Recommendations to harmonize European early warning dosimetry network systems

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ABSTRACT: After the Chernobyl nuclear power plant accident in 1986, followed by the Fukushima Nuclear power plant accident 25 years later, it became obvious that real-time information is required to quickly gain radiological information. As a consequence, the European countries established early warning network systems with the aim to provide an immediate warning in case of a major radiological emergency, to supply reliable information on area dose rates, contamination levels, radioactivity concentrations in air and finally to assess public exposure. This is relevant for governmental decisions on intervention measures in an emergency situation. Since different methods are used by national environmental monitoring systems to measure area dose rate values and activity concentrations, there are significant differences in the results provided by different countries. Because European and neighboring countries report area dose rate data to a central data base operated on behalf of the European Commission, the comparability of the data is crucial for its meaningful interpretation, especially in the case of a nuclear accident with transboundary implications. Only by harmonizing measuring methods and data evaluation, is the comparability of the dose rate data ensured. This publication concentrates on technical requirements and methods with the goal to effectively harmonize area dose rate monitoring data provided by automatic early warning network systems. The requirements and procedures laid down in this publication are based on studies within the MetroERM project, taking into account realistic technical approaches and tested procedures.

KEYWORDS: Data acquisition concepts; Dosimetry concepts and apparatus; Overall mechanics design (support structures and materials, vibration analysis etc); Radiation monitoring

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1 Introduction

Currently, about 5500 area dose rate monitoring stations are operated in Europe as part of an early warning network. The different national networks comprise a variety of different detector systems (i.e., different dosemeters and spectrometers) and the operators use different analysis methods. In addition, the density of the networks, the measuring intervals, the calibration procedures and even the quantity in which results are reported are still different from country to country. In the case of a nuclear accident with transboundary implications, the lack of qualified information
Figure 1. Example of a screen view of the EURDEP system. Measuring stations are displayed as dots. Their colour gives information on the measured dose rate in steps (the darker the color, the higher the measured dose rate at the date, when the screen shot was made in May 2017).

may therefore cause again significant problems when dose rate levels reported from various countries shall be exchanged or interpreted on a European scale. After the Chernobyl accident, the European Commission established a central data management system for the automatic exchange of radiological data on a continuous base called European Radiological Data Exchange Platform (EURDEP) [1]. This data exchange system makes radiological monitoring data from most European countries available nearly in real-time (figure 1) and liberates EU Member State Authorities to have to report environmental monitoring data via the official European Community Urgent Radiological Information Exchange (ECURIE) system.

This paper summarizes the basic results of the EU funded MetroERM project, which aims at the harmonization of measured results of early warning network systems.

For the purpose of data harmonization the EURDEP system has been upgraded in the past years by the so-called AIRDOS extension [2]. The referring data, the individual characteristic parameters of the probes of the area dose rate monitoring stations, have been provided by national network operators mainly on the basis of investigations in the framework of the WG3 EURADOS intercomparisons performed by the European Radiation Dosimetry Group (EURADOS) and in parallel by the so-called intercalibration (INTERCAL) exercises performed by the German Federal Office for Radiation Protection (BfS).
In a first step, probes installed in the national area dose rate monitoring networks have been investigated in the framework of the EURADOS intercomparison and the INTERCAL inter-calibration exercises. In a second step, input was provided to the EURDEP system by national area dose rate monitoring network operators taking into account the individual characteristic parameters of the area dose rate monitoring probes.

EURADOS addressed the problem of comparability of dose rate measurement results from the metrological point of view by its working group WG3 “Environmental Radiation Monitoring”. EURADOS WG3 therefore invited the operators of national area dose rate early warning networks to participate in European intercomparison programs in 1999, 2002, 2006, 2008, 2009 and 2012. Further intercomparisons were performed in 2015 and 2016 by the MetroERM project. The investigations and experiences made during these intercomparison exercise programs also help new and potentially new member states of the European Union to ensure that the presuppositions to join the EURATOM treaty, as far as environmental radiation monitoring is concerned, are sufficiently fulfilled. As a second approach, BfS operates the so-called inter-calibration site permanently, which allows different network operators to directly compare the performance of their detectors on a long-term basis.

Table 1 lists information on early warning stations, which report data to the European data exchange platform. However, additional dose rate monitoring networks exist in many countries. On a national scale, it is useful to combine the different monitoring networks. Thus, monitoring networks have to be harmonized on national and European scale. The harmonization of measuring and data evaluation methods is a prerequisite for a reliable assessment of the exposure of the population.

In the following sections, the minimum requirements and recommendations are described to improve and harmonize area dose rate measurements in Europe, because standardized and agreed methods of data collection and validation procedures are needed to correctly assess the exposure of the population caused by environmental radioactivity.

2 Network functions and current situation

Area dose rate monitoring networks are installed in all European countries belonging to the European Union (EU) and many neighboring countries. The EU member states and many other countries agreed to exchange measured dose rate data via the European data exchange platform (EURDEP) [1]. Routinely measured and validated data are published via both, the public and the access restricted part of this platform. In table 1 some information about the monitoring stations integrated in the EURDEP network are listed as published on the EURDEP website (the status in 2005 was published in [3]).

Beyond the routine mode, area dose rate monitoring networks support the following tasks [2]:

• The so-called early warning function of the networks allows the detection of abnormal situations (events) with enhanced dose rate and/or enhanced artificial radioactivity in the environment due to an accidental or un-peaceful release of radioactivity.

• The delineation of affected areas with enhanced dose rate and/or enhanced artificial radioactivity in the environment on the basis of spatially distributed dose rate data.

• Hazard and risk mapping as a core function of area dose rate monitoring networks: data are provided for decision support systems to assess the distribution of external doses to the public.
Table 1. European early warning networks for dose rate monitoring, status April 2017. The transmission method of all listed countries is FTP download by mirroring software.

| Country          | Representative measuring period | Transmission interval | Number of stations | Area  | Stations per area |
|------------------|---------------------------------|-----------------------|--------------------|-------|-------------------|
|                  | hh:mm                           | hh:mm                 |                    | km²   | 1/1000 km²        |
| Austria          | 01:00                           | 00:30                 | 333                | 83878 | 3.95              |
| Azerbaijan       | 00:30                           | 01:00                 | 6                  | 86600 | 0.07              |
| Belarus          | 00:10                           | 12:00                 | 40                 | 207595| 0.19              |
| Belgium          | 01:00                           | 00:55                 | 125                | 30528 | 4.06              |
| Bulgaria         | 01:00                           | 01:00                 | 28                 | 110994| 0.26              |
| Croatia          | 00:30                           | 00:02                 | 32                 | 56542 | 0.58              |
| Cyprus           | 01:00                           | 00:56                 | 8                  | 9251  | 0.86              |
| Czech Republic   | 01:00                           | 01:00                 | 64                 | 78864 | 0.81              |
| Denmark          | 00:17                           | 01:36                 | 11                 | 43094 | 0.26              |
| Estonia          | 00:17                           | 00:54                 | 18                 | 45227 | 0.40              |
| Finland          | 01:00                           | 00:15                 | 266                | 338432| 0.79              |
| France           | 01:00                           | 00:57                 | 852                | 668763| 1.27              |
| Germany          | 01:00                           | 00:55                 | 1887               | 357121| 5.29              |
| Greece           | 01:00                           | 02:00                 | 23                 | 131957| 0.17              |
| Greenland        | 00:16                           | 01:36                 | 3                  | 2166086| 0.00             |
| Hungary          | 01:00                           | 00:57                 | 120                | 93036 | 1.29              |
| Iceland          | 00:10                           | 00:10                 | 4                  | 103125| 0.04              |
| Ireland          | 01:00                           | 01:00                 | 15                 | 70182 | 0.21              |
| Italy            | 01:00                           | 00:08                 | 227                | 301338| 0.75              |
| Latvia           | 00:10                           | 00:10                 | 21                 | 64589 | 0.33              |
| Lithuania        | 00:10                           | 00:10                 | 13                 | 65300 | 0.20              |
| Luxembourg       | 01:00                           | 00:30                 | 13                 | 2586  | 6.57              |
| Macedonia        | 00:05                           | 01:00                 | 17                 | 25713 | 0.47              |
| Malta            | 01:00                           | 04:48                 | 12                 | 316   | 12.66             |
| Netherlands      | 01:00                           | 00:19                 | 168                | 41548 | 4.04              |
| Norway           | 01:00                           | 00:49                 | 40                 | 385199| 0.10              |
| Poland           | 01:00                           | 00:53                 | 25                 | 312685| 0.08              |
| Portugal         | 00:10                           | 01:00                 | 13                 | 92212 | 0.14              |
| Romania          | 00:10                           | 00:15                 | 193                | 238391| 0.96              |
| Russia (European)| 00:10                           | 03:00                 | 129                | 3960000| 0.03          |
| Serbia           | 00:30                           | 01:01                 | 8                  | 77474 | 0.09              |
| Slovenia         | 00:30                           | 00:29                 | 27                 | 20273 | 3.80              |
| Slovak Republic  | 01:00                           | 01:30                 | 134                | 49034 | 0.22              |
| Spain            | 01:00                           | 16:00                 | 11                 | 504645| 0.09              |
| Sweden           | 01:00                           | 01:12                 | 77                 | 450295| 0.06              |
| Switzerland      | 00:59                           | 00:58                 | 168                | 41285 | 3.25              |
| Turkey           | 01:00                           | 01:00                 | 191                | 814578| 0.23              |
| Ukraine          | 01:05                           | 24:00                 | 157                | 603500| 0.26              |
| United Kingdom   | 01:00                           | 01:00                 | 92                 | 219331| 0.42              |

*Indicated times are valid for routine operation. During an emergency all transmission intervals should be 02:00 hours or less.

#Within the harmonisation process the decision was made that all networks shall use the same representative measuring period of 1 h, i.e. 1 h data are to be send to the EURDEP database.
Area dose rate monitoring networks are operated in different modes:

- **Routine mode** of operation: all monitoring stations report normal levels of environmental radioactivity.

- **Alert mode** of operation: after the computer-assisted detection of an abnormal situation, experienced personnel will evaluate the radiological situation and decide about further actions.

- **Intensive mode** of operation: an abnormal situation has been confirmed by authorised personnel; measured data are collected for further decision making purposes based on delineation and risk mapping.

During routine monitoring, measured area dose rate data can directly be used as input for mapping tools. During the alert and the intensive mode, net dose rates should to be calculated for a more exact delineation of affected areas. For this purpose, the dose rate due to the natural background has to be subtracted from the measurement results, which is a problem, because the level of the natural background depends on weather conditions (see paragraph “Variability of the natural area dose rate”).

In 1987, the European Council mandated the ECURIE system in the event of a radiological or nuclear emergency [4] by Council Decision 87/600 EURATOM [5]. The member states are obliged to promptly notify the European Commission (EC) and all Member States potentially affected when they intend to take counter-measures in order to protect their population against the effects of a radiological or nuclear accident. Alarm or warning messages are distributed to inform quickly about enhanced levels of artificial radioactivity in the environment by using the ECURIE system if any anomaly is detected requiring further countermeasures to protect the population. Additionally, the IAEA Convention on Early Notification of a Nuclear Accident urges member states to notify potentially affected countries in the event of a nuclear accident that may have transboundary radiological consequences.

### 2.1 Motivation

Due to the diversity of national area dose rate monitoring systems, dose rate data from different European countries are not directly comparable. This is caused by various physical properties of the diverse types of probes, the way measuring sites are selected and probes are installed. In addition, networks are operated differently with respect to alarm levels, data transmission cycles and data validation procedures. Finally, the networks are designed differently with respect to territorial coverage and density. To obtain comprehensive and reliable information on the actual radiological situation, readings of different detector types have to be corrected and the operational modes have to be aligned. To harmonize area dose rate monitoring networks on a European scale, the European Commission initiated the so-called AIRDOS project “Evaluation of existing standards of measurement of ambient dose rate; and of sampling, sample preparation and measurement for estimating radioactivity levels in air”. In a first step this project covered detailed assessment and evaluation of systems for continuous measurement of the area dose rate in the EU (the final report of this project, [2] is not publicly available, but accessible for EURDEP data providers and national Competent Authorities).

Secondly, an AIRDOS extension has been implemented in the EURDEP system which contains all relevant information necessary for the subsequent harmonization of data and operational modes.
This data base covers relevant information on the detector characteristics like photon sensitivity, inherent background (self-effect), energy dependence of the detector response and response to secondary cosmic radiation. The AIRDOS extension also includes station related information like height above ground, height above sea level and whether the station fulfils minimum requirements of an ideal site (according to 3.2.2). In addition, parameters like data validation procedures and internal network alert procedures have been compiled.

Common interfaces, procedures of data exchange and data formats have been defined to develop and operate the EURDEP platform. But because of the differences in the detector systems, networks and methods of data evaluation the data are often hardly comparable. Improved comparability is a prerequisite for the transborder assessment of the radiological situation in routine mode as well as in a nuclear emergency. Algorithms have to be implemented to calculate harmonized data including uncertainties from raw data.

2.2 Utilization of network dose rate data

Especially after an accidental or intentional release of radionuclides, the potential of early warning dose rate monitoring networks for the assessment of area dose rates is important. In principle an enhanced external exposure to the population can only partly be assessed from the increase of the measured external net dose rate in a first step. More exact effective dose values can be calculated if the nuclide vector of the released radionuclides is taken into account and if models of ingestion and inhalation are applied. After the passage of a contaminated plume the activity concentrations on the ground (contamination levels) can be assessed e.g. from in-situ gamma spectrometric measurements in combination with dose rate data [6]. From these data the external exposure in the environment can be assessed.

On the other hand, decision support systems like RODOS (Real time Online DecisiOn Support system) may be used to quantify the activity concentration deposited on ground on the basis of measured dose rate values [7, 8]. For this purpose, the comparability of dose rates measured at different locations is very important. Site criteria will be addressed in section 3.2.2.

In some studies $^{222}\text{Rn}$ is used as a natural tracer for validating climate models (typically assuming a constant and homogenous $^{222}\text{Rn}$ source). Based on the observed correlation between the $^{222}\text{Rn}$ flux and the terrestrial dose rate, annual, seasonal and weekly $^{222}\text{Rn}$ flux maps for Europe can be derived [30].

A smaller share of the total annual effective dose to the public is caused by external radiation (terrestrial and cosmic component) — e.g. in Germany 0.7 mSv of 4 mSv in total (including 2 mSv from human activities). Area dose rate monitoring data may supply information on the dose caused by external radiation in the case of outdoor stays. However it is necessary to assume a certain mean duration of outdoor stays, and that the dose rate is identical in rural and urban areas. Locations which are adequate for detecting nuclear incidents (according to section 3.2.2) are not necessarily representative for typical indoor and outdoor ambient dose equivalent rates, to which the population is exposed (as reported in annex B of [9], the indoor to outdoor exposure ratios range from 0.6 to 2.3). Outdoor measurements according to the site criteria in section 3.2.2 will have a high sensitivity to artificial changes in the area dose rate, but these measuring sites, ideally on open grassland, are not representative of where people stay all day long. Especially in the case of a nuclear event, the
incorporation radionuclides will considerably contribute to the effective dose. This exposition path is not covered by external dose rate measurements.

3 Requirements and recommendations

3.1 Dose rate detectors and spectrometers installed in early warning networks

At the same location in the same radiation environment, different detectors will indicate systematically different results, because parameters like the energy response of the probe, the response to different components of the environmental radiation, the instrument electronics (depending e.g. on the temperature), the sensitivity and the algorithms for calculating the dose rate are different. Furthermore, the calibration of different systems differs from country to country and sometimes from detector to detector. Finally, the network operators process their data differently [10].

When an area dose rate monitoring network is installed or upgraded, the choice of the dosemeter or detector type will have a vital influence on the performance of the whole system. Often Geiger-Müller tube based instruments are used because they are not too expensive, their construction is simple and their robust design allows the operation over many years. Proportional counters, scintillation counters and ionization chambers may offer a lower energy dependence of the response, but are often more expensive and sometimes more difficult to maintain. The sensitivity of scintillation counters and high pressure ionization chambers is much higher compared to other types of instruments, especially to that of Geiger-Müller tubes. Hence, in particular in the natural environment, the measuring precision of Geiger-Müller tube based instruments is in general lower (because of the relatively low counting statistics) than that of the other instruments caused by the small amount of detector material in a Geiger-Müller tube.

In recent years, spectroscopy systems using scintillation detectors or semiconductors have become affordable. Hence, more and more area dose rate monitoring stations will be equipped with these types of detectors. If the spectral information is converted to dose rates correctly, these detectors could be operated as ideal detectors with a very high sensitivity. Moreover, they allow the access of additional information about nuclide specific activity concentrations in the environment. Furthermore, spectrometers can identify dose rate relevant rain events without the need to operate additional rain sensors, because radon progeny causes a typical pattern in the spectra which can be used for the identification of natural dose rate increases.

Harmonization of area dose rate monitoring networks is only possible if the physical properties of the installed probes and of the corresponding electronics fulfill certain minimum requirements. In the following, basic requirements for dose rate detectors and spectrometric systems are listed. A major function of spectrometric systems installed in early warning systems is, in addition to the calculation of activity concentrations, dose assessment, especially, if additional dosemeters are not installed. Spectrometric systems, which are used both for dose rate calculations and information about nuclide vectors, shall fulfill the same requirements as dosimetry systems (listed in 3.1.1 and 3.1.2).

3.1.1 Technical requirements for dose rate detectors

In the following, minimum detector requirements are listed. These requirements are based on the standard IEC EN 60846 [11], but were altered with respect to the special boundary conditions under
which area dose rate detectors are operated in early warning systems. Testing methods are defined in the standard IEC EN 60846 in detail. The effective range of measurement is the range over which the performance of an instrument meets the following requirements.

Measuring quantity. Due to EU Directive 2013/59/EURATOM, the quantity ambient dose equivalent rate, short: $H^*(10)$, is compulsory if area dose rate measurements are performed. It is additive for all kinds of ionizing radiation. In environmental monitoring values are typically indicated in nSv/h or µSv/h.

Preferred detector types. Proportional counters, high pressure ionization chamber, scintillation detectors and spectrometers are superior to Geiger-Müller counters, because the energy of detected photons can be internally evaluated by these instruments. If the processing of the measured signals is adjusted properly with respect to $H^*(10)$, the response can be widely independent from the photon energy. In contrast, instruments based on Geiger-Müller tubes always show, inter alia, a strong dependence of the response on the photon energy (they show a steep increase of their response at high energies). In general, spectrometers can be used to calculate dose rate values routinely with a high precision. But the conversion of spectra to dose rate values implemented in many commercial instruments leads only to a rough estimation, because oversimplified algorithms are used. These

![Algorithm for background calculation](image)

Figure 2. Algorithm for background calculation (avg. is the average value, std.dev its standard deviation).
facts are derived from several intercomparisons, which both included dosimetric and spectrometric instruments [10, 12].

**Dose rate measuring range.** The detector shall at least cover a dose rate range from 0.010 µSv/h to 10 mSv/h. In the past, values above 10 mSv/h were only observed in the proximity of a damaged nuclear reactor. Instruments placed in the vicinity a nuclear reactor shall present a measuring range up to 10 Sv/h. For other stations, it is more important to have a high sensitivity rather than a wide dose rate range.

**Energy range of photon radiation.** The detector shall at least cover an energy range from 80 keV to 3 MeV. The relative response of the detector due to radiation energy for photon radiation shall be within the range from 0.75 to 1.54 with respect to the standard calibration. Photons with a low energy (<100 keV) do not contribute to the dose rate in environmental dosimetry considerably, because they are shielded to a large extent by air and objects, when the detector is located far from a source of ionizing radiation.

**Angular response.** For a dose rate detector installed on a flat ground a homogeneous response in a 360° plane azimuthally around a vertical axis is required. Deviations of the relative response in this plane shall be within a range from 0.95 to 1.05. The relative response of the detector due to a variation of the incident angle of radiation in other directions shall not exceed 1.54. The active volume of the probe shall have cylindrical or spherical form.

**Linearity and statistical fluctuations.** The nonlinearity of the indicated dose rate values shall be confined to 10 % of the relative response. In case of an integration time of 10 min, the variation of the indicated value due to the nonlinearity of the relative dose rate response shall not exceed the limit of ±10 % over the whole of the effective range of measurement. The coefficient of variation of the relative dose rate indication shall neither exceed the limit of 10 %.

**Inherent background.** After internal background subtraction, the inherent background (also known as self-effect) shall not exceed 10 nSv h$^{-1}$. The drift of the inherent background shall be smaller than 2 nSv in one year. The internal background can only be measured precisely in a low-background facility deep underground.

**Response time.** When subjected to a dose rate the dose equivalent meter shall within 1 min indicate at least 91 % but not more than 111 % of the appropriate increase in dose.

**Temperature range.** The detector shall cover a temperature range from -20° to 50°. Over the rated range of temperature, the indication shall remain within –13 % to +18 % of that obtained under standard test conditions. Depending on the country-specific climate, a different range could be defined.

**Relative humidity.** The complete range from 0 % to 100 % shall be covered. The indication shall not vary by more than –9 % to +11 % from that obtained under standard test conditions, for all possibly occurring relative humidities. Detector systems installed in early warning systems are exposed to all weather conditions. Accordingly, they have to be sealed against moisture and dust. IP65 according to EN 60529 shall be fulfilled at minimum.
Atmospheric pressure. In pressure range between 70 kPa and 106 kPa, the response of the instrument shall not vary beyond the uncertainty of measurement under reference conditions. Open ionization chambers, which depend on the air pressure and other weather conditions, are not used as probes in early warning systems. Other types of detectors do not depend on air pressure.

Data format of measured values. Data of dosimetry network systems are processed and stored electronically, while often the probes do not have a display. Measured values shall be displayed in a scientific reading of measured values with a three digit mantissa (e.g. x, yz E ±ab), because the effective dose rate measuring range covers several orders of magnitude (see paragraph “Dose rate measuring range”).

Time interval of readout. The automatic read-out of data of the detector shall happen at least every 10 min. Hence, the maximum measuring interval is 10 min, as well. The online availability is checked in the same frequency. During one measuring interval the detector shall record enough counts or events to ensure sufficient statistical significance of the measured data. For simplicity it is advised to use the same measuring interval for spectrometers. To apply automatic data validation algorithms, shorter readout intervals are useful (3.3.4.1).

Information about data quality. Indication shall be given of operation conditions in which the accumulation of dose equivalent is not accurate (within these specifications), for example, low battery or detector failure. Invalid data have to be marked. If the prevailing dose rate exceeds the upper dose rate limit of the measuring range, a dose rate overload has to be indicated. The instrument shall not indicate low or zero values as a consequence of an overload.

Electromagnetic compatibility. The requirements concerning electromagnetic compatibility are defined in IEC EN 60846. Any deviations due to the tests shall not exceed ±0.7 times the lower limit of the effective range while the instrument is operated in the most sensitive range. Special precautions shall be taken in the design of a detector to ensure proper operation in the presence of electromagnetic disturbances, particularly radio-frequency fields (tests are performed on the basis of IEC 61000-4-2, IEC 61000-4-3, IEC 61000-4-6, IEC 61000-4-8).

Influence quantities. The rated range of any influence quantity has to be stated in the documentation by the manufacturer. Rated range of use is the range of values of an influence quantity or instrument parameter over which the instrument will operate within the specified limits of variation. Its limits are the maximum and minimum rated values. Especially the admissible and rated temperature range, humidity range and pressure range are of interest.

Information on the instrument. The manufacturer has to supply the following information to the network operator: the quantity to be measured; the rated dose rate range; the rated range of photon energy, the reference point and reference orientation; the type of radiation the detector is suitable for (example: photon radiation, secondary cosmic radiation); instructions for use; certificates of type testing if applicable.

Algorithm to evaluate the indicated value. The manufacturer shall deliver the evaluation algorithm of the indicated value starting from the signals of the detector and ending at the indicated value. This shall include all the calculations and/or the decision tree. If more than one signal is
used to evaluate the indicated value, the manufacturer has to supply a possibility to read out the separate signals of the detector. The manufacturer shall state the general form of the model function for the dose rate measurement.

**Influence of rain on the detection level.** To exclude rain events from radiological events, all dose rate measuring stations shall be equipped with rain sensors. Alternatively, real-time weather radar data can be used evaluated by the central data processing system of the network. But the latter method is not as reliable because the spatial and time resolution of the weather radar data is limited. If no precipitation data are available, the dose rate should be investigated as a function of time, because the time-dependent gradient of the dose rate can be used as an indicator of rain events (see paragraph “Variability of the natural area dose rate”). Spectrometric detectors allow to clearly distinguish the nature of increased dose rate levels.

**Sensitivity concerning increased levels of dose rate.** The instrument shall be able to detect an enhanced net dose rate down to 10 nSv/h in 1 hour. Typically, a contamination of some kBq/m² causes a rise of the dose rate in the order of 1 nSv/h (depending strongly on the nuclide - e.g. a surface contamination by $^{137}\text{Cs}$ of 1 kBq/m² causes a dose rate of 2 nSv/h). The advantage of area dose rate monitoring stations is the comprehensive information on the time evolution of measured dose rates. Beyond the alert function the activity concentration in air can be assessed from dose rate measurements during the passage of the contaminated cloud. After the passage of the cloud, activity deposited on the ground can be assessed from net dose rate values by subtraction of the background observed before by the same detector. The sensitivity of this method is only sufficient, if affected areas with an enhanced net dose rate of at least 10 nSv/h can be detected.

### 3.1.2 Technical requirements for spectrometers

Currently there are different types of spectrometers commercially available which can be used for environmental radiation monitoring. Spectrometers based on cadmium zinc telluride (CZT) semiconductors and lanthanum bromide (LaBr₃) scintillation spectrometers are, for example, increasingly used. Both spectrometer types have an energy resolution, which is significantly higher than that of a NaI detector, and can be operated at room temperatures, as well. A drawback of LaBr₃ is an internal contamination with $^{138}\text{La}$, which raises the inherent background of the spectrometer. Drawback of CZT semiconductors is the low response to photons of higher energy, which dominate the natural dose rate, because only relatively small crystals of this material can be produced (currently, the largest volume available is about 3 cm³).

**Energy resolution.** A main requirement for a spectrometer to be used at any location in the environment is that there is no need for cooling the detector. Another important criterion is the energy resolution of the spectrometer. It must be better than 3% at 661 keV, so that disambiguates which could arise in realistic release scenarios are avoided (e.g., the prominent emission lines of $^{137}\text{Cs}$ at 662 keV and of $^{134}\text{Cs}$ at 605 keV should be separated). In many cases, a spectrometer with poorer resolution cannot distinguish natural background gamma lines from the lines of artificial isotopes, e.g. $^{214}\text{Pb}$ from $^{131}\text{I}$ lines.
Sensitivity. The sensitivity of the spectrometer is also important to obtain spectra with adequate statistics in an acceptable time. For example, a spectrum of a LaBr$_3$ spectrometer with a crystal of 1 inch$^3$ has at normal background over 10 000 counts within measuring time of 10 min, when the spectrometer is operated in the natural environment.

Data processing of spectrometric data. When spectrometers are integrated into a monitoring network, the central processing system will be used for detailed spectral analysis. Monitoring stations can offer only very limited capacities for spectrum analysis. Therefore, it is reasonable to transfer measured spectra to the headquarters for further analysis. Centralized analysis is more powerful since more sophisticated spectrum analysis tools can be applied. Central data management systems have to be designed to keep track of detector energy calibration, efficiency calibration and detector energy resolution calibrations for each detector installed in the network. The central data management system also must keep track of the history of these calibration parameters.

Dose rate calculation from spectra. A detector based on a NaI crystal or a LaBr$_3$ crystal (or any other detector material) does not produce electrical pulses proportional to any dosimetric quantity. In addition, the housing of the detector has an influence on the response curve. A time consuming disconsolation of the measured spectra is not needed to calculate ambient dose equivalent rates from spectra. Instead, a simple method is very common: first of all, the spectrum is divided in a number of energy regions (e.g. 7 regions were chosen in [13]). The conversion from the actual response of a spectrometer to a dosimetric quantity is made by applying energy dependent conversion coefficients to all regions of the measured spectra. These coefficients can be measured by recording spectra using different (preferably) mono-energetic radioactive sources with emission lines of different energy. The count rate of energy regions multiplied with its mean energy and with the corresponding conversion coefficient must be equal to the ambient equivalent dose rate at the some location. To extract all conversion coefficients, a system of equations has to be solved. An alternative to measuring the calibration coefficients is to perform Mont Carlo simulations of mono-energetic radiation hitting a detector [14]. But these simulations need some supporting measurements, because the computer code might not describe all relevant dimensions and materials correctly in every detail.

3.2 Stations in networks

3.2.1 Strategy/topology

The design of the topology of an area dose rate monitoring network shall be based on a preceding threat analyses, the extension of the area to be monitored, the density of the population, the geological topography of the covered area, the location of nuclear power facilities and on the purpose of the network (only alert function or further functions) as well as on the technical performance (e.g. spatial resolution). The use of spectrometers in addition to dosemeters leads to higher installation costs and to a higher complexity of the data evaluation, but the possibility to access information about nuclide concentrations is a major advantage for decision makers to support appropriate countermeasures and for the calculation of atmospheric dispersion models. If network stations are equipped with rain sensors or spectrometers (or if alternatively precipitation information derived from weather radar systems is used), the sensitivity and reliability of the early warning function is remarkably improved. Even rather small spectrometric detectors were tested which allow the clear distinction
identification of the reason of increased dose rates in moderate measuring times like 10 min [15]. Some basic considerations on emergency monitoring strategies can be e.g. found in [16].

When a network is established or modernized, the following strategic criteria play a major role: the duty cycle of the dose rate data acquisition (100% in an ideal case), the reliability of the installed hardware (low failure rate and high resilience), the reliability of the data transmission, the flexibility of the system architecture (independent from manufacturer of single components, easy integration of other components like probes of different type) and the costs of acquisition and service. A collaboration with public institutions (e.g. national weather service) could reduce the operating costs. If the area dose rate monitoring system is partly run by a commercial company, it is very important to define the contractual commitments very clearly and in detail. The following recommendations are related to the network topology.

Areal density of monitoring stations. At least 1 station per 1000 km$^2$ shall be installed if the dose rate of large areas has to be observed (corresponding to a mean distance between neighboring stations of approximately 30 km). In most countries located in central Europe, the density of stations is about 5 times higher. If the recommended density of stations cannot be realized (e.g. because of budgetary issues) stations should be preferably installed in regions with high population density and close to nuclear facilities. If monitoring stations are placed in the vicinity of nuclear facilities, at least 8 stations shall be located in a circle of about 2 km diameter. The number of stations has to be increased, if the radius is larger. The higher the density of monitoring stations, the higher is the chance to detect nuclear incidents early. Especially if delineation calculations on the basis of dose rate measurements are planned, the grid size of the network must be adapted to the required resolution of the calculations.

Mobile teams. Regarding the restricted spatial resolution of stationary monitoring networks (even in case of the dense German area dose rate monitoring network), information from mobile teams is needed especially in the vicinity of an accidental release. Vehicle based teams with handheld devices help to improve the data base for this delineation task. Without additional location specific background information, the net dose rate approach is not applicable. This restricts the detection of affected areas down to about 0.3 $\mu$Sv/h. The disadvantage of the mobile approach is that staff is needed to perform the measurements and that the staff may be subject to unwanted exposures, as some ten measurements would be realistic per day and mobile unit. More advanced vehicle based teams use automatic (semi-) spectrometric systems to track dose rate on-line while driving. A disadvantage of vehicle based mobile teams is that they are restricted to streets and areas reachable by cars. As an alternative, mobile teams may utilize transportable, autonomous probes. These types of probes allow independent operation for a period of several weeks or even years.

3.2.2 Station properties

The natural radiation at a certain location depends on the terrestrial radiation (TR) and the secondary cosmic radiation (SCR). The latter is a function of the altitude and depends also on geographical latitude, air pressure and solar activity. On the one hand, the TR is produced by natural radioactivity in the soil and the air, on the other hand artificial radioactivity from global fallout and accidental fallout (e.g. Chernobyl) as well as additional sources contribute to this component. The ambient dose rate generated by TR strongly depends on the location of the probe and can vary even within
a distance of a few meters. In urban environments, the natural activity of artificial materials used for sealed areas or buildings dominates the TR. In Europe, TR varies between 10 and 500 nSv/h depending on the geological conditions at the detector location. The long-term mean SCR depends on the height of the probe above sea level. It can vary between 33 nSv/h at sea level and 82 nSv/h at a height of 2700 m [17].

After the passage of a contaminated plume, the measured dose rates should be “representative” for the radiation of artificial activity deposited on the ground. This aspect of representativeness was systematically investigated in [18]. The topography or environment of a measuring site has a strong influence on the dose rate, because shielding, on the one hand, leads to a decrease in dose rate and building materials, on the other hand lead to an increase in dose rate. Such effects can cause changes in dose rate by a factor of 2 or 3. In addition to topographical requirements, however, a continuously operated monitoring station may need an external power supply and telecommunication infrastructure. Thus, the sites of real area dose rate monitoring stations typically do not fulfil the conditions of an ideal site. In some networks, probes are even mounted at walls or on the roof of buildings, though dose rate measurements at such locations are not representative. For such real probe locations, a site characterizing method using site evaluation factors was proposed [18]. The following sections comprise minimum requirements concerning the installation of monitoring stations and the recommendations to minimise disturbing influence factors.

**Site criteria.** Probes shall be mounted 1 m above ground on a regularly mowed lawn or open meadow area. To guarantee a minimal comparability of the data of different measuring sites, bushes, trees or buildings should have at least a minimum distance of 20 m from the probe (depending on their height). Shielding of the probes has to be avoided where possible. If a heavy snow load is expected, the height of the probes could be increased to 2 m, so that they are not covered completely by snow during winter time. No water sink shall be near the probe. Transported radioactivity to a water sink near the probe can lead to a systematic increase of the dose rate in the case deposition during rain. The site should not have sealed areas because of water run-off (sealed areas show a systematic reduction of the dose rate in the case of precipitation). In addition, the site should not be shielded by a building and the probe should not be located on the roof of a building, because this leads to a systematic reduction of the variable component of the terrestrial radiation (especially in the case of a surface contamination) and of an enhancement of the static component of the terrestrial dose rate, which is produced by the building materials of the roof. A plant cover near the probe leads to a distortion of the measured values (a surrounding forest 70 m around the probe can lead to a factor 2 distortion in the case of a contamination). A radius of 100 m around the probe is needed to detect a 90% of a surface contamination. Therefore, this radius has to be regarded as the ideal radius of open grassland around the probe [18]. It is recommended to perform a site characterization procedure especially in the case of non-ideal sites, e.g. a simple site characterization procedure proposed by BfS [19].

**Precaution against power failure.** A malfunction of an area dose rate monitoring station caused by a temporary breakdown of the external power supply has to be prevented. Hence, the area dose rate monitoring station must be equipped with a battery back-up for power failures. The station should run on battery for at least 72 hours.
Combination of dosemeters and spectrometers. To minimize the difference between dose rate monitoring stations and spectrometric monitoring stations it is advisable to combine both instruments in one station. This solution minimizes the hardware differences and eases the work of the network administration.

3.3 Data handling

3.3.1 Station specific analysis

Data procession at monitoring stations. It is recommended to confine the data processing at the monitoring station mainly to dose rate calculations from measured signals. In addition, an automatic low-level validation of the data according to section 3.3.1 is advisable. To keep the area dose rate monitoring station hardware and software as simple as possible, it is reasonable to use the area dose rate monitoring station only as a platform where dose rate data are generated, collected and sent to the central data processing centre to be analyzed and stored. In the case of failure, maintenance of a central data processing centre is easier. Dose rate data shall be buffered by the electronics of the monitoring station at least for 72 hours to avoid data loss in the case of a breakdown of the telecommunication system.

Evaluation of spectra. If a spectrometer is operated at an area dose rate monitoring station, the simplest approach is to stabilize the energy calibration by the local hard or software. This can be done by fixing a known energy peak at a certain channel (by adjusting the high voltage or the fine gain of the multi-channel analyzer). The complexity of the spectrum management is increased if the temperature dependence of the amplifier is not compensated, because a new energy calibration has to be calculated for each spectrum.

3.3.2 Data transmission

A high reliability of the data transmission can be achieved as follows.

Independency of the data transmission from public networks. In the event of an emergency, public networks like GSM networks could break down. Using a separated network also implies a higher security of the data management. Dose rate data shall be transmitted to the central servers by using special networks, preferably run by governmental organizations. If this is not possible, an LTE or DSL based solution, realized as a virtual private network (protected against access from the internet), is advisable. To guarantee a higher availability, two independent network or telecommunication solutions can be combined.

3.3.3 Central data processing

A (so-far unpublished) valuation, carried out by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in 2007, provided the opportunity to distinguish different existing supervising systems. Generally, a differentiation between home-made (or dedicated software) and commercial software can be made. Depending on different factors (e.g. financial resources, manpower resources, delay, etc.) each solution has its own advantages and disadvantages (see following table):
| Software Type                                      | Acquisition cost | Human resources | Robustness | Lifetime | Scalability | Flexibility | Modularity |
|--------------------------------------------------|------------------|-----------------|------------|----------|-------------|-------------|------------|
| Home-made or dedicated software                  | +                | -               | -          | ≈        | +           | +           | +         |
| Software provided by the manufacturer of the probes | =                | +               | -          | -        | -           | -           | -         |

In any case, financial and personnel resources have to be taken into consideration. The creation of own software requires additional human resources. Software development and maintenance by external companies requires considerable financial resources. But for the supervision of the external company, human resources still are required. Maintenance and further development of the central server software has to be planned over a period of one decade at minimum. All applications shall be developed in a modular design (preferably object-orientated), quality controlled (according to the ISO 9000 series) and thus using supporting software management and development tools, well-defined test procedures, etc.

Minimum functions of the supervising system and referring recommendations are listed in the following.

**Data collection from probes.** The system shall be flexible enough to integrate the data send by different types of instruments without major developments. Object orientated interfaces are recommended.

**Data analyses.** The functions of the central data processing system (like alert generation, graphical presentations, data storage, etc.) require real-time or quasi real-time evaluations and the ability to handle all data send to the central systems by the network stations. The required computing power depends on the size of the network and the complexity of the applied algorithms.

**Data reporting.** The system has to manage events of increased dose rate and generate reports for the personnel on-duty, especially including alerts. It could be advisable to report certain technical alarms only during working days, differently than radiological alarms. The system has to be flexible in order to report data to users in different ways (graphs, alarms, parameters, system status information, etc.).

**Database operation.** The central data processing system has to store all dose rate data, parameters and condensed results of the data evaluation in a database. The system should to be able to export data easily in different ways and formats.

**Lifetime of the data processing system.** The lifetime of such a system should be at least 10 years. If the system is designed highly modular (i.e. object orientated) and quality controlled (especially well documented by using a software configuration management system), the lifetime is practically unlimited.

A universal supervisory control and data acquisition software should be used, which offers a long lifetime, high robustness and a high modularity and which uses a standard transfer protocol like OPC with connectors for all needed applications (OPC stands for object linking and embedding for process control). Such software is offered by different manufacturers.
3.3.4 Techniques and algorithms for data validation

The capability for the generation of an early warning or an alert depends on the technical properties of the installed detection system as well as on the ability to distinguish enhanced dose rate due to an accidental or un-peaceful release from natural occurring events and events due to incorrect readings.

Low level automatic validation. Several methods are proposed in order to reject increased dosimeter readings caused by short-term electromagnetic perturbations, probe’s malfunction or other reasons not based on enhanced radiation level. If single pulses of the probe are accessible, the following methods are realizable:

- Outlier detection algorithm — based on statistical analysis of the probe’s count rate by calculating the standard deviation and the mean. It should reject the single probe’s readings (collected several times per minute) which are not within 3 standard deviations from the one-minute average;

- Comparison of the results between probes in multi-probe detectors. This depends on the construction of the detectors. Two possibilities are considered: if two low-dose probes are installed at the same location, their dose rate values can be compared as a plausibility check. But caution is needed if only one low-dose and a high-dose probe are integrated in a detector system, because the high-dose probe is operated out of range and might be in an undefined condition. A comparison of the (long-term) results of both probes is only possible after supplying evidence that the high-dose probe can be used under normal environmental conditions without any problems or inconsistencies of the indicated values.

- The read-out system of some Geiger Muller based detectors may be influenced by bouncing pulses, so that a single photon event produces two or more counts. In such a case, when more than one pulse is detected in 2 ms time interval, the pulses can be attributed to only one physical photon event.

The outlier detection algorithm should be used for 1 minute subintervals. All other algorithms can be applied for 10 minutes averages. All these methods can be implemented in the detector / data logger or in the central database if the detailed data from the probes are available in the database.

Data which do not pass automatic validation algorithms should be marked as “not valid” and should automatically be excluded from the subsequent calculations.

Automatic pre-selection of results outside normal range. A low level automatic validation procedure filters out data which are outside the normal range taking into account data already converted into the units of ambient dose equivalent rate. A lower and an upper limit for each individual monitoring station have to be defined. Data which are within these limits are considered as “normal”. Values inside the limits are automatically marked as “valid” and those outside the limits are marked as “to be validated”. This pre-selection reduces the number of data to be manually validated, which is a prerequisite especially in networks with large numbers of probes. During emergency mode, the same procedure can be applied but recalculation of upper and lower limits will become necessary.
Variability of the natural area dose rate. The alert function of an area dose rate monitoring network is limited by the variability of dose rate due to natural processes. Precipitation may lead to an increase of the terrestrial component of the natural radiation by a factor of 2 or 3 because of the effective wash-out of radon progeny [20]. During such an event, the dose rate can be considerably increased due to activity deposited on the ground. After the rain event the dose rate decreases with an effective half-live of about 30 min due to the short half-lives of the dominant radio-nuclides $^{214}\text{Pb}$ (27 min) and $^{214}\text{Bi}$ (20 min). During rain, the additional net dose rate rarely exceeds 0.1 $\mu$Sv/h and this increase typically lasts for a few hours [21], because the radioactivity accumulated in the air and in the clouds is almost completely washed away within a limited period of time. Without precipitation events the dose rate measured in the natural environment varies with the air pressure (influencing the secondary cosmic radiation), soil humidity and natural activity in air (due to radon progeny). Typically, these effects result in dose rate variability of about ten percent of the average background [20, 22].

Distinction of rain events from radiological events. It is recommended to check if enhanced dose rate values can be explained by rain events. Therefore rain information should be available to the central data processing centre — either by the operation of spectrometers (from which the nuclide vector is derived), by the use of on-site meteorological instrumentation or by weather radar. However, rain information should not be used in automatic validation procedures. Artificial radiation could be detected during a rain event as well and if the measured value is higher than the upper limit, it should be checked manually, in any case. If no spectrometer is present, the method described in the following can be used. It is based on ideas explained in [23].

Alert level. The recommended value of the alert level for 10-minute data is 30 % above the background added to the 3 days sliding median, which is considered as the background level and should be calculated on a hourly basis ('moving mean value'). This recommendation is a compromise between reducing the internal alert level on the one hand and avoiding frequent false alerts due to natural occurring events, on the other hand. The algorithm for background calculation should allow the exclusion of rain events and short term increases. It can be calculated in the following iterative procedure, which is also illustrated in figure 2. Average values and their standard deviation ($\sigma$) are calculated from all the values from the past 7 days. Then the values, which are outside the limit of $2 \sigma$ from the average, are excluded and the whole procedure is repeated until there are no values to exclude.

3.3.5 Chain of alert and alarm raising

In general, the alert function of national early warning systems can be described by the following four-step approach [21]:

1. Generation of spontaneous reports: if a measured dose rate exceeds the alert level (according the preceding section), the observed data are transmitted immediately to the central server. If the regular time interval for data transmission is below 20 minutes, this step is not necessary.

2. Generation of an internal alert: the software installed at the central network server automatically performs an early warning check procedure. A network internal alert will automatically be generated, if the dose rate at a single station exceeds a given warning level and/or if at least two neighboring monitoring stations report enhanced dose rate levels. This neighborhood
criterion is, however, only applicable if the distance between neighboring stations is below 30 km [21].

3. Evaluation of the situation — Generation of an alarm: if a network internal alert is generated, the staff member on duty has to evaluate the situation as fast as possible and has to decide if the available information is sufficient to confirm or to suspend the internal alert. For this purpose, the time evolution of the data of the monitoring stations with enhanced data has to be checked. Additional data has to be considered e.g. dose rate values from neighboring stations or from other radiological networks and meteorological data. Automatic decision making systems (e.g. using trend analysis methods) could support the manual data evaluation.

4. Emergency mode: authorized personnel (e.g. from governmental authorities) has to confirm the network internal alert. In case the alert seems to be due to accidental release or unpeaceful action, the system is switched to the emergency mode of operation and decision on adequate actions is needed. If appropriate, an early notification message is distributed via ECURIE or via IAEA.

3.3.6 Subsequent validation

Data which have not passed the low-level automatic validation are marked as suspicious and have to be excluded from the calculation of the 1hour average values. The resulting 1hour average values should automatically be made available to EURDEP without delay and manual review. 1-hour data outside the normal limits should be published with the status „not valid”. They should be checked manually after subsequent review by expert. After review the status of “not validated” data will be changed either to “validated” or “not valid” depending on the outcome of the review process. Data which pass both tests should be automatically published with the status „validated”.

3.3.7 Reporting to EURDEP and data exchange

The EURDEP network is used by 39 European countries (including all EU Member States) to continuously exchange radiological monitoring data in a standard data-format. Data is made available to all participating organizations and competent authorities (European Commission and national authorities) almost in real-time by FTP, Email and through a protected website. In addition, the general public can access the data via the public EURDEP web-site. All data are stored in central nodes by: Joint Research Centre (JRC) in Ispra, German Federal Office for Radiation Protection (BfS) in Freiburg and Directorate-General for Energy (DG ENER) in Luxembourg. The incoming data are continuously monitored in the JRC node and warning messages are automatically sent by Email to the data-provider in case of interruptions of the data flow.

**Data format.** The minimum requirement is to make data available in the standard format, once a day during routine and every two hours during an emergency. But it is desirable to make data permanently available on an hourly basis. Data shall be transmitted to EURDEP in two standard formats (EURDEP 2.1 and IRIX 1.0). In addition, data may be directly uploaded on the private EURDEP website via an Excel file. One message consists of a generic header with basic information (originator, date, time, filename, etc.), information about the measuring stations (locality code, name, coordinates, height above sea level, etc.) and the monitoring data of the stations (dose rate...
value, date, time, mean background dose rate value, precipitation occurrence, nuclide specific air concentration, etc.). The monitoring data bloc is accompanied by a list of definitions (uncertainty, type of information, unit, validation flag, etc.). Additional information should be made available about the dose rate measuring system (response characteristics, meteorological data) to make a quantitative comparison of the dose rate data possible.

**Preferred interface.** EURDEP is preferably and almost completely operated as a distributed pull-network, where all data-providers would make their data available on a local FTP server. Data is downloaded with mirroring software and by using the FTP protocol. For this purpose, network operators have to make data available on FTP servers permanently (with password protected read-only access or even IP address filtering for security reasons). Data are collected from all network FTP servers by the mirroring software of the node in a 5 min interval. This information is published through the EURDEP website with a small delay of 10 min, which is necessary to process the data. All network operators have direct access to all other network FTP servers as frequently as desired. Moreover, authorized EURDEP users can download aggregated data on the private website.

### 3.3.8 Delineation on the basis of dose rate data

Delineation methods are used to map a potential release of radioactivity into the environment on the basis of national area dose rate monitoring data. The ability for the detection of an abnormal situation depends on the spatial density of the monitoring system. The probability for the detection of local events with a spatial extension less than 10 km$^2$ by any network is low. For an event with the spatial extension of 100 km$^2$, this probability is in the order of about 50% for some central European countries and less than 10% in most European countries. Considering the mapping function, the area per location should not exceed 20 km $\times$ 20 km = 400 km$^2$. If the area per location exceeds 1600 km$^2$, the delineation function can be regarded as poor.

For the surrounding of a nuclear power plant, a sector orientated ring-like design of the monitoring network is adequate. According to atmospheric dispersion models the alert function is fulfilled even for narrow plumes if 8 stations are located in a circle within 2 km distance (a circle divided in 45° steps) or 12 stations in a circle within 12 km (a circle divided in 30° steps) [24]. In case of an accidental release, step gradients of contamination patterns will occur in the near zone following the path of the plume. This can be concluded from atmospheric dispersion model calculations as well as from historical events [25]. Since wet deposition is much more effective than dry deposition, the radionuclide contamination patterns after accidental releases strongly depend on patterns of rain events. For example, after the Fukushima accident, the area where $^{137}$Cs contamination on ground exceeds 1 MBq/m$^2$ is in the order of 250 km$^2$ [26].

Analyzing the spatial resolution of rain events is a powerful method to test the mapping function of an existing monitoring network. In a first step, the maximal net dose rate of each station during a rain event is calculated. From these data the frequency distribution of maximal net dose rates (related to one rain event) is derived (an example is shown in figure 3). This distribution can be compared with the size of the area affected by the rain event, if the grid size of the monitoring network is taken into account.
Figure 3. Frequency distribution of stations with a maximal increase in dose rate (abscissa) due to four rain events which occurred on four different days. Example on the basis of data from the German IMIS network, recorded in 2011.

3.4 Quality assurance and improvement of dose rate measuring systems

3.4.1 Metrology

Determination of basic parameters. As part of the quality assurance program, the response of the instrument type to the terrestrial components as well as to the cosmic component of the natural radiation and the inherent background of the instrument under test shall be determined preferably before detector installation [17]. It is necessary to measure each response parameter separately by elimination of the other major influence quantities. The inherent background can be measured by observing the instrument reading when the instrument is operated in a low-level underground laboratory. At a depth of 200 m water equivalent, the cosmic radiation is effectively eliminated. The lack of low-level background conditions can be compensated by placing the detector within a 15 cm thick lead shield so that the radiation from the local rocks can also be eliminated. The measurement of the cosmic ray response can be made on a boat or on a floating platform, constructed from material of low radioactivity, on a fresh water lake or reservoir or at sea at least 100 m from the shore, if the surrounding is plain (otherwise, distance of up to 3 km are needed). The response to gamma radiation is preferable measured in a low-dose irradiation facility in a low-level underground laboratory. Details are found in the standard ISO EN 60846 in Annex C.

Control of detector properties. In practice, it will not be possible for the network operator to check by himself whether his dose rate measuring instruments fulfils all requirements listed in 3.1.1. Therefore, credit can be taken from references. A declaration of compliance with the standard ISO EN 60846 or a conformity assessment of the instrument type (an independent verification) can be used to show that the instrument fulfils basic criteria according to section 3.1.1. In Europe, such conformity assessments are performed by the Physikalisch-Technische Bundesanstalt, the
metrological institute of Germany. Even in the case of compliance declaration or a conformity assessment, the rated dose rate measuring range and the rated energy range have to be checked in addition, because some additional requirements are especially valid for early warning systems.

**Calibration.** Each detector shall be calibrated before it is installed in a dose rate monitoring station. These detectors are exposed to radiation of a wide energy range (first of all, by natural environmental radiation) and, therefore, preferably calibrated in a collimated $^{226}$Ra photon field (not included in ISO 4037-1) by using a sealed $^{226}$Ra source (in equilibrium with the daughter nuclides). The calibration shall be performed at low dose rates (e.g. 80 nSv/h - 250 nSv/h) typical for the natural environment. The photon field has to be collimated to suppress scattering. Usually, calibrations of dosemeters have been performed in a $^{137}$Cs photon field, at an energy of about 0.65 MeV. But most of the instruments used in early warning networks show a considerably higher response when they are exposed to photons with an energy higher than 1 MeV (e.g. in a $^{60}$Co photon field). Because the environmental radiation has a mean energy of about 1.2 MeV, a sealed Ra-226 source with a wide spectrum, that resembles the environmental radiation, is much more appropriate for calibration purposes.

As part of the calibration procedure, the inherent background of each instrument should be determined. This can be done in a simplified procedure by operating the instrument in a lead castle of a wall thickness of 15 cm, so that only the hard component of the secondary cosmic radiation is present (about 20 nSv/h). By assuming that the cosmic radiation level is approximately constant, this measurement reveals the inherent background of the instrument under test. This procedure shall be verified by performing such measurements with an instrument with a known inherent background (this information is obtained from calibration measurements in a low-level underground laboratory).

**Regular stability tests of detectors.** Regular tests of the long-term stability of the response of all installed area dose rate detectors shall be repeated at least every 3 years. Especially if a large number of detectors is operated in a network it might be too laborious and expensive to remove all probes to take them to a calibration facility. Instead, radioactive test sources can be used to irradiate detectors without removing them from their permanent measuring position. The type of nuclide used for these tests is not important, because only the stability of the response is checked, but not the absolute calibration. Very common are $^{137}$Cs sources, because the long half-life of this nuclide of 30 years eases the use of such a source. Often, manufacturers of detectors sell test caps which are exactly suitable for their probes. The activity of the test sources has so high that the fluctuation of the natural background does not have a major influence on the test result. On the other hand, the tests should not be performed in a dose rate range which is unrealistically highly above the natural background, because particularly the stability of the measuring range shall be tested, in which the instrument is normally operated. E.g., a $^{137}$Cs source with an activity of 100 kBq generates a dose rate of about 900 nSv/h in a distance of 10 cm.

The radioactive decay of the test sources has to be taken into account when the results of stability tests are evaluated. Since periodic tests have a strong logistical impact on the operation costs of the network, the frequency of tests has to be synchronized with maintenance visits at the network stations. To ensure the quality of the stability tests care shall be taken that during subsequent tests of the same detector the source is always placed exactly at the same location. This can be achieved by using a special source holder, if a test cap is not available. Measurement results
from repeated tests shall be stored in a database. The whole test procedure has to be described in a quality handbook, as it is part of the quality system.

To prevent any misinterpretation of area dose rate monitoring data, test data should be flagged and handled differently from routinely measured values, because data obtained from stability tests may not be reported to general radiological information systems like EURDEP. Results from stability tests have to be analyzed in-time by comparing previous and recent results. The difference of the dose rate values of subsequent stability tests of the same detector shall be below 2% per year. Otherwise, the long-term stability of the detector is not sufficient and the detector should be repaired or replaced.

### 3.4.2 Intercomparisons

The operators of early network systems should take part in EURADOS intercomparisons of WG3 (offered regularly by PTB, Germany) and in intercomparisons at the intercalibration site on the Schauinsland (offered by BfS, Germany). Both intercomparison programs are complementary: during the EURADOS intercomparison, some basic properties are tested, like response to dose rate, response to energy, inherent background, terrestrial und cosmic response and sensitivity of the instrument. At the intercalibration site, the long-term behavior of dosemeters under the natural weather conditions is studied simultaneously for all detectors.

**EURADOS WG3 intercomparisons.** One of the goals of Working Group on Environmental Monitoring (WG 3) of the European Radiation Dosimetry Group (EURADOS) is to help to harmonize the European early warning systems. In this context the working group 3 has performed several intercomparison of these systems [10, 27]. The main aim of the intercomparison was to ensure that the results reported by different countries during a nuclear accident, e.g. due to plumes of radioactivity transported in the atmosphere, will be consistent and thus comparable, so that similar conclusions can be drawn in the affected EU countries. The use of the same dose quantity, i.e. ambient dose equivalent, is an important presupposition.

Combining the results of the five intercomparisons performed so far 60 dosimetry systems from 36 institutions in 18 EU states were tested in total. Most of the tested dosimetry systems are already part of national early warning systems, but some other systems were tested to obtain information regarding future upgrading of networks.

The combination of the Ultra-low Background Underground Laboratory (UDO) [28] and two free-field sites (a floating platform on a lake showing an almost pure cosmic radiation field and a free-field gamma ray irradiation facility) provided the particular opportunity to precisely quantify the inherent background of the detectors and to calibrate them almost free of any background and traceable to PTB’s primary standards. In addition, the intercomparison comprised investigations on the energy and dose rate dependence of the detectors’ response to gamma radiation as well as on the response to cosmic radiation. The sensitivity of the detector systems to small dose rate variations, similar to that caused by a passing overhead radioactive plume, was studied under realistic free-field conditions by using the new free-field gamma ray irradiation facility.

One result was that the individual calibrations still showed discrepancies from the reference values up to 50%, which would be unacceptably high in the case of a real emergency situation. The UDO measurements show a pronounced deviation from a constant photon energy response (in some cases, variations of the response by a factor of 5 or even more were observed) [10].
The fact that the intercomparisons were held regularly showed that there is a large interest in the research methods of WG 3 and also in the PTB measuring sites for the dosimetry of environmental radiation. AIRDOS recommended that the EUROPEAN network operators should take part in these intercomparisons regularly as part of the quality management. Therefore, PTB will continue to perform there intercomparisons in the future.

**Intercomparisons at the intercalibration site.** A project to compare the response of different detector types was started in 1996 at the Schauinsland mountain close to Freiburg, Germany, where BfS has run a trace analysis laboratory for about 50 years. The facility is located on the Schauinsland mountain (1200 m above sea level). In contrast to the above mentioned intercomparison experiments performed by the European Dosimetry group (EURADOS), the aim of this inter-calibration experiment (INTERCAL) is to compare different area dose rate detector types over long periods and under rather unfavorable climatic conditions [29]. In summer 2007, the INTERCAL facility was re-designed for the simultaneous operation of up to 20 different ARDM detectors under the same environmental conditions. Probes are installed in a circular arrangement with a radius of 5 m. This design allows the simultaneous irradiation of all detectors at the same time using radioactive sources.

After completion of the modernization, the different components of the natural radiation fields at the INTERCAL facility were characterized. The contribution of charged particles and photons of the secondary cosmic radiation is in the order of 40 nSv/h. The terrestrial radiation has a slightly higher value and is not constant over the whole measuring site. The terrestrial component at different positions was investigated using a handheld device and varies between 72 nSv/h and 82 nSv/h. During rain events, the background level can be increased by a factor of 3 and can be reduced to by a factor of 10 by snow cover in winter. The facility provides rich additional instrumentation: several monitors are operated at the INTERCAL site, allowing to extend the investigation of area dose rate detectors by taking into account air-borne activity concentrations of aerosols, the nuclide specific activity on ground, the intensity of the cosmic radiation, the neutron flux, soil moisture, the amount of precipitation, air pressure, temperature and for example $^{222}\text{Rn}$-exhalation.

Today, 20 different area dose rate detector types are under operation representing about 20 states of the EU. The observed data are transferred to a common data base, thus allowing systematic evaluations of the data. With the data available since the start of the operation of the modernized INTERCAL facility, direct comparison and correlation methods have been developed. For example, comparison methods are used to detect technical problems of a particular area dose rate detector and to compare the time evolution of observed data of different detectors during single rain events. On the other hand, mean values of measured data observed by different area dose rate detectors in a certain time period are compared and correlation methods based on a linear regression allow the assessment of relative responses of different probes to variations of the natural radiation field [22]. In addition, two exposure experiments with $^{137}\text{Cs}$ and $^{60}\text{Co}$ sources were performed in 2009 and 2012.

### 4 Scientific applications

In the absence of an emergency situation, the information collected by the EURDEP system is a direct image of the natural background radiation and its variations in time and location. The small
variations observed in the natural radiation indirectly contain information about environmental conditions which can be very useful in a complementary context.

One application of early warning networks in a different context is the method to use the terrestrial dose rate as a proxy for the radon flux. $^{222}$Rn is commonly used as a natural tracer for validating climate models. To improve such models, a better source term for the $^{222}$Rn flux is necessary. Usually, a spatially and temporally uniform atomic flux rate of $1 \text{ cm}^{-2} \text{s}^{-1}$ from all ice-free land surfaces is assumed, with a lower $^{222}$Rn flux rate above a latitude of 60° N. Szegvary et al. [30] developed a method to relate the radon flux density to the closely associated terrestrial dose rate. The spatial variation in the terrestrial dose rate was found to describe almost 60% of the spatial variation in the $^{222}$Rn flux. Furthermore, a correlation was found between the temporal variations in the terrestrial dose rate and the $^{222}$Rn flux. Using this empirical correlation and after applying a spatial interpolation by kriging between the locations of the area dose rate monitoring stations [31], maps of the terrestrial dose rate were transformed into $^{222}$Rn flux maps providing first comprehensive and ground-validated radon flux-density maps on a $0.5^\circ \times 0.5^\circ$ grid for Europe.

This method is an attractive option for estimating radon flux densities in Europe since it uses the already available information provided by the EURDEP system under normal operation. The exhalation of radon is correlated with the exhalation of other gases, which play a role as greenhouse gases. The provision of spatially and temporally resolved $^{222}$Rn flux maps is a useful contribution to the ongoing effort to establish an observing system for greenhouse gas emissions in Europe [32].

A second method deals with soil moisture: the interrelationship between soil moisture and air temperature is significantly affected by the climate change. In some years very hot and dry periods during the summer months were observed in Europe. These periods were preceded by a depletion of soil moisture resulting in reduced latent cooling and amplified summer temperature extremes [33]. Since wide area soil moisture sensor networks do not exist, the use of terrestrial ambient dose equivalent rate data to derive soil moisture information in real-time would lead to the optimization of weather forecasting.

5 Conclusions

Most countries in Europe and also world-wide have established radiological surveillance strategies to ensure health and safety of the population in routine and emergency situations. Moreover, reliable data are required to correctly judge the radiological situation and to give advice to local authorities related to civil protection, but also with respect to advice concerning traveling, trade, transport, industry and tourism. Area dose rate monitoring has the purpose to inform about scale and intensity of any radioactive contamination in case of a nuclear emergency. In Europe about 5500 early warning stations are installed and continuously operated. Data from these stations are transmitted to the European Data Exchange Platform (EURDEP), providing a close to real-time picture of the radiological situation in Europe.

As a further application of early warning networks, available dose rates data from routine monitoring contain information on spatial and temporal variations of radon flux density and on soil moisture which depend in similar ways on geological and meteorological factors as the terrestrial component of the dose rate, which can be used by the scientific community for the optimization of models to determine effects of climate change.
At the moment, the precision of the dose rate data found in the EURDEP data base is limited because of technical differences between the installed detectors of different networks and methodical differences between network operators. Especially the site characteristics of the stations, the detector systems and their properties, the measurement procedures, the calibration methods and the methods of data evaluation are different. As a consequence, identical exposure conditions lead to considerable differences in the indicated values by a factor 2 or more. For a better quality of the measured dose rate data and for a better comparability more efforts in harmonization are needed to avoid unclear or even inconsistent results. This article supports this goal by listing many requirements and recommendations. They should be taken into account thoroughly if a network is installed, renewed or if a network shall be improved.

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