Strål säkerhets myndigheten
Swedish Radiation Safety Authority

Report

Radiological Consequences of Fallout from Nuclear Explosions

Appendix 2 – Nuclide Composition

2023:05e

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Date: November 2023
Report number: 2023:05e
ISSN: 2000-0456
Available at www.ssm.se

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1. Introduction

This appendix provides a detailed account of how the nuclide vector, used by the Swedish Radiation Safety Authority (SSM) in the dispersion and dose calculations and other analyses within the framework of this study, was developed.

The energy released in a nuclear explosion comes from fission of heavy atomic nuclei or from fusion of light atomic nuclei such as deuterium and tritium. To achieve fusion, a primary fission charge is required. Therefore, all nuclear explosions have a fission component, while the proportion of fusion energy can vary from zero to a relatively high proportion of fusion. Nuclides formed in fission are called “fission products”. Radioactive materials can also be formed in materials in and around an exploding nuclear weapon that are affected by high neutron fluxes during the explosion. Nuclides formed by neutron reactions are referred to as “activation products,” many of which are radioactive. In this study, the activation products have been divided into two subclasses, depending on whether neutron activation occurs in weapons components or in the environment.

For the radiological consequences considered by SSM in this report, the most important radioactive materials are either fission or activation products. The nuclide vector therefore consists of a set of fission and activation products with associated activities at a given time. Other radioactive materials can also be dispersed after a nuclear explosion, such as un-fissioned uranium and plutonium. However, these have not been considered in this report.

Radioactive substances decay into new substances that can in turn be radioactive as well. Based on the nuclide vector at a certain point in time, and with knowledge of the half-lives and decay products of the constituent nuclides, a new nuclide vector can be calculated for an arbitrary subsequent point in time. In this study, SSM has produced a nuclide vector containing 129 nuclides at the time 10 minutes after a nuclear explosion according to the main scenario. This nuclide vector describes at least 95% of the dose contribution during the time interval between the first day and the first year for the exposure pathways studied in the report.

This appendix describes, step by step, the calculations performed and trade-offs made in order to develop a representative nuclide vector for calculating radiological consequences in connection with nuclear explosions. Initially, Chapters 2 and 3 describe how activity for fission and activation products per kiloton explosive yield was estimated. Thereafter, Chapter 4 describes how the selection of nuclides has been made, from the initial thousand or so nuclides formed in the nuclear explosion, to the 129 that SSM deems necessary to calculate radiation doses to humans from the studied exposure pathways within the first year. Finally, Chapter 5 presents the nuclide vector for the main scenario. The nuclide vector is also presented in a normalised form (per kiloton explosive yield) with references to further reading on the selection of each nuclide.

2. Fission products

2.1. Fission reactions

In a nuclear explosion, large amounts of radioactive substances are produced, the majority of which are fission products formed in neutron-induced fission reactions in various parts of the weapon. Depending upon the design of the weapon, a number of different fission reactions may occur, with different fissioning materials and varying neutron energies. Details of this kind are not known, and in any case, SSM has strived for a generic analysis that is as representative as possible of different types of nuclear weapons. In the present study, SSM has therefore only considered the following three fission reactions: fission of U-235 and Pu-239 with fission spectrum neutrons (represented by monoenergetic neutrons of energy 1 MeV) and fission of U-238 with high-energy neutrons (represented by monoenergetic neutrons of energy 14 MeV). The first two reactions are assumed to represent a fission weapon and the latter fission in uranium parts in a fusion weapon [1].

2.2. Initial unit vector

The initial unit vector, i.e. the activity of fission products per kiloton (kt) at time t = 0, was estimated by the method reported by the Swedish Defence Research Agency (FOI) in Memorandum 7177 [2]. The estimation is based on three steps. First, the number of fissioned atoms N corresponding to an explosive yield of one kiloton from fission is calculated for each fission reaction as follows,

$$N = \frac{4{,}2 \cdot 10^{12}\ [\mathrm{J/kt}]}{E \times 1{,}6 \cdot 10^{-13}[\mathrm{J/MeV}]}$$

where E is the energy per fission [MeV]. Then the number of atoms formed by the fission products can be estimated by using tabulated fission yields y_i for each fission reaction. Finally, the initial unit activity, A_i [Bq/kt], of nuclide i is obtained by multiplication with the decay constant of the nuclide, λ_i [s^{-1}], as follows

$$A_i = N \cdot y_i \cdot \lambda_i$$

Input parameters and references are summarised in Table 1

Table 1. Input parameters, references and calculation results for initial unit vectors for the three fission reactions.

Fission reaction	Energy per fission, *E* (MeV)	Atoms per kiloton, *N*	Total initial activity, *A* (Bq/kt)
U-235 (fission neutrons) *	182.5 **	1.44E+23	5.57E+22
Pu-239 (fission neutrons) *	189.2 **	1.39E+23	4.18E+22
U-238 (high energy neutrons) *	183.6 **	1.43E+23	1.17E+23

*) Fission yields y_i from JEFF 3.1

**) E from ENDF-B-VIII-0

Subsequently, SSM has calculated decay and ingrowth for the initial unit vectors during 10 minutes from the time of the explosion to be used as input values in the source description

for further dispersion and dose calculations. The resulting unit vectors can be scaled linearly to model fission products from the desired fission yield. For example, activities from the fission products created in the fission process for the main scenario, 100 kt ground-level explosion with 50% fusion, can be obtained by multiplying a selected unit vector at 10 minutes by 50.

In Table 2 the total activity during the first hour for the three unit vectors, depending on the type of fission, is presented. For comparison, [3] gives a total activity per kiloton of the order of $1 \cdot 10^{21}$ Bq/kt after one minute and [4] $1.67 \cdot 10^{19}$ Bq/kt (450 MCi/kt) after one hour for an unspecified fission device. Both estimates agree well with the total activities reported in Table 2.

Table 2. Total activity per kiloton (Bq/kt) at different times for the three unit vectors.

	Total activity in the unit vectors (Bq/kt)		
Fission reaction	**t = 1 min.**	**t = 10 min.**	**t = 60 min.**
U-235	1.10E+21	1.01E+20	1.61E+19
Pu-239	9.68E+20	1.00E+20	1.48E+19
U-238	1.22E+21	1.05E+20	1.56E+19

3. Activation products

3.1. Introduction

During the explosion, materials in and around an exploding nuclear weapon are affected by high neutron fluxes. This leads to the formation of activation products, many of which are radioactive. Which activation products in particular are formed and in what quantity is even more dependent on the details of the specific explosion than is the case with fission products. SSM has nevertheless chosen to include a contribution from activation products in the analysis, based to some extent on empirical information and data as described below. The contribution of activation products to total radiation doses, and in particular the choice of specific activation products, is associated with large uncertainties and contains a greater degree of arbitrariness than in the case of fission products.

3.2. Method

The methodology for estimating the activation nuclide vector is based on published empirical "rules of thumb" along with published analyses of observed deposition from a dose point of view of.

- The activation fraction ("fission equivalent yield") according to the *KDFOC3* [5] fallout model for several types of nuclear explosions.
- Specific nuclides that make up the activation fraction from Hicks' analyses [6] [7] [8] [9] [10], mainly of fallout from nuclear tests in Nevada.

The available activity in *KDFOC3* is expressed as a dose rate one metre above ground one hour after the explosion, assuming that all fallout is spread evenly over a given area[1]. In order to include activation products in the same algorithm, *KDFOC3* expresses the dose contribution from activation products as *fission equivalent yield* (in kilotons). A kiloton of fission equivalent yield is defined as a fallout contribution that, over the period 10 minutes to 50 hours, releases the same gamma energy as the fission products from a kiloton of fission yield.

By analogy with the *KDFOC3* method, a fission equivalent yield contribution from the fusion part of a given explosion was therefore estimated according to the empirical rules of thumb used in *KDFOC3*. It was then determined which specific nuclides (activation products) should account for this contribution and what their mutual proportions should be. This was estimated from Hicks' analyses of fallout from test explosions in Nevada, which include a number of activation products.

The contribution to the ground dose from the initial set of activation products was calculated with SSM's *DosCalc*[2] software for the time period 10 minutes to 50 hours together with the contribution to the ground dose during the same time interval from a nuclide vector of fission products. The fission product vector chosen for this purpose was the distribution of fission products (except noble gases) from the fission of U-235 with monoenergetic (1 MeV) neutrons, since this gives the largest ground dose of the three fission reactions considered in the time interval in question. Finally, the activation nuclide

[1] Fission products from one kiloton of fission yield spread evenly over one square mile give an exposure rate of 3,000 R/h. For external exposure to gamma radiation, as in this case, this means a dose rate of 30 Gy/h absorbed dose.
[2] DosCalc v 1.0 (Manual 20-914)

vector was normalised so that its dose contribution is the *KDFOC3* estimated fraction of the dose contribution from the total nuclide vector (U-235 fission plus activation). The method was used to define two different activation nuclide vectors: one from weapons components and one from the ground (*i.e.* environment), which are normalised separately.

In the final step, the list of activation products was shortened to include only those with a significant dose contribution. This step also included a comparison with the dose contribution of the fission products (see Chapter 4).

3.3. Activation fraction

KDFOC3 proposes, as a rule of thumb, the following fission equivalent yield contributions from activation for nuclear weapons with significant fusion fraction (and not designed to specifically attenuate neutron fluxes) and "standard soil":

- 0.08 kt fission equivalent yield per kt of fusion yield from ground activation for a ground-level explosion
- An additional 0.08 kt of fission equivalent per kt of fusion yield from ground activation for buried explosions
- 0.02 kt fission equivalent yield per kt fusion yield from activation in weapons components

For detailed studies of specific scenarios (*e.g.* regarding weapon design or ground type), it would be necessary to consider the extent to which these rules of thumb are applicable, but in this study SSM has chosen to use them as they are. For the main scenario, a 100 kt ground-level explosion with a 50 % fusion fraction, this method results in 50 kt of fission products and 50 x (0.08 + 0.02) kt = 5 kt of fission equivalent contribution from the activation by fusion neutrons (4 kt of activation in the ground and 1 kt of activation in weapons components). The rules of thumb in *KDFOC3* do not include any activation contribution from explosions without a fusion component.

3.4. Potential activation products

The fission equivalent yield contribution from activation estimated according to the *KDFOC3* method above needs to be distributed as activity for a number of activation products to fit the nuclide vector, which is based on activity at time t = 10 minutes. Here, SSM has proceeded from Hicks' analyses of off-site fallout from nuclear tests in Nevada and adapted the results to a potential nuclide vector with activation products that can be expected given the circumstances surrounding the tests. The neutron activation nuclides included in Hicks' analyses can be divided into nuclides that are lighter than the fission products ("light") and nuclides that are heavier than the fission products ("heavy"). Somewhat different questions arise about the two groups.

3.4.1. Light activation products

The light activation products included in the Hicks analyses (plus two more, see below) are listed in Table 3. For each nuclide, several activation reactions may be possible, but the table lists only the activation reaction with the highest probability, which is then used further in the analysis. In Table 3 the assumed relative abundance is also given, based on Hicks' studies. Here, data from nuclear weapon tests at or below the ground surface have been used, as these can be assumed to be most relevant for describing possible activation products for the main scenario used in this study (*i.e.* a ground-level explosion). Among

these nuclear weapon tests, special importance has been attached to the relative abundance of activation products from *Sedan* (100 kt) and *Schooner* (30 kt) since these tests had a high fusion yield, which is in line with the main scenario.

Some nuclides could conceivably be produced both in connection with activation of weapons components and the environment (ground activation). SSM has therefore investigated which reactions might give rise to the activation products reported by Hicks. In this study, the following assumptions have been made to easily categorise individual nuclides to a certain type of activation:

- Particle reactions such as (n,p) are assumed to occur on weapon components because they only occur when the neutron energy exceeds a threshold value, and the highest energy neutrons can be expected to be closest to the source.
- Neutron capture reactions such as (n,γ) on materials common in ground material are assumed to occur in the environment
- Other capture reactions are assumed to occur in weapon components.

Table 3. Light activation products and limiting reactions considered in the present study. Relative abundance indicates numbers relative to others in the same group: weapons components or the environment. For example, ten times as many atoms of Mn-54 as Co-57 and ten times as many atoms of Fe-55 as Na-24 are assumed, but not necessarily ten times as many atoms of Mn-54 as Na-24.

Nuclide	Activation of	Potential reaction	Relative abundance
Be-7 *	Weapon components	^{6}Li(d,n)	10
Na-24	Environment	^{23}Na(n,γ)	1
Fe-55	Environment	^{54}Fe(n,γ)	10
Fe-59	Environment	^{58}Fe(n,γ)	0.1
Mn-54	Weapon components	^{54}Fe(n,p)	10
Mn-56	Environment	^{55}Mn(n,γ)	1
Co-58	Weapon components	^{58}Ni(n,p)	0.5
Co-58m	Weapon components	^{58}Ni(n,p)	0.5
Co-57	Weapon components	^{58}Ni(n,np)	1
Co-60	Weapon components	^{59}Co(n,γ)	1
Cu-64	Weapon components	^{63}Cu(n,γ)	0.1
Cu-67	Weapon components	^{67}Zn(n,p)	1E-6

* For simplicity, Be-7 is referred to in this study as an activation product, even though the dominant production reaction is likely to occur in the fusion fuel and does not primarily involve neutrons.

Two nuclides have been added in addition to the light activation products found in Hicks' analyses: Mn-56 and Co-58m. These appear in other works, such as Kraus and Foster [11], as potentially important activation products. In the case of Mn-56, the probability of neutron capture on the target nuclide Mn-55 is a factor of 50 higher than for the neutron capture that produces Na-24, but on the other hand, the average abundance of the target nuclide Na-23 in the earth's crust is about a factor of 50 higher than the abundance of Mn-55, which means that the relative abundance for Mn-56 is set to the same as for Na-24 [12].

Regarding the relative abundance of Co-58m, the same assumption has been used as in Kraus and Foster, *i.e.* that the abundance of Co-58m is the same as that of the ground state, Co-58. These two nuclides have therefore been assumed to share the reaction yield by setting the relative abundance to 0.5.

3.4.2. Heavy activation products

The same method as described above for the light activation products was used for the heavy activation products. The list of potential heavy activation products, and their relative abundances, which then emerges according to Hicks is shown in Table 4 together with possible production reactions. All the nuclides in the table can be assumed to be produced by neutron reactions in weapons components. The nuclides can be categorised into five groups as described below.

Uranium (U) and neptunium (Np)
Hicks reports a certain population of Np isotopes already at t = 0. However, these isotopes also form as decay daughters of uranium. From the reported results of test explosions it can be concluded that the number of atoms of U-239 and U-240 formed is expected to exceed the original number of atoms of the daughters Np-239, Np-240 and Np-240m by many orders of magnitude. The initial contribution of these Np isotopes can therefore be neglected. Instead, the Np isotopes will grow in from the respective U parent.

The three uranium isotopes U-237, U-239 and U-240 are included as potential heavy activation products. The relative abundances of U-237 and U-239 are assumed to be higher than those reported by Hicks for the *Sedan* and *Schooner* tests. Instead, the relative abundance of these nuclides has been based on a hypothetical case included in Hicks' account involving the fission of U-238. The corresponding relative abundance for U-240 is two orders of magnitude lower, in line with what Hicks reports.

Americium (Am) and curium (Cm)
The actinides Am-241 and Cm-242 can be assumed to be present in the fissile material via the decay of Pu-241 and activation of Am-241, respectively. Both nuclides give low gamma doses in connection with radioactive material deposited on the ground but could contribute to inhalation doses. However, a limitation in this study has been that un-fissioned fissile material such as Pu-239 is not considered. Therefore, Am-241 and Cm-242 have not been considered further as potential activation products.

Tungsten (W)
The tungsten isotopes may represent designs with heavy material other than uranium in certain components where it is often assumed that uranium is used, possibly to reduce the amount of fission products [13]. Hicks reports W-activation mainly in tests associated with the *Plowshare* programme, where limiting the amount of fission products would have been an important consideration[3], and especially in the tests with high explosive yield and high proportion of fusion (*Sedan* and *Schooner*). If so, it is not clear that the same trade-off is typical for a design intended for use in a nuclear weapon. On the other hand, it can be argued that tungsten is a very efficient material in some respects, even compared to uranium [14]. Whatever the design considerations are, the end result appears to be similar from the point of view of this investigation: if a tungsten design is used, W-187 especially may contribute to dose, but in return the dose contribution from fission products should be

[3] *Plowshare* was an American programme between 1958 and 1975 to investigate the technical and economic feasibility of using nuclear explosives for peaceful purposes, such as excavating ports and canals or stimulating the production of natural gas.

reduced. Overall, it is therefore assumed that uranium rather than tungsten is used where the choice exists. Therefore, the tungsten isotopes have not been considered further as activation products in this study.

Gold (Au)

The gold isotopes appear only in Hicks' accounts from the crater tests, where the material may have been used in structural details as a substitute for uranium, as a marker or as a neutron flux indicator. Since the presence is scattered – for example gold does not appear at all in Hicks' account of the atmospheric explosions – in the present study, gold has not been considered further as an activation product.

Lead (Pb)

As with tungsten, higher abundance of Pb-203 are reported in the *Plowshare* tests according to Hicks, with a relative abundance around 1. However lead is also a possible material in the radiation confinement of a thermonuclear device [14]. Unlike the tungsten isotopes, Pb-203 is therefore proposed to remain as a reasonable assumption for activation by a fusion device.

Table 4. Heavy activation products and limiting reactions considered in the present study with a relative abundance based on Hicks' analyses.

Nuclide	Activation of	Potential reaction	Relative abundance
W-181	Weapon components	^{182}W(n,2n)	-
W-185	Weapon components	^{184}W(n,γ)	-
W-187	Weapon components	^{186}W(n,γ)	-
Au-198	Weapon components	^{197}Au(n,γ)	-
Au-199	Weapon components	^{197}Au(n,γ)^{2}	-
Pb-203	Weapon components	^{204}Pb(n,2n)	1
U-237	Weapon components	^{238}U(n,2n)	10
U-239	Weapon components	^{238}U(n,γ)	10
Np-239	Weapon components	^{239}U beta-	-
U-240	Weapon components	^{238}U(n,γ)^{2}	0.1
Np-240	Weapon components	^{240}U beta-	-
Np-240m	Weapon components	^{240}U beta-	-
Am-241	Weapon components	Decay of ^{241}Pu	-
Cm-242 *	Weapon components	^{241}Am(n,γ)	-

*) Via Am-242 (16 hour half-life).

Residual un-fissioned Pu and U will contribute to the fallout problem, although not primarily via gamma doses from the ground, but are not addressed in this study.

3.5. Fission equivalent yield activation nuclide vector

Two activation nuclide vectors, one for the environment and one for weapon components, were calculated at t = 10 minutes. The activation nuclide vectors were normalised to fission equivalent yield activity as above so that the total contribution to the ground dose in the time window 10 minutes to 50 hours is the same as the corresponding contribution to the ground dose from 1 kt fission of Pu-239, U-235 and U-238 respectively. The results are presented in Table 5 and Table 6.

Table 5. Fission equivalent activity [Bq/kt] at t = 10 minutes from activation of the environment.

	Activity from fission equivalent yield (Bq/kt) after 10 min		
Nuclide	**Pu-239**	**U-235**	**U-238**
Na-24	5.48E+17	5.92E+17	5.61E+17
Mn-56	3.06E+18	3.30E+18	3.13E+18
Fe-55	3.44E+15	3.71E+15	3.52E+15
Fe-59	7.74E+14	8.35E+14	7.92E+14
Total	3.61E+18	3.90E+18	3.70E+18

Table 6. Fission equivalent activity [Bq/kt] at t = 10 minutes from activation of weapon components.

	Activity from fission equivalent yield (Bq/kt) after 10 min		
Nuclide	**Pu-239**	**U-235**	**U-238**
Be-7	2.04E+17	2.20E+17	2.09E+17
Mn-54	3.48E+16	3.76E+16	3.57E+16
Co-57	4.00E+15	4.32E+15	4.09E+15
Co-58	7.77E+15	8.38E+15	7.95E+15
Co-58m	1.45E+18	1.56E+18	1.48E+18
Co-60	5.64E+14	6.09E+14	5.78E+14
Cu-64	2.04E+17	2.20E+17	2.08E+17
Cu-67	4.21E+11	4.54E+11	4.31E+11
Pb-203	5.02E+17	5.41E+17	5.17E+17
U-237	1.61E+18	1.74E+18	1.65E+18
U-239	4.96E+20	5.36E+20	5.08E+20
Np-239 (from U-239)	1.18E+18	1.27E+18	1.21E+18
U-240	1.83E+17	1.98E+17	1.88E+17
Np-240m (from U-240)	1.14E+17	1.23E+17	1.16E+17
Np-240 (from U-240)	7.80E+12	8.42E+12	7.98E+12
Total	5.01E+20	5.42E+20	5.14E+20

The activation nuclide vectors for t = 10 minutes from the different normalisations are relatively similar. They do not differ by an exact scalar factor because the normalisation was done at t = 0, and the decay dynamics during the first 10 minutes alter the compositions slightly.

4. Selection of nuclides

The purpose of the nuclide vector is to obtain a set of nuclides and activities that represent doses within the time intervals and from the exposure pathways included in the present study. Nevertheless, the number of nuclides formed in connection with fission is very extensive and a selection has been made in order to obtain a manageable number. The selection has been made to ensure that the nuclide vector can be assumed to describe at least 95% of the dose contributions from each exposure pathway in all time intervals. The selection consisted of a number of steps that are described in detail below.

4.1. Fission exchanges

In the first selection step, SSM used the independent fission yields (JEFF 3.1) for the three fission reactions described above in Section 2.2. In total:

- 922 nuclides are created in the fission of Pu-239 with 1 MeV neutrons,
- 801 nuclides in the fission of U-235 with 1 MeV neutrons, and
- 938 nuclides in the fission of U-238 with 14 MeV neutrons.

In addition to these, stable nuclides and nuclides with very long half-lives are also formed during fission. Such nuclides were discarded in this step.

SSM then employed an activity at t = 0 per kiloton of fission for each nuclide according to the method described in Section 2.2. All nuclides in the three unit vectors were then allowed to grow in and decay for 10 minutes. The nuclides present after 10 minutes with an activity > 1 kBq/kt were then considered further in the selection. After 10 minutes the following remain:

- 463 nuclides for Pu-239,
- 385 nuclides for U-235, and
- 448 nuclides for U-238.

Of these, 14 are noble gases which have been dealt with separately, see Section 4.8 below.

4.2. Relative dose contributions from ground contamination

In the second selection step, SSM calculated the relative contribution of each nuclide per kiloton to the effective dose from radioactive material deposited on the ground. The calculations of relative contributions are based on an adult person standing unshielded on an infinite plane where the activity is located in the top layer of soil. The source was also assumed to be unchanged during the time periods studied, but radioactive decay and ingrowth were taken into account.

The dose calculation was performed with *DosCalc*, which uses dose factors for soil from *DCFPAK* [15] where the activity is assumed to be evenly distributed in the top 1 cm of the soil layer (ρ=1.6 g/cm³). Of the nuclides included in the nuclide vector for Pu-239, dose factors are known from *DCFPAK/DosCalc* for 363 nuclides (288 known for U-235 and 332 known for U-238). For other nuclides, a review was made based on activity levels and dose constants ($\Gamma_{H^*(10)}$), which indicate the dose rate per Bq from a point source for a specific nuclide. Dose constants were extracted from *Nucleonica* (JEFF 3.1 and ENDF-B-VIII-0) to identify which nuclides could be expected to make a non-negligible contribution to the effective dose from radioactive material deposited on the ground in any of the time windows below. This identified a further 17 nuclides that could potentially make a non-

negligible dose contribution for any of the three fission reactions studied. The method for estimating dose factors for these is described in Appendix 3 (Dispersion and Dose Calculations). The 17 nuclides were added to *DosCalc*.

4.2.1. Time windows

The dose calculations were performed for four different time windows:

- first day (first 24 hours) (10 min. – 24 h 10 min.)
- first week (24 hours 10 min. – 7 days 10 min.)
- first month (7 days 10 min. – 30 days 10 min.)
- first year (30 days 10 min. – 365 days 10 min.).

In the dose calculations, the source was allowed to decay to the beginning of each time window. Effective doses from the radioactive material deposited on the ground were then calculated for each nuclide, until the end of the respective time window.

4.2.2. Ranking

After supplementing the dose factors, the relative contribution to the ground dose from the nuclides from the three fission reactions could be calculated for each time window. The nuclides were then ranked according to their contribution to the total effective dose. The ranking was based on decay parents so that dose from ingrown daughter nuclides was counted towards the parent nuclide. The nuclides were then sorted according to their relative contribution in the four time windows, and the cumulative share of the total effective ground dose was calculated. A total of 12 such tables were calculated, one for each fission reaction (3 reactions) and time window (4 windows). The nuclides that were not needed to reach 95 % of the total effective dose in any time window were then discarded in this step. In Table 7 and Table 8 ranking tables for Pu-239 are presented for the four time windows. Corresponding tables are presented for U-235 and U-238 in Appendix – Ranking for U-235 and Appendix – Ranking for U-238 respectively.

Table 7. Ranking table for sorting nuclides describing the dose contribution from radioactive material deposited on the ground in two different time windows (first 24 hours and days 2-7) for fission of Pu-239 induced by 1 MeV neutrons. The calculation shows that 45 nuclides are needed to describe at least 95 % of the dose from the ground during the first 24 hours, and 16 nuclides to describe at least 95 % of the effective dose from the ground during days 2-7.

		Effective dose, first 24 hours			**Effective dose, days 2-7**	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Te-134	7.8 %	7.8 %	Te-132	31.1 %	31.1 %
2	Tc-104	7.3 %	15.1 %	Zr-97	18.6 %	49.7 %
3	I-135	6.0 %	21.1 %	Ba-140	10.2 %	59.8 %
4	I-134	5.8 %	26.9 %	I-133	8.7 %	68.6 %
5	Ba-142	5.3 %	32.1 %	Te-131m	4.3 %	72.9 %
6	Mo-101	5.1 %	37.2 %	Mo-99	4.0 %	76.9 %
7	Te-133m	5.0 %	42.2 %	I-135	3.3 %	80.2 %
8	Zr-97	4.9 %	47.1 %	Ce-143	2.9 %	83.1 %
9	Cs-138	4.0 %	51.1 %	La-140	2.2 %	85.3 %
10	La-142	3.9 %	55.0 %	I-131	2.2 %	87.5 %

11	Sb-131	3.7 %	58.7 %	Sr-91	2.1 %	89.6 %
12	Sr-92	3.1 %	61.9 %	Ru-103	1.4 %	91.0 %
13	Sb-130	2.6 %	64.5 %	I-132	1.2 %	92.2 %
14	Sr-93	2.6 %	67.1 %	Rh-105	1.2 %	93.4 %
15	Tc-105	2.5 %	69.5 %	Zr-95	1.0 %	94.4 %
16	Ba-141	2.3 %	71.8 %	Sb-127	0.9 %	95.3 %
17	Y-95	1.8 %	73.6 %	…	…	…
18	Y-94	1.8 %	75.4 %			
19	Rb-89	1.7 %	77.1 %			
20	Ru-105	1.6 %	78.7 %			
21	Sr-91	1.5 %	80.2 %			
22	Ce-146	1.4 %	81.5 %			
23	Te-132	1.4 %	82.9 %			
24	Te-133	1.3 %	84.2 %			
25	Sn-128	1.3 %	85.5 %			
26	Sb-130m	0.8 %	86.3 %			
27	La-143	0.7 %	87.0 %			
28	Cs-139	0.7 %	87.7 %			
29	Sb-129	0.7 %	88.4 %			
30	Pr-146	0.6 %	89.0 %			
31	I-133	0.6 %	89.7 %			
32	Sn-129m	0.6 %	90.2 %			
33	Rh-107	0.5 %	90.7 %			
34	Br-84	0.5 %	91.1 %			
35	Tc-101	0.5 %	91.6 %			
36	I-134m	0.4%	92.0 %			
37	Mo-102	0.4%	92.4 %			
38	Sn-127	0.4%	92.9 %			
39	Pr-147	0.4%	93.3 %			
40	Te-131m	0.4%	93.7 %			
41	Sb-129m	0.3%	94.0 %			
42	Sb-132m	0.3%	94.3 %			
43	Nd-151	0.3%	94.6 %			
44	Rb-90m	0.3%	94.9 %			
45	Sb-128	0.3%	95.2 %			
	…	…	…			

Table 8. Ranking table for sorting nuclides describing the dose contribution from the radioactive materials deposited on the ground in two different time windows (days 8-30 and days 31-365) for fission of Pu-239 induced by 1 MeV neutrons. This calculation shows that 10 nuclides are needed to describe at least 95 % of the effective dose from the ground during days 8-30, and 7 nuclides to describe at least 95 % of the effective dose the ground during days 31-365.

		Effective dose, days 8-30			Effective dose, days 31-365	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Ba-140	43.7 %	43.7 %	Zr-95	42.0 %	42.0 %
2	Te-132	19.6 %	63.3 %	Ba-140	21.7 %	63.7 %
3	La-140	8.4 %	71.7 %	Ru-103	16.6 %	80.3 %
4	Ru-103	7.2 %	78.9 %	Nb-95	6.3 %	86.6 %
5	Zr-95	6.3 %	85.2 %	Ru-106	3.9 %	90.5 %
6	I-131	5.7 %	90.9 %	La-140	3.0 %	93.5 %
7	Mo-99	1.9 %	92.8 %	Ce-141	1.6 %	95.1 %
8	Cs-136	1.0 %	93.7 %	…	…	…
9	Nd-147	0.9 %	94.6 %			
10	Ce-141	0.9 %	95.5 %			
	…	…	…			

In the 12 tables that were calculated, there are a large number of duplicates, *i.e.* nuclides that occur in several fission reactions or in several time windows. For example, Table 8 shows that only Nb-95 and Ru-106 are additional nuclides for the time window 31-365 days compared to the time window 8-30 days. In total, 59 unique nuclides (decay parents) were identified that are needed to describe at least 95 % of the dose from radioactive material deposited on the ground from the fission of Pu-239 in the four time windows. An additional three (U-235) and eight (U-238) unique nuclides are added using the same method for the other fission reactions. This provides a set of a total of 70 unique nuclides (decay parents) to describe in each time window at least 95% of the effective dose from radioactive material deposited on the ground.

4.2.3. Decay daughters

The dose calculation forming the basis for the ranking presented in Section 4.2.2 was done with *DosCalc*, where the dose from ingrown decay daughters is attributed to their parent. For example, about 75 % of the dose from a ground contamination of only Te-134 in the first 24 hours comes from the decay daughter I-134 growing in. However, I-134 is already included in the 70-member nuclide vector described above. SSM therefore proceeded to identify which daughters are growing in and making a non-negligible contribution (≥ 3 %) to effective dose from radioactive material deposited on the ground that can be attributed to a particular parent, but are not already included in the 70-member nuclide vector. A total of 16 daughters were added for Pu-239 and another five for U-238, totalling 21 daughters. No additional decay daughters were needed for U-235 as they were already identified in other fission reactions. The daughters and their relative dose contributions to their parents are shown in Table 9.

Table 9. Decay daughters added because of the contribution to the effective dose from radioactive material deposited on the ground. The dose contribution is reported as a proportion of the total effective dose from a ground contamination where only the parent is initially present.

No.	Parent	Daughter	Fission reaction	Dose contribution	Comments
1	Zr-97	Nb-97m	Pu-239	~ 32 % the first 24 hours	
2		Nb-97	Pu-239	~ 29 % the first 24 hours	
3	Sb-131	Te-131	Pu-239	~ 15 % the first 24 hours	
4	Sr-92	Y-92	Pu-239	~ 16 % the first 24 hours	
5	Sr-93	Y-93m	Pu-239	~ 7 % the first 24 hours	Parent of Y-93
6		Y-93	Pu-239	~ 3 % the first 24 hours	
7	Ba-141	La-141	Pu-239	~ 3 % the first 24 hours	Parent of Ce-141 (included)
8	Ru-105	Rh-105m	Pu-239	~ 3 % the first 24 hours	Parent of Rh-105 (included)
9	Sr-91	Y-91m	Pu-239	~ 30 % the first 24 hours	Y-91 can be ignored
10	Sn-128	Sb-128m	Pu-239	~ 70 % the first 24 hours	Parent of Sb-128 (included)
11	Cs-139	Ba-139	Pu-239	~ 13 % the first 24 hours	
12	Sb-129	Te-129	Pu-239	~ 3 % the first 24 hours	See Section 4.6 for Te-129m
13	Mo-102	Tc-102	Pu-239	~ 85 % the first 24 hours	
14	Nd-151	Pm-151	Pu-239	~ 27 % the first week	
15	Mo-99	Tc-99m	Pu-239	~ 40 % the first week	Tc-99 can be ignored
16	Ru-106	Rh-106	Pu-239	~ 100 % all time windows	
17	Cd-117	In-117m	U-238	~ 5 % the first 24 hours	Parent of In-117
18		In-117	U-238	~ 24 % the first 24 hours	
19	Pd-112	Ag-112	U-238	~ 100 % all time windows	
20	Cd-115	In-115m	U-238	~ 44 % the first week	
21	Ce-144	Pr-144	U-238	~ 70 % the first year	Pr-144m can be ignored

The nuclide vector needed to describe at least 95 % of the effective dose from radioactive material deposited on the ground for all fission reactions within the studied time windows consisted in this step of 91 nuclides (70 parents and 21 daughters).

4.3. Activation products

Among the activation products, those that make a non-negligible contribution to the effective dose from radioactive material deposited on the ground were identified. A detailed discussion on which activation products are included in the nuclide vector and which activities per kiloton are applied is presented in Chapter 3. Only activation products

expected to contribute to the dose in any of the time windows according to the method above were added. The activation products added in this step have no decay daughters that grow in and contribute significantly to the ground dose. The activation products added to the nuclide vector are listed in Table 10.

The activities (Bq/kt) added to the nuclide vector are a recalculation and conversion of the fission equivalent activities per nuclide presented in Table 5 and Table 6. The conversion is according to the methodology presented in Chapter 3 (for the main scenario), namely that fission equivalent activities for activation products from weapon components have been multiplied by a factor of 0.02 and fission equivalent activities for activation products from the environment have been multiplied by a factor of 0.08 in order to correspond to one kiloton from fusion. In all cases, the highest activity values from Table 5 and Table 6, *i.e.* values for U-235, have been used to conservatively account for differences between the three fission reactions. A discussion of this procedure, which was also used for fission products, can be found in Section 4.4.

Table 10. Activation products from activation of the ground (environment) and weapon components for the main scenario. The activity is expressed as Bq per kiloton of fusion at t = 10 min.

No.	Nuclide	Activity (Bq/kt)	Activation of
1	Na-24	4.74E+16	Environment
2	Mn-56	2.64E+17	Environment
3	Be-7	4.40E+15	Weapon components
4	Mn-54	7.52E+14	Weapon components
5	Co-58	1.68E+14	Weapon components
6	Co-60	1.22E+13	Weapon components
7	Pb-203	1.08E+16	Weapon components
8	U-237	3.48E+16	Weapon components
9	U-239	1.07E+19	Weapon components
10	Np-239	2.54E+16	Weapon components

The nuclide vector needed to describe at least 95 % of the effective dose from ground contamination for all fission reactions within the studied time windows, together with activation products, consisted in this step of 101 nuclides (70 parents, 21 daughters and 10 activation products).

4.4. Maximum vector

The nuclide vector should be representative irrespective of the type of fission. However, some things differ between different fission reactions that might occur in the nuclear weapon. The fission of Pu-239 produces slightly more iodine per kiloton than the fission of U-235 or U-238 (after 10 minutes a total of 2.4 EBq/kt for Pu-239, 2.0 EBq/kt for U-235, and 1.1 EBq/kt for U-238). In addition, the fission products from U-235 give slightly higher doses from radioactive material deposited on the ground per kiloton than Pu-239 and U-238 in the studied time windows. Therefore, to deal with the different fission

reactions used to represent the main scenario in this study, the highest activity per nuclide that can be expected per kiloton from any of the three fission reactions was applied. The same approach was used for the activation products, with U-235 giving the highest fission equivalent yield activity per kiloton and therefore controlling.

This approach – using a "maximum vector" – results in an overestimation of the activity per kiloton but has the advantage of not underestimating any nuclide that could contribute to the dose from a particular fission reaction during the nuclear explosion. Using the maximum vector overestimates the effective dose from radioactive material deposited on the ground by about 2-15 %, depending on the time window and fission reaction.

The number of nuclides where the activity of the maximum vector has been taken from the respective unit vector for the different fission reactions is shown in Table 11. In total, the activity per kiloton after 10 minutes was highest for 45 nuclides in fission of U-235, for 29 nuclides highest in fission of Pu-239 and for the remaining 27 nuclides highest in fission of U-238. In those instances where the activities produced per kiloton are generally highest for a particular element in connection with a particular fission reaction, these elements are also reported in Table 11. Note that this applies only to nuclides and elements among the 101 nuclides encompassed by this step and that the activation products have not been grouped. In other instances, such as for Cs, La and Te, the highest activity per kiloton varies significantly from isotope to isotope between the three fission reactions.

Table 11. Number of nuclides in the maximum vector with activities taken from the three fission reactions. The table also lists elements that generally have nuclides with the highest activity per kiloton for a particular fission reaction.

	Fission of Pu-239	**Fission of U-235**	**Fission of U-238**	**Total**
Number of nuclides	29	45	27	101
Share	28.7%	44.6 %	26.7 %	100.0 %
Element	I, Mo, Rh, Ru, Tc	Ba, Ce, Rb, Sr, Y, Zr	Ag, Br, Cd, In, Sb, Sn	

4.5. Relative dose contributions by inhalation

So far, the selection described above has been based solely on doses from radioactive material deposited on the ground. To ensure that nuclides which could contribute significantly to the effective dose by inhalation are not neglected, the expected relative contribution of all nuclides to the inhalation dose was investigated. The same method and criterion as for the dose from radioactive material deposited on the ground as described above was used, *i.e.* to identify and rank the nuclides based on their relative contribution to the effective dose. The nuclides needed to describe at least 95 % of the inhalation dose should then be added to the nuclide vector.

Dose coefficients for a one-year-old child from ICRP 119 [16] were used for the nuclides formed in the three fission reactions and remaining after one hour (activity > 0 Bq at t = 60 minutes). In total, dose coefficients were tabulated for:

- 243 of 401 nuclides (61 %) in the fission of Pu-239,
- 192 out of 331 nuclides (58 %) in the fission of U-235, and
- 226 out of 390 nuclides (58 %) in the fission of U-238.

It was assumed that inhalation occurs only after a time when the initial cloud has stabilised and the radioactive substances have been transported somewhat outside the area affected by the direct impact of the nuclear explosion. Therefore, t = 60 minutes was chosen, which reduced the number of nuclides to be considered in the analysis.

4.5.1. Supplementation of dose coefficients

Dose coefficients for a number of nuclides missing from ICRP 119 were obtained from other sources, as described in Appendix 3 (Dispersion and Dose Calculations). Nevertheless some 40 % of the nuclides remain, for which the dose coefficients are unknown. In order to ascertain whether any of these (without dose coefficients from ICRP or other sources) could make a non-negligible contribution to the inhalation dose, rough upper bounds for dose coefficients were estimated for those nuclides with activities greater than about 2 PBq per kiloton at t = 60 minutes (approximately a 10^{-4} fraction of the total activity of fission products plus the selected activation products at t = 60 minutes). The upper limit of the dose coefficient for nuclide X, D_X (Sv/Bq), was estimated from a comparison of the total decay energy of a longer-lived reference isotope W_I (W/Bq) with the known dose coefficient D_I (Sv/Bq). The relative decay energy $W_R = W_X/W_I$ produced during one half-life of isotope I multiplied by its dose coefficient D_I was considered a conservative estimate of the unknown dose factor, according to the following:

$$D_X = W_R \times D_I$$

If short-lived daughters were present, their total decay energy was also added to W_X. If long-lived daughters were present, the contribution to the total activity of those daughters was calculated. None of the nuclides without an ICRP dose coefficient tested in this way were found to make other than negligible contributions to the inhalation dose.

4.5.2. Ranking

Using the known dose coefficients and this method, the contributions to inhalation dose could be ranked for all nuclides of interest. The nuclides that need to be included in the nuclide vector to describe 95 % of the inhalation dose to a one-year-old child are listed in Table 12. A total of 48 nuclides are needed to fulfil this criterion for the three fission reactions. All of these are already included in the nuclide vector with 101 members due to their contribution to the dose from radioactive material deposited on the ground, except Pd-109 and Pr-145.

Table 12. Nuclides needed to describe 95 % of the inhalation dose to a one-year-old child for the three fission reactions, ranked according to their relative dose contribution.

	Fission of Pu-239		Fission of U-235		Fission of U-238	
No.	**Nuclide**	**Cumulative share**	**Nuclide**	**Cumulative share**	**Nuclide**	**Cumulative share**
1	I-133	13.5 %	I-133	11.6 %	I-133	11.7 %
2	I-135	23.2 %	I-135	20.3 %	I-135	20.2 %
3	Zr-97	27.9 %	Sr-92	27.0 %	Zr-97	25.2 %
4	I-134	31.9 %	Zr-97	32.3 %	Sr-92	30.0 %
5	La-142	35.9 %	Y-93	37.1 %	Y-93	34.0 %
6	Sr-92	39.7 %	La-142	41.3 %	Np-239	37.8 %
7	Np-239	43.4 %	I-134	45.3 %	Te-134	41.4 %
8	Y-93	46.7 %	Np-239	48.9 %	I-134	45.0 %
9	Te-133m	49.9 %	Te-134	52.1 %	La-142	48.4 %
10	U-239	53.0 %	Sr-91	55.4 %	U-239	51.6 %
11	Ru-105	56.0 %	La-141	58.6 %	Ba-139	54.3 %
12	La-141	58.9 %	Ba-139	61.7 %	La-141	56.9 %
13	Ba-139	61.7 %	U-239	64.7 %	Te-132	59.4 %
14	Te-132	64.3 %	Te-133m	67.7 %	Sr-91	61.9 %
15	Te-134	66.8 %	Cs-138	70.0 %	U-237	64.3 %
16	U-237	69.1 %	U-237	72.3 %	Te-133m	66.6 %
17	Cs-138	71.3 %	Te-132	74.6 %	I-131	68.6 %
18	I-131	73.2 %	Ce-143	76.3 %	Cs-138	70.5 %
19	Mn-56	74.9 %	Mn-56	78.0 %	Mn-56	72.3 %
20	Sr-91	76.6 %	Pr-145	79.6 %	Ru-105	74.0 %
21	Ce-143	78.1 %	I-131	81.2 %	Ba-141	75.7 %
22	Pr-145	79.5 %	Y-94	82.5 %	Pr-145	77.1 %
23	Tc-104	80.9 %	Y-92	83.6 %	Ce-143	78.5 %
24	Mo-99	82.1 %	Ba-141	84.8 %	Te-131	79.8 %
25	Te-131	83.2 %	Ba-140	85.9 %	Sb-131	81.0 %
26	Ba-140	84.3 %	Mo-99	87.0 %	Mo-99	82.2 %
27	Ba-141	85.3 %	Te-131	88.0 %	Y-94	83.3 %
28	Sb-131	86.3 %	Sb-131	88.9 %	Sb-130	84.3 %
29	Tc-101	87.3 %	Na-24	89.8 %	Sb-129	85.2 %

30	Y-94	88.2 %	Tc-101	90.5 %	Na-24	86.1 %
31	Na-24	89.1 %	Se-83	91.2 %	Tc-101	87.0 %
32	Sb-130	89.8 %	Ru-105	91.8 %	Y-92	87.8 %
33	Sb-129	90.6 %	Sb-130	92.4 %	Sn-128	88.6 %
34	Mo-101	91.3 %	Nd-149	93.0 %	Se-83	89.4 %
35	Nd-149	92.0 %	Sb-129	93.5 %	Nd-149	90.2 %
36	Y-92	92.7 %	Mo-101	94.1 %	Tc-104	91.0 %
37	Te-131m	93.3 %	La-143	94.6 %	Sb-128	91.7 %
38	Sn-128	93.7 %	Tc-104	95.0 %	Mo-101	92.3%
39	Rh-107	94.2 %	…	…	Br-84	92.9 %
40	Se-83	94.6 %			Ba-142	93.4 %
41	Sb-128	95.0 %			Sn-127	93.8 %
42	…	…			Te-133	94.2 %
43					La-143	94.6 %
44					Cd-117	94.9 %
45					Pd-109	95.2 %
					…	…

An additional investigatory assessment was conducted by ranking the nuclides according to their contribution to the inhalation dose to an adult. The ranking is similar but not identical, and to describe at least 95 % of the inhalation dose in both cases (one-year-old child and adult), seven additional nuclides need to be added (in addition to those in Table 12). The additional nuclides (Br-84, Ru-103, Rh-107, Sb-127, La-143, Ce-144, and Nd-147) are already included in the nuclide vector based on dose from radioactive material deposited on the ground.

After taking into account contributions to inhalation dose, with Pd-109 and Pr-145, the nuclide vector consists of a total of 103 nuclides.

4.6. Additional decay parents

Next, nuclides produced in fission or activation but not included in the 103 nuclides in the nuclide vector in the previous step were analysed. The analytical step aimed to identify nuclides that contribute significantly by decay to the ingrowth of one or more decay daughters that are already included in the 103-member nuclide vector, *i.e.* needed to describe at least 95 % of the dose from the ground or inhalation.

The following method was used to identify these additional parents:

- The number of nuclei of the parent and daughter at t = 10 minutes was calculated for the fission and activation products:

  $$N = A\ [Bq] / \lambda\ [1/s]$$

- The ratio of parent nuclei (F_M) to daughter nuclei is obtained by multiplying the number ratio of parent to daughter nuclei by the branching ratio of the parent-daughter decay pathway (BR):

$$F_M = BR * N_M / N_D$$

- If this fraction (F_M) exceeds 5 %, the parent was added to the nuclide vector.

The above method was applied to all nuclides in the nuclide vector consisting of 103 members. A total of nine parents were identified that significantly contribute to the daughter's activity, and where the daughter is needed to describe at least 95 % of the dose from the ground or inhalation. The added parents and the calculated proportion of parent nuclei to daughter nuclei (F_M) are presented in Table 13. The table also shows the activity of the parents at t = 10 minutes that was added to the nuclide vector.

Table 13. Additional decay parents included in the nuclide vector due to contribution by ingrowth to daughter nuclides.

No.	Nuclide (parent)	Activity at 10 min. (Bq/kt)	Daughter	Branching ratio	Share (F_M)
1	Co-58m	3.12E+16	Co-58	1	97 %
2	Nb-95m	5.55E+10	Nb-95	0.944	10 %
			Mo-95 (stable)	0.056	
3	Ru-107	2.30E+18	Rh-107	1	25 %
4	Ag-115	2.44E+17	Cd-115	0.942	48 %
			Cd-115m *	0.058	
5	Sn-127m	3.48E+17	Sb-127	1	16 %
6	Sn-130	3.70E+17	Sb-130	1	6 %
7	I-132m	2.17E+16	I-132	0.86	67 %
			Xe-132 (stable)	0.14	
8	Ce-145	2.39E+18	Pr-145	1	13 %
9	Te-129m	3.56E+13	Te-129	0.63	328 %
			I-129 **	0.37	

*) Cd-115m does not significantly contribute to the dose for any exposure pathway. Therefore, this branch has not been included in the nuclide vector.

**) I-129 does not significantly contribute to the dose for any exposure pathway. Therefore, this branch has not been included in the nuclide vector.

After adding these nine decay parent nuclides, the nuclide vector consists of 112 nuclides.

4.7. Cloud dose

In connection with the passage of the plume of radioactive material, a person can be externally exposed to ionising radiation from radioactive material in the plume (cloud). Since both the cloud dose and the dose from radioactive material deposited on the ground come from external exposure from the radioactive material in the cloud and the ground, respectively, SSM assumes that the most important nuclides for cloud dose are identical to

those for dose from radioactive material deposited on the ground. SSM has therefore not conducted any further analysis of relative contributions to cloud dose.

One exception is the noble gases described in the next section.

4.8. Noble gases

Fission also produces the noble gases krypton (Kr) and xenon (Xe). Noble gas nuclides are important in that they contribute to cloud dose and decay to other radioactive substances, which in turn contribute to inhalation dose or deposit on the ground and give dose from radioactive material deposited on the ground. Xenon decays to iodine (I) and caesium (Cs) while krypton decays to rubidium (Rb) and strontium (Sr).

Therefore, all noble gas nuclides with a half-life longer than one minute have been included in the nuclide vector. Other noble gas nuclides have decayed during the first 10 minutes, making their dose contributions negligible. In the same manner as described above, the highest activity for each nuclide from the three fission reactions (maximum vector) is used. The 13 nuclides from the noble gas group included in the nuclide vector in this step are shown in Table 14. The table also indicates from which fission reaction the activity used in the maximum vector is taken.

Table 14. Noble gases included in the nuclide vector.

No.	Nuclide	Activity at 10 min. (Bq/kt)	Fission reaction
1	Kr-83m	2.64E+15 *	U-238
2	Kr-85	2.83E+10	U-235
3	Kr-85m	7.10E+16	U-235
4	Kr-87	5.40E+17	U-235
5	Kr-88	3.48E+17	U-235
6	Kr-89	2.44E+18	U-235
7	Xe-131m	3.49E+10	Pu-239
8	Xe-133	4.16E+13	Pu-239
9	Xe-133m	1.22E+14	Pu-239
10	Xe-135	2.24E+16	Pu-239
11	Xe-135m	6.41E+17	Pu-239
12	Xe-137	4.34E+18	U-235
13	Xe-138	4.29E+18	U-235

*) The dispersion and dose calculations incorrectly used 1.87E+15 from U-235. However, U-238 gives a higher activity per kiloton, therefore the correct value according to the maximum vector selection method is reported here.

After adding these 13 nuclides, the nuclide vector consists of 125 nuclides.

4.9. Marker nuclides

Finally, three *marker nuclides* were added: Sr-89, Sr-90 and Cs-137. These are not needed to describe 95 % of the dose contributions from either inhalation or the ground. Instead, the primary reason for adding these three nuclides to the nuclide vector is that they were deemed important for further studies of longer-term problems associated with radioactive material deposited on the ground after a nuclear explosion, such as production of food for human consumption and decontamination. The marker nuclides with activity per kiloton are presented in Table 15. The table also indicates from which fission reaction the activity used in the maximum vector is taken.

Table 15. Marker nuclides in the nuclide vector for prolonged radioactive contamination from material deposited on the ground after a nuclear explosion.

No.	Nuclide	Activity at 10 min. (Bq/kt)	Fission reaction
1	Sr-89	2.33E+14	U-235
2	Sr-90	5.02E+12	U-235
3	Cs-137	5.47E+12	Pu-239
4	Ba-137m	2.31E+15	Pu-239

In this study, the decay daughter Ba-137m was also added to the nuclide vector, because it is implicitly included in the dispersion and dose calculations when the decay parent Cs-137 is considered. In fission, Ba-137m is formed with higher activities than the parent Cs-137, although the pair is expected to be in equilibrium within one hour. Sr-90 also has a daughter, Y-90, which can be expected to be in equilibrium with the parent after a time period of a few weeks. Y-90 has however not been included because for this study Sr-90 is sufficient as a marker nuclide.

After this last stage with three marker nuclides and one decay daughter, the nuclide vector consists of 129 nuclides that are representative for describing doses from the different exposure pathways for times between 10 minutes and one year.

5. Nuclide vector

The full nuclide vector used for the nuclear weapon case in the present study is given in the tables below. The nuclide vector consists of 129 nuclides selected according to the method described in Chapter 4. The nuclide vector can be regarded as being representative to describe at least 95 % of the dose contribution from activation and fission products, for the three fission reactions that have been considered in this study. The nuclide vector for the main scenario is given in Table 16. In Table 17 the same nuclide vector normalised to activity per kiloton is given. References for each nuclide are also stated in Table 17.

After a nuclear explosion, the dose rate from the fallout is expected to decrease with time *t* according to t^{-x}, where *x* is often set to about 1.2 [3]. Figure 1 shows the relative dose rate from the 129-member nuclide vector at different times for times between 10 minutes and 60 hours, normalised to the dose rate at one hour. The figure shows that the dose rate from the nuclide vector decreases as expected from the rule-of-thumb estimation.

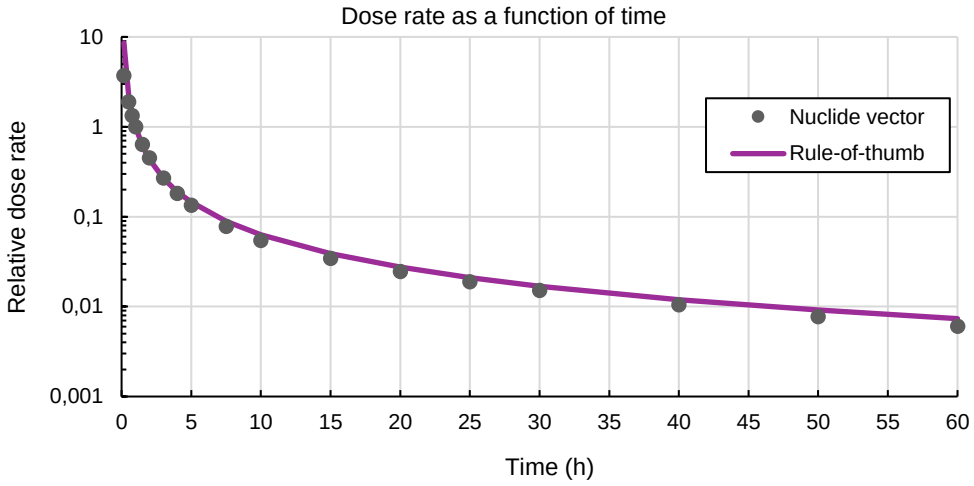

Figure 1. The dose rate from the nuclide vector for the main scenario at various times between 10 minutes and 60 hours (points) relative to the dose rate at 60 minutes. The figure also shows as a solid curve the dose rate according to $t^{-1.2}$.

Table 16. Nuclide vector for the main scenario, 100 kt ground-level explosion with 50 % fusion fraction. Activities 10 minutes after the explosion.

Nuclide	Activity (Bq)	Nuclide	Activity (Bq)	Nuclide	Activity (Bq)
Be-7	2.20E+17	Ru-103	9.25E+16	I-132	8.45E+17
Na-24	2.37E+18	Ru-105	9.05E+18	I-132m	1.09E+18
Mn-54	3.76E+16	Ru-106	6.15E+15	I-133	1.68E+18
Mn-56	1.32E+19	Ru-107	1.15E+20	I-134	4.98E+19
Co-58	8.40E+15	Rh-105	1.54E+16	I-134m	5.00E+19
Co-58m	1.56E+18	Rh-105m	2.39E+18	I-135	1.25E+19
Co-60	6.10E+14	Rh-106	6.15E+15	Xe-131m	1.74E+12
Se-83	8.55E+18	Rh-107	7.95E+19	Xe-133	2.08E+15
Kr-83m	1.32E+17	Pd-109	1.14E+18	Xe-133m	6.12E+15
Kr-85	1.41E+12	Pd-112	6.90E+17	Xe-135	1.12E+18
Kr-85m	3.55E+18	Ag-112	2.58E+16	Xe-135m	3.21E+19
Kr-87	2.70E+19	Ag-115	1.22E+19	Xe-137	2.17E+20
Kr-88	1.74E+19	Cd-115	1.50E+17	Xe-138	2.14E+20
Kr-89	1.22E+20	Cd-117	3.68E+18	Cs-136	5.40E+15
Br-84	2.71E+19	Cd-117m	8.25E+17	Cs-137	2.74E+14
Rb-89	1.56E+20	In-115m	3.04E+15	Cs-138	6.14E+19
Rb-90	1.11E+20	In-117	1.61E+17	Cs-139	2.83E+20
Rb-90m	5.63E+19	In-117m	1.84E+17	Ba-137m	1.16E+17
Sr-89	1.17E+16	Sb-127	8.20E+16	Ba-139	3.07E+19
(Sr-90)	2.51E+14	Sb-128	3.68E+17	Ba-140	2.68E+17
Sr-91	7.64E+18	Sb-128m	4.16E+18	Ba-141	1.84E+20
Sr-92	2.87E+19	Sb-129	2.54E+18	Ba-142	2.31E+20
Sr-93	2.67E+20	Sb-129m	1.60E+19	La-140	7.50E+15
Y-91m	5.07E+17	Sb-130	3.00E+19	La-141	6.12E+18
Y-92	9.41E+17	Sb-130m	6.40E+19	La-142	2.43E+19
Y-93	4.95E+18	Sb-131	9.40E+19	La-143	2.02E+20
Y-93m	6.70E+19	Sb-132	5.65E+19	Ce-141	4.62E+14
Y-94	2.00E+20	Sb-132m	6.60E+19	Ce-143	8.71E+17
Y-95	2.70E+20	Sb-133	6.65E+19	Ce-144	1.03E+16
Nb-95	2.80E+12	Sn-127	5.20E+18	Ce-145	1.19E+20
Nb-95m	2.78E+12	Sn-127m	1.74E+19	Ce-146	1.09E+20
Nb-97	5.20E+17	Sn-128	1.76E+19	Pr-144	3.28E+16
Nb-97m	4.71E+18	Sn-129m	4.73E+19	Pr-145	7.70E+18
Zr-95	2.71E+16	Sn-130	1.85E+19	Pr-146	3.44E+19
Zr-97	4.95E+18	Te-129	2.38E+17	Pr-147	8.58E+19
Mo-99	1.19E+18	Te-129m	1.78E+15	Nd-147	4.03E+16
Mo-101	2.28E+20	Te-131	2.63E+19	Nd-149	9.85E+18
Mo-102	2.60E+20	Te-131m	3.99E+17	Nd-151	3.10E+19
Tc-99m	1.73E+16	Te-132	8.10E+17	Pm-151	1.64E+17
Tc-101	1.09E+20	Te-133	1.32E+20	Pb-203	5.40E+17
Tc-102	2.62E+20	Te-133m	4.61E+19	U-237	1.74E+18
Tc-104	2.11E+20	Te-134	9.35E+19	U-239	5.35E+20
Tc-105	2.37E+20	I-131	1.40E+16	Np-239	1.27E+18

Table 17. Nuclide vector for a ground-level explosion with 50 % fusion fraction. Normalised activities (Bq/kt) 10 minutes after the explosion. Activities corresponding to those reported in Table 16 are obtained by multiplying by 50, because the yield from fission and fusion is 50 kt each for the main scenario. More generally, activities corresponding to a ground-based nuclear explosion with X kilotons of fission yield and Y kilotons of fusion yield are obtained by multiplying by Y the activities of the activation products and multiplying by X the other activities. For each nuclide, a reference to the mode of selection for the nuclide vector is given: (M) ground dose, see Section 4.2; (I) inhalation dose, Section 4.5; (Y) additional parents, Section 4.6; (G) noble gases, Section 4.8; and (L) marker nuclides, Section 4.9. Nuclides that are activation products (Section 4.3) are marked with (A) after the name of the nuclide. Other nuclides are fission products.

Nuclide	Activity (Bq/kt)	Reference	Nuclide	Activity (Bq/kt)	Reference
Be-7 (A)	4.40E+15	M	Sb-129m	3.20E+17	M
Na-24 (A)	4.74E+16	M, I	Sb-130	6.00E+17	M, I
Mn-54 (A)	7.52E+14	M	Sb-130m	1.28E+18	M
Mn-56 (A)	2.64E+17	M, I	Sb-131	1.88E+18	M, I
Co-58 (A)	1.68E+14	M	Sb-132	1.13E+18	M
Co-58m (A)	3.12E+16	Y	Sb-132m	1.32E+18	M
Co-60 (A)	1.22E+13	M	Sb-133	1.33E+18	M
Se-83	1.71E+17	M, I	Sn-127	1.04E+17	M, I
Kr-83m	2.64E+15	G	Sn-127m	3.48E+17	Y
Kr-85	2.83E+10	G	Sn-128	3.51E+17	M, I
Kr-85m	7.10E+16	G	Sn-129m	9.45E+17	M
Kr-87	5.40E+17	G	Sn-130	3.70E+17	Y
Kr-88	3.48E+17	G	Te-129	4.75E+15	M
Kr-89	2.44E+18	G	Te-129m	3.56E+13	Y
Br-84	5.42E+17	M, I	Te-131	5.26E+17	M, I
Rb-89	3.13E+18	M	Te-131m	7.97E+15	M, I
Rb-90	2.22E+18	M	Te-132	1.62E+16	M, I
Rb-90m	1.13E+18	M	Te-133	2.63E+18	M, I
Sr-89	2.33E+14	L	Te-133m	9,22E+17	M, I
(Sr-90)	5.02E+12	L	Te-134	1.87E+18	M, I
Sr-91	1.53E+17	M, I	I-131	2.80E+14	M, I
Sr-92	5.74E+17	M, I	I-132	1.69E+16	M
Sr-93	5.34E+18	M	I-132m	2.17E+16	Y
Y-91m	1.01E+16	M	I-133	3.35E+16	M, I
Y-92	1.88E+16	M, I	I-134	9.96E+17	M, I
Y-93	9.90E+16	M, I	I-134m	1.00E+18	M
Y-93m	1.34E+18	M	I-135	2.49E+17	M, I
Y-94	4.01E+18	M, I	Xe-131m	3.49E+10	G
Y-95	5.40E+18	M	Xe-133	4.16E+13	G

Nuclide	Activity (Bq/kt)	Reference	Nuclide	Activity (Bq/kt)	Reference
Nb-95	5.60E+10	M	Xe-133m	1.22E+14	G
Nb-95m	5.55E+10	Y	Xe-135	2.24E+16	G
Nb-97	1.04E+16	M	Xe-135m	6.41E+17	G
Nb-97m	9.42E+16	M	Xe-137	4.34E+18	G
Zr-95	5.42E+14	M	Xe-138	4.29E+18	G
Zr-97	9.91E+16	M, I	Cs-136	1.08E+14	M
Mo-99	2.38E+16	M, I	Cs-137	5.47E+12	L
Mo-101	4.56E+18	M, I	Cs-138	1.23E+18	M, I
Mo-102	5.20E+18	M	Cs-139	5.66E+18	M
Tc-99m	3.46E+14	M	Ba-137m	2.31E+15	L
Tc-101	2.17E+18	M, I	Ba-139	6.14E+17	M, I
Tc-102	5.24E+18	M	Ba-140	5.37E+15	M, I
Tc-104	4.22E+18	M, I	Ba-141	3.68E+18	M, I
Tc-105	4.73E+18	M	Ba-142	4.61E+18	M, I
Ru-103	1.85E+15	M, I	La-140	1.50E+14	M
Ru-105	1.81E+17	M, I	La-141	1.22E+17	M, I
Ru-106	1.23E+14	M	La-142	4.86E+17	M, I
Ru-107	2.30E+18	Y	La-143	4,04E+18	M, I
Rh-105	3.07E+14	M	Ce-141	9.24E+12	M
Rh-105m	4.78E+16	M	Ce-143	1.74E+16	M, I
Rh-106	1.23E+14	M	Ce-144	2.07E+14	M, I
Rh-107	1.59E+18	I	Ce-145	2.39E+18	Y
Pd-109	2.27E+16	I	Ce-146	2.18E+18	M
Pd-112	1.38E+16	M	Pr-144	6.55E+14	M
Ag-112	5.16E+14	M	Pr-145	1.54E+17	I
Ag-115	2.44E+17	Y	Pr-146	6.88E+17	M
Cd-115	3.00E+15	M	Pr-147	1.72E+18	M
Cd-117	7.35E+16	M, I	Nd-147	8.07E+14	M, I
Cd-117m	1.65E+16	M	Nd-149	1.97E+17	M, I
In-115m	6.07E+13	M	Nd-151	6.19E+17	M
In-117	3.22E+15	M	Pm-151	3.28E+15	M
In-117m	3.67E+15	M	Pb-203 (A)	1.08E+16	M
Sb-127	1.64E+15	M, I	U-237 (A)	3.48E+16	M, I
Sb-128	7.35E+15	M, I	U-239 (A)	1.07E+19	M, I
Sb-128m	8.31E+16	M	Np-239 (A)	2.54E+16	M
Sb-129	5.08E+16	M, I			

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Appendix – Ranking for U-235

In Table 18 and Table 19, the nuclides needed to reach 95 % of the total effective dose from radioactive material deposited on the ground in any of the four time windows (first 24 hours, days 2-7, days 8-30 and days 31-365) for fission of U-235 induced by 1 MeV neutrons are listed. The three additional nuclides for U-235 (Se-83, Rb-90 and Ce-141) are marked in bold in Table 18 and Table 19.

Table 18. Ranking table for sorting nuclides describing the dose contribution from radioactive material deposited on the ground in two different time windows (first 24 hours and days 2-7) for fission of U-235 induced by 1 MeV neutrons. The calculation shows that 39 nuclides are needed to describe at least 95 % of the dose from the ground during the first 24 hours, and 13 nuclides are needed to describe at least 95 % of the effective dose from the ground during days 2-7.

		Effective dose, first 24 hours			Effective dose, days 2-7	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Te-134	10.6 %	10.6 %	Te-132	29.1 %	29.1 %
2	Ba-142	6.4 %	17.0 %	Zr-97	22.2 %	51.3 %
3	Sr-92	5.7 %	22.8 %	Ba-140	11.3 %	62.6 %
4	Zr-97	5.6 %	28.4 %	I-133	8.2 %	70.8 %
5	I-135	5.5 %	33.9 %	Sr-91	4.2 %	75.1 %
6	Te-133m	4.8 %	38.7 %	Mo-99	3.9 %	79.0 %
7	I-134	4.4 %	43.1 %	Ce-143	3.7 %	82.7 %
8	Rb-89	4.1 %	47.2 %	I-135	3.2 %	85.9 %
9	La-142	4.0 %	51.2 %	Te-131m	2.5 %	88.3 %
10	Sr-93	3.9 %	55.1 %	La-140	2.3 %	90.7 %
11	Mo-101	3.9 %	59.0 %	I-131	1.9 %	92.6 %
12	Cs-138	3.7 %	62.7 %	Zr-95	1.3 %	93.9 %
13	Sb-131	3.5 %	66.2 %	I-132	1.1 %	95.1 %
14	Sr-91	2.9 %	69.1 %	…	…	…
15	Ba-141	2.6 %	71.7 %			
16	Y-94	2.4 %	74.2 %			
17	Tc-104	2.4 %	76.6 %			
18	Y-95	2.4 %	79.0 %			
19	Sb-130	2.1 %	81.1 %			
20	Te-133	1.6 %	82.7 %			
21	Ce-146	1.6 %	84.3 %			
22	Te-132	1.2 %	85.5 %			
23	Br-84	0.9 %	86.4 %			
24	La-143	0.9 %	87.3 %			
25	Cs-139	0.8 %	88.1 %			
26	Sn-128	0.7 %	88.8 %			
27	Pr-146	0.7 %	89.5 %			
28	Sb-130m	0.6 %	90.1 %			

29	Rb-90m	0.6 %	90.7 %
30	Tc-105	0.6 %	91.3 %
31	Sb-129	0.5 %	91.8 %
32	Sn-129m	0.5 %	92.3 %
33	Pr-147	0.4 %	92.8 %
34	**Rb-90**	0.4 %	93.2 %
35	I-133	0.4 %	93.6 %
36	Sb-132m	0.4 %	94.0 %
37	**Se-83**	0.4 %	94.4 %
38	Ru-105	0.4 %	94.7 %
39	Tc-101	0.3 %	95.1 %
	…	…	…

Table 19. Ranking table for sorting nuclides describing the dose contribution from radioactive material deposited on the ground in two different time windows (days 8-30 and days 31-365) for fission of U-235 induced by 1 MeV neutrons. The calculation shows that 8 nuclides are needed to describe at least 95 % of the effective dose from the ground during days 8-30 days, and 6 nuclides to describe at least 95 % of the effective dose from the ground during days 31-365.

		Effective dose, days 8-30			**Effective dose, days 31-365**	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Ba-140	48.5 %	48.5 %	Zr-95	52.5 %	52.5 %
2	Te-132	18.3 %	66.9 %	Ba-140	22.4 %	74.9 %
3	La-140	9.3 %	76.2 %	Nb-95	7.9 %	82.9 %
4	Zr-95	8.5 %	84.6 %	Ru-103	7.6 %	90.5 %
5	I-131	4.6 %	89.2 %	La-140	3.1 %	93.6 %
6	Ru-103	3.5 %	92.7 %	Ce-141	1.7 %	95.3 %
7	Mo-99	1.9 %	94.6 %	…	…	…
8	**Ce-141**	1.0 %	95.6 %			
	…	…	…			

Appendix – Ranking for U-238

In Table 20 and Table 21 the nuclides needed to reach 95 % of the total effective dose from radioactive material deposited on the ground in any of the four time windows (first 24 hours, days 2-7, days 8-30 and days 31-365) for the fission of U-238 induced by 14 MeV neutrons are listed. The eight nuclides added for U-238 (Pd-112, Cd-115, Cd-117, and Cd-117m, Sb-127, Sb-132, Sb-133 and Nd-149) are marked in bold in Table 20.

Table 20. Ranking table for sorting nuclides describing the dose contribution from the radioactive material deposited on the ground in two different time windows (first 24 hours and days 2-7) for fission of U-238 induced by 14 MeV neutrons. The calculation shows that 48 nuclides are needed to describe at least 95 % of the dose from the ground during the first 24 hours, and 18 nuclides to describe at least 95 % of the effective dose from the ground during days 2-7.

		Effective dose, first 24 hours			Effective dose, days 2-7	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Te-134	11.2 %	11.2 %	Te-132	30.8 %	30.8 %
2	I-135	5.1 %	16.4 %	Zr-97	20.1 %	50.9 %
3	Zr-97	5.1 %	21.4 %	Ba-140	9.2 %	60.1 %
4	Ba-142	4.9 %	26.3 %	I-133	7.5 %	67.5 %
5	Sb-131	4.5 %	30.9 %	Mo-99	4.0 %	71.6 %
6	Mo-101	4.5 %	35.4 %	Sr-91	3.0 %	74.6 %
7	Tc-104	4.0 %	39.4 %	I-135	3.0 %	77.6 %
8	Sr-92	3.9 %	43.3 %	Ce-143	2.7 %	80.3 %
9	Te-133m	3.6 %	46.9 %	**Sb-127**	2.6 %	82.9 %
10	Sb-130	3.2 %	50.1 %	I-131	2.2 %	85.1 %
11	Sr-93	3.1 %	53.3 %	La-140	1.9 %	87.0 %
12	La-142	3.1 %	56.3 %	Te-131m	1.7 %	88.7 %
13	Cs-138	2.7 %	59.1 %	**Pd-112**	1.6 %	90.3 %
14	Rb-89	2.7 %	61.8 %	I-132	1.2 %	91.5 %
15	I-134	2.5 %	64.3 %	Zr-95	1.0 %	92.5 %
16	Sn-128	2.2 %	66.6 %	Ru-103	1.0 %	93.5 %
17	Te-133	2.1 %	68.7 %	**Cd-115**	0.9 %	94.3 %
18	Ba-141	2.1 %	70.8 %	Rh-105	0.7 %	95.1 %
19	Sr-91	2.1 %	72.8 %	…	…	…
20	Y-94	1.9 %	74.8 %			
21	Y-95	1.8 %	76.6 %			
22	Tc-105	1.5 %	78.1 %			
23	Ce-146	1.5 %	79.6 %			
24	Te-132	1.2 %	80.8 %			
25	Br-84	1.2 %	82.0 %			
26	Sn-129m	1.1 %	83.1 %			
27	Sn-127	1.1 %	84.2 %			
28	Ru-105	0.9 %	85.1 %			

29	Sb-130m	0.9 %	86.0 %
30	Sb-129	0.8 %	86.9 %
31	Cs-139	0.7 %	87.6 %
32	**Cd-117**	0.7 %	88.2 %
33	La-143	0.7 %	88.9 %
34	Sb-132m	0.7 %	89.6 %
35	Pr-146	0.6 %	90.2 %
36	**Sb-133**	0.6 %	90.8 %
37	Pr-147	0.5 %	91.3 %
38	Sb-128	0.4 %	91.7 %
39	Sb-129m	0.4 %	92.1 %
40	Se-83	0.4 %	92.5 %
41	Tc-101	0.4 %	92.9 %
42	**Sb-132**	0.4 %	93.3 %
43	**Cd-117m**	0.4 %	93.7 %
44	I-133	0.3 %	94.0 %
45	Nd-151	0.3 %	94.3 %
46	**Nd-149**	0.3 %	94.6 %
47	Rb-90	0.3 %	94.9 %
48	Rb-90m	0.3 %	95.2 %
	…	…	…

Table 21. Ranking table for sorting of nuclides describing the dose contribution from radioactive material deposited on the ground in two different time windows (days 8-30 and days 31-365) for fission of U-238 induced by 14 MeV neutrons. The calculation shows that 10 nuclides are needed to describe at least 95 % of the effective dose from the ground during days 8-30, and 8 nuclides to describe at least 95 % of the effective dose from the ground during days 31-365.

		Effective dose, days 8-30			**Effective dose, days 31-365**	
No.	**Nuclide**	**Share**	**Cumulative share**	**Nuclide**	**Share**	**Cumulative share**
1	Ba-140	42.4 %	42.4 %	Zr-95	46.0 %	46.0 %
2	Te-132	20.8 %	63.2 %	Ba-140	21.1 %	67.1 %
3	La-140	8.1 %	71.3 %	Ru-103	12.7 %	79.8 %
4	Zr-95	6.9 %	78.2 %	Nb-95	7.0 %	86.7 %
5	I-131	5.5 %	83.7 %	La-140	3.0 %	89.7 %
6	Ru-103	5.4 %	89.1 %	Ru-106	2.7 %	92.4 %
7	Sb-127	2.3 %	91.4 %	Ce-141	1.6 %	94.0 %
8	Mo-99	2.1 %	93.5 %	Ce-144	1.4 %	95.4 %
9	Nd-147	1.1 %	94.6 %	…	…	…
10	Ce-141	0.9 %	95.5 %			
	…	…	…			

The Swedish Radiation Safety Authority (SSM) works proactively and preventively with nuclear safety, radiation protection, nuclear security, and nuclear non-proliferation to protect people and the environment from the harmful effects of radiation, now and in the future.

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E-print AB, 2023