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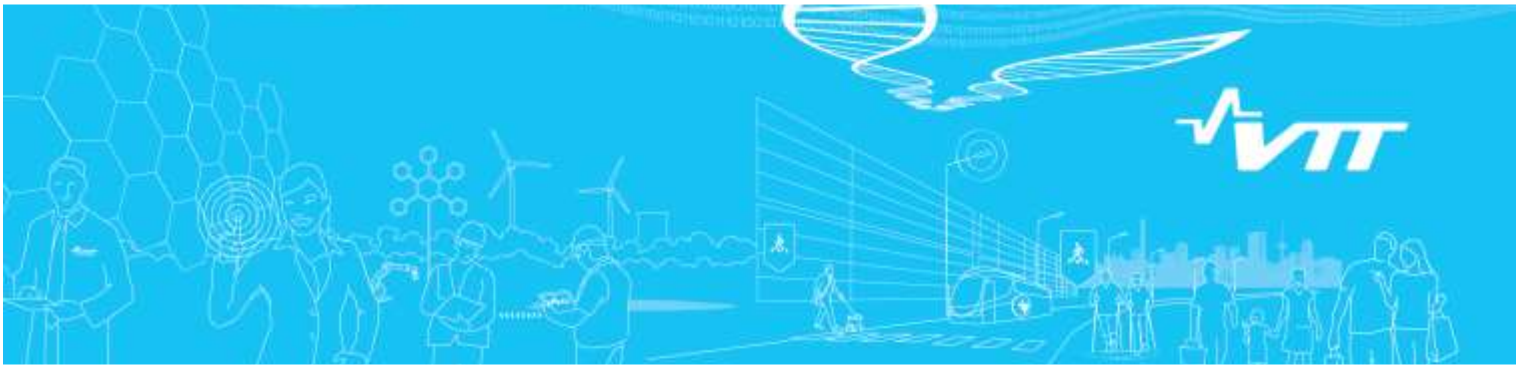

RESEARCH REPORT

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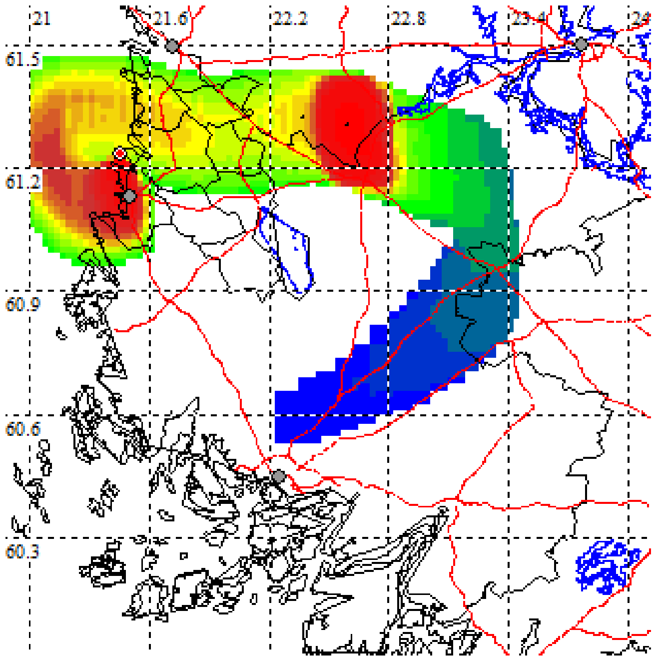

Dose estimates from severe accidents beyond emergency planning zone

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Confidentiality: Public

Report's title	
Dose estimates from severe accidents beyond emergency planning zone	
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Summary

Earth quake followed by a tsunami in 2011 initiated Fukusima Daichi accident which caused remarkable radiation effects in the environment of the power plant, even at longer distances. As a consequence of this event IAEA started to develop recommendations which consider emergency planning outside protection and emergency planning zones. In response to these recommendations STUK activated a study in which the purpose is to estimate possible radiation doses at long distances. Based on the predicted doses it is possible to assess what kind of countermeasures could be needed.

In this two-year study the focus in the first year is to evaluate the feasibility of the ARANO and VALMA models for the assessment and then in the second year actual calculations are carried out. Thus assuming significant releases to the atmosphere and using two alternative dispersion models radiation doses are obtained as a function of distance.
This is carried out by using the source terms specified by STUK and measured weather data from the Olkiluoto site. Different exposure pathways are used. The results of ARANO indicate that if the release magnitude exceeds the severe accident release especially the ingestion doses may rise clearly over the criteria for countermeasures beyond 20 km.
The VALMA model predicts external and inhalation doses based on the time-dependent weather data measured at the NPP weather mast. Generally, prediction of a single case can be considered more accurate than with ARANO, but the larger CPU time needed makes VALMA still unpractical for a very large number of dispersion cases.

Confidentiality	Public

Espoo 4.2.2015

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Preface

This report is a result of the COOLOCE-E project, which in turn is a part of the SAFIR 2014 research programme.

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Authors

Contents

1. Introduction

The draft of the general safety requirements of the IAEA presents requirements to plan radiological protection measures outside the traditional emergency planning zone [IAEA 2014]. For this purpose, it is necessary to evaluate radiation doses from severe accidents at the distances from 20 km up to 300 km. Because weather strongly affects the dose, it is necessary to treat weather conditions as a changing parameter in the dose distribution calculations. In principle, a large amount of different weather conditions are needed. Currently there are two primary codes, ARANO and VALMA, applicable for the task. ARANO is a straight line, constant weather model. VALMA is a trajectory based, changing weather model.

The objective is to clarify what technical possibilities are practically available to calculate probability distributions of radiation doses from different exposure pathways at distances beyond 20 km from the power plant. The ultimate target is to answer the question of what countermeasures should be prepared outside the traditional emergency planning zone.

2. Background

2.1 Time phases and distances of the protection measures

In the case of a severe accident at nuclear power plant (NPP) there are VAL 1 and VAL 2 Guides which determine in time and space the emergency procedures in the environment [STUK 2012a and 2012b]. At first it is necessary to define time phases and countermeasures established in the guidelines (Table 2.1).

Table 2.1. Time phases and countermeasures of an accident.

Early phase	**Intermediate phase**	**Recovery phase**
Sheltering	Sheltering	
Iodine tablets	Iodine tablets	
Evacuation	Evacuation	
Access control	Access control	Access control
	Relocation	Relocation
	Decontamination of people	
	Food and animal control	Food and animal control
	Medical care	
		Decontamination of land

Early phase includes time period from the beginning of the accident to the phase when dose rate does not significantly increase and there is no longer threat of new release. This happens when radioactive cloud has passed the area and there is no more release.

After the early phase radioactive substances deposited on the ground may cause dose rate to the people living in the area or contaminate agricultural food products and ingestion of these foodstuffs may cause internal dose to population. This phase is called here intermediate phase and it may last from a few days to a few years. After the intermediate phase there is the recovery phase in which human and social activities are adapted to the prevailing radiation situation. Duration of the recovering phase can be from weeks to decades.

There are two distances defined for various measures: protection zone “suojavyöhyke” and emergency planning zone “varautumisalue”. The planning distance for the protection zone measures extends to about five kilometres from the power plant and the emergency planning zone is applied for an area within a radius of about 20 km.

The YVL Guide C.3 gives deterministic specification that in the case of a severe accident, as defined in [Nuclear Energy Act 990/1987], resulting in a radioactive release, there shall not be need for evacuation beyond the protective zone (< 5 km) and no need for sheltering beyond the preparedness zone (< 20 km) [STUK 2013b].

The VAL Guides contain protective measures and intervention levels in early and intermediate phases of a nuclear or radiological emergency. Guides include principles and dose limits for protection of people in the early and intermediate phases of a nuclear or radiological emergency.

In Sweden there is under way a survey regarding how renewed recommendations of IAEA affect the national emergency preparedness guidelines. In the preliminary study a moderate need for revision was indicated [SSM 2014].

2.2 Protection of population in the early phase

Evacuation in the protection zone shall be done at the latest if there is threat of a significant amount of radioactive release from the power plant.

Table 2.2 shows the dose limits in the emergency planning zone published in VAL 1 (STUK 2012a) for the population protection in the early phase of an accident.

Table 2.2. Dose criteria for the population protection measures in the emergency planning zone in the early phase of an accident [STUK 2012a].

Protection measure	**Dose limit** (*
Sheltering - moderate sheltering	10 mSv (effective dose in 48 hours) 1-10 mSv (effective dose in 48 hours)
Ingestion of iodine tablets	10 mSv for a person less than 18 years, 100 mSv for adults (thyroid dose)
Evacuation	20 mSv (effective dose in 1 week)

(* Action is justified, if a dose for an unprotected person exceeds the dose limit

According to STUK 's instructions sheltering indoors means local sheltering. This is justified if the dose for an unprotected person is estimated to be more than 10 mSv within two days.

Moderate sheltering means that unnecessary outdoor presence is avoided if an unprotected person is expected to receive a dose from 1 to 10 mSv within two days.

By ingestion of stable iodine the accumulation of radioactive iodine in the thyroid gland can be effectively reduced. Iodine tablet only protects the thyroid gland but does not reduce other exposures. Stable iodine should be taken one to six hours prior to exposure to radioactive iodine, and the protection is perfect.

Short-term evacuation means promptly implemented evacuation which lasts for around one week. Evacuation is necessary, if the dose for an unprotected person is expected to exceed 20 mSv during the first week, or if the local sheltering is longer than 2 days. Evacuation should be carried out before the arrival of the radioactive cloud to the area.

Operational intervention level (OIL) means external dose rate derived from the dose limit or other directly measurable or evaluable quantity such as, for example, the deposited activity or concentration in foodstuffs.

Operational intervention levels are for:

- sheltering 0.1 mSv/h,
- moderate sheltering 0.01 mSv/h,
- ingestion of iodine tablets 0.1 mSv/h,
- access control 0.1 mSv/h.

If operational intervention level is exceeded or it is anticipated to be exceeded, protection measure is generally necessary.

2.3 Protection of population in the intermediate phase

The objective of the protection measures is that the dose due to the radiation incident does not exceed the maximum level dose of 20 mSv during the first year, when taking into account all routes of exposures at early phase and intermediate phase, as well as the protection measures to reduce the impact of exposures.

If the dose caused by exposure during the first year is expected to be:
• greater than 10 mSv , protective measures shall be adopted to reduce the exposure of the population
• 1-10 mSv, protective measures are usually justified
• less than 1 mSv, protective measures can be adopted to reduce the exposure, especially when they are easy and reasonably practicable.

Possible countermeasures in the intermediate phase are e.g. prolongation of sheltering, relocation of population “väestön pidempiaikainen poissiirto”, access control, decontamination of inhabitants, dwellings and ground, control or prohibition of foodstuffs.

3. Objective of the current task

The target in COOLOCE-E is to clarify with the existing calculation models whether in the case of a severe accident release there would be need for countermeasures outside the preparedness zone of 20 km. Possibly there could be weather conditions in which radioactive material could spread outside emergency planning zone causing there high doses. This question arose as a consequence of the Fukusima accident in March 2011, when countermeasures were extended beyond 20 km from the power plants [WHO 2012]. Deterministic effects are not expected at longer distances, but countermeasures there could reduce the risk of stochastic effects.

In the preliminary phase of the study the purpose is to find out if the existing calculation models ARANO and VALMA are able to calculate doses for this purpose at longer distances or what modifications and improvements in the models should be done. ARANO is a local scale model unable to consider changing weather conditions during dispersion and therefore probably inaccurate at longer distances. VALMA can consider changing weather conditions and therefore it is more accurate at longer distances, but calculation time may be long and currently the code does not include ingestion doses. Finally in 2015 a more focused and extended study about doses at longer distances will be performed.

The proposed two new zones are planned to be extended to the distances from 20 km up to 100 km and from 100 km up to 300 km from a power plant [STUK 2013a].

In the first zone (extended planning zone) the purpose is to identify areas within a period that would be effective in reducing the risk of stochastic effects by taking: (1) urgent protective actions and other response actions (e.g. evacuation) within a day following a release and (2) early protective actions and other response actions (e.g. relocation) within a week to a month following a release (see table 2 below from IAEA 2014, Appendix 2).

In the second new zone (ingestion and commodities planning zone) the purpose is to study if there is need to take response actions (1) for protecting the food chain and water supply systems as well as for protecting commodities other than food from contamination following a significant release and (2) for protecting the public from the ingestion of food, milk and drinking water and from the use of commodities other than food with possible contamination following a significant release. [IAEA 2014, Appendix 2].

Figure 3.1 illustrates the different protection zones around a nuclear power plant. It should be noted that the zone A includes the circular area but the other zones contain only a sector according to wind direction. In this study the focus is in the zones C and D.

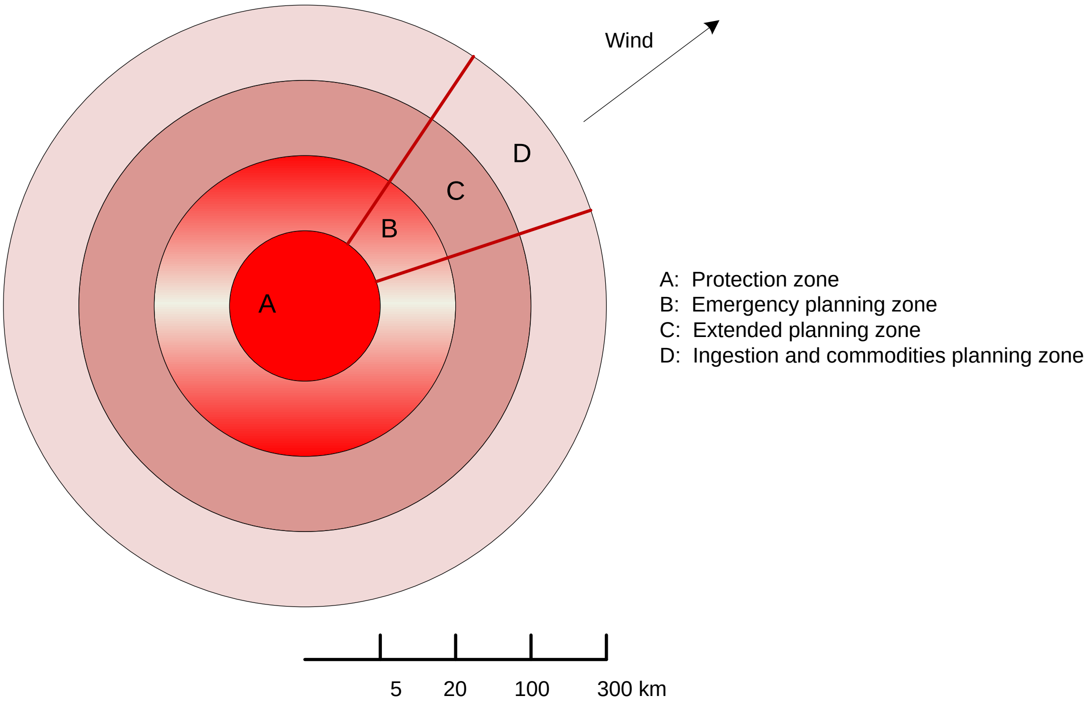

Figure 3.1. Graph of the protection zones around a nuclear power plant.

Table 3.1 provides generic criteria for use in developing a protection strategy and operational criteria for effective implementation of protective actions and other response actions to reduce the risk of stochastic effects in a nuclear or radiological emergency as elaborated in Ref. [IAEA 2014].

Table 3.1. Generic criteria for protective actions and other response actions in an emergency to reduce the risk of stochastic effects [IAEA 2014].

Projected dose that exceeds the following generic criteria: Take urgent protective actions and other response actions		
$H_{Thyroid}$ (equivalent dose)	50 mSv in the first 7 days	Iodine thyroid blocking
E (effective dose)	100 mSv in the first 7 days	Sheltering; evacuation; decontamination; restriction on consumption of food, milk and drinking water; contamination control; public reassurance
Projected dose that exceeds the following generic criteria: Take early protective actions and other response actions		
E	100 mSv per annum	Temporary relocation; decontamination; restriction on food, milk and drinking water; public reassurance
Dose that has been received and that exceeds the following generic criteria: Take longer term medical actions to detect and to effectively treat radiation induced health effects		
E	100 mSv in a month	Screening based on equivalent doses to specific radiosensitive organs (as a basis for medical followup), counselling

Table 3.2 provides generic criteria for use in developing a protection strategy and operational criteria for effective implementation of protective actions and other response actions to reasonably reduce the risk of stochastic effects from ingestion of food, milk and drinking water and from use of other commodities in a nuclear or radiological emergency.

Generic criterion of 1/10 of the generic criteria for early protective actions and other response actions given in Table 3.2 is established for food, milk and drinking water and other commodities restrictions to ensure that the dose from all exposure pathways, including ingestion, will not exceed the generic criteria for early protective actions and other response actions given in Table 3.1.

If restriction of consumption of food, milk and drinking water will result in severe malnutrition or dehydration because replacements are not available, food, milk and drinking water with concentration levels projected to result in a dose above the generic criteria in table

3.2 may be consumed until replacements are available, or the affected people can be relocated, provided this will not result in doses above the generic criteria in Table 3.1.

Table 3.2. Generic criteria for food, milk and 1 drinking water and other commodities to reduce the risk of stochastic effects in an emergency [IAEA 2014].

Generic criteria		Examples of protective actions and other response actions
Projected dose from ingestion of food, milk and drinking water that exceeds the following generic criteria: Take protective actions and other response actions as justified.		
E	10 mSv per annum	Stop consumption and distribution of non-essential food, milk and drinking water and restrict use and distribution of other commodities. Replace essential food, milk and drinking water as soon as possible or relocate the people if replacements are not available. Estimate the dose of those who may have consumed food, milk and drinking water or used other commodities that may result in a dose exceeding the generic criteria to determine if medical counselling and follow-up is warranted in accordance with Table 3.1.

In summary based on the figure 3.1 and tables 3.1 and 3.2 a simplified approach to answer the question – what countermeasures are needed beyond 20 km, is:

- Area A, B: not relevant in this study
- Area C: to study if the dose level of 100 mSv is exceeded in a week or in a year
- Area D: to study if the dose level of 10 mSv is exceeded in a year from ingestion

Adopting this approach means that there is finally no need to estimate more accurately the number of stochastic effects based on the collective dose. This approach is recommended by IAEA [IAEA 2014].

4. Tools for the evaluation

The tools which are evaluated in this task are ARANO and VALMA. Both models are developed at VTT.

4.1 ARANO

ARANO was developed at VTT in 1970's and it was initially used for nuclear power plant siting studies. ARANO is a straight line Gaussian type dispersion model, weather remains the same until the plume exits the computation area. Spreading of an emission in the air is calculated on the basis of the application of the diffusion model using the Kz theory where a vertical dispersion and the impact of dry fallout as boundary condition on the scavenging of the cloud are taken into account [Nordlund et al. 1979]. Rain intensity is considered by exponential depletion employing washout coefficient. Annual weather data from one meteorological mast is converted into joint frequency matrix of annual weather statistics.

The exposure pathways are: external radiation from the cloud and fallout, internal exposure from inhalation and ingestion. In ingestion dose seasonal variation due to summer and winter conditions are taken into account. Short-term countermeasures include sheltering, evacuation and iodine tablets. Long-term countermeasures include relocation, land decontamination and food ban.

When risks to the society are calculated it is necessary to know demographic data in the environment of the power plant. In ARANO population data is given in polar coordinates (segmented by radial lines - r,Θ). In this annular grid the angle size is 30 degrees which means that data is given in 12 sectors for distance intervals defined by the user.

Agricultural production is given in the same format. The nutrition exposure pathways and the corresponding foodstuffs in ARANO are: cow milk, cattle meat, green and root vegetables and grain products. In general availability of exact agricultural production data is unsure, because statistical data usually consist of production data in coarse grid.

4.2 VALMA

VALMA is a dispersion and dose assessment code for accidental atmospheric radioactive releases [Ilvonen, 2002]. It was developed at VTT in late 1990's and its main purpose was to serve as an emergency preparedness tool for radiation safety authorities (STUK in Finland). In such use, it is essential to produce predictions of concentrations, depositions, dose rates and doses in a reasonably short time to enable possible rapid countermeasures. It is not possible to perform CFD-like calculations that may last hours or days. Furthermore, it is possible that the best existing weather data cannot be received due to e.g. increased web traffic. For this reason, VALMA was made flexible enough to work with many kinds of weather data, starting from single-point measurements at the weather mast of an NPP (or several masts) and ending with Monte Carlo particles (even a limited number) that can be calculated, based on NWP (numerical weather prediction) models, with the SILAM dispersion model at FMI (Finnish Meteorological Institute). Regardless of the source of weather data, VALMA offers the flexibility to calculate with changing source term estimates, including released nuclide inventory and the temporal and height distributions of different nuclides. It is also easy to set the spatial and temporal grids and to view the Lagrangian trajectories and dozens of result quantities on map or as temporal trends at chosen locations.

In short, VALMA works by dividing the release into a finite number of ’packets’ or ’puffs’, each of which corresponds to a ’slot’ in time and release height. For each packet, VALMA computes a possibly winding central trajectory, which the packet will follow according to available wind information. VALMA follows each packet along the trajectory and calculates its
spread, chain decay and deposition scavenging at the same time. VALMA calculates dozens of radiologically interesting quantities, like concentrations, depositions, dose rates and doses via different exposure pathways, together with their time derivatives and integrals. In contrast to an Eulerian dispersion model, VALMA uses a grid only to represent and accumulate the result quantities, not for calculating them.

5. Dose calculations

5.1 Exposure pathways

There are four exposure pathways considered in this study: direct external radiation through a cloud, direct external radiation through fallout and internal exposure from a radioactive material through inhalation or nutrition. The inhalation dose caused by dry matter dusting in the air has not been examined because the significance of the exposure route is generally considered to be minor in Finnish conditions due to ground flora and seasonal changes. Sections 1–4 present the calculation parameter selections related to the exposure routes.

1) External radiation from the activity in cloud

The protection factor value for people is 1.0, meaning that 100% of the dose received by a fully-unprotected person is taken into account when the release duration is short. If the release duration is longer than few hours it is reasonable to assume that the person is not outdoors all the time and the shielding factor is less than 1. The dose is received as the cloud passes.

2) External radiation through fallout

The protection factor, i.e. the relation between the true dose and the dose received without any protection, is 0.3 in all personal doses. The calculation criterion assumes that the following protection factors prevail in the nuclear power plant facility’s environment for external radiation originating from fallout:

- Outdoors 0.7

- In a detached house 0.4

- In a multi-storey house 0.1

In addition, it is assumed that people spend 10% of their time outdoors and 90% indoors. A total of 40% of the population live in detached houses and 60% in multi-storey house, resulting in the following calculation:

$0.1 \cdot 0.7 + 0.36 \cdot 0.4 + 0.54 \cdot 0.1 = 0.3$

The total durations examined for the exposure varies from hours to one year.

3) Internal radiation dose through inhalation

The protection factor is 1, i.e. no protection is assumed to exist. The inhalation rate is 22.2 m^3/h [ICRP 1995]. The inhalation dose factors are from [STUK 1999].

4) Doses through nutritious substances

Doses through agricultural products have been calculated using the AGRID model included in the ARANO program [Kakko et al., 1984]. According to the model, the nutrition dose depends on the season during which the emission occurs. If radioactive fallout occurs in the winter, radioactive nuclides will not pass to people through the food chain before the following growing season through roots. On the other hand, if the radioactive fallout occurs in the summer, some of the depositing radionuclides remain on plants and some fall to the ground. The fallout falling on plants means that a significant volume of radionuclides may pass to people in a short period through different nutritious substances. As a result, fallout during the growing season can cause a multiple dose through nutrition compared to a dose caused by similar fallout occurring outside the growing season.

Nutritious substances are assumed to be used for 1 year. The following conservative values have been used for the nutritious substances used annually by a person in the critical group: cow’s milk 365 kg, beef 50 kg, vegetables 60 kg, grain 100 kg and root crops 100 kg. These nutrition rates are slightly higher than the values published in the Finnish nutrition research report [KTL 2008]. According to the AGRID model, the duration of the growing season for agricultural products is assumed to be 60 days and the duration of the grazing period for cattle is 100 days.

5.2 Countermeasures in ARANO

5.2.1 Short-term countermeasures

In the acute phase of an accident short-term countermeasures are: sheltering, evacuation and iodine tablets. These measures shall be performed mostly based on the limited and perhaps uncertain information. Local sheltering with doors and windows closed is purposed to decrease exposure to the external radiation from the cloud and fallout. Effectiveness of sheltering depends also on the construction material of the shelters. In general wooden houses are less sheltering than concrete houses.

In ARANO sheltering is taken into account by using sheltering factor for external radiation from the cloud and from the fallout. Population can be divided into two shielding factor groups, of which the first one is assumed to be out of doors and the second one indoors when the plume is passing over. Later both groups spend outdoors e.g. 10% of time and the rest of time indoors.

Evacuation is especially useful if it is carried out before the plume reaches the evacuation point. If evacuation is going on when the plume is already overpassing the area, the evacuees expose to direct radiation from the plume.

In ARANO there are two parameters affecting the evacuation: distance and evacuation time. The distance means that all the inhabitants are evacuated up to that range instantly after the time given for the evacuation. The time is calculated since the plume has reached the point. If the time value is 0, the population has been evacuated before the plume is spread to the point and dose to the population is 0. Actually there are two distance and time parameters. For example it possible to define that groundshine dose is integrated until the planned evacuation time point at 4 hours up to 5 km and 24 hours at longer distances.

Also the parameter “warning time” affects evacuation. If there is a sure knowledge that the release will start after a certain time period, there is a period of warning time available for the initiation of evacuation before the release to the environment begins.

Stable iodine tablets can be used for thyroid blocking. This prevents radioiodine to be taken up from the blood.

In ARANO there is not a direct input for iodine tablets, but it can be taken into account in calculation by reducing internal dose from iodine isotopes.

5.2.2 Long-term countermeasures

Long-term countermeasures include relocation, land decontamination and food ban. It can be assumed that after the acute phase of an accident there is now sufficiently time to consider and evaluate different countermeasures and their combinations. Relocation refers to moving people away from the contaminated area for a longer time period (weeks, months, years). Decontamination of land means cleaning and removal of radioactive substances. Food prohibition is based on ingestion dose levels or ground concentrations.

In the case that external radiation dose exceeds a limit value the first protection measure could be decontamination. If the cleaned area after decontamination is still too contaminated, staying there shall be reduced or denied. Criterion for the contaminated area can be based on the external radiation dose from fallout during 30 years. As reference it can be mentioned that 0.1 Sv/30a approximately corresponds to the dose from normal background radiation.

6. ARANO input data

Source term

In ARANO radionuclide package operates on the basis of material classes, which are groups of elements that have similar chemical properties. The default number of classes is 8. Table 6.1 shows an example on the grouping of the elements into the classes.

Table 6.1. Grouping of the elements into classes used in ARANO.

Element group	Nuclides
1. Noble gases	Kr, Xe
2. Halogens	I
3. Alkali Metals	Cs, Rb
4. Chalcogens	Te, Sb
6. Platinoids	Ru, Rh, Pd, Mo, Tc, Co
7. Lantanides	La, Zr, Nd, Nb, Pm, Pu, Pr, Y, Cm, Am
8. Others	H, N, C, Ar, Cr, Mn, Fe, Zn, Ag

There are two ways to give the amount of the radioactive release:

1. Define the release for the isotopes in Bqs,

2. Give the reactor inventory in Bqs and the release fraction for each element group.

Radioactive releases are described with a discrete probability spectrum. In addition to the release magnitude the following parameters shall be given:

- start and end time of the release
- warning time
- release altitude

There can be only one release and one release height in one run. The start and end times are given relative to shut down. Warning time means time to start countermeasures before the release starts.

Release altitude means effective release altitude. If there is energy release or moment, the final release altitude shall be estimated separately. In the release of radioactive material into the atmosphere account has been taken of the possible mixing effect of plant buildings.

It is planned that one of the release categories is the release of the severe accident corresponding to 100 TBq of the Cs-137 isotope. Other nuclides are determined to be released in the same ratio of the core inventory. The alternative release could be e.g. tenfold.

<u>Weather data in ARANO</u>

For the testing purposes the Olkiluoto site is used. The weather data measured at the altitude of 100 m at the power plant meteorological mast is used. The mast measurements are converted to represent hourly values. Theoretically one year includes weather data of 8760 hours (leap year 8784 hours). If there is invalid reading the corresponding value is removed from the annual data. The release altitude is assumed to be 100 m corresponding to the altitude of the ventilation stack. Figures 6.1-6.4 illustrate frequencies of different weather parameters covering the years from 2009 to 2013.

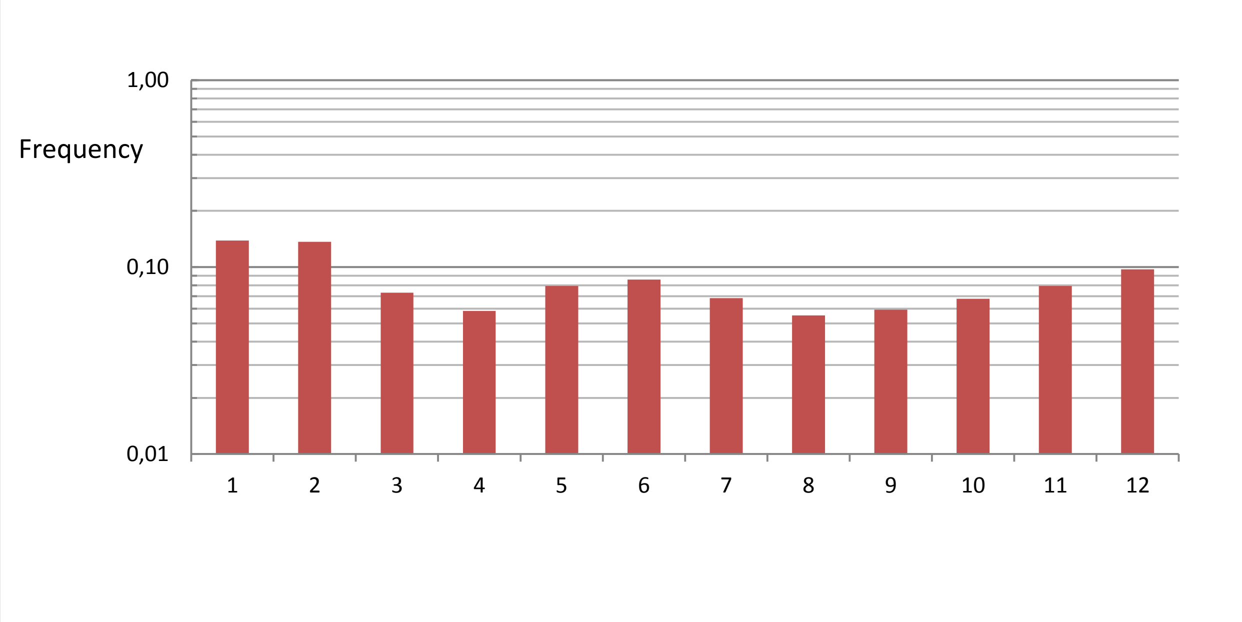

Figure 6.1. Frequences in dispersion sectors. Sector 1 is 0…29 degrees, sector 2 is 30…59 degrees etc. Zero degrees corresponds to the direction of the north. Olkiluoto weather mast 2009…2013, altitude 100m.

Figure 6.1 demonstrates that dispersion to the north dominates, but also dispersion to the south is significant. On the coast this means that winds are mostly blowing along the shoreline and less over the shoreline.

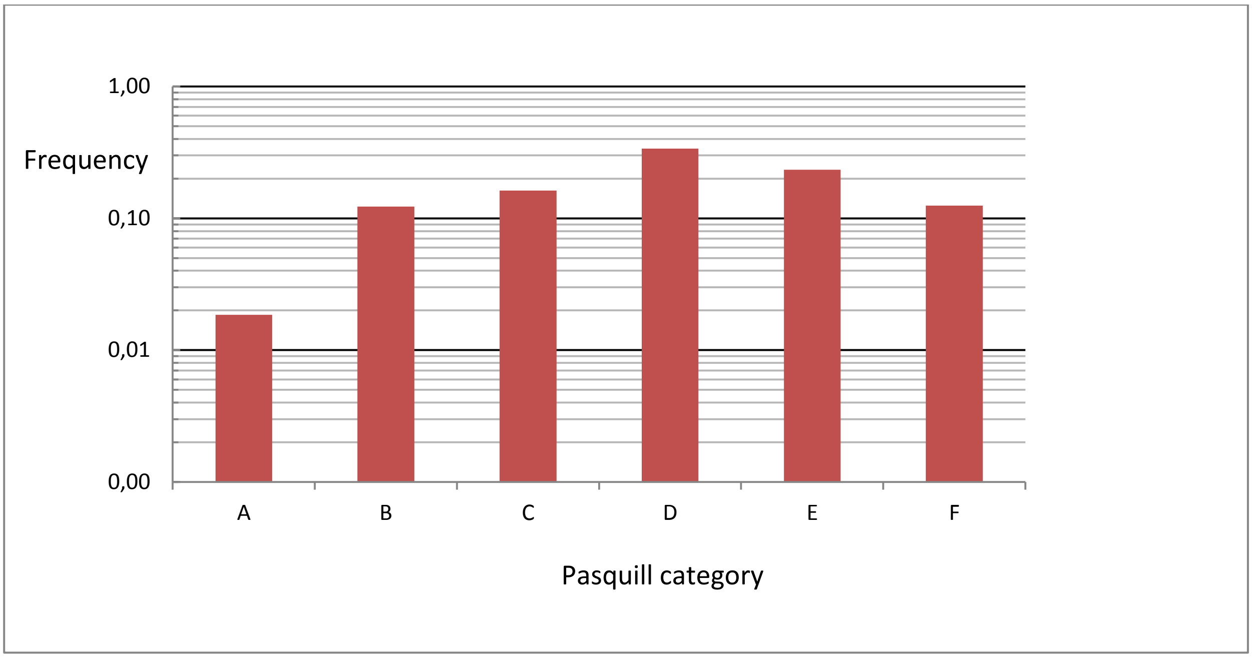

Figure 6.2. Frequences of Pasquill stability categories (A,…F). Olkiluoto weather mast 2009…2013, altitude 100m.

Figure 6.2 indicates that the neutral stability category D includes about 34% and the labile stability category A only 2% of the weather conditions. The stable category F includes about 12% of the weather conditions.

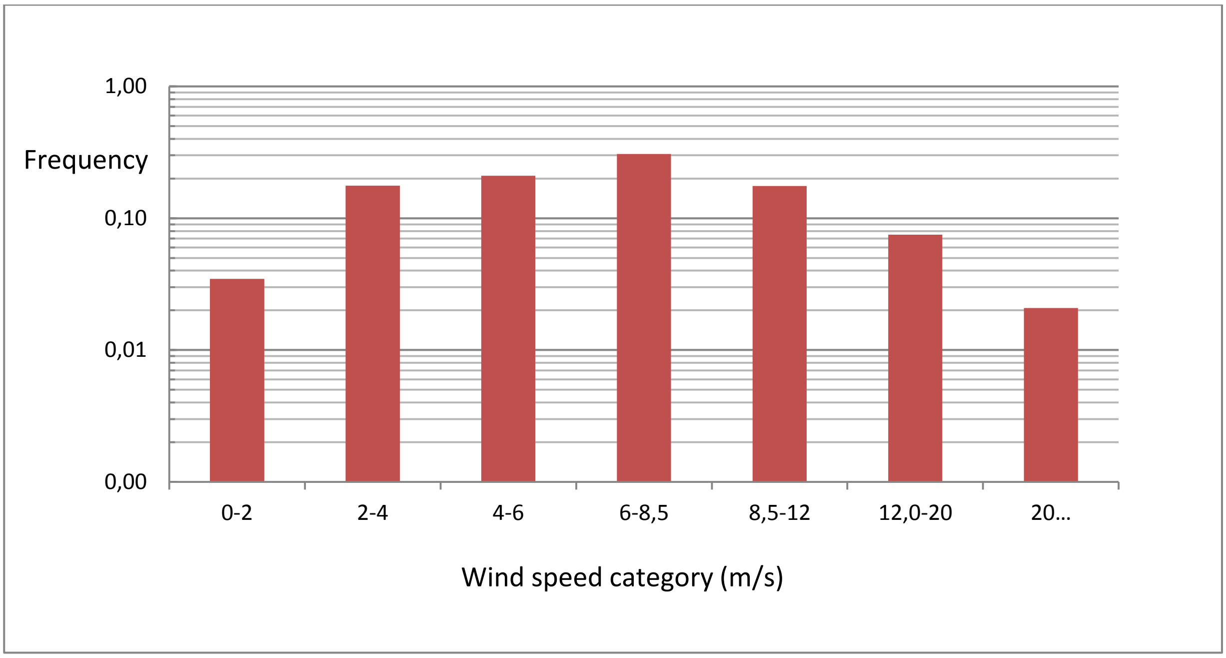

Figure 6.3. Frequences of wind speed categories. Olkiluoto weather mast 2009…2013, altitude 100m.

The most dominating wind speed category is 6…8.5 m/s including 30% of the situations. Very slow wind category 0…2 m/s covers only 3% of the time.

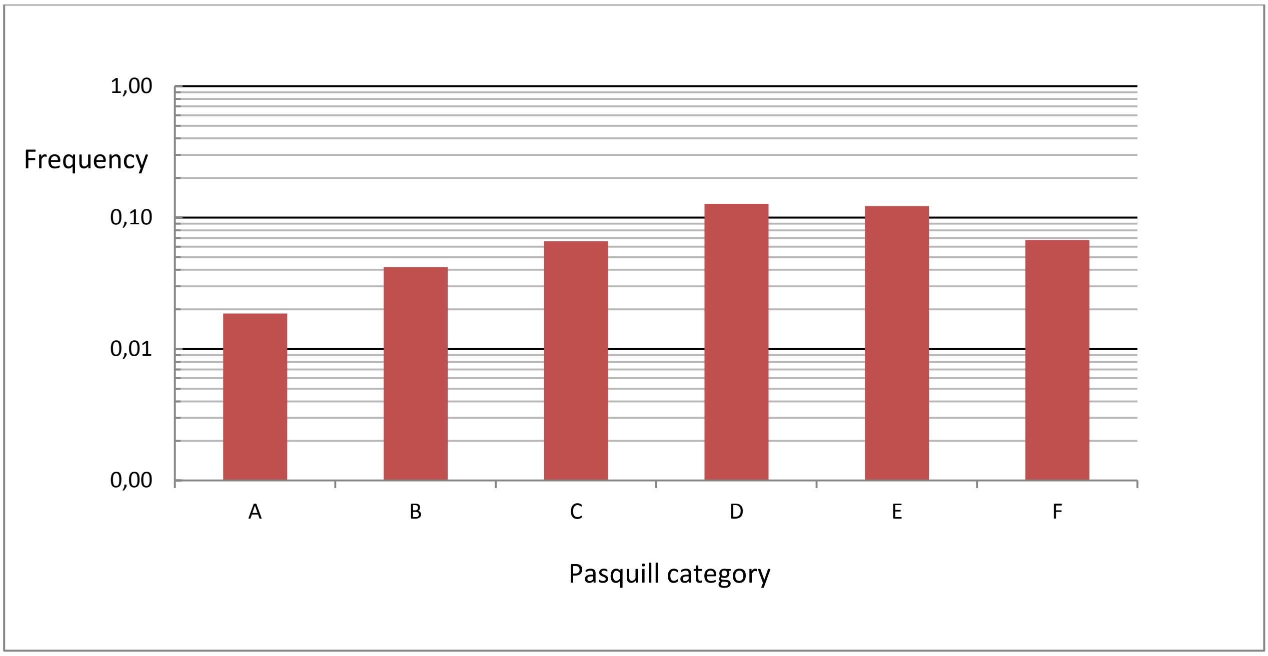

Figure 6.4. Frequences of rain in Pasquill stability categories (A,…F). Olkiluoto weather mast 2009…2013, altitude 100m.

Figure 6.4 shows that rain is observed about 12% of time in the stability categories D and E. In category F rain occurs in 7%.

7. Preliminary observations about doses calculated by ARANO

7.1 Source terms

First the test calculations were done using ARANO. In this case doses from a severe accident releases are considered. There are three alternative release categories considered to be reasonable in this phase. The release start time is assumed to be four hours after shutdown and the release duration is set to three hours. The release altitude is 100 m. Table 7.1 shows the activity inventory and the release cases:

Case 1: Noble gases 1%, I-131 1000 TBq, Cs-137 100 TBq (Severe accident release)

Case 2: Noble gases 20%, iodine + caesium 2%

Case 3: Noble gases 100%, iodine + caesium 20% (No containment)

Table 7.1. Inventory and releases of the OL3 reactor for the nuclides used here (TVO 2004). Releases shall be corrected according to decay times during delays in the release start time and duration.

Nuclide	OL3 inventory [Bq]	Release [Bq]		
Noble gases		**Case 1**	**Case 2**	**Case 3**
Kr-85	5.7E+16	5.7E+14	1.1E+16	5.7E+16
Kr-85M	1.3E+18	1.3E+16	2.6E+17	1.3E+18
Kr-87	2.5E+18	2.5E+16	5.0E+17	2.5E+18
Kr-88	3.5E+18	3.5E+16	7.0E+17	3.5E+18
Xe-133	9.7E+18	9.7E+16	1.9E+18	9.7E+18
Xe-133M	3.1E+17	3.1E+15	6.2E+16	3.1E+17
Xe-135	3.0E+18	3.0E+16	6.0E+17	3.0E+18
Xe-135M	2.1E+18	2.1E+16	4.2E+17	2.1E+18
Xe-138	8.6E+18	8.6E+16	1.7E+18	8.6E+18
Iodine				
I-131	4.8E+18	1.0E+15	9.6E+16	9.6E+17
I-132	7.0E+18	1.5E+15	1.4E+17	1.4E+18
I-133	1.0E+19	2.1E+15	2.0E+17	2.0E+18
I-134	1.1E+19	2.3E+15	2.2E+17	2.2E+18
I-135	9.5E+18	2.0E+15	1.9E+17	1.9E+18
Cesium + rubidium				
Cs-134	9.3E+17	1.5E+14	1.9E+16	1.9E+17
Cs-136	2.3E+17	3.6E+13	4.6E+15	4.6E+16
Cs-137	6.4E+17	1.0E+14	1.3E+16	1.3E+17
Cs-138	9.3E+18	1.5E+15	1.9E+17	1.9E+18
Rb-88	3.6E+18	5.6E+14	7.2E+16	7.2E+17
Rb-89	4.7E+18	7.3E+14	9.4E+16	9.4E+17

7.2 Results

7.2.1 Case 1, external doses and inhalation

Calculations are done for the distances starting at 5 km and extending to 300 km. The effective dose representing different integration times is based on the statistical weather data. The dose includes external radiation from the cloud and ground and internal dose from inhalation. Dose is presented either as a function of distance (the 95 per cent fractile) or the dose distribution at certain distance point is presented. Figure 7.1 illustrates the total dose. Two alternative integration times for the groundshine are considered.

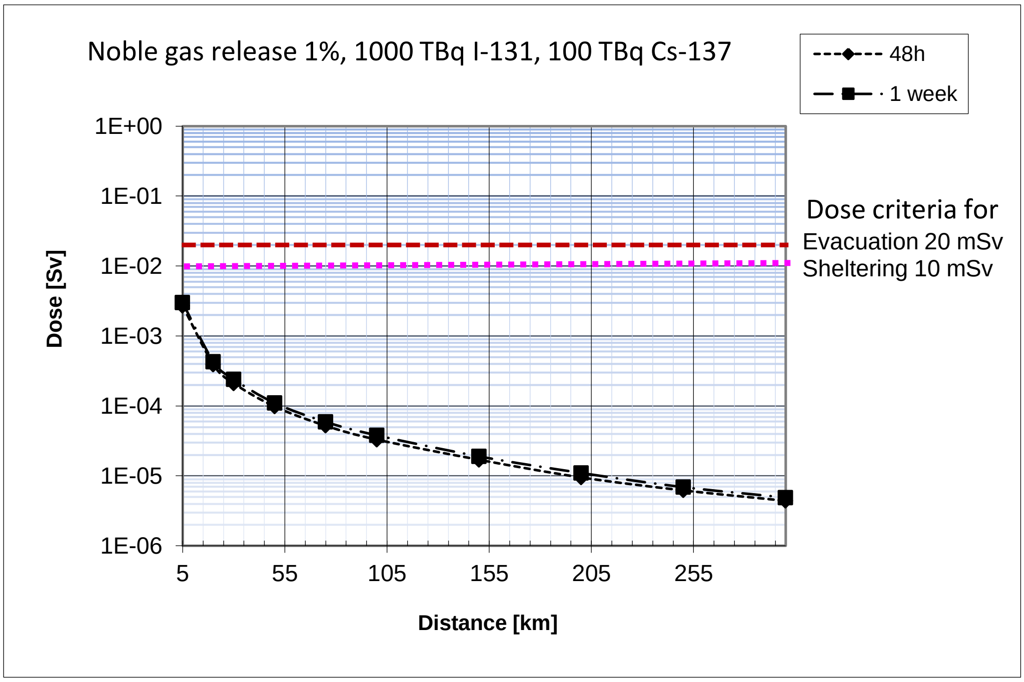

Figure 7.1. The dose of 95% fractile as a function of distance from the power plant. Release case 1, two integration times of external radiation from the ground.

Relating to the YVL Guide C.3 figure 7.1 indicates that in the case of a severe accident:

- need for evacuation will not arise outside the protective zone (5 km radius)
- need for the public to stay indoors will not arise outside the emergency planning zone (20 km radius)
-

Figure 7.2 presents the dose components, in addition the projected dose for one year integration is presented.

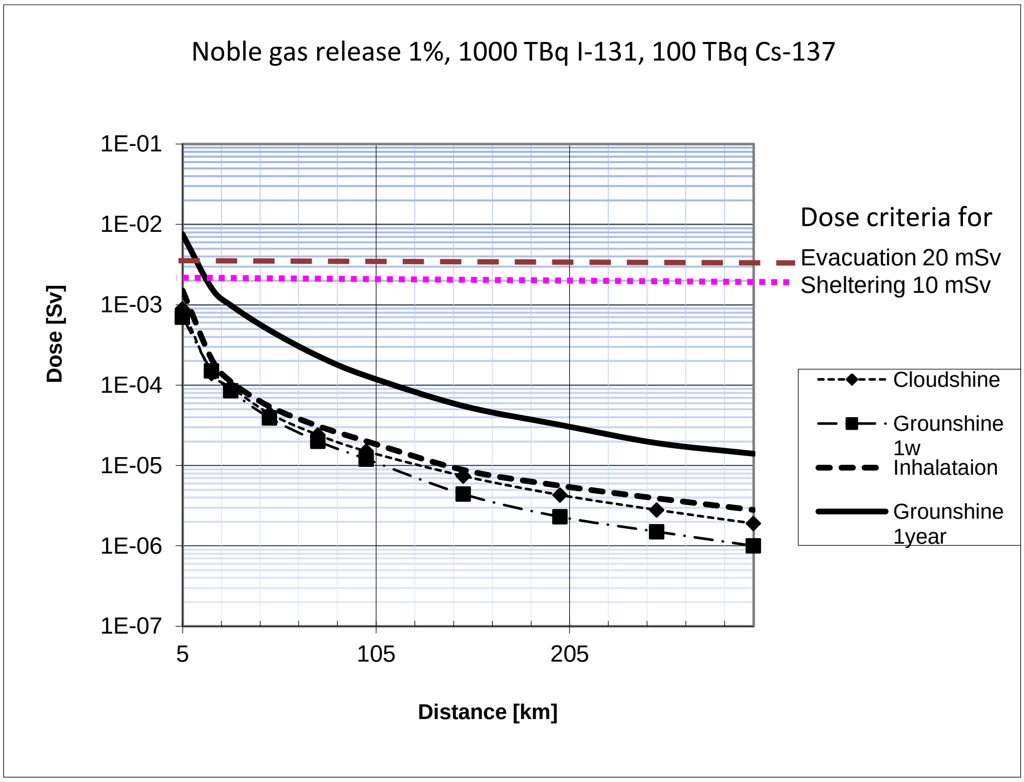

Figure 7.2. The dose components 95% fractile as a function of distance from the power plant. Release case 1, one year integration time of external radiation from the ground is added.

Although external dose from ground is integrated for one year period the dose does not exceed the criteria for sheltering or evacuation beyond 20 km.

Figure 7.3 illustrates the imaginary case where the rain occurrence is delayed to begin not at the release point but at 50 km from the power plant. In ARANO this means that in all dispersion cases where rain occurs, dispersion starts in dry conditions but changes rainy at the distance of 50 km.

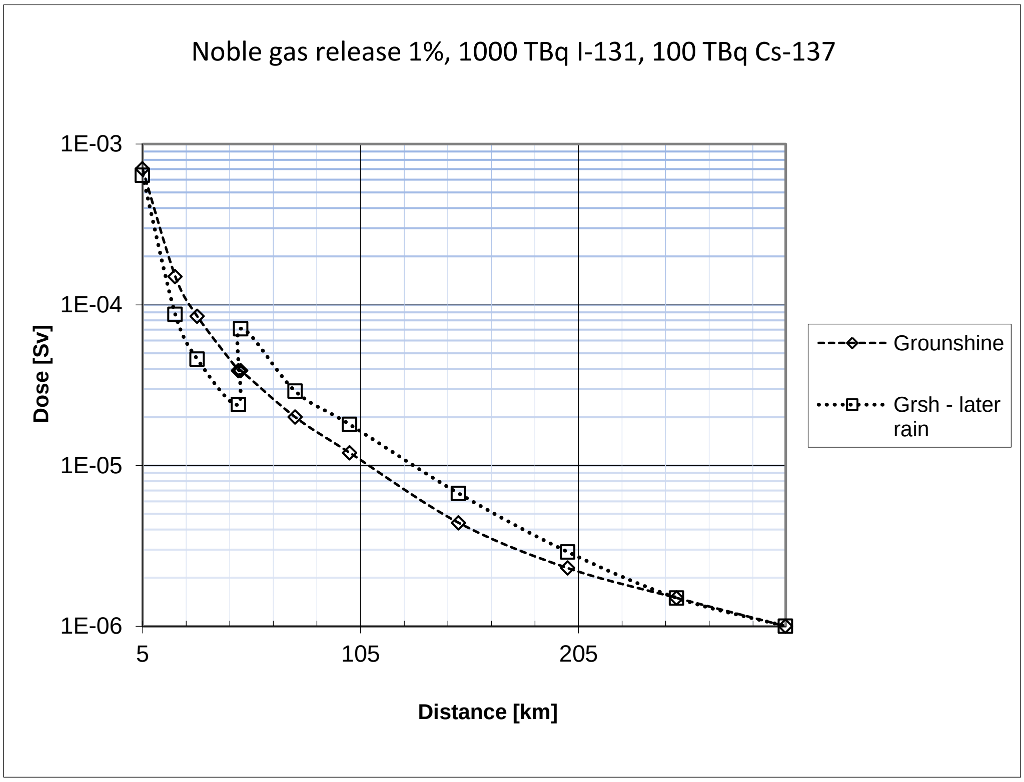

Figure 7.3. Effect of rain starting only at 50 km from the power plant. Release case 1, one week integration time of external radiation from the ground (fractile of 95%).

Figure 7.3 shows the effect of delayed rain. On this presupposition the dose increases suddenly but not sufficiently to reach the dose limits.

Figures 7.4 and 7.5 illustrate external dose from the ground at the distance points of 20 and 50 km. Effect of rain start point is shown.

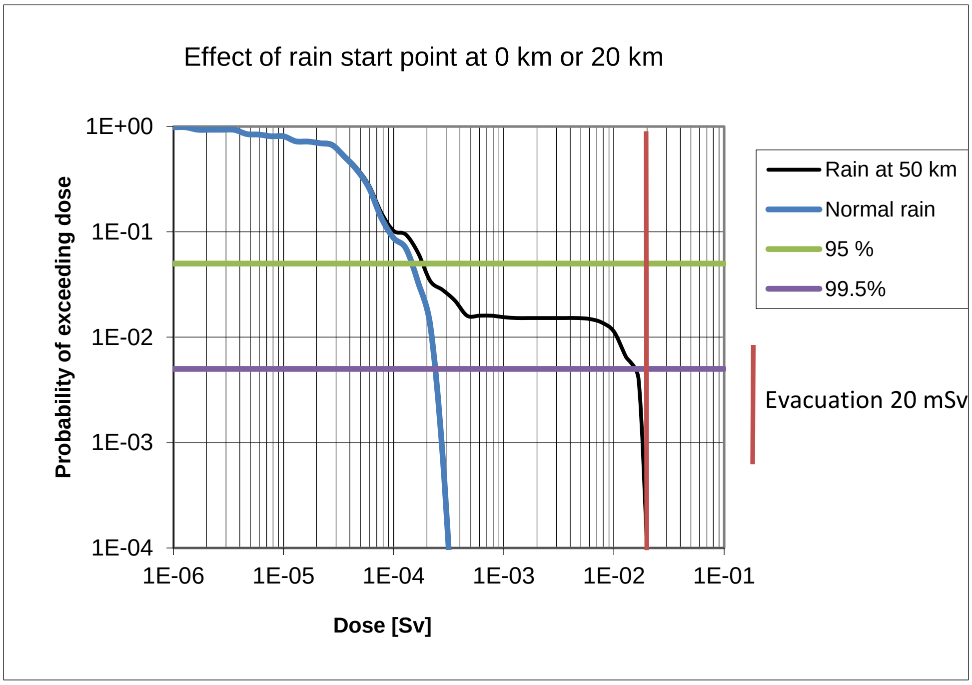

Figure 7.4. Groundshine dose distribution at the distance of 20 km. Effect of rain starting at the power plant or only at 20 km from the power plant. One week integration time of external radiation from the ground.

Figure 7.4 depicts that the 95% fractile value is less dependent on the rain start point but 99.5% fractile value is markedly more dependent on the rain start time. The same trend can be seen in figure 7.5 which represents the distance of 50 km.

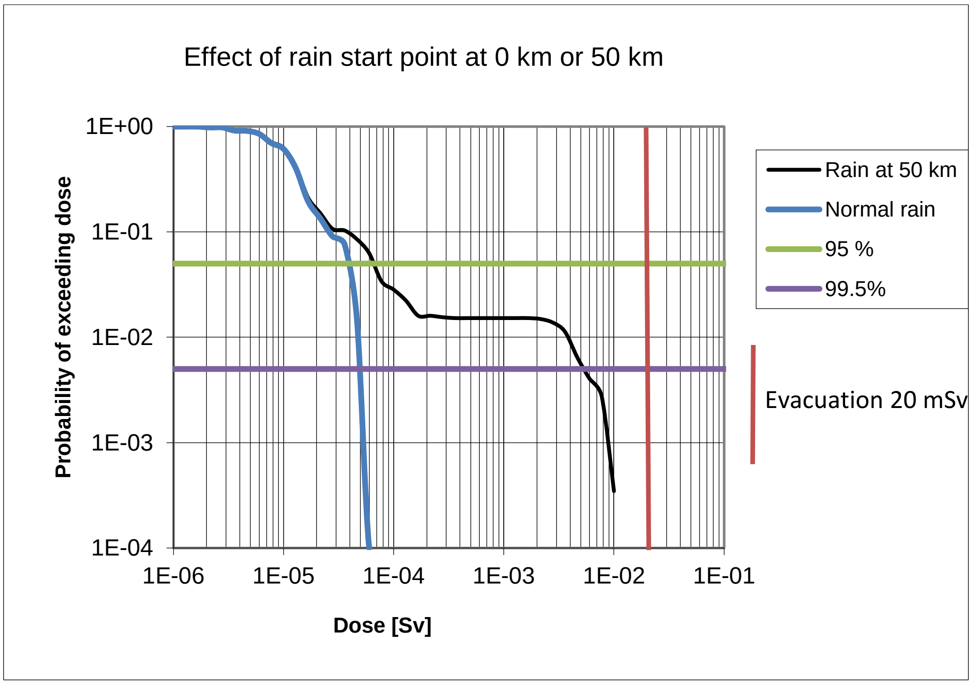

Figure 7.5. Groundshine dose distribution at the distance of 50 km. Effect of rain starting at the power plant or only at 50 km from the power plant. One week integration time of external radiation from the ground.

7.2.2 Case 1, ingestion doses

Ingestion doses are considered separately. Due to seasonal variations the calendar time of deposition affects significantly on the projected doses. Here cow's milk and meat as well as green vegetables are considered. Figure 7.6 illustrates annual doses from ingestion. Firstly the seasonal variation is seen when deposition occurs in summer during growing and pasturing season and secondly outside growing season. The annual ingestion dose in summer may be an order of magnitude greater than the dose in winter.

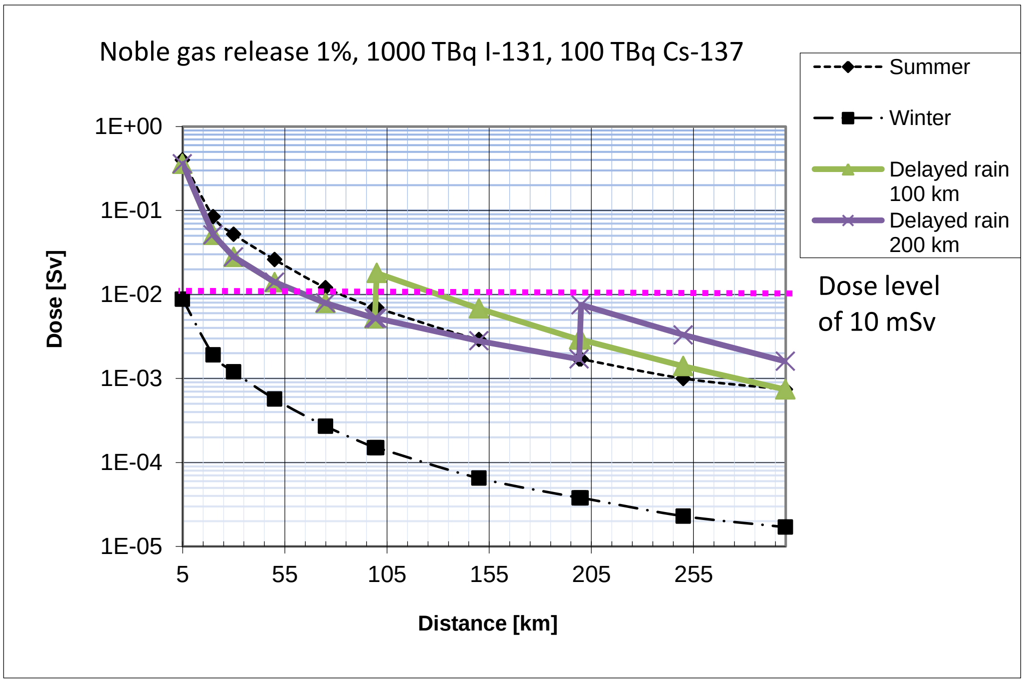

Figure 7.6. Annual ingestion dose (fractile of 95%), release case 1. Effect of rain starting only at 100 or 200 km from the power plant.

Firstly figure 7.6 shows that the dose level of 10 mSv is not exceeded in winter. In summer conditions the limit value may be exceeded up to distance of 70 km. Figure 7.6 shows also the effect of delayed rain. If the rain starts only at the distance of 100 km, the dose increases suddenly and exceeds the dose limit of 10 mSv. If the rain starts only at the distance of 200 km, the dose level of 10 mSv is not achieved. It can be concluded that the maximum distance where delayed rain may cause exceeding of the dose limit is about 170 km.

Figure 7.7 illustrates ingestion dose at the distance of 50 km in summer conditions with two rain occurrence possibilities.

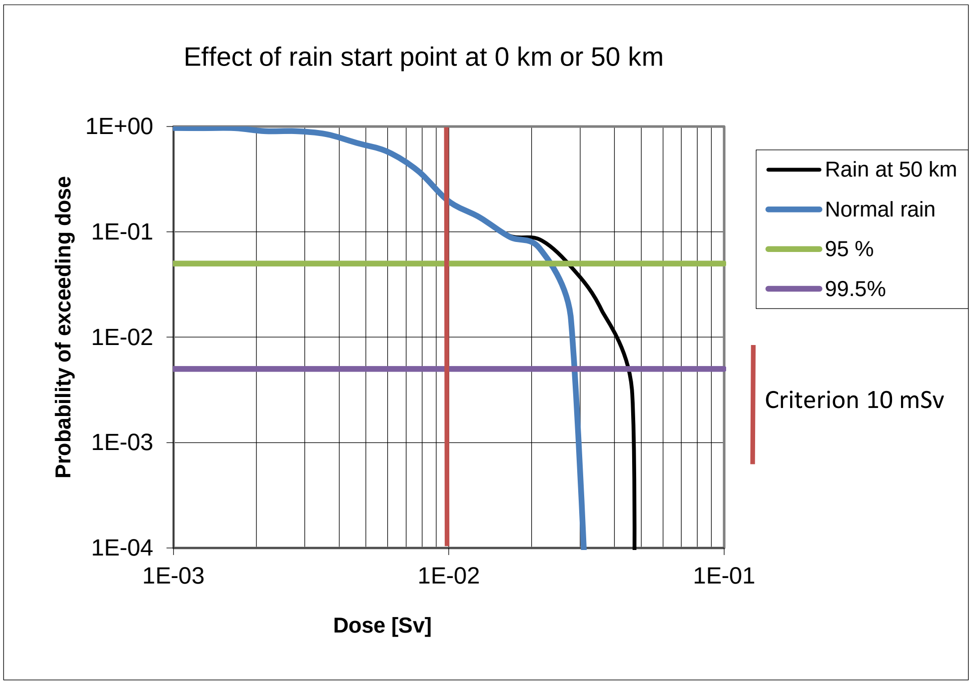

Figure 7.7. Ingestion dose distribution at the distance of 50 km in summer. Effect of rain starting at the power plant or only at 50 km from the power plant.

The dose limit value of 10 mSv is exceeded at the 95% and 99.5% fractiles. Figure 7.8 illustrates doses at the distance of 100 km.

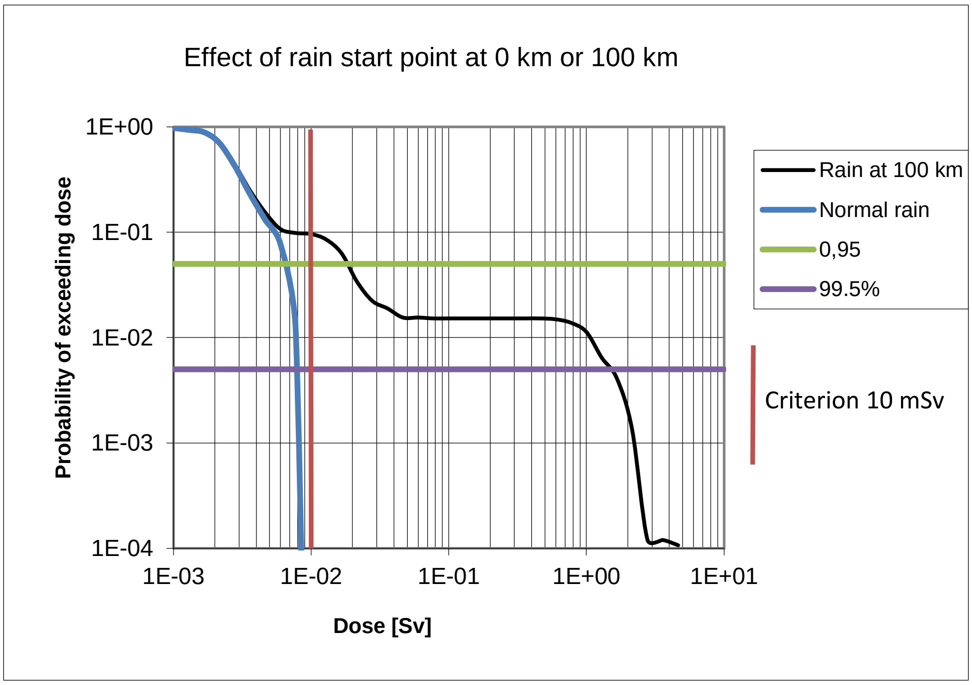

Figure 7.8. Ingestion dose distribution at the distance of 100 km in summer. Effect of rain starting at the power plant or only at 100 km from the power plant.

Now the dose criterion of 10 mSv is exceeded only if rain start time is delayed.

7.2.3 Case 2, external doses and inhalation

Calculations are done for the distances starting at 5 km and extending to 300 km. The effective dose representing different integration times is based on the statistical weather data. The dose includes external radiation from the cloud and ground and internal dose from inhalation. Dose is presented as a function of distance (the 95 per cent fractile). Figure 7.9 illustrates the total dose. Two alternative integration times for the groundshine are considered.

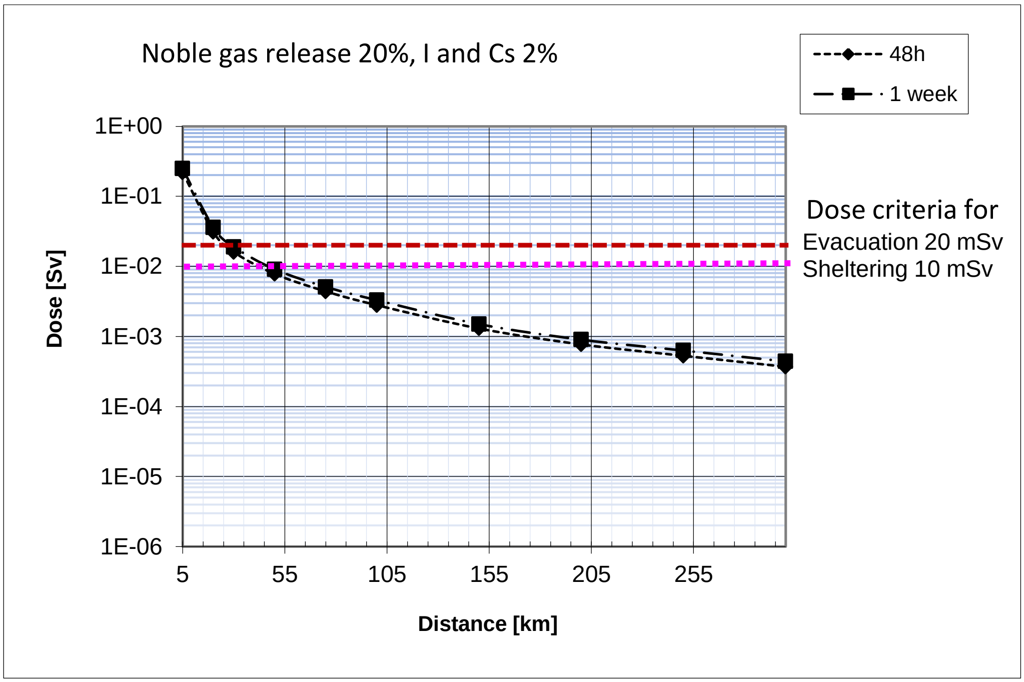

Figure 7.9. The dose of 95% fractile as a function of distance from the power plant. Release case 2, two integration times of external radiation from the ground.

Figure 7.9 indicates that the total dose exceeds the criterion for sheltering up to the distance of 50 km. The criterion for evacuation is not exceeded beyond 20 km.

Figure 7.10 presents the dose components, in addition the projected dose for one year integration is presented.

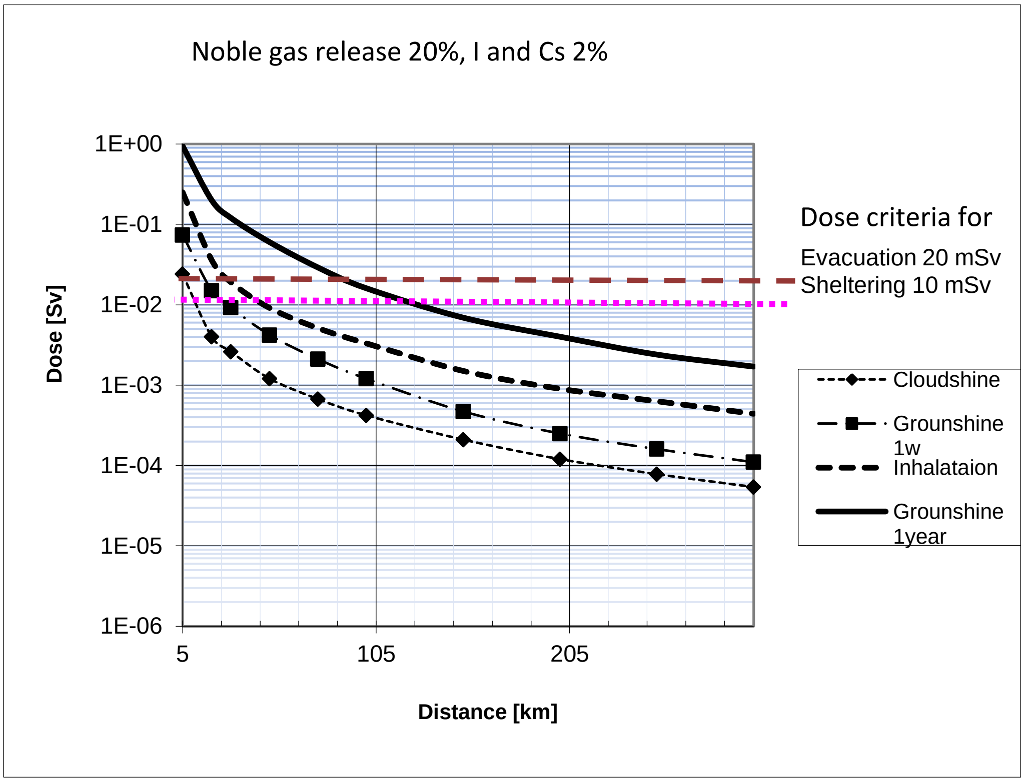

Figure 7.10. The dose components 95% fractile as a function of distance from the power plant. Release case 2, one year integration time of external radiation from the ground is included also.

Figure 7.10 depicts that dose from inhalation dominates in the acute phase but if exposure time is longer than one week then external dose from the ground becomes dominating component. The IAEA dose criterion of 100 mSv is not clearly exceeded beyond 20 km.

Figure 7.11 illustrates the imaginary case where the rain occurrence is delayed to begin not at the release point but 50 km from the power plant. In ARANO this means that in all dispersion cases where rain occurs, dispersion starts in dry conditions but changes rainy at the distance of 50 km.

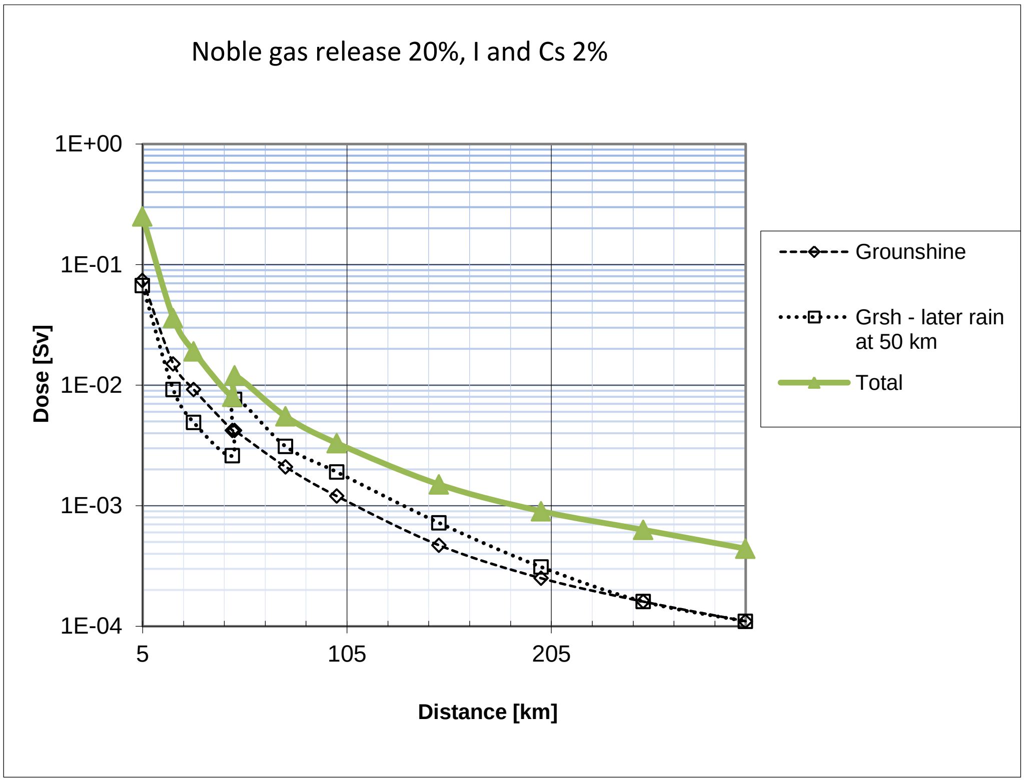

Figure 7.11. Effect of rain starting only at 50 km from the power plant. Release case 2, one week integration time of external radiation from the ground (fractile of 95%).

Figure 7.11 shows the effect of delayed rain. On this presupposition the dose increases suddenly sufficiently to reach the dose limit of sheltering. It is obvious that the IAEA criterion of 100 mSv could be exceeded beyond 20 km if the rain starts later.

7.2.4 Case 2, ingestion doses

Figure 7.12 illustrates annual doses from ingestion. Firstly the seasonal variation is seen when deposition occurs in summer during growing and pasturing season and secondly outside growing season. The annual ingestion dose in summer may be an order of magnitude greater than the dose in winter.

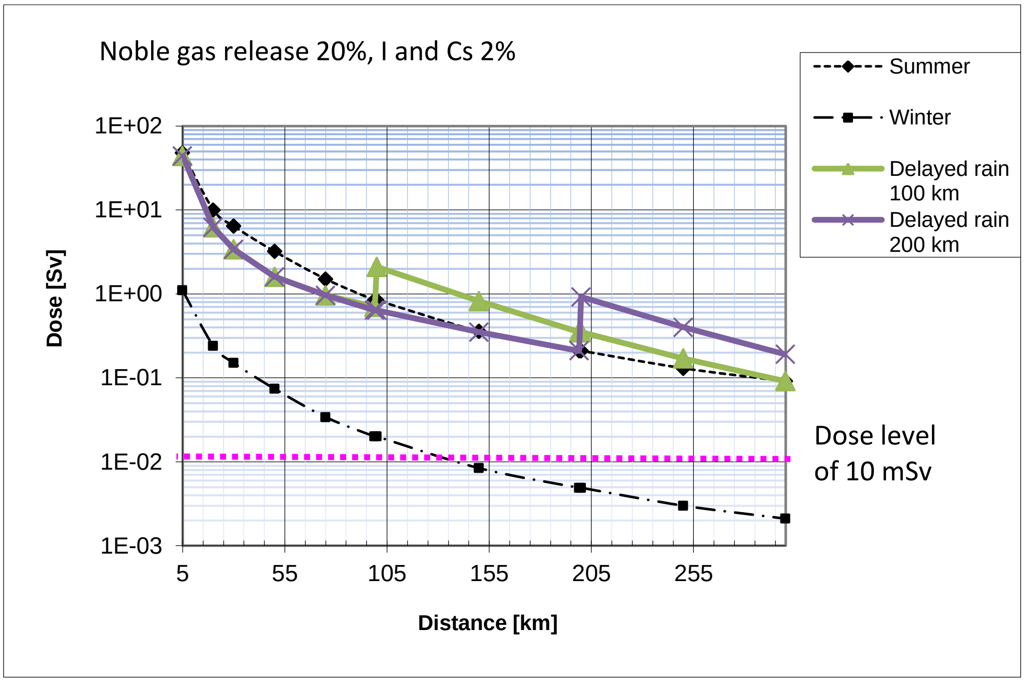

Figure 7.12. Annual ingestion dose (fractile of 95%). Effect of rain starting only at 100 or 200 km from the power plant.

Firstly figure 7.12 shows that the dose level of 10 mSv is exceeded in winter conditions up to 150 km. In summer conditions that limit value would be exceeded up to 300 km. Figure 7.12 shows also the effect of delayed rain although high dose values are obtained without that assumption. The ingestion dose is still about 1 Sv at the distance of 100 km.

7.2.5 Case 3, external doses and inhalation

Calculations are done for the distances starting at 5 km and extending to 300 km. The effective dose representing different integration times is based on the statistical weather data. The dose includes external radiation from the cloud and ground and internal dose from inhalation. Dose is presented as a function of distance (the 95 per cent fractile). Figure 7.13 illustrates the total dose. Two alternative integration times for the groundshine are considered.

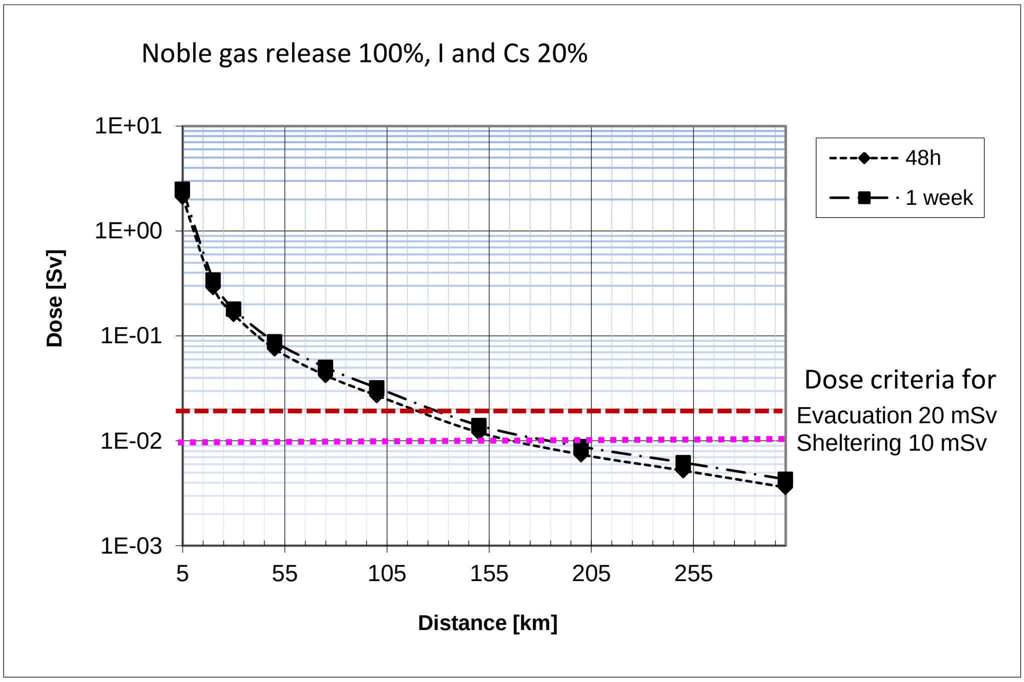

Figure 7.13. The dose of 95% fractile as a function of distance from the power plant. Release case 3, two integration times of external radiation from the ground.

Figure 7.13 indicates that the total dose exceeds the criterion for sheltering up to the distance of 50 km.

Figure 7.14 presents the dose components, in addition the projected dose for one year integration is presented.

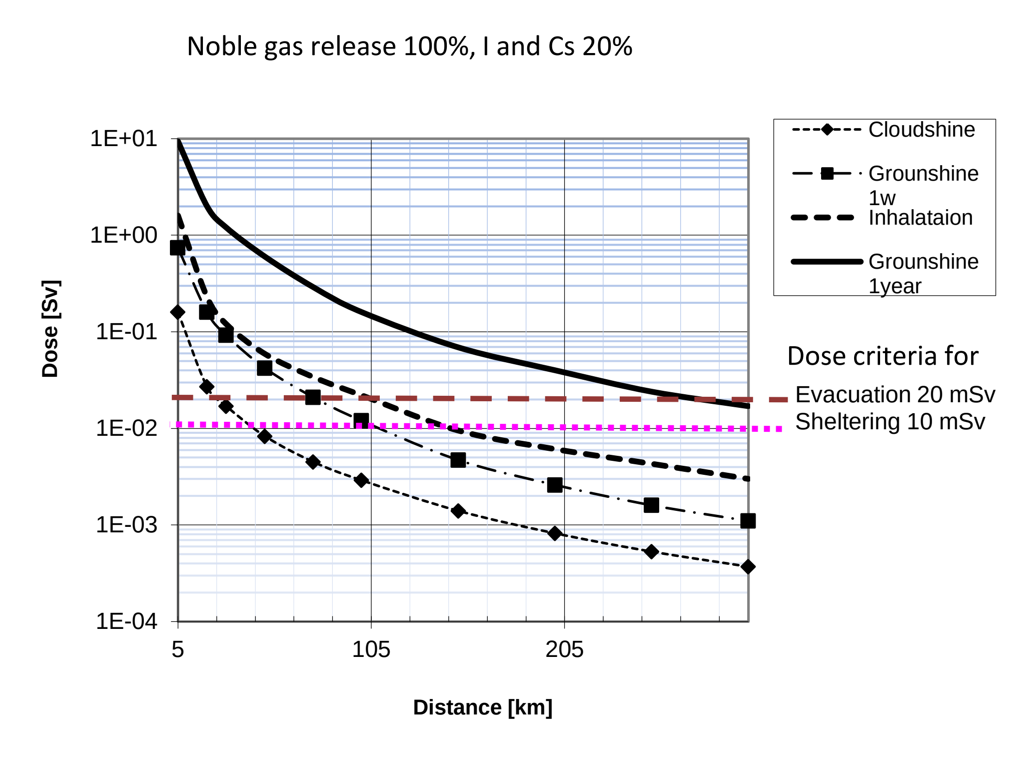

Figure 7.14. The dose components 95% fractile as a function of distance from the power plant. Release case 3, one year integration time of external radiation from the ground is included also.

Figure 7.14 depicts that dose from inhalation dominates in the acute phase but if exposure time is longer than one week then external dose from the ground becomes dominating component. The IAEA dose criterion of 100 mSv could be exceede up to the distance of 120 km.

Figure 7.15 illustrates the imaginary case where the rain occurrence is delayed to begin not at the release point but 200 km from the power plant. In ARANO this means that in all dispersion cases where rain occurs, dispersion starts in dry conditions but changes rainy at the distance of 200 km.

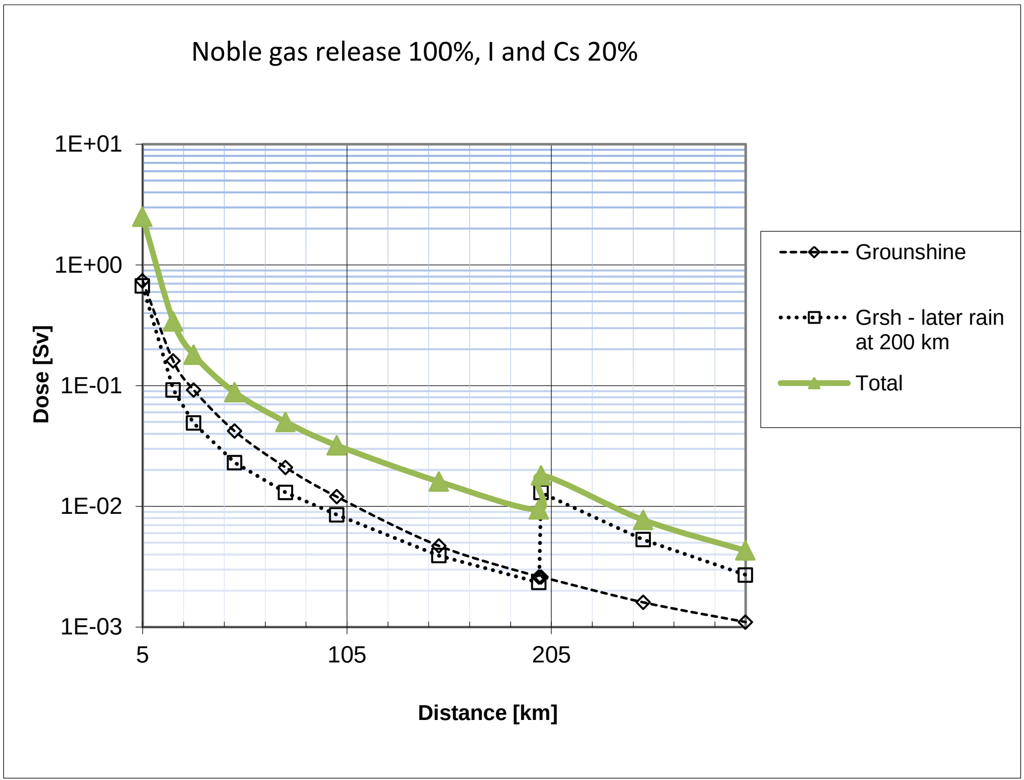

Figure 7.15. Effect of rain starting only at 200 km from the power plant. Release case 3, one week integration time of external radiation from the ground (fractile of 95%).

Figure 7.15 shows the effect of delayed rain. On this presupposition the dose increases suddenly sufficiently to reach the dose limit of sheltering still at the distance of 220 km.

7.2.6 Case 3, ingestion doses

Figure 7.16 illustrates annual doses from ingestion. Firstly the seasonal variation is seen when deposition occurs in summer during growing and pasturing season and secondly outside growing season. The annual ingestion dose in summer may be an order of magnitude greater than the dose in winter.

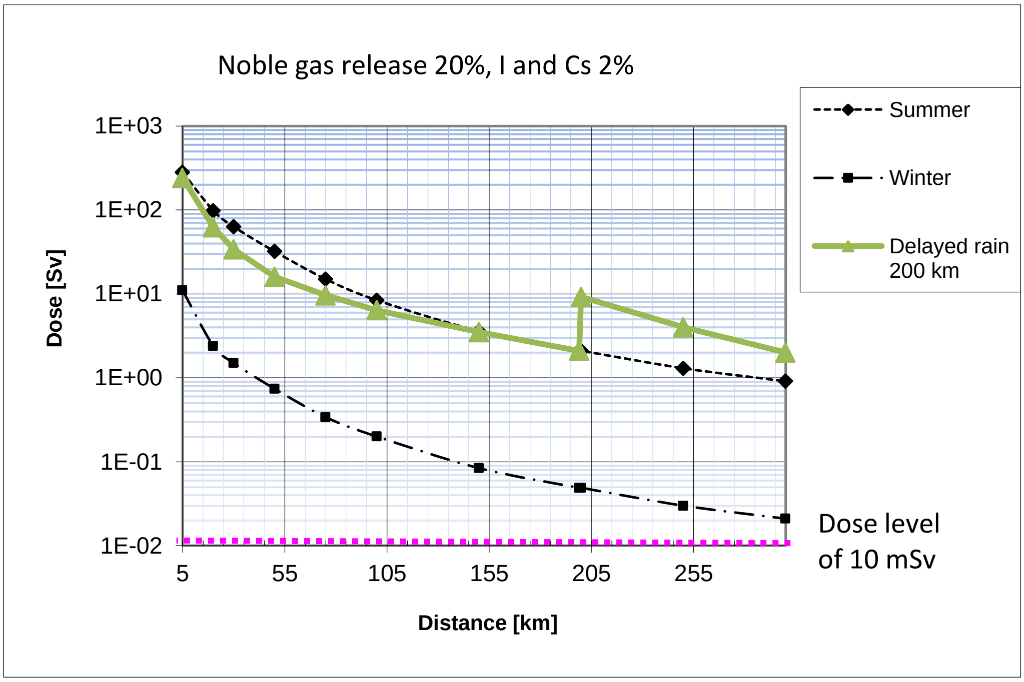

Figure 7.16. Annual ingestion dose (fractile of 95%). Effect of rain starting only at 200 km from the power plant.

Figure 7.16 shows that the dose level of 10 mSv is exceeded in winter conditions even up to 300 km. In summer conditions dose values are very high reaching 1 Sv at the distance of 300 km. Figure 7.16 shows also the effect of delayed rain causing e.g. 10 Sv at the distance of 200 km.

8. Preliminary observations about doses calculated by VALMA

As described above, ARANO and VALMA are very different models regarding the handling and use of weather data. ARANO weather data can be characterized as follows:

- Years-long weather data is divided into 1008 classes of weather situations, of which only 84 (6 stabilities x 7 wind speeds x 2 rain conditions) lead to different individual doses.
- Each weather situation is described by constant weather (constant in both space and time). Even a long release follows the wind at its starting time as one ‘chunk’. It follows the one and same straight line central trajectory, no matter how long and how far.
- Considering the statistical nature of typical ARANO use, the above restrictions are not a problem, as possible errors in single cases are evened out by the large number of weather cases, e.g. 43824 hourly cases in 5 years’ time.

VALMA use of weather data can be characterized as follows:

- The intended use of VALMA is mainly based on SILAM-generated particle trajectories, which are in turn based on NWP (numerical weather prediction) model. Using SILAM data, fairly good dose predictions can be made.

- VALMA can also use measurements at a weather mast (e.g. NPP mast), even several masts if available. However, the procedure is similar to SILAM trajectories: VALMA calculates a bunch of trajectories based on the available wind data.

- VALMA-generated trajectories are inevitably of low quality, when compared with a 3D flow field from NWP. Furthermore, usually only one measuring point is available, which means that VALMA can only work reliably sufficiently close to the weather mast.

- With SILAM data, dispersion is implied by the particle trajectories, whereas with VALMA trajectories, traditional σ_y standard deviations are needed. According to the number of trajectories, a numerical parameter (limit radius of area considered) is used. With SILAM data, it should be small, and with one central trajectory it should be large (e.g. 3 σ_y). In this work, there may be too little horizontal dispersion of the plume, as the VALMA version used had the limit parameter set automatically according to the number of trajectories, which in turn was as high as 721 (generated by VALMA itself).

Otherwise than weather, ARANO and VALMA have many similar features. Both calculate the chain decay of dozens of nuclides, and both have several dose pathways, in which the major difference is the absence of ingestion doses in VALMA, which was designed as an emergency radiation prediction tool.

For the VALMA comparison calculations, it was attempted to define the radioactive source term exactly the same as for the above ARANO calculations. Of the 9 available nuclide groups, 3 were used: noble gases, iodine and the Cs group. Table 8.1 gives a list of the 21 nuclides used, their inventory amounts and released fractions. The release was assumed to start 4 hours after reactor SCRAM, and the duration of the release was set to 3 hours.

Table 8.1. Radioactive nuclides included in the hypothetical major release at Olkiluoto NPP. Noble gases, iodine, cesium and rubidium were included. After nuclide name, the activity (Bq) in inventory is given, followed by the fraction released into the atmosphere.

```
'I-131'     4.8e18  20 %
'I-132'     7.0e18  20 %
'I-133'     1.0e19  20 %
'I-134'     1.1e19  20 %
'I-135'     9.5e18  20 %
'CS-134'    9.3e17  20 %
'CS-136'    2.3e17  20 %
'CS-137'    6.4e17  20 %
'RB-88'     3.6e18  20 %
'RB-89'     4.7e18  20 %
'CS-138'    9.3e18  20 %
'KR-85'     5.7e16  100 %
'KR-85M'    1.3e18  100 %
'KR-87'     2.5e18  100 %
'KR-88'     3.5e18  100 %
'XE-133'    9.7e18  100 %
'XE-135'    3.0e18  100 %
'KR-89'     6.0e17  100 %
'XE-133M'   3.1e17  100 %
'XE-135M'   2.1e18  100 %
'XE-138'    8.6e18  100 %
```

The central question in this work is to find out the practical possibilities to predict doses at distances 100…300 km, using a large number of potential cases (release and weather). This objective involves at least two separate considerations:

- What is the accuracy of predictions at distances 100…300 km?
- What is the calculation time needed to make predictions for a large number of cases, e.g. one certain release with 5 years' hourly weather data?

A partial answer to the CPU time question is given by Table 8.2, where we see that typical VALMA time to calculate one case was 7 minutes (powerful Intel Core i7 laptop). Based on this observation, we get that the total CPU time for 5 years' hourly weather would be 43824 x 7 min = 213 days. So, exhaustive calculation of the whole data with VALMA seems unpractical, even now in 2015. Furthermore, VALMA calculation time depends strongly on several numerical parameters, like number of trajectories, density of the result grid, limit radius of puff effective area etc. VALMA has systems for automatic calculation of a large number of cases, but still some source code development would be needed for the proposed task. On the other hand, ARANO is so fast that the calculations of this work can be done in seconds.

Weather data for VALMA comparison cases

In this work, hourly weather data measured by TVO at the Olkiluoto NPP weather mast during 2009-2013 was used. The number of measurements is 5 x 365 x 24 + 24 (year 2012 was leap year) = 43824. For each hour, the data contains the following quantities:

- Wind speed
- Wind direction
- Temperature difference, from which we get the Pasquill-Gifford stability class (A, B, C, D, E, F)
- Intensity of rain

It was decided to perform the VALMA comparison with the cases for which ARANO had predicted the highest radiation doses. As may be expected, these were the class with lowest wind speed and stable mixing conditions (stability class F). From these cases, only those were picked which had spread direction into the inland of Finland, which makes them more interesting with regard to potential countermeasures. This choice resulted in 45 cases out of the total 43824. So, we are deliberately discussing the worst 1/1000 of the weather situations. However, the purpose here is only to investigate the usability of VALMA and compare with ARANO. It turned out that the year of the Fukushima disaster (2011) happened to contain most of the worst cases, and the following 3 cases (Table 8.2) were picked from that year.

Table 8.2. Weather situations from Olkiluoto measured weather data, chosen from year 2011, that were used for the VALMA comparison calculations. The given hourly initial values correspond to the release duration of 3 h.

Date	Code	Initial wind speed (m/s)	Initial spread dir	Intitial stability	Rain	Calculation time (s)
17.6.2011	21533	2-2-2-1	south	F-E-E-F	16-22 h	408
9.9.2011	23567	2-1-1-1	north	F-E-D-E	11-17 h	329
25.9.2011	23934	2-2-1-1	S-E	F-F-D-D	-	448

The measured weather data had to be transformed to the format accepted by VALMA. A first look into how the dispersion situations look like is provided by the VALMA-generated trajectories, 8 of which are shown in Figure 8.1, 8.2 and 8.3, for cases 21533, 23567 and 23934, respectively. In each Figure, the 8 trajectories start uniformly in time during the release duration of 3 hours. It must be noted here that the trajectories can only be reliable near the weather mast, but for technical reasons their whole length in 20 hours is shown.

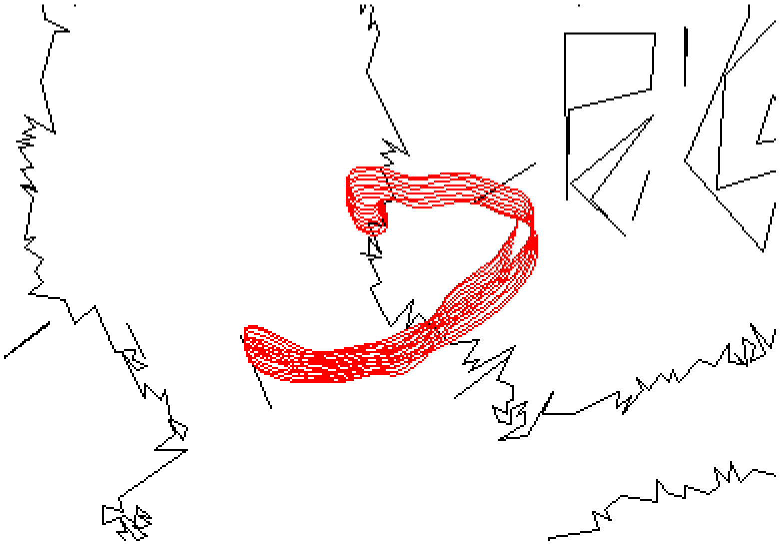

Figure 8.1. Advection in case 21533, described by 8 trajectories starting during 3 hours, calculated by VALMA using single-point wind measurements. Note: Weather data is reliable only near the source. Initial spread direction is south towards Rauma (low wind speed), after which the plume turns clockwise through west and north towards east, in the direction of Tampere.

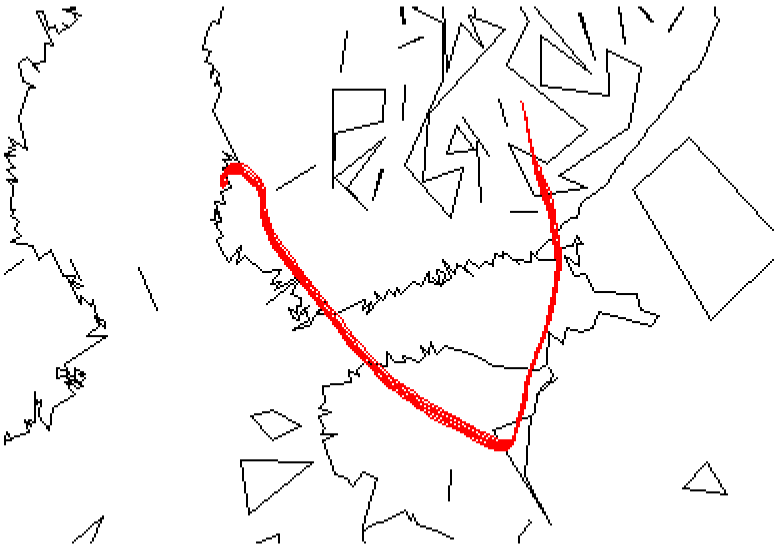

Figure 8.2. Advection in case 23567, described by 8 trajectories starting during 3 hours, calculated by VALMA using single-point wind measurements. Note: Weather data is reliable only near the source. Initial spread direction is north (low wind speed), after which the plume turns clockwise through east towards south-east, in the direction of Turku.

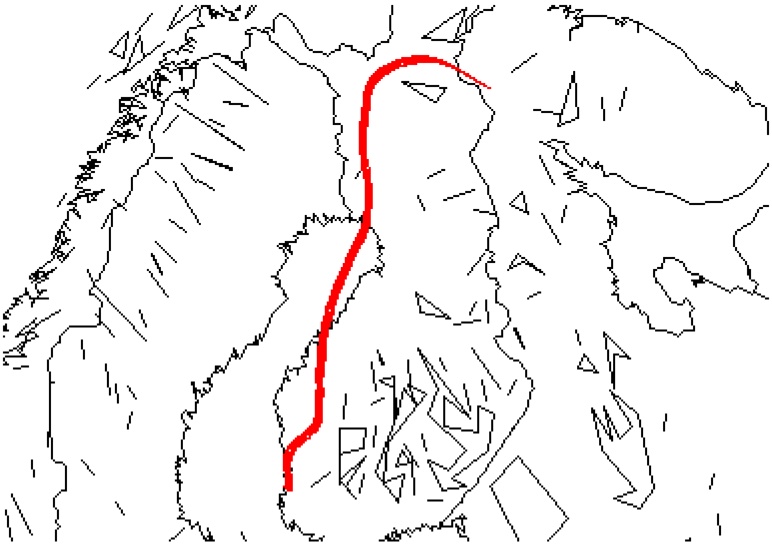

Figure 8.3. Advection in case 23934, described by 8 trajectories starting during 3 hours, calculated by VALMA using single-point wind measurements. Note: Weather data is reliable only near the source. Initial spread direction is south-east, after which the plume turns clockwise through east towards north, in the direction of Pori, and then into the inland of Finland.

VALMA calculates several types of result quantities: concentrations in air (Bq/m3), deposited amounts (Bq/m2), dose rates (Sv/s) and doses (Sv):

```
Total dose (external + inhalation)
Total external dose rate (cloud + fallout, all nuclides)
Total external dose (cloud + fallout, all nuclides)
Cloud gamma dose rate
Cloud gamma dose
Fallout gamma dose rate
Fallout gamma dose
d/dt_inhal of effective inhalation dose (50 years)
Effective inhalation dose (50 years)
d/dt_inhal of inhalation dose to thyroid (50 years)
Inhalation dose to thyroid (50 years)
-Nuclide-wise concentrations in air
-Nuclide-wise deposition on ground
```

In this report, only the total dose (external dose + inhalation dose commitment) and the total external dose rate were chosen for presentation. The total dose can readily be compared with ARANO results, though there is the inevitable difficulty that ARANO expresses them as a function of distance on the straight-line central trajectory, whereas VALMA results are based on curvilinear trajectories and are presented on an ordinary map background. External dose rate was chosen as an additional quantity due to its importance in practical emergency situations, and due to its informativeness in showing where high amounts of radioactive nuclides were deposited. It should be noted that one week after the release start (Figure 8.4-8.9), the cloud has passed the observed area and the external dose rate actually comes from deposition only.

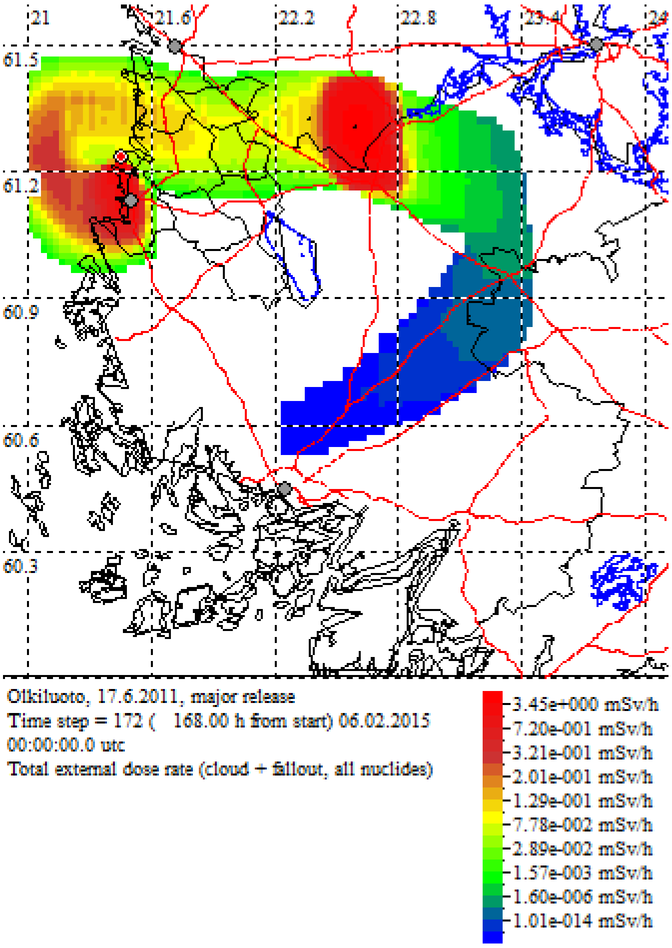

Figure 8.4. VALMA-predicted external dose rate one week after the start of the release in case 21533 (17.6.2011). Yellow color (middle / median of the scale) corresponds to appr. 0.1 mSv/h. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 35 km.

Figures 8.4 and 8.5 show the VALMA-predicted total dose and external dose rate one week after the release which was assumed to start on June 17, 2011 (case code 21533). The dispersion started with stable conditions and a very low wind speed. There was rain after 16 hours.

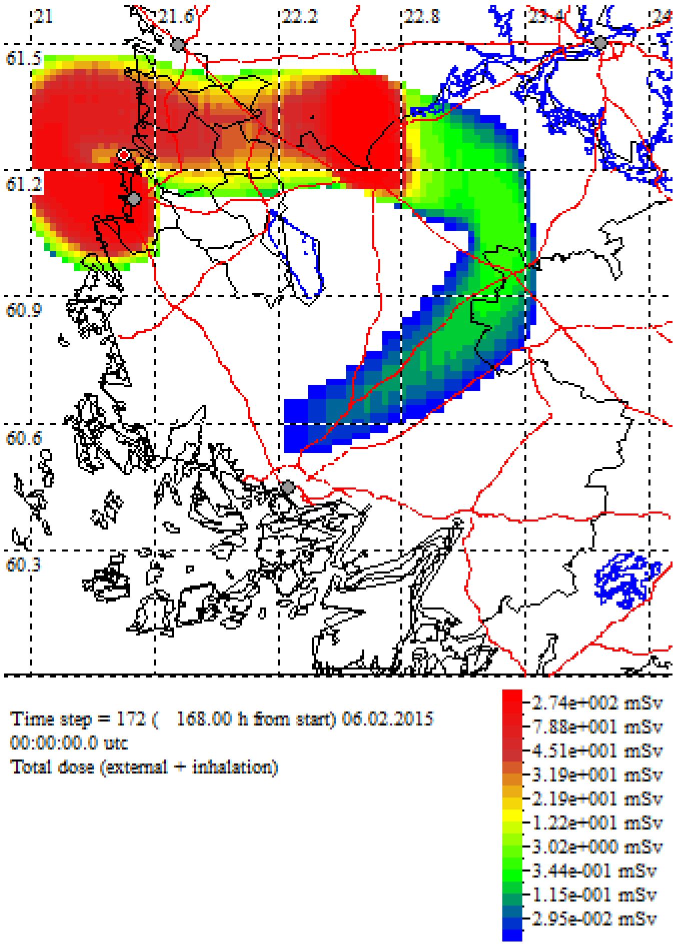

Figure 8.5. VALMA-predicted total dose (external gamma from cloud and fallout + inhalation dose commitment) one week after the start of the release in case 21533 (17.6.2011). Yellow color (middle / median of the scale) corresponds to appr. 13 mSv. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 35 km.

As it is relatively difficult to find exact values of dose from the color scale, Table 8.3 is provided with some chosen points, generally from plume centreline of Figure 8.5, and the total dose (external + inhalation) at them.

Table 8.3. Some values of total dose from Figure 8.5, picked interactively by using the VALMA GUI. The Table starts from source and proceeds approximately along the plume centerline trajectory. Note: The exact values should be considered only with extreme care, as they are subject to the effect of several numerical and other choices.

Latitude N	Longitude E	Total dose (1 week) mSv
61.149	21.473 (Rauma)	1400
61.344	21.580	54.7
61.310	22.057	30.6
61.306	22.184	42
61.315	22.573	1020
61.258	22.836	18
60.959	23.342	0.249

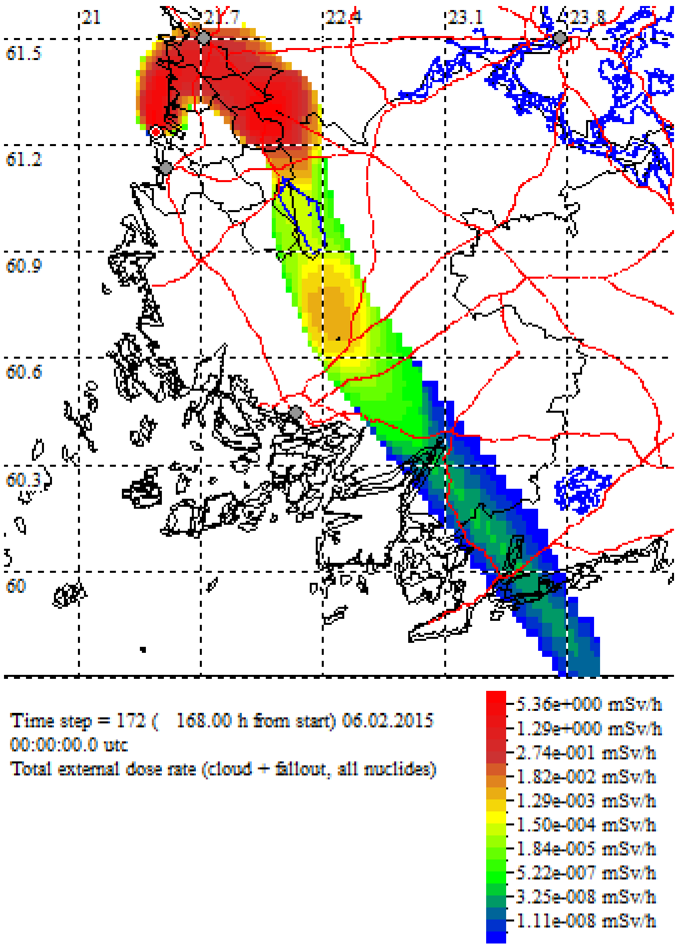

Figure 8.6. VALMA-predicted external dose rate one week after the start of the release in case 23567 (9.9.2011). Yellow color (middle / median of the scale) corresponds to appr. 0.5µSv/h. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 35 km.

Figures 8.6 and 8.7 show the VALMA-predicted total dose and external dose rate one week after the release which was assumed to start on September 9, 2011 (case code 23567). The dispersion started with stable conditions and a very low wind speed. There was rain after 11 hours.

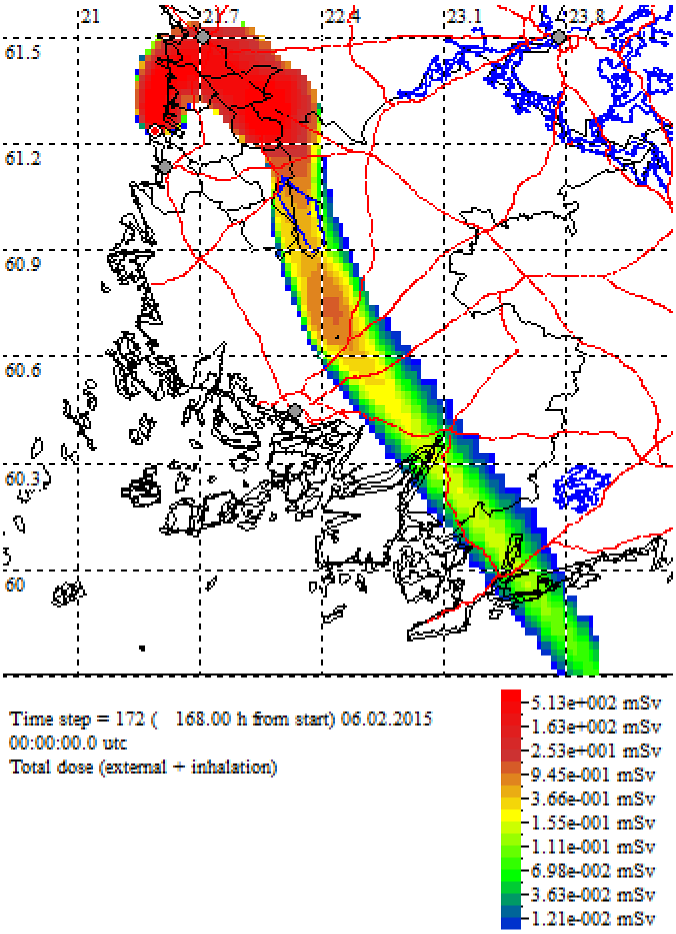

Figure 8.7. VALMA-predicted total dose (external gamma from cloud and fallout + inhalation dose commitment) one week after the start of the release in case 23567 (9.9.2011). Yellow color (middle / median of the scale) corresponds to appr. 0.2 mSv. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 35 km.

Table 8.4 is provided with some chosen points, generally from plume centreline of Figure 8.7, and the total dose (external + inhalation) at them.

Table 8.4. Some values of total dose from Figure 8.7, picked interactively by using the VALMA GUI. The Table starts from source and proceeds approximately along the plume centerline trajectory. Note: The exact values should be considered only with extreme care, as they are subject to the effect of several numerical and other choices.

Latitude N	Longitude E	Total dose (1 week) mSv
61.510	21.701 (Pori)	30.5
61.358	22.000	532
61.177	22.195	12.7
60.974	22.299	0.448
60.912	22.310	0.408
60.743	22.471	1.02
60.450	22.793	0.171

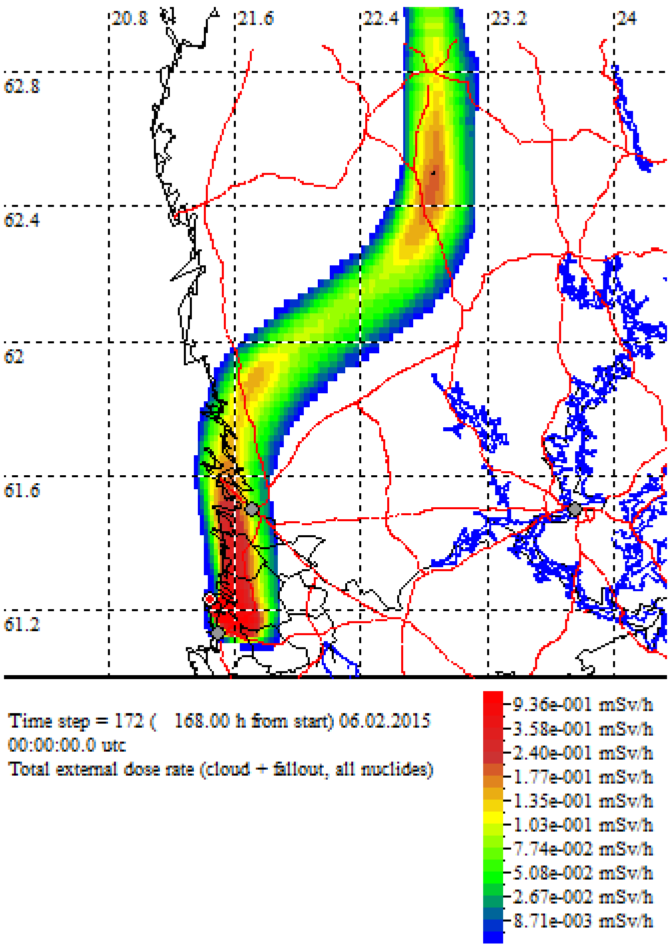

Figure 8.8. VALMA-predicted external dose rate one week after the start of the release in case 23934 (25.9.2011). Yellow color (middle / median of the scale) corresponds to appr. 0.1 mSv/h. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 45 km.

Figures 8.8 and 8.9 show the VALMA-predicted total dose and external dose rate one week after the release which was assumed to start on September 25, 2011 (case code 23934). The dispersion started with stable conditions and a very low wind speed. There was no rain.

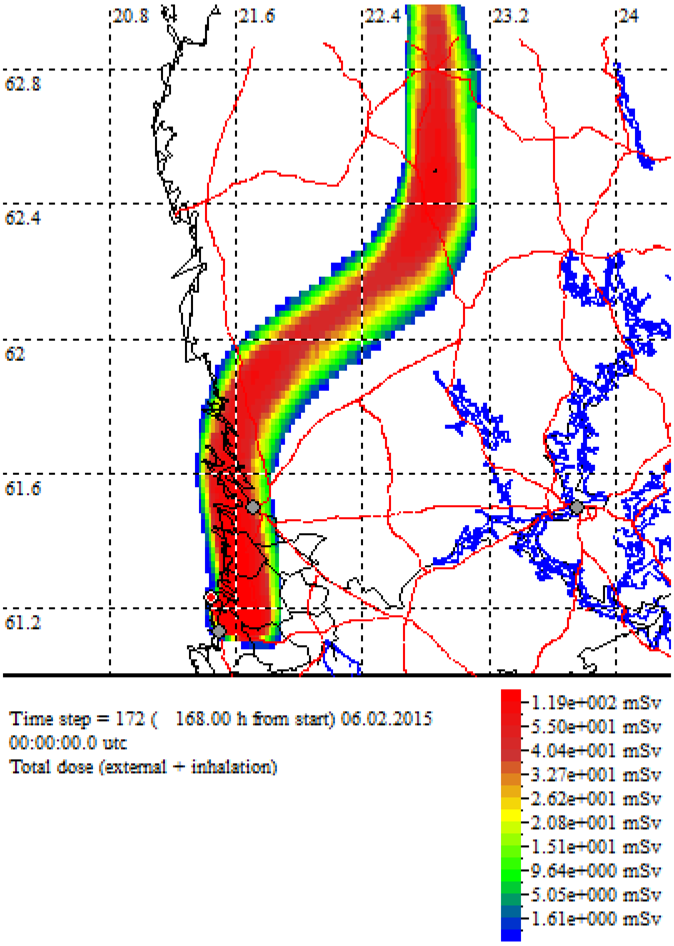

Figure 8.9. VALMA-predicted total dose (external gamma from cloud and fallout + inhalation dose commitment) one week after the start of the release in case 23934 (25.9.2011). Yellow color (middle / median of the scale) corresponds to appr. 21 mSv. Red circle = Olkiluoto, grey = Rauma, Pori etc. Side of a dotted rectangle is appr. 45 km.

Table 8.5 is provided with some chosen points, generally from plume centreline of Figure 8.9, and the total dose (external + inhalation) at them.

Table 8.5. Some values of total dose from Figure 8.9, picked interactively by using the VALMA GUI. The Table starts from source and proceeds approximately along the plume centerline trajectory. Note: The exact values should be considered only with extreme care, as they are subject to the effect of several numerical and other choices.

Latitude N	Longitude E	Total dose (1 week) mSv
61.184	21.637	680
61.338	21.637	165
61.504	21.687 (Pori)	52.6
61.724	21.599	63.9
61.819	21.650	66.8
61.926	21.839	61.2
62.122	22.383	42

9. Conclusions

The objective is to clarify what technical possibilities are practically available to calculate probability distributions of radiation doses from different exposure pathways at distances beyond 20 km from the power plant. The ultimate target is to answer the question of what countermeasures should be prepared outside the traditional emergency planning zone.

The central question in this work is to find out the practical possibilities to predict doses at distances 100…300 km, using a large number of potential cases (release and weather). This objective involves at least two separate considerations:

- What is the accuracy of predictions at distances 100…300 km?
- What is the calculation time needed to make predictions for a large number of cases, e.g. one certain release with 5 years' hourly weather data?

The accuracy of predictions cannot yet be clearly judged. There is no experimental data used in this work to compare with simulations. Some possibilities exist, like Chernobyl, the Algeciras Cs-137 release, or Fukushima. However, there are always difficulties with knowledge of the source term and weather conditions. Furthermore, NWP-based weather data (3D flow field) should be used for best results.

A partial answer to the CPU time question is given by Table 8.2, where we see that typical VALMA time to calculate one case was 7 minutes (powerful Intel Core i7 laptop). Based on this observation, we get that the total CPU time for 5 years' hourly weather would be 43824 x 7 min = 213 days. So, exhaustive calculation of the whole data with VALMA seems unpractical, even now in 2015. On the other hand ARANO calculates the whole data set in seconds.

As a conclusion ARANO is capable of calculating results as planned but a significant defect at long distances may be constant weather all the dispersion time. VALMA is capable of calculating results in changing weather conditions (ingestion pathway is currently not available). Weather data can be based either on one point (e.g. a meteorological mast) or on the particle trajectories of a numerical weather prediction model. In these cases calculation time induces problem and it is necessary to reduce the amount of trajectories.

Regarding the capability of VALMA to produce useful predictions for the range of 100-300 km from a large number of real weather cases, the following improvements are suggested:

1) Addition of ingestion dose pathways as nuclide-specific scalar factors, different for summer and winter period.

2) Reduction of CPU time by numerical choices and sampling of weather data.

3) Use of SILAM weather data for reliable predictions at the longer ranges.

These improvements could possibly be done in 2015 (CASA projects), depending on STUK judgement on their importance.

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