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Swedish Radiation Safety Authority

Report

Radiological Consequences of Fallout from Nuclear Explosions

Appendix 6 – Detailed Results (General)

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1. Introduction

This appendix presents calculation results that do not relate to radiation doses or do not depend upon the age of the exposed person. An exception is Section 3.3, where calculated doses and dose rates from ground contamination are presented to illustrate the implications of different levels of ground contamination H+1. The results are presented with few comments and explanations.

Appendix 3 (Dispersion and Dose Calculations) describes how the calculations and the processing of the data were performed.

1.1. Standard calculations

Unless otherwise stated, the following applies to the results presented:

- The calculations have been done for a representative location, a Swedish city in the interior about 200 km from the coast.
- The calculations have been done for weather at 13-hour intervals between 23 January 2021 and 21 January 2022, totalling 663 individual calculations, using SMHI's *MATCH-BOMB* calculation model with numerical weather data from the *AROME* model on a grid with a resolution of 2.5 km.
- The results apply to a nuclear explosion, a 100 kiloton ground-level explosion with a 50 % fusion component, using the nuclide vector developed by SSM and described in Appendix 2 (Nuclide Composition).

1.2. Other results from the calculations

Calculations have also been made for radiation doses to one-year-old children and for radiation doses to adults, and these results are presented in Appendix 4 (Detailed Results (Children)) and Appendix 5 (Detailed Results (Adults)).

2. Absorbed dose to the skin

SSM has roughly estimated the conditions under which fallout from a nuclear explosion could cause severe deterministic health effects on the skin through the deposition radioactive material on the skin. The dose criterion used for severe deterministic health effects on the skin was 10 Gy RBE-weighted absorbed dose to a depth of 0.4 mm, see Appendix 1 (Radiation Protection).

Table 1 shows the greatest distances for which an amount of fallout that (assuming a given time of arrival) can give 10 Gy absorbed dose to the skin is exceeded for specified percentiles of occurring weather cases. The results are ultimately based on ground deposition criteria (see Section 3.1).

The rapid decay of the fallout, particularly in the first hours after the explosion, means that the dose rate to the skin from a given amount of deposited fallout decreases rapidly. This makes the presentation of the results for absorbed dose to the skin from deposition of fallout on the skin relatively complex. An example is therefore given below to show how the tables should be read.

Example: *The fifth row of Table 1 shows that fallout in an amount capable of delivering at least 10 Gy of absorbed dose to the skin can occur out to a distance of 60 km from the explosion. "May occur" here means that the greatest distance at which that amount of fallout occurs exceeds 60 km if 90 % of the occurring weather cases are considered. Furthermore, for this amount of fallout to deliver at least 10 Gy of absorbed dose to the skin, the fallout would need to fall on the skin within 6 hours of the nuclear explosion, and the skin not be decontaminated for at least 10 hours.*[1]

Table 1. Greatest distances for which a fallout capable of delivering **10 Gy absorbed dose to the skin** is exceeded when 70 %, 80 % and 90 % of occurring weather cases are considered, given different contamination times (time after the explosion, *i.e.* age of the fallout) and a duration of exposure (*i.e.* time from contamination to decontamination) of 10 hours.

Time of contamination	70 %	80 %	90 %
30 minutes after the explosion	130 km	150 km	170 km
60 minutes after the explosion	110 km	120 km	140 km
2 hours after the explosion	82 km	92 km	110 km
3 hours after the explosion	69 km	77 km	89 km
6 hours after the explosion	48 km	53 km	60 km
12 hours after the explosion	27 km	30 km	36 km

The results shown in Table 1 are based on *ground deposition criteria* expressed as H+1 (see Section 4.6 of the main report), *i.e.* the modelling has sought maximum distances at which a given ground deposition (corresponding to the fraction of the nuclide vector that can deliver a certain absorbed dose to the skin) is exceeded. SSM has also used *distance criteria* for ground deposition (see Section 3.2). These results can be used to illustrate the importance of the fallout arrival time and the duration of the exposure on the skin for the resulting absorbed dose to the skin. Table 2-4 gives the estimated absorbed dose to the skin

[1] Even though it takes 10 hours to obtain 10 Gy of absorbed dose to the skin from this fallout, most of the dose is received much faster. After about 60 minutes, 2 Gy has been received (using the same model and assumptions), which is a dose above which severe deterministic health effects on the skin cannot be completely excluded.

as a function of the arrival time of the fallout for different durations of exposure, for the highest ground deposition that can occur at 10 km, 30 km and 100 km distance from the explosion if 90 % of the occurring weather cases are considered (see Table 7 in Section 3.2).

Table 2. Highest RBE-weighted absorbed dose to the skin from fallout contamination at 10 km from the explosion, arriving at different times, for given durations of exposure.

	Arrival of fallout (time after the explosion)				
Exposure duration	**30 minutes**	**60 minutes**	**2 hours**	**3 hours**	**6 hours**
30 minutes	110 Gy	54 Gy	23 Gy	14 Gy	6.8 Gy
2 hours	220 Gy	130 Gy	66 Gy	46 Gy	24 Gy
10 hours	320 Gy	220 Gy	140 Gy	110 Gy	68 Gy

Table 3. Highest RBE-weighted absorbed dose to the skin from fallout contamination at a distance of 30 km from the explosion, arriving after varying times, for given durations of exposure.

	Arrival of fallout (time after the explosion)				
Exposure duration	**30 minutes**	**60 minutes**	**2 hours**	**3 hours**	**6 hours**
30 minutes	37 Gy	18 Gy	7.5 Gy	4.7 Gy	2.3 Gy
2 hours	72 Gy	41 Gy	22 Gy	15 Gy	7.9 Gy
10 hours	110 Gy	72 Gy	47 Gy	36 Gy	22 Gy

Table 4. Highest RBE-weighted absorbed dose to the skin from fallout contamination at a distance of 100 km from the explosion, arriving after different times, for given durations of exposure.

	Arrival of fallout (time after the explosion)				
Exposure duration	**30 minutes**	**60 minutes**	**2 hours**	**3 hours**	**6 hours**
30 minutes	7.8 Gy	3.7 Gy	1.6 Gy	1.0 Gy	0.47 Gy
2 hours	15 Gy	8.7 Gy	4.6 Gy	3.2 Gy	1.7 Gy
10 hours	23 Gy	15 Gy	9.8 Gy	7.6 Gy	4.7 Gy

The tables show that the distances at which severe deterministic health effects on the skin could occur under the given conditions are comparable to the distances at which high effective doses from ground contamination in particular can occur, see Appendix 4 (Detailed Results (Children)) and Appendix 4 (Detailed Results (Adults)). In other words, at the distances where high radiation doses can be obtained directly from the ground in a short period of time (without adequate protection), the fallout can also cause severe deterministic health effects on the skin. However, the distances and effective doses from the ground reported in the above-mentioned appendices are daily doses. Contamination of the skin may occur during a short stay in the open, if one is outside during the time the fallout arrives. In order to facilitate to some extent a comparison between the effects of radiation doses from the ground with the effects of possible contamination on the skin, Table 5 gives the effective doses from the ground obtained for an adult during a short (30 minutes) unshielded exposure to the highest ground contamination (90th percentile in Table

7 in Section 3.2) occurring at the specified distances, for different presumed arrival times of the fallout.

Table 5. Effective dose from the ground to an adult during 30 minutes exposure time for the maximum ground contamination that can occur at the specified distances, if 90 % of the occurring weather cases are considered and the fallout is assumed to arrive at the given times after the explosion.

Distance	Maximum ground contamination (H+1, 90 %)	Arrival of fallout (time after the explosion)					
		30 min	60 min	2 h	3 h	6 h	12 h
10 km	1,700 GBq/m^2	2.7 Sv	1.5 Sv	0.67 Sv	0.40 Sv	0.16 Sv	0.069 Sv
30 km	550 GBq/m^2	0.89 Sv	0.48 Sv	0.22 Sv	0.13 Sv	0.052 Sv	0.023 Sv
50 km	310 GBq/m^2	0.50 Sv	0.27 Sv	0.13 Sv	0.075 Sv	0.030 Sv	0.013 Sv
100 km	120 GBq/m^2	0.19 Sv	0.10 Sv	0.047 Sv	0.028 Sv	0.011 Sv	0.005 Sv

3. Time-invariant ground deposition (H+1).

See Section 4.6 of the main report for an explanation of the term “H+1” and how SSM has used H+1 as a ground deposition criterion in the modelling.

3.1. Greatest distances for a given ground deposition (H+1)

Table 6. Greatest distances for given ground deposition levels (H+1) that are exceeded when 70 %, 80 % and 90 % of occurring weather cases are considered.

Ground deposition (H+1)	70 %	80 %	90 %
9 GBq/m^2	> 330 km	> 330 km	> 330 km
10 GBq/m^2	320 km	> 330 km	> 330 km
15 GBq/m^2	260 km	290 km	> 330 km
20 GBq/m^2	220 km	250 km	290 km
25 GBq/m^2	200 km	220 km	260 km
30 GBq/m^2	180 km	200 km	230 km
35 GBq/m^2	160 km	180 km	210 km
40 GBq/m^2	150 km	170 km	200 km
45 GBq/m^2	140 km	160 km	190 km
50 GBq/m^2	130 km	150 km	170 km
60 GBq/m^2	120 km	130 km	160 km
70 GBq/m^2	120 km	130 km	140 km
80 GBq/m^2	110 km	120 km	140 km
90 GBq/m^2	100 km	110 km	130 km
100 GBq/m^2	93 km	100 km	120 km
110 GBq/m^2	87 km	97 km	110 km
120 GBq/m^2	81 km	91 km	100 km
130 GBq/m^2	76 km	85 km	99 km
140 GBq/m^2	74 km	81 km	94 km
150 GBq/m^2	70 km	78 km	90 km
160 GBq/m^2	67 km	74 km	86 km
170 GBq/m^2	64 km	71 km	82 km
180 GBq/m^2	61 km	67 km	77 km
190 GBq/m^2	58 km	64 km	74 km
200 GBq/m^2	55 km	62 km	72 km
225 GBq/m^2	51 km	56 km	65 km
250 GBq/m^2	47 km	52 km	59 km
300 GBq/m^2	40 km	44 km	50 km
350 GBq/m^2	35 km	40 km	46 km

400 GBq/m²	31 km	35 km	40 km
450 GBq/m²	27 km	30 km	36 km
500 GBq/m²	24 km	28 km	32 km
550 GBq/m²	22 km	25 km	30 km
600 GBq/m²	20 km	24 km	27 km
650 GBq/m²	19 km	22 km	25 km
700 GBq/m²	18 km	20 km	23 km
750 GBq/m²	16 km	19 km	22 km
800 GBq/m²	15 km	17 km	21 km
850 GBq/m²	14 km	17 km	20 km
900 GBq/m²	13 km	15 km	19 km
950 GBq/m²	12 km	14 km	17 km
1,000 GBq/m²	11 km	13 km	16 km
1100 GBq/m²	10 km	12 km	14 km
1200 GBq/m²	9 km	11 km	13 km
1300 GBq/m²	< 8 km	10 km	12 km
1400 GBq/m²	< 8 km	9 km	11 km
1500 GBq/m²	< 8 km	< 8 km	10 km
1600 GBq/m²	< 8 km	< 8 km	9 km
1,700 GBq/m²	< 8 km	< 8 km	8 km
1800 GBq/m²	< 8 km	< 8 km	< 8 km

3.2. Greatest ground deposition (H+1) at specified distances.

Table 7. Greatest ground deposition (H+1) exceeded at specified distances when 70 %, 80 % and 90 % of occurring weather cases are considered.

Distance	70 %	80 %	90 %
10 km	1200 GBq/m²	1400 GBq/m²	1,700 GBq/m²
25 km	510 GBq/m²	590 GBq/m²	670 GBq/m²
30 km	410 GBq/m²	480 GBq/m²	550 GBq/m²
50 km	220 GBq/m²	260 GBq/m²	310 GBq/m²
100 km	83 GBq/m²	97 GBq/m²	120 GBq/m²
150 km	38 GBq/m²	47 GBq/m²	60 GBq/m²
200 km	20 GBq/m²	27 GBq/m²	34 GBq/m²
250 km	14 GBq/m²	18 GBq/m²	22 GBq/m²
300 km	10 GBq/m²	12 GBq/m²	16 GBq/m²

3.3. Effective dose and dose rate H*(10) from ground deposition (H+1)

In order to facilitate the interpretation of what a certain value of ground deposition expressed in H+1 means, SSM has calculated the effective dose resulting from exposure during a given period of time starting at a given time after the explosion, for some different values of ground deposition H+1. The calculations are made with SSM's software *DosCalc*[2], with dose coefficients from *DCFPAK* [1], valid for the effective dose to an adult from fallout homogeneously distributed in the top soil layer (to a depth of 1 cm). The results are presented in Table 8. The calculations apply to SSM's nuclide vector for the main scenario (50 % fission and ground burst).

Table 8. Effective dose (mSv) from the ground during different exposure times (starting at different times after the explosion) for different levels of ground deposition H+1. Received effective dose for a given exposure time beginning at a given time after the explosion scales linearly with the level of ground deposition. For example, the tabular value of 87 mSv effective dose for 30 minutes of exposure to 100 GBq/m^2 H+1 starting 60 minutes after the explosion means that 150 GBq/m^2 would yield 1.5×87 mSv effective dose for a 30 minute exposure starting 60 minutes after the explosion.

Exposure duration	Ground deposition (H+1)	Initial exposure (time after the explosion)					
		30 min	60 min	2 h	3 h	6 h	12 h
30 minutes	10 GBq/m^2	16	9	4	2.4	1.0	0.4
	25 GBq/m^2	41	22	10	6	2.4	1.0
	50 GBq/m^2	81	43	20	12	5	2.1
	75 GBq/m^2	120	65	30	18	7	3
	100 GBq/m^2	160	87	40	24	10	4
60 minutes	10 GBq/m^2	25	14	7	4	1.8	0.8
	25 GBq/m^2	62	36	18	11	5	2.0
	50 GBq/m^2	130	72	35	22	9	4
	75 GBq/m^2	190	110	53	33	14	6
	100 GBq/m^2	250	140	71	44	18	8
2 hours	10 GBq/m^2	35	21	11	8	3	1.5
	25 GBq/m^2	86	54	29	19	8	4
	50 GBq/m^2	170	110	57	38	17	8
	75 GBq/m^2	260	160	86	57	25	12
	100 GBq/m^2	350	210	120	76	33	15

SSM has also calculated the dose rate that would be measured at different times after the explosion for a given level of ground deposition H+1. The results are presented in Table 9. In this calculation, dose coefficients for ambient dose equivalent (H*(10)) have been used to relate to what a dose rate instrument would show. The dose coefficients are taken from ICRP 144 [2] and assume deposition shielded by a soil thickness of 0.5 g/m^2, which agrees well with the assumptions of the dose calculations shown in Table 8.

Table 9. Dose rate (ambient dose equivalent, H*(10)) (mSv/h) from the ground at different times after the detonation for different levels of ground deposition H+1. The dose rate at a given time scales

[2] DosCalc v 1.0 (Manual 20-914)

linearly with the level of ground deposition. For example, the tabular value of 120 mSv/h ambient dose equivalent from 75 GBq/m^2 H+1 at the time 2 hours after the explosion means that 150 GBq/m^2 would give 2×120 mSv/h ambient dose equivalent at the time 2 hours after the explosion.

Ground contamination (H+1)	**Time after the explosion**					
	30 min	**60 min**	**2 h**	**3 h**	**6 h**	**12 h**
10 GBq/m^2	78	37	15	9	3	1.4
25 GBq/m^2	190	92	38	22	8	3
50 GBq/m^2	390	180	77	44	16	7
75 GBq/m^2	580	280	120	66	25	10
100 GBq/m^2	780	370	150	88	33	14

References

[1] K. F. Eckerman and R. W. Leggett, "DCFPAK 3.02 (Dose Coefficient Data File Package)," Oak Ridge National Laboratory, 2013.

[2] International Commission on Radiological Protection (ICRP), Publication 144 - Dose Coefficients for External Exposures to Environmental Sources, 2020.

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