Title	Dose estimates at long distances from severe accidents
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Citation	RESEARCH REPORT : VTT-R-00589-16 VTT, 2016, pages 41.
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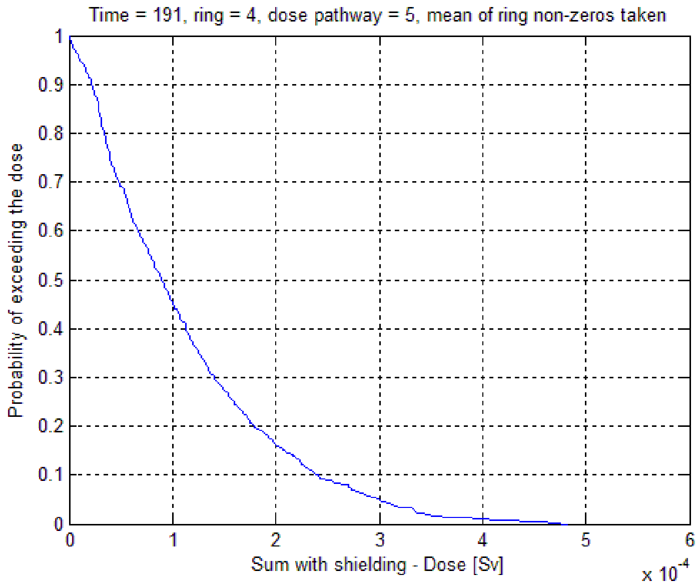
RESEARCH REPORT

VTT-R-00589-16



Dose estimates at long distances from severe accidents

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Confidentiality: Public

Report's title	
Dose estimates at long distances from severe accidents	
Customer, contact person, address SAFIR2018 – The Finnish Research Programme on Nuclear Power Plant Safety 2015-2018	**Order reference** SAFIR 6/2015
Project name Comprehensive Analysis of Severe Accidents	**Project number/Short name** 102311/CASA
Authors Jukka Rossi, Mikko Ilvonen	**Pages** 41
Keywords ARANO, VALMA, source term, atmospheric dispersion, dose assessment, radiological consequences, deposition, external dose rate	**Report identification code** VTT-R00589-16

Summary

In 2011 Fukusima Daiichi accident caused remarkable radiation dose levels in the environment of the power plant, even at longer (>20 km) 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.

Preliminary calculations proved that there can be relatively high dose values at long distances if the source term is large. Furthermore, it seemed to be useful to take into account changing weather conditions during plume dispersion. This is possible in the winding trajectory model VALMA. Initially VALMA was developed for emergency planning purposes but now the model had to be extended in order to enable processing of trajectory data of one year and dose calculations in a probabilistic approach. The extension is technical.

The results of VALMA indicate that if the release magnitude exceeds significantly the criterion value (100 TBq for Cs-137) for the severe accident offsite dose levels may exceed IAEA's criteria for countermeasures beyond 20 km. Release magnitude affects directly to the distances. Acute health effects there are not expected, but the risk of stochastic effects could be reduced by applying appropriate countermeasures.

Confidentiality	Public

Espoo 19.2.2016

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Distribution (customer and VTT)

SAFIR2018 Reference Group 5
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Preface

This report is a result of the CASA project, which in turn is a part of the SAFIR 2018 research programme.

Espoo 19.2.2016

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Contents

1. Introduction

After a few draft versions IAEA published the general safety requirements for planning radiological protection measures outside the traditional emergency planning zone [IAEA 2015]. In order to evaluate this requirement, it is necessary to compute radiation doses at the distances from 20 km up to 300 km from severe accidents. The present emergency planning zone extends to the distance of 20 km from the NPP site.

In the first part of this project comparison calculations with ARANO and VALMA had been done [Rossi, Ilvonen 2015]. ARANO is a straight line, constant weather model. VALMA is a trajectory based, changing weather model. Because weather strongly affects the dose especially at longer distances, it is necessary to treat weather conditions as a changing parameter in the dose distribution calculations. The conclusion of the preliminary calculations was that VALMA is more applicable for this task because then atmospheric dispersion of the release plume can be described more realistically. In principle, a large amount of different weather conditions are needed to determine also probabilities of the doses.

The current objective is to determine probability distributions of radiation doses from different exposure pathways at distances beyond 20 km from the power plant. Different release magnitudes are used. Weather data covers winding trajectory data for one year. Finally, the calculated dose estimates are compared with the threshold values given in the recommendations of IAEA and then necessity of the countermeasures can be elucidated and concluded.

2. Protection measures for the population

2.1 Time phases and countermeasures of an accident

The Guides of STUK define about countermeasures and operation in emergency planning. In short Table 2.1 lists different environmental countermeasures for the three time phases [STUK 2012a and 2012b]. A protective measure can be combination of different countermeasures (e.g. simultaneous sheltering, iodine tablet and access control).

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

The VAL Guides of STUK 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.

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.

2.2 Distance concept and protective measures

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 (Cs-137 release reduced to 100 TBq), 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].

2.3 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 of the population from the protection zone. 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.

2.4 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 context of CASA is to evaluate with the VALMA model whether in the case of a severe accident release there would be need for countermeasures outside the preparedness zone of 20 km. There could be weather conditions in which radioactive material could spread outside emergency planning zone causing there small individual doses, but possibly remarkable collective dose. 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]. Although deterministic effects are not expected at longer distances, countermeasures there could reduce the risk of stochastic effects.

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, EPD) the purpose is to identify areas within a period of time that would be effective in reducing the risk of stochastic effects by taking protective actions and other response actions within a day to a week or to a few weeks following a release (see table 2 below from IAEA 2015, Appendix 2). Width of the EPD is studied later on herein.

In the second new zone (ingestion and commodities planning zone, ICPD) the purpose is to identify if there is need to take response actions (1) for protecting the food chain and water supply 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 2015, Appendix 2]. Width of the ICPD is studied in the future studies.

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 2015].

Table 3.1. Generic criteria for protective actions and other response actions in an emergency to reduce the risk of stochastic effects [IAEA 2015].(appreviated)

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; prevention of inadvertent ingestion; restrictions on food, milk and drinking water and restrictions on the food chain and water supply; restrictions on commodities other than food; contamination control; decontamination; registration; reassurance of the public
Projected dose that exceeds the following generic criteria: Take early protective actions and other response actions		
E	100 mSv in the first year	Temporary relocation; prevention of inadvertent ingestion; restrictions on food, milk and drinking water and restrictions on the food chain and water supply; restrictions on commodities other than food; contamination control; decontamination; registration; reassurance of the public
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	Health screening based on equivalent doses to specific radiosensitive organs (as a basis for longer term medical follow-up), registration, 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 2015]. (appreviated)

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	Restrict consumption, distribution and sale of non-essential food, milk and drinking water and restrict the use and distribution of other commodities. Replace essential food, milk and drinking water as soon as possible or relocate the people affected if replacements are not available. Estimate the doses of those who might have consumed food, milk and drinking water or used other commodities to determine whether this may have resulted in doses warranting medical attention in accordance with Table 3.1.

Figure 3.1 illustrates the circular rings around a nuclear power plant. These rings represent the distances 15, 20, 50, 100, 200 and 300 km, where doses are calculated. Actually these rings consist of points on the circle. This means that every time when the plume is crossing the ring, the corresponding point dose value is written in the data file. Using several rings for the results helps to create better insight of the dose behaviour in the calculation area. For example Helsinki and Stockholm are situated clos to the ring of 200 km.

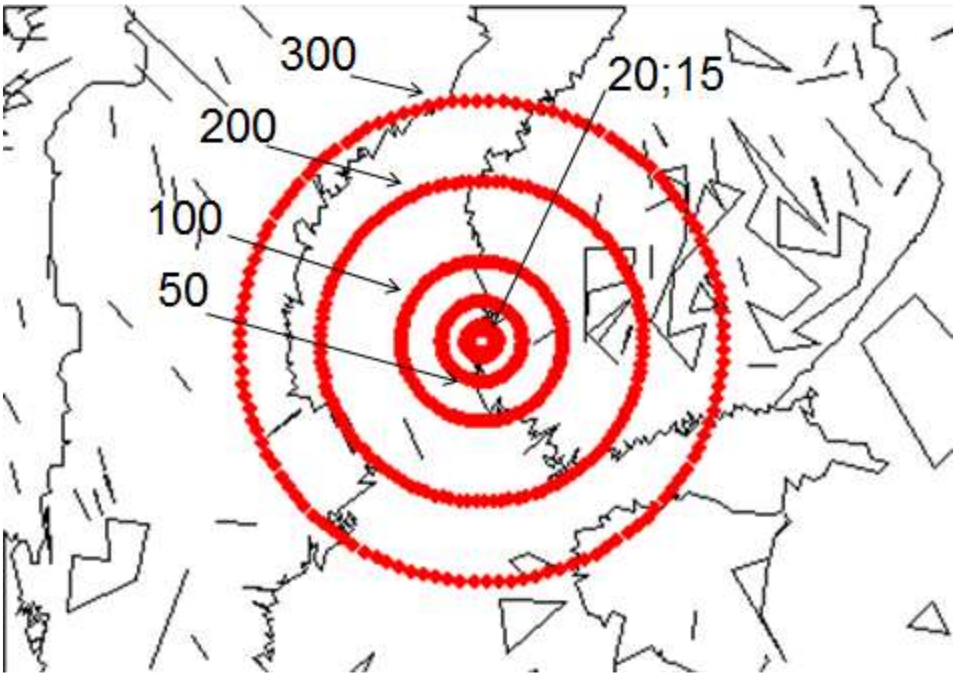


Figure 3.1. Graph of the calculation distances around the nuclear power plant. Ring 1 corresponds to 15 km,ring 2 to 20 km, ring 3 to 50 km, etc.

On each ring there are 120 calculation points (3° lateral spacing) given in the geographical coordinates (lat, lon) and the dose values are calculated at the point when the plume parts cover the point.

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 to calculate the dose at the rings and especially at the distances of:

- 20 to 100 km: to study if the dose level of 100 mSv is exceeded in a week or in a year
- 100 to 300 km: 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 2015].

4. VALMA model for the evaluation

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 days. Furthermore, it is possible that the best existing weather data from FMI cannot be received due to e.g. increased web traffic. The weather data is produced by FMI (Finnish Meteorological Institute) with Monte Carlo particles (even a limited number) that can be calculated, based on NWP (numerical weather prediction) models, with the SILAM dispersion model. Another option is the weather mast data. 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 receives from SILAM or computes by itself from mast data 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 a Eulerian dispersion model, VALMA uses a grid only to represent and accumulate the result quantities, not for calculating them.

For the current task a probabilistic approach was needed and the VALMA model had to be extended to enable processing of numerous weather conditions from the trajectory data of one year. The extension is technical (does not affect physical models).

4.1 Weather data

The weather data was provided by FMI. The data consists of the air parcel trajectories (no mass) of the year 2012 based on the numerical weather predictions of ECMWF (The European Centre for Medium-Range Weather Forecasts). The data covers the grid area of 1000*1200 km (56.8137...65.6583N, 10.7129...32.1711E). The calculation resolution of the ECMWF data was 16 km. There are 20 trajectories in every 12 minutes resulting in the 100 trajectories in one hour. The total number of the trajectories is 878400 (2012 was leap year). Trajectory is followed for 96 hours if not leaving the calculation area. The release point is Olkiluoto and the release height of the trajectories was 0-200 m. For the current calculations the trajectories starting between the altitudes of 80 and 120 m were sampled for the calculations. This corresponds to the height of the ventilation stack from which the release was assumed to occur. For the future work, other release heights should be used, too.

4.2 Exposure pathways

There are three exposure pathways considered in this study: direct external radiation from the radioactive cloud, direct external radiation from fallout and internal exposure from a radioactive material through inhalation. Ingestion pathway is not included. The inhalation dose caused by dry matter dusting in the air (resuspension) 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 the 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, can be determined. The calculation criterion assumes that the following protection factors due to shielding by buildings etc. 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 value of 0.3 was used in ARANO calculations. In VALMA calculations the value of 1.0 was used for the dose combination pathway 4 (outdoors) and the value of 0.5 (shielding) for the dose combination pathway 5. This explains partly why VALMA shows higher doses.

The total durations examined for the exposure are one week (step 190) and one year (step 191).

3) Internal radiation dose through inhalation

The protection factor is 1, i.e. no protection is assumed to exist. Inhalation rate is 22.2 m^3/24 h in ARANO and 21 m^3/24 h in VALMA [ICRP 1995]. The inhalation dose factors are from [STUK 1999].

4.3 Source terms

Three alternative release categories of severe accident source terms are considered [STUK 2013a]. 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 80…120 m. This means that the trajectories starting at the altitude between 80…120 m are picked by VALMA for the calculation. Table 4.1 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 4.1. Inventory and releases of the OL3 reactor for the nuclides used here (TVO 2004). Releases shall be corrected by chain decay 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

5. Results calculated by VALMA

5.1 VALMA output example by User Interface

Initially VALMA was tailored for emergency preparedness use. In the following two examples of its functions and output properties are shown (Fig. 5.1). The examples show the basic output on the map. The purpose was to indicate (as single and not necessarily representative examples) the behaviour of the plume in two different dispersion conditions. There exist 31 output quantities, but here only one of them (total dose) is visualized. Two different sets of trajectory data are used. Source term is that of the severe accident used in this study (Case 1).

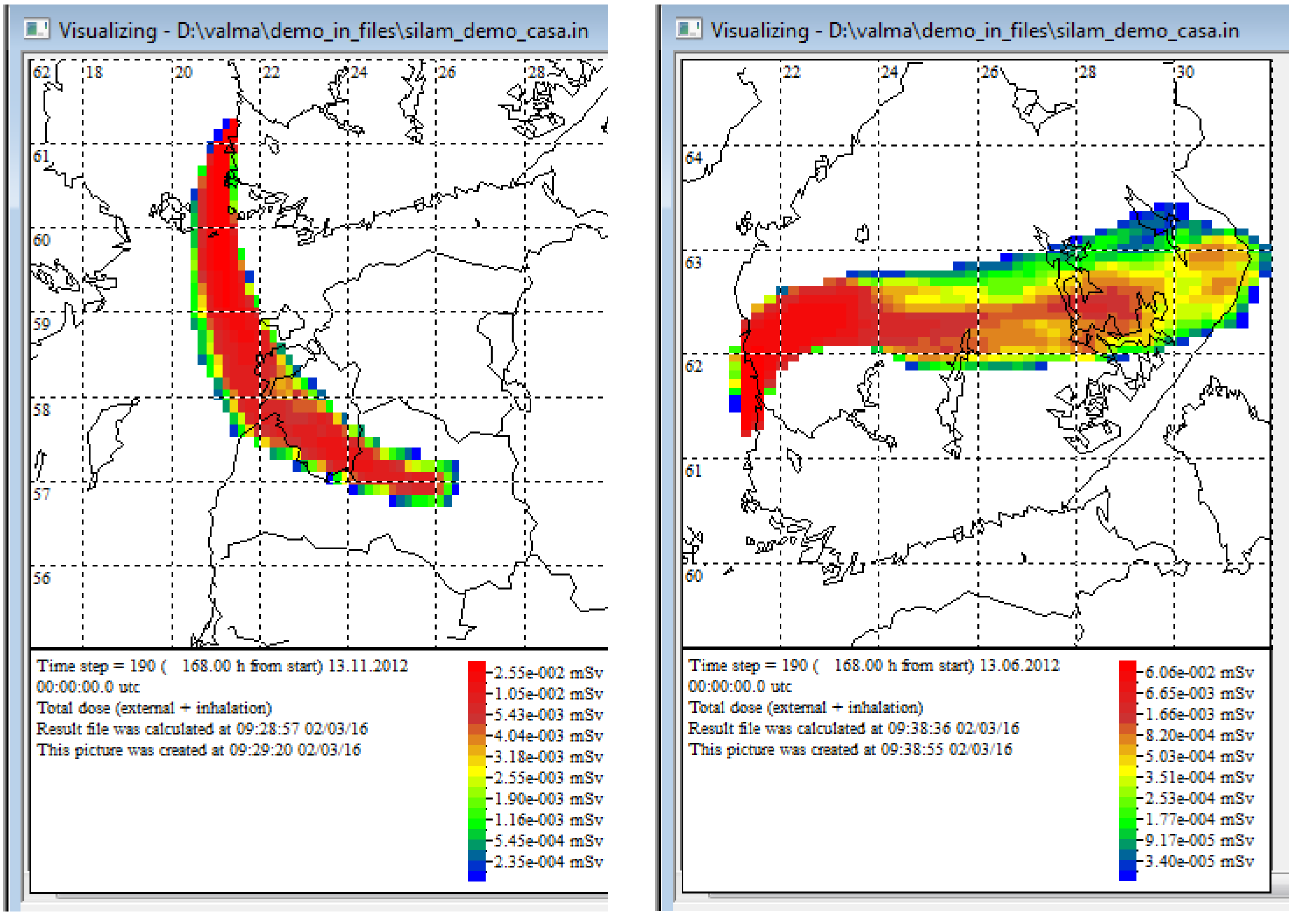


Figure 5.1 Examples of the VALMA GUI outputs. Total dose in one week is presented with two different release starting times.

Figure 5.1 illustrates the areas affected by the plume on the map. Figures indicate how the prevailing wind fields affect the plume dispersion. This also depicts that in the case of a large number of releases, there is always a single dispersion case as the basis of the resul data. These kinds of pictures are not needed when a large number of weather cases are calculated as is the case in CASA.

5.2 Trajectory data

Trajectory data of June 2012 is illustrated in Figure 5.2. The results are calculated at the points on the rings. There are 120 smoothly (3° lateral spacing) distributed geographical points on each ring. The number of the affected points at the rings of 15, 20, 50, 100, 200 and 300 km (ring 6) are shown.

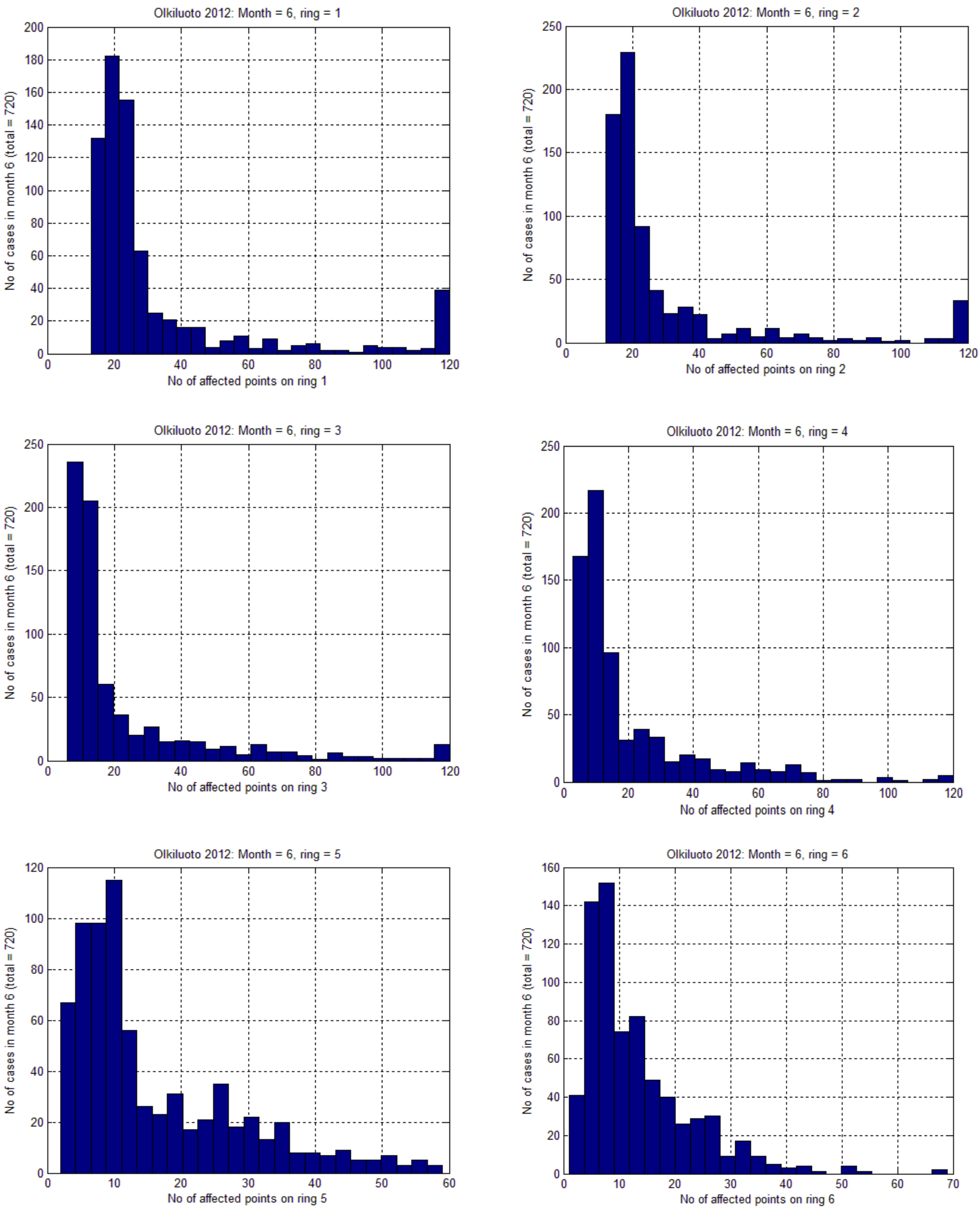


Figure 5.2. Number of affected points at the rings shown in Fig 3.1 is depicted. Based on the trajectory data in June and the release starting every hour (total 720) followed 96 hours.The points are located at 3° lateral spacing. Total lateral spread was most typically 30°-60°. Note the scale of x-axis varies.

Figure 5.2 indicates that at the shortest distance the number of the affected points is mostly less than 30. When the distance is expanded the number of affected points is reduced. Also the number of cases with very few affected points is increased. Because one point corresponds to 3 degrees, the figures indicate roughly the plume spread. For example 20 affected points corresponds to the spreading angle of 60 degrees. Reduction with distance may be numerical artifact, resulting from VALMA shifting to wind field dominated spread.

5.3 Preliminary results by ARANO for comparison

In 2014 preliminary results were calculated by the ARANO model. Here some results are represented to indicate findings and facilitate comparisons.

Figure 5.3 presents the dose components as a function of distance, in addition the projected dose for one year integration time is presented.

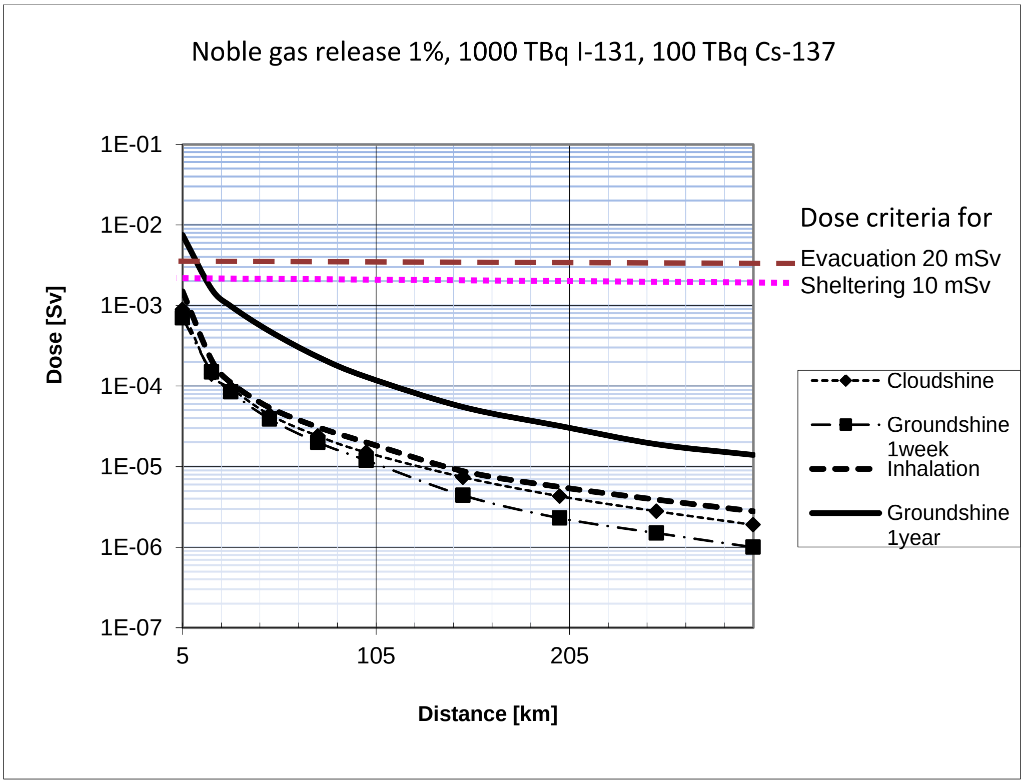


Figure 5.3. ARANO - The dose components, 95% fractiles as a function of distance from the power plant. Weather mast data covers the years from 2009 to 2013. Release case 1, one year integration time of external radiation from the ground is added. [Rossi, Ilvonen 2015].

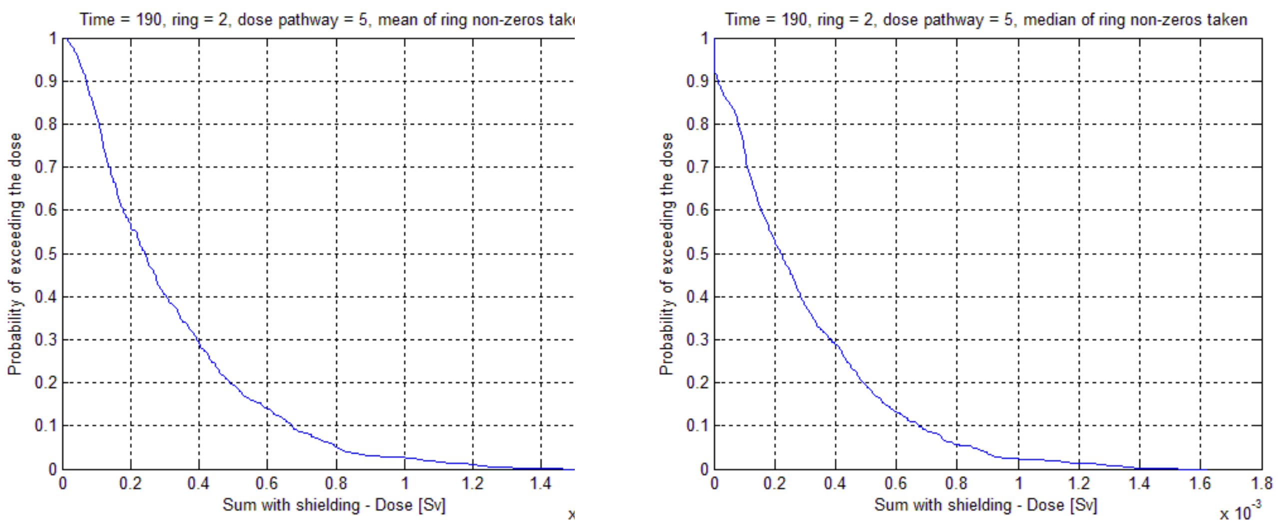
Here the value representing the dose is based on the mean value in the dispersion sector (30 degrees) and the 95% percentiles are picked into the figure. The dose below which 95% of the cases are. Figure 5.3 illustrates contributions from different exposure pathways. Groundshine is less significant if short-term period (1 week) is considered but the most significant if one year dose is calculated. If the doses are compared to the dose criteria of STUK for countermeasures, it is found that due to the release of the basic severe accident there is no need for early protective measures beyond 20 km.

5.4 VALMA results – Trajectory data of June 2012

Running time of VALMA with one month trajectory data depends on the machine and extent of trajectory data and number of trajectories used per case. Execution times proved to be from 10 hours to 26 hours. Difference between months may be several hours. The results presented here are compiled from a larger material consisting of the VALMA outputs. Here the starting point is the point_res.x file of VALMA output. X is the run number and is the starting hour within the month, too. This file includes the normal VALMA output for the geographical coordinates called also measurement points and are specified for the six rings as described before. For example in the case of June there will be 720 point_res.x files. The total size of these monthly output files is about 4 GB.

The next step is to pick up the results for the time points of one week and one year which best correspond to the time specifications of the IAEA's recommendations. From these data different distributions, e.g. complementary cumulative density functions (ccdfs) are prepared. Because at a certain time point several measurement points at a ring may be affected, it is necessary to select in some way the quantity for the ccdf. Here three different choices were used: mean, median and maximum. The values are determined from the non-zero values on the ring. It should be noticed that the shielding factor of 0.5 for fallout was used in VALMA but the corresponding value in ARANO was 0.3.

Figure 5.4 illustrates different dose quantities at the ring of 20 km when the integration time is one week or one year. Time 190 is one week and 191 is one year. The dose combination 5 is the total dose from the external radiation from the plume and fallout (including shielding) and internal dose from inhalation.



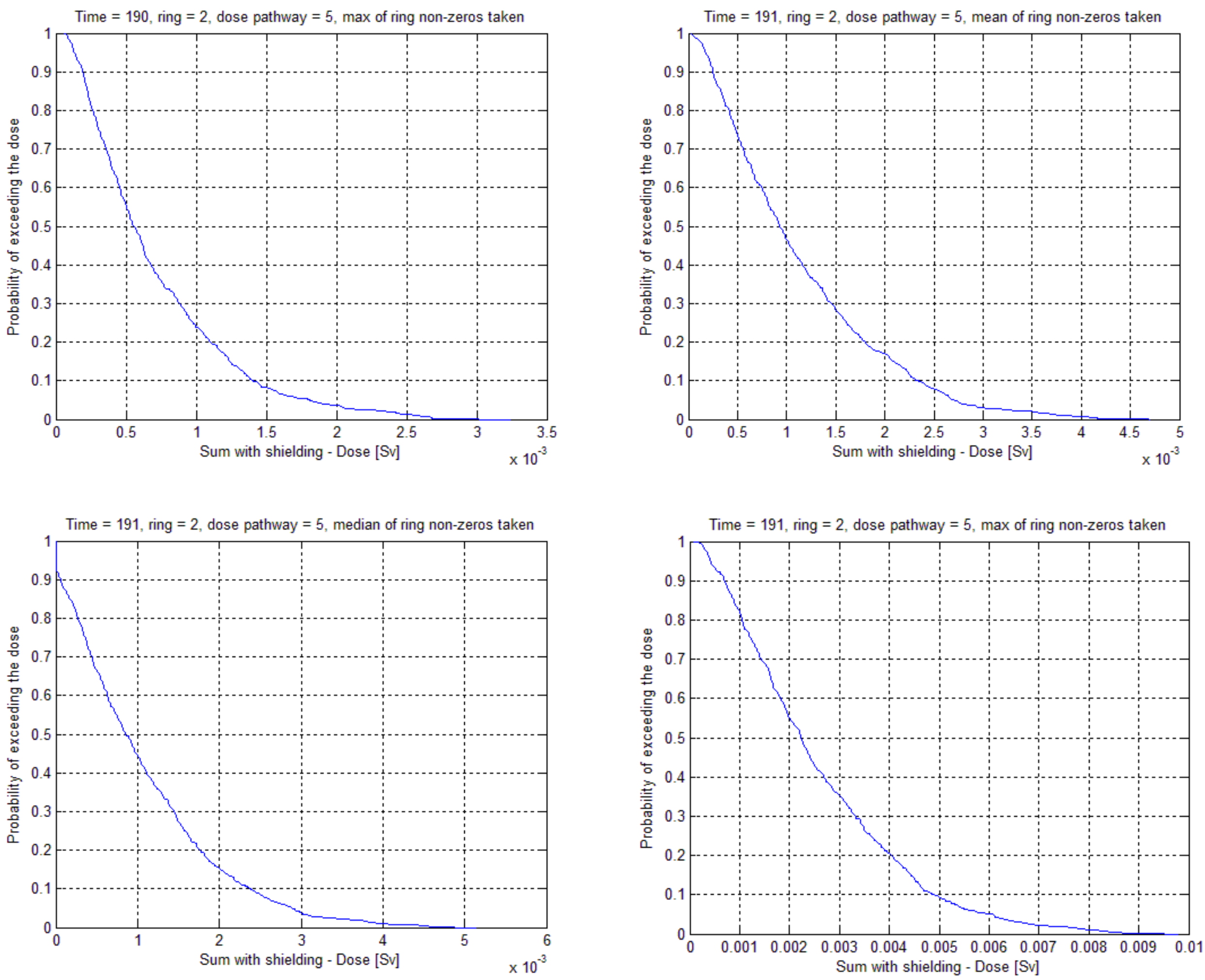


Figure 5.4. Significance of different dose statistics: mean, median and maximum. Curve for total dose, 20 km, two time integrals: 1 week (190) and 1 year (191). Trajectory data of June. Note different horizontal scales.

Figure 5.4 illustrates that difference between mean and median values is small in both time periods. Instead the maximum value is higher roughly with a factor of two. If the absolute values are studied it can be found that the values at the 95% level are 0.8 mSv in one week and 3 mSv in one year when the mean and medium values are considered. The corresponding values are 2 and 6 mSv in the case of the maximum values.

In figure 5.3 the corresponding values of ARANO (using sector mean) are 0.2 and 1 mSv. The difference is quite small, a factor of 3 for the mean value (one year).

Figure 5.5 illustrates significance of the dose components at the distance of 100 km.

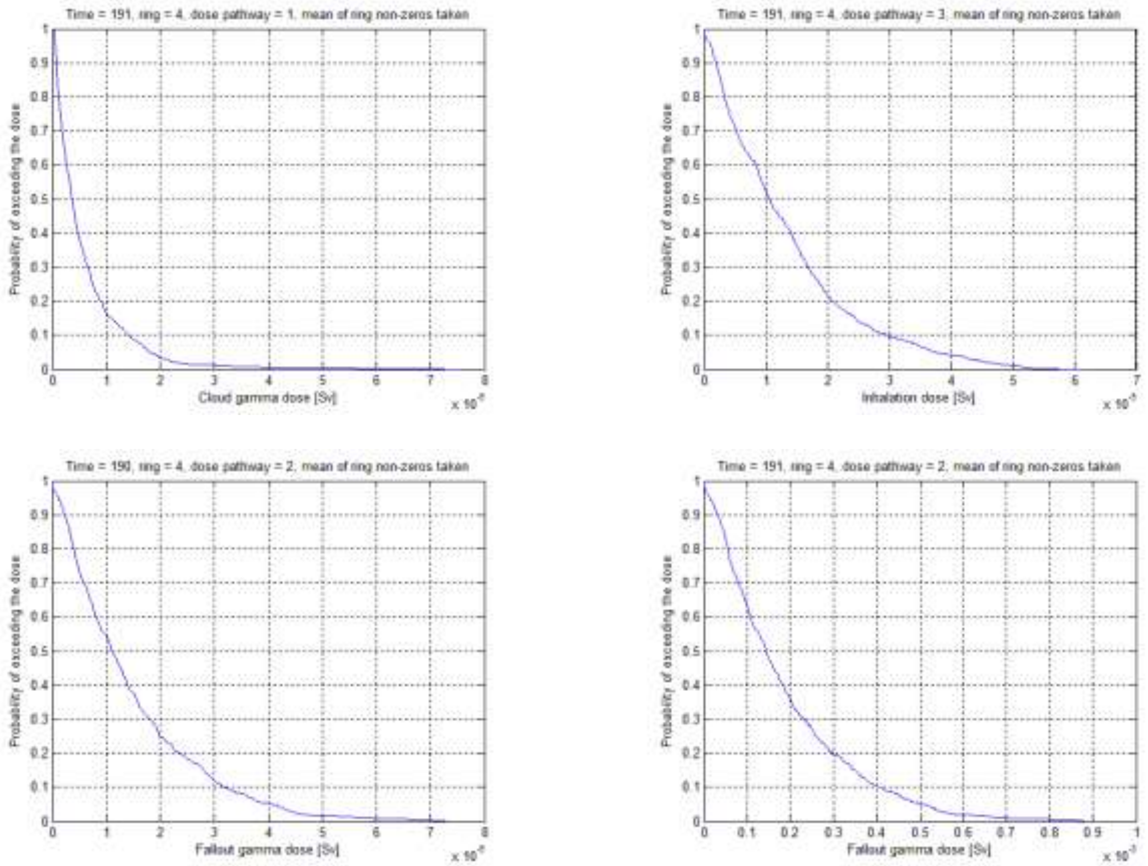


Figure 5.5. Significance of the dose components. Distance 100 km. In the upper part are cloudshine and inhalation. In the lower part there are groundshine doses with time integral of one week (190) and one year (191). Trajectory data of June.

Figure 5.5 illustrates that the doses for cloudshine and inhalation are roughly the same magnitude and also the dose from groundshine when one week integration is considered. But if groundshine dose is integrated for one year, the groundshine dose is roughly tenfold without shielding. If the shielding factor of 0.5 for groundshine is used, the groundshine dose is larger with a factor of 5.

Figure 5.6 illustrates the total dose at six rings assuming one week integration time. The ccdf of the mean value of affected points is presented. Shielding factor for groundshine is included.

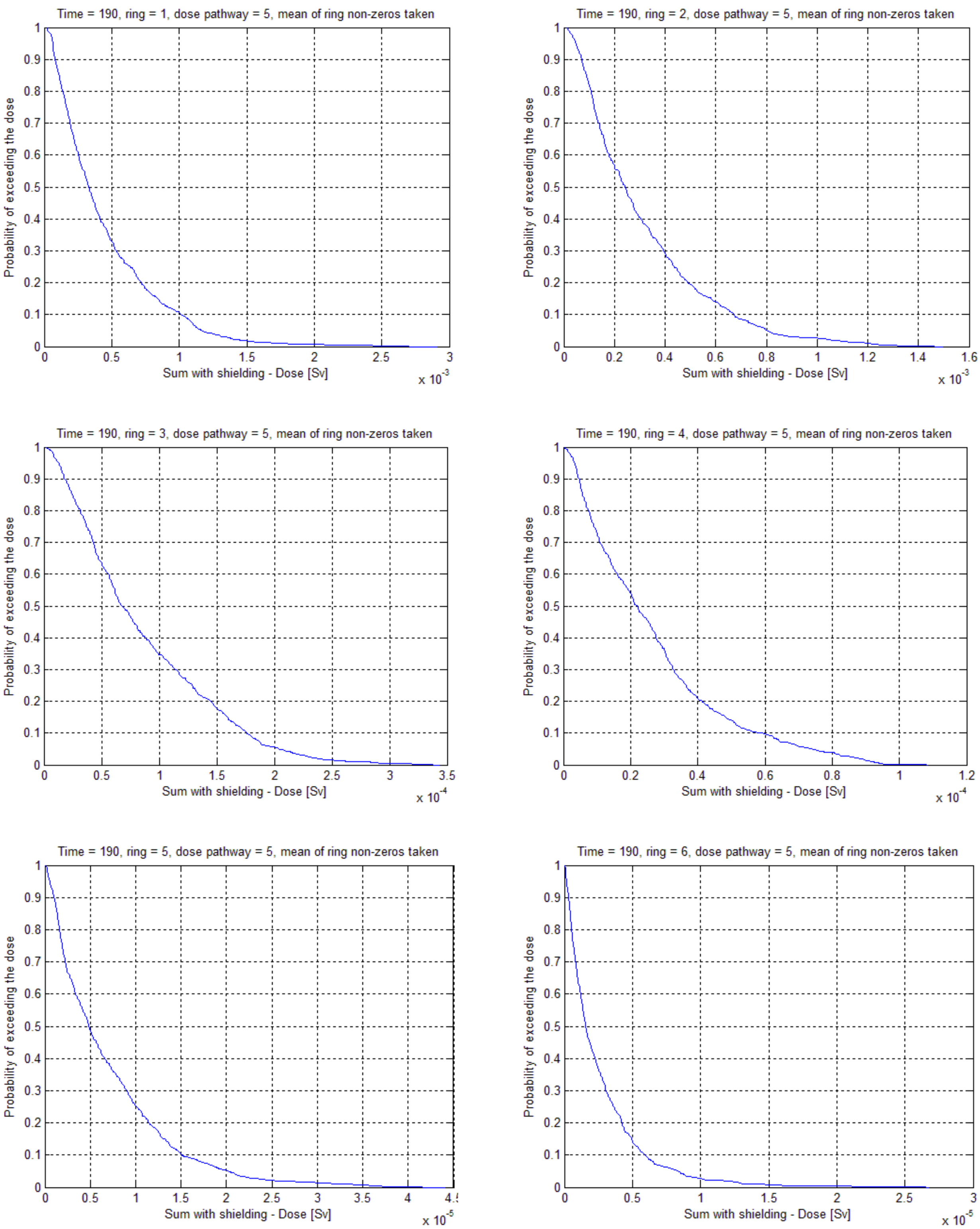


Figure 5.6. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 week (190). Trajectory data of June.

Figure 5.6 illustrates that when the distance increases the dose correspondingly decreases monotonically. The 95% percentile mean values (= 5% probability of exceeding) at the distances of the rings are: 1.2, 0.8, 0.2, 0.07, 0.02 and 0.008 mSv. Compared to the ARANO results in figure 5.3, VALMA's doses are higher with the factor of two. This can be understood better if figure 7.1 is studied in [Rossi, Ilvonen 2015].

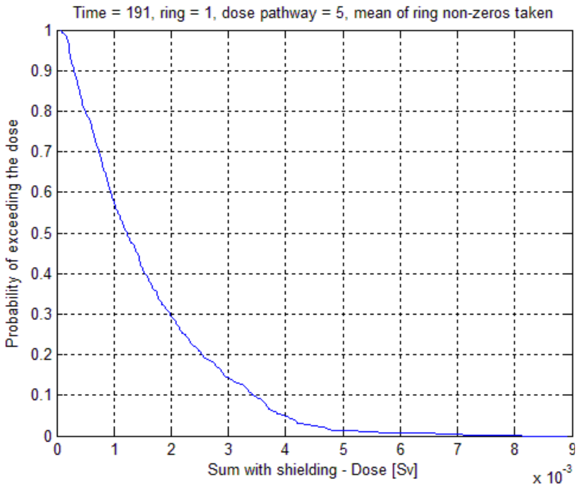
Table 5.1 shows the 95% percentile values picked from the figure 5.6.

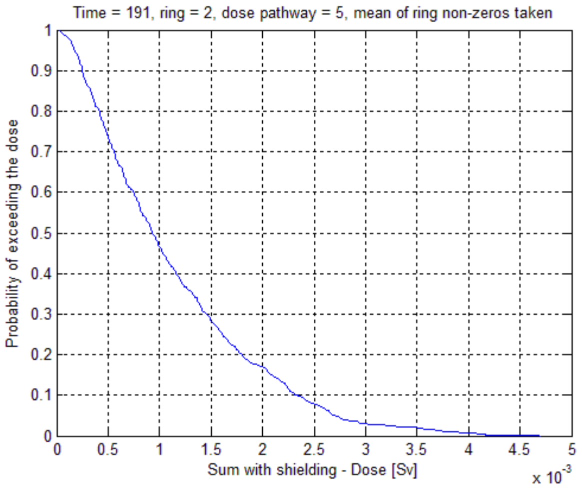
Table 5.1. Total dose [mSv] at six distances, 95% percentile. Time integral of 1 week. Trajectory data of June.VALMA results and ARANO comparison.

Distance [km]	**Mean**	**Median**	**Maximum**	**ARANO(mean)**
15	1.2	1.3	2.5	0.9
20	0.8	0.8	1.7	0.6
50	0.2	0.2	0.5	0.1
100	0.07	0.07	0.2	0.04
200	0.02	0.02	0.05	0.01
300	0.008	0.007	0.02	0.005

The maximum value is about twofold compared with the mean and median values in VALMA. The mean value provided by ARANO is roughly less or equal to half of the mean and median values of VALMA.

Figure 5.7 illustrates the total dose at six rings assuming one year integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.





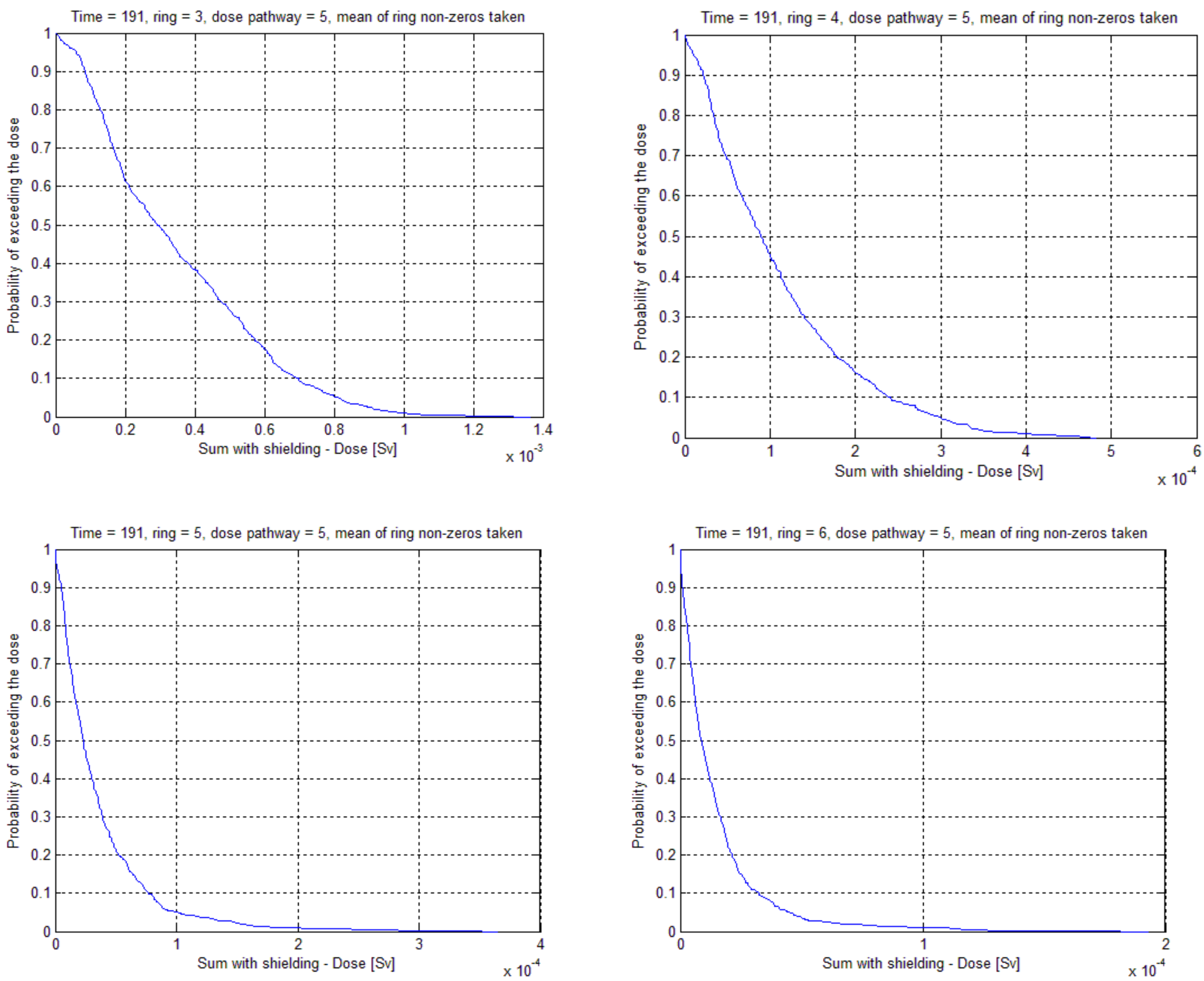


Figure 5.7. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 year (191). Trajectory data of June.

Figure 5.7 again illustrates that when the distance increases the dose correspondingly decreases monotonically. The 95% values at the distances of the rings are: 4, 2, 0.8, 0.3, 0.1 and 0.05 mSv. Compared to the ARANO results in figure 5.3, VALMA's doses are now with the factor of three higher. Groundshine dose is the most important component due to longer exposure time and lesser shielding used in VALMA results in higher dose value. If the ratio of the shielding factors (0.3/0.5 = 0.6) in VALMA and ARANO is taken into account, the difference in the total dose is about a factor of 2.

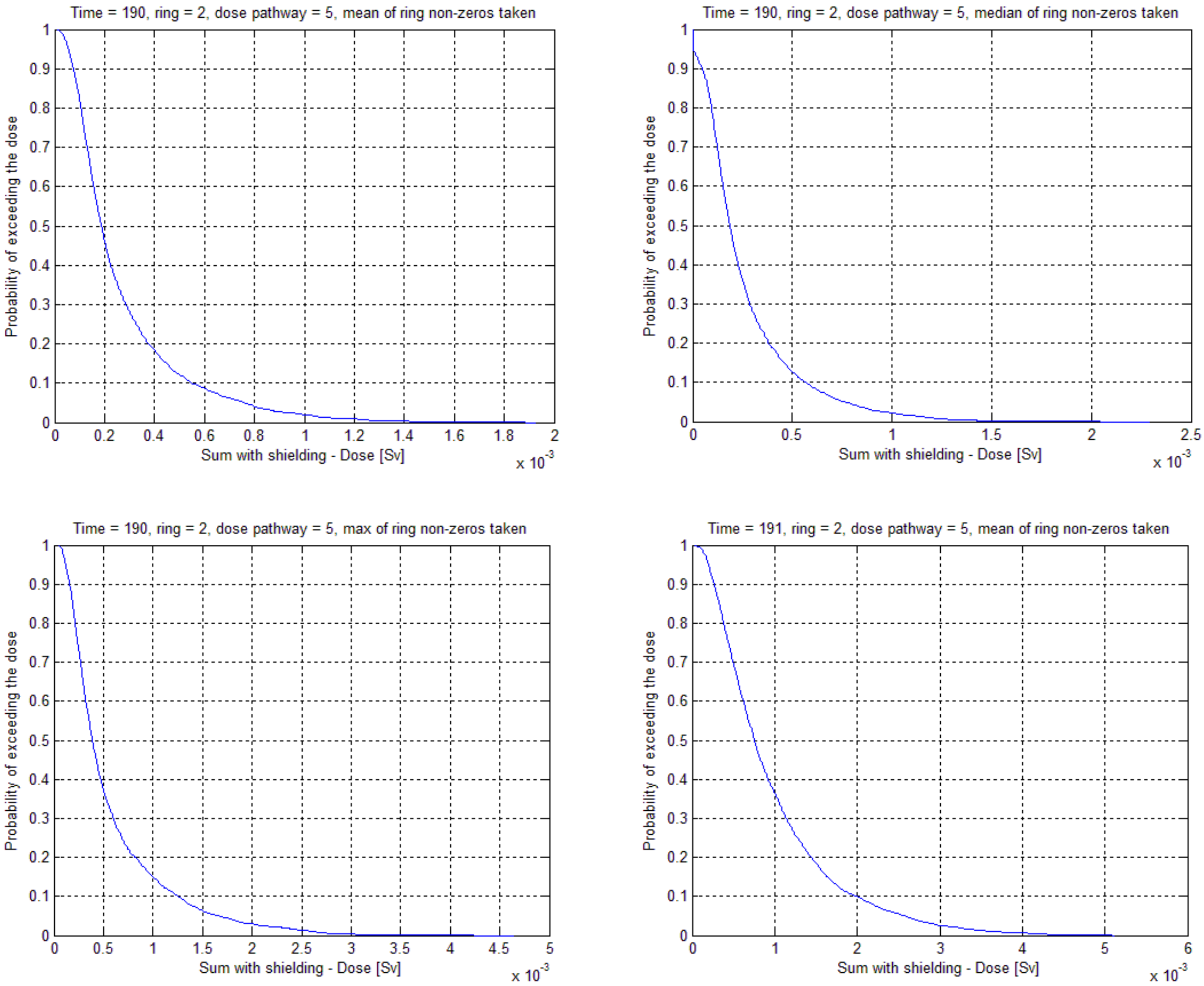
As a conclusion from these preliminary calculations for one month trajectory data (June 2012) it is shown that the release specified for the severe accident (case 1) results in small doses. In addition VALMA calculates higher doses than ARANO but difference is not outstandingly large; here a factor of two was found.

5.5 VALMA results – Trajectory data representing four seasons in year 2012

Due to restricted recources in 2014 (and time spent for modifications) instead of 12 months trajectory data only 4 months were first taken into account. This means that the trajectory data of March, June, September and December are compiled to represent the whole year. The idea is that possibly and hopefully a sample from each season may sufficiently help in generation of results covering different dispersion conditions during a year.

The source term is again Case1 (Table 3.1), so the results are comparable with the results calculated for June in the previous chapters. Based on this assumption a conclusion can be drawn how the results calculated for June represent the results for the whole year. Later in this report we calculate results from more severe releases using only the weather data of June.

Figure 5.8 illustrates different dose quantities at the ring of 20 km when the integration time is one week or one year. Time 190 is one week and 191 is one year. The dose pathway 5 is the total dose from the external radiation from the plume and fallout (including shielding) and internal dose from inhalation.



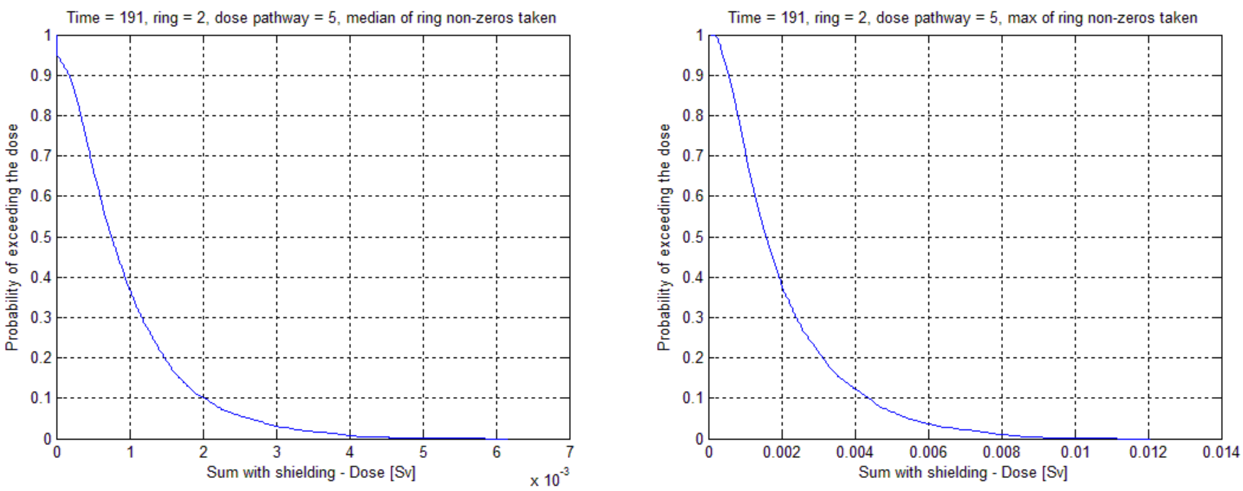
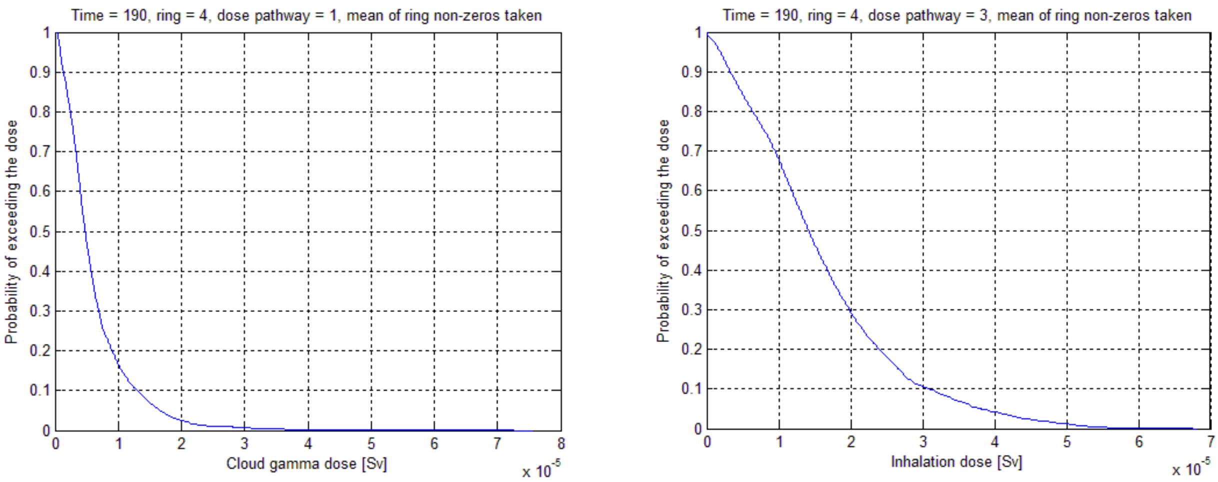


Figure 5.8. Significance of different dose statistics: mean, median and maximum. Curve for total dose, 20 km, two time integrals: 1 week (190) and 1 year (191).

Figure 5.8 (4 seasons) can be compared with Figure 5.4 (June only). Differences in curves seem to be quite small when the 95% percentiles are considered.

Figure 5.9 illustrates significance of the dose components at the distance of 100 km.



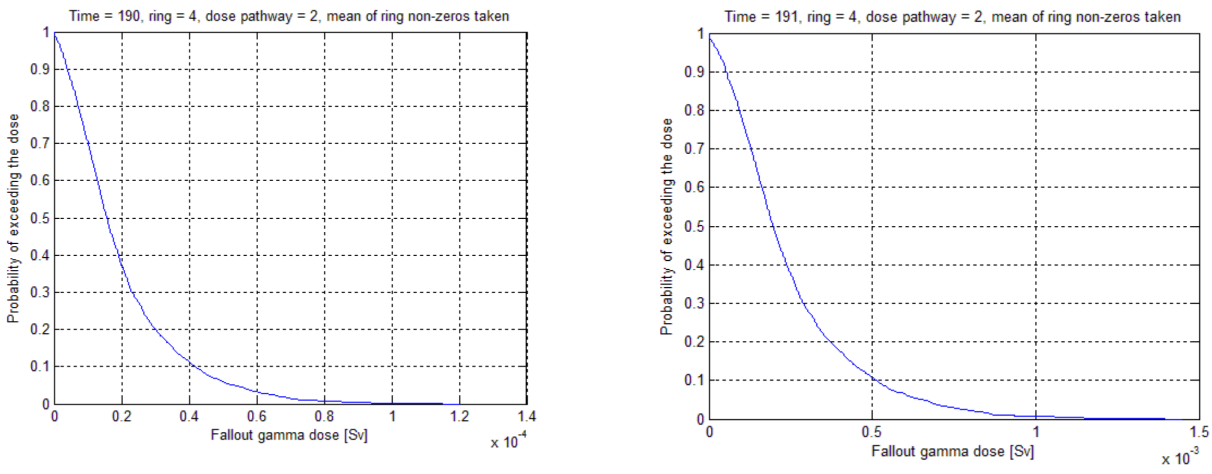
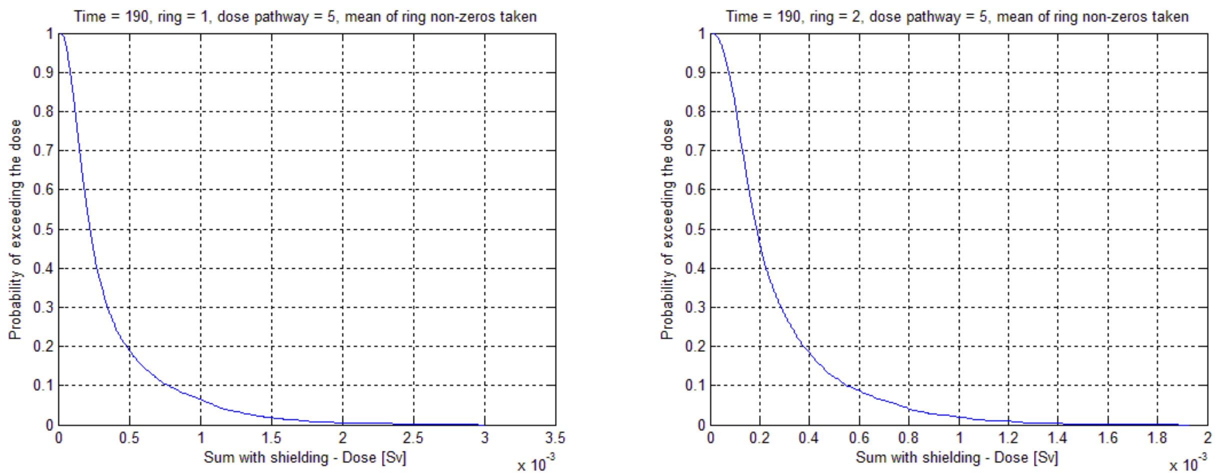


Figure 5.9. Significance of the dose components. Distance 100 km. In the upper part are cloudshine(1) and inhalation(3). In the lower part are groundshine doses(2) with time integral of one week (190) and one year (191).

Figure 5.9 can be compared with Figure 5.5. There are some differences in curves but at the 95% percentile differences in curves of the cloud gamma and inhalation doses seem to be quite small. In the case of fallout gamma the dose of June is 20% smaller than the dose based on four month's weather data at the 95% percentile.

Figure 5.10 illustrates the total dose at six rings assuming one week integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.



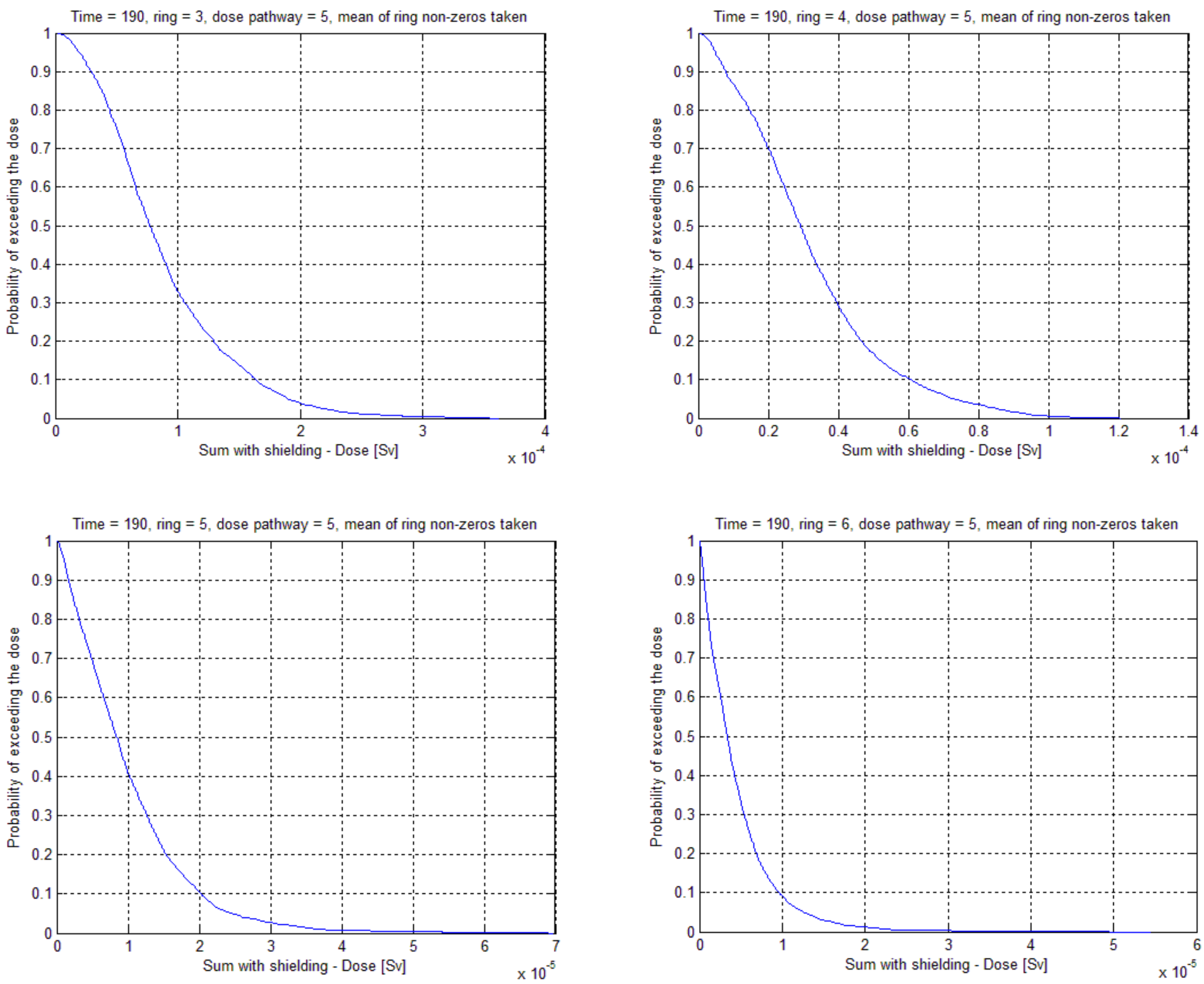


Figure 5.10. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 week (190).

Figure 5.10 (4 seasons) can be compared with Figure 5.6 (June only). There are some differences in the forms of the curves but at the 95% percentile differences in curves seem to be quite small. At the larger distances of 200 and 300 km the dose of June (95%) is about half of the dose based on the four month weather.

Figure 5.11 illustrates the total dose at six rings assuming one year integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.

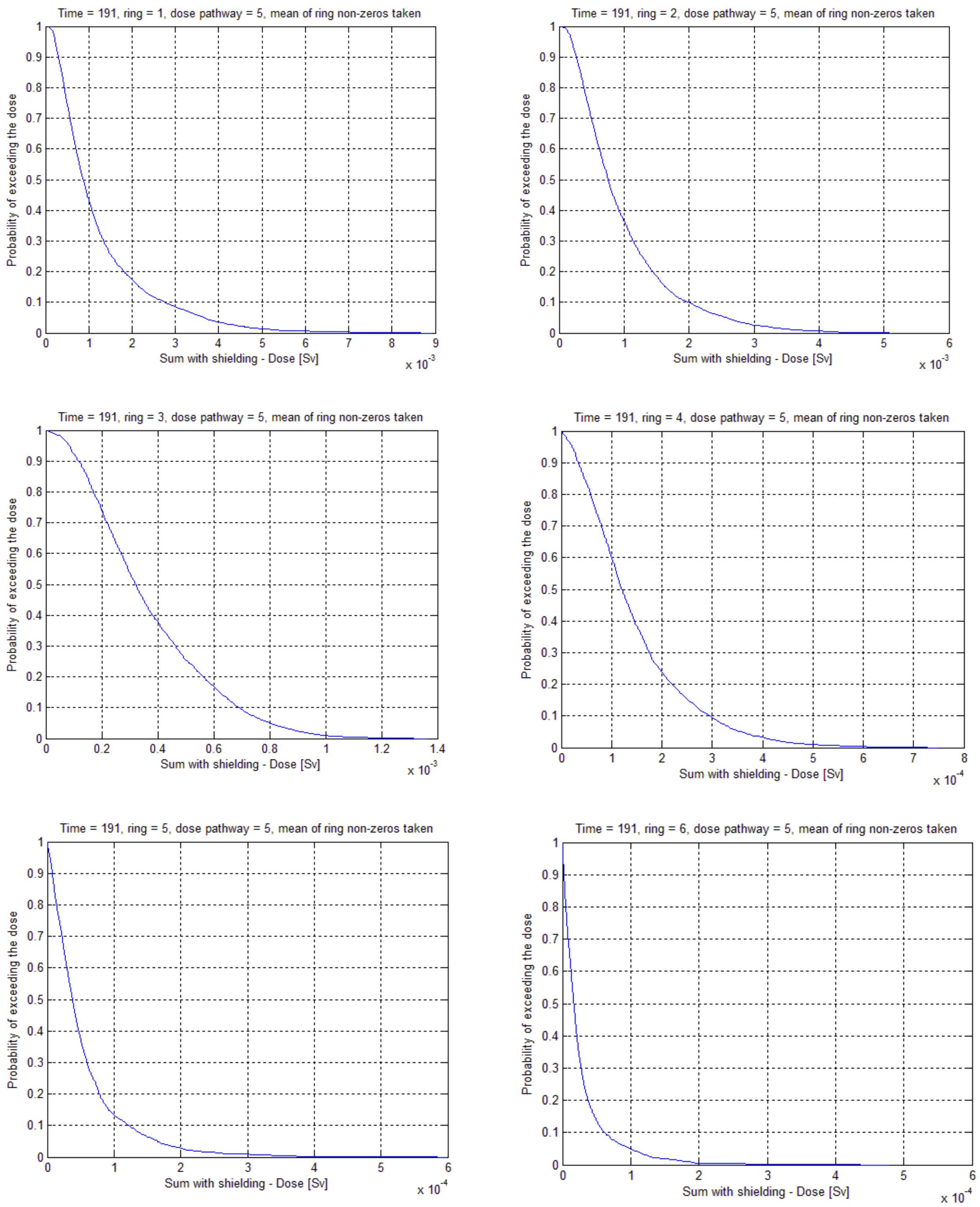


Figure 5.11. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 year (191).

Figure 5.11 (4 seasons) can be compared with Figure 5.7(June only). There are some differences in the forms of the curves but at the 95% percentile differences in curves seem to be quite small. At the larger distances of 200 and 300 km the dose (95%) of June is about half of the dose based on four month's weather data.

As a conclusion from these calculations of four month trajectory data compared to one month data it is shown that differences in doses are quite small at the 95% percentile level. However at longer distances of 200 and 300 km four month weather data results in a twofold dose. At lower percentiles differences are larger. This indicates that only preliminary rough dose estimates can be done with the trajectory data of one month. This does not exclude the possibility that by employing longer term trajectory data projected dose values might increase.

Table 5.2 shows the 95% percentile values picked from the figures.

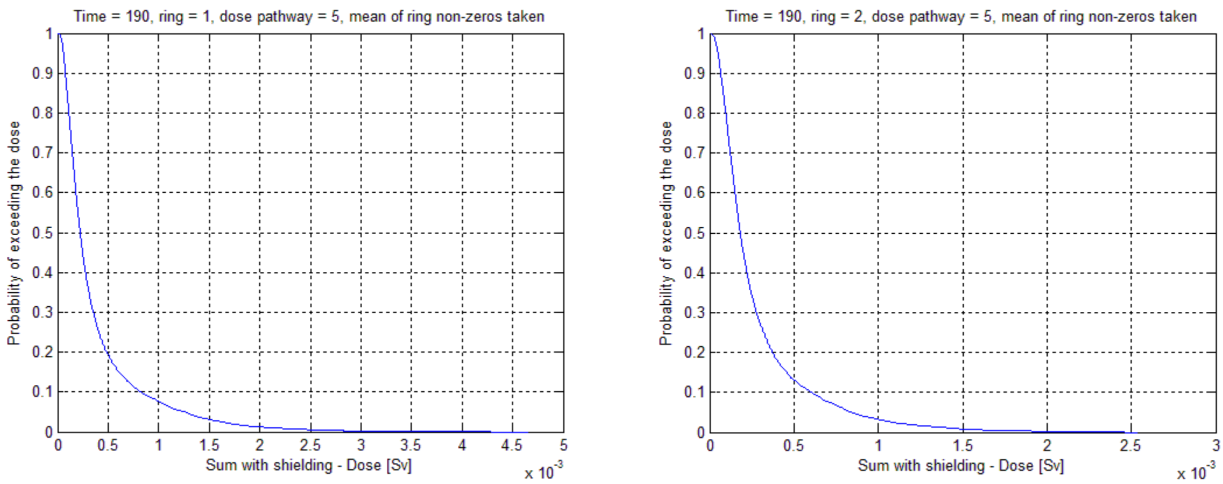
Table 5.2. Total dose [mSv] at six distances, 95% percentile. Time integral of 1 week. Trajectory data of March, June, September and December.

Distance [km]	**Mean**	**Median**	**Maximum**	**ARANO(mean)**
15	1.1	1.1	2.5	0.9
20	0.8	0.7	1.7	0.6
50	0.2	0.2	0.4	0.1
100	0.07	0.07	0.2	0.04
200	0.03	0.02	0.06	0.01
300	0.014	0.01	0.03	0.005

Doses in Table 5.2 (4 seasons) can be compared with the doses of Table 5.1(June only). With the trajectory data of four seasons there is not much difference in the doses. However worth mention is an observation that the doses at the distance of 300 km are now roughly twofold compared to the doses in Table 5.1. Another finding is that employing long-term winding weather data results in the individual dose estimate which decreases when distance increases.

5.6 VALMA results – Trajectory data of the whole year 2012

Figure 5.12 illustrates the total dose at six rings assuming one week integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.



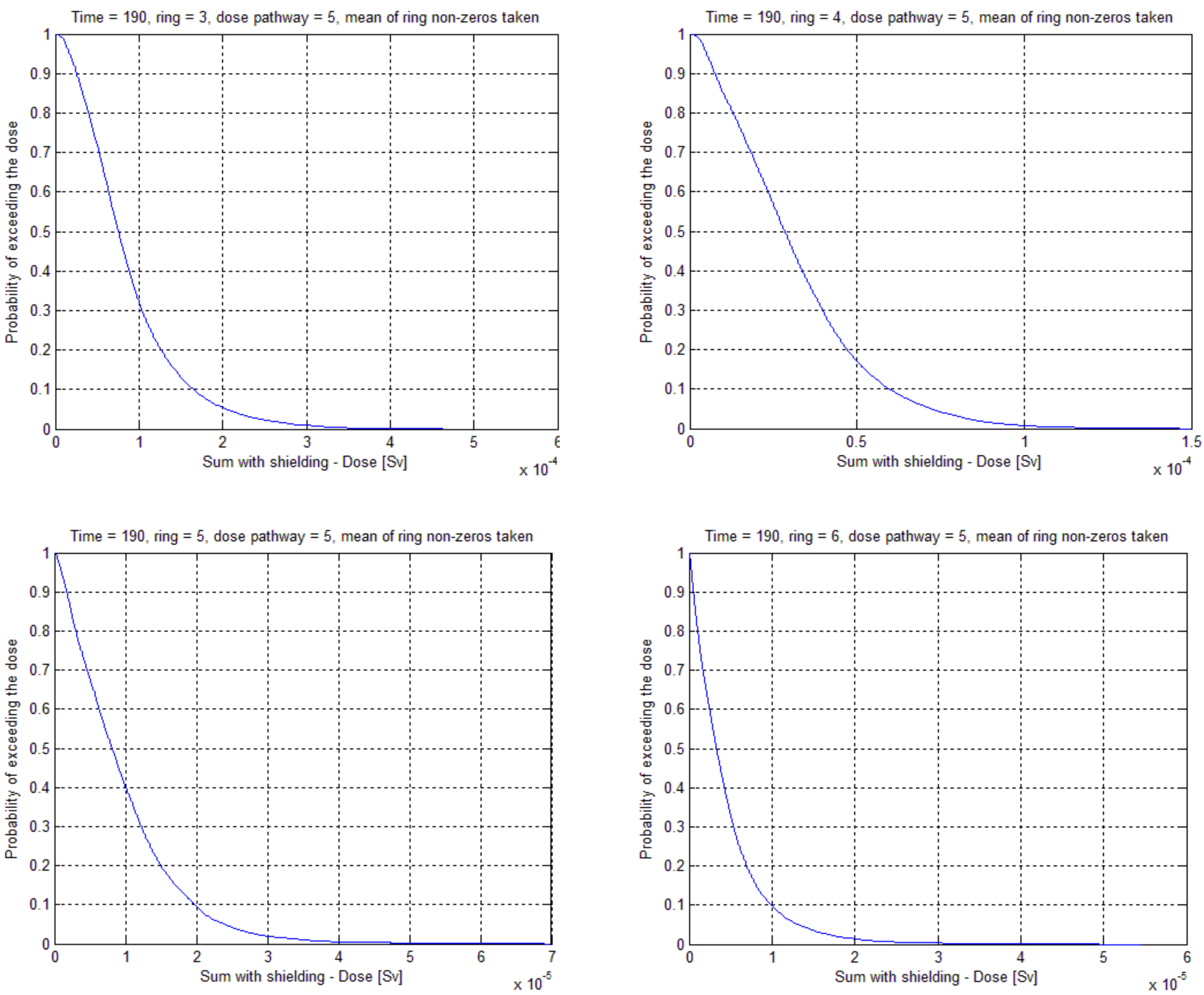


Figure 5.12. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 week (190). Trajectory data of 2012.

Figure 5.12 (12 months) can be compared with Figure 5.10 (4 seasons). There are only minor differences in the forms of the curves but at the 95% percentile differences in curves seem to be quite small.

Figure 5.13 illustrates the total dose at six rings assuming one year integration time. The ccdf of the mean value is presented. Shielsding factor for groundshine is included.

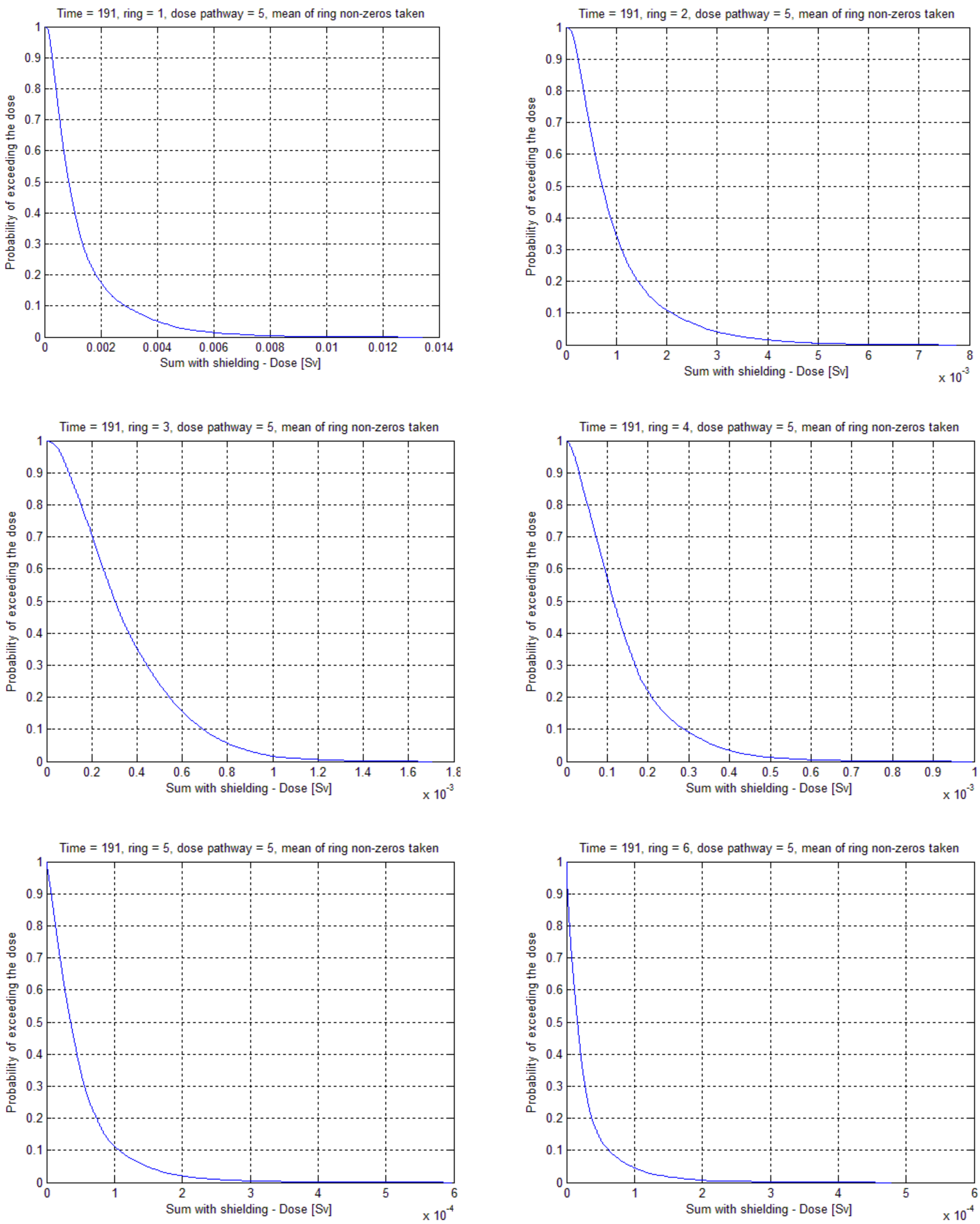


Figure 5.13. Mean value of the total dose at six distances (rings 1…6). Time integral of 1 year (191).Trajectory data of 2012.

Figure 5.13 (12 months) can be compared with Figure 5.11 (4 seasons). There are only minor differences in the forms of the curves but at the 95% percentile differences in curves seem to be quite small.

As a conclusion from the calculations of four month's trajectory data compared to the whole year data it is shown that differences in doses are quite small at the 95% percentile level.

Table 5.3 shows the 95% percentile values for a dose in one week picked from the figures.

Table 5.3. Total dose [mSv] at six distances, 95% percentile. Time integral of 1 week. Trajectory data of the four months and the whole year 2012.ARANO mast weather 2009…2013.

	Trajectory data 4 months			**Trajectory data of whole year**			
Distance [km]	**Mean**	**Median**	**Maximum**	**Mean**	**Median**	**Maximum**	**ARANO(mean)**
15	1.1	1.1	2.5	1.3	1.2	2.9	0.9
20	0.8	0.7	1.7	0.8	0.8	2.0	0.6
50	0.2	0.2	0.4	0.2	0.2	0.5	0.1
100	0.07	0.07	0.2	0.07	0.07	0.17	0.04
200	0.03	0.02	0.06	0.025	0.023	0.055	0.01
300	0.014	0.01	0.03	0.014	0.012	0.03	0.005

The dose values at the 95% percentile are quite equal in the case of mean and median values for the both trajectory data. The maximum values are two-threefold compared to the mean and median values. This means that the trajectory data of four months results in the almost equal dose values compared with the trajectory data of the whole year. The ARANO doses are roughly half of the doses of VALMA up to the distance of 100 km but at longer distances the difference is 3.

Table 5.4 shows the 95% percentile values for a dose in one year picked from the figures.

Table 5.4. Total dose [mSv] at six distances, 95% percentile. Time integral of 1 year. Trajectory data of the four months and the whole year 2012.

	Trajectory data of whole year		
Distance [km]	**Mean**	**Median**	**Maximum**
15	4	4	8
20	3	3	7
50	0.8	0.8	1.8
100	0.4	0.4	0.8
200	0.15	0.12	0.4
300	0.1	0.09	0.25

The results presented in Table 5.4 are larger than in Table 5.3 due to longer integration time of groundshine. Absolute dose values are at the level where no countermeasures are needed based on IAEA's recommendations.

5.7 Larger releases

5.7.1 Preliminary results by ARANO for comparison

Case 2

In 2014 preliminary results were calculated by the ARANO model for case 2 (Noble gases 20%, iodine + caesium 2%). Figure 5.14 is copied from the previous study and presents the dose components. In addition to cloudshine and inhalation dose, goundshine dose of one week and one year are presented.

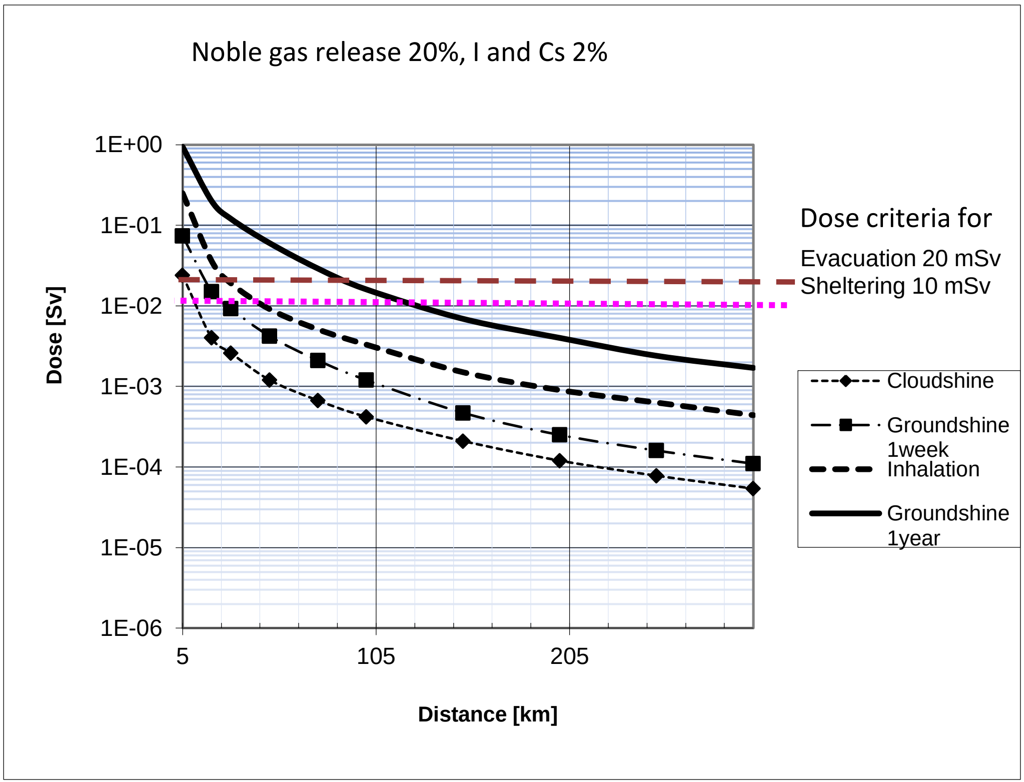


Figure 5.14. ARANO - The dose components (mean value over dispersion sector), 95% fractiles as a function of distance from the power plant. Weather data covers the years from 2009 to 2013. Release case 2. [Rossi, Ilvonen 2015].

Figure 5.14 depicts that dose from inhalation dominates in the acute phase but if exposure time is one year then external dose from the ground becomes dominating component. The IAEA dose criterion of 100 mSv is slightly exceeded beyond 20 km when the one year dose is considered, but not if one week's dose is considered.

Case 3

In 2014 preliminary results were calculated by the ARANO model for case 3 (Noble gases 100%, iodine + caesium 20%). Figure 5.15 is copied from the previous study and presents the dose components. In addition to cloudshine and inhalation dose, goundshine dose of one week and one year are presented.

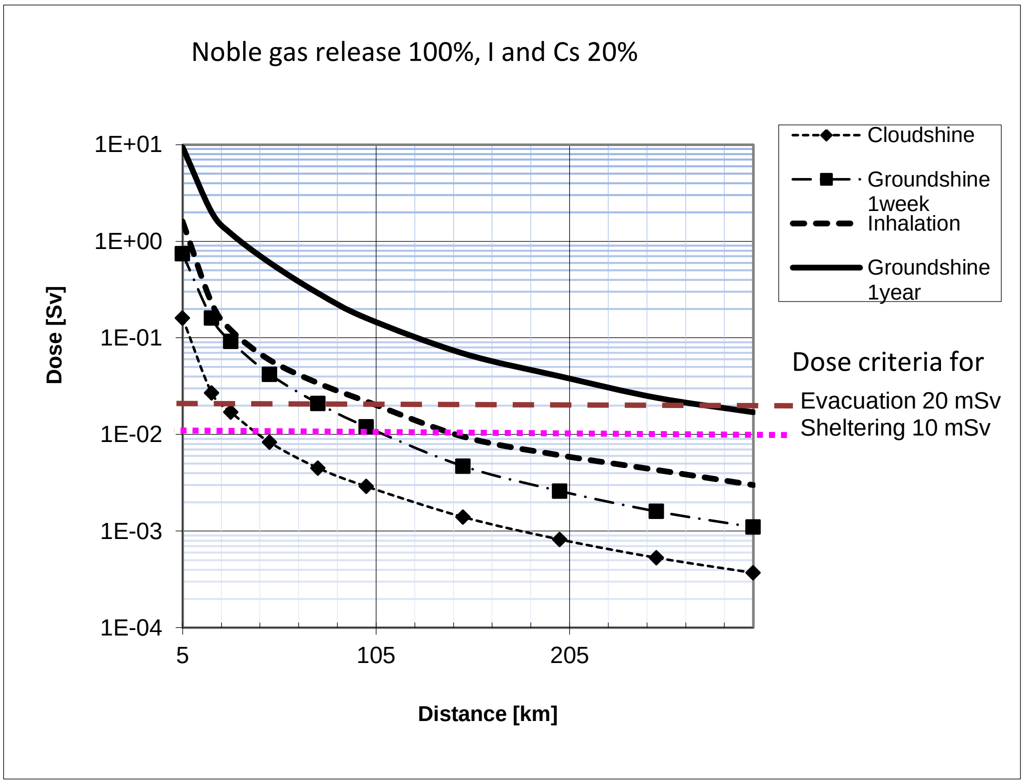


Figure 5.15. ARANO - The dose components (mean value over dispersion sector), 95% fractiles as a function of distance from the power plant. Weather data covers the years from 2009 to 2013. Release case 3. [Rossi, Ilvonen 2015].

Figure 5.15 depicts that dose from inhalation dominates in the acute phase but if exposure time is one year then external dose from the ground becomes dominating component. The IAEA dose criterion of 100 mSv could be exceeded up to the distance of 120 km.

5.6.2 VALMA results

Case 2

Figure 5.16 illustrates the total dose at six rings assuming one week integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.

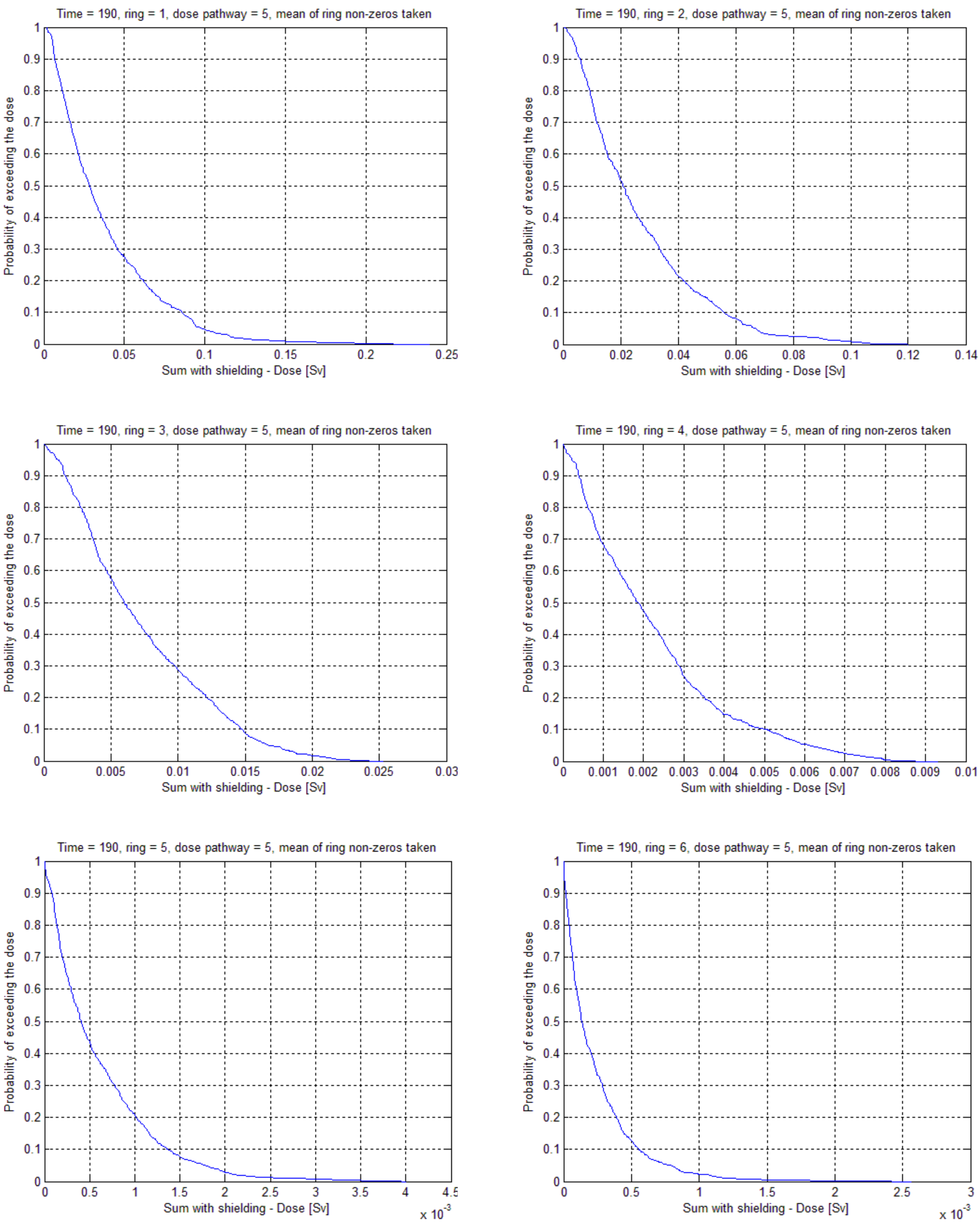


Figure 5.16. Mean value of the total dose at six distances (rings 1…6). Case 2, time integral of 1 week (190). Trajectory data of June 2012.

Figure 5.16 illustrates that when the distance increases the dose correspondingly decreases monotonically. Table 5.5 shows the 95% percentile values (= 5% probability of exceeding) picked from the results calculated by VALMA when the trajectory data of June was used, integration time of one week, source term case 2. Also ARANO results for this case are included [Rossi, Ilvonen 2015].

Table 5.5. Total dose [mSv] at six distances, 95% percentile, case 2. Time integral of 1 week. Trajectory data of June. ARANO for comparison.

Distance [km]	Mean	Median	Maximum	ARANO(mean)
15	100	110	200	50
20	70	70	150	35
50	17	16	40	9
100	6	6	14	3.5
200	2	2	4	1
300	0.7	0.6	2	0.5

Doses in Table 5.5 show that the mean and median values are almost the same, but the maximum value on the ring is twofold. The ARANO results are half of the mean and median values. If compared to the IAEA's recommendation values, only the maximum value (150 mSv) at 20 km exceeds the criterion of 100 mSv.

Table 5.6 shows the 95% percentile values picked from the VALMA figures, integration time one year, source term case 2. Also ARANO results for this case are included.

Table 5.6. Total dose [mSv] at six distances, 95% percentile, case 2. Time integral of 1 year. Trajectory data of June.

Distance [km]	Mean	Median	Maximum	ARANO(mean)
15	450	450	900	300
20	300	340	700	200
50	90	90	210	60
100	35	35	80	15
200	10	10	30	4
300	5	5	15	2

The doses of Table 5.6 depict the same trend as before.The IAEA's criterion value of 100 mSv is exceeded in all results beyond 20 km and even beyond 50 km if the maximum value on the ring is used.

Based on Table 3.1 this means that in the case of type case 2 source term urgent and early protective actions and other response actions should be taken in the extended planning zone, EPD, situated outside the preparedness zone of 20 km.

As it emerged in chapter 5.5 the results based on the trajectory data of June may underestimate the dose at longer distances by a factor of two if compared to the results based on four month's trajectory data. If here the dose values of 200 and 300 km are multiplied by 2 the results remain despite below 100 mSv.

In the future it would be useful to make the calculations fot the case 2 with the whole year trajectory data.

Case 3

Figure 5.17 illustrates the total dose at six rings assuming one week integration time. The ccdf of the mean value is presented. Shielding factor for groundshine is included.

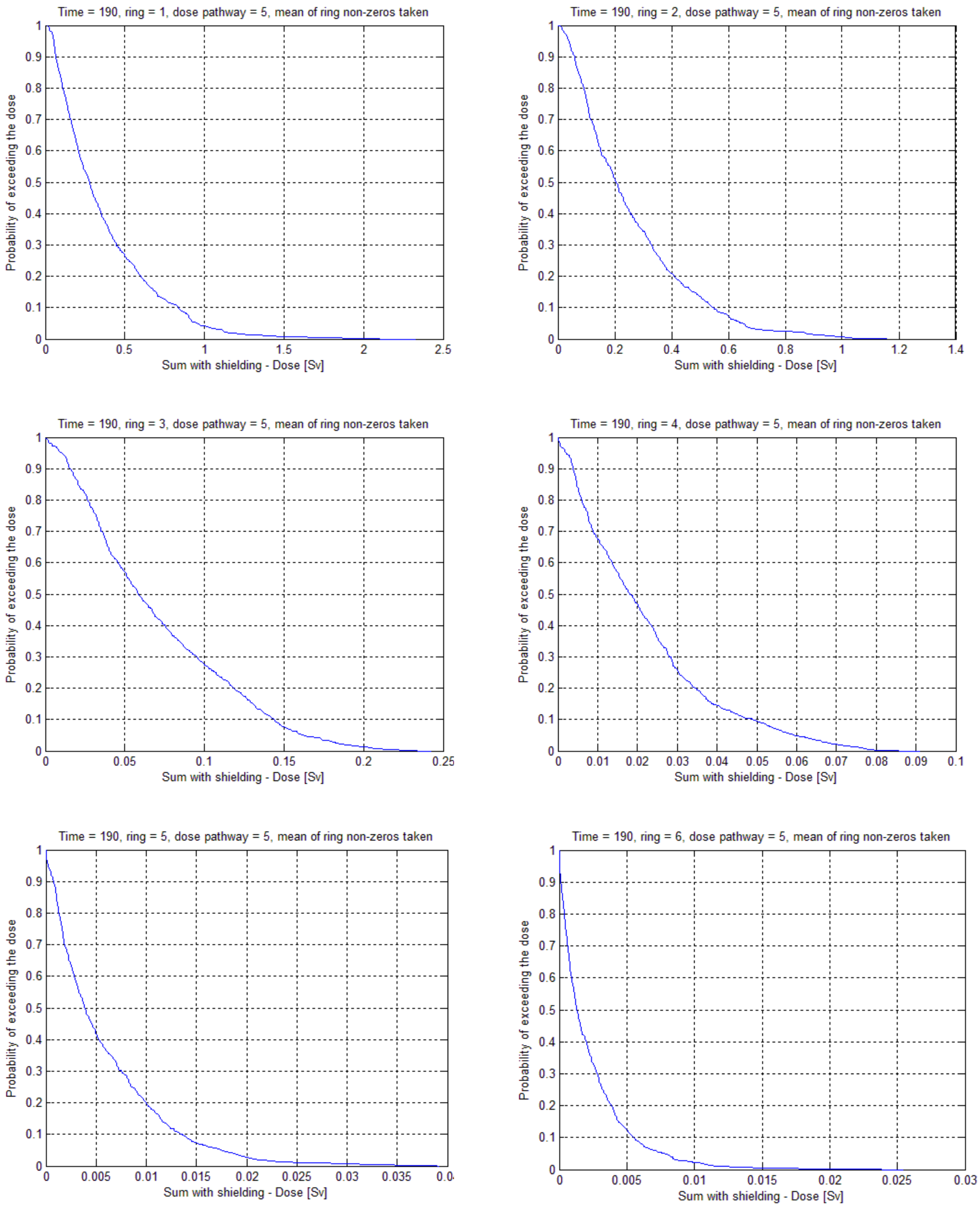


Figure 5.17. Mean value of the total dose at six distances (rings 1…6). Case 3, time integral of 1 week (190). Trajectory data of June 2012.

Figure 5.16 illustrates that when the distance increases the dose correspondingly decreases monotonically. Table 5.7 shows the 95% percentile values picked from the figures, integration time one week, source term case 3. Also ARANO results for this case are included.

Table 5.7. Total dose [mSv] at six distances, 95% percentile, case 3. Time integral of 1 week. Trajectory data of June.

Distance [km]	**Mean**	**Median**	**Maximum**	**ARANO(mean)**
15	1000	1100	2000	500
20	700	700	1500	350
50	170	160	350	60
100	60	60	140	20
200	15	15	40	7
300	7	6	16	3

Doses in Table 5.7 show that the mean and median values are almost the same, but the maximum value is twofold. The ARANO results are half of the mean and median values. If compared to the IAEA’s recommendation values, the mean and median values exceed 100 mSv up to the distance between 50 and 100 km. The maximum value exceeds 100 mSv up to the distance between 100 and 200 km.

Table 5.8 shows the 95% percentile values picked from the figures, integration time one year, source term case 3. Also ARANO results for this case are included.

Table 5.8. Total dose [mSv] at six distances, 95% percentile, case 3. Time integral of 1 year. Trajectory data of June.

Distance [km]	**Mean**	**Median**	**Maximum**	**ARANO(mean)**
15	4500	4600	9300	3000
20	3000	3400	6900	2000
50	900	900	2100	550
100	350	350	800	150
200	120	100	330	40
300	50	48	130	20

The doses of Table 5.8 depict the same trend as before.The limit value of 100 mSv is exceeded in all VALMA results up to the distance of 200 km and even beyond 300 km if the maximum value is used.

If a possibility of underestimation of the dose values as it emerged in chapter 5.5 is taken into account the IAEA's criterion value of 100 mSv could be exceeded even at the distance of 300 km based on the mean and median values.

Based on the IAEA's recommendations of Table 3.1 this means that based on the mean and median values in the case of release 2 type source term, urgent and early protective actions and other response actions should be taken in the extended planning zone, EPD, but not beyond the distance of 50 km. But in the case of type 3 source term preparedness for countermeasures should extend to the distance of 300 km. If conclusions are based on the maximum dose values the countermeasure distances are clearly longer, even roughly twofold.

In the future it would be useful to make the calculations fot the case 3 with the whole year trajectory data.

6. Conclusions

The computation method for processing a large amount of trajectory data in calculation of off-site radiation doses by the VALMA model has been created. The method has a probabilistic approach to calculate doses in different weather conditions. Utilizing supporting tools various result quantities can be picked from the outputs. These are e.g. mean, median and maximum values of the doses.

The objective was to evaluate doses and determine probability distributions of doses at distances beyond 20 km from the power plant when three different severe accident release magnitudes were used. Weather data used in the calculations consists of FMI's SILAM-based winding trajectory data for one year. The calculated dose estimates are compared with the threshold values given in the recommendations of IAEA and then necessity of the countermeasures can be elucidated and concluded. Because early health effects are not expected the aim of the countermeasures is to reduce the risk of statistical health effects.

Use of long-term weather data enables presentation of the results in a probabilistic way when doses are first calculated in a large number of weather conditions and finally the complementary cumulative density functions are built. This means that e.g. the probabilities of exceeding the threshold values recommended by IAEA can be determined.

The national emergency planning zone extends to the distance of 20 km. If the severe accident release is reduced to the level defined in the Nuclear Energy Act (100 TBq Cs-137) the dose levels at the distance of 20 km remain clearly below the limit value of 100 mSv. But if the release exceeds significantly the criterion of the severe accident, offsite doses may increase over the level of 100 mSv. In the second release case the release fraction of iodine and cesium were 2% and the expected distance for exceeding the dose criterion for countermeasures is less than 50 km but if the maximum doses are considered the distance might be nearly 100 km. In the third release case the release fraction of iodine and cesium were 20% and the expected distance for exceeding the dose criterion for countermeasures is about 200 km but if the maximum doses are considered the distance might be even beyond 300 km. The current case 2 and 3 results are based on the trajectory data of one month which probably underestimates doses slightly. Countermeasures would consist of sheltering, evacuation, decontamination, access control, relocation and food control.

Ingestion doses were not calculated in this report due to limited resources. As a qualitative estimate, ingestion dose is important when the release includes iodine and cesium. If deposition occurs during growing season potential doses from contaminated foodstuffs may be significant. In the case of the releases considered in this study it is quite probable that dose criteria are exceeded also from ingestion pathways. Then countermeasures would focus to stop consumption of food.

In the future the most interesting tasks would be expanding current results of the cases 2 and 3 to include the whole year trajectory data of 2012 and inclusion of ingestion pathways. Also effects of the release altitude would be studied.

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