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Swedish Radiation Safety Authority

Report

Radiological Consequences of Fallout from Nuclear Explosions

2023:05e

Author: Anders Axelsson, Peder Kock, Jan Johansson, Jonas Lindgren, Anna Maria Blixt Buhr, Jonas Boson, Ulf Bäverstam, Simon Karlsson
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Summary

In this report, Strålsäkerhetsmyndigheten, the Swedish Radiation Safety Authority (SSM), presents an analysis of the potential radiological consequences of fallout from the nuclear explosions at distances between about 10 kilometres and about 300 kilometres from the explosion, and the effect of various protective actions. The contents of the report constitute a knowledge base and not a ready-made planning basis. However, certain conclusions can be drawn and already taken into account in emergency preparedness planning.

General background

SSM is the main regulatory body with overall responsibility regarding radiation protection and nuclear safety in Sweden. As part of the national radiation protection preparedness, SSM works proactively and preventively for radiation protection and nuclear safety and is responsible for *i.a.* professional expertise and expert knowledge and decision-making support in the field of radiation protection, including dispersion prognoses, radiation monitoring and radiation protection assessments. This responsibility remains unchanged during a heightened state of alert.

The Government of Sweden has emphasised the importance of a coherent total defence planning to increase the overall capability of the Swedish total defence. The current guidance[1] states that planning should be based on the assumption that nuclear weapons may be used against Sweden. Increased knowledge of the possible radiological consequences of fallout from nuclear explosions can therefore constitute a valuable basis for developing the Swedish national defence.

Purpose and method

Since 2018, SSM has conducted a project to study the radiological consequences of fallout from nuclear explosions. The main purpose of the study has been to develop an understanding and further knowledge concerning radiological consequences, particularly with regard to early consequences for the general public, and the effects of various protective actions. Another aim has been to develop SSM's capabilities in dispersion and dose calculations. This study provides a platform for further development.

A nuclear explosion produces large amounts of radioactive material, which can lead to radioactive fallout. In the explosion, the radioactive substances are mixed in a cloud with weapon residues and materials from the surroundings. As the cloud cools, radioactive particles are formed and spread by wind over large areas. The most serious radiological consequences of fallout are associated with nuclear explosions at ground level. For nuclear explosions without ground contact, fallout warranting urgent protective actions is not expected to the same extent.

On behalf of SSM, the Swedish Defence Research Agency (FOI) has constructed nuclear weapon cases that can be assumed to be representative of how an attacker would use nuclear weapons operationally to achieve military objectives. As the main scenario, SSM has

[1] Looking Forward – Action Plan to Promote and Develop Coherent Planning for the Swedish Total Defence 2021-2025

chosen the nuclear weapon case that is expected to result in the most serious radiological consequences, *i.e.* a nuclear explosion at ground level with an explosive yield of 100 kilotons. To produce more generally applicable results, SSM's analysis is based on statistical evaluation of results from dispersion and dose calculations for a large number of different historical weather cases.

One starting point in emergency planning for radiation protection is the level of radiation dose known as the reference level. The planning should enable radiation doses to be no higher than the current reference level. In addition, below the reference level, the optimisation of radiation protection should continue. The value chosen for the reference level depends on the circumstances of the situation under consideration. The reference level for exposure of members of the public in an emergency exposure situation that currently applies under the Swedish Radiation Protection Ordinance (20 mSv annual effective dose) is not an appropriate starting point for the optimisation of radiation protection in the event of a nuclear explosion. The risks arising from the exposure must be balanced against other risks that may exist in such a situation. The overall objectives for radiation protection in emergency exposure situations are nevertheless still applicable, *i.e.* that severe deterministic health effects (acute radiation injury) should be avoided or minimised, and that the probability of stochastic health effects (mainly cancer) should be reduced as far as reasonably achievable. In the report, three possible reference levels associated with fallout from nuclear explosions have been used in the evaluation: 100, 500 and 1,000 mSv annual effective dose.

Scope

The report focuses on areas at such a distance from the explosion that radiation doses from the fallout constitute the main consequences. Initial ionizing radiation and other direct effects are therefore not included. In the first instance, consequences that give rise to the need for urgent action are addressed. The effectiveness of the protective actions of sheltering indoors, evacuation, and the administration of iodine tablets is evaluated, as well as the need for management of acute radiation injuries.

A number of urgent protective actions that may be relevant in the context of nuclear explosions (personal decontamination, measures to avoid or reduce inadvertent ingestion, and early measures for food and goods) are not addressed in this report. More long-term or indirect radiological consequences that may occur as a result of the fallout, such as consequences for food production or transport, are also not addressed.

Results and conclusions

Radiation doses from fallout after a nuclear explosion can in some cases be so high that they are lethal, life-threatening or result in permanent injury to an unprotected person at distances up to tens of kilometres. It is important to plan for good protection against fallout in areas at these distances. It is also important to plan for good protection at large distances, up to hundreds of kilometres, to reduce long-term radiological consequences. Since the location of the explosion is not known in advance, this means that such planning may be needed in large parts of the country.

In the short term, radiation doses are entirely dominated by radiation from radioactive material deposited on the ground. This is an important difference compared with releases from a severe nuclear power plant accident, where the largest contribution to radiation doses during the first few days comes from inhalation of radioactive material in the air. The radiation dose that may be received from fallout decreases rapidly with time after the nuclear explosion. Sheltering in premises that offer good protection against radiation from ground deposition of radioactive material during the first days after a nuclear explosion is therefore effective and allows high radiation doses to be avoided even in areas affected by heavy fallout. Examples of such protection are protective shelters, protected spaces, command centres with fortifying protection, basements, or similar premises that protect against radiation and where it is possible to stay for several days.

After a nuclear explosion, it takes some time for the fallout to arrive (depending on distance and weather) and this time may be sufficient to seek good shelter. Evacuation in this situation increases the risk of people being unprotected if evacuation is not completed before the fallout arrives. It is also difficult to predict in time which areas will not be affected by fallout. Rapidly seeking good shelter in the event of a nuclear explosion is therefore a more appropriate protective action than evacuation.

After the need to shelter in premises offering good protection has ceased, there may be areas where it is inappropriate to remain. Such areas may need to be evacuated in order to limit longer-term radiation doses from the radioactive material deposited on the ground. The capability and planning in place for nuclear emergency preparedness, *e.g.* to rapidly map ground deposition over large areas, can provide a good basis for further development.

Iodine tablets have no practical function in the event of fallout from nuclear explosions. Within the distances where iodine tablets could be warranted, good protection is required to avoid high radiation doses from the radioactive material deposited on the ground. In such shelters, radiation doses to the thyroid are so low that iodine tablets are not warranted. This is a another difference compared to releases from a severe nuclear power plant accident, where taking iodine tablets can be an important measure to reduce radiation doses to the thyroid.

Need for further investigation and development

Some areas related to the results of the report appear to warrant urgent continued investigation by the responsible Government agencies.

This report shows the need to plan for shelter offering good protection for the public in connection with fallout after a nuclear explosion. The inquiry report *Ett stärkt skydd för civilbefolkningen vid höjd beredskap* [*A Strengthened Protection of the Civilian Population during a Heightened State of Alert*] (SOU 2022:57) emphasises the importance of access to protective shelters and other protected spaces for the civilian population. In its report, the inquiry proposes a number of measures with regard to protective shelters and other protected spaces.

Radiation protection legislation for the general public and workers not involved in total defence needs to be reviewed. The report shows that the regulations that apply to the public in peacetime are not suitable for all situations that may arise during a heightened state of alert. For workers who are not part of total defence, it should be investigated whether the rules that apply in peacetime are suitable for the situations that may arise during a heightened state of alert.

To enable decisions on protective actions and other response actions in the event of nuclear explosions, situation assessments based on the best possible information about the event need to be produced quickly. Which actors should collaborate in such a process needs to be investigated. The forms and content of their interaction also need to be developed. The design of reports to support decision-making is also dependent on the planning that exists for protective actions and other response actions. The development of collaboration must therefore, as with nuclear emergency preparedness, go hand in hand with the development of relevant decision support.

The system for alert, warning and communication with the public in connection with fallout from nuclear explosions needs to be developed. The development needs to consider several issues that are dependent on time and distance conditions when it comes to protection against radioactive fallout from nuclear explosions. There may be large areas that will not be affected by fallout, and where protective actions can be avoided by early analysis of prevailing weather conditions. Furthermore, there may be large areas that will eventually be affected, but where there is time to get to prepared premises that offer good protection from radiation for several days, instead of rushing to a closer but inferior and less sustainable shelter. The amount of time people need to spend sheltering from fallout on the ground depends on the amount of fallout at the site, and cannot be determined in advance. Without their own measurement capability, people in shelters depend on information from the responsible authorities about when they can leave the shelter. This information needs to be followed by recommendations on how to proceed after sheltering has ceased.

Appropriate intervention levels for food in connection with nuclear explosion fallout need to be developed. Fallout from a nuclear explosion can affect foodstuffs at great distances. The consequences for the production of food can be evaluated with the method used in this study, but this requires the availability of appropriate intervention levels, *i.e.* levels of ground contamination where a certain protective action may need to be taken. Fallout from nuclear weapons is so different from fallout in connection with nuclear power plant accidents that it cannot be assumed that the intervention levels for foodstuffs that have previously been developed can be used.

What capacity for radiation monitoring should be available at the local, regional and national levels, as well as what types of radiation monitoring should be carried out at various stages in connection with a nuclear explosion, needs to be further investigated. Radiation monitoring capabilities are needed at all levels of society, from national resources for qualified analyses and large-scale mapping of fallout to local capabilities for determining whether it is possible to leave a shelter. For radiation monitoring in connection with a nuclear explosion, prepared support is also needed for interpretation of measurement results, for example to provide guidance on when it may be appropriate to leave initial shelter.

Going forward, SSM intends to continuously improve its modelling capabilities for fallout from nuclear explosions. The Swedish Radiation Safety Authority will also, in collaboration with other relevant Government agencies and other stakeholders, use the current and future results to analyse and contribute to improving society’s protection against fallout from nuclear explosions.

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1. Introduction

In this report, the Swedish Radiation Safety Authority (SSM) presents an analysis of the potential radiological consequences of fallout from nuclear explosions and the effect of the various protective actions.

"Fallout" refers to radioactive material that is dispersed through the air after a nuclear explosion and eventually falls to the ground. In this study, the concept of fallout includes not only material deposited on the ground, but also radioactive material in lower air layers that can cause radiation doses at ground level via inhalation or external exposure.

1.1. Background and purpose

SSM has overall responsibility regarding radiation protection and nuclear safety in Sweden. As part of the national radiation protection preparedness, it works proactively and preventively for radiation protection and nuclear safety in Sweden and has a responsibility to take measures to prevent, identify and detect emergency exposure situations that could lead to harm to human health or the environment. SSM is responsible *i.a.* for providing expertise and knowledge as well as decision support in the field of radiation protection, including dispersion and dose prognoses, radiation monitoring and radiation protection assessments. This responsibility remains unchanged during a heightened state of alert.

The Government of Sweden has decided that planning for Swedish total defence should be resumed. During the current defence decision period, the Government of Sweden has further emphasised the importance of coherent total defence planning to increase the overall capability of the total defence. The current action plan for the total defence [1] states that planning should be based on the possibility of nuclear weapons being used against Sweden. Increased knowledge of the possible radiological consequences of fallout from nuclear explosions can therefore constitute a valuable basis for the development of the Swedish total defence.

Based on SSM's responsibilities and the current focus of the Swedish total defence planning, the Authority has since 2018 been conducting a project to study the radiological consequences of fallout from a nuclear explosions. The project is documented in this report.

One main objective of the study has been to develop an understanding and further knowledge concerning the radiological impact of fallout from nuclear explosions, particularly with regard to consequences for the general public and the effects of protective actions. The study has resulted in in-depth impact assessments under varying conditions, and for varying exposure pathways for ionising radiation from the fallout after a nuclear explosion. The results can be used to draw conclusions about the need for and effects of possible protective actions, and the report thus constitutes a knowledge base for emergency preparedness planning.

Another purpose has been to develop SSM's capabilities in dispersion and dose calculations for fallout from nuclear explosions. Forecasts for fallout can have different purposes and take place under different conditions. There may be time and resource limitations on the level of detail in the description of fallout that can be achieved, or that is useful. Several different tools are therefore needed, from very rapid and inherently schematic and standardised methods to full-scale dispersion and dose prognoses.

Both in terms of knowledge of the radiological impact of fallout from nuclear explosions and in terms of capability development, the intention is for the study to provide a platform for further development.

1.2. Choice of methodology

The analysis is based on results from dispersion and dose calculations aimed at estimating radiological consequences at different distances from the explosion site at different times, for different nuclides and via different exposure pathways for ionising radiation. By using advanced dispersion and dose calculations, better predictions are obtained than with simpler idealised fallout patterns. Furthermore, the aim has been to produce more generally useful results than would be the case if individual examples or case studies were selected. A large number of historical weather cases have therefore been used in the calculations.

SSM has largely used, combined and further developed methods and modelling tools used in previous analyses and investigations. The methods are briefly described in Chapter 4 and in more detail in Appendix 2 (Nuclide Composition) and Appendix 3 (Dispersion and Dose Calculations). In this section, the discussion aims to justify the choice of methods and illustrate continuity with proven tools and methodologies.

SSM has previously developed proposals for the design of new emergency planning zones and distances around Swedish nuclear power plants [2] using a method that in many respects and in applicable parts is similar to that used in this study. The previous investigation used dispersion and dose calculations based on a few different postulated events at the Swedish nuclear power plants and a large number of different weather scenarios. The methods then used for statistical treatment of modelling outcomes have also been deemed useful in the analysis of fallout from nuclear explosions in the present study.

In the investigation of new emergency planning zones and distances, dispersion models suitable for that type of release were used. In this study, a different source description and a different dispersion model have been used. Both the source description and dispersion model, originating from the Swedish Defence Research Agency (FOI) and the Swedish Meteorological and Hydrological Institute (SMHI), respectively, have been used by SSM for a long time and have been further developed in some respects during the study.

The source description is based on an empirical American parameterisation of the stabilised radioactive cloud about 10 minutes after a nuclear explosion [3]. The source description is supplemented by what is referred to as the nuclide vector, which describes the nuclide composition. SSM has carried out fairly extensive work to select which nuclides need to be represented in the dispersion and dose calculations, and the quantity of each nuclide. To a large extent, the same principles have been used for selection as in the investigation of new emergency planning zones and distances. Mainly, the selection has been based on the contribution of the nuclides to the radiation dose from ground contamination during different time periods extending up to and including the first year. In addition, the selection was completed by analysing the contribution of different nuclides to the inhalation dose in order not to miss important nuclides for internal exposure. The dominant contribution to external exposure from airborne radioactive material is assumed to be represented by the same nuclides as for ground dose. The selection is described in detail in Appendix 2 (Nuclide Composition). More on the different exposure pathways can be found in Section 3.2.1.

1.3. Nuclear weapon scenarios and choice of main scenario

As a starting point for assessing the radiological consequences of nuclear explosions in the Swedish total defence planning, FOI has, on behalf of SSM, produced examples that can be assumed to be representative of how an attacker would use nuclear weapons [4]. SSM has based its choice of scenario to study on these nuclear weapon cases. FOI points out that the nuclear weapon cases are limited to operational use primarily for the purpose of achieving military objectives, with explosive yields and other employment parameters chosen to achieve optimal military effect. At the same time, FOI points out that the nuclear weapon cases have a preponderance of those that provide the most serious situation regarding ground contamination with radioactive material, although these are not necessarily the most likely.

Of the eight nuclear weapon cases presented by FOI, two are ground-level detonations with an explosive yield of 100 kilotons[1], the targets being a harbour facility in one case and a military facility outside a medium-sized city in the other. Two are aerial explosions (height 700 m) with an explosive yield of 100 kilotons, where the targets are a port facility and a mobilisation site. One case is an anti-ship strike in a harbour with a yield of 10 kilotons on the water surface of the harbour basin. Two are multi-weapon strikes (4 x 3 kilotons in one case and 3 x 10 kilotons in the other) by ground-level detonations against a military installation and a major airport respectively. The last nuclear weapon case is an operation where the initiation of the warhead fails and 5 kg of plutonium is released when the conventional explosive in the weapon explodes.

FOI proposes that nuclear weapons with explosive yields of 10 kilotons or less in the examples are assumed to be fission weapons, while others are assumed to have a fusion fraction of 50 %.[2]

A ground contact explosion is expected to have more severe radiological consequences from fallout than a non-ground contact explosion. Furthermore, the literature in the field gives reason to believe that the fallout from a water explosion is generally less of a problem than from a ground-level detonation [5]. Among the examples, SSM has therefore chosen as the main scenario for this study a ground-level detonation with an explosive yield of 100 kilotons and a fusion fraction of 50 %. This scenario, among the possible representative examples developed by FOI, should produce the most serious radiological consequences from fallout and is therefore, from SSM's point of view, best suited as a basis for emergency preparedness planning.

A chemical explosion with dispersion of plutonium does not fall within the scope of this study. For accidents or antagonistic events involving chemical release of hazardous substances, including radioactive material, other methods and tools need to be used. However, un-fissioned weapon-grade plutonium would be expected in the fallout after a nuclear explosion, and as one of several sensitivity analyses, SSM has investigated whether it is likely that the inclusion of one or a few kilograms of plutonium in the modelling would significantly affect the results regarding the radiological consequences presented in the report. SSM has found that this is not the case.

[1] One kiloton means an energy release equivalent to 1,000 tonnes of conventional high explosive.
[2] See Chapter 2 on fission and fusion.

1.4. Scope and limitations

SSM has chosen to restrict the scope of this study in several respects.

The analyses deal with the radiological consequences that may arise due to radioactive fallout from nuclear explosions. Initial (nuclear) radiation and other direct forms of impact are not addressed, as they must be analysed with other tools and methods, require different planning and management, and have a more limited distribution in time and space. The focus is thus on areas that are at such a distance from the explosion that the main impact is radiation doses from the fallout, roughly some kilometres or more. In addition, the usefulness of the dispersion model used, with about 2.5 km resolution, can be expected to be limited within distances of about the same size as the source, which in the main scenario has a radius of about 5.5 km, see Section 2.2. In practice, this has meant that in the analyses SSM has not considered results at distances of less than 8 km from the explosion.

Furthermore, the analyses primarily address those effects that give rise to the need for urgent protective actions, such as sheltering indoors or evacuation, and other urgent measures to reduce the consequences of the fallout. Other, mainly more long-term or indirect effects that may occur as a result of the fallout, such as effects on food production or transport, have not been addressed.

With regard to effects on food, urgent protective actions may also be necessary due to the fallout, such as advising against the use of drinking water from surface water sources or banning the marketing of milk, but SSM has chosen to address consequences for food at a later stage. Impacts on production of food for human consumption can be addressed with the methodology used here, as was done in the study on new emergency planning zones and distances [2]. However, this requires that intervention levels, *i.e.* levels of ground contamination that are expected to produce a certain level of radioactive material in different foodstuffs, can be determined. Fallout from a nuclear explosion is so different from fallout from the release that might occur with a nuclear power plant accident that it cannot be assumed that the intervention levels for food safety developed for nuclear power plant accidents can be used in the event of weapon nuclear explosion. A more extensive investigation aimed at developing suitable intervention levels for foodstuffs in connection with fallout from nuclear explosions is planned in co-operation with FOI, which in a previous method study [6] has developed examples of intervention levels for drinking water from surface water sources under different conditions.

2. Fallout from nuclear explosions

2.1. Origin of fallout

The energy released in a nuclear explosion generally derives partly from fission (splitting) of heavy atomic nuclei (uranium or plutonium) and partly from the fusion (merging) 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. The main scenario used in this report is a nuclear explosion with a total energy release of 100 kilotons (kt) – *i.e.* the equivalent of 100,000 tonnes of conventional high explosives – of which half the energy (50 kt) is generated by fission and the other half by fusion.

A nuclear explosion produces large amounts of radioactive material, which can lead to radioactive fallout. The proportion of fusion is important for the amount of fallout generated, as most of the radioactive residues from the explosion are fission products (i.e. fission residues). These are not produced in fusion reactions. However, both fission and fusion reactions give rise to intense neutron radiation, which in turn creates radioactive material by activating materials in the weapon or its surroundings, called activation products. In relative terms (per kiloton), fusion produces more neutrons than fission, and at higher energy, thus creating relatively more activation products.

All radioactive material are initially present in gaseous form in the fireball formed in the explosion. They are carried upwards together with other weapon debris and material from the environment, e.g. from the ground if the explosion occurs at a sufficiently low altitude. A radioactive cloud is formed which stabilises as it cools and heat-driven expansion slows. In the cloud, radioactive particles are formed via condensation and by the trapping of radioactive material on material from the environment which is mixed into the cloud. The distribution of particles in the cloud and their size are important factors that influence the radiological consequences of fallout. If the explosion occurs just below, at or near the ground surface, some of the activity remains in the crater formed. In addition, airborne particles of varying sizes are formed. Fairly large particles of ground material mixed with fission and activation products fall to the ground near the explosion site. Smaller particles may be carried over greater distances and fall to the ground as localised fallout. If the explosion occurs at a sufficiently high altitude, very small particles are formed which are normally dispersed and diluted over large distances, known as global fallout. This does not usually pose an acute radiological problem, unless precipitation brings material to the ground. For a 100 kt nuclear explosion, the “sufficient height” in this respect is about 350 metres.

The radioactive material formed are composed of a large number of different nuclides, and are mainly fission products, although the contribution of activation products is not negligible in all cases. Which nuclides are formed and how much of each nuclide depends on many factors, some of which are difficult to calculate or know for a given explosion. For example, the occurrence depends on neutron fluxes in different parts of the weapon and the materials used in a given nuclear weapon. Certain assumptions must therefore be made to analyse the consequences of the radioactive fallout.

2.2. Dispersion

The nuclides that appear in the atmosphere will be further dispersed. The dispersion is generally determined by their initial distribution in space, by wind and precipitation, and by the physico-chemical form of the various nuclides, e.g. whether they are in gaseous or particulate form and, in the latter case, how they are distributed among particles of varying sizes.

The initial state (source) in the dispersion model used is the stabilised cloud, which is assumed to be fully formed after 10 minutes. For the main scenario (100 kt ground-level explosion), the upper part of the stabilised cloud reaches a height of about 14,500 m, and the radius of the main cloud is about 5,500 m. The radioactivity is distributed in different parts of the cloud and on particles of varying sizes. The radioactive material in the source cloud will then be dispersed over large areas and reach the near-surface air, eventually depositing on the ground.

The size and extent of the area affected by fallout for a given nuclear weapon scenario depends on the meteorological conditions (wind, precipitation, etc.) and the nature of the terrain (topography and land use).

2.3. Composition and radioactive decay of fallout

In order to give an idea of the similarities and differences between the fallout from a nuclear explosion and the fallout that may result from a radioactive release during a severe nuclear power plant accident, Figure 1 compares the effective dose from ground contamination per day after a nuclear explosion with fallout from a nuclear power plant accident. The comparison is scaled so that the ground contaminations give the same effective doses during Day 8. For the nuclear power plant case, the nuclide composition represents an imagined worst-case scenario for a release from a Swedish nuclear power plant (event without functioning mitigation systems, see [2]). Since this release continues for two days after the initial event, the comparison starts at Day 3, even though fallout, especially from a nuclear explosion, can in many cases arrive earlier than that. It should be noted that for the selected nuclear power plant case, the radiation doses are dominated by the inhalation dose, while the comparison here refers only to external dose from the ground. For fallout from the nuclear explosion, the ground dose is instead the dominant exposure pathway. For the nuclear explosion case, the nuclide composition contained in SSM’s nuclide vector for the main scenario has been used, see Appendix 2 (Nuclide Composition).

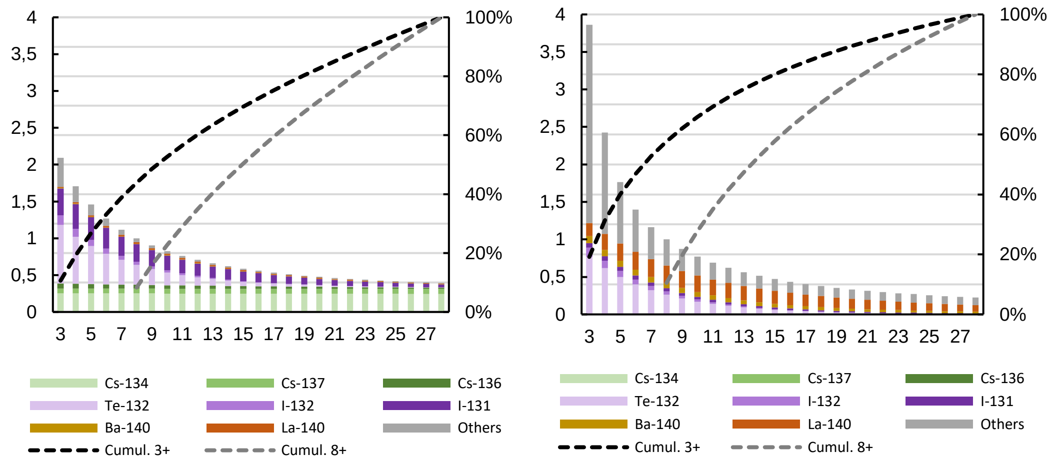

Figure 1. Effective dose per day from radioactive material deposited on the ground in connection with a nuclear power plant accident (without functioning mitigation systems) during days 3 to 28 (left) compared with the corresponding dose for fallout from weapon nuclear explosion (right). Bars and the left vertical scale show the effective dose from the ground per day, normalised to the dose received during Day 8. Dashed lines and the right vertical scale show the evolution of the accumulated effective dose from the ground contamination starting on Day 3 and starting on Day 8, as a proportion of the total dose received up to Day 28.

It can be noted that partly different nuclides are important for the radiation doses received from the ground. For the nuclear power plant case, the relatively long-lived Cs-134 plays a major role, and dominates after a couple of weeks, while it is not present in the case of fallout from a nuclear explosion. In the nuclear explosion fallout, the shorter-lived decay pair Ba-140/La-140 plays a major role, as well as, at least initially, shorter-lived nuclides among the "others" (e.g. the fission products I-133 and Zr-97/Nb-97 and the activation products Na-24 and Np-239). In both cases, the short-lived decay pair Te-132/I-132 plays an important role in the first few weeks.

The composition of nuclear explosion fallout, with a high proportion of short-lived nuclides, means that the dose rates decrease very rapidly with time. This is particularly evident if one also considers the first few days after the nuclear detonation. On the left in Figure 2 the effective doses received per day from the ground contamination starting 10 minutes after the detonation, *i.e.* Day 1 are stated. The normalisation is the same as in Figure 1, *i.e.* the value 1 corresponds to the dose received during Day 8. Thus, the effective dose from the ground contamination in the first 24 hours is about 120 times the dose received during Day 8 and about 20 times the dose received during Day 2. The right-hand side in Figure 2 shows the relative doses received per day from the ground contamination if the first three hours after the explosion are excluded – which may, for example, illustrate the situation at a site where the fallout arrives three hours after the detonation. Overall, it is clear that there is much to be gained by avoiding early exposure to the fallout.

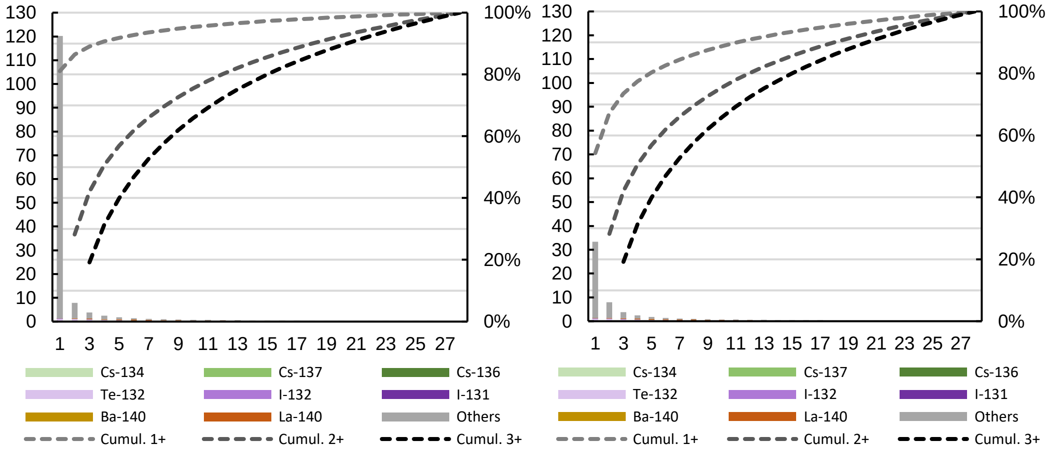

Figure 2. Effective dose per day from nuclear fallout on the ground during Day 1 to Day 28, including (left) and excluding (right) the first three hours after the explosion. Bars and the left vertical scale show the effective dose from the ground per day, normalised to the dose received during Day 8. Dashed lines and the right vertical scale show the development of the accumulated effective dose from the ground contamination starting on Day 1, starting on Day 2 and starting on Day 3, as a proportion of the total dose received up to and including Day 28.

Figure 2 shows that the radiation dose from the ground contamination during the first days is completely dominated by very short-lived nuclides. In Figure 3 the same daily doses are shown as in Figure 2, but with modified vertical scales to show the development during the subsequent days.

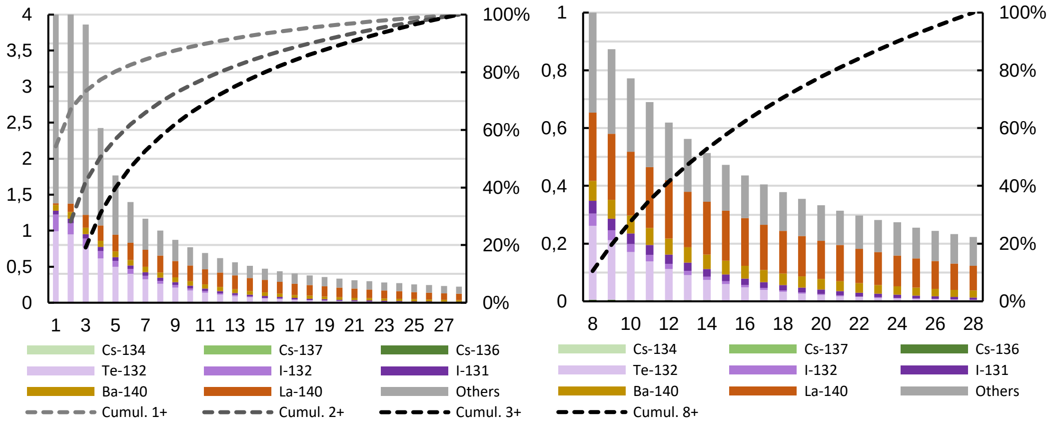

Figure 3. Effective dose per day from nuclear explosion fallout on the ground during Days 1 to 28 (left), excluding the first three hours after the explosion, and during Day 8 to Day 28 (right). Bars and the left vertical scale show the effective dose from the ground per day, normalised to the dose received during Day 8. The vertical scale in the left frame is interrupted for Day 1 and Day 2; the full scale is shown on the right in Figure 2. Dashed lines and the right vertical scale show the evolution of the accumulated effective dose received from the ground contamination from the day indicated in the legend, as a proportion of the total dose received up to Day 28.

The group "other" for the nuclear explosion fallout shown in Figures 1-3 includes a large number of nuclides. Therefore, the most important nuclides from the point of view of dose are also presented in tabular form in Table 1. Nuclides that are represented separately (outside the "other" group) in Figures 1-3 are shown in bold. The calculations were made with SSM's *DosCalc*[3] software, where the dose from ingrown decay daughters has been attributed to the parent. For example, Te-132 and its daughter I-132 are reported separately, but the reported value for Te-132 includes the dose contribution from I-132 that grows in

[3] *DosCalc* v 1.0 (Manual 20-914)

during the calculation. The row for I-132 instead reports the dose contribution from the I-132 that existed at the start of the calculation.

Table 1. Contribution to the ground dose (%) from those nuclides in nuclear fallout that account for at least 2 % of the total ground dose. Nuclides that are represented separately (outside the "other" group) in Figures 1-3 are shown in bold.

Day 1 (from 10 minutes)	**%**	**Day 1 (from 3 hours)**	**%**	**Day 2**	**%**	**Day 3**	**%**	**Day 8**	**%**
Te-134	7.4	Zr-97	11.5	Zr-97	21.8	**Te-132**	**19.7**	**Te-132**	**25.7**
Xe-138	5.6	I-135	11.3	Na-24	15.0	Zr-97	16.6	**La-140**	**23.6**
Tc-104	4.7	Na-24	8.8	**Te-132**	**11.9**	Na-24	10.1	**Ba-140**	**7.0**
Ba-142	4.4	Kr-88	7.4	I-133	8.5	I-133	7.8	U-237	6.4
I-135	4.4	Sr-92	6.8	Sr-91	5.5	Np-239	6.8	Np-239	6.0
Kr-88	4.1	La-142	6.1	I-135	5.3	**La-140**	**4.6**	**I-131**	**4.4**
Sr-92	4.0	I-134	6.1	Np-239	4.4	Te-131m	3.3	**I-132**	**4.2**
Zr-97	3.9	Sr-91	5.7	Te-131m	2.8	**I-132**	**3.2**	Ru-103	2.7
I-134	3.7	Ru-105	4.2	Xe-135	2.8	Ce-143	3.1	Mo-99	2.6
Te-133m	3.3	I-133	3.5	Ce-143	2.5	U-237	2.8	Sb-127	2.6
Mo-101	3.3	Mn-56	3.1			Mo-99	2.4	Zr-95	2.6
Na-24	3.0	**Te-132**	**3.0**			**Ba-140**	**2.4**	Mn-54	2.0
Sb-131	3.0					Sr-91	2.0		
Rb-89	2.9								
La-142	2.7								
Sr-93	2.7								
Cs-138	2.6								
Sb-130	2.1								
Sr-91	2.0								

3. Radiation protection

3.1. Starting points for radiation protection

3.1.1. Regulation of radiation protection during a heightened state of alert

Radiation protection in Sweden is regulated primarily via the Swedish Radiation Protection Act [7] and the Swedish Radiation Protection Ordinance [8] along with Regulations issued by SSM. The Swedish regulation of radiation protection follows the EU Radiation Protection Directive from 2013 [9], which in turn is based on recommendations published by the International Commission on Radiological Protection (ICRP) in 2007 [10].

The regulation of radiation protection in the Swedish Radiation Protection Act, the Swedish Radiation Protection Ordinance and SSM Regulations also apply in connection with a heightened state of alert, unless otherwise announced on the basis of the legislation. The Government of Sweden, the Swedish Armed Forces, and the Swedish Radiation Safety Authority are authorised to issue regulations that deviate from the current legislation regarding workers in the Swedish total defence. The Swedish Armed Forces are currently working on developing regulations for their own personnel. However, no corresponding work is underway to develop regulations for workers in the Swedish total defence who are not employed by the Swedish Armed Forces.

It is unclear whether current legislation allows the Swedish Government or any other governmental body to issue regulations that deviate from current radiation protection legislation for the general public or workers in general. For the general public, this should be investigated further, as it is clear *i.a.* from this report that the rules and regulations that apply to the general public in peacetime are not suitable for all situations that may arise during a heightened state of alert. For workers who are not part of the Swedish total defence, it should first be investigated whether situations may arise during a heightened state of alert where the rules applicable to employees in peacetime are not appropriate. If it turns out that there are such situations, the mandate to issue regulations that deviate from the regulations in peacetime for workers who are not part of the Swedish total defence also needs to be investigated.

3.1.2. Exposure situations

The regulation of radiation protection is based on three exposure situations that are intended to cover the entire range of possible exposure situations: *planned exposure situations, emergency exposure situations,* and *existing exposure situations.* Planned exposure situations are common activities involving ionising radiation. Emergency exposure situations are situations where urgent protective actions need to be either prepared or implemented immediately. Fallout from a nuclear explosion could give rise to an emergency exposure situation. An existing exposure situation is a situation that already exists when a decision on control needs to be made. An emergency exposure situation due to fallout from a nuclear explosion can transition to an existing exposure situation when there is no longer a need to prepare for or take urgent protective actions.

There is a clear link between rescue services under the Swedish Civil Protection Act [11] and emergency exposure situations under the Swedish Radiation Protection Act [7]. If the criteria for rescue services are fulfilled and the severe adverse consequences have been or can be caused by a radiation source, the criteria for an emergency exposure situation are also met in almost all conceivable situations. Rescue services in response to fallout from a nuclear explosion is an example of a situation that is also an emergency exposure situation.

3.1.3. Principles of radiation protection

Radiation protection is based on three principles: *justification*, *optimisation* and *application of dose limits*. *Justification* means that any decision modifying an exposure situation must do more good than harm. *Optimisation* means that the probability of exposure, the number of people exposed and the amount of radiation dose to each individual is to be kept as low as reasonably achievable, taking financial and societal factors into consideration. It is the overall radiation protection that should be optimised, and not individual protective actions. In an emergency exposure situation, for example as a result of radioactive fallout from a nuclear explosion, what this means in practice is that each individual protective action must be justified. It is then the combination of protective actions that needs to be both justified and optimised, taking into consideration that the combination of protective actions resulting in the lowest total dose is not necessarily the best in all possible circumstances. The third principle, the application of *dose limits*, is only used in planned exposure situations and therefore is not further discussed in this report.

3.1.4. Radiation protection objectives in the event of an emergency exposure situation

In an emergency exposure situation, there are two overall objectives of radiation protection: to avoid or minimise severe deterministic effects[4] and to reduce the likelihood of stochastic effects[5] as far as reasonably achievable [12]. Protective actions to avoid or minimise severe deterministic effects are almost always justified, even though some considerations of overriding risks may be necessary in the context of fallout from a nuclear explosion. Careful consideration is required for protective actions taken to reduce the likelihood of stochastic effects. In a heightened state of alert, higher radiation, doses may be justified compared to in peacetime, but the extent to which this is justified must be determined based on the particular event and the prevailing circumstances.

3.1.5. Reference levels

Reference levels are used in optimisation to limit individual radiation doses in the context of both emergency exposure situations and existing exposure situations. Reference levels represent a level of dose above which it is inappropriate to plan for exposure to occur and below which optimisation of radiation protection should continue. The value chosen for the reference level depends on the circumstances of the particular situation under consideration. A strategy for protective actions during an emergency exposure situation must both allow doses to be kept below pre-determined reference levels and radiation protection to be optimised. An example of the practical implementation of a strategy could be emergency response plans for fallout from nuclear explosions. In the evaluation of whether a strategy enables doses to be kept below selected reference levels, radiation doses to a representative person[6] are calculated. In the event of radioactive fallout from a nuclear

[4] *Severe deterministic effects* refers to early health effects that arise as a direct result of exposure to ionising radiation and that are so severe that they are fatal, life-threatening or result in permanent harm that impairs quality of life.

[5] *Stochastic effects* are random health effects that may arise in the long term as a result of exposure to ionising radiation. The probability of their occurrence increases with an increased radiation dose, but the severity of the health impact, if it does occur, is independent of the amount of the radiation dose. Cancer is one example of a stochastic effect.

[6] A representative person receives a radiation dose that is representative of the radiation doses to the more exposed members of the public, with the exception of persons with extreme or rare habits [34].

explosion, a representative person is normally a one-year-old child. The conclusions on protective actions presented in this report are therefore based on a one-year-old child.

Reference levels for emergency exposure situations are regulated in the Swedish Radiation Protection Ordinance. The reference level for exposure of members of the public in an emergency exposure situation is 100 mSv annual effective dose for events at a nuclear power plant not taken into account in the design of the nuclear reactor and 20 mSv annual effective dose for all other events, including fallout from nuclear explosions [8]. However, a reference level of 20 mSv effective dose is not an appropriate starting point for the optimisation of radiation protection for fallout from a nuclear explosion. The risks arising from the exposure must be balanced against other risks that may exist in such a situation.

However, the overall objectives for radiation protection in an emergency exposure situation are still applicable. Severe deterministic effects should be avoided or minimised. A reference level should therefore not be set higher than 1,000 mSv effective dose [13]. Thereafter, the probability of stochastic effects, mainly cancer, should be reduced to the extent reasonably achievable. Based on what applies in peacetime, a minimum reference level should be set at 100 mSv effective dose. An appropriate step between 100 mSv and 1,000 mSv could be to set a reference level at 500 mSv. At this level, deterministic effects, even those that are not severe, can probably be avoided. In this report, three possible reference levels associated with the fallout from nuclear explosion have therefore been used in the evaluation: 100, 500 and 1,000 mSv annual effective dose.

3.2. Protective actions and other response actions

3.2.1. Exposure pathways

As a result of fallout from a nuclear explosion, people can be externally and internally exposed to ionising radiation. External exposure involves exposure to ionising radiation from radioactive material outside the body. Internal exposure involves exposure to ionising radiation from radioactive material that have entered the body. The exposure can take place via various exposure pathways. External exposure can occur from radioactive material in the air, on the ground or from radioactive material on the skin, clothing, or hair. Internal exposure may occur via inhalation, via ingestion of foodstuffs affected by the fallout or via inadvertent ingestion of *e.g.* radioactive material deposited on the skin.

In this report, external exposure from radioactive material in the air, on the ground and (partly) radioactive material deposited on the skin has been studied, as well as internal exposure from radioactive material entering the body via inhalation. Internal exposure from radioactive material entering the body via consumption of food and drinking water or inadvertent ingestion has not been studied. However, it is reasonable to assume that these exposure pathways are also of considerable importance in connection with the fallout from nuclear explosions. The Swedish Radiation Safety Authority therefore intends to investigate these exposure pathways more closely in future studies.

In the dispersion and dose calculations, external exposure from radioactive material in the air and on the ground gives rise to cloud dose and ground dose, respectively. External exposure from radioactive material on the skin gives rise to skin dose. Internal exposure via inhalation of radioactive material gives rise to inhalation dose and, by extension, thyroid dose. Both external and internal exposure can give rise to a red bone marrow dose, but as the contribution from radioactive material on the ground is completely dominant, only the ground dose has been considered in the calculation of red bone marrow dose.

3.2.2. Protective actions and other response actions

Protective actions aim to avoid or minimise future exposure and are based on the basic rules of radiation protection, see the text box below. In the event of a large-scale accident involving the release of radioactive material, the following protective actions may be relevant: precautionary evacuation, evacuation prior to and during the release, sheltering indoors, administration of iodine tablets, actions to avoid or reduce inadvertent ingestion, decontamination of persons, actions regarding food and drinking water for human consumption, actions for goods, relocation (*i.e.* evacuation due to ground contamination, after the release of radioactive material and dispersion of fallout has ceased), and remediation [14]. In the context of fallout from a nuclear explosion, several of these protective actions may also be relevant.

Basic rules for protection against radiation:

- Avoid being close to a source of radiation for any period longer than essential
- Maintain as much distance as possible between you and the source of the radiation
- Have as much shielding material as possible between you and the source of the radiation
- Avoid ingesting or inhaling radioactive material
- Avoid having radioactive material coming into contact with your skin

Sheltering indoors reduces external exposure from radioactive material on the ground and in the air, as well as internal exposure via inhalation of radioactive material or inadvertent ingestion of radioactive material. The degree of protection for each exposure pathway differs between different premises. With the administration of iodine tablets, the absorption of radioactive iodine to the thyroid gland is reduced. Iodine thyroid blocking provides some protection against severe deterministic effects resulting from exposure to the thyroid gland for all age groups and also reduces the risk of developing thyroid cancer for people under 40 years of age, especially children and foetuses. Relocation has the effect of the cessation or reduction of exposure to radioactive material deposited on the ground after the fallout has ceased accumulating, provided that relocation is to an area unaffected or only slightly affected by the fallout.

The protective actions of personal decontamination, actions to avoid or reduce inadvertent ingestion, actions regarding food and drinking water for human consumption, actions for goods and remedial actions may also be relevant in the context of nuclear explosions, however these are not considered in this report. Evaluating the need for these protective actions requires the development of criteria for when these actions may be justified in the context of fallout from nuclear explosions.

Precautionary evacuation cannot be excluded, but it is based on information about the threat of the employment of nuclear weapons or warning of an impending nuclear strike. Precautionary evacuations are therefore not further considered in this report. Evacuation before and during fallout is not an appropriate protective action in the context of nuclear explosions because the time before the arrival of the fallout can be expected to be too short for evacuation to take place and because it is difficult to judge whether movement to a safer area is taking place.

In addition to protective actions, there are other response actions aimed at mitigating the radiological consequences of an emergency exposure situation. In the context of fallout from nuclear explosions, management of severe deterministic effects, personal monitoring and estimation of individual radiation doses may be relevant. Management of severe deterministic effects involves medical treatment in the health care system. This report addresses the need for management of severe deterministic effects for children and adults due to red bone marrow and skin exposure. The need for management of severe deterministic effects on the thyroid gland has also been evaluated, but no such need arises at the distances covered by the calculations, *i.e.* distances greater than 8 km. For foetuses, there are some additional possible health effects that are not addressed in this report. Personal monitoring and estimation of individual radiation dose are also not addressed.

3.2.3. Protection factors

The protection factor when sheltering indoors refers to the ratio between the radiation dose indoors (with protection) and the radiation dose one would receive outdoors (without protection) for the identical location and duration of the exposure. This means that the lower the protection factor is, the more effective is the protection obtained. The protection factor can vary greatly, depending on *i.a.* the type of building, the building materials, the type of ventilation, and the particle size of the radioactive material in the fallout. This report deals with single-family houses and similar dwellings (referred to here as “houses”), larger apartment buildings, schools and similar (referred to as “large buildings”), protective shelters that fulfil the requirements for SR 15 [15], basements in large concrete buildings, and protective shelters in basements in large concrete buildings or the equivalent.

In general, the greater the volume and the denser the material between the source of the radiation (in this case radioactive material in the air or deposited on the ground) and an individual sheltering indoors, the more effective the shielding against external exposure will be. This means that concrete buildings and many basements will provide good protection against exposure from radioactive material present outside the building. As a general rule, filtered ventilation or switched-off ventilation with a low airflow rate also provides good protection against internal exposure from inhalation, as it reduces the amount of radioactive material entering the premises.

The effect of taking iodine tablets can also be described by a protection factor. In this context, the protection factor refers to the ratio between the radiation dose with the administration of iodine tablets and the radiation dose without the intake of iodine tablets, for the identical location and duration of the exposure. Sheltering indoors also leads to lower thyroid doses, as the concentration of radioactive iodine in the air is lower indoors than in the air outdoors.

Normal residency over time in an area affected by fallout from a nuclear explosion also provides protection from exposure to radioactive material on the ground. This applies to the period of time after sheltering indoors is terminated, or in areas affected by fallout, but not affected to the extent that sheltering indoors was justified. See Appendix 1 (Radiation Protection) for the underlying reasoning and values for the protection factors.

3.3. Generic criteria and dose criteria

A *generic criterion* is a value of radiation dose to an unprotected person which, when exceeded or likely to be exceeded over a specified period of time, in most instances will justify the application of protective actions. A *dose criterion* is a value of radiation dose to an unprotected person which, when exceeded or likely to be exceeded during a specified period of time, in most circumstances will justify a particular protective action or other response action. Thus, generic criteria express that protective actions should be taken while dose criteria express that a specific protective or other response action should be taken. Generic criteria and dose criteria are chosen so that the protective actions taken enable the radiation dose to the general population to be kept below the chosen reference level.

In this report, SSM has used generic criteria for varying combinations of sheltering indoors initially and normal residency during the remainder of the year, expressed in effective dose. For the individual protective actions of sheltering indoors, relocation due to ground contamination and taking iodine tablets, SSM has used dose criteria expressed in effective dose and equivalent dose to the thyroid gland. For the need to manage severe deterministic health effects, SSM has used dose criteria for red bone marrow, skin and thyroid expressed in RBE-weighted absorbed dose to each organ. See Appendix 1 (Radiation Protection) for underlying reasoning and values for generic criteria and dose criteria.

4. Methodology

4.1. General overview

SSM has performed dispersion and dose calculations for the radioactive fallout from a nuclear explosion according to the main scenario (100 kt ground level explosion with 50 % fusion) at a site in Sweden. The calculations differ from each other only in terms of the time of the detonation, *i.e.* in terms of prevailing weather conditions. Calculations have been carried out for explosions at 13-hour intervals during one year. A total of 663 calculations were carried out.

The source used in the calculations, known as the source term, has consisted of the stabilised initial cloud about 10 minutes after the detonation (Section 4.2) and a nuclide vector describing the relative distribution of radioactivity between different nuclides (Section 4.3). The dispersion and dose calculations have been made to allow radiation protection evaluation (Section 4.4).

The results of the calculations have been analysed statistically, with some results relating directly to criteria defined in the calculations, and others obtained by post-processing the output of the calculations.

4.2. Source term

The source term for the dispersion and dose calculations consists partly of a description of the stabilised cloud that is assumed to exist 10 minutes after the explosion and the total activity in the cloud, and partly of a nuclide vector, *i.e.* how the activity in the cloud is distributed among different radionuclides. Several simplifying approximations and assumptions have been made in the modelling. The existence of a stabilised cloud with an extent and dimensions independent of weather conditions is one such approximation. The influence of the nuclear explosion on meteorological conditions, *e.g.* in the form of local precipitation near the explosion site, has also been neglected. The impact of these simplifications is assumed to be limited, as the study focused on radiological consequences at greater distances (see Section 1.4). The source term is determined in the model by the following parameters:

- Explosive yield
- Proportion of the explosive yield derived from fusion
- Height of the detonation above the ground

The nuclide vector and the selection of the constituent nuclides are described in Section 4.3, and in more detail in Appendix 2 (Nuclide Composition).

The source description includes the dimensions of the initial cloud and how the radioactivity is distributed between the various parts of the cloud and on varying particle sizes. This is described in greater detail in Appendix 3 (Dispersion and Dose Calculations). According to the model, the main scenario used by SSM produces an initial cloud (which constitutes the initial state for the dispersion calculation) with a height of about 14,500 metres and a maximum radius of about 5,500 metres. Almost half of the radioactivity (about 45 %) is found in the main cloud, at an altitude between about 9,000 m and about 14,500 m, and just over half in the stem of the mushroom-shaped initial cloud. A small proportion (less than 1 %) consists of relatively large particles in a “base cloud” near the ground, which deposits in the vicinity of the explosion. The majority of the radioactivity is fission products, with a small contribution of activation products from the ground and the weapon structure.

The radioactivity in the cloud is distributed over varying particle size fractions, but the composition, *i.e.* the relative amount of each radionuclide on the particles, is the same throughout the model and is described by the nuclide vector (see Section 4.3). This is an approximation that disregards fractionation, i.e. that substances with varying chemical properties may behave differently in the particle formation phase and be distributed on varying sized particles. SSM has not taken into account initial fractionation or the fact that different substances may behave differently during dispersion or after deposition on the ground.

4.3. Selection of nuclides

SSM has developed a nuclide vector that has been used in dispersion and dose calculations and other analyses within the framework of this study. The nuclide vector is a set of fission and activation products with associated activities at a given time. Other radioactive material that may be dispersed after a nuclear explosion, such as un-fissioned plutonium, have not been considered as they are of less importance to the radiological consequences considered. Radioactive materials decay into new materials that can be radioactive. Knowing the nuclide vector at a given time, calculations of decay and ingrowth give the activities of these nuclides at an arbitrary later time.

The nuclide vector used in this study contains 129 nuclides at the time 10 minutes after a nuclear explosion according to the main scenario. In a nuclear explosion, about a thousand different fission products are formed. The selection of nuclides has therefore been a major part of the work on the nuclide vector. The selection has been made on the basis of the criterion that the nuclide vector should describe at least 95 percent of the dose contributions for the exposure pathways and times considered in this study. The nuclide vector should therefore describe at least 95% of the total effective dose from ground, cloud and inhalation from the first day to the first year. The nuclide vector also includes the iodine isotopes needed to describe at least 95% of the thyroid dose from inhalation of radioactive iodine. The selection has been made in a stepwise manner, taking into account the various exposure pathways and decay processes.

A complete set of fission products immediately after the detonation was calculated for three representative fission reactions: fission of Pu-239 and U-235 induced by neutrons of energy 1 MeV and fission of U-238 induced by neutrons of energy 14 MeV. First, the relative contribution of the nuclides to the ground dose was calculated. Based on this calculation, 91 nuclides, including dose-bearing daughters, were identified that are needed to describe the ground dose. The nuclides needed to describe inhalation dose were then calculated. Two additional nuclides, in addition to the 91 nuclides already identified, were included for this exposure pathway. The analysis then focused on which noble gases can be expected to contribute primarily to cloud dose. This resulted in 13 nuclides from the noble gas group being included in the nuclide vector. Eight parents that did not qualify on their own, but which decay into an already identified dose-bearing daughter nuclide and thus make a non-negligible contribution to the dose were also added. Finally, four nuclides were included which, although not needed according to the above criterion (at least 95% of the dose), may be relevant and of interest to include as marker nuclides in the dispersion calculations for further studies of long-term effects, such as impact on the production of food for human consumption or the need for remedial actions.

The contribution of the activation products to the radiation dose, and in particular the choice of specific nuclides, is associated with greater uncertainties than for the fission products. In order to select which activation products to include, SSM has used the “fission equivalent yield” according to the *KDFOC3* fallout model [3] for varying types of nuclear explosions. One kiloton of fission equivalent yield produces the same dose from the ground in the period 10 minutes to 50 hours after the explosion as the fission products from one kiloton of fission yield. In accordance with the proposed rules of thumb in the *KDFOC3* model, a fission equivalent yield of 0.1 kt fission equivalent per kiloton of fusion yield is assumed in a given explosion. For the main scenario, 5 kt of fission equivalent yield is therefore assumed, where 4 kt are assumed to originate from activation of soil and 1 kt from activation of weapons components. It was then determined which specific nuclides should account for this fission equivalent contribution and what their mutual proportions should be. SSM has estimated this from published analyses of fallout from test explosions in Nevada, USA, which include a number of activation products. The selection in terms of contribution to the dose was then made using the same method and criteria as for the fission products. In this way, SSM has included 11 activation products in the nuclide vector.

After 10 minutes, the nuclide vector consists of 129 nuclides – 118 fission products and 11 activation products – which were then used in the dispersion and dose calculations. The nuclide vector is presented in Table 2. A full description of the method and selection is given in Appendix 2 (Nuclide Composition).

Table 2. Nuclide vector (at 10 minutes) for the main scenario: 100 kt at ground level with 50 % fusion

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

4.4. Radiation protection evaluation

Using dispersion and dose calculations, SSM has evaluated the maximum distances at which a certain radiation dose can be exceeded. Evaluations have been made for various time periods and for varying degrees of protection. In the situations where the radiation doses were calculated for an unprotected person during a limited period of time, the evaluation was performed against dose criteria for individual protective actions. In cases where radiation doses have been calculated for persons taking an individual protective action during a limited period of time, the evaluation has been performed against values selected by SSM[7]. In cases where radiation doses are calculated for combinations of initial protection and protection during the remainder of the first year, the evaluation has been performed in relation to generic criteria if no specific protective actions are taken and in relation to reference levels if one or more protective actions are taken. SSM has also used dispersion and dose calculations at specified distances to evaluate the highest effective doses for various combinations of initial protection and protection during the remainder of the first year, as well as the highest effective doses from varying exposure pathways. See Appendix 1 (Radiation Protection) for the underlying reasoning on the link to reference levels, generic criteria and dose criteria, as well as a summary of the combinations of initial protection and protection during the remainder of the first year that have been evaluated.

SSM has also used dispersion and dose calculations to evaluate the maximum distances at which a certain ground contamination (H+1) can be exceeded and the highest ground contamination (H+1) at specified distances. See Section 4.6 for an explanation of the term "H+1". The results are presented in Appendix 6 (Detailed Results (General)) and can be used to retrospectively evaluate *e.g.* radiological consequences for food for human consumption.

4.5. Dispersion and dose calculations

Using the *MATCH-BOMB* [16] [17] [18] dispersion model, SSM has calculated how radioactive material from the explosion is dispersed in the atmosphere and deposited on the ground for two days after the explosion. The source used in the dispersion calculation is the stabilised initial cloud, which is assumed to exist about 10 minutes after the explosion, with a content of radioactive material distributed on particles of varying sizes in different parts of the cloud (see Section 4.2). Appendix 3 (Dispersion and Dose Calculations) describes in detail the model used by SSM to calculate the atmospheric dispersion and ground contamination of the material originally present in the stabilised initial cloud.

Air concentration and ground contamination from the dispersion calculations have been used for dose calculations with the *ARGOS* [19] decision and analysis support system. The contribution of the various nuclides to the total effective dose from the considered exposure pathways has been calculated during the dispersion phase, and after the dispersion phase when only the ground dose contributes to the total effective dose (see Section 3.2.1 on exposure pathways). In addition, the equivalent dose to the thyroid gland from inhalation of radioactive iodine has been calculated using *ARGOS*.

Based on the ground contamination results, some other dose calculations have also been performed using SSM's *DosCalc* software (absorbed dose to red bone marrow and additional effective dose calculations) and manually (absorbed dose to skin).

[7] For practical reasons, SSM has chosen values that correspond to the dose criteria for each protective action.

The dose calculations have been performed for a one-year-old child and for an adult. For more details, see Appendix 3 (Dispersion and Dose Calculations).

For each calculation case with *MATCH-BOMB* and *ARGOS*, radiation doses and ground contamination of radioactive material from the fallout have been calculated at each location in the calculation area, and the following modelling results have been saved:

- Maximum distances from the explosion where selected criteria for varying radiation doses and ground contamination are exceeded.
- Maximum values for varying radiation doses and ground contamination at selected distances.

Modelling results from all calculations have been compiled into cumulative frequency distributions for each criterion. From the frequency distributions can be determined

- For each criterion (dose or ground contamination) the distances corresponding to given percentiles of the maximum distance distribution.
- For each criterion (distance), the values of dose or ground contamination corresponding to given percentiles of the maximum value distribution.

The material from the above calculations and analyses allows statements of the type

- The greatest distance at which the effective dose D is exceeded is X, given that P % of all weather cases are considered.
- The highest equivalent dose to the thyroid gland exceeded at distance X is D, given that P % of all weather cases are considered.

4.6. Time-invariant description of deposition: "H+1"

Modelling the fallout using a single nuclide vector allows the modelling to be partly based on time-invariant (non-decaying) amount of fallout. SSM uses the term H+1 for such time-invariant fallout. For a given point in the modelling, results expressed in H+1 can be converted to actual activity, in total or for a particular nuclide. This only requires defining the total amount of H+1 in the model and calculating the time evolution of the nuclide vector via radioactive decay. H+1 is expressed in becquerels for simplicity, even though it is a "computational quantity" that does not decay.

The total amount of H+1 in the model is set at $2 \cdot 10^{19}$ Bq per kiloton of fission yield. The number is actually arbitrary to SSM's application, but comes from the source model (*NWSwamp*) developed by FOI [20] and corresponds to common standard values for gamma emission from the fission products 60 minutes after a nuclear explosion with a fission yield of 1 kt [5] [21]. In addition, there is a share from activation per kiloton of fusion yield. For the main scenario with 100 kt ground-level explosion and 50 % fusion yield, this means that the total amount of H+1 in the model is $1.10 \cdot 10^{21}$ Bq.[8] This corresponds quite well to the total activity in the SSM nuclide vector for the main scenario 60 minutes after the detonation ($1.09 \cdot 10^{21}$ Bq), which is not a coincidence since both numbers are based on estimates of the activity of the fission products per kiloton after 60

[8] Here, SSM has used the activation fraction from *KDFOC3* [3] discussed in Section 4.3 (which for the main scenario gives a total activation fraction of 10 % of the fission yield), although these relate to contributions to ground dose during a certain time interval (10 minutes to 50 hours), not contributions to activity after 60 minutes. In fact, the activation contribution to the activity is different from the activation fraction to the ground dose, and varies with time after the explosion. After 60 minutes, the share of activation products in the activity of the nuclide vector is about 13 %. This does not matter as the total amount of H+1 in the model is an arbitrary parameter, although the numerical agreement with the total activity of the nuclide vector at 60 minutes is an advantage in some respects.

minutes.[9] The reference time of 60 minutes after the explosion is also the reason for the designation H+1.

Modelling the fallout based on H+1 can provide valuable information. A limitation of this procedure is that ground contamination results from dispersion modelling refer to results when dispersion modelling has ceased (after 48 hours). Nevertheless, it can be useful. A number of dose calculation criteria that can be related to ground contamination under different conditions, e.g. for estimating equivalent doses to red bone marrow or to skin, have been converted using the nuclide vector to calculation criteria expressed in ground contamination of H+1. In addition, a large number of calculation criteria expressed in terms of ground contamination H+1 have been defined to reflect the impact of deposition via ground contamination at arbitrary distances. Below are some examples to illustrate how this works.

Example: *Knowing the nuclide vector for the main scenario, one can calculate that a ground contamination containing per* m^2 *a proportion of* $1.6{\cdot}10^{-10}$ *of the total activity in the nuclide vector is required to give an unprotected adult an effective dose of 100 mSv from the ground during the second day after the explosion. To model where an unprotected adult can receive 100 mSv effective dose from the ground during the second day, the ground contamination criterion of* $1.6{\cdot}10^{-10}\ m^{-2} \times 1.10{\cdot}10^{21}\ Bq \approx 180\ GBq/m^2$ *H+1 can then be used.*

Example: *If the dispersion calculation indicates that the highest ground deposition obtained at a distance of 30 km from the explosion (taking into account 90 % of all weather events) is 550* GBq/m^2 *H+1, then knowing the nuclide vector for the main scenario, the highest dose rate obtained from the ground at a distance of 30 km from the explosion at various times can be calculated. 550* GBq/m^2 *H+1 represents a proportion* $5.50{\cdot}10^{11} / 1.10{\cdot}10^{21} = 5.0{\cdot}10^{-10}$ *of the total activity in the nuclide vector. A ground deposition corresponding to the total nuclide vector per* m^2 *gives an effective dose rate to an adult of* $1.03{\cdot}10^{9}$ *Sv/h two hours after the explosion. The ground deposition of 550* GBq/m^2 *H+1 then gives a dose rate of* $5.0{\cdot}10^{-10} \times 1.03{\cdot}10^{9}\ Sv/h \approx 520\ mSv/h$ *two hours after the explosion. Three hours after the explosion, the total nuclide vector per* m^2 *gives a dose rate of* $5.93{\cdot}10^{8}$ *Sv/h. The ground deposition of 550* GBq/m^2 *H+1 thus gives a dose rate of* $5.0{\cdot}10^{-10} \times 5.93{\cdot}10^{8}\ Sv/h \approx 300\ mSv/h$ *three hours after the explosion.*

It may be worth repeating that the ground deposition given by the dispersion calculation refers to the result after the dispersion modelling has ceased (after 48 hours). The examples thus assume that the fallout calculated actually occurred within the first 24 hours (the first example) and within two or within three hours, respectively (the second example).

[9] Both figures are actually somewhat higher than usual estimates of the actual activity of fission products (*e.g.* $1.7{\cdot}10^{19}$ Bq per kiloton of fission from [21]). The reasons for this are different. The figure of $2{\cdot}10^{19}$ Bq after 60 minutes per kiloton of fission represents the gamma emission from a fictitious monoenergetic gamma source that should give the same dose rate from the ground as fission products, which may be useful for modelling ground dose from fallout (see [5] Sections 9.154-9.160 and [21] pages 5-66 for details). The corresponding figure for SSM's nuclide vector ($1.9{\cdot}10^{19}$ Bq per kiloton of fission) is also too high, which is due to the fact that SSM has used what is referred to as a maximum vector so as not to risk underestimating contributions from important dose-carrying nuclides whose production rates differ between different possible fission reactions, see Appendix 2 (Nuclide Composition).

5. Results

The results of the calculations are presented in detail in the results appendices (4-6), but with a minimum of comments. A selection of the results is presented here to support the discussion and conclusions in Chapter 6.

The calculations have been made for five different types of initial protection, with the following designations: *house*, *large building*, *protective shelter (SR 15)*, *basement*, and *protective shelter (basement).* These are explained in more detail, including assumed protection factors, in Appendix 1 (Radiation Protection). For external exposure from ground deposition after the initial sheltering has ended, calculations have been made for two types of normal residency: *house* and *large building*. For normal residency, it has been assumed that people on average stay indoors 80 % of the time.

5.1. Effective dose from different exposure pathways

This section presents the results of calculations of the effective dose obtained from varying exposure pathways at an early stage. The exposure pathways considered are the effective dose from external exposure from ground contamination and from the plume, and the committed effective dose from internal exposure by inhalation. For the cloud dose and inhalation dose, the entire dispersion phase is considered, *i.e.* the first two days after the nuclear explosion for which modelling of the dispersion of radioactive material is performed, and for ground dose either the first or the first two days after the explosion are considered.

Figure 4 shows the highest total effective dose from all exposure pathways received by an unprotected one-year-old child and by an unprotected adult at various distances from the explosion. Solid lines show results where effective dose from the ground was calculated for the first 24 hours after the explosion, while dashed lines show results for the first two days. The dose obtained during the first 24 hours dominates.

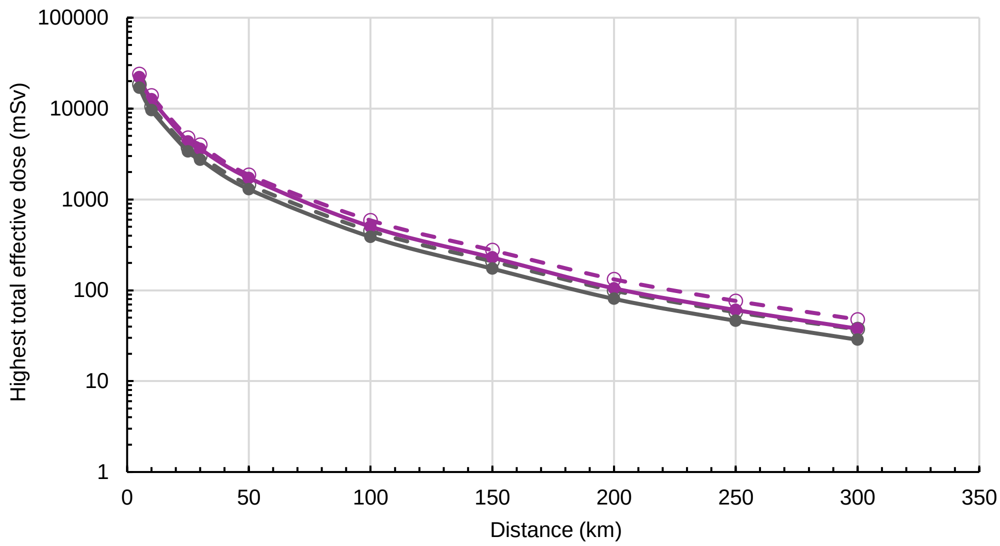

Figure 4. Highest total effective dose received by an unprotected one-year-old child (purple) and an unprotected adult (grey) at specified distances from the detonation if 90 % of occurring weather cases are considered. Solid lines show the effective dose during the first day after the explosion and dashed lines show the effective dose during the first two days.

The calculations also show that the total effective dose obtained at all distances is completely dominated by the contribution from external exposure from the ground. Figure 5 shows the contributions from the other two exposure pathways considered as a proportion of the effective dose from the ground obtained during the first 24 hours. At relatively short distances, the cloud dose makes a larger contribution than the inhalation dose, but never exceeds one percent of the first 24 hours ground dose. At greater distances, the contribution from the inhalation dose is greater than the cloud dose, but still amounts to a maximum of just over one percent of the ground dose during the first 24 hours. At large distances, the contributions from cloud and inhalation dose are too small to be calculated with the available modelling precision.

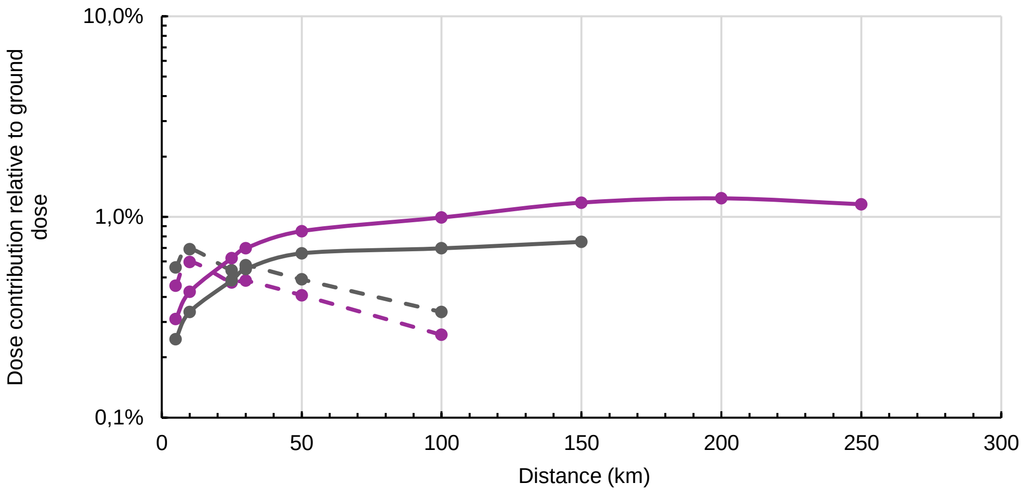

Figure 5. The highest effective dose from external exposure to the cloud (dashed lines) and the maximum committed effective dose from inhalation (solid lines) of an unprotected one-year-old child (purple) and an unprotected adult (grey) at specified distances from the explosion if 90 % of occurring weather cases are considered, as a proportion of the maximum effective dose from external exposure from the ground during the first 24 hours after the explosion.

5.2. Total effective dose after protective actions

Assuming that the public can be protected by sheltering indoors during the first two days, the total effective dose to occupants residing in a house in the first year will exceed the various reference levels out to the distances shown in Tables 3a and 3b for an adult and a one-year-old child, respectively, given various types of initial protection. Within these distances, evacuation or other measures would be necessary in some areas to keep doses below the respective reference levels.

Table 3a. Greatest distances at which the total effective dose in the first year exceeds the various reference levels for adults living in a house when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

	First year (adults living in a house)								
Initial protection (2 days)	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	150	170	200	61	68	78	38	43	49
Large building	120	140	160	39	46	53	20	24	28
Protective shelter (SR 15)	110	120	140	36	41	46	18	21	24
Basement	100	110	130	35	40	45	17	20	23
Protective shelter (basement)	100	110	130	34	39	44	17	19	23

Table 3b. Greatest distances at which the total effective dose in the first year exceeds the various reference levels for a one-year-old child living in a house when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

	First year (one-year-old child living in a house)								
Initial protection (2 days)	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	170	190	220	74	82	94	47	52	59
Large building	140	160	180	52	56	65	27	30	35
Protective shelter (SR 15)	130	140	160	47	50	58	24	27	31
Basement	130	140	160	46	49	57	23	27	31
Protective shelter (basement)	130	140	150	45	48	56	23	26	30

Assuming that no real advance warning can be expected, the only possible and effective protective action immediately after the explosion is to stay in high protection factor shelters for the first few days. Such sheltering with high protection factor can lead to low radiation doses even at quite short distances from the explosion. It is only after sheltering indoors has ended that it is possible to take other measures. Therefore it may be of interest to evaluate the need for additional protective actions (here mainly evacuation) required to keep doses below the reference levels for the case when all effective dose is obtained after the first phase, when fallout is no longer dispersed and sheltering indoors has ended. Table 4 shows the distances at which the various reference levels are exceeded in the first year, assuming that no effective dose is received during the first two days.

Table 4a. Greatest distances at which the total effective dose in the first year exceeds the reference levels, given that no effective dose is received during the first two days, for adults living in a house or a large building when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

	First year (adult, no effective dose in the first two days)								
Residing	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	100	110	130	33	39	44	17	19	23
Large building	69	73	98	17	20	24	< 8	< 8	13

Table 4b. Greatest distances at which the total effective dose during the first year exceeds the reference levels, given that no effective dose is received during the first two days, for a one-year-old child living in a house or a large building when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

	The first year (one-year-old child, no effective dose for the first two days)								
Residing	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	130	140	150	45	48	56	23	26	30
Large building	85	85	110	23	27	31	12	13	15

Table 4 thus gives the distances within which certain areas may have to be evacuated in order to keep the radiation doses below the reference levels, assuming that no radiation dose is received during the first two days. Within the distances given in Table 4, there may be areas where evacuation needs to be carried out more urgently. Tables 5 and 6 give the distances within which the reference levels may be exceeded within one month and one week after the detonation, respectively, again assuming no radiation doses were received during the first two days.

Table 5a. Greatest distances at which the total effective dose in the first month exceeds the reference levels, assuming no effective dose is received in the first two days, for adults living in a house or a large building given when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

Residing	First month (adult, no effective dose in the first two days)								
	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	87	90	110	19	20	24	9	9	11
Large building	50	54	63	< 8	< 8	< 8	< 8	< 8	< 8

Table 5b. Greatest distances at which the total effective dose in the first month exceeds the reference levels, assuming no effective dose in the first two days, for a one-year-old child living in a house or a large building when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered.

Residing	First month (one-year-old child, no effective dose in the first two days)								
	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	99	110	130	23	27	31	12	15	15
Large building	59	66	76	13	16	20	< 8	< 8	9

Table 6a. Greatest distances at which the total effective dose during the first week exceeds the reference levels, given that no effective dose is obtained during the first two days, for adult living in a house or a large building when 70%, 80% and 90%, respectively, of occurring weather cases are considered.

Residing	The first week (adult, no effective dose for the first two days)								
	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	46	49	60	10	10	10	< 8	< 8	< 8
Large building	27	32	25	< 8	< 8	< 8	< 8	< 8	< 8

Table 6b. Greatest distances at which the total effective dose in the first week exceeds the reference levels, assuming no effective dose in the first two days, for a one-year-old child living in a house or a large building when 70%, 80% and 90%, respectively, of occurring weather cases are considered.[10]

Residing	First week (one-year-old child, no effective dose in the first two days)								
	Distance (km) for 100 mSv			Distance (km) for 500 mSv			Distance (km) for 1,000 mSv		
House	57	66	74	*14*	*11*	16	< 8	< 8	9
Large building	34	*41*	*40*	< 8	< 8	9	< 8	< 8	< 8

5.3. Organ doses

SSM has calculated the distances at which threshold doses[11] for severe deterministic health effects may be exceeded for three organs: the thyroid, the skin and the red bone marrow. In addition, the equivalent dose to the thyroid has been calculated in order to evaluate the effect of the possible protective action of administration of iodine tablets. The respective dose criteria are discussed in Appendix 1 (Radiation Protection). This section presents the main results for these organ doses.

The fission product iodine can be present both in a fallout from nuclear explosions and in releases from nuclear power plant accidents. The calculations show that the threshold dose for severe deterministic effects to the thyroid is not exceeded in the area included in the calculations, i.e. at a distance greater than 8 km from the explosion. The thyroid dose is included in the calculations as a contribution to the effective dose, but to evaluate the need for iodine tablets it is not sufficient to study possible effective doses. In connection with severe nuclear power plant accidents, thyroid doses can constitute the main part of the effective dose, and can be very high even at moderate effective doses. SSM has therefore

[10] In some cases, numerical limitations in the computational data used to estimate the effective dose given varying combinations of protective actions result in unphysical steps, so that, for example, a slightly greater distance results for the 80th percentile than for the 90th. In the table, such unphysical steps are indicated by *italicising* the distances. Despite the numerical limitations, the distances are presented using two digits to better illustrate overall trends.
[11] Threshold doses imply an increased incidence of severe deterministic effects among persons receiving radiation doses above this level.

calculated the equivalent dose to the thyroid in order to evaluate the effect of administration of iodine tablets as a possible protective action.

5.3.1. Equivalent dose to the thyroid gland

Tables 7a and 7b show the greatest distances at which the dose criteria for the administration of iodine tablets for adults and one-year-old children, respectively, are exceeded during the dispersion phase when 90 % of occurring weather cases are considered. The tables have been supplemented with approximate effective dose at each distance, estimated on the basis of results for the highest effective dose at specified distances (where the ground dose is calculated during the first 24 hours and inhalation and cloud dose during the entire dispersion phase). The tables also show the estimated contribution of the thyroid dose to the total effective dose.

The lowest level shown in the tables, 50 mSv equivalent dose to the thyroid, is the dose criterion used for the distribution of iodine tablets in Swedish emergency planning for severe nuclear power plant accidents. This thyroid dose can be exceeded outside the immediate vicinity of the nuclear explosion (< 8 km) for the cases shown in the tables – children and adults who are unshielded or living in houses and for children living in a large building. It is not exceeded outside the vicinity of the explosion for other types of shelters included in the modelling (SR 15 protective shelter, basement room in a concrete building, and a protective shelter in a basement of a concrete building).

Intake of iodine tablets can be assumed to reduce the equivalent dose to the thyroid gland to one-tenth, but as the tables show, this represents only a marginal reduction in the total effective dose. For example, the contribution of the thyroid dose of about 2.5 mSv to the total effective dose of about 440 mSv for an unprotected one-year-old child at a distance of about 110 km would be reduced to about 0.25 mSv, leaving the total effective dose essentially unchanged. Sheltering indoors reduces not only the thyroid dose but also the total effective dose, and is in any case required to reduce the high effective doses that can be obtained at the distances shown in the tables. This is further discussed in Section 6.3.3.

Table 7a. Greatest distances at which the equivalent dose to the thyroid for adults exceeds the specified levels. The table also shows the approximate effective dose during the first 24 hours after the explosion at each distance and the estimated contribution of the thyroid dose to the total effective dose. 90 % of occurring weather cases have been considered.

	Adults		
Thyroid dose	Distance	Effective dose at this distance (first 24 hours)	Contribution of thyroid dose to effective dose
		Outdoors	
50 mSv	68 km	800 mSv	~2.5 mSv
100 mSv	35 km	2,100 mSv	~5 mSv
500 mSv	< 8 km	> 11,000 mSv	~25 mSv
		Indoors in a house	
50 mSv	35 km	850 mSv	~2.5 mSv
100 mSv	11 km	3,300 mSv	~5 mSv
500 mSv	< 8 km	> 4,600 mSv	~25 mSv

Table 7b. Greatest distances at which the equivalent dose to the thyroid gland for a one-year-old child exceeds the specified levels. The table also shows the approximate effective dose during the first 24 hours after the explosion at each distance and the estimated contribution of the thyroid dose to the total effective dose. 90 % of occurring weather cases have been considered.

	One-year-old child		
Thyroid dose	Distance	Effective dose at this distance (first 24 hours)	Contribution of thyroid dose to effective dose
		Outdoors	
50 mSv	110 km	440 mSv	~2.5 mSv
100 mSv	74 km	890 mSv	~5 mSv
500 mSv	9 km	13,000 mSv	~25 mSv
		Indoors in a house	
50 mSv	74 km	360 mSv	~2.5 mSv
100 mSv	43 km	850 mSv	~5 mSv
500 mSv	< 8 km	> 5,700 mSv	~25 mSv
		Indoors in a large building	
50 mSv	9 km	1,300 mSv	~2.5 mSv
100 mSv	< 8 km	> 1,400 mSv	~5 mSv
500 mSv	< 8 km	> 1,400 mSv	~25 mSv

5.3.2. Absorbed dose to the skin

SSM has estimated the conditions under which fallout from a nuclear explosion could cause severe deterministic health effects on the skin by deposition of radioactive material on the skin. Table 8 shows the greatest distances for which the dose criterion for severe deterministic effects on the skin (10 Gy RBE-weighted absorbed dose to a depth of 0.4 mm) is exceeded at a duration of exposure, *i.e.* time from contamination to decontamination, of 10 hours. Contamination times have been varied and the fallout is assumed to cause the same activity concentration on the skin as on the ground. Other assumptions are presented in Appendix 3 (Dispersion and Dose Calculations).

Table 8. Greatest distances at which fallout that can produce severe deterministic health effects on the skin is exceeded when 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered, given varying contamination times and a duration of exposure of 10 hours. Distances that probably cannot be reached from the explosion site even at a transport speed of 20 m/s are in brackets.

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

The rapid decay of fallout, especially in the first hours after the explosion, means that the dose rate to the skin from a given amount of deposited fallout decreases very rapidly. This makes the presentation of the results for absorbed dose to the skin from deposition of fallout on the skin relatively complex. The modelling in this case is also based on time-invariant deposition quantities (H+1, see Section 4.6) on the ground at the end of the dispersion phase (after two days), on which the known time dependence of the dose rate has been superimposed. This means that even distances that are unlikely to be reached by deposition at the specified times considering most of the occurring weather cases, are included in Table 8. They have been retained in order to provide an indication of the times and distances that may be broadly relevant, however the most obvious cases (requiring a transport speed of greater than 20 m/s) have been placed in parentheses.

Another way to give an idea of the conditions under which skin contamination may need to be considered with relative urgency is to consider deposition at a given distance. Table 9 gives the skin dose that can be obtained from contamination by fallout at a distance of 30 km from the explosion, given the maximum fallout at this distance if 90 % of occurring weather cases are considered, and given varying times of contamination (arrival of fallout) and duration of exposure (time between contamination and decontamination).

Table 9. Highest RBE-weighted absorbed dose to the skin (to a depth of 0.4 mm) for contamination by fallout at 30 km from the explosion, arriving after varying times, for given durations of exposure.

	Arrival of fallout (time after the explosion) at 30 km distance				
Duration of the exposure	30 minutes	60 minutes	2 hours	3 hours	6 hours
30 minutes	37 Gy	18 Gy	7.5 Gy	4.7 Gy	2.3 Gy
2 hours	72 Gy	41 Gy	22 Gy	15 Gy	7.9 Gy
10 hours	110 Gy	72 Gy	47 Gy	36 Gy	22 Gy

In this situation too, it should be noted that the modelling is not really designed for this type of dose estimate, but SSM has made the estimate by combining the time-invariant amount of fallout on the ground after two days with the strongly time-dependent dose rate from the fallout. With regard to Table 9, this means, for example, that a "hidden precondition" for a 30-minute exposure time to fallout deposited on the skin 60 minutes after the explosion to give a skin dose of 18 Gy is that this fallout corresponds to the full amount of fallout deposited at the site in question during the two-day dispersion phase. Nevertheless, the overall results indicate that the risk that contamination with relatively fresh fallout (hours after the explosion) may cause severe deterministic effects on the skin must be considered.

5.3.3. Absorbed dose to red bone marrow

SSM has estimated distances at which fallout from a nuclear explosion could give rise to severe deterministic health effects on red bone marrow via external exposure from radioactive material deposited on the ground.

Table 10 shows the greatest distances at which an unprotected one-year-old child can have severe deterministic effects on red bone marrow based on varying exposure start times. The table shows, for example, that if exposure starts 6 hours after the explosion, the threshold dose for severe deterministic effects on red bone marrow can be exceeded at a distance of 19 km, if 90 % of the weather cases are taken into account.

Table 10. Greatest distances at which the dose criterion for severe deterministic health effects to red bone marrow is exceeded over 10 hours for a one-year-old child if 70 %, 80 % and 90 %, respectively, of occurring weather cases are considered, assuming exposure starts at given times after the explosion.

1,000 mGy during 10 hours starting after	**70 %**	**80 %**	**90 %**
3 hours	25 km	28 km	33 km
6 hours	14 km	16 km	19 km
12 hours	< 8 km	< 8 km	9 km
≥ 24 hours	< 8 km	< 8 km	< 8 km

6. Discussion

This chapter aims (Sections 6.1 and 6.2) to summarise and discuss the approach, the limitations of the calculations and the impact of these limitations on the validity and robustness of the results, and (Sections 6.3 and 6.4) to summarise key conclusions drawn by SSM from the results and suggest areas for further investigation.

6.1. Limitations in calculations and modelling

SSM's modelling in the course of this study has dependencies and limitations in several respects. These are discussed in this section, both in terms of their impact on the conclusions of the study and more generally.

6.1.1. Input parameters

Important input parameters in the calculations are the explosive yield, the height of the explosion above the ground and the proportion of the explosive yield derived from fusion. In a general case, all of these can be difficult to determine. It is therefore relevant and of interest to consider how the modelling results will depend on these input parameters. The explosive yield affects the dimensions of the initial cloud and thus directly affects the subsequent dispersion and dose calculations. For nuclear weapons that do not have a very high fusion fraction (which applies to all nuclear weapon cases developed by FOI on behalf of SSM [4], including the main scenario chosen by SSM), the total activity in the fallout is dominated by fission products. The activity of the fission products is linearly dependent on the part of the explosive yield derived from fission. The remaining part of the total activity consists mainly of activation products, and in SSM's modelling this share is determined partly by the part of the explosive yield that derives from fusion and partly by the distance to the ground. For explosions above a certain height above the ground, the fallout contains no activation products from the ground. The detonation height also has a major impact on the proportion of the total activity in the cloud that can cause significant radiological consequences via fallout. For explosions above a certain height above the ground, a sufficiently large proportion of the radioactivity is carried by such small particles that significant localised fallout is unlikely to occur, at least outside the vicinity of the explosion.

In this study, SSM has chosen as its main scenario a nuclear weapon employment with the parameters discussed earlier (100 kt ground-level detonation with 50 % fusion). When assessing other sources of error, it may be appropriate to first consider the impact of these parameters on the modelling. For example, if the fission yield is 75 kt instead of 50 kt, with the same fusion yield (50 kt) the total explosive yield is 125 kt. This would produce an initial cloud with slightly varying dimensions, but above all it would mean 50 % more activity from fission products and about 45 % more dose impact from the fallout at a given location. If instead the height of the detonation is varied so that the detonation occurs at 50 m above the ground instead of at the ground surface, the activity of particles likely to contribute to fallout of radiological significance is reduced by more than 20 %.

6.1.2. The ground surface and water surface

The results presented relate to fallout from ground-level nuclear explosions, which have more severe radiological consequences than explosions at higher altitudes. Nuclear explosions below, near or above a water surface have not been considered. The nature of the surface (ground or water) can be assumed to influence the dispersal of radioactive material both through the dimensions of the initial cloud and through its composition in terms of the distribution of radioactive material in the cloud and on the outside and inside of varying types and sizes of particles. In general, a nuclear explosion adjacent to a water surface can be expected to produce particles in the atmosphere that are smaller than for an explosion adjacent to a land surface. Hence, the radiological consequences of early fallout can also be expected to be smaller for such a nuclear explosion [21].

6.1.3. Selection of a representative site

In this study, SSM has endeavoured to obtain results that are as generic as possible, *e.g.* the greatest distance from the explosion where a certain degree of impact is obtained, regardless of the location of the explosion. However, the choice of location can be expected to influence the results to some extent, due to factors such as prevailing weather, topography, land use and proximity to water surfaces.

In particular, proximity to large bodies of water can be expected to have an impact. SSM has not used a land mask in the calculations, *i.e.* outcomes over water are handled in the same way as over land. This is because the chosen location of the explosion has no particular significance for the interpretation of the results, and it is therefore not relevant or of interest to have results that reflect how that particular location is situated in relation to large bodies of water. However, fallout is generally dispersed at greater distances over water surfaces than over land surfaces, so some influence on the results, *e.g.* by proximity to the coast, can be expected. To limit this effect, SSM has chosen a site for the explosion that is located inland, about 200 kilometres from the coast.

However, a certain impact of the choice of location can be expected to remain, and to get an idea of how large this impact may be, SSM has compared the results of calculations for explosions at a small number of different locations in Sweden. The comparison indicates that different choices of site give differences in distance results of up to 20 %, in some cases more, compared with the site chosen for the main calculations. For the cases that give the greatest deviations from the site chosen for the main calculations, the deviations can be qualitatively explained by the fact that at these sites, geography and prevailing winds interact so that a large part of the dispersion takes place over the sea.

Insofar as the results of the present study are mainly used to assess the effects of fallout transported over land, *e.g.* from an explosion on the Swedish mainland to another location on the Swedish mainland, the contribution of the choice of location for the calculations to the uncertainty in the results applied to another location can thus be estimated to be up to around 20 % but probably lower.

6.1.4. Handling of activation products

Most of the activity included in the calculations is derived from fission products. In addition, SSM has included a contribution from neutron activation products, which is a standardised representation of the dose contribution from activation of the environment and weapons components. The specific radionuclides included in the respective contributions (fission, activation of the environment and activation of weapons components), as well as the size of the contributions, can be varied in the general case depending on the information that may be available.

In the calculations on which this report is based, SSM has assumed a contribution from fission products that conservatively represents the yield of each fission product regardless of fission fuel. For the size of the two contributions from activation, SSM has made assumptions according to rules of thumb for standard soil and “a well-defined weapon design” [3]. Specific radionuclides from activation have been selected based on reported observations and analyses made after ground-based nuclear weapons tests. The selection can be modified if more specific information is available, *e.g.* on which substances are included in soil or buildings at a certain location. SSM’s selection includes nuclides that also appear in other calculations and summaries in the literature (see e.g. [22] [23] [24]). However, there is inevitably an element of arbitrariness in the selection of specific nuclides, and conclusions based on results dependent on a single activation product should be used with caution. It should then be ensured that that particular activation product can reasonably be expected in the scenario in question. The present study contains no such conclusions.

6.1.5. Fractionation

In general, the post-explosion condensation processes as substances in the cloud cool and form radioactive particles are expected to lead to relative excesses of volatile substances on small particles and of refractory substances on larger particles. This is expected to lead to relative excesses of volatiles and their decay products in the fallout at greater distances from the explosion and of refractory substances and their decay products at lesser distances. Such fractionation, *i.e.* varying dispersion of different radionuclides, has not been considered in SSM’s modelling. SSM has conducted a sensitivity study in which scattering of only “small” particles (< 50 µm) was compared with the scattering of the full expected range of particle sizes. Neglecting this fractionation effect led to a very strong overestimation of deposition of nuclides on “small” particles at short distances (less than 50-100 km) and an underestimation of the corresponding deposition at long distances (> 100-150 km). This shows that the effect of fractionation can be significant, but the overall effect of fractionation on calculation results for *e.g.* external effective dose from the ground is difficult to estimate quantitatively from this comparison.

Therefore, a rough fractionation effect test was attempted using the method described in [25]. The method has not been used in the dispersion and dose calculations on which the reported results are based, but should be seen as an approximate maximum estimate of the extent to which the dose calculations at varying distances and times should be affected by fractionation. Elements present in the fallout were divided into two classes: volatile and non-volatile according to the scheme presented in [26]. Complete separation of volatiles and non-volatiles at the time of 20 seconds after the explosion was applied to fission products from fast-neutron fission of Pu-239. Dose rates after one hour and after 12 hours from fallout on the ground were calculated assuming that all activity in the fallout was volatile (an extreme case of the fractionation effect expected at large distances from the explosion), and assuming that all activity was non-volatile (an extreme case of the fractionation effect expected at small distances from the explosion). The results indicate that such an “extreme effect” could change the dose results obtained without taking fractionation into account by 20-30 %.

6.1.6. Dose calculations

Radiation doses caused by the fallout from a nuclear explosion have been calculated for varying exposure pathways. Effective doses and organ doses (red bone marrow) obtained via external exposure from fallout on the ground are considered to have been calculated with the best accuracy.

The accuracy of the calculation of the inhalation dose (and thus the thyroid dose) is limited by the fact that the calculated doses relate to the committed effective dose from relatively small particles in the size range known as the “standard aerosol” (roughly 0.1 - 1 µm). Fallout from a ground-contact nuclear explosion can be expected to contain a much wider range of particle sizes, with a significant proportion of the activity being carried by much larger particles.[12] This can generally be expected to lead to an overestimation of the inhalation dose in the calculations performed (see further discussion of the dependence of dose factors on particle size in [27]).

The accuracy of the calculation of the cloud dose is limited by the fact that the dose via this exposure pathway was calculated on the basis of the concentration of radioactive material suspended in the air layer closest to the ground (up to a few tens of metres). In the dose calculation, this concentration has been assumed to apply throughout the airspace, which can lead to both overestimation and underestimation of the cloud dose (depending on the actual distribution of radioactive material at altitude).

The results of this study show that the effective dose from external exposure from the ground is by far the dominant exposure pathway, so that the limitations on the accuracy of the calculation of inhalation dose, thyroid dose and cloud dose are of minor importance for the conclusions. The exception is the conclusion on the need for iodine tablets, which is based on dose to the thyroid gland from inhaled radioactive iodine. In this case, however, SSM assesses that thyroid doses, like other inhalation doses, are overestimated rather than underestimated.

The estimates of absorbed dose to the skin are, among other things, dependent on assumptions about how the concentration of fallout on the ground relates to the concentration on the skin. This relationship is highly scenario dependent (humidity, particle sizes, area of skin involved, clothing, hair growth, *etc.*). The estimates of possible skin doses in this report are based on a generic assumption that the concentration on a contaminated skin area is the same as the concentration on the ground, which is within the range of possibilities. Thus, the results indicate that the occurrence of severe deterministic health effects on the skin is a possibility that must be considered, but do not provide a quantitative prediction of the skin doses that will be obtained in all circumstances given a particular ground contamination.

6.1.7. Un-fissioned plutonium

The present study neglects the impact of un-fissioned plutonium, *i.e.* plutonium that was fission fuel in the nuclear weapon but was not consumed in fission reactions. To estimate the potential impact of un-fissioned plutonium on the calculation results, some simple but conservative assumptions have been made regarding the amount and composition of un-fissioned plutonium. These assumptions are likely to lead to an overestimation of the impact of un-fissioned plutonium.

The conservative assumptions made mean that un-fissioned plutonium could add a proportion of around 10^{-12} to the ground dose rate from the fallout after 10 minutes compared to the ground dose rate from the nuclide vector in the main scenario, and a

[12] The particle size distribution in the fallout varies with the distance from the explosion (with larger particles tending to fall closer to the explosion and smaller particles being carried further away), but a closer study of some results with the dispersion model used by SSM indicates that the activity in the near-surface (i.e. inhalable) air can be carried by particles larger than 20 µm even out to large distances (>200 km).

proportion of around 10^{-6} after 365 days when many other nuclides in the fallout have decayed. From the point of view of ground dose, un-fissioned plutonium does not need to be considered.

Furthermore, the assumptions mean that, compared to the nuclide vector in the main scenario, un-fissioned plutonium could contribute an additional 1 % to the inhalation dose at the time 60 minutes after the detonation and an additional 16 % at the time 200 minutes after the detonation. While these contributions are not negligible, given the limited role of inhalation as an exposure pathway overall (see Section 5.1), it can be concluded that consideration of the inhalation dose from un-fissioned Pu would not affect the conclusions of the present work. Moreover, the assumptions made must be considered very conservative. If one instead uses estimates of the total amount of plutonium introduced into the global environment by above-ground nuclear weapons tests [28] and the summed fission explosive yield of these nuclear weapons tests [29] and uses the resulting average value, the additional contribution of un-fissioned plutonium to the inhalation dose is much smaller.

Assumptions and analysis are described in greater detail in Appendix 3 (Dispersion and Dose Calculations).

The above conclusions apply to the time perspective and the exposure pathways considered in the study. For other exposure pathways, especially in a longer time perspective, the picture could be different in terms of the importance of taking into account the dispersion of plutonium compared to the fission and activation products included in the nuclide vector used here. This could include, for instance, long-term impact on the food supply or inhalation doses from resuspension of fallout on the ground.

6.1.8. Tritium and C-14

Tritium (H-3) is formed in fusion reactions when a nuclear weapon with a fusion component is detonated, and most of it is consumed as fuel in further fusion reactions in the detonation. However, some of the tritium produced is not consumed. A small amount of tritium is also produced by neutron reactions on nitrogen in the surrounding air. Neutron reactions on nitrogen in the air also form C-14. Both tritium and C-14 are part of the radiological source term from a nuclear explosion, but have been neglected in this study.

On the basis of a parameterisation [29] that estimates the amount of tritium and C-14 added to the atmosphere by different mechanisms per kiloton of fusion and per kiloton of fission in a nuclear explosion, neither tritium nor C-14 is considered to affect the conclusions in this report. Assumptions and analysis are described in greater detail in Appendix 3 (Dispersion and Dose Calculations).

As in the case of un-fissioned plutonium (Section 6.1.7), this applies within the scope of the study, and the picture could be different in a longer time perspective.

6.2. Comparisons with other studies and methods

6.2.1. Relative importance of exposure pathways

The results of this study show that one of the most important differences between fallout from a nuclear explosion and releases from a severe nuclear power plant accident is the relative importance of the varying exposure pathways for the radiation doses received by an unprotected person during the dispersion phase. For the nuclear weapon fallout, external dose from the ground dominates, while the inhalation dose, in particular via uptake of radioactive iodine in the thyroid gland, dominates in a severe nuclear power plant accident. This difference has important implications for the effectiveness of protective actions and it is therefore appropriate to compare the present results with other studies.

Table 11 compares the relative magnitude of the three contributions to total effective dose considered in this study (ground dose, cloud dose and inhalation dose) with the corresponding results of two other studies [23] [27]. The comparison should be made with caution, as there are many parameters that distinguish the different cases. A detailed comparison therefore risks being misleading. However, the main message is consistent in that external exposure from radioactive material deposited on the ground is the most important exposure pathway also during the dispersion phase.

Table 11. Relative magnitude of the contributions to total effective dose from external ground dose, external cloud dose and internal committed dose from inhalation in the present study and in two other studies of radiation doses from nuclear explosion scenarios.

Source	**Scenario**	**Relative proportion of total effective dose (***)**		
		Ground	Clouds	Inhalation
Lidström *et. al.* [27]	100 kt uranium fission, ground burst, adult at a distance of 30 km, 20-200 min. (*)	96.8 %	1.0 %	2.3 %
Kraus and Foster [23]	10 kt uranium fission (**), adult at a distance of 10 km, 0-24 hours	97.0 %	2.6 %	0.3 %
This study	100 kt (50 % fission), ground burst, adult at a distance of 30 km, 0-24 h, 90th percentile of 663 weather scenarios.	98.9 %	0.6 %	0.5 %

(*) *Lidström et al.* focus on the inhalation dose, and therefore have considered a time interval (20-200 minutes) that includes the passage of the radioactive plume over the reference distance of 30 km. The short time interval means that the ground dose has a relatively lower weight than in the present study and [23], where the ground dose is integrated from the arrival time of the fallout to 24 hours after the explosion. Exposure to the cloud (external cloud dose and inhalation) occurs only during the plume passage, which may imply a significantly shorter time interval.

(**) Kraus and Foster do not specify the height of the explosion, but the scenario to which their study relates (US DHS National Planning Scenario 1) and their discussion of particle sizes suggests a ground level explosion.

(***) Kraus and Foster's calculation of total effective dose also includes a contribution not shown in the table (with a relative proportion of 0.1 %) from inhalation of radioactive material swirling up from the ground (resuspension). Resuspension is not considered in the present study or in [27]. In calculating the proportions for the scenario in [27], the midpoint of the estimated range given by Lidström *et. al*. has been assumed for the ground dose, and it has been assumed that the absorbed doses (whole body dose) given by the authors also correspond to the effective dose.

6.2.2. Ground dose from idealised fallout patterns

In this study, SSM has performed detailed dispersion and dose calculations. A faster and in some situations more appropriate way of estimating radiological consequences from fallout after a nuclear explosion is to use what is referred to as "idealised fallout patterns". There are a variety of ways to do this, with varying degrees of complexity. The software program

KlangVerk [30], developed by FOI, uses a parameterisation from [5] to calculate elliptical fallout patterns (with a circular component around ground zero) based solely on explosive yield and a wind speed. Fallout patterns estimated with *KlangVerk* can be used as an example to obtain an idea of how fallout patterns calculated with *MATCH-BOMB* may relate to idealised fallout patterns. Fallout patterns estimated with *KlangVerk* were compared with the output from *MATCH-BOMB* calculations for 72 different weather cases. The input data to *KlangVerk* were wind speeds at ground level, reported at the SMHI weather station at the relevant location at each time.

Figure 6 indicates the distance to the most remote point where the indicated dose rates (absorbed whole body dose from the ground at the time 60 minutes after the explosion) are obtained. Weather cases with very low reported wind speed at ground level have been omitted for *KlangVerk*, as a wind speed above 1 m/s is required for the programme to calculate a fallout pattern. On an overall level, the correlation is relatively good. The predictions of the individual weather cases differ considerably, however, and with *MATCH-BOMB* there is not a very strong correlation between the wind speed at ground level and the maximum extent of the fallout pattern.

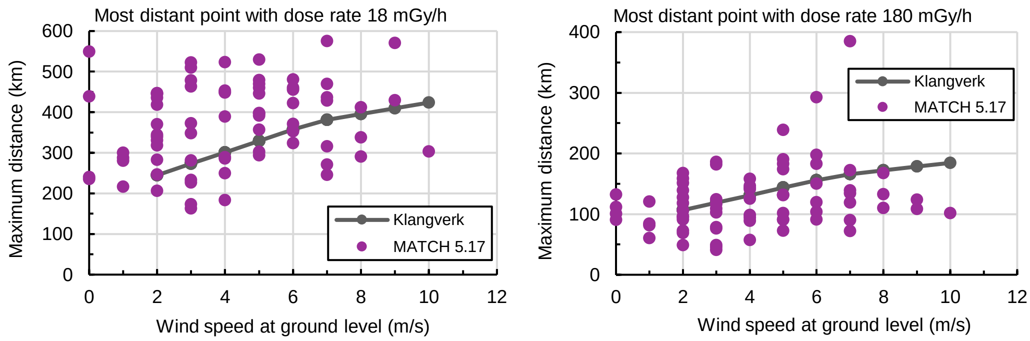

Figure 6. Greatest distance to a point where the dose rates of 18 mGy/h (left) and 180 mGy/h (right) are obtained (corrected to the time 60 minutes after the explosion) as calculated by *KlangVerk* and *MATCH-BOMB*, for the case of a 100 kt ground-level explosion with 50 % fusion fraction and for varying reported ground level wind speeds.

When estimating idealised fallout patterns, an "effective wind speed" can be used, *i.e.* a single wind speed that represents as closely as possible wind speeds at varying heights in the cloud. Similarly, wind shear, *i.e.* the fact that the wind can have different directions at different heights, can be taken into account to varying degrees. This can be relatively important. *KlangVerk* has only one wind speed as input, but this could be the "effective wind speed" possibly corrected for wind shear if wind data for different altitudes is available. This has not been done here, but instead the example illustrates the result of using only the most easily available information (wind speed and direction at ground level). If the elliptical fallout patterns from *KlangVerk* are laid out according to the reported wind direction at ground level at various times, relatively large deviations from the results of the corresponding *MATCH-BOMB* calculations are obtained in many cases, especially for low wind speeds. This is illustrated in Figure 7, which shows that the wind direction at ground level is not a sufficient input to produce a useful prediction of the areas at risk from deposition using idealised fallout patterns.

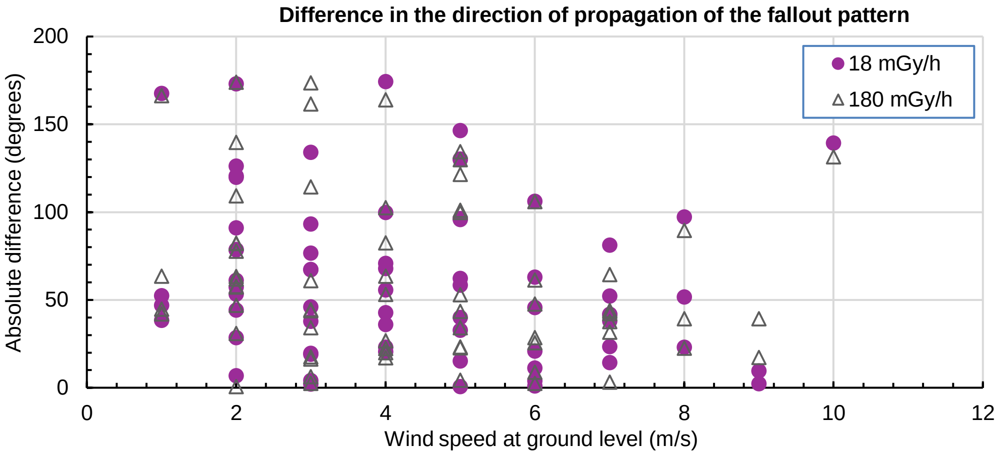

Figure 7. The absolute value of the difference between the bearing calculated by *MATCH-BOMB* from the explosion site to the furthest point with a given dose rate and the reported wind direction on the ground (i.e. the simplest wind direction to use for laying an idealised fallout pattern).

6.3. Conclusions on emergency preparedness planning

The main conclusions relevant to emergency preparedness planning are summarised in this section.

6.3.1. Time aspects

Time is of the essence – it is important to act in the right way at the right time

- The radiation dose that can be received from fallout after a nuclear explosion decreases rapidly with time.
- Time of arrival of fallout depends on distance and weather conditions.
- The time before the arrival of fallout should be used to quickly seek good shelter.

Radiation doses from fallout after a nuclear explosion are dominated by radionuclides that are short-lived, compared to what can be expected after a nuclear power plant accident (see discussion in Section 2.3). The radiation doses associated with the fallout from a nuclear explosion can be greatly reduced by quickly moving indoors in good shelter, even if the time spent in good shelter is limited. How long one needs to shelter at a given location to avoid a certain radiation dose depends on the amount of fallout deposited at that particular location. The rapid decay of fallout means that it is always advantageous to delay unprotected exposure to fallout at an early stage by waiting to enter a contaminated area or by waiting to leave your shelter.

Unlike the direct effects in the immediate vicinity of the nuclear explosion (*e.g.* blast wave, heat and initial ionising radiation), radioactive fallout takes some time to reach a given area. The time taken depends on weather conditions, but distances where sheltering is necessary may be such that this time is sufficient to warn and shelter the population in threatened areas. For example, Figure 4 (Section 5.1) shows that an effective dose of about 1,000 mSv can be obtained during the first 24 hours at a distance of about 70 km. With typical wind speeds, it can take several hours for the fallout to reach this distance. However, the time it takes for the fallout to reach locations where high radiation doses can be obtained cannot be expected to be long enough for large-scale evacuation before or during fallout to be an effective protective action, as discussed in Section 6.3.4.

Even after the initial sheltering phase, ground contamination remains, delivering radiation doses over a longer period of time to people living and working in an area. Unlike the case during and immediately after the spread of fallout from a nuclear explosion, this can be managed by other measures and on a slightly longer timescale, ultimately the relocation of people from particularly affected areas. Such areas can only be identified via radiation monitoring.

More long-term radiological consequences can arise because the fallout also contains some long-lived radionuclides that can give radiation doses over time, for example via radioactive material in foodstuffs. The impact on the production of food for human consumption, either in the short term (*e.g.* drinking water from surface water sources) or in the long term, has not been assessed in the work presented in this report.

6.3.2. Radiation dose from the ground contamination dominates

Good initial shelter against fallout on the ground is the most important

- Early radiation doses from nuclear explosion fallout are dominated by radiation from fallout deposited on the ground.
- In some cases, early radiation doses can be so high that they are fatal, life-threatening or result in permanent injury.
- Sheltering in premises with good protection effectively reduces radiation doses from fallout deposited on the ground.
- The time that sheltering needs to continue depends on the ground contamination at the site.

The results in Section 5.1 show that the exposure pathway that dominates radiation doses from nuclear explosion fallout, even during the dispersion phase, is external exposure from material deposited on the ground. Dose from inhalation and dose from external exposure from radioactive material suspended in the air in the early stages represent a small proportion (a few percent) of the total dose. After the passage of the radioactive plume, only ground contamination contributes to the radiation dose.

The results also show that during the first two days an unprotected person can receive an effective dose of more than 100 mSv out to 200-250 km from the explosion, and more than 1,000 mSv out to 50-75 km. The results presented in Section 5.3.3 show that for an unprotected person, severe deterministic health effects due to high doses to red bone marrow can occur out to about 30 km. This means that the management of severe deterministic effects needs to be considered in planning.

Sheltering indoors in premises with good protection, *e.g.* a basement in a large concrete building, protects against severe deterministic health effects and reduces the risk of stochastic health effects by severely limiting the effective dose from fallout on the ground during the first few days. With a protection factor of 0.01 (basement of a large concrete building), the distance out to which 100 mSv effective dose can be obtained in the first two days is limited to about 12 km and with a protection factor of 0.001 (protective shelter in a basement of a large concrete building) to less than the 8 km that is the approximate limit of the modelling validity range. This approaches the distance where the direct effects of the nuclear explosion dominate the damage. Detailed results for various combinations of shelter are presented in Appendices 4-5.

6.3.3. Iodine tablets

Iodine tablets have no practical function in the event of a nuclear explosion

- Iodine tablets will only provide protection for the thyroid gland from radioactive iodine entering the body, *e.g.* via inhalation.
- In the event of nuclear explosion fallout, inhaled radioactive iodine contributes a very small part of the total radiation dose.
- At distances where iodine tablets could be considered, it is necessary to stay in good shelter against radiation from radioactive substances deposited on the ground.
- In such shelter, the radiation doses to the thyroid gland are also so low that iodine tablets are not warranted.

Section 5.3.1 presents results for equivalent dose to the thyroid, and compares them with total effective doses obtainable at the respective distances. The results imply that although iodine tablets may help to reduce the relatively low thyroid doses that may be incurred, they are of little significance compared to the high effective doses that may be incurred at the respective distances due to exposure from radioactive material deposited on the ground. This fact affects the assessment of the effectiveness and justification of the protective action of distribution and administration of iodine tablets in a nuclear weapons context.

At the distances where thyroid doses that could warrant the administration of iodine tablets may occur, sheltering indoors in premises that offer good protection against exposure from the radioactive material deposited on the ground is required to avoid a significantly increased risk of stochastic effects via high effective doses from the ground.

SSM's conclusion is that iodine thyroid blocking has no practical function in connection with nuclear explosions, for several reasons:

- Thyroid doses at high levels (above 500 mSv) are unlikely to occur for unsheltered survivors.
- At distances where iodine tablets could be warranted according to peacetime dose criteria, sheltering indoors in premises offering good protection is required in order to reduce effective doses from the ground contamination. Staying in such premises can be expected to reduce even already comparatively low doses from inhalation, *e.g.* to the thyroid.
- The time expected to be available in the event of nuclear explosions means that additional distribution is not possible. For iodine tablets to be used at all, they must therefore be pre-dispensed. The benefit of such pre-distribution is very limited, as thyroid doses will be low if the sheltering indoors takes place in premises offering good protection.

However, in order to optimise radiation protection, it is warranted to ensure that the premises prepared for sheltering indoors either have air filters or that doors, windows and ventilation can be switched off during sheltering. Nor can it be excluded that simple measures to temporarily seal gaps *etc.* may be useful for protection in simpler premises.

6.3.4. Evacuation

Evacuation in connection with the fallout from a nuclear explosion is not effective.

- The time before fallout arrives after an explosion is short, and it is difficult to predict which areas may be affected by fallout.
- Evacuation in connection with a nuclear explosion may increase the risk of people being unprotected when the fallout arrives.
- Instead, it is important to utilise the time available to seek out good shelter.

Emergency planning for nuclear power plant accidents includes planning for *evacuation* at an early stage in order to avoid severe deterministic health effects (precautionary evacuation of the precautionary action zone) and to reduce the risk of stochastic health effects (evacuation of parts of the urgent protective action planning zone, UPZ). Evacuation takes place to locations outside the UPZ, which extends out to about 25 kilometres from each nuclear power plant. Decisions on evacuation are based on conditions at the affected power plant and the possibility of implementing other protective actions (sheltering indoors and administration of iodine tablets). When evacuating parts of the UPZ, decisions on which directions to cover can be based on dispersion and dose prognosis.

SSM has not evaluated the possibilities of precautionary evacuation of large areas threatened by attack. Unlike in the case of a nuclear power plant accident, however, in the event of a confirmed nuclear explosion, evacuation is unlikely to work as an urgent protective action to reduce radiation doses from fallout at an early stage. The time for fallout from a confirmed nuclear explosion to reach people can be expected to be too short to carry out large-scale evacuation. Nor can it be expected to be possible to determine, in time and with sufficient certainty, which areas will not be affected by fallout, *i.e.* areas to or via which evacuation could take place. Unlike in the case of a severe nuclear power plant accident, radiation doses from nuclear explosion fallout reaching people during evacuation are dominated by early external exposure, and cannot be limited to any significant extent by the administration of iodine tablets (see Section 6.3.3). Taken together, these factors mean that attempts to evacuate in connection with a confirmed nuclear explosion may increase the risk of people being exposed to high radiation doses from early fallout. Instead, sheltering indoors in premises with good protection from fallout on the ground should be prioritised.

Planning for *relocation* due to ground contamination is part of preparedness for nuclear power plant accidents in order to limit the effective dose from ground contamination in the longer term. Decisions on relocation due to ground contamination are made based on the results of radiation monitoring, taking into account the effect of any remedial actions on reducing radiation doses Following a nuclear explosion resulting in radioactive fallout, relocation may be required in some areas for the purpose of limiting radiation doses received after the early sheltering phase. This is discussed in Section 6.3.5.

6.3.5. Affected areas over time

Relocation or evacuation due to ground contamination may be required

- After cessation of sheltering in premises with good protection, relocation may be required in areas out to large distances from the explosion to limit radiation doses in the long term.
- At shorter distances from the explosion, there may be areas where evacuation due to ground contamination needs to be carried out urgently.
- The distances that may be relevant depend on the radiation doses that can be obtained and the circumstances in general.

Radiological impact over time has been analysed by modelling radiation doses received during the first year after the explosion, excluding an initial sheltering phase. These results (see Section 5.2) show that protective actions such as relocation or other measures and restrictions due to ground contamination may be necessary in some areas out to large distances (over 100 km) in order to keep effective dose below 100 mSv in the first year after the explosion (excluding the first two days). At shorter distances, more urgent action may be required. At distances out to tens of kilometres, relocation due to ground contamination or other measures in some areas may be necessary within a week. If the level of ambition is instead set at 500 mSv effective dose (excluding the first two days), relocation due to ground contamination or other restrictions may be necessary within the first year at distances out to a few tens of kilometres, and in the absolute vicinity of the explosion (around ten kilometres) within a week.

6.3.6. Skin contamination

Measures to protect the skin may be necessary

- Fallout depositing on the skin within a short time after a nuclear explosion can result in radiation doses to the skin that are at such high levels that they are lethal, life-threatening or result in permanent injury.
- It is important to protect the skin from the fallout.
- Urgent decontamination of persons may need to be carried out if the fallout is on the body.

Although the estimates of potential skin doses from fallout contamination on the skin made in this study are fairly rough, it is clear that the risk of deterministic and severe deterministic effects on the skin from fallout may need to be considered, and that the management of severe deterministic effects on the skin needs to be addressed in planning.

Measures to protect against contamination by fresh fallout, as well as urgent personal decontamination measures, may need to be prioritised at relatively large distances. At these distances, protection against external exposure from radioactive material deposited on the ground is required to avoid high effective doses during the first few days. However, a short stay outdoors during the arrival of the fallout may result in a contamination that could lead to severe deterministic effects on the skin, if decontamination is not performed within a few hours. Such effects could occur even in cases where the effective dose incurred while outdoors is low enough to rule out other deterministic effects.

In this respect, the situation differs from a severe nuclear power plant accident, where severe deterministic effects on the skin from fallout contamination can be largely excluded outside the affected site [31].

6.3.7. Comparison with emergency planning for nuclear power plant accidents

Elements of emergency planning for nuclear power plant accidents provide a good basis for nuclear explosion fallout preparedness

- The planning for relocation that is part of Swedish nuclear power plant emergency preparedness can be used as a basis for the corresponding planning for relocation after a nuclear explosion.
- Local, regional and national monitoring capabilities may need to be used for similar purposes as in nuclear power plant emergency preparedness (*e.g.* identifying areas where relocation needs to be prioritised).
- Local monitoring capability is also important as a basis for early decisions.

There are a number of important differences between radioactive fallout from a nuclear explosion and radioactive material dispersed in a serious nuclear power plant accident, with core meltdown and vessel melt-through followed by releases without functioning mitigation systems. There are also some similarities, particularly with regard to capabilities that exist within society's preparedness for nuclear power plant accidents and that can be utilised in existing or developed form for the purpose of strengthening preparedness for fallout from nuclear explosions. This section summarises some key differences and similarities, with the differences mentioned separately earlier in this chapter.

Nuclear explosion fallout can deliver high radiation doses during the dispersion phase to much greater distances than would be the case in a severe nuclear power plant accident.[13] This means, among other things, that it is much more difficult to determine which areas will be affected by fallout, and which could be used in a possible evacuation. This, combined with the fact that the location and other circumstances of the explosion (*e.g.* explosive yield and height above the ground) cannot be assumed to be known in advance, means that evacuation before or during the ongoing spread of radioactive material is not a realistic possibility in emergency planning for nuclear weapons. Instead, evacuation risks leading to high radiation doses if people are affected by the fallout during ongoing evacuation.

As in the case of a severe nuclear power plant accident, after a nuclear explosion it may be necessary to relocate people due to ground contamination, in order to limit radiation doses received after the dispersion phase. This may be necessary after a ground-level nuclear explosion at distances comparable to or greater than the corresponding distance after a severe nuclear power plant accident if the same dose criterion (20 mSv effective dose over one year) is applied.

Within nuclear power plant emergency preparedness, there is planning for radiation monitoring after radioactive fallout in connection with a nuclear power plant accident. Such measurements are aimed at rapidly identifying areas where relocation is needed, and to

[13] This applies to the main scenario considered by SSM in the study, i.e. an explosion on the ground (which can be expected to result in the most serious radiological consequences from fallout). In the case of an air burst, there need not be any fallout of radiological significance.

provide a basis for prioritisation. Measurements also aim to identify areas where measures may be needed to reduce radiation doses from the ingestion of food. The capability that exists for this purpose can be used as a starting point for developing similar preparedness for monitoring fallout after a nuclear explosion. Local monitoring capability can be expected to be very important for the same reasons as in the case of a nuclear power plant accident, but also at a very early stage to determine, for example, when it is possible to leave good shelter.

6.4. Suggestions for further investigation

This report shows the need to plan for good shelter for the public in connection with fallout after a nuclear explosion. A Swedish Government Commission of Inquiry tasked with submitting proposals on how a modern and well-adapted physical protection for the civilian population against the direct consequences of acts of war on Swedish territory should be designed has recently completed its work. The Commission's report [32] was submitted to the Government of Sweden in November 2022. The report emphasises the importance of access to protective shelters and other protected spaces for the civilian population and proposes a number of measures to achieve and maintain appropriate, effective and modern physical protection for the civilian population.

In addition to the need for good shelter, a number of areas related to what has been discussed in this study are important for further investigation in collaboration with the responsible Government agencies. In conclusion, SSM briefly discusses a few proposals for further work, all of which concern the areas of responsibility of other Government agencies as well.

6.4.1. Framework for radiation protection during a heightened state of alert

An investigation is needed into what the framework for radiation protection should look like under conditions other than in peacetime. This may, for example, concern the reference levels that may be reasonable to use during a heightened state of alert and during war. Such an analysis needs to take into account that partly different trade-offs may need to be made between radiation protection and other societal interests (*e.g.* the supply of energy and food security) than is the case in peacetime.

This study can usefully be carried out in two stages. A first step aims to clarify the starting points that should apply to radiation protection during a heightened state of alert and during war. In a second step, proposals for modified or extended regulation are then developed to support relevant radiation protection under conditions other than in peacetime.

6.4.2. Decision-making regarding radiation protection in case of nuclear explosions

In the event of a nuclear power plant accident, SSM produces (and continuously updates) a Nuclear and Radiological Assessment Report (*Kärntekniskt och radiologiskt underlag*, KRU) to support SSM's advice to incident commanders and other decision-makers and as a basis for decisions. SSM has also, in collaboration with relevant stakeholders (*e.g.* incident commanders and relevant central Government agencies), produced relatively extensive material to support decisions on radiation protection in the event of an accident at a Swedish nuclear power plant [14].

Decisions regarding protective actions and other response actions in connection with nuclear explosions also require documentation, which needs to be produced quickly and based on the best possible information about the event. It needs to be investigated which stakeholders should be involved in such a process, as well as the form and content of their interaction. The design of decision-making documents also depends on the needs of different decision-makers, and thus on the planning that exists for protective actions and other response actions. As with nuclear power plant emergency preparedness, development should go hand in hand with the development of relevant decision support.

6.4.3. Alerting and warning in case of nuclear explosion fallout threat

Time and distance constraints on protection against fallout from nuclear explosions raise issues that need to be considered in the design of an appropriate system for alert, warning and communication with the public. The warning time for a nuclear attack may be very short or non-existent, and in the target area may allow quickly seeking protection from direct effects (blast waves, thermal radiation and initial ionising radiation). To the extent that protection is effective against direct effects, it should also provide protection against fallout in the vicinity of the detonation. The situation with regard to fallout outside the area reached by direct effects is different in several respects.

Very large areas lie within distances (hundreds of kilometres) that could be reached by fallout resulting in high levels of ground contamination and warranting urgent protective actions. However, the areas actually affected are considerably smaller. In any given situation, is it possible to determine with sufficient speed and certainty which areas are likely to be affected by the fallout and which are not, and can planning be designed to utilise this information?

The time between the explosion and the arrival of fallout that warrants seeking of a fallout shelter can be relatively long (hours). In areas that will eventually be affected by fallout, there may be time to optimise protection – e.g. to seek a prepared protective shelter where staying for several days is possible, rather than rushing to a closer but poorer shelter in these respects.

The amount of time that needs to be spent sheltering against ground contamination depends on the dose rate at the site, *i.e.* how much radioactive material has been deposited, and cannot be determined in advance.[14] Without their own monitoring capability, people in shelters depend on information from the responsible authorities about when they can leave the shelter. This information is likely to need to be followed, immediately or within a short period of time, by some form of recommendation for behaviour after leaving the shelter. Should evacuation due to ground contamination be carried out urgently? Should access to the outdoors be restricted for the time being? Can various activities continue as usual?

In this report, SSM has considered the scenario of a ground-level explosion, which can be expected to produce the worst possible outcome in terms of fallout. Other types of nuclear weapon employment are possible, and more likely against many targets. Furthermore, the explosive yield may be different from the one assumed by SSM. If, in a given situation, it is possible to determine essential parameters such as explosion height and explosive yield sufficiently quickly, use such information in some form of dispersion and dose prognoses, translate the result into a radiation protection assessment and weigh it against other relevant

[14] The dose rate, as discussed in previous sections, decreases rapidly over time, no matter how high it is initially. This does not mean however that there is a given time after which the dose rate always allows a certain behaviour (*e.g.* to leave the protective shelter). For a given site, it depends on how high the dose rate was at the outset.

factors, this could influence the assessment of where and when various protective actions and other response actions are warranted. This assumes, however, that such information can be rapidly produced and shared between authorities.

6.4.4. Radiation doses from food and inadvertent ingestion

Exposure through the ingestion of radioactive material, via food or inadvertently via the entry into the body of fallout deposited in the environment or on *e.g.* hands, has not been addressed in this report. For that purpose, a partially different selection of nuclides for modelling than the selection used by SSM in this work may prove to be appropriate, as the current set is intended to represent primarily the effective dose through external exposure from the ground and inhalation.

The radiological consequences of fallout from nuclear explosions on the production of food for human consumption, in the short and long term, have not been addressed in this report. In order to be able to estimate such radiological consequences on various types of production of food for human consumption, in addition to ground contamination results from SSM's dispersion modelling, intervention levels are also needed, developed by modelling the uptake and transport of radioactive material via the production and food chain to humans, as well as radiation doses from ingestion of food given various consumption patterns over time.

One part of such an investigation would be the development of limits for radionuclides from nuclear weapons fallout in foodstuffs given appropriate dose criteria for different situations and supply situations in peace, a heightened state of alert, and war. It is not a foregone conclusion that limits developed under the assumption of nuclide composition typical of a severe nuclear power plant accident are fully applicable to nuclear weapons fallout. Once limits have been developed, appropriate intervention levels can be calculated.

6.4.5. Planning documents and advice for radiation monitoring

The Swedish Radiation Safety Authority has produced a planning basis concerning the need for regional radiation monitoring in connection with a Swedish nuclear power plant accident [33]. Similarly, further work is needed as to how radiation monitoring should be performed at different stages after a nuclear explosion. As mentioned above, a capacity for radiation monitoring is needed at all levels of society, from national resources for nuclide-specific analyses and large-scale mapping of fallout to local capacity to determine whether it is possible to leave a shelter. What capacity for radiation monitoring should be available at local, regional and national levels needs to be investigated.

For radiation monitoring in connection with a nuclear explosion, prepared support for interpretation of monitoring results is also needed. Operational intervention levels developed for peacetime radiological emergencies are not necessarily adequate when measuring fallout after a nuclear explosion. The rapid decay of the dose rate associated with a nuclear explosion also makes it more difficult to estimate future doses. Intervention levels that can be used when interpreting monitoring results from simple measurements need to be developed, for example to provide guidance on when it may be appropriate to end initial sheltering.

7. Final comment

The range of possible outcomes regarding the radiological consequences of fallout after a nuclear explosion is large. Not least, the outcome is affected by the weather conditions prevailing at the time of and after the explosion. Individual examples and scenarios can be illustrative and useful in different contexts, but are not sufficient as a basis for emergency planning.

Instead, the results in terms of distances, radiation doses and ground contamination presented in this report represent the most severe radiological consequences that can be expected under a given proportion (70 %, 80 % or 90 %) of a wide range of weather conditions. However, it should be remembered that these results do not necessarily represent what actually happens in the event of a nuclear explosion either. Firstly, the results represent a statistical outcome and not actual weather conditions for a given real explosion. Second, they represent a number of assumptions about the nuclear explosion itself (explosive yield, explosion height, *etc.*). Thirdly, as with all modelling, there are limitations in how radiation doses, distances and ground contamination are modelled for a nuclear explosion with given parameters.

The conclusions regarding emergency planning presented in the report (Section 6.3) have been developed taking into account the above limitations. These conclusions can therefore already be taken into account in emergency planning. Beyond that, the intention is that the results in the report will form part of a growing body of knowledge on the radiological consequences of nuclear explosions, although they do not constitute a complete planning basis for protection against fallout from nuclear explosions. Approaching, where applicable, the level of development of planning and decision-making tools available for nuclear power plant emergency preparedness for severe accidents should instead be seen as a longer-term goal. In its continued work, SSM therefore intends to continuously improve its modelling, *e.g.* with regard to impacts on food production and in many of the respects discussed in Section 6.1. SSM also intends, in collaboration with responsible authorities and other stakeholders, to use the current and future results to analyse and contribute to improving the society's protection against fallout from nuclear explosions.

Appendices

1. Radiation Protection
2. Nuclide Composition
3. Dispersion and Dose Calculations
4. Detailed Results (Children)
5. Detailed Results (Adults)
6. Detailed Results (General)

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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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