}Cs, for ^{60}Co and for higher energies (1400- 3000 keV). The co-ordinates from a GPS navigation receiver were merged with radiation data.

2.2 Data Acquisition

The measuring system was collecting spectra in 5 s intervals, but in practice the real acquisition time varied from 5.5 s to 9 s. This was partly due to the operation of hard disk and indirectly partly due to incompatibility problem of Compaq-computers and SAMPO-code. The energy calibration of the spectrometer was checked every three hours. This procedure was necessary in moving vehicle conditions and during long measurement days. Weather and temperature changes caused some drift of the gain and peaks.

For each measured spectra the sampling location was determined by GPS navigation system utilising TSIP-type protocol between the PCMCIA-card and PC. The other system for dose-rate measurement used TAIP-code for localisation with separate hardware set-up. The latter system was observed to have superior reliability and speed to find co-ordinates. Dose-rate and co-ordinate determination system, SAHTI, was used for this real-time application (Ilander et al, 1996).

The sampling geometry is shown for both campaigns in Fig. 1. Both systems were installed inside the vehicle (temperature, weather and attention avoidance).

The equipment had good view out of the car through windows to left, right and back. Photon absorption in the glasses and other structures of the car was ignored. See, however, appendix A5 for discussion of the mass-absorption coefficient. When high and narrow peaks in total count time series or in ROI-windows were observed, especially together with enhanced dose rate, the vehicle was stopped for a checking procedure with hand dosimeters. The alarms were chosen to give a warning signal if the peak doubled the base line or exceeded a pre-set count limit, as chosen for normal Estonian background activity. At interesting places with enhanced dose rate, such as metal furnace backyard or a few statues or bridges, an additional spectrum was measured.

The energy calibration was checked with ^{137}Cs and ^{60}Co sources of 37 kBq (1 μCi) before collecting the spectra for 500 s or 1000 s. Dead time in normal monitoring was below 7% and during calibration about 12 %. Large rocks and stone buildings in cities caused several false alarms as well as road type changes when driving across a junction. In addition to monitoring with the mobile real-time systems, the measurement patrol went by foot to former rocket bases. Hand dosimeters and equipment for taking swipes were used.

2.3. Sensitivity of Detectors

The carborne radiation monitors were tested in 1995 for point source responses at distances of 10 m, 20 m, 50 m, 100 m, 150 m, and 200 m using vehicle speed of 20 km/h and 50 km/h. The source had a nominal activity of 1.85 GBq (^{137}Cs). The detection of the ^{137}Cs source was visually clear up to 50 m for the spectrometer and up to 20 m for PIC. In these measurements (Figs. 3 and 4, respectively) the 5x5" NaI scintillator was almost equally sensitive as a 36.9% HPGe detector for the ^{137}Cs source. It could be detected from the distance of 100 m at the speed of 20 km/h when the background was well known. Signal to background ratio is typically higher for the HPGe detector than for the NaI detector. However, the statistical accuracy of the HPGe is poorer. The high caesium background of 50 kBq/m² on the test field decreases efficiency of point source detection. However, in Estonia the caesium fallout is small (<10 kBq/m²) and thus the detection limits are lower than in Finland.

The PIC is at its detection limit at 50m. At that distance the spectrometers gave visually clear signals. The results of PIC are affected by the driving speed and timing, since it takes about 15 to 30 s to adopt to the new dose rate level completely.

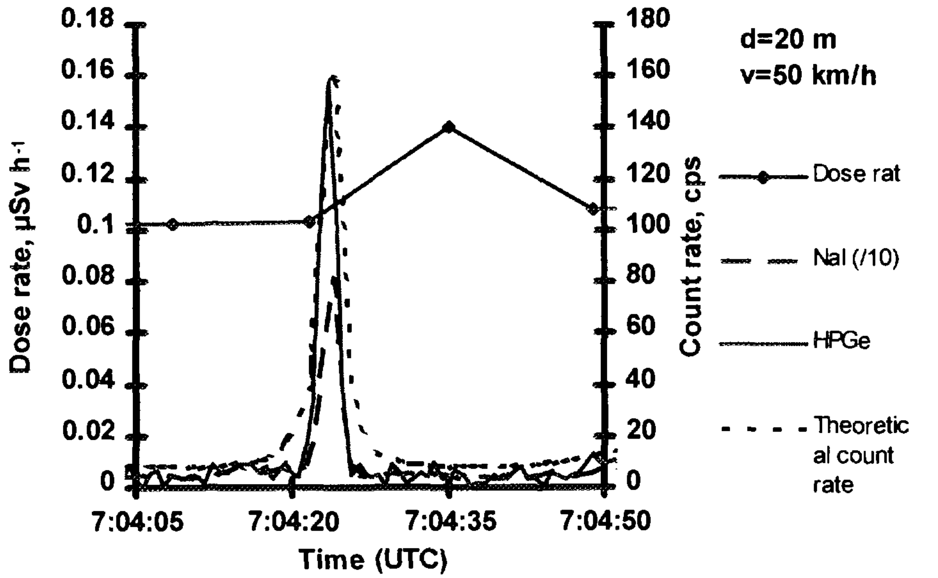


Figure 3. *Response of PIC, NaI(Tl) and HPGe detectors in a ¹³⁷Cs source pass driving test in Vesivehmaa air field, Finland. Passing distance 20 m with 50 km/h velocity. HPGe (37%) was not used in Estonia.*

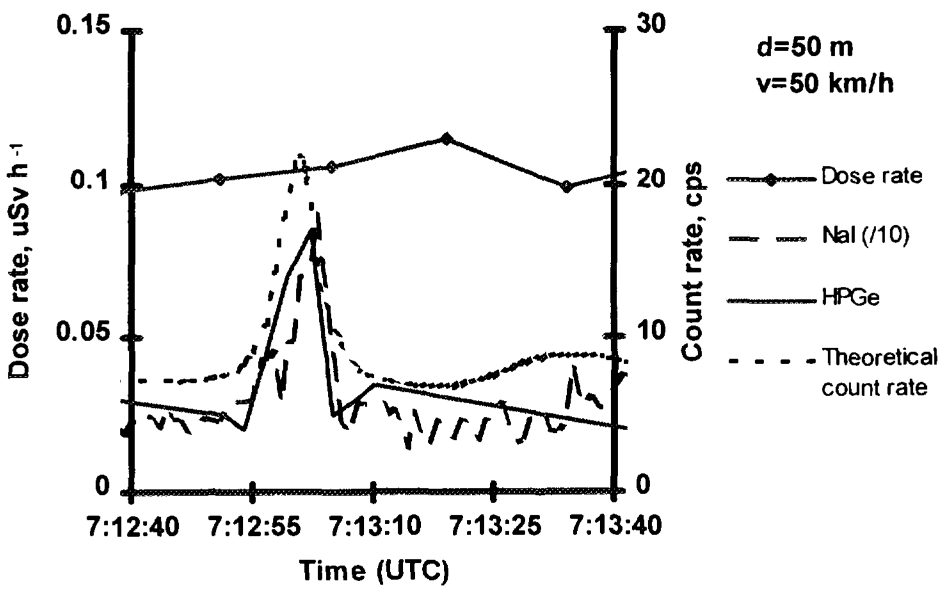


Figure 4. *Response of PIC, NaI(Tl) and HPGe detectors in a ¹³⁷Cs source pass driving test in Vesivehmaa air field, Finland. Passing distance 50 m with 50 km/h velocity. HPGe (37%) was not used in Estonia.*

2.4 Apparatus Performance in Estonia

The proper operation of the apparatus, vehicle and information system, is essential, and they must be tested before the measurement period. Unfortunately in this project the test period was too short and, consequently, several problems occurred, most of them of practical nature.

Without an adequate communication system in a foreign country, the device maintenance is extremely difficult or impossible. GSM telephone works well near the most Estonian cities, but 450 NMT would give a more reliable performance (radio technical sense, not security or cryptographical sense). The NMT phone in the patrol car had to be closed because of the problems caused by the local phone pirates. A fax would have been useful for maintenance communication.

The electricity supply is essential for reliable operation of the apparatus. The operating voltages should be chosen carefully to produce steady loading of the electric system and wasting of energy should be minimised. In the patrol car the operating voltage was 24 V whereas the equipment needed about 12 V. Since 24 V was made by two 12 V batteries in series, only one battery was used for the power supply of the equipment.

The ignition system of the car failed in Estonia and it took several days to sort out the problem. In fact the car had to be sent back to Finland to repair the initial service failures.

The customs papers must be ordered and pre-filled to give the correct description of the apparatus. Formalities exist, but before going, also the return papers should be ready, for possible maintenance-related transportation. In this project two days were lost at the Estonian customs during arrival and two days during departures.

Spectrometer. Sometimes the temperature raised inside the car above 50 °C, which caused performance problems for the electronics. One inverter was destroyed, as well as a battery of NOMAD. Almost every device suffered from some instabilities due to enormous temperatures. Air conditioning would have been essential for long-term stable operation.

Data processing. The program SAMPO crashed several times per day before acceptable operation was achieved in the real-time measurements. The failure of the computer occurred due to *stack overflow error R6000 run time error*, which could appear on the screen at the beginning of a spectrum series, after 6 spectra for example, but also after 500 spectra. For the measurements, the only type of computer available was Compaq LTE Elite 4/40 CX, which caused incompatibility problems with SAMPO-code. The program has been tested elsewhere with other computer types, showing no such problems as was encountered in the measurements.

In the real-time mode, the program left previously measured titles and spectra names on the screen. This was a cosmetic problem rather than a real one. However, there were occasionally, especially during post analysis, a few white dots on the screen. These dots appeared on the line cursor locations on the screen (during data acquisition SAMPO can analyse other spectra).

SAMPO refused to save the spectra to a pre-set directory. Copying large amount of data from exe-directory to a more appropriate directory may take hours. Despite of the difficulties, thousands of spectra were collected per day.

3 RESULTS

3.1 Dose Rates

Typical dose rate results are given in Table II for the most interesting places. Several smaller targets are listed with their measured dose rate in Table III. The dose-rate map over Estonia is shown in Fig. 5 (pages 26-27).

Table II. *Typical dose rates in Estonian counties (GM).*

County	Cities	Military Bases	Domestic Waste Storage	Customs	Road sides
Harjumaa	0.07-0.14	0.07-0.14	<0.14	-	<0.14
Ida-Virumaa	0.07-0.14	<0.14	<0.14	-	<0.14
Jõgeva	(0.1)	0.1	0.1	-	<0.1
Läänemaa	0.07	0.07	0.07	-	0.07
Lääne-Virumaa	0.07	0.07	0.07		0.07
Pärnumaa					<0.08
Põlva	0.05-0.12	-	0.05-0.08	0.05-0.08	<0.12
Rapla				-	<0.09
Saaremaa	0.08	0.07	0.09	-	<0.09
Tartu	0.08	0.05-0.08	0.07	0.06	<0.09
Valga	0.07-0.11	0.06-0.1	0.07	0.08	<0.09
Viljandi	0.05-0.14	0.1	0.08	-	<0.09
Võru	0.07	0.05-0.13	0.07	0.05-0.11	<0.09

Table III. *Dose rates at some targets (GM).*

County/city	Object	Dose Rate, [μSv/h]
Harjumaa/Saku	Nuclear Waste Storage	12*
Harjumaa/Kehrä	Kehrä Market Place	0.14
Harjumaa	A tombstone business	0.18-0.26
Ida-Virumaa	Sillamäe Gate	0.16
Lääne-Virumaa		
Pärnumaa	Lemme	0.38
	Tahkuranna memorial	0.2
Põlva/Räppina	A stone in a basement	0.14
Tartu	A peat vessel sensor	1.34**
	Valumechanica entrance	0.3-0.53
	Rõngu restaurant memorial	0.41
	A pile of stones on a field	0.21
Valga	A Railroad Bridge	0.17
Viljandi	Pikk junction	0.14-0.17

*Near the door of the storage
**Industrial equipment

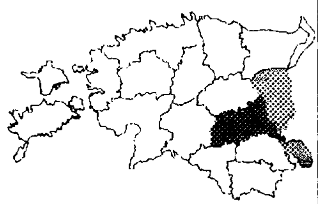
3.2. Real-Time Monitoring

The gamma spectroscopy real-time monitoring produced 100 Mbytes of data. Appendix A6 gives an example of the water-fall screen that was used for data visualisation. Some spectra from interesting places are in appendixes A7-A12. In post analysis, the total count rate and the count rates in appropriate energy windows were thematically mapped (results not shown). The energy windows were chosen to correspond the energies of ^{137}Cs, ^{60}Co and ^{240}Am.

In many places it was difficult to distinguish, which is a 'remarkable source' and should be screened in detail. In Tartu, for example, the dose rate indicated the presence of several radioactive sources (Table III). However, these environmental findings are explained by natural radioactivity or caesium from Chernobyl fall-out.

3.3 Counties

3.3.1. Tartumaa



A metal furnace was screened by the carborne equipment and hand dosimetry. In two spots (pines in flower beds about 1 m diameter) the scintillator measurement revealed the presence of ^{137}Cs in the plantation mould, at the Valumechanica entrance (see appendix A10). Hand dosimetry showed 0.53 μSv/h at the bushes and 0.3 μSv/h on the ground at a window. Enhanced caesium contamination was shown without any doubt. It is possible that during the plantation works Chernobyl fall-out contaminated soil has been transported to the area. $^{134}Cs/^{137}Cs$ ratio was not determined. If further studies are warranted, a sample needs to be taken for detailed laboratory studies.

At a restaurant entrance in Rõngu square, a Granite Statue memorial was distinguished from background activity. With hand dosimeter a dose rate of 0.41 μSv/h was noticed. Strong contribution of ^{40}K, Th and U was found, but no signs of ^{137}Cs (see appendix A11). Low dose rates were measured near other granite statues and memorials, as in Kavandu village, for example (0.08 μSv/h).

In Tartu City at the junction of Kalevi and Martha Streets an alarm signal was generated by the apparatus. A spectrum was recorded. Nothing hazardous was found despite of high total count rate (compared to background). The signals originated from rocky basements and building materials. The spectrum showed strong contribution of ^{40}K, Th and U. No ^{137}Cs was found (see appendix A11).

An old local domestic waste storage area was screened. The domestic waste had been buried in the soil and the dose rate was 0.07 μSv/h as measured by Geiger-Müller counter. Nothing special was found.

An old Russian rocket base near Rõngu was screened. The spectrometer count rate increased when the base was approached from the road over the swamp. No man-made nuclides were found. The enhancement of count rate could be explained by sand and concrete. The soil was told to be polluted by diesel and kerosene emissions.

Another old Russian rocket base showed no signs of increased artificial activity. The background dose rate was very low (0.07 μSv/h), as well as spectrometer count rate.

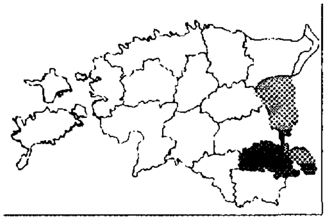
Ilmatsalu School environment was screened. Hand dosimetry and vehicle installed Geiger counter system showed nothing exceptional.

In an Estonian army base, in garage hall 5 at a storage room, the hand dosimetry revealed on the floor a dose rate of 0.15 μSv/h, which is double or triple the normal background dose rate on the area. A wipe sample was taken for further analysis (W1) from a 70 cm * 70 cm horizontal floor made of wood and painted brown. The spectrometric analysis showed nothing special.

In a peat combustion power plant, a ^{60}Co source is installed to control peat vessel surface. At 1 m distance from the source, a hand dosimeter showed 1.34 μSv/h. Radioactivity indicating signs were present, but entrance to the source was not prohibited. The system belongs to fuel level control system and is an example of radioactive source in duty in supervised conditions.

A frontier guard tower was visited at Peipsi in Nina village. The dose rate was 0.06 μSv/h.

3.3.2. Põlvamaa



To screen suspicious places of enhanced radiation or deserted sources, the local guide showed Koidula, Hõpeoja, Saatse (0.06 µSv/h each), Veski (0.08 µSv/h) customs stations and Valgjärve TV-tower (0.06-0.09 µSv/h). The dose rate was low also in Valgjärve School (0.05-0.09 µSv/h) and Kanepi's domestic waste disposal place (0.05-0.08 µSv/h) and in Põlva (0.05-0.07 µSv/h).

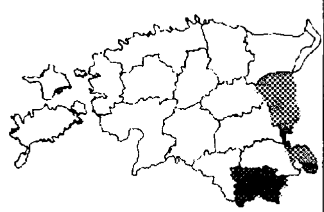
A vegetation free spot at a farm was introduced to the patrol. This round spot with diameter of four meters had dose rate of 0.05-0.1 µSv/h. NaI(Tl) could not distinguish the place from background at 30 m distance. Closer inspection was not possible due to a deep ditch between the field and the road.

Põlva railroad station was screened as well as a metal storage place, but nothing suspicious was found. Räppina area and three domestic waste disposal places were screened, but the dose rate was low, 0.05-0.11 µSv/h, as determined consistently with several instruments. Roads covered with new tar showed higher count rate in the low energy region of spectra than dirt roads.

Somewhat enhanced activity trend was found in Cs-window in Räpina area. This might be an indication of small local Chernobyl fall-out, or an indication of uranium containing natural minerals.

At the Peipsi beach in Rigala village a dose rate of 0.09 µSv/h was measured. In Piusa there was a quartz sand mine. In the caves the hand dosimeters showed 0.05 µSv/h. Near the Piusa caves and the rail road, a potential source was searched, but nothing was found.

3.3.3. Võrumaa

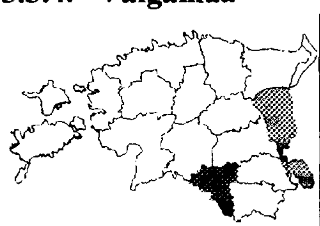


In Võru in Nursi, an old Russian military base was screened. Nothing suspicious was found. The dose rate was 0.05-0.13 μSv/h. The only significant finding was the decreased level of counts at the ^{40}K peak energies in the Nursi, although large concrete structures were present. A wild story about a buried broken nuclear missile somewhere in Võru area was told by local people, but the authorities knew this story and confirmed that it is fortunately only a story.

Võru city domestic disposal place was screened with dose rate of 0.07 μSv/h. Customs places at Latvian border were visited. In Kalkahju the dose rate was 0.05-0.11 μSv/h and in Vaste-Roosa 0.08 μSv/h. At the Russian border nothing special was found; the dose rate was 0.07-0.11 μ/Sv/h.

A tourist trap, the highest place in Baltic countries, Suur Munamägi (318 m) was screened. Dose rate was 0.09-0.12 μSv/h.

3.3.4. Valgamaa



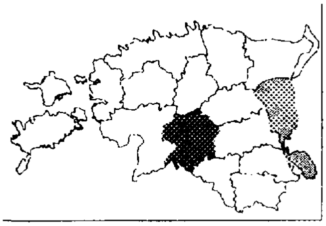
In Valga, a domestic waste disposal place was screened, but revealed nothing anomalous (0.07 μSv/h). In Uniküla, Metsniku, Sangate and Vilaski bases the dose rate was 0.06-0.1 μSv/h. The screened targets varied from military accommodation to medium distance missile storage. A metal collection place was inspected (0.08 μSv/h). Outside of Valga town the customs place Lilli was visited (0.08 μSv/h).

Near town Valga a railroad bridge was studied in detail by NaI(Tl) due to exceptionally high count rates. The GM-dosimetry revealed a dose rate of 0.17

μSv/h at 1 meter distance. Nuclides from uranium and thoron decay series were present as well as ^{40}K. The bridge was old and made of granite stones. In Holdre, in western Valga and in Laatre the dose rate was 0.07 μSv/h-0.11 μSv/h.

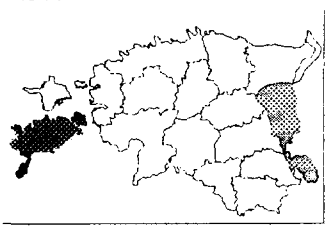
At a bus station in Torva the dose rate was 0.08 - 0.13 μSv/h. Higher values were found near stone buildings. Torva domestic disposal waste storage place had dose rate of 0.08 μSv. Local tourist trap, Koorkülan kuopat was inspected. The dose rate was 0.05 μSv/h inside similar caves as encountered in Piusa in Põlva county. The dose rate was low also in a tourist resort Otepää (0.09 μSv/h).

3.3.5. Viljandimaa



In Viljandi city the dose rate varied between 0.05-0.14 μSv/h. At the street Pikk enhanced count rates were observed by NaI(Tl). However, the spectrum at the location did not reveal any artificial nuclides. An explanation may be the stone-made buildings nearby. The highest dose rate in Viljandi was measured at this cross road: 0.14-0.17 μSv/h. The spectrum showed strong ^{40}K peak and also contribution of Th and U series was high (see appendix A7). In Suislepa the dose rate in an old Russian military airport was 0.1 μSv/h.

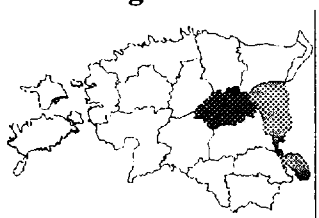
3.3.6. Saaremaa



An old Russian military base was screened. Only normal background dose rates were found around 0.07 μSv/h. At a domestic waste disposal place near town Kuresaare the dose rate was 0.09 μSv/h. At Kaalijärve there is a meteorite impact area, where the dose rate was 0.06-0.12 μSv/h; the higher values are due to rocky environment. Spectrum was measured, but nothing exceptional was found. Strong presence of thoron series and ^{40}K was seen as well as clearly the peaks of the uranium series. Some ^{137}Cs was detected (appendix A8).

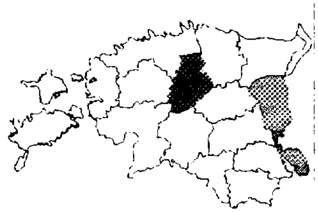
During the voyage to Saaremaa by ship, the instruments recorded the lowest dose rate (0.03 μSv/h), which mainly originates from cosmic rays. Total count rate was below 150 counts/s, while in cities the count rate can vary between 900-2000 counts/s, and in rural areas between 500-800 counts/s. The spectrometer collected a spectrum during the voyage. The count rate was very low, (see appendix 10). The ferry, its cargo or the measuring vehicle itself carried some ^{137}Cs contamination (see appendix A8).

3.3.7. Jõgevamaa



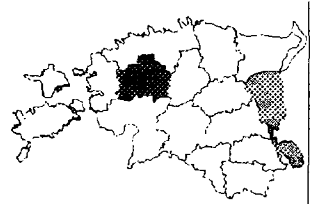
In Jõgeva county there is an old radar base left by the Russians. No anomalous activity was detected. The dose rate was 0.10 μSv/h. A domestic waste disposal place in Jõgeva was screened and the dose rate was 0.10 μSv/h. In addition, the local authorities asked us to monitor a Russian old shooting area at Puurmanni near the Tallinn-Tartu-road. Nothing was found, neither from the cities Põltsamaa and Jõgeva.

3.3.8. Järvamaa



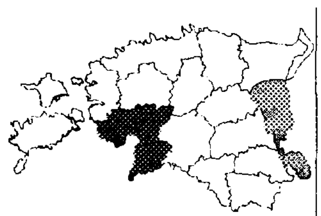
In Järva county, Paide and Türi cities were screened (0.08 μSv/h). An old Russian airport in Nurmsi, Arkma air port and Töörakõrve and Tapa areas had normal background and dose rate of 0.07-0.09 μSv/h. The domestic waste disposal place in Paide was screened; nothing anomalous was found.

3.3.9. Raplamaa



In Rapla county, measurements were performed in the cities Märjamaa and Kohila on the Via-Baltica road. Prillimäe domestic waste storage place, Rajala's old Russian military base and Uusküla military base showed no anomalies. At Via-Baltica, north from Märjamaa, there was a false alarm, which obviously originated from tar on the road. New tar on broad lanes seemed to produce increased count rate in the low energy range of the spectrum.

3.3.10. Pärnumaa

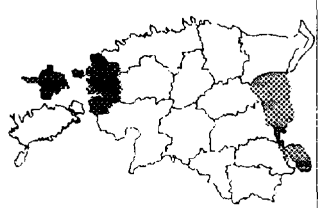


In Pärnumaa a military base was screened (0.06 μSv/h). Dose rate of 0.20 μSv/h was recorded near an old Estonian president memorial in Tahkuranna. As an example of apparatus sensitivity, this granite memorial caused 30 % count rate enhancement in NaI(Tl) monitor from a distance of 50 m.

In Lemme bus stop there was a place with increased dose rate, (detected already in 1995). This place was inspected with NaI(Tl), GM and hand dosimeters to reveal compositional anomalies from normal soil. Nothing suspicious was found; 0.30 μSv/h was measured by hand dosimeter among the sand hills at the lowest location on the yard. A spectrum was collected with acquisition time of 1000 s (20 % dead time). The analysis showed qualitative traces of uranium-decay series and a huge thoron peak (see appendix A9).

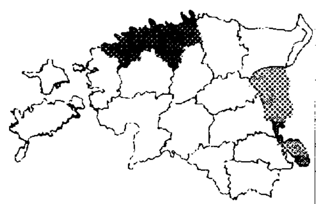
Another interesting place was found in Pärnu. Hand dosimeters revealed dose rate oscillations between 0.05-0.1 μSv/h on Audru fur farm.

3.3.11. Läänemaa



Läänemaa was screened, including island Vormsi and Hiiumaa. The latter is an island and actually a county. The measured dose rates were low, about 0.06 μSv/h as determined with PIC. Local dose rates at Vormsi and Hiiumaa were even lower. Both islands served Russian government as military areas. No signs of artificial activity was found[1].

3.3.12 Harjumaa



The dose rate was 12 μSv/h at the entrance of a nuclear waste storage in Saku. The sources were kept locked in a hut. Paldiski and Pakri Peninsula are a former training base for crews of nuclear submarines. Entrance to the furthest corner of the peninsula was prohibited in 1995. The dose rate varied between 0.05-0.07 μSv/h. An extensive American study showed no enhanced activity in the environment (Feimster, 1995).

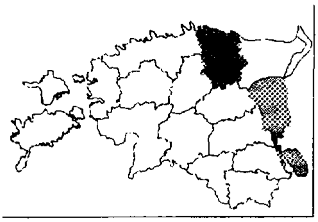
In Harjumaa there are several former Russian military bases: Paldiski, Ämari military airport area, Paljassaare base and Suurkive missile base. In Paljassaare there was a small area (100 m^2), where the dose rate varied between 0.06 - 0.12 μSv/h. Transported soil may explain the variability in Paljassare and Ämari. The bases were in awful shape; all loose parts were either taken or demolished.

The domestic waste storage place of Tallin was searched, but nothing hazardous was found, excluding a local pioneering archaeologist devoted to recycling business.

[1] In 1995 the local police arrested a man selling a 4 kg piece of uranium at the market place of Haapsalu (Laanesoo, 1995)

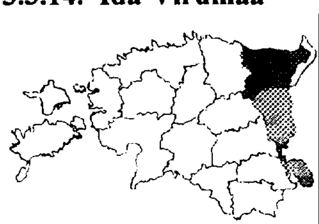
In 1995 the dose rate was observed to vary considerably on Kehrä market place. Therefore, in 1996 a spectrum was collected. ^{40}K peak was the most dominant (see appendix A9) but also U and Th components were strong. Maximum dose rate was 0.14 µSv/h.

3.3.13. Lääne-Virumaa



The dose rates at Lääne-Virumaa were about 0.06 µSv/h. In the city of Tapa an old military area was seen to be clean, except for kerosene (5-7 m deep layer in the soil). In the city of Kunda nothing special was found, except concrete dust, being dispersed annually 36 000 tn. At the border of Lääne-Virumaa there was a spot at the road side, where the patrol stopped for source search. Nothing special was found, but the post analysis revealed a clear presence of ^{137}Cs and ^{40}K. Uranium decay series peaks (352, 609, 1120,1765 keV) and thoron series peaks (911, 2610 keV) were identified with slightly elevated count rates (see Appendix A7).

3.3.14. Ida-Virumaa



In Sillamäe area there are 6.5 million tons of radioactive waste. The area is closed for outsiders. The dose rate may rise locally up to 20-40 µSv/h (Mustonen 1994, Ehdwall et al. 1994). The current danger to the population is radon emitted from the waste pile. However, in Sillamäe city the dose rates were below 0.12 µSv/h. The swipes at the fence of the waste storage contained no man-made nuclides. However, a spectrum at the gate was recorded showing extraordinary strong presence of nuclides from uranium decay series (appendix A12).

The burning stone areas did not indicate any problems related to artificial or enhanced natural radioactivity. The ash mountains did not induce enhanced dose rates.

3.4 Measurements on Tallinn-Narva Road

During the voyage from Tallin to Narva dose rate and spectra were recorded. Fig. 6 shows dose rate (GM), and total counts of the spectrometer as well as counts in the ROI-channels. The patrol stopped for a suspicious source search on a mole hill at the county border of Lääne-Virumaa, but did not find anything. However, a spectrum was collected (Appendix A7). Fig. 7 shows dose rate along Via Baltica from Tallin to Pärnu as measured in 1995 using PIC.

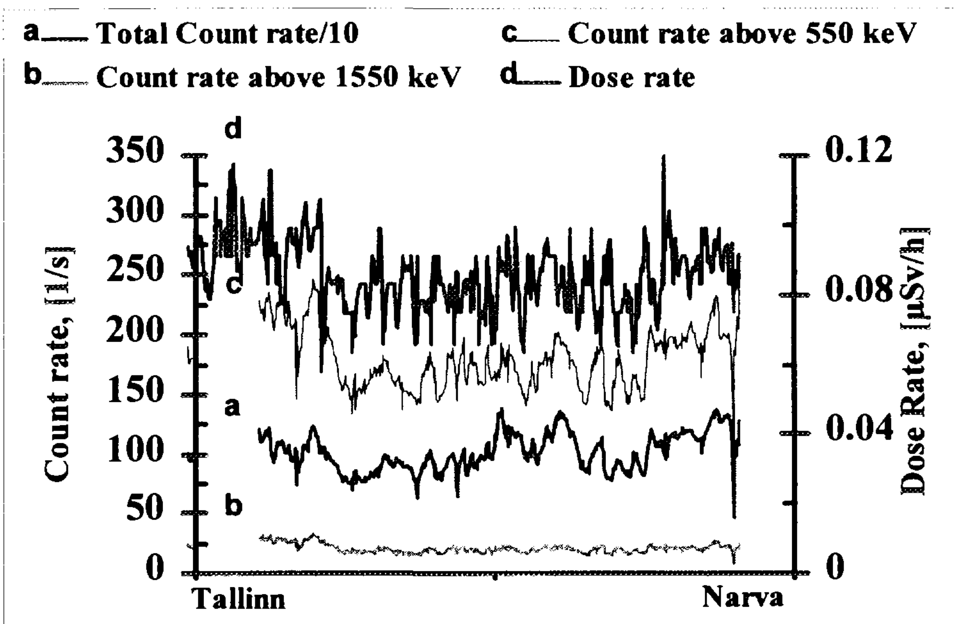


Figure 6. *Dose rate, cumulative count rate in ROI-channels on Tallin-Narva road. A sharp peak in dose rate is seen near Sillamäe gate. The change is not seen on spectral data that are averages for a square of 500×500 m². However, the presence of artificial activity is clear, seen in the raw data. See Appendix A6.*

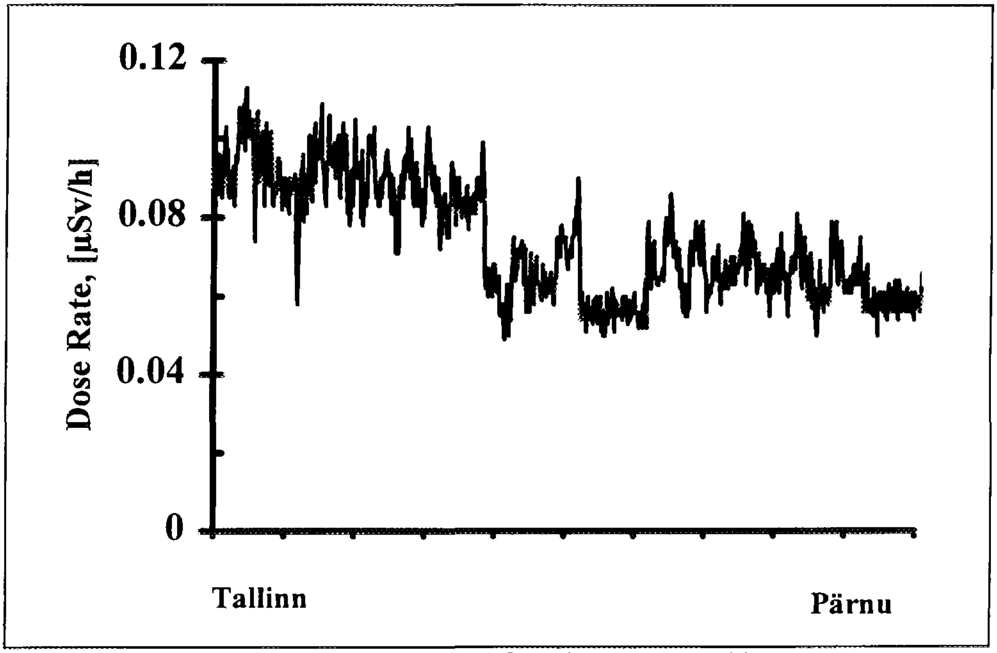


Figure 7. *Dose rate on Tallin-Pärnu road (PIC), 12. June 1995.*

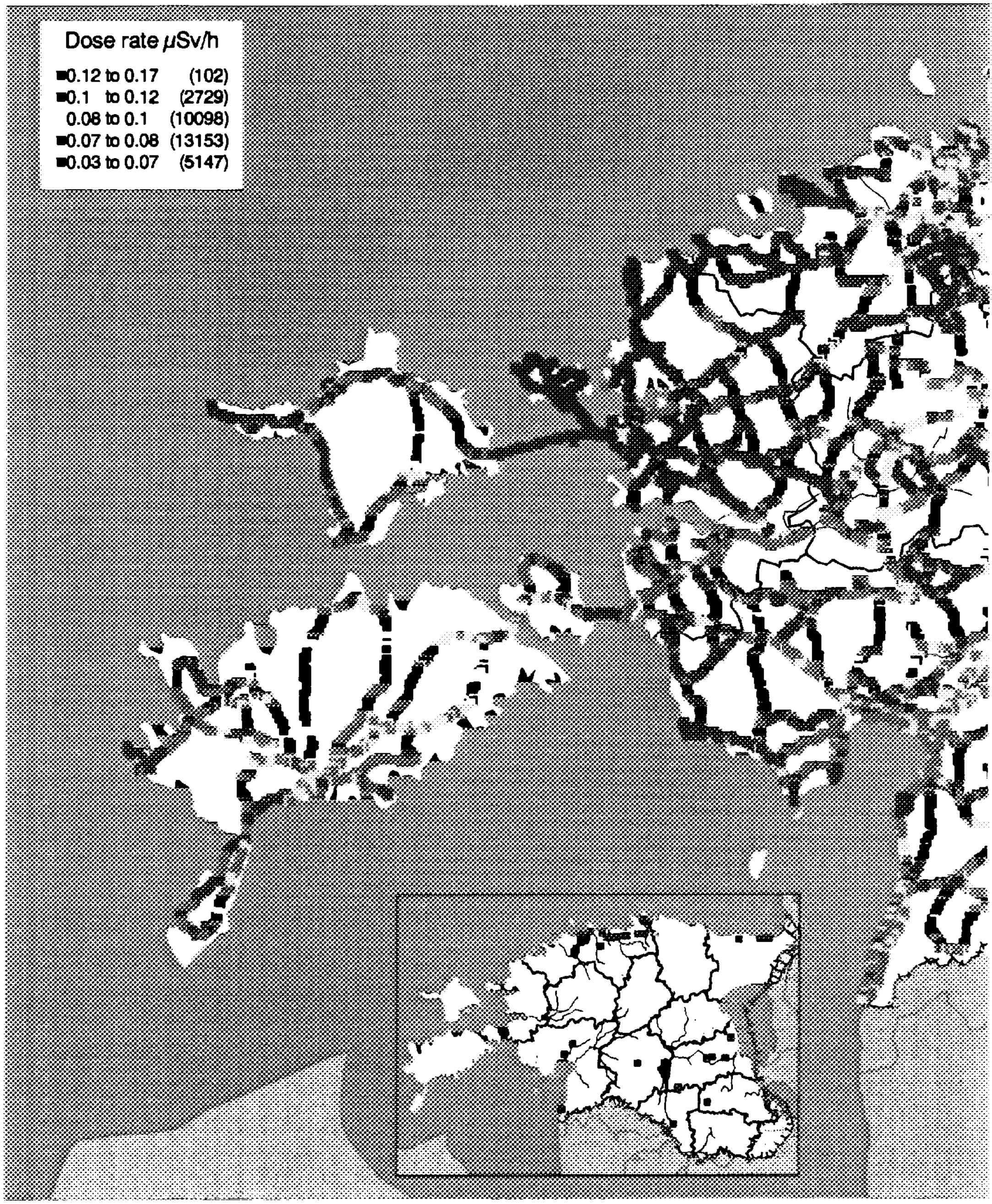
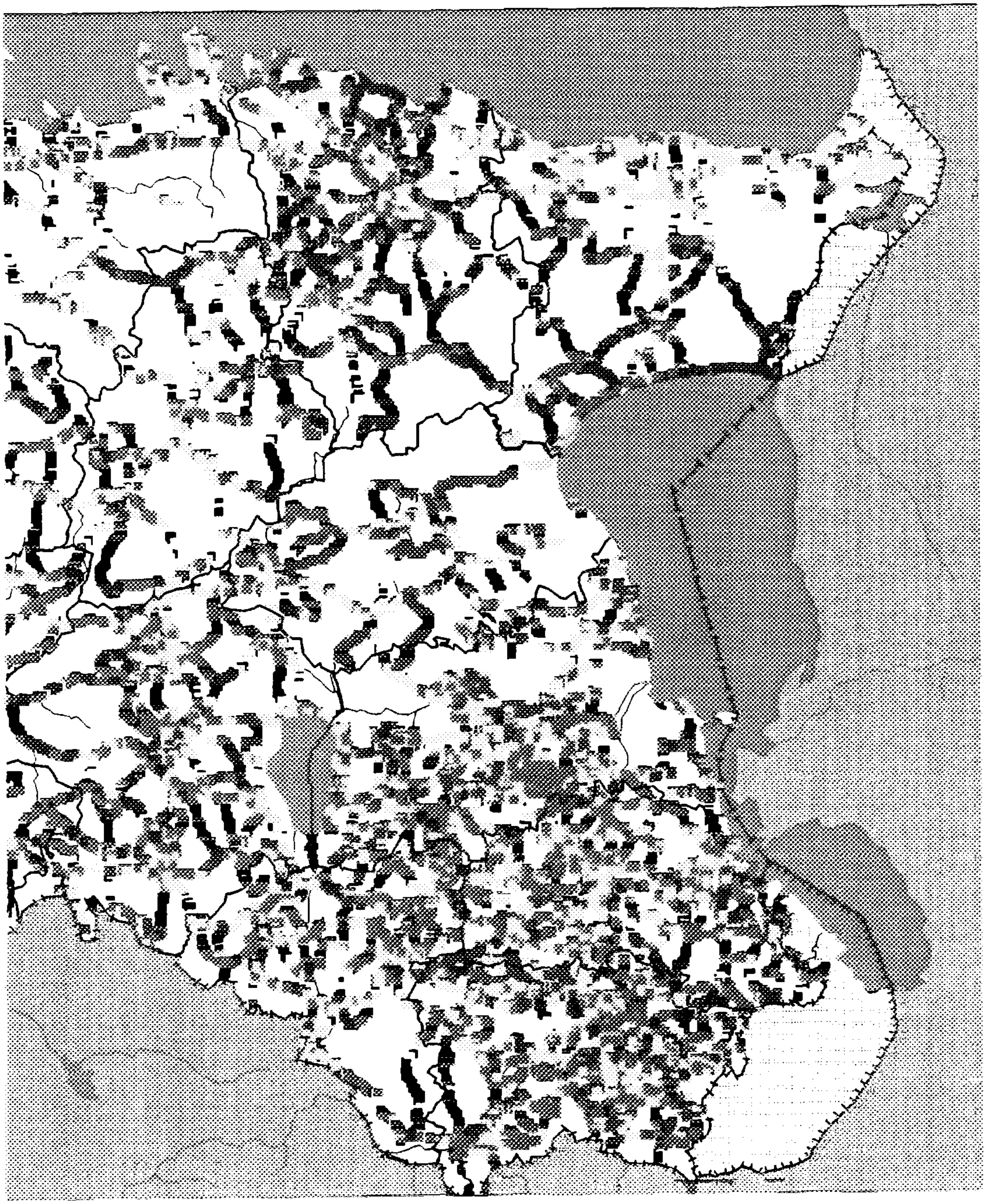


Figure 5. *Dose-rate map over Estonia (1995-1996). Each dot represents dose rate on road averaged over a distance of 500 m. The insert box shows locations of dose rate measured in the category of 0.12 μSv/h-0.17 μSv/h.*



4 DISCUSSION

The environmental survey of Estonia showed that the dose rate all over the country is small. The average dose rate, measured from 400 000 points on Estonian roads, is 0.080 μSv/h (σ = 0.013). The background radiation level is very small in western parts of the country, in the county of Läänemaa in particular. In Finland, the dose rate is equally small only in Lapland. In southern Finland there are areas where the dose rate due to natural radionuclides is above 0.25 μSv/h.

Caesium deposition was not measured systematically. However, the survey showed that the Chernobyl fall-out in Estonia is almost negligible compared with Finland or Sweden, for example. The initial plume from the Chernobyl accident did not hit the Estonian territory. The plume was transported at high altitudes above the Baltic Sea towards the Nordic countries. Thus, the total fall-out in Estonia was small, although at later stages of the accident also Estonia received some debris.

A Nordic field exercise for monitoring radioactive fall-out and for finding lost radiation sources was carried out in Finland in august 1995 within the frames of the Nordic Nuclear Safety Research (NKS). The exercise was named RESUME95 - Rapid Environmental Surveying Using Mobile Equipment. The test took place in the area around Asikkala and Padasjoki, 25 - 50 km north of Lahti. Teams from Denmark, Finland, Norway, Sweden, France, Scotland, Germany, and Canada took part in various measurements. In this field test the Finnish Centre for Radiation and Nuclear Safety and the Helsinki University of Technology developed special software to integrate different measuring equipment for finding lost radiation sources. One of the systems developed, based on a 5"x5" NaI crystal, was used in Estonia to search for point sources near the roads. The survey in 1995 and 1996, screening roads more than 35,000 km, did not reveal a single source. The conclusion is that the general environmental radiation safety in Estonia is good, although it cannot be excluded that radiation sources are abandoned at locations that are far away (>100 m) from the roads or are shielded or partially shielded.

5 REFERENCES

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APPENDIX A1

Dose Rate Measurement Using Pressurised Ionisation Chamber (PIC)

Reuter-Stokes RSS-112 apparatus:

Central Unit:

-Data is read from PIC central unit to PC via RS-port

High pressurised ionisation chamber:

-Gamma and Röntgen radiation detector in energy range 0.07-10 MeV with nearly linear response.

-Relative accuracy ±5 %

-Dose rate range 0-1 mSv/h:

Low range 0-5 μSv/h

High range 0.05-1 mSv/h

-Electrical sensitivity:

Low range: 20 mV/(μR/h)

High range: 100 mV/(μR/h)

-Temperature error: 0.06 %/°C

-Operating temperature: -25-+55 °C

Computer:

COMPAQ LTE Elite 4/40 CX

Satellite Navigation:

Trimble Mobile GPS: PCMCIA-card and satellite antenna

Software:

SAKU program packet to processes the PIC-dose rates and GPS-co-ordinates into SVO+ data format on the hard disk. SAKU supports MAPINFO desktop mapping and real time monitoring.
In addition to graphics, alarm signals are generated above a pre-set limit

Additionally

A hand dosimeter: ALNOR RDS-120, Dose rate range 0.05 μSv/h - 10 Sv/h

APPENDIX A2

Geiger-Müller-Counter (GM) ALNOR RD-02L

Detector consists of two halogen energy compensated GM-tubes, (Mullard ZP 1221, Philips ZP 1304). Ambient dose equivalent energy response, detection of gamma and röntgen rays.

Dose Rate Range: 0.01 μSv/h-10 Sv/h

Response Dependence on Radiation Energy:
±20% in 80 keV- 1.3 MeV
±30% in 50 keV- 3 MeV

Calibration Accuracy:
±5% of ^{137}Cs exposure in +20 °C

Measurement Accuracy
±15% from 0.03 μSv/h to 10 Sv/h

Operational Temperature
±20% in range -40°C - + 70°C

Response Dependence on Power Supply
±10% in range 0.7 - 1.2 times nominal operating voltage +12 V

Response to Angle of Incidence
±15% within ±180° horizontally from the calibration direction
±30% within ±45° vertically from the calibration direction

Statistical Fluctuation ± 15% with Integration Time 10 min in the range of 0.1 μSv/h-10 Sv/h

Capacity for 864 measurements, automatically recorded

Source voltage + 12 VDC ± 2.4 VDC
Power Consumption 20 mA/+12 VDC at normal background radiation

Class of enclosure IP 67

APPENDIX A3.

Characteristics of Scintillator Spectrometer Apparatus. NOMAD Hardware Specifications (ORTEC, Nomad model 92X-P)

Amplifier:

-Gain: 4 to 1000 continuously adjustable from computer. Minimum step =1/4000
-Integral non-linearity <±0.025% from 0 to 10 V
-Equivalent input noise < 7μV RMS at 6-μs shaping time for gains >100
- *Temperature coefficient* <0.01%/°C *for gain and* <±10 μV/°C *for* Dc level, 0 to 50 °C

Bias Supply:

-Polarity selection for HPGe or NaI operation
-NaI operation 0 to ±2000 V, 250 μA maximum,
Stability <±100 ppm/°C

ADC:

-Differential non-linearity <±1% over 99% range
-Dead time correction according to Gedcke-Hale method
-Dead time correction accuracy : Area of reference peak changes <±3% as the count rate increases from 0 to 50 000/s, 6 μs shaping time.
-Conversion time 25 μs, fixed.
-Gain instability <50 ppm/°C

Micro processor:

-Intel 80C186 64 RAM

APPENDIX A4

DETAILS OF SAMPO 90 SOFTWARE FOR GAMMA-RAY SPECTROMETRY (VERSION 3.40)

1 Spectrum transfer and display

Up to 16 k channel spectra can be read from various sources:

- ASCII files
- Binary SAMPO files; in addition, the binary spectrum files from the following MCA-systems are recognised:
    - AccuSpec
    - Canberra S100
    - Nucleus PCA
    - Ortec
- Direct read and control for the following MCA-systems:
    - Stand alone MCAs using Canberra serial and parallel interface
    - Canberra/ND Accuspec acquisition boards
    - ABB LP7000 series GPIB bus MCAs

A flexible spectrum window supports live display, cursor, dual spectra, peak add and drop, peak fitting, shape calibration fitting, display of analysis results and various options to view the spectrum.

2 Automated calibrations

- Calibrations for peak shape, efficiency and energy
- Energy and efficiency calibrations can be generated using calibration source line library
- peak shape fitting
- Annihilation line treated as a special case in the shape calibration
- In addition to interpolation/extrapolation, various functions can be fitted to the calibration data:
    - Polynomials from 0 to 9 degree
    - Logarithmic polynomials from 0 to 9 degree
    - Square root polynomials from 0 to 9 degree

3 Peak search

- Method of smoothed second differences
- Peak found in the minimum of the second differences is strong enough (search threshold)
- Location is weighted average over the second differences
- Shape checks discriminate against Compton edges

APPENDIX A4

- Strong enough peaks are accepted for fitting
- Search in user defined part of the spectrum
- Search and fitting thresholds are adjustable
- User can insert peaks by hand directly to the spectrum
- User can insert peaks by entering peak channel or energy

4 Peak shape fitting

- Gaussian with exponential tails
- Width and starting points of the tails are smoothly varying
- Calibrated by non-linearly fitting a 7-parameter function to well defined peaks
- Fitting is done to peaks found in the peak table, fitting threshold is adjustable
- Interactive visual check of the fit
- Fitting interval can be modified by the user
- Residuals and goodness-of-fit parameters serve as indicators of the fit quality

5 Peak fitting

- Pre-calibrated peak shape fitted to data
- Minimisation is done with respect to background parameters (2 in linear and 3 in parabolic mode) and peak heights
- Up to 32 peaks are fitted together in the intervals up to 200 channels (in special versions even more)
- Non-linear and linear fitting
- Peak positions and areas can be frozen and/or freed in any combinations in a multiple fit
- Interactive control over fit
- Fitting intervals can be modified, peaks can be added and dropped
- Residuals and goodness of fit indicators are available
- Fitting residuals analysis: peaks are automatically added in or dropped from the positions where the residual analysis finds missing or extra peaks

6 Nuclide identification

- Identification using gamma line libraries that can be edited by the user
- 'Close enough' peaks from the library define the nuclide as a candidate
- Confidence limit that can be modified by the user

Half-lives taken into account

APPENDIX A4

- Interfering nuclides calculated by weighted least squares method using library line and spectrum line intensities
- Activities calculated and corrected for decay during counting, cooling, irradiation and sample collection
- Minimum detectable activities calculated
- Maximum permissible concentrations calculated
- (Iodine)dose equivalents calculated
- Average decay energies calculated
- Background peaks subtracted.

7 **Report generation**

- Versatile report generation available using special Report Generator Language (RGL)
- RGL is full featured programming language that uses Reverse Polish Notation (RPN). Wide variety of mathematical functions are available, IF -conditions, FOR -loops, output formatting, string operations, keyboard input, a selection of SAMPO functions and full access to SAMPO internal variables
- Also the end user can write RGL programs of his own to tailor the report output
- Many sample report examples written in RGL available varying from standard report of gamma spectrum analysis to a browser of gamma line library

8 **Macros**

- Macros are a way of automatic spectrum collection and analysis as well as some routine tasks
- Macros can be automatically generated using a Macro Recorder
- Sample data can be automatically added to macro collected spectra using pre-defined sample files
- Macros can also handle keyboard input

APPENDIX A5

Photon Absorption in the Vehicle

The attenuation of gamma rays through car windows was measured. Spectra of a ^{137}Cs point source of 1 μCi were measured with an HPGe-spectrometer. The source was put at a distance of 695 mm from the detector centre, inside the car at the window, and a spectrum was acquired. Another spectrum was recorded with the same set-up, but the source was outside the window. Seven channels were chosen to describe the ^{137}Cs peak. Background was subtracted and r^2-correction was made. The peak areas were divided. A penetration of 90 % was observed for 661 keV photons through Securite glass with thickness of 4 mm.

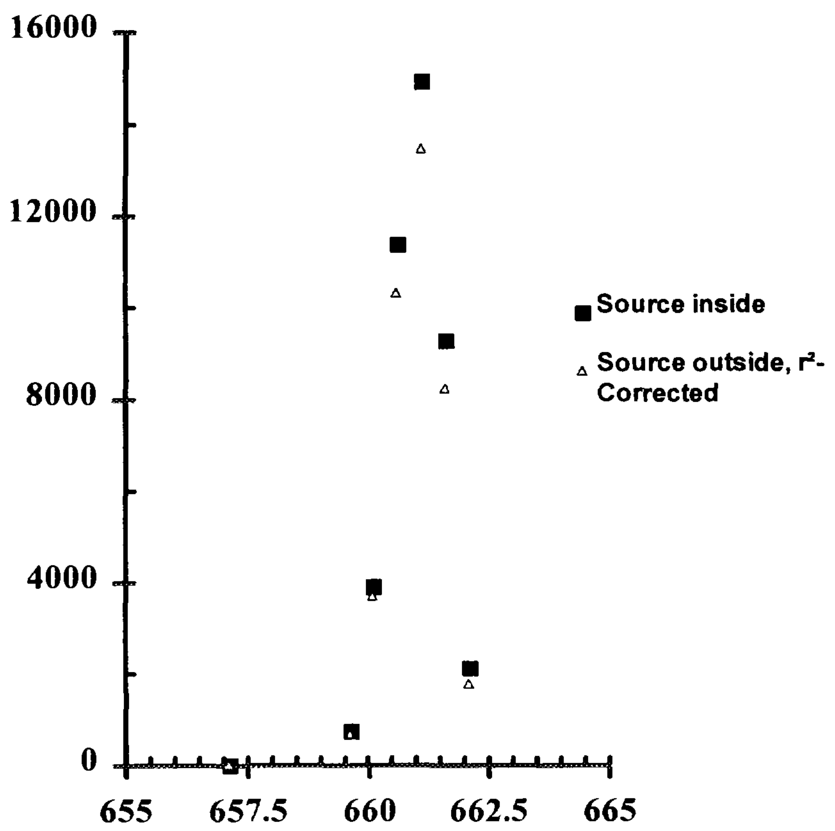
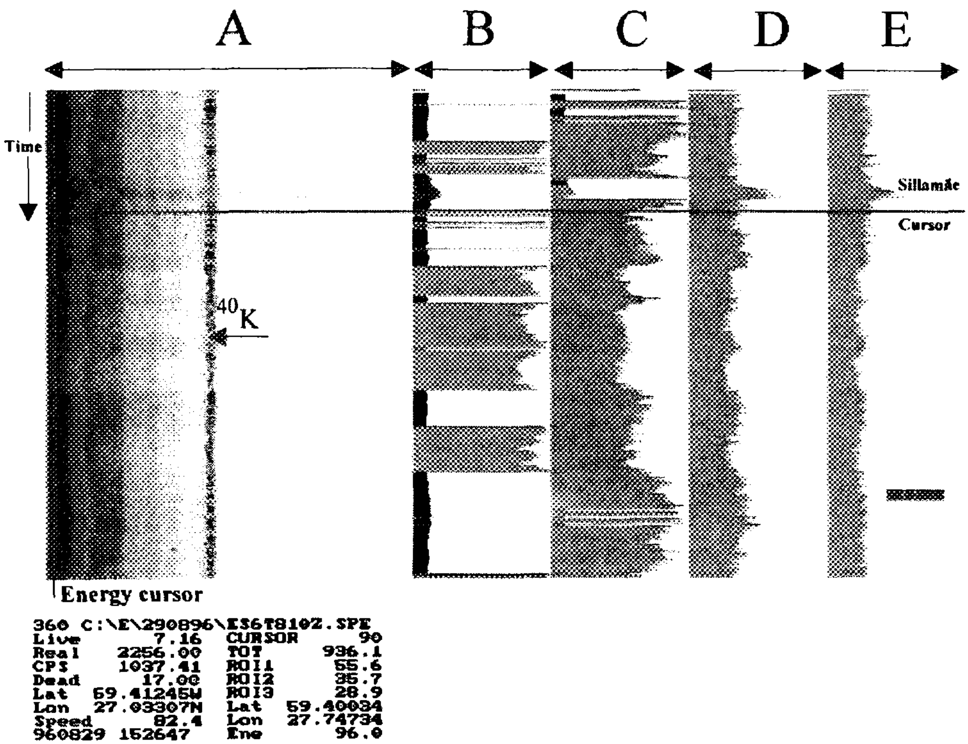


Figure A5.1. ^{137}Cs peaks for mass-absorption measurement.

APPENDIX A6

Colour Coded spectra of SAMPO on Screen in Real Time

Enhanced radiation at the gate of a nuclear storage area in Sillmäe is clearly seen in the "water-fall" presentation of spectra.



A Energy Spectrum 0-3000 keV, colour coded CPS[2]

B CPS in A, colour coded total count rate

C ROI 1. CPS in energy range 626-696 keV, ^{137}Cs window

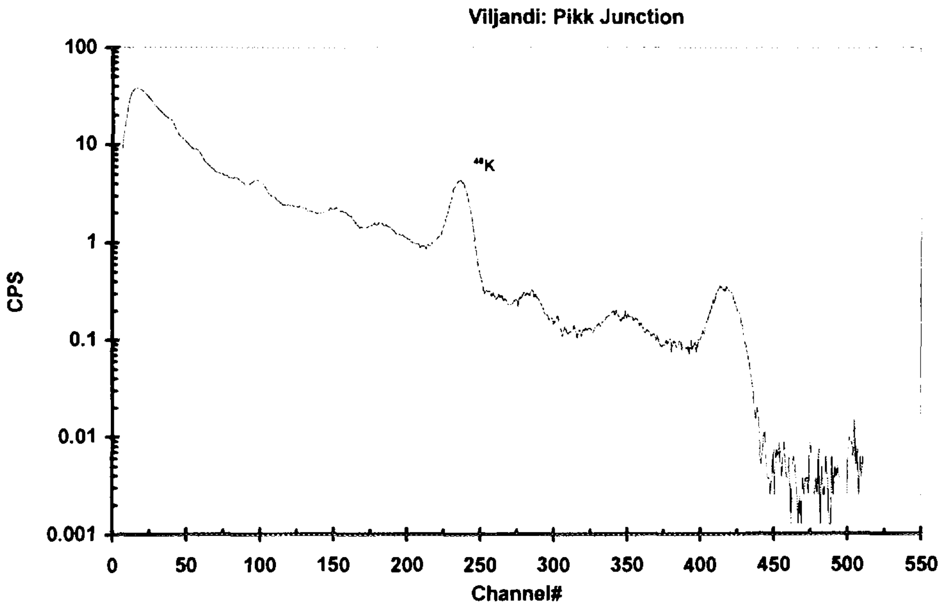
D ROI 2. CPS in energy range 1140-1360 keV, ^{60}Co window

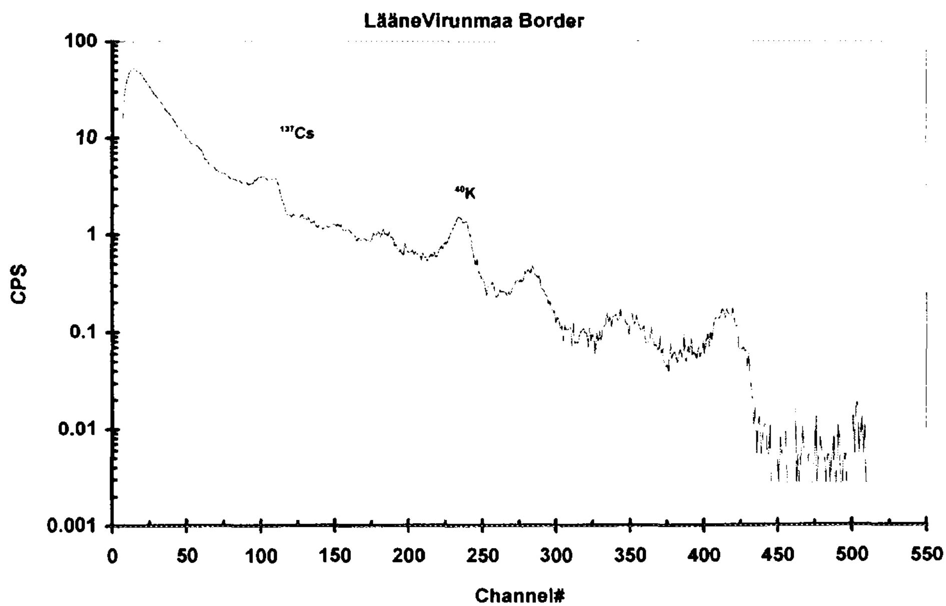
E ROI 3. CPS in energy range 1400-3000

[2] Each horizontal line contains one spectrum. The colours (here in grey scale) indicate count rate in each channel (pixel).

APPENDIX A7

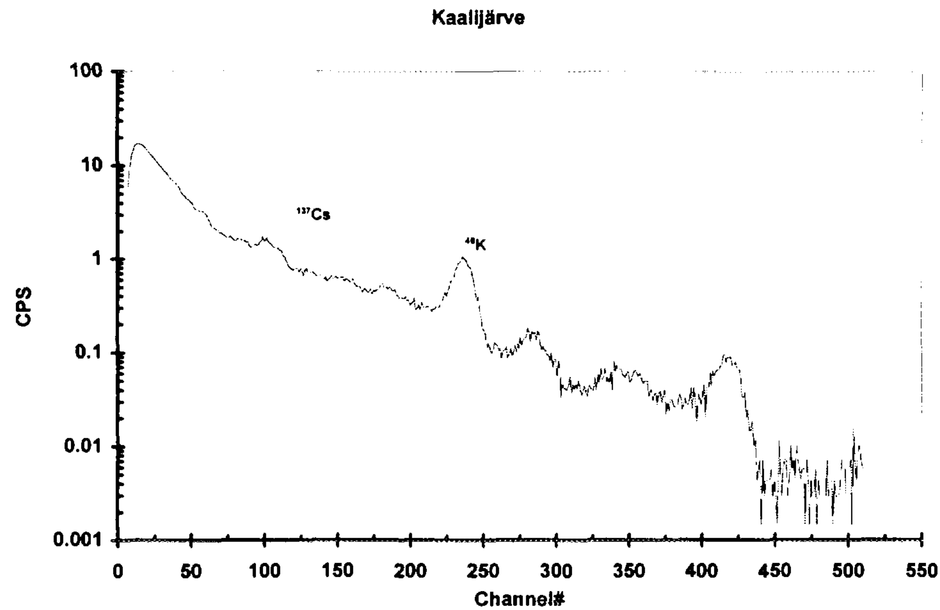
SPECTRA FROM VILJANDI PIKK JUNCTION (6. Aug 1996) AND LÄÄNE-VIRUMAA BORDER (along Tartu-Narva road, 29. Aug 1996). Acquisition times 802 s and 369 s, respectively.

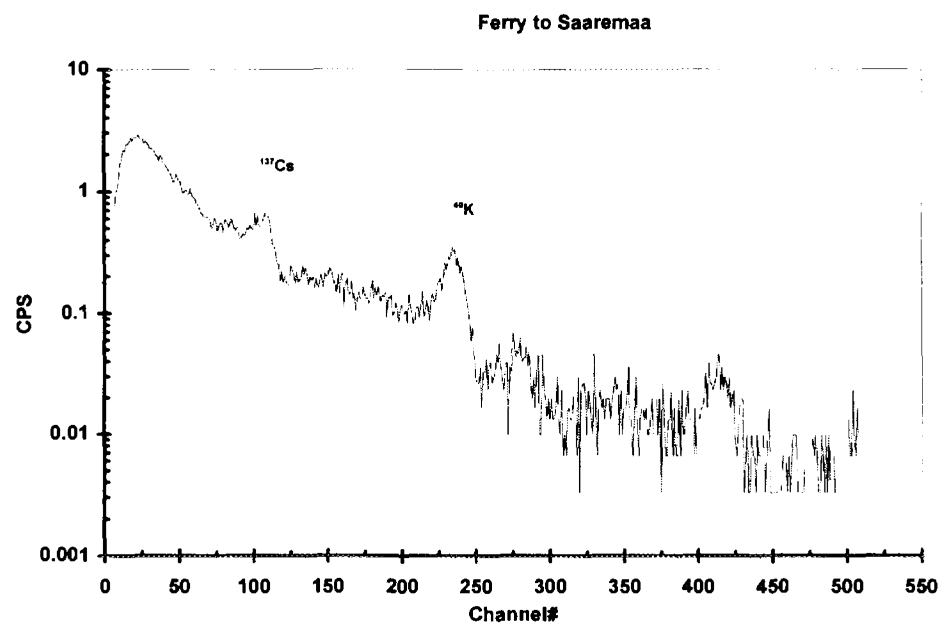




APPENDIX A8

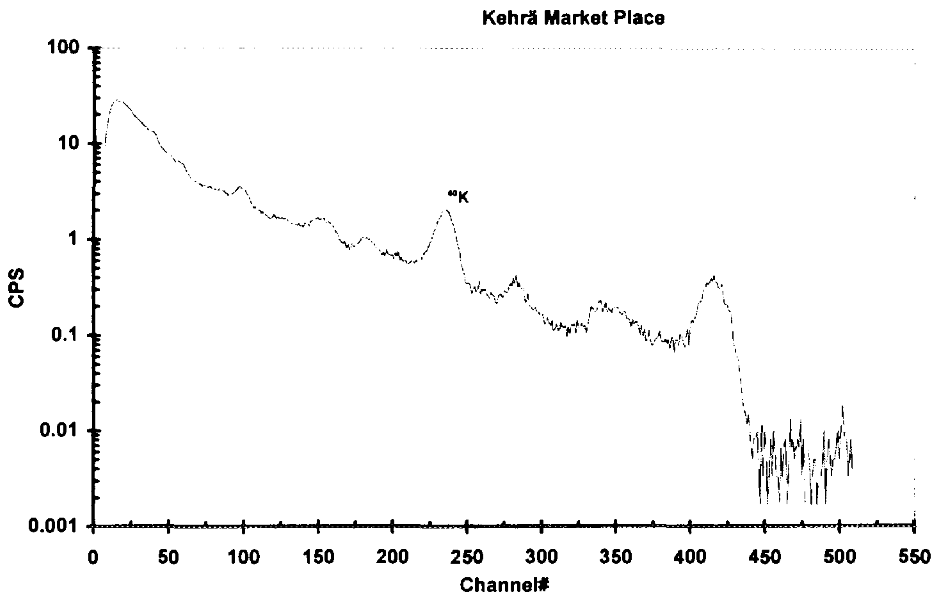
SPECTRA FROM KAALIJÄRVE METEORITE IMPACT AREA (28. Aug 1996) AND SAAREMAA FERRY (28. Aug 1996) Acquisition times 689 s and 307 s, respectively.

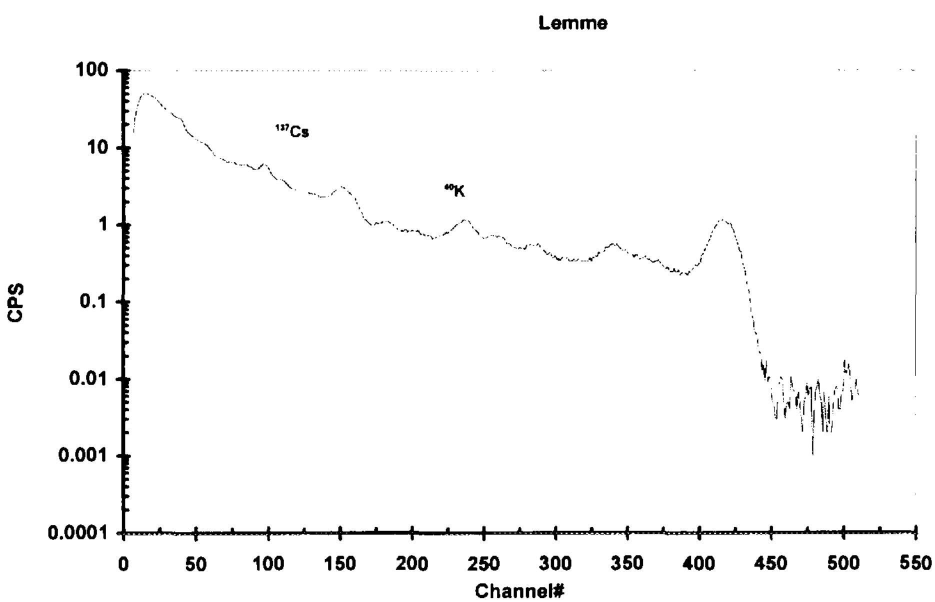




APPENDIX A9

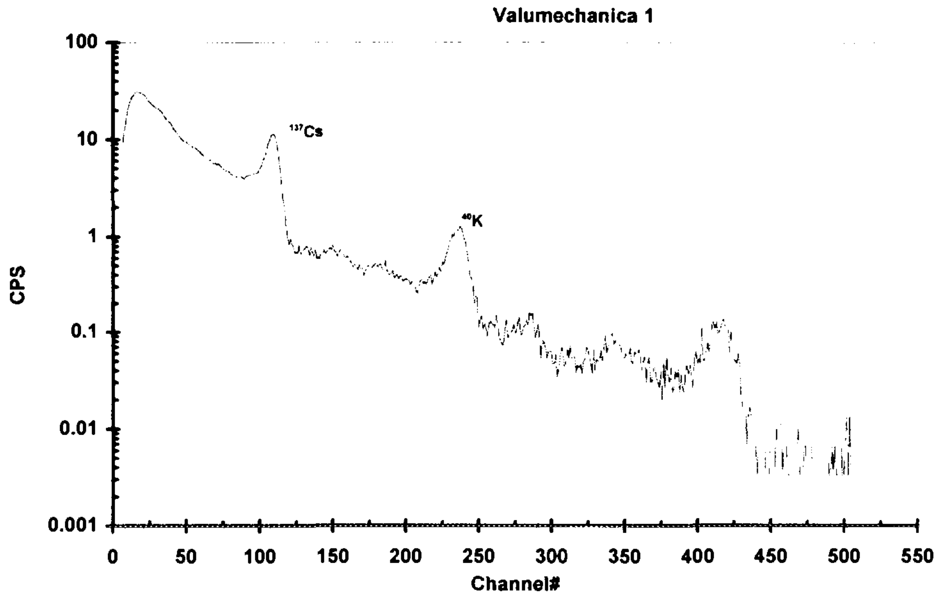
SPECTRA FROM KEHRÄ MARKET PLACE (17. Jul 1996) AND LEMME BUS STOP (from Pärnu to south, (21. Jul 1996). Acquisition times 603 s and 1010 s, respectively).

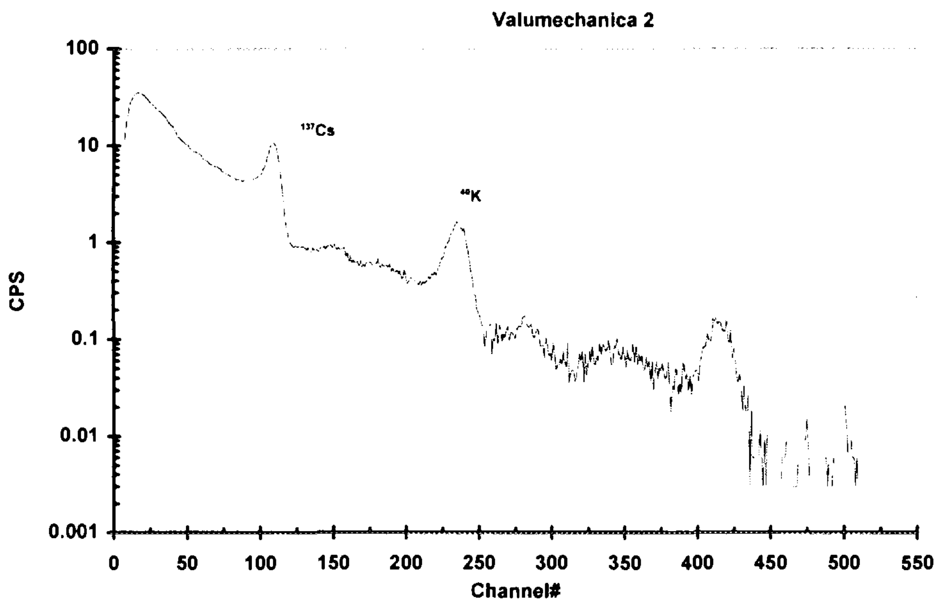




APPENDIX A10

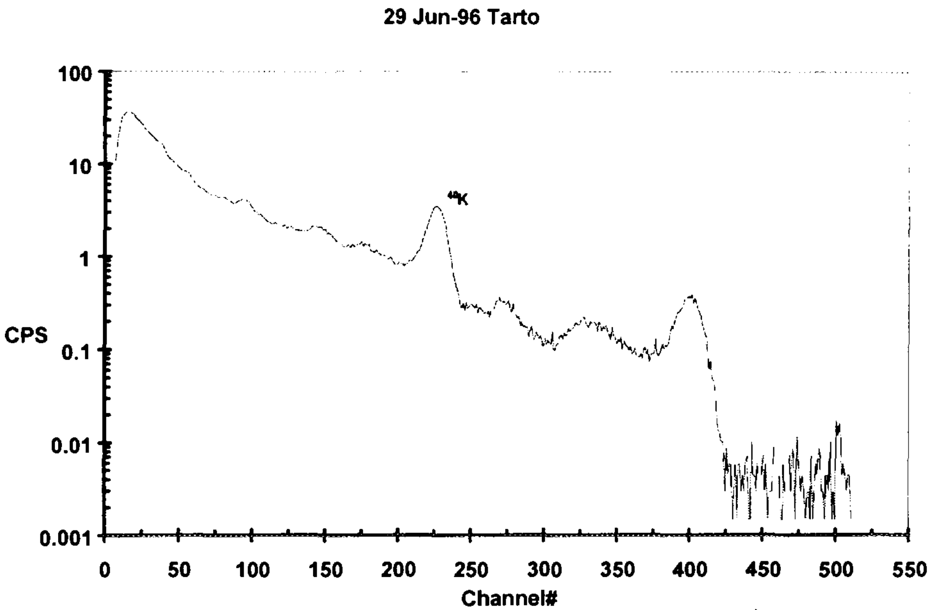
SPECTRA FROM VALUMECHANICA ENTRANCE IN TARTU CITY (12. Jun 1996). Acquisition times 302 s and 335 s, respectively.

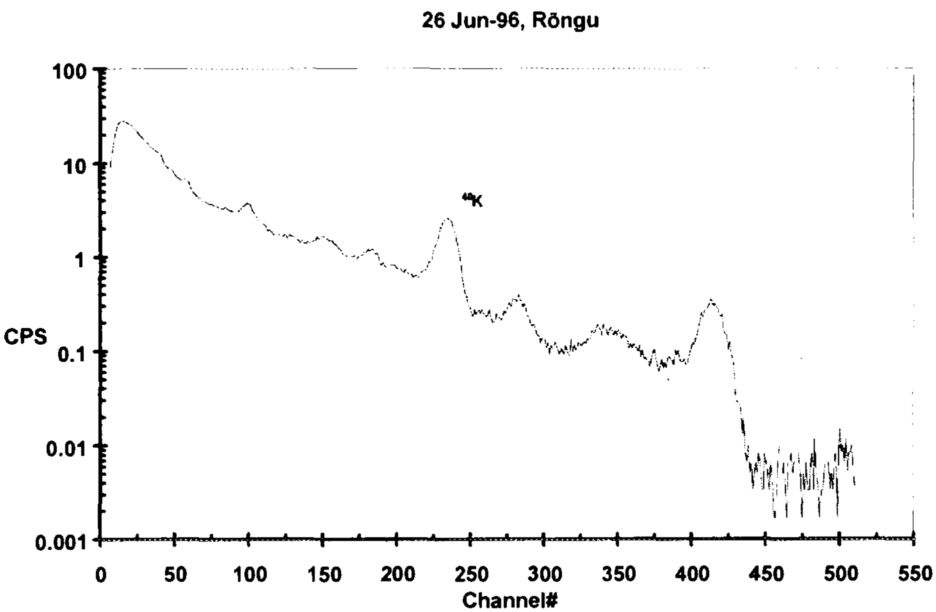




APPENDIX A11

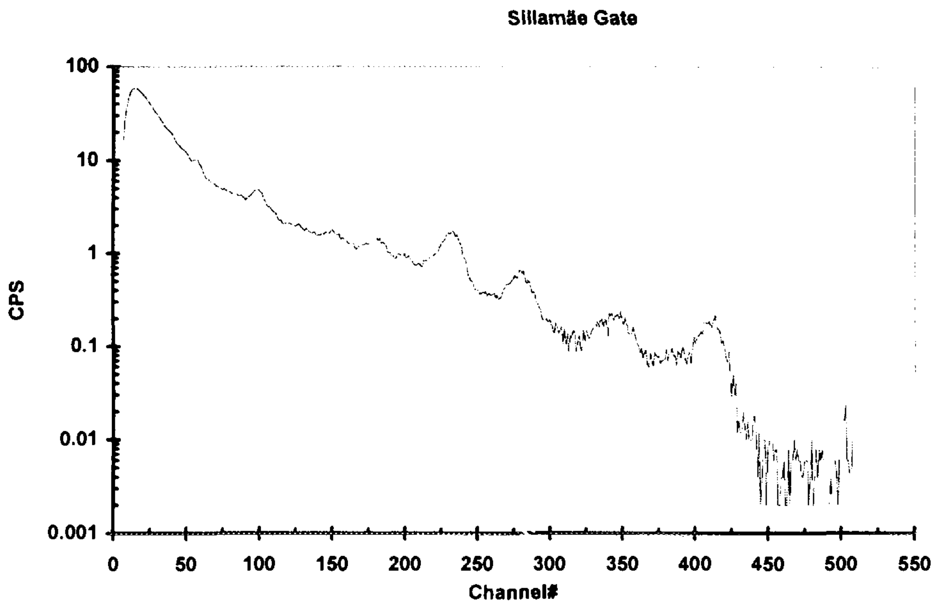
SPECTRA FROM MARTHA AND KALEVI JUNCTION IN TARTU CITY (29. Jun 1996) AND SPECTRA OF MEMORIAL IN RÕNGU SQUARE (26. Jun 1996). Acquisition times 685 s and 602 s, respectively.





APPENDIX A12

SPECTRUM FROM SILLAMÄE ENTRANCE GATE TO NUCLEAR STORAGE AREA (29. Aug 1996). Acquisition time 506 s.



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