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Requirements to a Norwegian National Automatic Gamma Monitoring System

Bent Lauritzen, Per Hedemann Jensen and Flemming Nielsen

Risø National Laboratory
Roskilde
Denmark
April 2005

Risø-R Report

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Requirements to a Norwegian National Automatic Gamma Monitoring System

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Abstract. An assessment of the overall requirements to a Norwegian gamma-monitoring network is undertaken with special emphasis on the geographical distribution of automatic gamma monitoring stations, type of detectors in such stations and the sensitivity of the system in terms of ambient dose equivalent rate increments above the natural background levels. The study is based upon simplified deterministic calculations of the radiological consequences of generic nuclear accident scenarios. The density of gamma monitoring stations has been estimated from an analysis of the dispersion of radioactive materials over large distances using historical weather data; the minimum density is estimated from the requirement that a radioactive plume may not slip unnoticed in between stations of the monitoring network. The sensitivity of the gamma monitoring system is obtained from the condition that events that may require protective intervention measures should be detected by the system. Action levels for possible introduction of sheltering and precautionary foodstuff restrictions are derived in terms of ambient dose equivalent rate. For emergency situations where particulates contribute with only a small fraction of the total ambient dose equivalent rate from the plume, it is concluded that measurements of dose rate are sufficient to determine the need for sheltering; simple dose rate measurements however, are inadequate to determine the need for foodstuff restrictions and spectral measurements are required.

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1 Introduction

In the event of a nuclear or radiation emergency resulting in the dispersion of radioactive materials into the environment, the effective implementation of measures for the protection of the public will largely depend upon the adequacy of advance preparation. This should include the preparation of emergency response plans to control and limit the consequences of the accident.

The IAEA has published requirements entitled *Preparedness and Response for a Nuclear or Radiological Emergency* [1] in which it is required that operational criteria be established for promptly assessing the results of environmental monitoring in order to implement effective urgent and longer-term measures to protect the public against the exposure to radionuclides released to the environment by a nuclear or radiological accident. In accordance with these requirements and also from the experience gained in most of the European countries affected by the Chernobyl accident many IAEA Member States have established a network of monitoring stations to detect a passing radioactive plume released to the atmosphere by an accident at a nuclear facility.

In Norway such a network of monitoring stations has been in operation for many years. The Norwegian Radiation Protection Authority (NRPA) has in a "Request for Proposal - Modernization of the automatic gamma monitoring system in Norway" [2] called for an assessment of the overall requirements for a national Norwegian monitoring network with special emphasis on the geographical distribution of monitoring stations, type of detectors in such stations and the sensitivity of the system in terms of dose rate increments relating to specific countermeasures.

1.1 Background

The purpose of an automatic gamma monitoring system is to provide early warning of nuclear accidents and/or to provide a first, rough assessment of the radiological situation with the purpose of introducing protective measures in the early (emergency) phase of a nuclear accident. The present study presents the rationale for a distributed network of automatic gamma monitoring stations in Norway. The major issues considered in the study are (1) type of gamma monitors, (2) sensitivity of these monitors in terms of the minimum detectable incremental dose rate level related to international recommended intervention levels, and (3) the spatial density of gamma monitoring stations required to comply with the rationale behind the monitoring network, with special emphasis on nuclear power plants in neighbouring countries. The potential for early information on accidental dispersion of anthropogenic radioactivity will in part be limited by political/economical constraints imposed on the monitoring system; a quantification of these aspects will, however, be outside the scope of this study.

A nuclear accident is normally divided into three phases: a *pre-release phase* with a time scale of hours/days, a *release phase* with a time scale of hours/days and a *post-release phase* with a time scale of weeks/months/years, depending on the nature of the release. Protective measures to be taken with the purpose of averting radiation exposure from atmospheric releases of radioactive materials are often divided into preventive, urgent and late protective measures, relating to the three phases of the accident as indicated in Fig. 1. Automatic gamma monitoring stations are normally justified only for warning and assessment purposes in the emergency phase of an accident and not as basis for post-emergency countermeasures because in this phase a reasonably complete picture of radiation and contamination levels in the environment will be available based on more extensive mobile survey measurements and environmental sampling and analyses.

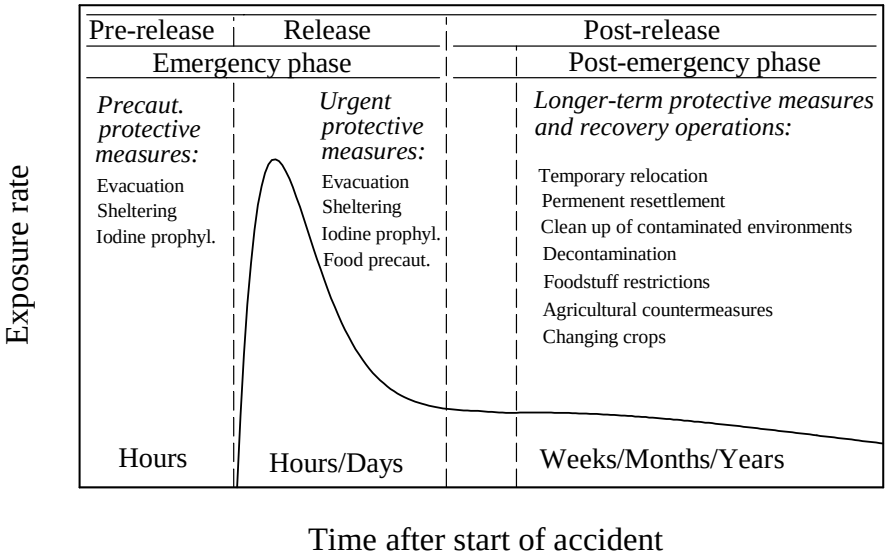

Figure 1. Time phases for introduction of protective measures in a nuclear accident. In the pre-release phase countermeasures are introduced based on plant conditions. In the release phase countermeasures are introduced based on measurements and plant conditions. In the post-release phase countermeasures and recovery operations are introduced based on measurements.

1.2 Method of investigation

The purpose of the present study has been twofold, namely to determine the sensitivity of a gamma monitoring system in radiological situations that may require specific early phase countermeasures and to determine the geographical density of such a system. The study has been based upon simplified deterministic calculations of the radiological consequences of generic nuclear accident scenarios. A more comprehensive study would have required a probabilistic safety assessment (PSA).

Two release scenarios are considered in the study: (1) a noble gas release with a minor content of iodine and (2) a release of noble gases, iodine and particulates. A decay time during transport is assumed to be 24 hours corresponding to a distance from the release point to the point of detection of 200 - 1,000 kilometres, depending on wind speed. The plume passage time is assumed to be 4 hours.

An "order-of-magnitude" assessment has been made of the possible (minimum) external gamma dose rates that can be measured by an automatic gamma measuring system given a radiological situation that calls for one or more specific urgent countermeasures in the emergency phase. Rather inexpensive urgent countermeasures are sheltering and precautionary foodstuff restrictions. The doses averted from these urgent protective measures can be assessed from measurements of the ambient dose equivalent rate from the plume and activity deposited on the ground (gross gamma dose rate) and from measurements of the surface contamination density on ground and its nuclide composition (gamma spectrometry).

The minimum density of gamma monitoring stations has been estimated from an analysis of the dispersion of radioactive materials over large distances. For this investigation calculations with the RIMPUFF atmospheric dispersion/dose model using historical weather data have been performed [3], and requirements to the density of gamma monitoring stations have been estimated based on the assumption, that the radioactive cloud may not slip unnoticed in between stations of the monitoring network.

1.3 Existing system

The existing Norwegian automatic monitoring system has been established to detect potential radioactive releases from foreign or domestic sources. These include nuclear power plants in surrounding countries, the nuclear reactors at Halden and Kjeller, and nuclear-powered vessels [4].

The gamma-monitoring network comprises 28 monitoring stations, 11 of which being equipped with Reuter-Stokes ionization chamber detectors while 18 stations have NaI(Tl) scintillation detectors with multi-channel analyzers for gamma spectrometry. For both systems an alarm level is set at 40 $nSv \cdot h^{-1}$ increase in the total gamma dose rate (ambient dose equivalent rate). In addition, alarm criteria for the gamma spectrometers are applied for an increase in the radiation level within either of the ^{131}I, ^{134}Cs, and ^{137}Cs energy windows.

In addition to the gamma-monitoring network, the emergency monitoring program includes high- and low-volume air-monitoring stations, capabilities for mobile survey measurements, airborne measurements, analyses of foodstuffs and environmental samples, and for contamination measurements [4].

2 Rationale of a national gamma monitoring network

Because of the need to act quickly in case of a nuclear or a radiological emergency, there is merit in establishing - in advance - values of surrogate quantities for doses that could be averted by different countermeasures. Such operational quantities can be more readily assessed from conditions pertaining when decisions need to be made, *e.g.* expressed as ambient dose equivalent rates, which could be measured at a network of monitoring stations distributed within the country in a grid with a density determined by pre-selected accident or threat scenarios [5].

2.1 Objectives of an automatic gamma monitoring system

Urgent countermeasures in the emergency phase of a nuclear accident can be triggered before activity concentrations or dose rates can be measured in the environment. The basis for such measures would be plant conditions, *e.g.* measured activity concentration or dose rate within the containment and the probability of a release from the containment to environment [6]. Urgent countermeasures can also be triggered by environmental measurements of gamma dose rates, *e.g.* obtained from the automatic monitoring network.

Doses from activity released into the environment can be averted by specific countermeasures, but avertable doses are not a measurable quantity. Measurements in the environment of external dose rates and gross activity concentrations in air combined with model calculations of doses can, however, predict avertable doses by a given urgent countermeasure. Automatic monitoring systems are therefore useful in the emergency phase of an accident, both as a warning system (alarm) and as a tool to predict doses to the affected population (assessment).

The objectives of a system of national automatic gamma measuring stations are shown schematically in Fig. 2. It appears from the figure that if a radioactive plume passes a measuring station, an alarm relating to a specific countermeasure or a combination of countermeasures can be triggered; the “alarm branch”. Precautionary countermeasures may or may not be invoked, depending on other information that may be available in the situation. Further (mobile) measurements may be initiated in order to assess the situation.

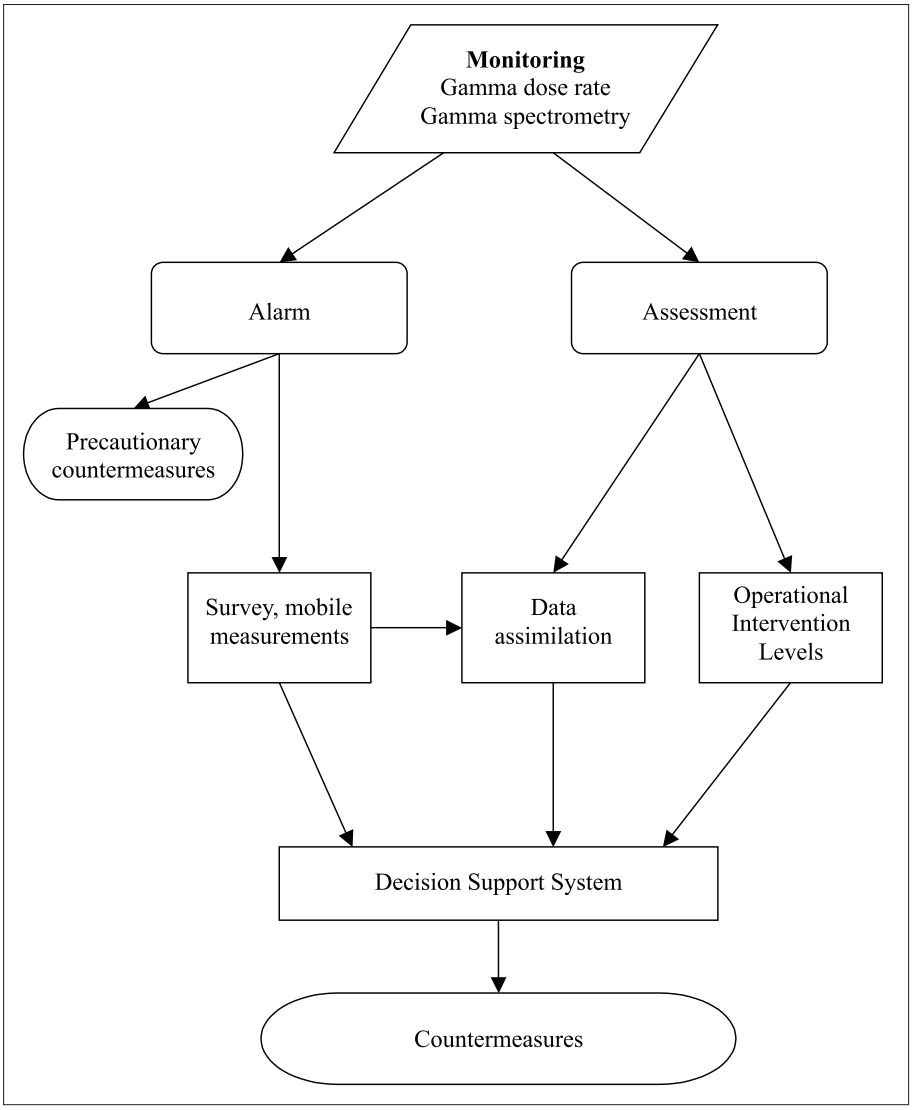

Figure 2. Flow chart showing the procedures following an alarm from the proposed automatic gamma monitoring system at Norwegian territory.

In the assessment branch, the severity of a radiological situation is assessed, either based directly (solely) on data from the automatic monitoring network by comparing with predefined, optimized operational intervention levels (OILs) [5, 7], or through a data assimilation process where various data, *e.g.* from mobile measurements, are combined to assess the situation [8, 9]. The assessment process may be initiated by an alarm, or may be carried out automatically, not depending on an initial alarm.

Since the authorities will have an interest in acquiring information on the dispersion of anthropogenic radionuclides in the environment, the alarm level from this perspective should be set as low as possible, limited only by technical/economical constraints. These constraints constitute a lower limit to the sensitivity (detection limit) of the monitoring system. In setting the alarm level, it is, however, important that false alarms, *e.g.* due to natural variations in the background level, are kept at a minimum. An upper limit to the sensitivity is obtained by requiring that events that may necessitate protective intervention measures should be detected. This upper limit is determined by the action level for the countermeasure. Hence, the dose rate detection limit(s) of the system should be better than the action level associated with the possible onset of protective countermeasures.

2.2 Threat scenarios

Despite all the precautions that are taken in the design and operation of nuclear facilities and the conduct of nuclear activities, there remains a possibility that a failure or an accident may give rise to a nuclear or radiological emergency. In some cases, this may give rise to the release of radioactive materials within facilities and/or into the public domain, which may necessitate emergency response actions. Adequate preparations should be established and maintained at local and national levels and, where agreed between States, at the international level to respond to emergencies.

According to the IAEA, the nature and extent of emergency arrangements should be commensurate with the potential magnitude and nature of the threat associated with the facility or activity [1]. Any threat associated with nuclear facilities in nearby States should also be considered. In the threat assessment, any populations at risk should be identified and, to the extent practicable, the likelihood, nature and magnitude of the various radiation related threats should be considered. Facilities, sources, practices, on-site areas, off-site areas and locations should be identified for which a nuclear or radiological emergency could warrant precautionary urgent protective actions to prevent severe deterministic health effects, urgent protective actions to reduce stochastic effects by averting doses, and agricultural countermeasures, countermeasures to ingestion and longer term protective measures.

The following four threat scenarios have been considered by the NRPA as the main nuclear or radiological threats in relation to a Norwegian automatic gamma monitoring system:

(1) accidents at nuclear power reactors

(2) accidents involving nuclear powered vessels

(3) accidents at a Norwegian research reactor

(4) terrorist activities

The four threat scenarios pose different requirements to a monitoring system. However, a reasonably sparse national automatic gamma-monitoring network may only effectively address the first of these threat scenarios, while the remaining three scenarios require either a much denser network and/or the existence of an operational mobile monitoring system to allow for local mapping of affected territory, including monitoring for pure beta-emitters.

(1) Accidents at nuclear power reactors outside Norway

A number of nuclear power plants are situated in the neighbouring countries to Norway as shown in Fig. 3. The minimum distance from the Norwegian border/coastline to these plants ranges from about 200 to 1,000 kilometres. The reactors are of different types and design and the potential threat from the plants also differ due to the differences in safety systems of the plants, *e.g.* lack of pressure vessel at the nuclear reactors in the former Soviet Union, cf. Table 1, below.

The threat posed by the different power plants depend both on the risk for accidents with releases of radioactive materials to the atmosphere and on the distance from Norwegian territory. The RBMK-type power plants at Ignalina and Leningrad are considered to have a have a higher probability of accidents where radioactive materials are dispersed into the atmosphere than the light water or gas-cooled reactors of Finland, Sweden, UK and Germany. This is to some extent balanced by the smaller risk associated with atmospheric dispersion over large distances [10].

Automatic gamma monitoring stations placed on Norwegian territory in a proper network can address the threat scenarios from the nuclear power reactors outside Norway.

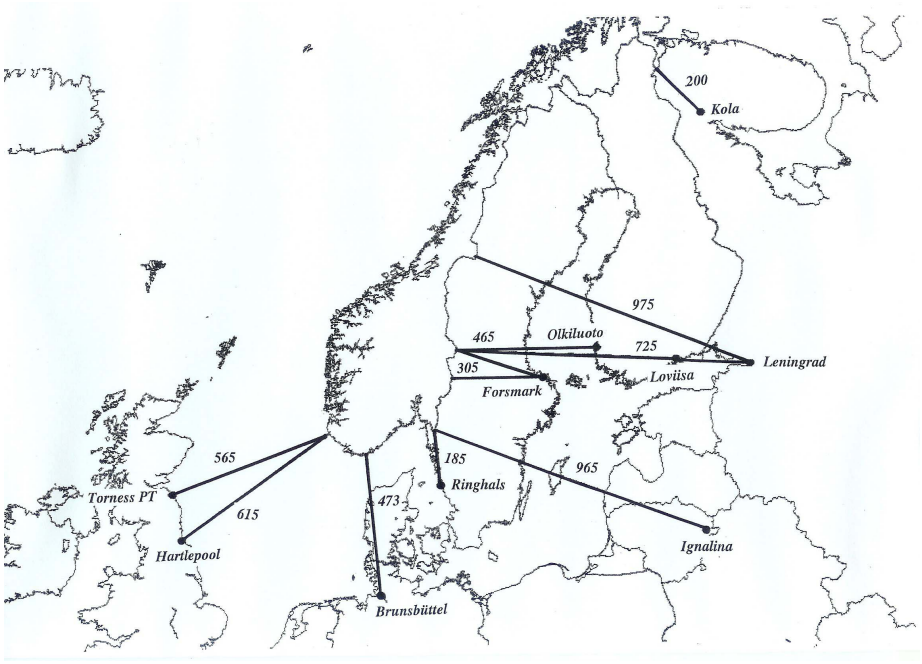

Figure 3. Position of nuclear power plants outside Norway with the distance from the Norwegian border or coast line in kilometres.

(2) Nuclear powered vessels

Reactor accidents may occur at nuclear-powered vessels, *e.g.* submarines or nuclear-powered icebreakers with releases of radioactive material to the atmosphere. Historically, a large number of accidents have occurred in nuclear powered vessels, especially submarines of the Soviet (Russian) Navy. The frequency of accidents has, however, been decreasing since the early 1960'es, partly because of a decreasing number of submarines of the navy, and partly because of a more safe design of the newer classes of submarines [11].

Two types of accidents are of relevance for radioactive releases to the atmosphere: criticality accidents and loss of cooling accidents (LOCA). The Soviet Navy has suffered five criticality accidents in the past during refuelling or repair/testing at the naval shipyards, and six LOCA while the ships were at sea. In addition, a few coolant solidification accidents have occurred that might have lead to a LOCA [11].

Criticality accidents are unlikely to occur during normal operation, while neutron flux monitors and control systems are in operation, but they may happen during refuelling or maintenance while the safety systems have been shut off. During refuelling the submarine hull is cut open and a criticality accident will result in a release of radionuclides to the atmosphere. Especially during de-fuelling when used fuel is present, a criticality accident could result in a release of large amounts of activity. LOCAs may occur, *e.g.* when the core cooling is reduced because of a coolant leakage. They occur in particular during reactor operation or shortly after reactor shutdown, when the decay heat still is significant. If the fuel is damaged during a LOCA, radioactive materials may be dispersed inside the reactor compartment and the vessel.

In design of an early warning system for accidents at nuclear-powered vessels, two important factors to be considered are the likelihood and the severity of an ac-

cident, and the location of the accident, *i.e.* the distance from Norwegian territory. Criticality accidents are unlikely to occur except when the vessels is undergoing refuelling or maintenance at a shipyard, and in this respect, the nuclear-powered vessel can be considered a stationary potential source. LOCAs in nuclear-powered vessels may occur at sea, but the source term is unlikely to be significant and to pose a threat to Norwegian territory, the only possible exception being accidents in one of the small number of nuclear-powered surface vessels.

Automatic gamma monitoring stations placed on Norwegian territory may address criticality accidents, but may not effectively address LOCAs.

(3) Accident at a Norwegian reactor
Accidents can occur on the two research/isotope producing reactors placed at Norwegian research establishments. Although a national automatic gamma-monitoring network may detect an accidental release of radionuclides from these reactors, local emergency arrangements and detection systems would be significantly more efficient to reveal such an accident. Therefore, a national automatic gamma monitoring system should not be based on the threat scenarios from Norwegian research reactors.

(4) Terrorist activities
Scenarios for breaching the security of a source with the malevolent intent of causing radiation exposure are characterized in terms of their threat, a term that is widely used to describe a variety of security risks that may confront facilities housing nuclear and other radioactive substances. To respond effectively to possible security breaches, it is necessary to recognize and anticipate the kind of threat that might trigger such an event. Possible scenarios include:

- detonation of conventional explosives shrouding an ordinary radioactive source, such as those commonly used in medicine and industry, whose security has been breached
- contaminating a specific site or environment with radioactive materials where the principal aim is the long-term loss of a site such as a railway station, bus terminal, financial district, or other key infrastructure facility
- contaminating food or water supplies with unsecured radioactive materials where the aims are to expose the public consuming the contaminated food or drink the contaminated water; and stop food or water supplies to the public
- attack on or sabotage of safety-related systems at nuclear facilities holding large inventories of radioactive materials; this type of facilities encompass nuclear power plants, research reactors, nuclear-fuel reprocessing plants and radioactive waste management installations
- diversion of nuclear materials, particularly special fissionable materials, such as ^{235}U and ^{239}Pu, and the development, construction and use of a crude nuclear weapon, usually known as an '*improvised nuclear device*'

The scenarios are, however, completely different in threat, genesis and likelihood but they are rather similar in their ultimate consequence, namely unexpected situations of uncontrolled public radiation exposure and radioactive contamination of the environment. The common element is the intent to generate terror by dispersing radioactive substances in public areas. There is therefore a common need to be able to promptly assess and communicate the consequences of any event. No single event can be used as a basis for development of response plans. An automatic gamma monitoring system would therefore not be adequate to detect a "radiological attack".

3 Density of gamma monitoring network

3.1 Method of investigation

In deciding on the density of monitoring stations, the likelihood of detecting anthropogenic radioactivity in the environment with the purpose of reducing the adverse effects of radiation should be balanced against the costs of setting up and operating the network. Modelling the likelihood of detection will be subject to uncertainty. The likelihood of detection depends both on the spatial and temporal extension and on the variability of the radioactive contamination. However, the likelihood will increase as the density of the monitoring network is increased, until the distance between monitoring stations are comparable to the spatial extension of the radioactive contamination. For a non-uniform, fractal distribution of the contamination it is further important for the detection probability that the sum of the fractal dimensions of the network and the radioactive plume is larger than two [12].

Considering radioactive releases that are transported towards the Norwegian border from abroad, the distance between monitoring stations located at the border should be compared to the linear extension of the plume, in the transverse direction of the mean advection direction from the release point. When the distance between stations is comparable to the linear, transverse extension of the plume, adding more stations will not significantly improve the likelihood of detecting the plume.

For a more detailed assessment, *e.g.* for a rough mapping, of the spatial and temporal distribution of a radioactive contamination a larger density of monitoring stations is required. In principle, the distance between monitors should for this purpose be small compared to the linear scale of variation of the contamination field. While such a dense network can be established for monitoring in the close neighbourhood of a potential nuclear accident source, *e.g.* for off-site monitoring around the research/isotope producing reactors at Halden and Kjeller, it will be a much more demanding task for widespread nuclear threats, such as those associated with the nuclear power plants in the countries surrounding Norway.

In the following, only potential nuclear threats from locations in neighbouring countries, for which the long-range atmospheric dispersion of radioactive materials may affect Norwegian territory, are considered. The likelihood that a national network of automatic gamma monitoring stations located at or close to the Norwegian border will detect the radioactive plume will depend on the transverse extension of the plume as it reaches the Norwegian border.

3.2 Atmospheric dispersion

The transverse extension of the plume has been examined by performing a large number of calculations with the RIMPUFF atmospheric dispersion model [3], using historical weather data [13]. The effective transverse extension depends both on the size of each released puff, which grows as function of the travel time, on the initial dispersion at the source as well as on the duration of the release and the monitoring time (averaging time). Because of wind shear, a large vertical extension of the plume will affect the horizontal, transverse plume size.

A short release time (and monitoring time) implies a narrower plume. Hence a lower limit for the plume transverse extension is obtained for an instantaneous release with little initial dispersion. On the other hand, considering the distance from the Norwegian border to the major nuclear installations in surrounding countries, cf. Fig. 3, only reasonably large accidents may have a substantial effect on Norwegian territory. A large accident at a nuclear power plant, with core damage

and release of radioactive material to the atmosphere, will have a minimum duration of maybe a few hours, before the release can be contained. The upper limit of the release duration could be several days, as demonstrated by the Chernobyl accident [14]. For the present investigation the duration of the release is assumed to be 4 hours.

Using numerical weather prediction model data for the year 2004, a radioactive plume released at a hypothetical reactor position was followed for 48 hours and the time-integrated activity concentration in air was calculated. The width of the plume, defined as the root mean square angular dispersion at a fixed radius was calculated at distances up to 800 km from the release point. In total, approx. 300 such calculations were performed spanning the year 2004, to cover the variation in weather patterns during the year. Details of the numerical investigations are provided in Appendix A.

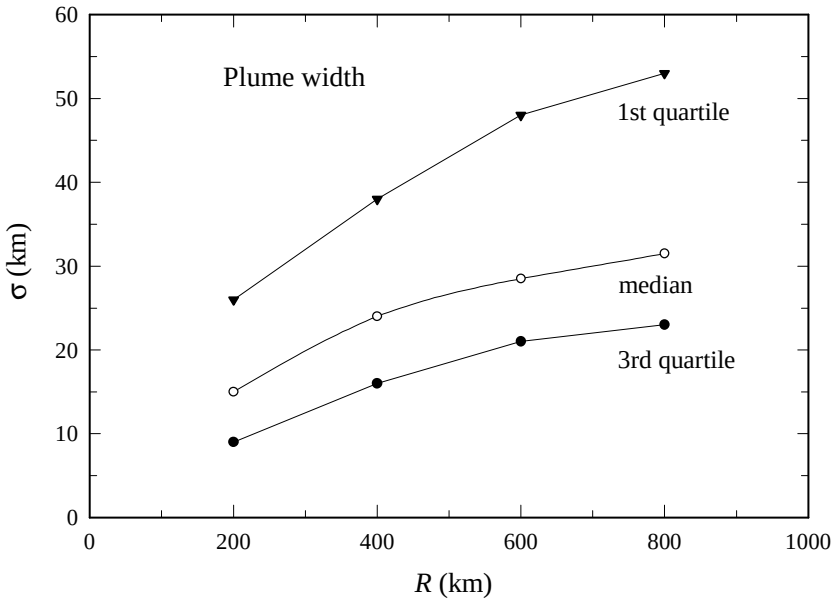

Figure 4. Plume r.m.s. transverse extension (σ) as function of distance R from the release site.

In Fig. 6 (Appendix A) the distribution of plume widths are shown for distances 200 - 800 km from the release site, and in Fig. 4 the median and the first and third quartiles of the distribution are shown. While the width of each plume may display an irregular dependency on the distance, the typical widths inferred from the distribution shown in Fig. 4 are seen to increase roughly as a square root of the distance, consistent with a diffusing cloud.

The median plume width (1σ) at distances given by the closest distances from the Norwegian border/coastline to nuclear power plants outside Norway are listed in Table 1, cf. Fig. 3, using the simple parameterization of the distance dependency given in Appendix A. Note, however, that reasonably conservative assumptions have been made in defining the release scenario.

Assuming a Gaussian shape of the crosswind plume profile and a plume width given by the median value the minimum measured dose rate at monitoring stations separated by, *e.g.* 4σ will be $\exp(-2) \approx 0.14$ relative to the maximum value observed at the plume centreline. However, a much more irregular shape than the smooth Gaussian profile should be expected from the turbulent, long-range atmospheric dispersion. This will add to the variability and may reduce the probability of detecting the radioactive plume. A quantification of these aspects has not been carried out in this study.

Table 1. Selected nuclear power plants in surrounding countries, with distances from the Norwegian border. The last column shows the median transverse extension of the plume (1σ) at the border, assuming the radioactive plume to reach Norway at the position of the shortest distance from the power plant.

Nuclear power plant	Reactor type	Power plant position	Distance from Norwegian border	Median r.m.s. plume width
Ringhals	BWR, PWR	57° 15' N, 12° 05' E	185 km	15 km
Kola	VVER	67° 30' N, 31° 30' E	200 km	16 km
Forsmark	BWR	60° 25' N, 18° 10' E	305 km	20 km
Olkiluoto	BWR	61° 10' N, 21° 30' E	465 km	24 km
Brunsbüttel	BWR	53° 54' N, 09° 12' E	473 km	25 km
Torness PT	AGR	55° 55' N, 02° 15' W	565 km	27 km
Hartlepool	AGR	54° 40' N, 01° 15' W	615 km	28 km
Lovisa	VVER	60° 30' N, 26° 10' E	725 km	30 km
Ignalina	RBMK	55° 20' N, 26° 10' E	965 km	35 km
Leningrad	RBMK	59° 55' N, 30° 25' E	975 km	35 km

4 Sensitivity of gamma monitoring system

An upper limit to the sensitivity of the automatic gamma monitoring system is obtained by requiring that nuclear accidents that may necessitate protective actions to be taken in Norway should be detected by the system. It is assumed that the accidents involve atmospheric releases of radioactive materials, which are transported towards Norwegian territory from abroad. The relevant protective actions in the emergency phase include sheltering, iodine prophylaxis and foodstuff restrictions.

The monitoring network may include dose rate meters recording increments in the ambient dose equivalent rate or a similar quantity, and gamma spectrometers from which the dose rate in radionuclide-specific energy windows and/or radionuclide activity concentration in air can be estimated, *e.g.* assuming a semi-infinite distribution of radionuclides in air.

4.1 Detection limits

In general, remedial actions should be taken if the averted dose by the action offsets the total costs of intervention. To aid emergency planning, generic optimized interventions levels for specific protective actions have been recommended by IAEA, cf. Table 2 [15]. A protective action should be invoked if the avertable, effective dose to a sample of the population exceeds the intervention level for the action, *i.e.* for $\Delta E > \Delta E_{IL}$.

Table 2. IAEA recommended generic intervention levels for urgent protective measures expressed in terms of avertable individual doses [15, 16].

Protective action	Generic intervention level	Comments
Sheltering	10 mSv averted	Duration not to exceed 2 days
Evacuation	50 mSv averted	Duration not to exceed 7 days
Iodine prophylaxis	100 mGy averted	Dose to thyroid

For foodstuffs, intervention levels (Guideline Levels) are defined in terms of the activity concentration of radionuclides in the foodstuffs, above which restrictions on the use and distribution of the foodstuffs should be invoked, cf. Table 3.

Table 3. Guideline Levels for radionuclides in foods following accidental nuclear contamination for use in international trade from the Codex Alimentarius Commission [17].

GUIDELINE LEVELS FOR FOODSTUFFS		
	Recommended values (Bq/kg)	
Radionuclides	Foods destined for general consumption	Milk and infants food
^{134}Cs, ^{137}Cs, ^{103}Ru, ^{106}Ru, ^{89}Sr	1,000	1,000
^{131}I		100
^{90}Sr	100	
^{241}Am, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu	10	1

Considering all possible accident scenarios, characterized by the release, atmospheric transport and deposition, radiation exposure pathways as well as the affected population, both the dose averted by the remedial action, ΔE, and the gamma radiation dose rate, $\dot{E}_\gamma(x)$, detected by a monitoring station at location x, are associated with large variability and should be treated as stochastic variables. In Fig. 5, the joint distribution of avertable dose and measured dose rate is shown schematically. Note that the avertable dose, ΔE, and the dose rate, $\dot{E}_\gamma(x)$, may refer to two different locations: the first being the location of the population sample considered, while the latter being the location of the monitoring station.

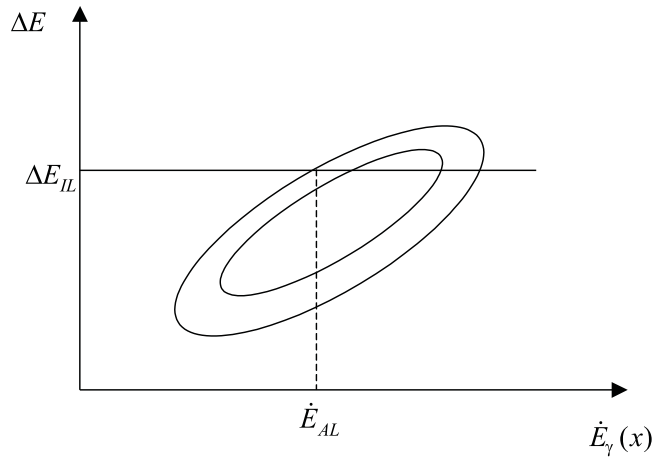

Figure 5. Schematic drawing of joint distribution of observed gamma dose rate, $\dot{E}_\gamma(x)$, and the avertable dose, ΔE. The action level for dose rate is the minimum dose rate for which the avertable dose is equal to the intervention level, ΔE_{IL}.

An action level in terms of the measured dose rate can be defined for any of the monitoring stations as

$$\dot{E}_{AL} = \min\left\{\dot{E}_\gamma(x)\,|\,\Delta E = \Delta E_{IL}\right\} \tag{1}$$

From Fig. 5 it then follows, that situations where the measured dose rate is smaller than the action level will not require intervention, *i.e.*

$$\dot{E}_\gamma(x) < \dot{E}_{AL} \;\Rightarrow\; \Delta E < \Delta E_{IL} \tag{2}$$

If the sensitivity of the gamma monitoring system, in terms of detectable increments in dose rate above the background level, is better than the action level given in Eq. (1), it follows that events that require intervention will be detected by the monitoring system. Hence, the action level provides an upper limit to the sensitivity (detection limit) of the monitoring system.

A somewhat less strict, but more practical definition of the action level is

$$\dot{E}_{AL} = \Delta E_{IL} \, \min \left\{ \frac{\dot{E}_\gamma(x)}{\Delta E} \right\} \tag{3}$$

from which the relation (2) also follows. Here, the minimum is taken over all scenarios, *i.e.* not only those for which $\Delta E = \Delta E_{IL}$. In applying Eq. (3), however, care should be taken only to consider accident and exposure pathway scenarios for which it is conceivable that interventions are justified. Eqs. (1) and (3) apply to a single monitoring station. For a grid of monitoring stations in a network, $\dot{E}_\gamma(x)$ in Eqs. (1) and (3) is the highest of the measured dose rates, assuming it is sufficient that a single monitoring station registers an event. In the following, the action level defined in Eq. (3) will be used.

If the measured quantity is the dose rate within an energy window, registered in gamma spectrometry, the definition in Eq. (3) still applies for $\dot{E}_\gamma(x)$ now being the window-dose rate and the action level is defined accordingly. However, the sensitivity of detecting nuclide-specific dose rates will be less; in the following, therefore, it is assumed that the monitoring system records the total gamma dose rate (or the total count rate over all energies at a gamma spectrometer). Assumptions on the nuclide composition in the plume can always be used to assess the dose rate contribution from specific radionuclides and thus the action level for a nuclide-specific countermeasure like iodine prophylaxis.

4.2 Action levels for specific countermeasures

In the following action levels for sheltering and foodstuff restrictions are evaluated, based on the definition, Eq. (3). The method may readily be extended to include other countermeasures, *e.g.* evacuation and iodine prophylaxis.

Sheltering

The generic optimized intervention level for sheltering is $\Delta E_{IL} = 10$ mSv, assuming that sheltering will not last longer than two days, cf. Table 2. The gamma dose rates recorded by the monitoring network may have contributions both from the plume and from deposited material,

$$\dot{E}_\gamma(x) = \dot{E}_{\mathrm{plume}}(x) + \dot{E}_{\mathrm{ground}}(x) \tag{4}$$

while the dose avertable by sheltering at a (different) position y consists of the external radiation dose and the inhalation dose,

$$\Delta E(y) = \Delta E_{\mathrm{plume}}(y) + \Delta E_{\mathrm{ground}}(y) + \Delta E_{\mathrm{inh}}(y) \tag{5}$$

The action level for dose rate given in Eq. (3) is obtained by varying the dose rate in Eq. (4) and the avertable dose in Eq. (5) over all the accident and exposure pathway scenarios considered. The two quantities will be highly correlated; however, by taking the ratio of the dose rate to the avertable dose, a trivial scaling of the severity of the accident, *e.g.* scaling the total released activity at the accident, will have no effect on the action level given in Eq. (3).

Two release scenarios have been considered: (1) a noble gas release with a minor content of iodine and (2) a release of noble gases, iodine and particulates. In both cases, the plume passage time is assumed to be 4 hours. The travel time from the release point to the point of detection is assumed to be 24 hours, corresponding to a travel distance of the order of 200 - 1,000 km, implying that many of the short-lived radionuclides have been reduced significantly by decay during transport. The maximum dose rate recorded by the gamma-monitoring network is arbitrary assumed to be approximately 1/4 of the maximum dose rate in air at the plume centreline. Details of the calculations are provided in Appendix B.

In Table 4, the action levels for sheltering and foodstuff restrictions are shown for the two scenarios.

Foodstuff restrictions

In principle, a dose rate action level for foodstuff restriction can be defined similarly to the action level for sheltering defined in Eq. (3), by estimating the doses avertable by *e.g.* imposing a ban on specified foodstuffs and comparing these avertable doses to an optimized intervention level for the countermeasure. However, rather than avertable dose it is more practical to consider an intervention level in terms of activity concentrations in foodstuffs.

Following the Codex Alimentarius guidelines [17], generic intervention levels, $c_{IL}^{(k)}$, are defined for the activity concentration of $c^{(k)} = \sum_i^{(k)} c_i$ for radionuclides "i" belonging to the group (k), cf. Table 3. Similarly to Eq. (3) the intervention level for foodstuff restrictions in terms of a measured dose rate $\dot{E}_\gamma(x)$ is defined as

$$\dot{E}_{AL} = \min_{(k)} \left\{ c_{IL}^{(k)} \min \left(\frac{\dot{E}_\gamma(x)}{c^{(k)}} \right) \right\} \tag{6}$$

where the first minimum is taken over the different radionuclide groups and the second minimum is taken over the different accident scenarios considered. As for sheltering, if the maximum observed dose rate at the monitoring stations is smaller than the action level defined in Eq. (6), the radionuclide activity concentrations in food will not exceed the specified intervention levels ($\mathrm{Bq\,kg^{-1}}$) for each radionuclide group, *i.e.*

$$\dot{E}_\gamma(x) < \dot{E}_{IL} \Rightarrow \left\{ \forall k : c^{(k)} < c_{IL}^{(k)} \right\} \tag{7}$$

For foodstuffs, the possible activity concentrations will vary considerably, depending *e.g.* on the time of year and on the nature and amount of rainfall. Considering the same two accident scenarios as for the sheltering countermeasure, action levels for foodstuff restrictions have been calculated; details of the calculation are given in Appendix A.

Table 4. Action levels of dose rate for sheltering and foodstuff restrictions.

Countermeasure	Scenario (1)	Scenario (2)
Sheltering	5,000 $\mu\mathrm{Sv\,h^{-1}}$	70 $\mu\mathrm{Sv\,h^{-1}}$
Foodstuff restrictions:		
beef	14,000 $\mathrm{nSv\,h^{-1}}$	20 $\mathrm{nSv\,h^{-1}}$
lamb	9,000 $\mathrm{nSv\,h^{-1}}$	3 $\mathrm{nSv\,h^{-1}}$
leafy vegetables	7 $\mathrm{nSv\,h^{-1}}$	0.3 $\mathrm{nSv\,h^{-1}}$
beef	5 $\mathrm{nSv\,h^{-1}}$	0.5 $\mathrm{nSv\,h^{-1}}$

The results are shown in Table 4. In Scenario 1 transfer to foodstuffs only consists of iodine; in Scenario 2 transfer to beef and lamb is dominated by caesium isotopes while transfer of ^{131}I determines the action levels for leafy vegetables and milk.

5 Results and conclusions

A main objective of a national automatic gamma monitoring system is to detect anthropogenic radioactivity in the environment and to provide a first assessment on whether emergency measures are needed to protect the public against the exposure of radionuclides.

According to IAEA requirements [1] default operational quantities should be established for, *e.g.* (a) the results of environmental monitoring in order to decide on or to adapt urgent protective actions to protect the public, and (b) environmental measurements and radionuclide concentrations in food in order to decide on effective agricultural countermeasures, including a restriction of the consumption, distribution and sale of locally produced foods and agricultural produce.

A gamma monitoring system distributed nationwide is capable of detecting an atmospheric plume released in an accident outside the borders of the country. Different monitoring systems can be used, *e.g.* high-pressure ionization chambers and scintillation counters operated as a gamma spectrometer. The present study has addressed issues on such gamma measuring systems with regards to:

- the sensitivity of the system to be used in an emergency situation that requires urgent protective measures
- the geographical density (grid density) of the system within the country

Action levels expressed as the maximum ambient gamma dose equivalent rate at any of the measuring stations below which an urgent countermeasure is not needed have been calculated for sheltering and foodstuff restrictions. It appears from these calculations that for sheltering rather simple measuring systems, *e.g.* a GM-system, can easily measure the action level for both scenarios selected, namely 500 μSv h^{-1} for Scenario 1 (noble gas + iodine release) and 70 μSv h^{-1} for Scenario 2 (noble gas + iodine + particulate release).

Action levels for foodstuff restrictions are more diverse when expressed as ambient dose equivalent rate. For Scenario 1, action levels for restricting the foodstuffs beef and lamb can easily be measured with a simple dose rate system whereas the action level for restricting leafy vegetables and milk (due to its content of ^{131}I) hardly can be measured, even with a sophisticated dose rate measuring system. Also for Scenario 2, where the foodstuff contamination consists of several radionuclides of caesium, iodine, strontium and ruthenium, simple dose rate measurements would not be adequate to trigger foodstuff restrictions apart from maybe restrictions on beef. Therefore, in emergency situations where particulates contribute with even a small fraction of the total activity concentration, supplementary measurements are needed, *e.g.* gamma spectrometry to determine the iodine and caesium content of the plume.

Action levels for other countermeasures can be determined from the same methodology as for sheltering and foodstuff restrictions. For evacuation the methodology is exactly the same as for sheltering. For iodine prophylaxis information on the relative plume activity concentration of ^{131}I at the detector position and the intervention level for iodine prophylaxis (100 mSv as avertable equivalent dose to thyroid) is needed to derive the action level for iodine prophylaxis.

The geographical density of a network of measuring systems in Norway can be determined from considerations concerning the plume width at the Norwegian

border in case of a nuclear accident at each of the nuclear power plants in surrounding countries. Accidents at plants close to the border will require a denser network than accidents at power plants at more distant positions. For an accident at the Ignalina nuclear power plant in Lithuania, assuming that the monitoring stations are separated with a distance of about 150 kilometres, the minimum dose rate measured at a monitoring station would be about 15% of the maximum dose rate that could have been observed in the plume centreline at the same distance from Ignalina (approximately 1000 kilometres). In this case, if the detector(s) at the measuring stations have a (combined) sensitivity, which enables the station to detect an incremental dose rate of about 10 - 20% of the existing background dose rate, the maximum incremental dose rate in the plume centreline would have been about equal to the existing background dose rate.

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Appendix

A Long-range atmospheric dispersion

The transverse extension of an atmospheric plume at large distances from the location of the source is estimated with the RIMPUFF atmospheric dispersion model. RIMPUFF is a puff diffusion model developed for real-time simulations of plume dispersion [3]. The puff dispersion is controlled by local turbulence levels and wind field provided by a meteorological pre-processor, LSMC [18]. Meteorological data was taken from the HIRLAM numerical weather prediction model. RIMPUFF calculates activity concentrations and gamma doses from radioactive decay. For the present calculations, the time-integrated activity concentration in surface air, ρ, is used as a measure of the plume growth.

A plume consisting of a ^{85}Kr gas was released at position (54° 10' N, 23° 10' E). At distances R = 200, 400, 600, and 800 km $\rho(R, \theta)$ is evaluated as a function of the direction angle θ from the release point, and the root-mean-square angular fluctuation σ determined. The calculations were repeated approx. 300 times with different release times spanning the year 2004, to be representative for both the seasonal variations as well as the variations associated with the time-of-day of the release [13].

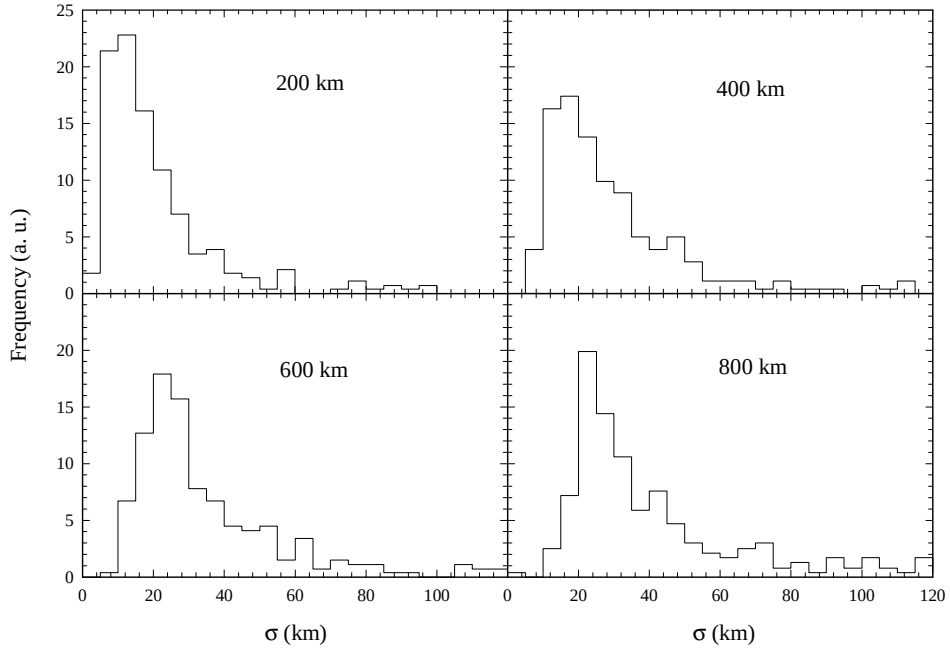

Figure 6. Frequency of horizontal r.m.s. plume widths, transverse to the direction from the release point to the point of observation.

Each release was taken as a ground release with no initial plume rise. The duration of the release was 4 hours, considered a probable duration of a major release from a PWR, while perhaps on the shorter side for major accident at a RBMK reactor. The puff dispersion and integration time was taken as 48 hours from the beginning of the release. After 48 hours the majority of puffs had left the HIRLAM domain used in the calculations while in some cases, *e.g.* because of the presence of low-pressure systems, the krypton plume was still inside the 800 km radius circle. The 48 hours however, was considered an upper time limit for detection of the radioactive plume by an automatic gamma-monitoring network.

In Fig. 6 the frequency of plume widths recorded at distances 200 - 800 km

from the release site is shown, and in Fig. 4 the quartiles of the distribution of widths are shown as function of the distance. The widths are seen to grow roughly as the square root of the distance from the release site. A simple parameterization of the median is

$$\sigma = 1.13\, R^{0.5}\ \mathrm{km}^{0.5} \tag{A.1}$$

B Action levels for sheltering and foodstuff restrictions

In this appendix, action levels in terms of measured dose rate are estimated for sheltering and foodstuff restrictions. The system of exposure pathways and the symbols used are shown in Fig. 7. The model used for calculating the action levels is available as a spreadsheet.

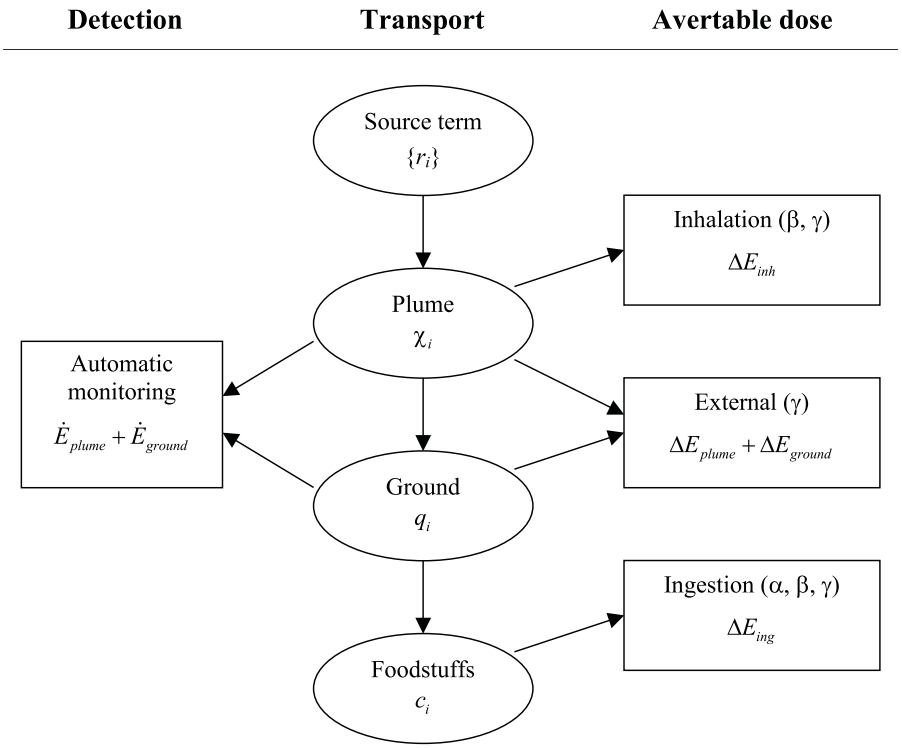

Figure 7. Atmospheric dispersion of radionuclides, with symbols shown for the transport of radionuclides, observed gamma dose rates at automatic monitoring stations, and the avertable external and internal doses.

B.1 Atmospheric dispersion and deposition

It is assumed that at large distances from the release site, the radioactive plume attains a stationary form during plume passage, characterized by a shape parameter, χ_0, and a uniform radionuclide composition, so that the activity concentration of radionuclide "i" can be written

$$\chi_i(\mathbf{r}) = \chi_0(\mathbf{r})\, f_i \tag{B.1}$$

The shape parameter, $\chi_0(\mathbf{r})$, is given by the total activity concentration in air ($\mathrm{Bq\,m^{-3}}$) and is assumed to be time-independent during plume passage, while f_i ($0 \leq f_i \leq 1$) is the relative concentration of the radionuclide.

For an accident where radioactive material is transported towards Norwegian territory from abroad, the activity concentration in air will decrease with the distance from the release site because of physical decay, dilution and deposition. Hence, the largest activity concentration in air, $\chi_{0,\max}$, will be observed on the border, at the plume centerline. The activity concentration at a monitoring station located at the border will in generally be smaller by a factor $\alpha(x)$,

$$\chi_0(x) = \alpha(x)\, \chi_{0,\max} \qquad 0 \leq \alpha \leq 1 \tag{B.2}$$

where $\alpha(x)$ depends on the distance from the plume centreline to the monitoring station.

Activity on the ground builds up during plume passage because of dry and wet deposition. For a constant dry deposition velocity, v_d, wet scavenging coefficient, Λ, and mixing layer height, H, the activity on the ground becomes,

$$q_i(\mathbf{r},t) = \chi_i(\mathbf{r})\,(v_d + \Lambda H) \times \begin{cases} t, & t < T \\ T, & t > T \end{cases} \tag{B.3}$$

where the radioactive material is assumed to be confined within the atmospheric mixing layer and the activity concentration to have a uniform vertical distribution. Furthermore, it is assumed that depletion of activity from the plume during plume passage can be ignored, which is valid for a short plume passage time, T.

Table 5. Radionuclides released from an RBMK-reactor in scenarios 1 and 2 and the composition at the position of the gamma monitoring system. A transport time of 24 hours is assumed for calculating the radionuclide composition at the detectors.

		Scenario 1		Scenario 2	
Radionuclide	Core content [PBq]	Release fraction [%]	Composition at detector [%]	Release fraction [%]	Composition at detector [%]
^{85}Kr	34	100	0.6	100	0.6
^{87}Kr	2,300	100	0.0	100	0.0
^{88}Kr	3,200	100	0.17	100	0.17
^{89}Sr	3,400	-	-	0.1	0.06
^{90}Sr	260	-	-	0.1	0.005
^{103}Ru	5,200	-	-	0.1	0.09
^{106}Ru	1,500	-	-	0.1	0.03
^{131}I	3,300	0.1	0.06	1	0.6
^{132}Te	4,800	-	-	1	0.7
^{133}Xe	5,800	100	94.0	100	92.6
^{135}Xe	1,700	100	5.1	100	5.0
^{134}Cs	200	-	-	1	0.04
^{136}Cs	120	-	-	1	0.02
^{137}Cs	340	-	-	1	0.06

Two release scenarios have been considered for an accident of a RBMK reactor. In Scenario 1, only noble gases and a small fraction of iodine is release from the reactor, while in Scenario 2, the release contains large amounts of aerosols. The radionuclide inventory is taken from [19]. The relative concentrations of the most important radionuclides are given in Table 5.

B.2 Activity transfer to foodstuffs

Deposited activity will be transferred to plants and food products, either via direct deposition on the plant surface or indirectly, through root uptake of deposited activity. Transfer to the plants varies strongly with time of deposition with maximum transfer to the plants during the growth season, where direct deposition is the dominating pathway.

The peak activity concentration in foodstuffs, $c_{i,\max}$, is proportional to the activity concentration on the ground after plume passage,

$$c_{i,\max} = TF_i \, q_i(T) \tag{B.4}$$

where TF_i ($\mathrm{m^2\,kg^{-1}}$) denotes the transfer factor of radionuclide "i" for the foodstuff considered. The activity concentration c_i ($\mathrm{Bq\,kg^{-1}}$) will decrease over time, with Eq. (B.4) giving the peak value. The total activity concentration in a foodstuff of a radionuclide group (k) is obtained by summing over all radionuclides in the group, cf. Table 3,

$$c^{(k)} = \sum_i^{(k)} c_i = \sum_i^{(k)} TF_i \, (v_d + \Lambda H)_i \, \chi_i \, T \tag{B.5}$$

where Eqs. (B.3 - B.4) have been used.

Table 6. Transfer factors in ($m^2\,kg^{-1}$) for peak concentration in foodstuffs per unit deposited activity. Activity is deposited on October 1. The transfer factors are obtained with the ECOSYS model [20].

Radionuclide	Beef	Lamb	Leafy vegetables	Milk
^{89}Sr	$1.3{\cdot}10^{-3}$	$1.1{\cdot}10^{-3}$	$4.0{\cdot}10^{-1}$	$5.0{\cdot}10^{-2}$
^{90}Sr	$2.0{\cdot}10^{-3}$	$1.7{\cdot}10^{-3}$	$4.0{\cdot}10^{-1}$	$8.0{\cdot}10^{-3}$
^{103}Ru	$6.0{\cdot}10^{-4}$	$6.0{\cdot}10^{-4}$	$3.0{\cdot}10^{-1}$	$8.0{\cdot}10^{-5}$
^{106}Ru	$1.1{\cdot}10^{-3}$	$9.0{\cdot}10^{-4}$	$4.0{\cdot}10^{-1}$	$1.1{\cdot}10^{-4}$
^{131}I	$2.0{\cdot}10^{-4}$	$3.0{\cdot}10^{-4}$	$4.0{\cdot}10^{-1}$	$6.0{\cdot}10^{-2}$
^{132}Te	$8.0{\cdot}10^{-5}$	$3.0{\cdot}10^{-4}$	$3.0{\cdot}10^{-1}$	$8.0{\cdot}10^{-3}$
^{134}Cs	$9.0{\cdot}10^{-2}$	$5.0{\cdot}10^{-1}$	$4.0{\cdot}10^{-1}$	$7.0{\cdot}10^{-2}$
^{136}Cs	$1.7{\cdot}10^{-2}$	$1.3{\cdot}10^{-1}$	$3.0{\cdot}10^{-1}$	$5.0{\cdot}10^{-2}$
^{137}Cs	$8.0{\cdot}10^{-2}$	$5.0{\cdot}10^{-1}$	$4.0{\cdot}10^{-1}$	$7.0{\cdot}10^{-2}$

B.3 Dose rates

Radiation from the plume and from deposited radioactive material on the ground contribute to the external dose rate, while activity in the plume and on the ground contribute to the inhalation and ingestion doses, respectively. Neglecting external beta radiation, the effective dose rate from external radiation comprises external gamma dose rate from the plume,

$$\dot{E}_{\mathrm{plume}} = \sum_i \chi_i \, \dot{e}_{\mathrm{plume},i} \tag{B.6}$$

and external gamma dose rate from deposited material,

$$\dot{E}_{\mathrm{ground}}(t) = \sum_i q_i(t) \, \dot{e}_{\mathrm{ground},i} \tag{B.7}$$

The conversion factor $\dot{e}_{\mathrm{plume},i}$ for external gamma dose rate from the plume is estimated for semi-infinite plume geometry, while the conversion factor for external gamma dose rate from deposited activity is estimated for an infinite plane surface and an effective relaxation depth of 3 mm, corresponding to fresh deposition on a gravelled area [21].

The inhalation dose rate is obtained as,

$$\dot{E}_{\mathrm{inh}} = I \sum_i \chi_i \, e_{\mathrm{inh},i}(50) \tag{B.8}$$

where I is the breathing rate ($m^3\,s^{-1}$), and the conversion factor $e_{\mathrm{inh},i}(50)$ is the (50 year) committed effective dose per unit intake of the radionuclide [16].

The dose conversion factors for external radiation and for inhalation doses are shown in Table 7.

Table 7. Effective dose conversion factors for external gamma radiation from a semi-infinite plume and an infinite plane surface, and for inhalation.

Radionuclide	$\dot{e}_{\gamma,\mathrm{plume}}$ [$\mathrm{Sv\,m^3\,Bq^{-1}\,s^{-1}}$]	$\dot{e}_{\gamma,\mathrm{ground}}$ [$\mathrm{Sv\,m^2\,Bq^{-1}\,s^{-1}}$]	$e_{\mathrm{inh}}(50)$ [$\mathrm{Sv\,Bq^{-1}}$]
^{85}Kr	$1.4{\cdot}10^{-16}$	-	-
^{87}Kr	$2.0{\cdot}10^{-14}$	-	-
^{88}Kr	$5.7{\cdot}10^{-14}$	-	-
^{90}Sr	-	-	$1.6{\cdot}10^{-7}$
^{103}Ru	$2.7{\cdot}10^{-14}$	$3.1{\cdot}10^{-16}$	$3.0{\cdot}10^{-9}$
^{106}Ru	$1.1{\cdot}10^{-14}$	$1.4{\cdot}10^{-16}$	$6.6{\cdot}10^{-8}$
^{131}I	$2.1{\cdot}10^{-14}$	$2.6{\cdot}10^{-16}$	$7.4{\cdot}10^{-9}$
^{132}Te	$1.1{\cdot}10^{-14}$	$1.6{\cdot}10^{-15}$	$2.0{\cdot}10^{-9}$
^{133}Xe	$1.9{\cdot}10^{-15}$	-	-
^{135}Xe	$1.3{\cdot}10^{-14}$	-	-
^{134}Cs	$8.5{\cdot}10^{-14}$	$1.0{\cdot}10^{-15}$	$2.0{\cdot}10^{-8}$
^{136}Cs	$1.1{\cdot}10^{-13}$	$3.0{\cdot}10^{-16}$	$2.8{\cdot}10^{-9}$
^{137}Cs	$3.1{\cdot}10^{-14}$	$3.9{\cdot}10^{-16}$	$3.9{\cdot}10^{-8}$

B.4 Avertable doses

Sheltering during plume passage may reduce the external gamma doses from the plume and from deposited activity on the ground and the inhalation dose. The avertable dose by sheltering is obtained for the three pathways defined in Eqs. (B.6 - B.8),

$$\Delta E = \Delta E_{\mathrm{plume}} + \Delta E_{\mathrm{ground}} + \Delta E_{\mathrm{inh}} \tag{B.9}$$

$$\Delta E_{\mathrm{plume}} = (1 - L_{\mathrm{p}})\, T \sum_i \chi_i\, \dot{e}_{\mathrm{plume},i} \tag{B.10}$$

$$\Delta E_{\mathrm{ground}} = (1 - L_{\mathrm{g}})\, \frac{T^2}{2} \sum_i (v_d + \Lambda H)_i\, \chi_i\, \dot{e}_{\mathrm{ground},i} \tag{B.11}$$

$$\Delta E_{\mathrm{inh}} = (1 - F)\, T\, I \sum_i \chi_i\, e_{\mathrm{inh},i}(50) \tag{B.12}$$

where $L_{\mathrm{p\,(g)}}$ is the plume (ground) location factor, *i.e.* the ratio of indoor to outdoor dose rate, and F is the corresponding building filtration factor [22, 23].

B.5 Action levels

The total external gamma dose rate at the site of the monitoring station is obtained from Eqs. (B.1 - B.3) and (B.6 - B.7),

$$\begin{aligned} \dot{E}_\gamma(x) &= \dot{E}_{\mathrm{plume}}(x) + \dot{E}_{\mathrm{ground}}(x) \\ &= \chi_0\, \alpha(x) \sum_i f_i \left[\dot{e}_{\mathrm{plume},i} + (v_d + \Lambda H)_i\, t\, \dot{e}_{\mathrm{ground},i} \right] \quad t < T \end{aligned} \tag{B.13}$$

To estimate the action levels for sheltering/foodstuff intervention given by Eqs. (3) and (6), the minimum of the ratio of external gamma dose rate given in Eq. (B.13) to the avertable dose/activity concentration in foodstuff will be used. For sheltering the action level is given by,

$$\dot{E}_{AL} = \Delta E_{IL} \times \min \left\{ \frac{\alpha(x) \sum_i f_i \left[\dot{e}_{\mathrm{plume},i} + (v_d + \Lambda H)_i \; t \; \dot{e}_{\mathrm{ground},i} \right]}{T \sum_i f_i \Big[(1 - L_{\mathrm{p}}) \, \dot{e}_{\mathrm{plume},i} + (1 - L_{\mathrm{g}}) \frac{T}{2} (v_d + \Lambda H)_i \, \dot{e}_{\mathrm{ground},i} + (1 - F) \, I \, e_{\mathrm{inh},i}(50) \Big]} \right\} \tag{B.14}$$

The external gamma dose rate and the avertable dose in Eq. (B.14) refer to the monitoring station and the location for intervention, respectively; the minimum of the ratio will be for a scenario with rainfall at the location for intervention but with no rainfall at the monitoring station.

The minimum external gamma dose rate at a monitoring station occurs at $t = 0$, before the start of deposition to the ground. For a given release scenario, *i.e.* for fixed relative radionuclide concentrations f_i, the numerator and denominator become uncorrelated, and the action level for sheltering can be written,

$$\dot{E}_{AL} \approx \Delta E_{IL} \times \frac{\alpha_{\min} \sum_i f_i \, \dot{e}_{\mathrm{plume},i}}{\max \left\{ T \sum_i f_i \Big[(1 - L_{\mathrm{p}}) \, \dot{e}_{\mathrm{plume},i} + (1 - L_{\mathrm{g}}) \frac{T}{2} (v_d + \Lambda H)_i \, \dot{e}_{\mathrm{ground},i} + (1 - F) \, I \, e_{\mathrm{inh},i}(50) \Big] \right\}} \tag{B.15}$$

Similarly, for a fixed release scenario the action level for foodstuff restrictions is obtained from Eqs. (6) and (B.5),

$$\begin{aligned} \dot{E}_{AL} &= \min_{(k)} \left\{ c_{IL}^{(k)} \min \left(\frac{\alpha \sum_i f_i \, \dot{e}_{\mathrm{plume},i}}{T \sum_i^{(k)} f_i \, TF_i \, (v_d + \Lambda H)_i} \right) \right\} \\ &\approx \frac{\alpha_{\min} \sum_i f_i \, \dot{e}_{\mathrm{plume},i}}{T_{\max} \, (v_d + \Lambda H)_{\max}} \cdot \min_{(k)} \left\{ \frac{c_{IL}^{(k)}}{\sum_i^{(k)} f_i \; TF_{i,\max}} \right\} \end{aligned} \tag{B.16}$$

where it has been assumed that the dry and wet deposition parameters are similar for all depositing radionuclides.

B.6 Parameter values

The parameter used for estimating the action levels given in Eqs. (B.15) and (B.16), are summarized in Table 8, where the intervals of typical parameter values also are provided. The minimum/maximum parameter values used for the present calculation of action levels correspond to the endpoints of the parameter intervals.

In choosing the minimum/maximum parameter values for estimating the action levels, care must be taken not to assume unreasonable small/large values, which will lead to unrealistic small action levels. In principle, one may ascribe a probability density function to each parameter, and the parameter intervals in Table 8 then correspond to a given percentile of the parameter values. Outlying values of the parameters will be associated with low probabilities, and by systematically choosing outlying values one will compound small probabilities.

In a full probabilistic study the action levels can be defined as a lower percentile of the dose rates at the monitoring stations, and estimated from the joint probability distribution of all variable parameters, including the relative radionuclide concentrations f_i.

Table 8. Parameter values used for dose calculations.

Symbol	Description	Value
L	Building location factor (plume, ground)	0.1 - 0.7
F	Building location filtration factor	0.2 - 0.5
I	Breathing rate	$2.3{\cdot}10^{-4}$ m^3 s^{-1}
v_d	Dry deposition velocity	0.001 m s^{-1}
Λ	Wet deposition scavenging coefficient	0.0001 s^{-1}
H	Mixing layer height	200 - 1000 m

Mission

To promote an innovative and environmentally sustainable technological development within the areas of energy, industrial technology and bioproduction through research, innovation and advisory services.

Vision

Risø's research **shall extend the boundaries** for the understanding of nature's processes and interactions right down to the molecular nanoscale.

The results obtained shall **set new trends** for the development of sustainable technologies within the fields of energy, industrial technology and biotechnology.

The efforts made **shall benefit** Danish society and lead to the development of new multi-billion industries.