



Strål
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Swedish Radiation Safety Authority

Report

Food contamination from fallout following a nuclear explosion

2026:08e

Author: Anders Axelsson, Anna Maria Blixt Buhr, Jan Johansson,
Peder Kock, Jonas Lindgren, Catharina Söderström

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Summary

After a nuclear explosion, small particles may be dispersed as fallout over large areas and cause radioactive ground deposition. Radiation doses may be received from the fallout in several ways. One such exposure pathway is the ingestion of foodstuffs contaminated by the fallout, either directly or through agricultural production in areas with ground deposition.

The Swedish Radiation Safety Authority (SSM) develops consequence analyses and other forms of support for national emergency preparedness in managing radioactive fallout, both in planning and in the form of advice during response to an event. With regard to foodstuffs, there is a need for an evidence base to support:

- the work of relevant authorities in developing preparedness to protect food supply chains in the event of fallout following a nuclear explosion
- the planning and development of measurement and analytical capabilities
- the production of situation reports and consequence analyses based on dispersion prognoses and measurements
- international cooperation for protection against radioactive fallout from nuclear explosions.

SSM has therefore studied how different types and levels of radioactive ground deposition resulting from a nuclear explosion may affect the amount of radioactive substances entering foodstuffs, what radiation doses may be received through the consumption of food contaminated by fallout, and how these doses can be limited through the application of limit values for radioactive substances in foodstuffs.

In this report, SSM presents estimates of

- radiation doses that may be received through the ingestion of contaminated food following fallout that results in radioactive ground deposition
- radiation doses that may be received if the concentration of radionuclides in foodstuffs is limited through the application of the limit values set out in Council Regulation (Euratom) 2016/52 ('the Council Regulation')
- the levels of radioactive ground deposition at which these limit values may risk being exceeded in food produced in the contaminated area.

The estimates are based on modelling carried out on behalf of SSM by the Technical University of Denmark (DTU). In the modelling, transfer factors have been derived to describe the transfer of radioactive substances in ground deposition to different types of foodstuffs.

Results from dispersion calculations of the type used in SSM's report 2023:05, *Radiological Consequences of Fallout from Nuclear Explosions*, indicate that areas with significant fallout could arise at distances of up to approximately 150 km from the explosion, covering an area of up to approximately 800 km² following a ground-level nuclear explosion with a yield of 100 kilotons.¹ Here, 'significant fallout' refers to fallout that, 48 hours after the explosion, results in an effective dose rate from the ground of several millisieverts per hour.

The analysis presented by SSM in this report shows that, in the absence of countermeasures, committed effective doses approaching one thousand millisieverts could be received through single intakes at an early stage (the first two months after the explosion) of food from areas with significant fallout as described above. Radiation doses at that level may cause acute radiation injuries. Possible annual doses during the second year from the ingestion of food from areas with significant fallout have also been estimated. These estimates show that, without protective actions, committed effective doses exceeding one hundred millisieverts could be received during the second year after fallout. Radiation doses at that level imply a significantly increased risk of developing cancer.

¹ At shorter distances and over smaller areas, significantly higher ground deposition may occur, while at greater distances and over larger areas, lower ground deposition may occur.

The analysis also shows that the application of the limit values set out in the Council Regulation may result in annual doses from the ingestion of foodstuffs contaminated by fallout following a nuclear explosion being limited to a few tens of millisieverts or less. Under the conditions otherwise assumed in establishing the Council's limit values², radiation doses from food can likely be kept below the reference level (one millisievert committed effective dose per year) on which the limit values are based. Consequently, these limit values have been used to estimate the levels, expressed for example in measurable quantities such as dose rate, of radioactive ground deposition from fallout following a nuclear explosion that could lead to exceedance of the limit values in foodstuffs.

² It is assumed, in particular, that one tenth of food intake consists of foodstuffs contaminated up to the specified limit values, and that the remaining proportion of intake consists of uncontaminated food.

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1. Introduction

In this report, the Swedish Radiation Safety Authority (SSM) presents an analysis of possible consequences for foodstuffs following radioactive fallout after a nuclear explosion. The analysis includes estimates of possible radiation doses from the intake of contaminated food, the effect of applying limit values to the concentration of radionuclides in food, and the development of potential intervention levels that can be used to limit the intake of radioactive substances in food in the event of ground deposition from fallout after a nuclear explosion.

1.1. Overview

The report first provides a brief introduction (Chapter 1), followed by an overview description of the radioecological modelling on which the analysis is based (Chapter 2). The analysis and results are then presented. The analysis itself consists of three parts.

In the first part, possible committed effective doses from consumption of contaminated foodstuffs are estimated for an early phase (the first two months after fallout)¹ and a later phase (the second year after fallout). The first part is described in Chapter 3.

In the second part, an estimate is made of how committed effective doses from contaminated foodstuffs can be limited through the application of limit values for radionuclides in food. The analysis uses the limit values set out in Council Regulation (Euratom) 2016/52 on maximum permitted levels of radioactive contamination of food and feed following a nuclear accident or any other case of radiological emergency ('the Council Regulation') in order to assess the extent to which these limit values are suitable for use in the event of fallout from a nuclear explosion. The second part is described in Chapter 4.

In the third part, possible intervention levels are estimated, i.e. levels of ground deposition that may lead to exceedance of limit values for radionuclides in foodstuffs. The third part is described in Chapter 5.

Finally, comments are provided regarding the need for further work (Chapter 6).

1.2. Starting points

The analysis is based on

1. radioecological modelling, carried out by the Technical University of Denmark (DTU) on behalf of SSM, of the transfer of radionuclides from fresh ground deposition of radioactive fallout to various foodstuffs [1] [2]
2. radionuclide composition in fallout from nuclear explosions previously used and described by SSM in *Radiological Consequences of Fallout from Nuclear Explosions* [3]

¹ In this report, the term 'early phase' will be used in a general sense, as indicated here: the period during which the impact of fallout on radionuclide concentrations in foodstuffs can be reasonably assumed to be adequately represented by modelling the first two months following fallout. Note that this use of the term differs from the uses defined by the IAEA and the ICRP in discussing response to nuclear and radiological emergencies.

- intake data for different foodstuffs derived from the European Commission report [4], which forms the basis for the limit values set out in the Council Regulation.

The radioecological modelling is briefly described, including the results used in the analysis, in Chapter 2.

The radionuclide composition used represents a nuclear explosion at ground level with a 50% fusion fraction. The fallout is assumed not to fractionate, i.e. all parts of the fallout are assumed to contain the same distribution of radionuclides, which changes only through radioactive decay. This distribution is referred to as a *nuclide vector*. The nuclide vector consists partly of fission products and partly of activation products, i.e. nuclides created through neutron activation of materials in the weapon or the surrounding environment. The selected activation products are intended to represent a hopefully reasonable and generic selection and quantity that could be present in fallout after a nuclear explosion, but it is difficult to state with any certainty which activation products, or in what quantities, would be present in an actual nuclear explosion. Certain parts of the analysis are therefore also carried out under partially different assumptions, e.g. that only fission products are present in the fallout. In this way, the significance of the assumptions made regarding activation products can be assessed to a certain degree. The construction and composition of the nuclide vector and all assumptions made are discussed in detail in the aforementioned work [3].

Table 1 presents the intake data used in the analyses. The foodstuffs in the radioecological modelling [1] [2] are listed (left-hand column), together with the food groups they are assumed to represent in the intake data from the EU Commission [4] that were used (second column from the left). The source of the intake data does not distinguish between different types of ‘meat’, so intake of ‘beef’, ‘pork’, and ‘chicken’ has been treated separately where necessary. In most cases the radiation doses are similar, and in such cases the type of ‘meat’ yielding the highest dose has been selected to represent the entire intake.

Table 1. Intake data used in the analyses

Foodstuff	Assumed equivalent in [4]	Annual intake (kg) from [4]	
		Child	Adult ²
Radioecological modelling [1] [2]			
Wheat flour	Cereals	20	115
Potatoes	Potatoes	10	126
Leafy vegetables	Vegetables	13*	156
Fruit and berries	Fruit	7*	172
Milk	Dairy products	200	206
Beef			
Pork	Meat	10	106
Chicken			

*The referenced source [4] states total annual intake of ‘fruit and vegetables’ for children as 20 kg. In this analysis, the group has been split into vegetables (represented by ‘leafy vegetables’) and fruit (partly represented by ‘berries’) based on data in an underlying report [5] supporting [4].

The assumption that ‘leafy vegetables’ are represented by ‘vegetables’ is likely to lead to a significant overestimation of the committed effective dose from vegetable consumption,

² For adults, the *EU adult higher values* have been used, in order to provide a conservative (i.e. high) estimate of possible radiation doses. The referenced source also states *EU adult lower values*. Overall, the differences are large, e.g. an annual intake of 58 kg of cereals is stated as the *EU adult lower value* and an intake of 115 kg as the *EU adult higher value*.

since doses per unit mass of contaminated ‘leafy vegetables’ are high (see Chapter 3). In reality, it can be assumed that a large proportion of vegetable consumption consists of vegetables such as carrots, cucumbers, and tomatoes among others, which are not necessarily contaminated in the same way or to the same extent as leafy vegetables.

Drinking water has not been included in the analysis presented here, mainly because a thorough analysis of how drinking water production from surface water sources may be affected by radioactive fallout after nuclear explosions or reactor accidents has already been carried out by the Swedish Defence Research Agency (FOI) [6]. However, see the further discussion on this in Chapter 6.

2. Radioecological modelling

The radioecological modelling was carried out using the ECOSYS model [7]. Using the model, unit transfer factors F were calculated. Unit transfer factors refer to concentrations [Bq/kg] in selected types of food per initial ground deposition per unit area [Bq/m²] of important radionuclides.

For a given initial ground deposition M_n [Bq/m²] of radionuclide n , the maximum concentration $K_{n,i,max}$ [Bq/kg] reached in food group i is given by the transfer factor $F_{n,i}$ (as obtained from the modelling) as follows:

$$K_{n,i,max} = F_{n,i} \cdot M_n \quad (1)$$

The modelling, including the selection of radionuclides, is described in detail in K. Andersson’s reports on the work carried out at DTU on behalf of SSM [1] [2]. Only a brief summary is provided here, including the resulting unit transfer factors $F_{n,i}$ that have been used further in the analysis.

2.1. Selection of radionuclides and foodstuffs

The starting point for the selection of radionuclides is the same as in SSM’s previous work [3] as described above, with the addition of a small number of other nuclides that may be dispersed in a nuclear explosion but were not prioritised in the earlier work: Pu-239, Pu-240, Pu-241, Am-241, tritium (H-3), and C-14. Since the radioecological modelling could only include a limited number of nuclides, a further selection was made among the nuclides mentioned, based on an initial estimate of their relative importance for radiation doses from food intake.

For the modelling of the early phase (first two months after the explosion), radionuclides were selected based on the product (‘dose product’) of their relative abundance in the nuclide vector and the dose coefficient for committed effective dose via ingestion at relevant time points. In total, 23 radionuclides were selected for modelling of the early phase. For the modelling of the later phase (second year after the explosion), radionuclides were selected based on the dose product at relevant time points weighted by the ecological transfer factor for wheat. In total, 12 radionuclides were selected for modelling of the later phase. The combined dose products of the selected nuclides accounted for a high proportion (85–100%) of the total dose product for the entire nuclide vector.

None of the plutonium isotopes were selected using the method described above for either time phase, nor was Am-241. Tritium and C-14 were assessed separately, but these nuclides were also not considered to be of sufficient importance relative to the rest of the selection to justify inclusion in the radioecological modelling, neither for the early nor the later phase.

Table 2 shows the nuclides selected for modelling in the two different time phases, sorted according to the nuclide groups used in the Council Regulation. None of the selected nuclides belong to the group of alpha-emitting isotopes of plutonium or transplutonium elements. Some nuclides that could be important in an early phase have half-lives shorter than 10 days, a group that is not covered in the Council Regulation (except for iodine isotopes, which have their own nuclide group in the regulation).

Table 2. Radionuclides selected for modelling for the specified time phases, including half-lives and origin (fission or neutron activation)

First two months				Second year			
Nuclide	T _{1/2}	Origin	Ingrowth from	Nuklid	T _{1/2}	Origin	Ingrowth from
Isotopes of strontium				Isotopes of strontium			
Sr-89	50,6 d	fission		Sr-89	50,6 d	fission	
Sr-90	28,8 a	fission		Sr-90	28,8 a	fission	
Sr-91	9,63 h	fission					
Isotopes of iodine							
I-131	8,02 d	fission					
I-133	20,8 h	fission					
I-135	6,57 h	fission					
Other nuclides with half-life > 10 days				Other nuclides with half-life > 10 days			
Y-91	58,5 d	fission	Sr-91	Mn-54	313 d	activation	
Zr-95	64,0 d	fission		Fe-55	2,74 a	activation	
Ru-103	39,3 d	fission		Fe-59	44,5 d	activation	
Ru-106	1,02 a	fission		Co-57	272 d	activation	
Te-132	3,20 d	fission		Co-58	70,9 d	activation	
Cs-136	13,0 d	fission		Co-60	5,27 a	activation	
Cs-137	30,0 a	fission		Ru-106	1,02 a	fission	
La-140	1,68 d	fission	Ba-140	Sn-123	129 d	fission	
Ba-140	12,8 d	fission		Cs-137	30,0 a	fission	
Pr-143	13,6 d	fission	Ce-143	Ce-144	285 d	fission	
Ce-141	32,5 d	fission					
Ce-144	285 d	fission					
Others (half-life < 10 days)							
Y-93	10,2 h	fission					
Zr-97	16,7 h	fission					
Ce-143	1,38 d	fission					
U-237	6,75 d	activation					
Np-239	2,36 d	activation					

A number of different types of foodstuffs were selected for modelling. The aim of this selection was partly to represent large parts of a varied diet, and partly to represent different types of crops and different production methods with varying transfer factors for

radionuclides from ground deposition to foodstuffs. For modelling of the early phase, ECOSYS standard values for storage times, i.e. the time between fallout and consumption of finished food products, were assumed. The selected foodstuffs are shown in Table 1, and the assumed storage times are given in Table 3.

2.2. Assumptions and conditions

The transfer of radionuclides from ground deposition to food over time is a complex process. Many properties of radioactive fallout following a nuclear explosion that can be assumed to be important for the transport of radionuclides in the food chain are insufficiently known. For emergency response planning, generally applicable results are also preferable to results that are highly dependent on the circumstances of a specific area or event. A number of simplifying assumptions have therefore been necessary. Throughout, conservative assumptions have been made, i.e. assumptions that are likely to overestimate rather than underestimate the concentrations in foodstuffs. Key assumptions include:

- particle size 0.5 μm
- direct dry deposition on standing crops; no precipitation during deposition
- fallout occurring during the harvest season
- cattle are assumed to graze; feed for other animals is assumed to be stored for a period before use
- no differences in physico-chemical form have been considered; all radionuclides are assumed to occur in nature in readily soluble form
- no measures such as rinsing, peeling, or similar processes, which could significantly reduce certain types of contamination, have been taken into account. This also includes measures such as specifically protecting animal feed, or feeding grazing animals with clean feed. These types of measures are instead regarded as protective actions that can be taken to reduce radiation doses that would otherwise be received.

A detailed account, justification, and discussion of the assumptions made is provided in K. Andersson's modelling reports [1] [2].

2.3. Results

The results of the radioecological modelling are presented as the maximum concentration of each selected radionuclide reached in each selected foodstuff, per initial ground deposition per unit area, both for an early phase (the first two months) and a later phase (the second year). Ground deposition at 48 hours after a ground-level explosion with a 50% fusion fraction has been assumed as the 'initial ground deposition', because this is a plausible point in time when initial sheltering against fallout transitions to 'normal habitation', and 'normal' food production and consumption resume. The results for the first two months are given in Table 3. The results for the second year are given in Table 4.

For the early phase (Table 3), 'berries' were modelled [1], whereas for the second year (Table 4) both 'fruit' and 'berries' were modelled [2]. The same transfer factors were obtained for 'berries' as for 'fruit' in the later modelling. In the present analysis, therefore, 'fruit and berries' have consistently been used for both the early phase and the second year, assuming that the transfer factors would be similar also in the early phase.

Tabell 3. Transfer factors $F_{n,i}$ for the early phase, i.e. maximum concentration [Bq/kg] of modelled radionuclides n reached in the first two months after the explosion in selected foodstuffs i , per initial ground deposition density [Bq/m²]

Nuclide	T _{1/2}	Foodstuff with assumed time to consumers							
		Wheat flour	Potatoes	Leafy vegetables	Berries*	Milk	Beef	Pork	Chicken
		45 d	7 d	1 d	2 d	1 d	14 d	2 d	7 d
Sr-89	50,6 d	2,6E-02	1,9E-04	1,4E+00	4,5E-02	8,2E-02	1,9E-03	3,4E-05	6,2E-05
Sr-90	28,8 a	4,8E-02	4,2E-04	1,0E+00	4,7E-02	9,0E-02	2,8E-03	1,0E-04	1,4E-04
Sr-91	9,63 h	0,0E+00	2,2E-20	2,5E-01	1,5E-03	1,1E-03	3,5E-15	9,7E-08	1,4E-10
Y-91	58,5 d	2,7E-02	8,4E-06	1,4E+00	4,5E-02	7,3E-04	4,0E-05	9,7E-07	5,1E-08
Y-93	10,2 h	2,6E-33	5,7E-21	2,7E-01	1,8E-03	1,9E-05	1,4E-17	2,3E-09	1,2E-13
Zr-95	64,0 d	6,3E-07	1,2E-08	1,1E+00	2,8E-02	3,9E-05	2,7E-08	9,1E-11	2,2E-11
Zr-97	16,7 h	6,8E-22	2,2E-15	5,2E-01	6,3E-03	3,9E-06	1,3E-16	1,0E-11	6,0E-14
Ru-103	39,3 d	2,1E-02	3,4E-05	1,4E+00	4,5E-02	1,4E-04	4,5E-04	1,2E-05	5,7E-07
Ru-106	1,02 a	4,3E-02	8,1E-05	1,4E+00	4,6E-02	1,8E-04	1,1E-03	3,2E-05	6,5E-07
I-131	8,02 d	3,6E-03	8,3E-03	1,3E+00	9,4E-02	2,1E-01	1,1E-04	7,2E-06	1,1E-05
I-133	20,8 h	8,7E-17	2,6E-09	6,3E-01	1,4E-02	5,1E-02	2,2E-10	8,5E-07	3,7E-08
I-135	6,57 h	0,0E+00	9,2E-25	1,2E-01	4,6E-04	1,7E-03	2,0E-21	5,3E-09	4,9E-14
Te-132	3,20 d	6,4E-06	4,0E-04	1,1E+00	3,2E-02	1,7E-02	8,7E-06	2,5E-05	1,2E-05
Cs-136	13,0 d	1,0E-02	1,2E-02	1,3E+00	1,0E-01	1,2E-01	2,0E-02	3,0E-03	3,2E-03
Cs-137	30,0 a	1,1E-01	1,3E-01	1,4E+00	2,3E-01	1,6E-01	2,7E-01	2,7E-02	1,2E-02
La-140	1,68 d	2,7E-10	8,0E-10	9,2E-01	2,0E-02	2,2E-04	1,3E-09	9,1E-08	2,1E-09
Ba-140	12,8 d	5,2E-03	4,1E-06	1,3E+00	5,6E-02	1,6E-02	1,1E-04	7,3E-06	2,2E-05
Pr-143	13,6 d	4,5E-03	1,7E-06	1,3E+00	4,2E-02	6,2E-04	5,8E-06	2,7E-07	3,7E-08
Ce-141	32,5 d	1,9E-02	5,0E-06	1,4E+00	4,5E-02	7,1E-04	2,3E-05	1,0E-06	8,4E-08
Ce-143	1,38 d	3,4E-12	1,1E-10	8,4E-01	1,7E-02	1,8E-04	3,2E-10	6,9E-08	9,8E-10
Ce-144	285 d	4,1E-02	1,4E-05	1,4E+00	4,6E-02	7,7E-04	7,3E-05	1,7E-06	8,2E-08
U-237	6,75 d	2,1E-04	3,0E-07	1,3E+00	3,8E-02	1,2E-06	4,0E-08	9,9E-09	7,8E-08
Np-239	2,36 d	2,7E-08	5,4E-09	1,0E+00	2,6E-02	4,6E-07	4,6E-10	5,6E-09	1,7E-08

*For the early phase, 'berries' were modelled [1], whereas for the second year, both 'fruit' and 'berries' were modelled [2] (see text).

Tabell 4. Transfer factors $F_{n,i}$ for the second year, i.e. maximum concentration [Bq/kg] of modelled radionuclides n reached in month 13–24 after the explosion in selected foodstuffs i , per initial ground deposition density [Bq/m²]

Nuclide	T _{1/2}	Foodstuff with assumed time to consumers							
		Wheat flour	Potatoes	Leafy vegetables	Fruit and berries*	Milk	Beef	Pork	Chicken
		45 d	7 d	1 d	2 d	1 d	14 d	2 d	7 d
Mn-54	313 d	2,6E-02	4,5E-02	3,4E-02	2,4E-02	1,1E-03	1,7E-03	3,3E-04	6,9E-05
Fe-55	2,74 a	1,8E-05	4,0E-05	4,0E-05	5,0E-05	3,0E-04	1,1E-03	1,2E-04	1,4E-05
Fe-59	44,5 d	3,2E-08	1,9E-07	1,9E-07	2,3E-07	1,3E-06	4,7E-06	5,1E-07	6,1E-08
Co-57	272 d	4,1E-03	2,1E-04	8,6E-03	3,1E-03	9,5E-04	2,0E-03	2,3E-04	2,2E-03
Co-58	70,9 d	1,9E-04	1,5E-05	6,2E-04	2,3E-04	6,9E-05	1,4E-04	1,7E-05	1,6E-04
Co-60	5,27 a	1,0E-02	4,9E-04	1,9E-02	7,0E-03	2,1E-03	4,5E-03	5,2E-04	4,9E-03
Sr-89	50,6 d	4,8E-05	9,1E-04	1,4E-03	1,5E-03	8,4E-05	5,2E-04	1,0E-05	1,6E-06
Sr-90	28,8 a	1,6E-02	1,3E-01	2,0E-01	2,2E-01	1,2E-02	7,6E-02	1,5E-03	2,4E-04
Ru-106	1,02 a	8,4E-05	1,5E-04	2,7E-03	3,8E-04	1,9E-04	7,0E-03	1,3E-04	3,2E-06
Sn-123	129 d	8,0E-03	1,1E-02	5,1E-03	3,2E-02	1,8E-03	1,1E-02	2,2E-04	3,5E-05
Cs-137	30,0 a	1,1E-02	9,8E-03	2,2E-02	2,3E-02	3,1E-02	6,5E-01	1,2E-01	5,1E-02
Ce-144	285 d	1,3E-04	5,6E-05	7,8E-05	1,0E-04	3,8E-05	1,9E-04	1,2E-05	3,2E-07

* For the early phase, 'berries' were modelled [1], whereas for the second year, both 'fruit' and 'berries' were modelled [2] (see text).

2.4. Comparisons with modelling of strontium and caesium

To provide an indication of how the assumptions made in the modelling may affect the results, a comparison is presented here between activity concentrations in different foodstuffs calculated using the transfer factors in Table 3 and the range of activity concentrations estimated in two other studies.

To demonstrate the need for and effect of different countermeasures to reduce caesium concentrations in food following fallout, Rosén and Eriksson [8] modelled activity concentrations of caesium in crops and foodstuffs under a range of different conditions. The modelling is mainly based on Cs-137, the authors note that the presence of Cs-134 that can be expected in fallout from a nuclear power plant accident does not significantly change the results during the year of fallout. In contrast to a nuclear power plant accident, Cs-134 is not expected to be present to any significant extent in fallout from a nuclear explosion. However, in the early phase after a nuclear explosion, caesium fallout (and estimated caesium concentrations in food) is dominated to a large extent by the short-lived isotope Cs-136, which is not as prominent in a release from a nuclear power plant accident. To enable a meaningful comparison with Rosén and Eriksson, fallout consisting of pure Cs-137 has therefore been assumed in the estimates based on K. Andersson's transfer factors (Table 3). The comparison is shown in Table 5.

Tabell 5. Activity concentrations of caesium in foodstuffs obtained from the modelling results used in this report (K. Andersson [1]) compared to results from Rosén and Eriksson [8]

Compared foodstuffs/crops		Activity concentration (Bq/kg) from 100 kBq/m ² fallout of Cs		
Andersson	Rosén and Eriksson	Andersson Cs-137 only Maximum first 2 months Conservative assumptions	Rosén and Eriksson Value reached in fallout year Different conditions and methods*	
			Lowest	Highest
Wheat flour	Bread	11 000	40	4 800
Potatoes	Potatoes	13 000	20	500
Leafy vegetables	Pasture grass (arable land)	140 000	5 500	220 000
Fruit and berries	-	-	-	-
Milk	Milk	16 000	450	17 600
Beef	Beef	27 000	150	137 000
Pork	Swine meat	2 700	60	7 200
Chicken	-	-	-	-

*Mainly (depending on crop/foodstuff) time of fallout, time after fallout, grazing, feed ration and sowing time

Table 6 shows a similar comparison between results based on transfer factors for strontium in Table 3 and activity concentrations of strontium in crops and foodstuffs under different conditions calculated by Rosén et al. [9].

Table 6. Activity concentrations of strontium in foodstuffs obtained from the modelling results used in this report (K. Andersson [1]) compared to results from Rosén et.al. [9]

Compared foodstuffs/crops		Activity concentration (Bq/kg) from 100 kBq/m ² fallout of Sr		
Andersson	Rosén et.al.	Andersson Maximum first 2 months Conservative assumptions	Rosén et.al. Value reached in fallout year Different conditions and methods*	
			Lowest	Highest
Wheat flour	Bread	2 600	6	890
Potatoes	Potatoes	20	80	80
Leafy vegetables	Pasture grass (arable land)	140 000	18 600	686 700
Fruit and berries	-	-	-	-
Milk	Milk	8 200	20	2 300
Beef	Beef	190	10	7 100
Pork	Swine meat	3	< 1	20
Chicken	Chicken meat	6	< 1	4

* Mainly (depending on crop/foodstuff) time of fallout, time after fallout, grazing, feed ration and sowing time

The purpose of the comparisons in Tables 5 and 6 is not to demonstrate or discuss the degree of agreement between the results, which were produced for different purposes and therefore under different assumptions, but to illustrate the wide range of possible outcomes in this type of modelling. For more detailed comparisons, not only the assumed conditions but also other assumptions and methods would need to be compared in detail. This is outside the scope of the present report. For example, the calculations in [9] are based on wet deposition, since experience from the Chernobyl accident showed that most of the fallout in Sweden was associated with precipitation. The modelling carried out by DTU on behalf of SSM [1] [2], on the other hand, is based on dry deposition, which can be expected to dominate in the case of extensive fallout following a ground-level nuclear explosion, particularly within a distance of a few hundred kilometres.

3. Committed effective dose from contaminated foodstuffs

The committed effective dose E from contaminated foodstuffs as a result of fallout from a nuclear explosion is calculated as the sum of the dose contributions $e_{n,i}$ from radionuclide n in the fallout via foodstuff i .

$$E = \sum_{n,i} e_{n,i} \quad (2)$$

The dose contribution $e_{n,i}$ [Sv] from radionuclide n through intake of contaminated foodstuff i is calculated from the activity concentration $K_{n,i}$ [Bq/kg] of radionuclide n in foodstuff i , the transfer factor $F_{n,i}$ [Bq/kg per Bq/m²] (as given by the radioecological modelling [1] [2]), the dose coefficient for committed effective dose via ingestion d_n [Sv/Bq] [10], the intake m_i [kg] of food i (see Table 1), and the initial ground deposition M_n [Bq/m²] of nuclide n :

$$e_{n,i} = K_{n,i} \cdot d_n \cdot m_i = M_n \cdot d_n \cdot F_{n,i} \cdot m_i \quad (3)$$

When concentrations $K_{n,i}$ are calculated from the transfer factors $F_{n,i}$ used in this analysis, what is actually obtained are the maximum concentrations ($K_{n,i,max}$) reached during a given time period (see Equation 1 in Chapter 2 above). This approximation is used throughout the analysis and may have greater or lesser significance depending on how rapidly the concentrations $K_{n,i}$ change during the period over which the intake m_i is assumed to occur.

Through summations, partial dose contributions e_n from radionuclide n via all foodstuffs, or e_i via foodstuff i from all radionuclides, are calculated in the same way:

$$e_n = \sum_i e_{n,i} = M_n \cdot d_n \cdot \sum_i (F_{n,i} \cdot m_i) \quad (4)$$

$$e_i = \sum_n e_{n,i} = \sum_n (M_n \cdot d_n \cdot F_{n,i}) \cdot m_i \quad (5)$$

The initial ground deposition M_n of nuclide n is given by the nuclide's fraction of the total activity of the nuclide vector at the time of the initial ground deposition, and by the 'amount of fallout' that gave rise to the deposition. In SSM's modelling of fallout following nuclear explosions, a time-invariant (non-decaying) fallout quantity denoted 'H+1' is often used. A given source term in the modelling is represented by a specified amount of H+1; for example, when SSM models a ground-level nuclear explosion with a yield of 100 kilotons and a 50% fusion fraction, the source term contains a total of $1.1 \cdot 10^{21}$ Bq H+1. For a given modelled source term, a nuclide vector is also defined, i.e. a list of the nuclides included in the modelling and their activities. Thus, a modelling result expressed in H+1 (e.g. a ground deposition of 100 GBq/m² H+1) can always be converted into ground deposition of the radionuclides included in the nuclide vector at a given time after the explosion. In particular, 100 GBq/m² H+1 corresponds to a ground deposition of 22 MBq/m² of Ba-140 at 48 hours after the explosion, or a ground deposition of 17 MBq/m² of Ba-140 at 7 days after the explosion.

To provide an indication of possible consequences of foodstuff contamination, modelling results will be used here for an early phase (roughly a few days to a few months), during which high committed effective doses can be received over a short time and through single intakes of contaminated food (Section 3.2), and modelling results for the second year after fallout on agricultural land, which illustrate longer-term levels of impact (Section 3.3).

3.1. Assumed ground deposition

The results presented in Sections 3.2 and 3.3 refer to a ground deposition of 100 GBq/m² H+1 (see above). The results can be scaled linearly with the assumed ground deposition (e.g. a ground deposition of 10 GBq/m² H+1 gives one tenth of the radiation doses reported under the various assumptions for 100 GBq/m² H+1).

Table 7 provides some reference values to illustrate the potential impact in different respects of a ground deposition of 100 GBq/m² H+1. Gamma dose rates and ground deposition can be scaled linearly to other values of H+1 ground deposition. Greatest distances and greatest affected areas cannot be scaled in the same way. The values are taken from calculations performed by SSM using the method described in [3] (distances

and areas³) and calculated using SSM's software DosCalc⁴ (dose rates and nuclide-specific ground deposition). The dose rate calculations were performed using the nuclide vector discussed in Section 1.2 above. With a different nuclide composition (e.g. in the case of a pure fission explosion), the dose rates corresponding to a ground deposition of 100 GBq/m² H+1 would be somewhat different.

Table 7. Reference values to illustrate the impact of a ground deposition of 100 GBq/m² H+1

Type of impact	Impact
Greatest...	
	distance 150 km
	area 800 km ²
...with > 100 GBq/m ² H+1 for 100 kilotonnes Ground-level explosion with 50% fusion fraction (90% of occurring weather cases considered)	
Effective gamma dose rate from the ground* after...	
	60 minutes 370 mSv/h
	48 hours 2,6 mSv/h
	7 days 580 µSv/h
	365 days 7 µSv/h
Ground deposition of...	
	I-131 after 7 days 17 MBq/m ²
	Ba-140 after 48 hours 22 MBq/m ²
	Cs-137 30 kBq/m ²
	Sr-90 26 kBq/m ²

Dose rate was calculated as H(10) using dose factors from ICRP [11] for a fallout distribution in the surface layer of the ground of 0,5 g/cm².

3.2. 'Maximum daily doses' in the early phase

Table 8 provides an estimate of the committed effective dose from an average daily intake consisting solely of food contaminated by a ground deposition of 100 GBq/m² H+1, assuming that the intake occurs at a time when all radionuclides reach their maximum during the early phase (the first two modelled months).

The assumption that the activity concentration of all radionuclides reaches its maximum simultaneously at the time of intake is clearly a simplification. Due to different decay dynamics and different chemical and biological properties, different radionuclides reach their maximum concentration at different times. In particular, many short-lived radionuclides that are important for radiation doses (e.g. iodine isotopes) can only be present at maximum concentration for a short period. The doses shown in Table 8 are therefore referred to as 'maximum daily doses'. Although it is unlikely that a single real daily intake would result in these doses, the maximum daily doses may be interpreted as indicative of doses that could be received over a short period through single intakes of locally produced food during the days in the early phase after fallout when various important radionuclides reach their peak concentration. For comparison, to illustrate the

³ Calculation of the maximum affected area for a given modelling quantity has been added since the calculations described in [3].

⁴ DosCalc v 1.0 (Manual 20-914)

significance of short-lived nuclides for doses in the early phase, results are also given in which the contribution from nuclides with half-lives shorter than 10 days has been excluded.

Table 8. Maximum daily doses (see text) in the early phase from different foodstuffs for a ground deposition of 100 GBq/m² H+1

Foodstuff	Maximum daily dose (committed effective dose, mSv)			
	All nuclides		Only nuclides with half-life >10 days	
	Children	Adults	Children	Adults
Wheat flour	1,4	1,1	0,6	0,5
Potatoes	1,0	1,5	0,003	0,02
Leafy vegetables	520	780	50	80
Fruit and berries	12	37	1	3
Milk	620	80	8	1
Beef*	0,03	0,07	0,01	0,05
Pork*	0,003	0,007	0,001	0,004
Chicken*	0,003	0,005	0,001	0,003

*Dose estimates for beef, pork and chicken were calculated under the assumption that the entire daily intake of 'meat' consists exclusively of the specified type.

3.3. Later phase (second year)

Table 9 provides an estimate of the committed effective dose that could be received during the second year after fallout, assuming that only food from agricultural land contaminated with 100 GBq/m² H+1 is consumed during the year. In the estimate, it is assumed that all food is contaminated at the highest level reached during the second year. The calculated doses should therefore be regarded as a conservative (i.e. high) estimate, even though radionuclide concentrations in food are unlikely to vary as rapidly during the second year as in the early phase, since contamination during the second year consists of relatively long-lived radionuclides.

There is greater uncertainty regarding which activation products may be present in fallout, and in what quantities, than is the case for fission products. Among the activation products included in SSM's nuclide vector for a ground-level explosion with a 50% fusion fraction, Mn-54 is of particular importance for estimated doses during the second year. To illustrate the significance of uncertainties regarding which nuclides are present in the fallout, Table 9 therefore also shows estimated doses if Mn-54 is excluded from the calculation.

Since this no longer concerns (as in the early phase) single intakes at a maximally unfavourable point in time, but rather intake over time, it is meaningful to sum doses from different foodstuffs into a total committed effective dose from food for the second year (although it is likely overestimated as noted above). The total committed effective dose is calculated under the assumption that all intake of 'meat' consists of beef, which gives the highest dose. The table also provides annual doses for pork and chicken, assuming that all 'meat' intake instead consists of these foodstuffs.

Tabell 9. Maximum annual doses during the second year from various foodstuffs, given a ground deposition of 100 GBq/m² H+1

Foodstuff	Second year maximum dose (committed effective dose, mSv)			
	Children		Adults	
	Including Mn-54	Excluding Mn-54	Including Mn-54	Excluding Mn-54
Wheat flour	7	1,4	10	2
Potatoes	8	3	28	14
Leafy vegetables	13	8	42	29
Fruit and berries	6	4	43	33
Milk	13	11	5	5
Beef*	7	6	37	36
Total	54	35	170	130
Pork*	0,6	0,5	5	5
Chicken*	0,3	0,3	2	2

*Dose estimates for beef, pork, and chicken are calculated under the assumption that the entire intake of 'meat' during the second year consists exclusively of the specified type. The dose contribution from 'meat' that results from assuming that the entire intake consists of beef has been used to estimate the total dose.

3.4. Discussion and conclusions regarding radiation doses

It is evident that high committed effective doses could rapidly be received through intake of contaminated food in an early phase after fallout, and that certain food groups (directly contaminated crops such as leafy vegetables, and milk from grazing animals) are particularly important from a radiation protection perspective.

Committed effective doses from food contamination in the longer term, with more long-lived fission products such as Cs-137 (half-life 30 years), Sr-90 (29 years), and possibly activation products such as Mn-54 (300 days) and Co-60 (5 years), can be expected to be lower than those that may be received in the early phase, but in return they may affect food production over a considerably longer period. In addition to the nuclides mentioned with half-lives of a year or more, fallout from a nuclear explosion also contains nuclides with 'medium' half-lives, such as Sr-89 (51 days), which may play a significant role throughout the first year. The transition between the 'early phase' and 'long term' is therefore not as distinct as the analysis above, with two separate time phases, might suggest. A gradual transition to the situation (second year) described in Section 3.3 can be assumed.

It is also possible to form an estimate of potential doses during the remainder of the first year by assuming that radionuclide concentrations in food after the first two months change only through radioactive decay. This scenario is equivalent to assuming that the food consumed during the rest of the first year was exclusively produced during the first two months after fallout. Under this assumption, summing the intake exclusively of contaminated food during the remainder of the first year (after the first two months) yields a committed effective dose that could reach approximately 3 000 mSv for an adult and approximately 2 000 mSv for a one-year-old child. These estimated doses are mainly attributable to 'leafy vegetables' and (for the one-year-old) to 'milk'. If these food groups are excluded (such as by assuming that these particular foods could be replaced by food from uncontaminated areas), the committed effective doses from food during the remainder of the first year are approximately 200 mSv (adult) and approximately 80 mSv (one-year-old).

To better characterise possible radiation doses under different conditions during the first year after fallout, more detailed and time-resolved radioecological modelling would be required.

In addition to the mainly conservative assumptions described in Chapter 2 and above in Chapter 3, all the above analysis of radiation doses from contaminated food assumes that all food consumed has been produced in areas with the assumed ground deposition from fallout (100 GBq/m² H+1). If only part of the intake consists of contaminated food, the doses decrease proportionally.

4. Effect of limit values for dose from contaminated foodstuffs

Council Regulation (Euratom) 2016/52 sets maximum permitted levels for concentrations of radionuclides in foodstuffs. The specified levels are intended to be applied following a nuclear accident or any other case of radiological emergency that may lead to contamination of food and feed. The purpose is to limit radiation doses via food contaminated by large-scale dispersion of radioactive substances to below one millisievert committed effective dose per year. In the development of the Council's limit values, it has been assumed (for the foodstuffs considered here) that one tenth of consumed food is contaminated up to the maximum permitted level, and that the remaining intake is not contaminated at all.

The limit values for concentrations of radionuclides in foodstuffs set out in the Council Regulation are shown in Table 10. The Regulation specifies limit values for the sum of activities of all nuclides within defined groups. The groups are: (i) isotopes of strontium, (ii) isotopes of iodine, (iii) other nuclides with half-lives longer than 10 days, and (iv) alpha-emitting isotopes of plutonium or heavier elements than plutonium. The table also shows to which groups in the Council Regulation the radionuclides used in the analysis belong.

Table 10. Maximum permitted levels for different groups of radionuclides in various foodstuffs as specified in Council Regulation (Euratom) 2016/52. The table also indicates which specific nuclides within each group were included in the analysis.

Foodstuff	Council limit values (Bq/kg) for different nuclide groups				
	Strontium	Iodine	> 10 days	< 10 days*	Alpha emitters
Early phase	Sr-89, Sr-90, Sr-91	I-131, I-133, I-135	Y-91, Zr-95, Ru-103, Ru-106, Cs-136, Cs-137, Ba-140/La-140, Ce-143, U-237, Pr-143, Ce-141, Ce-144	Y-93, Zr-97, Te-132, Np-239	None
Second year	Sr-89, Sr-90	None	Mn-54, Fe-55, Fe-59, Co-57, Co-58, Co-60, Ru-106, Sn-123, Cs-137, Ce-144	None	None
Wheat flour	750	2000	1250	-	80
Potatoes	750	2000	1250	-	80
Leafy vegetables	750	2000	1250	-	80
Fruit and berries	750	2000	1250	-	80
Milk	125	500	1000	-	20
Beef	750	2000	1250	-	80
Pork	750	2000	1250	-	80
Chicken	750	2000	1250	-	80

*This nuclide group is not included in the Council Regulation.

The radiation doses that may be received through consumption of foodstuffs in which the concentration of radioactivity is limited by a given value depend on which radionuclides contribute to the activity. The Council's limit values have been specifically developed with regard to releases in connection with a nuclear power plant accident. The nuclide composition in fallout from a nuclear explosion can be expected to differ significantly from the nuclide composition in a release associated with a nuclear power plant accident, such as with respect to the content of Cs-137 (relatively much lower in the nuclear weapon case) and Sr-90 (relatively much higher in the nuclear weapon case). In order to assess to what extent the Council's limit values are also suitable for use in the case of fallout from a nuclear explosion, SSM has investigated which committed effective doses could be received from consumption of food with radionuclide concentrations that comply with the Council's limit values, assuming that the radionuclides originate from fallout from a nuclear explosion. It is important to note that the analysis, despite the aim of representing a large part of the diet (see Section 2.1), is based on a limited selection of foodstuffs. Important food categories included in the Council Regulation that are missing are primarily 'liquid food'.⁵

4.1. Calculation of doses when applying limit values

To investigate which committed effective doses could be received through consumption of food with radionuclide concentrations limited by specified values, the concentrations of radionuclides in food from a given initial ground deposition were scaled down by a factor $G_{g,i}$ calculated for each nuclide group g and foodstuff i . The factor $G_{g,i}$ was calculated such that the sum of the activity concentrations $K_{n,i}$ in foodstuff i of nuclides n

⁵ 'Liquid food' is defined as products falling within heading 2009 and Chapter 22 of the Combined Nomenclature (see Annex I to Council Regulation (EEC) No 2658/87; also e.g. <https://cnwebb.scb.se>). The group includes mineral water, fruit, berry and grape juices, soft drinks and other beverages with added sugar, beer, wine, and spirits, as well as vinegar. Milk and drinking water are not included in this group, although the Council's limit values for 'liquid food' are calculated taking tap water consumption into account.

in nuclide group g , after multiplication by $G_{g,i}$, matches the limit value $R_{g,i}$ for nuclide group g in foodstuff i , i.e.

$$G_{g,i} = \frac{R_{g,i}}{\sum_{n \in g} K_{n,i}} = \frac{R_{g,i}}{\sum_{n \in g} M_n F_{n,i}} \quad (6)$$

where the concentrations $K_{n,i}$ [Bq/kg] of radionuclide n in foodstuff i are calculated from the initial ground deposition M_n [Bq/m²] of radionuclide n and the transfer factor $F_{n,i}$ [Bq/kg per Bq/m²] for radionuclide n to foodstuff i , according to Chapter 2.

For each nuclide group g , the activity concentrations for nuclides in the other nuclide groups were also scaled down by the same factor $G_{g,i}$, so that for each foodstuff four sets of activity concentrations for all nuclides were obtained, where in each set all activities were limited based on the limit value for one of the nuclide groups. For each foodstuff there is then a *limiting* nuclide group: the nuclide group for which, when the sum of the activity concentrations in the group corresponds to the limit value, the sum of the activity concentrations in the other nuclide groups remains below their respective limit values. The limiting nuclide group is denoted with index $g = r$.

Estimation of the resulting committed effective doses e_i through intake of foodstuff i , when radionuclide concentrations are limited by the limit values $R_{r,i}$, can then be calculated by inserting in expression 5 (Chapter 2) the factor $G_{g,i} = G_{r,i}$ for the limiting nuclide group r for foodstuff i :

$$e_i = G_{r,i} \cdot \sum_n (M_n d_n F_{n,i}) \cdot m_i = \frac{R_{r,i}}{\sum_{n \in r} M_n F_{n,i}} \cdot \sum_n (M_n d_n F_{n,i}) \cdot m_i \quad (7)$$

The use of a nuclide vector to model fallout means that the initial ground deposition M_n for nuclide n can be written as

$$M_n = M \cdot \mu_n \quad \sum_n \mu_n = 1 \quad (8)$$

where μ_n are the elements of the unit nuclide vector (i.e. each nuclide's relative fraction of the total activity) and the scaling factor M represents the total activity in the ground deposition:

$$M = \sum_n M_n \quad (9)$$

The absolute activity in the ground deposition can then be eliminated from Equation 7, which can instead be written as

$$e_i = \frac{R_{r,i}}{\sum_{n \in r} \mu_n F_{n,i}} \cdot \sum_n (\mu_n d_n F_{n,i}) \cdot m_i \quad (10)$$

which makes it clear that the doses obtained in this part of the analysis, as expected, are not dependent on ground deposition, but rather on the activity concentrations permitted in food. However, the expression does depend on the relative activity fractions of radionuclides in the original fallout (i.e. the nuclide vector). As in other parts of the analysis, SSM's nuclide vector for a ground-level explosion with a 50% fusion fraction has been used (see Section 1.2) unless otherwise stated.

4.2. Early phase (first two months)

Table 11 shows an estimate of the committed effective doses that may be received during the first two-month period after fallout over agricultural land, assuming that the entire food intake during the two-month period consists of food produced on that land and that radionuclide concentrations in the food intake are limited by the values specified in the Council Regulation. The fallout is assumed to originate from a ground-level nuclear explosion with a 50% fission fraction. The limiting nuclide group is also indicated, according to the definition in Section 4.1 above.

Table 11. Estimated doses from intake exclusively of contaminated foodstuffs during the first two months following a nuclear explosion, if the concentrations of radionuclides are limited by the values specified in Council Regulation (Euratom) 2016/52

Foodstuff	Committed effective dose (mSv)		Limiting nuclide group
	Children	Adults	
Wheat flour	0,2	0,1	>10 days
Potatoes	0,6	0,9	Iodine
Leafy vegetables	0,4	0,6	>10 days
Fruit and berries	0,3	0,8	>10 days
Milk	2	0,2	Iodine
Beef*	0,07	0,2	>10 days
Total	3	3	
Pork*	0,08	0,2	>10 days
Chicken*	0,08	0,2	>10 days

*Dose estimates for beef, pork and chicken were calculated under the assumption that the entire intake of 'meat' during the period consists of the specified type. The dose contribution from 'meat' that results from assuming that the entire intake consists of beef has been used to estimate the total committed effective dose.

Since the transfer factors developed so far refer to the first two months (and the second year) after fallout, it is difficult to extend the analysis to the remainder of the first year after fallout. It can be assumed that there is a gradual transition to the situation during the second year described in Section 4.3. An indication of possible doses can be obtained by assuming that radionuclide concentrations in food after the first two months change only through radioactive decay. This scenario is equivalent to assuming that the food consumed during the remainder of the first year was exclusively produced during the first two months. An analysis under this assumption, and otherwise using the same method as described above, shows that the committed effective dose to an adult over the entire first year could then reach approximately 8 mSv (where the largest contributions during the remainder of the year – months 3–12 – come from 'potatoes' and 'meat'), and to a one-year-old child approximately 6 mSv (with the largest contributions during the remainder of the year coming from 'milk' and 'wheat flour'). The limiting nuclide groups are in both cases the same as those indicated in Table 9, except for the foodstuffs 'potatoes' and 'milk'. For 'potatoes', the limiting nuclide group after the first two months changes from 'isotopes of iodine' to 'other nuclides with half-lives longer than 10 days'. For 'milk', the limiting nuclide group after the first two months changes from 'isotopes of iodine' to 'isotopes of strontium'.

4.3. Later phase (second year)

Table 12 shows an estimate of the committed effective doses that may be received during the second year after fallout over agricultural land, assuming that the entire food intake

consists of foodstuffs produced on land affected by fallout and that radionuclide concentrations in the food intake are limited by the values specified in the Council Regulation. The fallout is assumed to originate from a ground-level nuclear explosion with a 50% fusion fraction. In addition to estimated doses and the limiting nuclide group (see Section 4.1), one or more nuclides that dominate the dose contribution are also indicated for each foodstuff, either for both children and adults or for one of the age groups.

Table 12. Estimated doses from intake exclusively of contaminated foodstuffs during the second year following a nuclear explosion, if the concentrations of radionuclides are limited by the values specified in Council Regulation (Euratom) 2016/52

Foodstuff	Committed effective dose (mSv)		Limiting nuclide group	Important nuclide(s)
	Children	Adults		
Wheat flour	0,09	0,13	>10 days	Mn-54
Potatoes	0,07	0,22	>10 days	Mn-54, Sr-90
Leafy vegetables	0,13	0,42	>10 days	Mn-54, Sr-90
Fruit and berries	0,09	0,63	>10 days	Mn-54, Sr-90
Milk	2,2	0,9	>10 days	Mn-54, Sr-90, Cs-137
Beef*	0,3	1,4	>10 days	Sr-90, Ru-106, Cs-137
Total	3	4		
Pork*	0,1	1,3	>10 days	Cs-137
Chicken*	0,1	0,9	>10 days	Cs-137

*Dose estimates for beef, pork and chicken were calculated under the assumption that the entire intake of 'meat' during the period consists of the specified type. The dose contribution from 'meat' that results from assuming that the entire intake consists of beef has been used to estimate the total committed effective dose.

Since it became apparent that the activation product Mn-54 is important for dose calculations and that the results of the analysis depend on the nuclide vector used, SSM in this section also investigated possible doses using alternative nuclide vectors.

The first alternative examined is a nuclide vector in which the activation product Mn-54 has been excluded from the nuclide vector used in the rest of the analysis (ground-level explosion with a 50% fusion fraction, see Section 1.2), including in the calculation of the limiting factors $G_{g,i}$ (see Section 4.1 above). The results are shown in Table 13.

Table 13. Estimated doses from intake exclusively of contaminated foodstuffs during the second year following a nuclear explosion, if the activation product Mn-54 is excluded from the nuclide vector, and the concentrations of radionuclides are limited by the values specified in Council Regulation (Euratom) 2016/52

Foodstuff	Committed effective dose (mSv)		Limiting nuclide group	Important nuclide(s)
	Children	Adults		
Wheat flour	0,5	0,9	>10 days	Sr-90
Potatoes	0,3	1,4	Sr	Sr-90
Leafy vegetables	0,5	1,9	Sr	Sr-90
Fruit and berries	0,3	2,0	Sr	Sr-90
Milk	2,0	0,9	Sr	Sr-90, Cs-137
Beef*	0,3	1,7	>10 days	Sr-90, Ru-106, Cs-137
Total	4	9		
Pork*	0,2	1,6	>10 days	Cs-137
Chicken*	0,1	0,9	>10 days	Cs-137

*Dose estimates for beef, pork and chicken were calculated under the assumption that the entire intake of 'meat' during the period consists of the specified type. The dose contribution from 'meat' that results from assuming that the entire intake consists of beef has been used to estimate the total committed effective dose.

Note that removing nuclides from this part of the analysis does not necessarily mean that the resulting committed effective doses from ingestion of food contaminated up to the specified limit values will be lower. The reason is that these doses are determined by the limit values applied and by the relative activity ratios of the nuclides (see Equation 10).

In particular, it may appear counterintuitive that many dose contributions become significantly higher when Mn-54 is excluded from the nuclide vector (compare values in Table 12 with those in Table 13). This is because, in this part of the analysis, it is the different limit values for radionuclides in food, not a fixed ground deposition, that determine how high the radiation doses will be. Mn-54 constitutes a large share of the activity but does not belong to the nuclides with the highest dose coefficients. Without Mn-54, the sum of activities in the group 'other nuclides with half-lives longer than 10 days' becomes smaller relative to the group 'isotopes of strontium'. This allows the total activity in food to increase until a limit value is reached again, in this case most often the limit value for the strontium group.

The second alternative examined is a nuclide vector consisting only of fission products. This was done by excluding all activation products from the nuclide vector used in the rest of the analysis (ground-level explosion with 50% fusion fraction, see Section 1.2). The results are shown in Table 14.

Table 14. Estimated doses from intake exclusively of contaminated foodstuffs during the second year following a nuclear explosion, if the fallout consists only of fission products, and the concentrations of radionuclides are limited by the values specified in Council Regulation (Euratom) 2016/52

Foodstuff	Committed effective dose (mSv)		Limiting nuclide group	Important nuclide(s)
	Children	Adults		
Wheat flour	1,2	2,5	Sr	Sr-90
Potatoes	0,3	1,4	Sr	Sr-90
Leafy vegetables	0,5	1,9	Sr	Sr-90
Fruit and berries	0,3	2,0	Sr	Sr-90
Milk	1,8	0,9	Sr	Sr-90, Ru-106, Cs-137
Beef*	0,3	1,9	>10 days	Sr-90, Ru-106, Cs-137
Total	4	11		
Pork*	0,2	1,7	>10 days	Cs-137
Chicken*	0,1	0,9	>10 days	Cs-137

*Dose estimates for beef, pork and chicken were calculated under the assumption that the entire intake of 'meat' during the period consists of the specified type. The dose contribution from 'meat' that results from assuming that the entire intake consists of beef has been used to estimate the total committed effective dose.

4.4. Discussion and conclusions regarding the Council's limit values

The purpose of the analysis presented here regarding radiation doses from the intake of foodstuffs in which radionuclide concentrations are restricted by the Council's limit values has primarily been to examine to what extent the specified limits are appropriate for use in a situation involving large-scale radioactive fallout following a nuclear explosion, i.e., whether they lead to restriction of committed effective doses from food intake to the intended extent.

The results in Sections 4.2 and 4.3 show that consumption exclusively of foodstuffs contaminated by fallout from a nuclear explosion up to the limit values specified in the Council Regulation may lead to committed effective doses of a few millisieverts in an early phase (the first months), and to doses during the second year after fallout of a few millisieverts, or to on the order of ten millisieverts depending on the assumed nuclide vector. At the end of Section 4.2, a discussion was presented regarding potential radiation doses during the (somewhat later) part of the first year that has not yet been modeled with ECOSYS. Based on that discussion, it appears reasonable that committed effective doses during the entire first year from ingestion exclusively of food contaminated up to the maximum permitted concentrations according to the Council's limit values could also amount to on the order of ten millisieverts.

Given the assumptions used in deriving the Council's limit values (that one tenth of the consumed food is contaminated up to the maximum permitted levels and the rest is not contaminated at all), committed effective doses from ingestion after fallout from a nuclear explosion could thus amount to around one millisievert. Under the same assumptions, and with the same level of ambition regarding radiation doses from food, the Council's limit values should therefore be suitable for use also in a situation where crops have been contaminated by fallout from a nuclear explosion, at least until a more detailed analysis of the nuclide composition of the fallout has been carried out. If these assumptions are not

met, i.e., if a larger proportion of food than one tenth is contaminated, the radiation doses will be correspondingly higher.

These conclusions regarding the effect of applying the Council's limit values to restrict committed effective doses from ingestion of food contaminated by fallout from a nuclear explosion also hold if the nuclide composition of the fallout is varied through different assumptions about the presence of neutron activation products.

5. Intervention levels for food impact

Intervention levels are measurable quantities linked to the need to take a specific action. Thus, by defining intervention levels for the impact of radioactive fallout on foodstuffs, the aim is to facilitate the assessment of whether a given ground deposition, measured or calculated, may lead to a situation where measures should be taken to limit radiation doses from the ingestion of foodstuffs.

The limit values specified in the Council Regulation have, in the previous section, been found to be suitable for use also in the case of fallout following a nuclear explosion, at least initially. SSM has used the dose calculations presented above, together with the Council's limit values, to derive appropriate intervention levels for the impact on foodstuffs after such fallout. If fallout in an area is assessed to exceed these intervention levels, this indicates a risk that the Council's limits for radionuclide concentrations may be exceeded in food produced in the area.

5.1. Method to calculate intervention levels

Given a set of limit values $R_{g,i}$ [Bq/kg] for the activity concentration of a given group g of radionuclides in foodstuff i , intervention levels D_i [Bq/m²] can be estimated for ground deposition that may lead to exceedance of these limits in foodstuff i . In calculations of fallout following nuclear explosions, SSM often uses the time-invariant fallout metric H+1 (see Chapter 3). Table 7 provides, for orientation, some measures of what a ground deposition of 100 GBq/m² H+1 represents. In SSM's modelling, the total fallout from a nuclear explosion at ground level of 100 kilotons with a 50% fusion fraction contains, by definition, $1.1 \cdot 10^{21}$ Bq H+1. In this work, estimated intervention levels will primarily be expressed in terms of the time-invariant fallout metric H+1.

If the activity of a given nuclide n constitutes a fraction H_n of the total fallout amount (H+1) at the time of initial ground deposition (assumed to be 48 hours after the explosion according to the discussion in Chapter 3), a possible intervention level $D_{g,i}$ [Bq/m²] (expressed in H+1) for exceedance of the limit value $R_{g,i}$ [Bq/kg] for the nuclide group g in foodstuff i can be calculated based on transfer factors $F_{n,i}$ [Bq/kg per Bq/m²] using the following expression:

$$D_{g,i} = \frac{R_{g,i}}{\sum_{n \in g} (F_{n,i} \cdot H_n)} \quad (11)$$

The summation in the denominator is carried out over the nuclides in nuclide group g .

The overall intervention level D_i for exceedance of a set of limit values in foodstuff i is given by the nuclide-group-specific intervention level $D_{g,i}$ that results in the limit values for the other nuclide groups not being exceeded in foodstuff i . The nuclide group for which this intervention level is determined is the limiting nuclide group.

5.2. Indicative intervention levels from the Council's limit values

Indicative intervention levels for exceedances of foodstuff limit values during the first two months following fallout, calculated as described above based on the limit values specified in the Council Regulation and the nuclide vector for a ground-level explosion with a 50% fusion fraction, are presented in Table 15. In addition to the intervention level calculated in terms of the time-invariant deposition metric H+1, the limiting nuclide group is also shown, along with examples of what each deposition level corresponds to in terms of measurable quantities such as external dose rate from the ground and ground deposition of selected key radionuclides.

Tabell 15. Indicative intervention levels for exceedance of the Council's limit values in an early phase (first months)

Fallout metric	Intervention level							
	Wheat flour	Potatoes	Leafy vegetables	Fruit and berries	Milk	Beef	Pork	Chicken
Limiting nuclide group	>10 d	Iodine	>10 d	>10 d	Iodine	>10 d	>10 d	>10 d
H+1 (GBq/m ²)	0,2	1	0,001	0,04	0,005	5	50	55
Dose rate* at t = 60 min (mSv/h)	0,7	4	0,004	0,2	0,02	20	180	200
Dose rate* at t = 7 days (μSv/h)	1	6	0,006	0,2	0,03	30	290	320
I-131 at t = 7 days (kBq/m ²)	30	230	0,2	7	0,8	830	8 300	9 100
Cs-137 (kBq/m ²)	0,06	0,3	0,0003	0,01	0,001	1,5	15	16

Dose rate was calculated as $H^(10)$ using dose factors from ICRP [11] for a fallout distribution in the surface layer of the ground of 0,5 g/cm².

Indicative intervention levels for exceedances of the Council's foodstuff limit values at a later stage (the second year after fallout), based on the nuclide vector for a ground-level explosion with a 50% fusion fraction, are presented in Table 16. The table also shows the intervention levels resulting from the calculation when the activation product Mn-54 is excluded from the analysis, as well as the intervention levels obtained when all activation products are excluded.

Table 16. Indicative intervention levels for exceedance of the Council's limit values in the longer term (second year), with limiting nuclide groups, for the case with all modelled nuclides included in the analysis, for the case with the activation product Mn-54 excluded, and for the case with all activation products excluded

Foodstuff	All nuclides		Excluding Mn-54		Excluding all activation products	
	Limiting nuclide group	Intervention level GBq/m ² H+1	Limiting nuclide group	Intervention level GBq/m ² H+1	Limiting nuclide group	Intervention level GBq/m ² H+1
Wheat flour	> 10 d	1,4	> 10 d	38	Sr	120
Potatoes	> 10 d	0,8	Sr	10	Sr	10
Leafy vegetables	> 10 d	1,0	Sr	6,6	Sr	6,6
Fruit and berries	> 10 d	1,5	Sr	6,1	Sr	6,1
Milk	> 10 d	17	Sr	18	Sr	18
Beef	> 10 d	3,9	> 10 d	4,7	> 10 d	5,3
Pork	> 10 d	25	> 10 d	32	> 10 d	34
Chicken	> 10 d	40	> 10 d	43	> 10 d	83

Tables (similar to Table 15) presenting certain measurable quantities corresponding to the deposition levels given in Table 16 are provided in the Appendix.

Several of the calculated intervention levels for impact during the second year are significantly higher than those calculated for short-term impact (Table 15), i.e. a higher deposition is required to produce long-term effects than short-term effects. This does not apply to potatoes, beef, pork, or chicken. For potatoes, this is because the H+1-weighted transfer factors in the denominator of Equation 11 in the early phase are consistently small and are entirely dominated by I-131, whereas in the second year they are dominated by Mn-54 with a weighted transfer factor similar to that of I-131 in the early phase. For the different types of meat, it is because the weighted transfer factors are dominated by caesium in both the early and later phases, and Cs-137 plays a more dominant role in the later phase than in the early phase.

5.3. Discussion and conclusions regarding intervention levels

Since fallout from a nuclear explosion in the early phase is dominated by short-lived radionuclides, the most easily measurable quantity (external dose rate) changes (decreases) very rapidly. The dose rates in Table 15 show that, for several foodstuffs, fallout that could lead to exceedances of limit values in the short term may be difficult to detect using simple measurements after a few days or weeks. In contrast, fallout that risks causing long-term foodstuff contamination should be detectable by dose rate measurements in an early phase (Table 16 and the corresponding dose-rate tables in the Appendix).

More generally, however, the analysis shows that it is difficult to establish appropriate intervention levels for food contamination before the radionuclides present in the fallout have been quantified through detailed measurements. In addition to the case of the activation product Mn-54 illustrated above, this also applies to other nuclides, such as the activation products Co-57 and Co-60.

There are some evident differences between the indicative intervention levels presented in Table 15 and the corresponding intervention levels used in emergency preparedness for severe nuclear power plant accidents [12]. The latter are derived from the same limit values (specified in the Council Regulation) as the intervention levels in Table 15, and the differences therefore arise from one or more of the following factors:

- assumptions regarding the composition of the fallout
- assumptions and approximations in the derivation of the intervention levels
- the radioecological modelling.

An example of the first factor is the intervention level for leafy vegetables expressed as ground deposition of Cs-137, where a value of 0.5 kBq/m² Cs-137 is used in nuclear emergency preparedness, whereas a value of 0.0003 kBq/m² is given in Table 15. In this case, the difference is mainly due to the fact that Cs-137 constitutes a negligible fraction of the activity in the limiting nuclide group (nuclides with half-lives longer than 10 days) in the early phase following fallout from a nuclear explosion. If Cs-137 is used as a ‘marker nuclide’ in an early phase, the activity concentration of Cs-137 corresponding to a given ground deposition (in this case 0.001 GBq/m² H+1) will therefore be very small. If, instead, Ba-140 (half-life 13 days) is chosen as the marker nuclide, the corresponding activity concentration of Ba-140 is found to be 0.3 kBq/m².

An example where all three factors interact and contribute to the difference between the two cases is the intervention level for milk expressed as ground deposition of I-131, where a value of 5 kBq/m² I-131 is used in nuclear emergency preparedness, whereas a value of 0.8 kBq/m² is given in Table 15. There is some difference in the relative distribution of iodine isotopes in the nuclide vectors used in the two cases. The nuclide vector used for fallout following a nuclear explosion contains significantly more of the short-lived isotope I-133 (half-life 20 hours), meaning that this isotope has been considered relevant alongside I-131 in the early phase. Since the modelling results used only provide maximum transfer factors during the first two months, this has been addressed by summing the maximum concentrations of the two isotopes in milk, even though they do not necessarily reach their maximum concentrations at the same time. This simplification is discussed in Section 3.2. For releases from a nuclear power plant accident, I-133 has not been considered when establishing the intervention level for I-131. This, in turn, results in a higher estimated ground deposition required to exceed the iodine limit value in milk, and a higher activity concentration of I-131 corresponding to that deposition, compared with the case of fallout from a nuclear explosion.

Finally, circumstances may arise in which higher limit values for radionuclides in foodstuffs than those specified in the Council Regulation need to be tolerated. Although in this report intervention levels have been calculated based on the Council’s limit values, intervention levels can (given appropriate input data) be calculated using Equation 11 based on any chosen set of limit values $R_{g,i}$.

6. Needs for further development

There are several steps where further development could reduce the significant uncertainties in the analysis presented here, or otherwise complement the analysis.

Radioecological modelling could be carried out for more radionuclides. This would improve the estimates of committed effective doses and intervention levels that have been

presented, since the estimates are clearly sensitive to whether certain individual radionuclides are included or not. This may be because these particular nuclides are especially important, but it may also partly be due to the limited initial selection of nuclides. Modelling results for more nuclides would also improve preparedness to supplement the present analysis with cases where the composition of fallout differs from what has been assumed here, as could be the case due to fractionation during the formation and dispersion of fallout, or due to the presence of other activation products.

Modelling of further foodstuffs could also increase understanding of which types of ingestion that may lead to particularly high committed effective doses over different time intervals. To the extent that new foodstuffs are modeled, the intake data used in the analysis would also need refinement. Chapter 1, for example, mentioned the likely overestimation of doses resulting from representing the intake of 'leafy vegetables' (which sometimes have high doses per unit mass intake) with intake data for 'vegetables' in general. If other types of vegetables, likely to be contaminated in different ways and to different extents, are modeled, intake data must also reflect the proportion of consumption represented by each modeled vegetable type.

Radioecological modelling could also be carried out for more, and possibly shorter, time periods, i.e., with higher temporal resolution, at least for periods during the first year after fallout. This would reduce the large uncertainties, especially in the very early phase, that arise from summing dose contributions from different nuclides even though they are likely to reach their maximum concentrations in food at different times.

It would also be of interest to extend the modelling to longer time horizons than the second year, mainly to enable comparison with earlier studies that have examined Cs-137 and Sr-90, which are assumed to be the most important nuclides in the long term. [13]

The radioecological modelling performed includes a number of assumptions, which have largely been conservative in nature (i.e., tending to overestimate rather than underestimate possible concentrations in food). It would be desirable to analyse these assumptions more closely to better understand how conservative the results of the analysis are. However, the potential to obtain a more useful analysis by making the radioecological model more detailed is likely limited in several respects. One example is that many properties of radioactive fallout following a nuclear explosion are poorly known or dependent on specific circumstances. Nor is a model that strongly depends on conditions in a specific area, or on season, or other details, necessarily preferable when the application is emergency response planning for an event occurring at a time and place unknown beforehand.

The Swedish Defence Research Agency (FOI) has modeled the uptake and dilution of radionuclides from fallout in lake water used as a source of drinking water, as well as, under various assumptions regarding water treatment in drinking water production, the concentrations of radionuclides that can be expected in consumers' drinking water. [6] FOI also calculated possible intervention levels based on the limit values for liquid foodstuffs specified in the Council Regulation. The need for modelling and analysis of the impact on drinking water from fallout following nuclear explosions has therefore not been as strong as for other foodstuffs, and the present work has not included analysis of impacts on drinking water. However, it could be of interest, based on FOI's modelling results [6], to estimate potential radiation doses from contaminated drinking water. Given the strong dependence on which nuclides are assumed to be present in the fallout, it

would also be of interest, based on FOI's modelling results, to estimate possible intervention levels under different assumptions about nuclide composition than those used by FOI.

DTU's work on behalf of SSM [1] [2] also included the uptake and dilution of radioactive fallout in surface water bodies, with the aim of using specified bioaccumulation factors to estimate which radionuclides are of greatest importance for committed effective dose through the consumption of fish. However, since fishing waters shortly after radioactive fallout are not systems in equilibrium, dynamic modelling is required to estimate activity concentrations in fish, committed doses under different conditions, and possible intervention levels. It would be of interest to carry out such modelling. Possibly, FOI's model [6] for time-dependent concentrations of radionuclides in lake water could also be useful as part of such an analysis.

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Appendix: H+1 Intervention levels expressed as measurable quantities

The intervention levels corresponding to the Council's limit values⁶, calculated using the method in Chapter 5 for the second year after a fallout event, are presented in Table 16. In this appendix, the same limit values are shown together with values for several quantities (dose rates and ground deposition) that could be measured at the specified fallout level (H+1). The tables indicate the limiting nuclide group using the notation '>10 d' for the sum of nuclides with half-lives longer than 10 days (excluding isotopes of iodine, strontium, or alpha-emitting isotopes of plutonium and transplutonium elements), and 'Sr' for the sum of strontium isotopes.

Intervention levels calculated for the second year after fallout are presented in Table B1 (with all nuclides included in the analysis), in Table B2 (with the activation product Mn-54 excluded from the analysis), and in Table B3 (with all activation products excluded from the analysis).

Table B1. Indicative intervention levels for exceedance of the Council's limit values in the longer term (second year), if all modelled radionuclides are included in the assumed nuclide composition

Fallout metric	Intervention level							
	Wheat flour	Potatoes	Leafy vegetables	Fruit and berries	Milk	Beef	Pork	Chicken
Limiting nuclide group	>10 d	>10 d	>10 d	>10 d	>10 d	>10 d	>10 d	>10 d
H+1 (GBq/m ²)	1,4	0,8	1,0	1,5	17	3,9	25	40
Dose rate* at t = 60 min (mSv/h)	5	3	4	6	62	15	92	150
Dose rate* at t = 7 days (μSv/h)	8	5	6	9	98	23	150	230
I-131 at t = 7 days (kBq/m ²)	230	130	180	7	2 800	660	4 100	6 600
Cs-137 (kBq/m ²)	0,4	0,2	0,3	0,01	5	1,2	7	12

Dose rate was calculated as H(10) using dose factors from ICRP [11] for a fallout distribution in the surface layer of the ground of 0,5 g/cm².

Table B2. Indicative intervention levels for exceedance of the Council's limit values in the longer term (second year), if the neutron activation product Mn-54 is excluded from the assumed nuclide composition

Fallout metric	Intervention level							
	Wheat flour	Potatoes	Leafy vegetables	Fruit and berries	Milk	Beef	Pork	Chicken
Limiting nuclide group	>10 d	Sr	Sr	Sr	Sr	>10 d	>10 d	>10 d
H+1 (GBq/m ²)	38	10	6,6	6,1	18	4,7	32	43
Dose rate* at t = 60 min (mSv/h)	140	37	24	22	66	17	120	160
Dose rate* at t = 7 days (μSv/h)	220	58	38	35	100	27	190	250
I-131 at t = 7 days (kBq/m ²)	6 300	1 700	1 100	1 000	3 000	780	5 300	7 100
Cs-137 (kBq/m ²)	11	3	2	2	5	1,4	9	13


Dose rate was calculated as H(10) using dose factors from ICRP [11] for a fallout distribution in the surface layer of the ground of 0,5 g/cm².

⁶ Council Regulation (Euratom) 2016/52

Table B3. Indicative intervention levels for exceedance of the Council's limit values in the longer term (second year), if all neutron activation products are excluded from the assumed nuclide composition

Fallout metric	Intervention level							
	Wheat flour	Potatoes	Leafy vegetables	Fruit and berries	Milk	Beef	Pork	Chicken
Limiting nuclide group	Sr	Sr	Sr	Sr	Sr	>10 d	>10 d	>10 d
H+1 (GBq/m ²)	120	10	6,6	6,1	18	5,3	34	83
Dose rate* at t = 60 min (mSv/h)	440	37	24	22	66	20	130	310
Dose rate* at t = 7 days (μSv/h)	700	58	38	35	100	31	200	480
I-131 at t = 7 days (kBq/m ²)	20 000	1 700	1 100	1 000	3 000	880	5 600	14 000
Cs-137 (kBq/m ²)	36	3	2	2	5	1,6	10	25

Dose rate was calculated as H(10) using dose factors from ICRP [11] for a fallout distribution in the surface layer of the ground of 0,5 g/cm².



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