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Potential consequences in Norway after a hypothetical accident at Leningrad nuclear power plant

Potential release, fallout and predicted impacts on the environment

Statens strålevern
Norwegian Radiation Protection Authority

Reference:
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Key words:
Leningrad nuclear power plant, hypothetical accident, radioactive fallout, environmental consequences in Norway

Abstract:
The report describes different hypothetical accident scenarios at the Leningrad nuclear power plant for both RBMK and VVER-1200 reactors. The estimated release is combined with different meteorological scenarios to predict possible fallout of radioactive substances in Norway. For a hypothetical catastrophic accident at an RBMK reactor combined with a meteorological worst case scenario, the consequences in Norway could be considerable. Foodstuffs in many regions would be contaminated above the food intervention levels for radioactive cesium in Norway.

Referanse:
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1Statens strålevern; 2Norges Meteorologiske Institutt; 3Scientific and Research Centre ”Radomir”, Russia.
Mulige konsekvenser for Norge ved en hypotetisk ulykke ved Leningrad kjernekraftverk. Potensielt utslipp, nedfall og miljøkonsekvenser.
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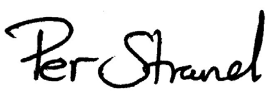
Resymé:
Rapporten beskriver forskjellige hypotetiske ulykkesscenarier ved Leningrad kjernekraftverk for både RBMK reaktorer og VVER-1200 reaktorer. Hypotetiske utslipp er kombinert med forskjellige meteorologiske scenarier og mulig radioaktivt nedfall i Norge er modellert. For en katastrofal ulykke ved en RBMK reaktor på Leningrad kombinert med en ugunstig værsituasjon, vil konsekvensene for Norge kunne bli store. I mange regioner vil forurensningen i matvarer overstige de fastsatte tiltaksgrenser for radioaktivt cesium i mat i Norge.

Head of project: Astrid Liland
Approved:



Per Strand, director, Department for Emergency Preparedness and Environmental Radioactivity.

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Potential consequences in Norway after a hypothetical accident at Leningrad nuclear power plant

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Østerås, June 2012

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For source term estimations:

M. Balonov (Scientific and Research Centre ”Radomir”, Russia) for the ”Final report on Assessment of Source Term Data for Hypothetical Accidents at Leningrad NPP Site”, reference [1].

V.F. Demin and Yu. P. Busulukov (Kurchatov Institute, Russia), I. Basic, M. Kulig, A. Strupczewski and B. Tomic (Enconet Consulting) for the report ”Source Term data for Leningrad NPP site”, reference [4].

For meteorological scenarios:

J. Bartnicki, H Haakenstad, A Benedictow (Norwegian Meteorological Institute) for the report ” Atmospheric Transport of Radioactive Debris to Norway in Case of a Hypothetical Accident in Leningrad Nuclear Power Plant”, reference [7]

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Contents

Extended Abstract

The Norwegian Radiation Protection Authority (NRPA) has conducted a collaborative project to evaluate possible consequences for Norway from a hypothetical accident at the Leningrad Nuclear Power Plant (LNPP), Russia, as part of the work performed under the Norwegian Nuclear Action Plan.

Two of the three accident scenarios considered in the study were developed for the RBMK-1000 reactors that are in operation at the LNPP and one scenario was developed for the new VVER-1200 reactors presently being constructed at the LNPP II site. For a worst case accident scenario, the predicted release is substantially higher from the old RBMK reactors than from the new VVER-1200 reactors.

Out of four combined accident/weather scenarios considered in this report, the scenario with the largest impact in Norway was considered to be a Chernobyl type accident coupled with real meteorological data from autumn 2001 with wind direction towards Norway and little precipitation.

For this hypothetical scenario, the total fallout of caesium-137 and caesium-134 were estimated to be 4.3 petabecquerels (PBq) and 2.8 PBq, respectively – which is about twice the total deposition in Norway after the Chernobyl accident. The highest deposition levels were predicted for Troms and Finnmark Counties in the northern part of Norway.

In order to assess the consequences for natural foodstuffs, the modelled radioactive fallout was coupled with data on transfer to the food chain and statistics on production and hunting. The assessment was limited to the terrestrial environment with a focus on wild berries, mushrooms and animals grazing unimproved pastures (i.e. game, reindeer, sheep and goats).

The largest consequences were predicted for semi-domestic reindeer, sheep and goat production. Up to 90 % of all semi-domestic reindeer could exceed the food intervention level for radioactive caesium in the first couple of years after the fallout, and 20-60 % likely to be above for years or even decades to come.

For lamb the number of affected animals in the first years could reach 300 000 (35 % of the total production), and as many as 100 000 could be above the intervention level in the following years.

The consequences for game in general were predicted to be low, but will to some extent depend on the regional distribution of the different species. For instance, red deer and roe deer are virtually absent in the most contaminated northern parts of Norway, whereas a considerable fraction of moose is found in these areas.

Berries from the southern part of Norway are not likely to be subject to gathering restrictions while berries in the northern part of Norway are at risk of being above the intervention level.

The activity concentrations in mushrooms will depend on species and affected areas. High accumulator species will probably be above the intervention level in the northern and south-eastern parts of Norway, while more popular species with lower accumulation are likely to be above limits in some northern areas only.

Based on the experience from the Chernobyl accident, the total predicted cost to society from a worst case hypothetical accident at Leningrad NPP could be considerable if there is a combination of a catastrophic accident and a meteorological worst case scenario.

Sammendrag

Som del av regjeringens handlingsplan for atomvirksomhet og miljø i nordområdene, har Statens strålevern ledet et samarbeidsprosjekt om mulige konsekvenser for Norge fra en hypotetisk ulykke på Leningrad kjernekraftverk (LNPP) i Russland.

To av de vurderte ulykkescenariene gjaldt de gamle RBMK-1000 reaktorene på LNPP, mens ett scenario omhandlet mulige ulykker ved VVER-1200 reaktorene som er under konstruksjon på området LNPP II. Ved en hypotetisk katastrofal ulykke, vil det estimerte utslippet være vesentlig høyere fra de gamle RBMK reaktorene enn fra de nye VVER-1200 reaktorene.

Fire kombinasjoner av ulykkessituasjon og værforhold er vurdert i denne rapporten. Den kombinasjonen som vil kunne gi de største konsekvensene for Norge, er en ulykke av Tsjernobyl-karakter med vindretning mot Norge og lite nedbør. En slik ugunstig værsituasjon er basert på reelle meteorologiske data fra høsten 2001.

For dette mest alvorlige scenariet, ble det totale hypotetiske nedfallet av cesium-137 og cesium-134 estimert til henholdsvis 4.3 petabecquerel (PBq) og 2.8 PBq, noe som er omtrent det dobbelte av det totale nedfallet i Norge etter Tsjernobyl-ulykken. Det høyeste nedfallet vil med denne værsituasjonen bli i Troms og Finnmark.

Konsekvensene for matproduksjonen i Norge ble vurdert ved å koble det radioaktive nedfallet med data om overføring i næringskjeder og produksjons- og jaktstatistikk. Studien er avgrenset til naturlige økosystemer, med vekt på bær, sopp og dyr på utmarksbeite (dvs. hjortevilt, reinsdyr, sau og geit).

Det vil bli størst konsekvenser for tamrein, sau og geiteproduksjon. Opptil 90 % av all tamrein vil kunne komme til å overstige tiltaksgrensen for radioaktivt cesium i matvarer de første årene etter nedfallet, mens 20-60 % trolig vil kunne ligge over tiltaksgrensen i mange år eller tiår etter en slik hypotetisk ulykke.

Når det gjelder lam, vil det berørte antall dyr det første året kunne nå 300 000 (35 % av den totale produksjonen) og så mange som 100 000 dyr vil kunne være over tiltaksgrensen i de påfølgende år.

Konsekvensene for hjortevilt vil generelt sett bli lave, men vil avhenge av den regionale variasjonen for de forskjellige artene. Hjort og rådyr er for eksempel fraværende i de mest forurensede nordlige delene av Norge, mens en betydelig andel av elg finnes her.

Bær fra den sørlige delen av Norge vil sannsynligvis ikke bli gjenstand for restriksjoner, mens bær fra den nordlige delen av Norge er i risikosonen for å overskride tiltaksgrensen for radioaktivt cesium i matvarer.

Aktivitetskonsentrasjonen i sopp vil avhenge av art og berørte områder. Høyakkumulerende arter vil kunne ligge over grenseverdien i både de nordlige og sør-østlige delene av Norge, mens mer populære arter med lavere opptak antagelig bare vil overstige tiltaksgrensen i noen nordlige områder.

Basert på erfaringen fra Tsjernobyl-ulykken, antas det at den totale samfunnskostnaden fra en verst tenkelig ulykke ved Leningrad kjernekraftverk kombinert med en svært ugunstig værsituasjon, vil kunne bli betydelig for Norge.

1 Introduction

The Norwegian Radiation Protection Authority (NRPA) has conducted a collaborative project to evaluate possible consequences for Norway from a hypothetical accident at the Leningrad Nuclear Power Plant (LNPP), Russia, as part of the work performed under the Norwegian Nuclear Action Plan.

The aim of the assessment is to study possible long-term environmental[1] consequences in Norway from potential releases of radioactive materials given specified 'worst-case' accident and weather situations based on meteorological trajectories.

A suit of radionuclides – including short lived noble gasses and iodine – will be released in case of an accident at LNPP. However, from the long-term perspective (i.e. months to years) the most important contaminants are (half-life in brackets): Cs-137 (30.2 y), Cs-134 (2.1 years) and Sr-90 (28.8 years). In this report emphasis will be put on caesium isotopes since these will give the most severe and long-lasting consequences.

Furthermore, the report will focus on the impact on the terrestrial environment (i.e. freshwater and marine ecosystems have been excluded). Special attention will be given to animals grazing on unimproved pasture and woodland, since the transfer of radioactive caesium is higher in such environments compared to cultivated areas in the long-term [12].

[1] Here interpreted as vegetation, animals and animal products important in connection with human food production. Doses to biota will not be considered in this report.

A brief overview of the report is provided below:

- **Section 2** presents background information on the Leningrad NPP.
- **Section 3** discusses the possible source term and the accident scenarios considered in the assessment.
- **Section 4** provides information on meteorological trajectories.
- **Section 5** describes meteorological worst case scenarios for Norway.
- **Section 6** discusses the SNAP model simulations performed with the combined use of source terms from the accident scenarios (section 3) and meteorological data from the selected worst case scenarios (section 5). Fallout results for Norway for different combinations of accident / meteorological scenarios are presented along with a comparison with the fallout from the Chernobyl accident.
- **Section 7** focuses on environmental modelling and transfer of radioactive caesium to vegetation and animals.
- **Section 8** discusses consequences for foodstuff production with a focus on wild berries, mushrooms, game, reindeer and domestic animals.
- **Section 9** gives final conclusions of this study.

2 Description of Leningrad NPP

The Leningrad Nuclear Power Plant (LNPP) is located on the shore of the Koporskaya Bay of the Gulf of Finland (at Sosnovy Bor, Russia). The LNPP site covers some 317 ha [1].

76 thousand people live in the area around the LNPP within a radius of 30 km.

The LNPP has four water-cooled graphite-moderated reactors of the channel type RBMK-1000. Each power unit has a nominal electric power of 1000 MW, thus the total nominal electric power is 4000 MW(e) [2].

The units were commissioned with a lifetime of 30 years: unit No. 1 - in 1973, unit No. 2 - in 1975, unit No. 3 - in 1979, and unit No.4 - in 1981.

The LNPP has experienced two radiation accidents which were accompanied by radionuclide releases into the environment: in November 1975 and March 1992 [1]. Based on the results from IAEA's safety missions in the 1990s, the LNPP implemented long-term safety upgrades. This has reduced the number of incidents at the plant. Since 1998 only two INES-1 events has been reported at the LNPP [3, 18].

In 2002, the licenses for operation of all the four LNPP power units were reissued by the radiation protection authority Gosatomnadzor of Russia. The service lifetime for power units No. 1 and No. 2 was extended for a period of 15 years in 2004 and 2006, respectively. Lifetime extension programs were implemented for the power unit No. 3 in 2009 and for the power unit No. 4 in 2010 [1].

The LNPP includes a complex for collecting, storing and processing of liquid (LRW) and solid (SRW) radioactive waste located on a separate site at a distance of 900 m from the coast of the Gulf of Finland.

Currently, the LNPP is preparing for a decommissioning phase, and a new site - LNPP II - is being developed nearby. Construction works for two new AES-2006 VVER 1200 MW reactors started in 2008. The reactors are being built by Rosenergoatom's enterprise SPbAEP JSC and are planned to be in operation in 2014 or 2015 [3, www.rosatom.ru].

3 Source terms

The source term data (i.e. the amounts of radionuclides that could be released to the atmosphere during an accident at a nuclear power plant) was derived for both types of power units: the first generation RBMK-1000 reactors (older design) and the new VVER-1200 reactors being constructed at the LNPP II site.

The source terms were estimated based on design basis and beyond design basis accident scenarios provided by the Scientific and Research Centre "RADOMIR", Russia [1], and Enconet Consulting Ges.m.b.H, Austria, who involved Russian scientists from the Kurchatov Institute of Russia [2]. The source term would depend on many parameters such as the type of accident, degree of burn-up of the fuel, technical features and the estimated length of the release time. Any changes in the parameters would give different estimates of the source term, but the two estimates of credible source terms were in good agreement.

Three accident scenarios were selected for our assessment: 2 scenarios for RBMK and one for VVER-type reactors. The Norwegian meteorological institute used this as input data for their atmospheric dispersion modelling [7] using the SNAP model (see chapter 6) where radioactive particles are released into a cylinder. The size and location of this cylinder is given in tables 1-3.

3.1 Accident scenario A

RBMK – design basis accident: the overheating of channels with a filtered release.

Characteristics of this scenario are based on computer simulation by SA codes for postulated scenarios, as a part of the design of the plant (Tab. 1).

Table 1: Accident Scenario A: source term [7].

Parameter	Description
Release Position:	59.83 N, 28.03 E
Isotopes:	^{134}Cs, ^{137}Cs
Release time:	Instantaneous
Total release for ^{134}Cs:	8.60E+12 Bq
Total release for ^{137}Cs:	1.96E+12 Bq
Cylinder base:	150 m
Cylinder top:	150 m
Cylinder radius:	10 m

3.2 Accident scenario B

RBMK catastrophic scenario: beyond design-basis accident with a large fraction of fuel damage.

The radiological characteristics are based on measured/calculated releases (Tab.2) from a real accident (Chernobyl accident, 1986) [4]. 25% of the total release is transferred within the first day of the accident.

Table 2: Accident Scenario B: source term [7].

Parameter	Description
Release Position:	59.83 N, 28.03 E
Isotopes:	^{134}Cs, ^{137}Cs, ^{89}Sr, ^{90}Sr
Release time:	10 days from the accident start
Total release for ^{134}Cs:	8.17E+16 Bq
Total release for ^{137}Cs:	1.25E+17 Bq
Total release for ^{89}Sr:	9.89E+16 Bq
Total release for ^{90}Sr:	9.00E+15 Bq
Cylinder base:	1200 m
Cylinder top:	2500 m
Cylinder radius:	100 m

3.3 Accident scenario C

VVER-1200 catastrophic release: the most severe radiological consequences that could occur as a result of a ‘credible’ accident scenario in a nuclear power plant of the newest design.

Table 3: Accident Scenario C: source term [7].

Parameter	Description
Release Position:	59.83 N, 28.03 E
Isotopes:	^{134}Cs, ^{137}Cs
Release time:	Instantaneous
Total release for ^{134}Cs:	4.40E+15 Bq
Total release for ^{137}Cs:	2.80E+15 Bq
Cylinder base:	30 m
Cylinder top:	30 m
Cylinder radius:	10 m

The definition of the Release Categories and the associated source term data were based on simulations conducted as a part of Level 2 Probabilistic Safety Assessment for a typical VVER-1200/V-320 plant. The analyses were carried out using the STCP code package and MELCOR code [4].

The radionuclide inventory of the core (Tab. 3) was based on Russian data derived for the original Soviet fuel [5].

As evident from Tables 1-3, all the accident scenarios include releases of Cs-137 and Cs-134. The release in scenario B also includes Sr-89 and Sr-90. In a real situation, the releases would – as mentioned in Section 1 – contain more isotopes. Details can be found in [1] and [4].

4 Meteorological trajectories

The border of Norway runs at a distance of 940 km westward of the LNPP (in the direction of Oslo the distance is 1020 km).

To analyse the atmospheric transport from LNPP to Norway in the longer time scale and to select worst case meteorological scenarios, a climatologic trajectory analysis, covering a 12-year period was performed by the Norwegian Meteorological Institute (met.no).

The trajectory analysis allowed estimating the probability of arrival to Norway, shortest and average time of arrival and selection of the conditions for the worst case fallout scenarios.

The climatologic trajectory analysis has been performed in two steps: a compilation of a 12-year period meteorological data (1995-2006) and a compilation of wind fields and computation of 10 days long, forward trajectories originating at the LNPP.

The meteorological data set used was a subset of the European Monitoring and

Environmental Program (EMEP) data, developed for modelling trans-boundary transport of air pollution in Europe [6, 7]. The subset consisted of precipitation fields for the ground level and instantaneous wind fields from the level σ = 925hPa. This level corresponds to 600m height above the terrain and represents relatively well the level of the bulk transport of pollutants in the atmospheric boundary layer.

The area in which meteorological data were available and trajectories were released was covered by the EMEP grid system with a resolution of 50 km at 60^0N in the Polar Stereographic Projection.

One trajectory was released every third hour (at 00, 03, 06, 09, 12, 15, 18, and 21) during the entire 12 years period. Time step between the consecutive points on each trajectory was 15 minutes. Altogether 34994 trajectories were released for the period 1995 – 2006 [7].

The trajectory analysis results suggest that the probability of arrival of a radioactive cloud released from the LNPP to Norway is approximately 20%. Further, the probability that the cloud will come to northern Norway is higher than to central and southern Norway. The analysis also showed that the shortest arrival time from LNPP to Norway is 18.25 hours, whereas average arrival time from LNPP to all parts of Norway is close to 5 days.

A blocking effect of the mountains is visible in the parts covering the west coast of Norway where the shortest arrival time is more than 46 hours.

5 Meteorological worst case scenarios

Based on the results of the climatologic trajectory analysis, three periods during 1995-2006 were selected for the accident scenarios described in chapter 3. These periods, referred to as meteorological worst case scenarios, were:

(1) 15-19 September 1995 (Scenario I);
(2) 6-17 April 1998 (Scenario II);
(3) 6-15 September 2001 (Scenario III).

The following criteria were used in the identification process:

- All trajectories released from the Leningrad NPP should come to the Norwegian Territory (for long term release: in the selected period).
- The arrival time to Norway should be as short as possible.
- The trajectories should be as dry as possible on the way to Norway.
- Populated areas of Norway should be on the trajectory way.
- The selected period should not be shorter than 10 days for long term release (Table 2).

For more information about the criteria see [7]. Details about the three weather scenarios are provided below.

5.1 Scenario I

For most of the shortest trajectories, the amount of precipitation on the way is too high for effective transport of radioactivity to Norway. Among three possible candidates with arrival time shorter than two days, the period 15-19 September 1995 was found most suitable for short term instantaneous release of radioactivity. The shortest arrival time to Norway (18 hours), does not leave much time for preparation and, in addition, this trajectory remains quite long in the territory of Norway, turning along the west coast to the north.

Meteorological worst case scenario I was used solely in connection with short term instantaneous releases, i.e. Accident scenarios A and C (Tables 1 and 3).

5.2 Scenario II and III

In order to find the periods of the longer and continuous transport to Norway from Leningrad NPP, suitable for the long term accidental release (Accident scenario B, Table 2), met.no analysed the cases with largest number of consecutive trajectories coming to Norway.

The first and the longest period of the transport to Norway is a cluster of 87 consecutive trajectories released at Leningrad NPP and coming to Norwegian areas (Scenario II). This scenario was chosen because of the potential for continuous arrival of radioactive contamination from Leningrad NPP to Norway. Coupled with the Accident scenarios B, we get several days with radioactive deposition in Norway. The longest (202 hours) arrival time for this scenario is at the beginning and the shortest (27 hours) at the end of the period. In average arrival time is 82 hours. The amount of precipitation on the way to Norway is in average 3.8 mm (the estimated range 0.2-11 mm).

The second longest period of the transport to Norway includes a cluster of 74 consecutive trajectories and last for about 9 days (Scenario III)., This is only slightly shorter than the 10 days criteria mentioned above and is thus used for the further assessment

Scenario III has a shorter average arrival time than Scenario II (44 hours) – ranging from 24 to 96 hours. However, the amount of precipitation on the way to Norway is in average higher (8.8 mm), ranging from 0.4 to 45 mm.

Consequently, the differences between these two scenarios are rather small, and it is therefore difficult to judge, without model simulations, which one is most dangerous for Norway from the meteorological point of view.

6 Simulation of fallout in Norway

To simulate the atmospheric transport of radionuclides to Norway for different combinations of accident/weather scenarios, the SNAP (Severe Nuclear Accident Program) dispersion model developed by the Norwegian Metrological Institute was used. [8-11].

The SNAP model input was comprised of the source term, derived from the specific accident scenario (A, B, C), meteorological worst case scenario (I, II, III) and a specified atmospheric transport and deposition period. Changing one or more of these parameters will have impact on the estimated deposition in Norway and hence the calculated consequences. In that perspective, the results given in the following should be interpreted as examples of what might happen given a specific accident with corresponding weather conditions. The composition, size and numbers of released particles could also influence on the dispersion and fallout [7, 17]. Fallout with a higher degree of particles would contribute to hot spots and particles could constitute high activity point sources via inhalation or ingestion by humans and animals [10]. For more information on particle considerations for this study, please see reference [7].

Four combinations of accident/meteorological scenarios were considered in the assessment: AI, CI, BII and BIII, and only radioisotopes of caesium were included since these are known to give the most severe and long-lasting consequences.

6.1 Scenarios AI and CI

For both accident scenarios A and C, atmospheric transport and deposition were simulated for 4 days (instantaneous release, weather scenario I). The predicted deposition of radioactive caesium in Norway following a design-basis RBMK accident (A) and weather scenario I (combined scenario AI) is shown in Figure 1, whereas the VVER-1200 catastrophic accident (C) and weather scenario I (combined scenario CI) is presented in Figure 2.

Both scenarios demonstrate how radioactive release from the Leningrad NPP can reach Norway in just a few hours period (18.25 hours). Since the deposition levels are very low in both cases (Figs. 1 and 2), there consequences for food production in Norway will be low. Measurements of radioactive substances in food and the environment can be envisaged for control purposes.

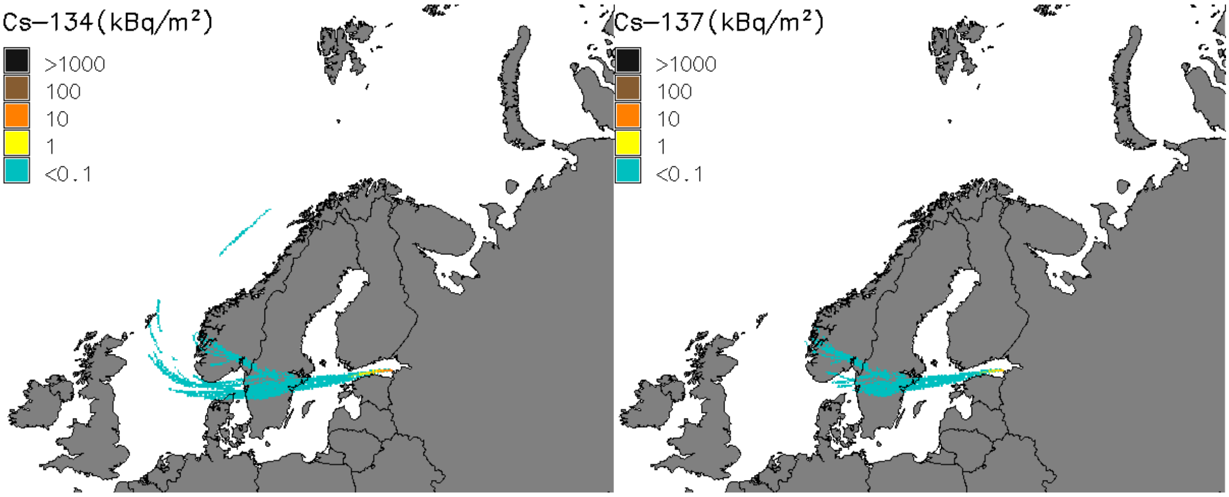


Figure 1: *Deposition maps for scenario AI.*

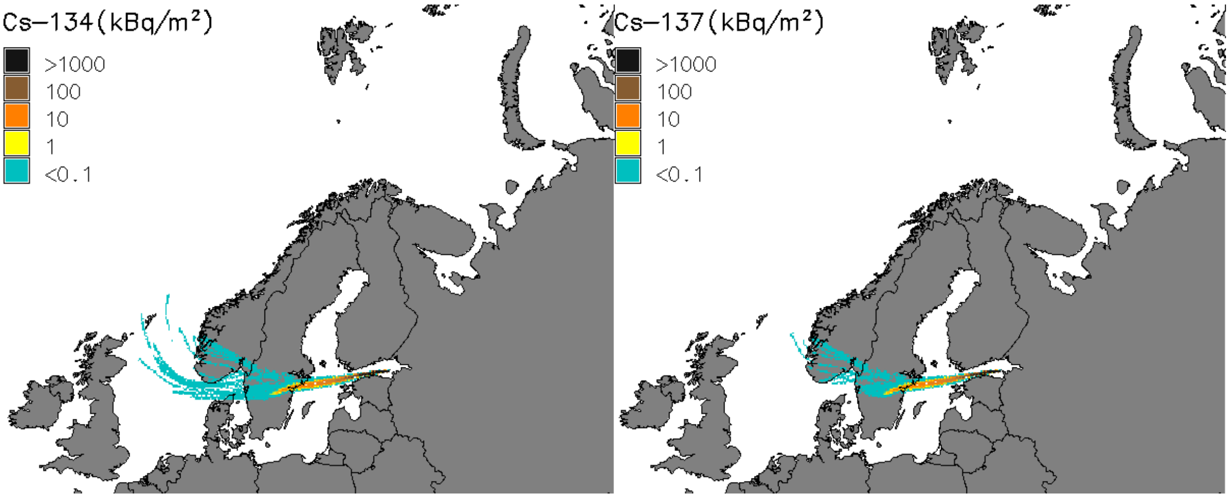


Figure 2: *Deposition maps for scenario CI.*

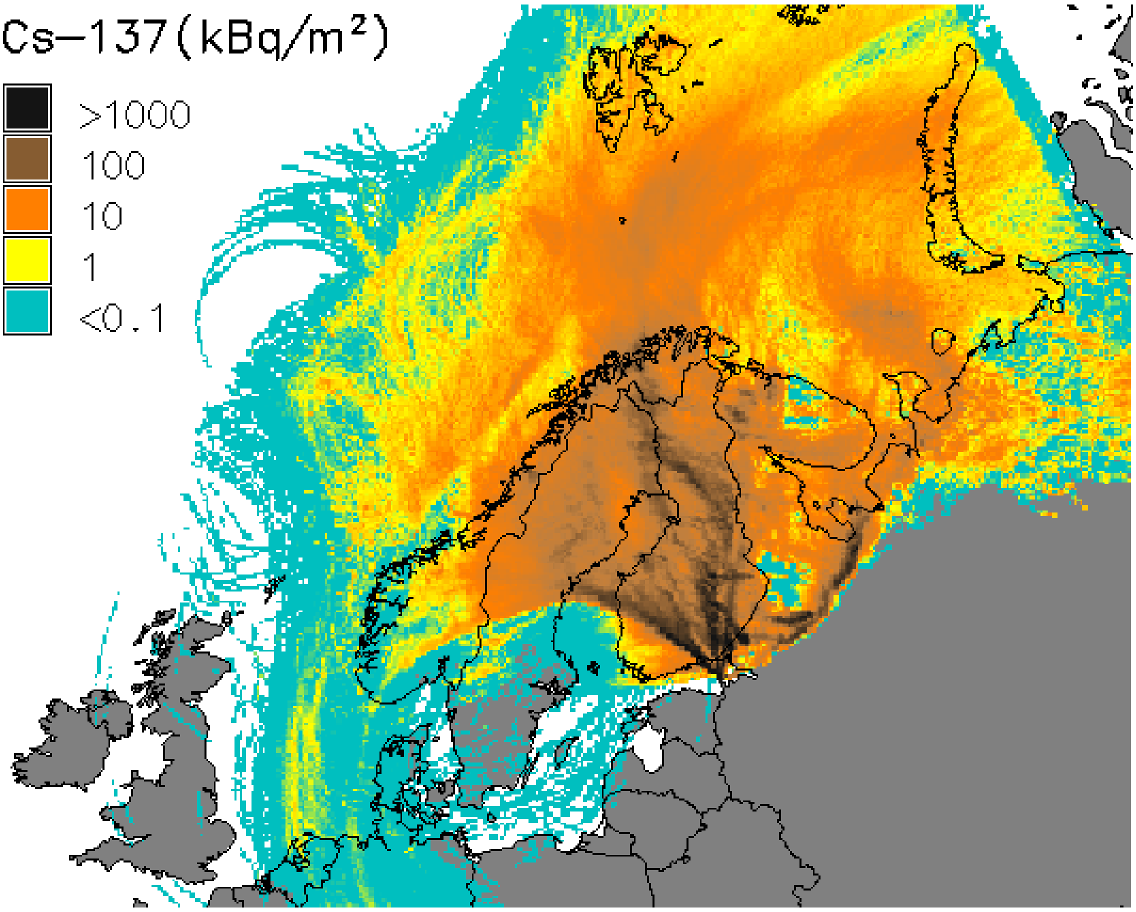


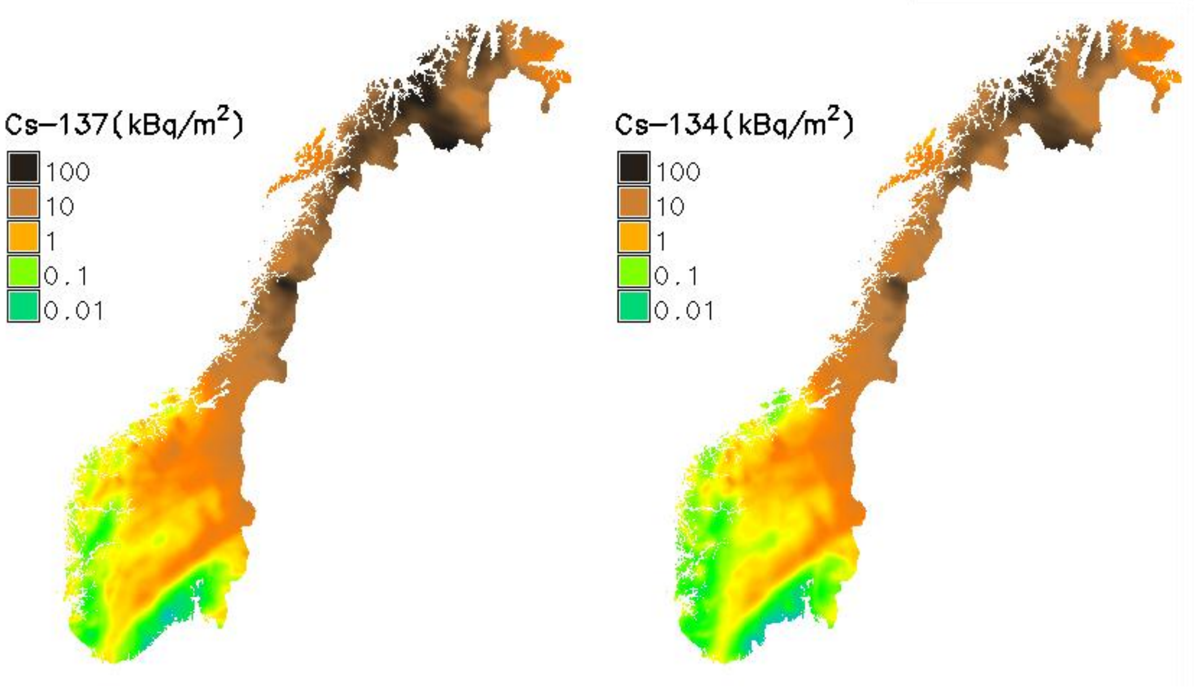
Figure 3: *Large scale deposition map for scenario BIII*

6.2 Scenarios BII and BIII

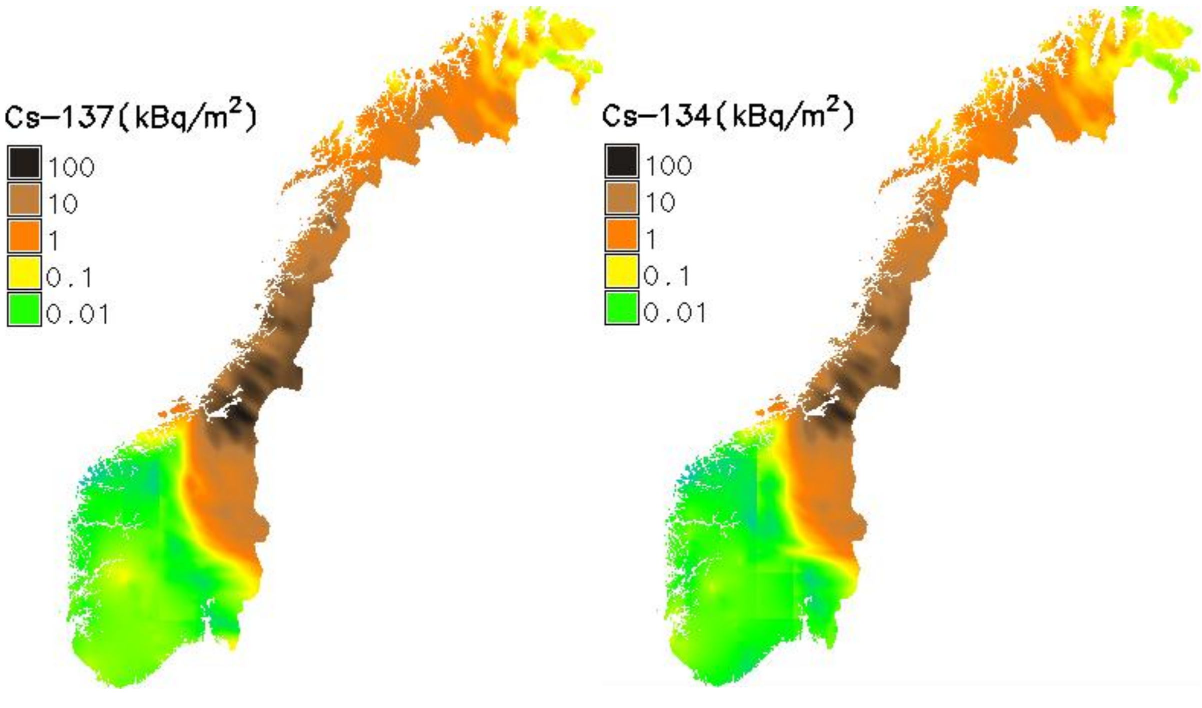
The result of a Chernobyl type accident (B) combined with the meteorological worst case scenario III (i.e. 10 days accidental release, 9 day simulation of atmospheric transport and deposition) is shown in Figure 3 for deposition of Cs-137. The highest predicted levels close to the LNPP reactor are above 1000 kBq per m^2 while the highest levels in Norway are about 100 kBq per m^2. As evident from Figure 3, both Sweden and Finland will receive larger radioactive fallout than Norway in this case.

Figure 4a shows the predicted deposition of radioactive caesium in Norway. The northern part of the country (i.e. Nordland, Troms and Finnmark Counties) will receive most of the fallout (87 %). The larger deposition of Cs-137 compared to Cs-134 is in agreement with the source term.

Corresponding deposition for weather scenario II is shown in Figure 4b. Here an 11 days simulation of atmospheric transport and deposition was performed. In comparison with BIII, the total deposition was predicted to be about 40%. However, the regional fallout pattern for BII is different – with a larger fraction of the total deposition in central Norway (i.e. Sør-Trøndelag, Nord-Trøndelag and Nordland Counties). Only about 30 % of the total fallout was deposited in northern Norway.



(a)



(b)

Figure 4: *Country specific deposition maps for scenarios BIII (a) and BII (b).*

6.3 Comparison of scenario BIII and the Chernobyl fallout

The total deposition of Cs-137 and Cs-134 from Scenario BIII was predicted to be 4.3 PBq and 2.8 PBq, respectively. This is about twice the deposited activity in Norway after the 1986 Chernobyl accident.

The fallout patterns, however, are different. As shown in Fig. 5, the most affected areas after the Chernobyl accident were the mountainous areas in southern Norway and the central Norwegian counties. Deposition densities for Cs-137 above 100 kBq per m^2 were found in certain municipalities. In contrast to scenario BIII, only small amounts of the Chernobyl caesium reached northernmost Norway.

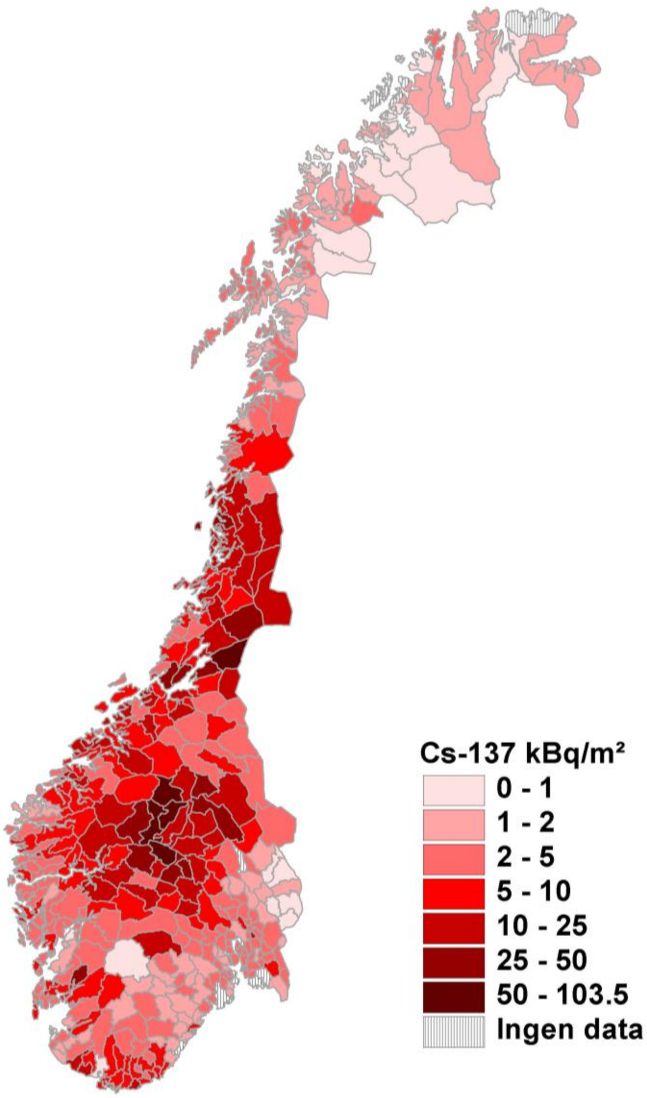


Figure 5: *Deposition of Cs-137 in Norway after the Chernobyl accident.*

7 Environmental modelling with a focus on foodstuffs

In Norway, sheep and goats – and to lesser extent milking cows[2] – graze on natural pastures during the summer season. Our focus will therefore be on these types of animals, plus reindeer and various types of game (i.e. moose, red deer and roe deer).

Wild berries and fungi are also included due to their importance in connection with human consumption and the particularly high uptake in certain species of fungi. For more thorough description of radioactive caesium in the natural ecosystems (e.g. uptake in vegetation, factors influencing radioactive caesium levels in free grazing animals, and countermeasures) we refer to [11].

To evaluate consequences of deposited radioactive caesium, the STRATOS model was used [11]. In brief, this model incorporates information regarding deposition, transfer to vegetation and animals, intervention levels for foodstuffs and geographical distribution of animals.

7.1 Transfer to vegetation and animals

To model transfer of radioactive caesium to various animals and vegetation, so called aggregated transfer factors (T_{ag}) were used. The reason is that usually the detailed information on soil parameters is not available for natural ecosystems, and especially information regarding clay content (and type) for natural soils in Norway is scarce. Moreover, the large diversity of plants species and varying abundance of mushrooms in the grazing area makes it difficult to specify animal diet.

The aggregated transfer factor is defined as the ratio between the activity concentration (C) in a given animal or plant (Bq/kg fresh weight) and the total deposition density (D) in the grazing area (Bq/m^2). Concentration of radioactive caesium in animals or vegetation can thus be derived from deposition data using the following equation:

$$\mathbf{C = D \times T_{ag}}$$

In some ecosystems the T_{ag} value varies largely with time due to e.g. fixation in soil, whereas in others the time since deposition does not have a large impact on levels in vegetation and animals (disregarding physical half-life).

To cope with regional and temporal variability we use three T_{ag}s representing a most likely (expected) value combined with reasonable minimums and maximums based on existing data from post-Chernobyl studies in Norway and other (Nordic) areas, together with more generic data from the IAEA [14, 15, 16]. No attempt is currently made to derive region specific T_{ag}s or to directly include effective ecological half-lives in the model, since the available data in most cases are too scarce.

A summary of the caesium transfer factors used in the model for various food stuffs is shown in Table 4; background details regarding derivation of T_{ag}s for each product are given in [11].

It should be noted that in years when mushrooms are particularly abundant in the natural pasture, the transfer might be 2-4 times higher than the "expected" for grazing animals.

Table 4: *Caesium transfer factors (m^2/kg): expected, minimum and maximum (all products are in fresh weight).*

Product	Harvest	Transfer factor		
		Exp	min	max
Berries	Jul-Sep	0.007	0.0003	0.04
Fungi	Jul-Oct	0.02	0.0005	0.2
Moose	Sep-Nov	0.02	0.005	0.2
Red deer	Sep-Nov	0.02	0.005	0.2
Roe deer	Oct-Des	0.05	0.005	0.2
Reindeer	Nov-Mar	0.25	0.05	1.5
Reindeer	Sep-Oct	0.15	0.05	0.5
Lamb	Oct-Des	0.04	0.01	0.2
Goat milk	Jun-Sep	0.007	0.001	0.02

[2] Dairy milk is mainly produced on farms with intensive use of high quality roughage and concentrates, less than 5 % is from uncultivated pastures [11].

7.2 Radioactive isotopes of caesium

For the assessments in this report, both Cs-137 and Cs-134 were considered. As shown in Figure 6, Cs-134 has a considerably shorter physical half-life than Cs-137. Consequently, it will only represent a problem in the first few years after a fallout.

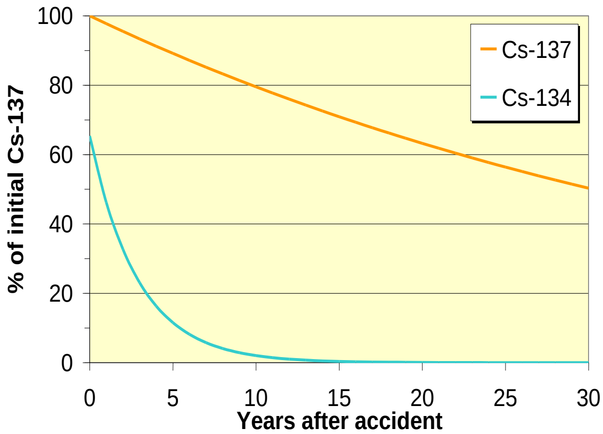


Figure 6: *Physical decay of radioactive isotopes of caesium with time. The initial deposition of Cs-134 was 65% of Cs-137 - as given by table 2.*

7.3 Contamination maps

In our assessments for this report we were interested in whether a natural product in a specific region is likely to be considered "clean" or not. That is, being below or above the specified intervention levels for food stuff contamination. Thus, the exact activity concentrations in products, as such, were not of direct interest.

Intervention levels state when dose limiting countermeasures[3] have to be activated. The current limits for radioactive caesium in foodstuffs for sale in Norway are given below.

- Reindeer and game meat: 3000 Bq/kg
- Freshwater fish: 3000 Bq/kg
- Milk and infant food: 370 Bq/kg
- Basic foodstuffs: 600 Bq/kg

[3] Examples are: food bans, dietary advice, additives given to animals to reduce gut uptake of radioactive caesium, provision of clean feed or changing the slaughter time.

An additional limit of 50 Bq/l has been specified by the industry for milk used in brown whey cheese production.

The contamination maps used in this report only deal with areas above or below the intervention level for a given T_{ag} for a given foodstuff.

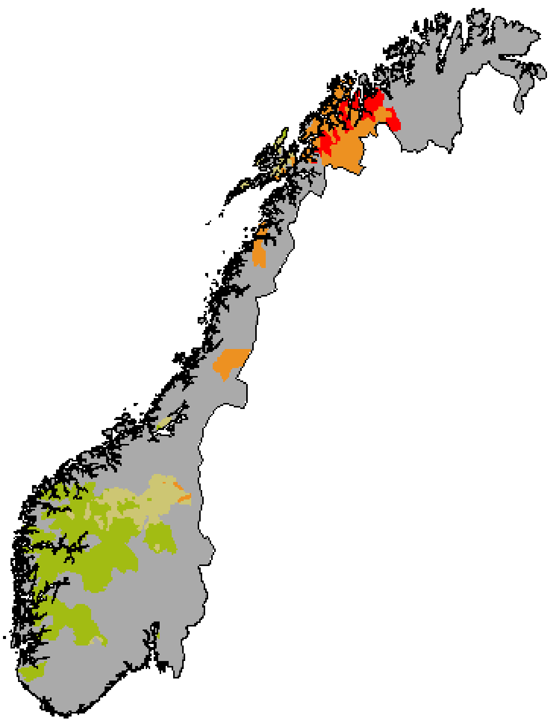


Figure 7: *Example of STRATOS modelling results: Areas where foodstuffs would be above intervention levels for expected transfer (orange), minimum transfer (red) and maximum transfer (khaki). Green areas are likely to be clean in all phases after the hypothetical accident. No production of the foodstuff in the grey areas.*

Colour coding is used to specify the affected areas as defined by the three T_{ag}s used per product: Clean areas (i.e. below the intervention level) using max transfer will be shown in green, whereas khaki areas are above the intervention level using max transfer. Furthermore, orange areas are above the intervention level using the expected transfer, while red colour denotes areas above the intervention level assuming the minimum transfer (i.e. sure to be above the intervention level no matter what).

An example of geographical representation is shown in Figure 7. It is important to note that as a logical consequence of the definition of the areas (by using different T_{ag}s), the khaki areas will include both the orange and red areas, whereas the orange areas will include the red areas. The actual interpretation of the coloured areas specified by the transfer factors will differ between products [11]. Yet, some general comments can be made. The max transfer factor can typically represent the first period after an accident or the particularly vulnerable areas[4]. If products do not exceed the intervention level using such a high transfer value, it is likely that the area will be "clean" (i.e. no need for countermeasures). Therefore the max T_{ag} may also be viewed as a screening value for areas where countermeasures may be necessary in some period after the hypothetical accident and areas where the countermeasures are not necessary.

The expected transfer factor is the transfer based on existing data from a mid- to long-term perspective (from years to decades), taking into consideration the hunting season for wild animals, slaughter time for domestic or semi-domesticated animals, and grazing period for milk production.

The min transfer factor represents areas of very low sensitivity to radioactive caesium and/or the situation decades after an accident. Consequently, the red colour represents areas where foodstuffs are very likely to exceed the intervention level in any case after the hypothetical accident.

Since intervention levels refer to radioactive caesium as a whole, Cs-137 and Cs-134 should be considered simultaneously when deriving the contamination maps. In order to do so, time since fallout needs to be taken into consideration in one way or the other. To maintain the simplicity of the STRATOS model, we have chosen to consider Cs-134 only for the max transfer factors (khaki areas) – as a representative of the first period after an accident. Thus, the other T_{ag}s will represent later years where Cs-134 will be of minor significance compared to Cs-137 (Fig. 6).

[4] For vegetation groups such as mushrooms it may also represent a high accumulating species.

7.4 Regional distribution of animals

Another important matter yet to be considered is the geographical distribution of animals of interest. For this purpose it is necessary to consider the GIS data regarding regional distribution of domestic and wild animals. The used data on distribution of various species of animals in Norway is given in Table 5.

For reindeer, however, updated information is provided in Appendix 1. The number of animals in each 1 x 1 km pixel has been generated from slaughter or hunting statistics from a specified area (e.g. a grazing area, a municipality or herding district – depending on the available geographical information). We have assumed that the relevant animals are uniformly distributed within this specified area (A), which indeed is not true – but as long as the area is small enough this will be a satisfactory approximation for our purpose.

Details and basic data used for various animals are given in [11].

Figure 8: *Free grazing sheep (photo: Martin Blom)*

Table 5: The regional data and sources for distribution of domestic and wild animals in Norway.

Animal type	Type of regional data	Period	Area (A)
Moose	Hunting statistics	2006-09	Municipality
Red deer	Hunting statistics	2006-09	Municipality
Roe deer	Hunting statistics	2009	Municipality
Semi-domesticated reindeer	Slaughter numbers	2007-10	Herding district
Wild reindeer	Hunting statistics	2008	Grazing area
Lamb	Distributions	2008	Grazing area
Goats	Milk production	2009	Municipality

7.5 Estimation of the number of affected animals

The number of affected animal in a particular region (N_i) or in Norway as a whole (N), can be generated using the following equation:

$$N = \sum_i N_i = \sum_i^n \left(\frac{I_i}{A_i}\right) n_i$$

Where,
I_i: number of 1 x 1 km pixels above the intervention level in area i
A_i: total number of 1 x 1 km pixels in area i
n_i: total number of animals in area i

For more information about the calculations we refer to [11].

8 Consequences for foodstuffs

When assessing impacts in this report, our main focus was on scenario BIII (i.e. Chernobyl type accident scenario (B) combined with the meteorological scenario III), as the deposition from this scenario results in the most severe consequences for Norway. However, a more limited assessment for scenario BII is given in section 8.3.

Based upon the max transfer factors, all natural products from areas with a deposition <2 kBq/m^2 should be below the intervention level. The most sensitive animals/products are reindeer, goat whey cheese, high accumulating mushrooms species and lamb, whereas wild berries, game and goat milk are less sensitive. For the latter, no countermeasures should be necessary in any period after the hypothetical accident as long as the deposition is below 15-20 kBq/m^2. Still, one cannot rule out the possible need for countermeasures in areas below this deposition level e.g. in years where mushrooms are abundant in the pastures.

8.1 Radiocaesium in vegetation (scenario BIII)

***Figure 9:** Crowberries/Krekling (empetrum nigrum) (Photo: Håvard Thørring)*

8.1.1 Wild berries

As can be seen from Figure 10, berries from the southern parts of Norway are within the green zone after the hypothetical deposition, and are therefore not likely to be subject to gathering restrictions. In the central and northern part, however, berries are at risk of being above the intervention level.

Based on available soil-to-plant transfer data, bilberries and cloudberries are likely to have higher concentrations of radioactive caesium than cowberries and raspberries [14,15].

No areas were predicted to be above the intervention level of 600 Bq/kg, using the minimum transfer factor and thus, no red areas are shown in Figure 10.

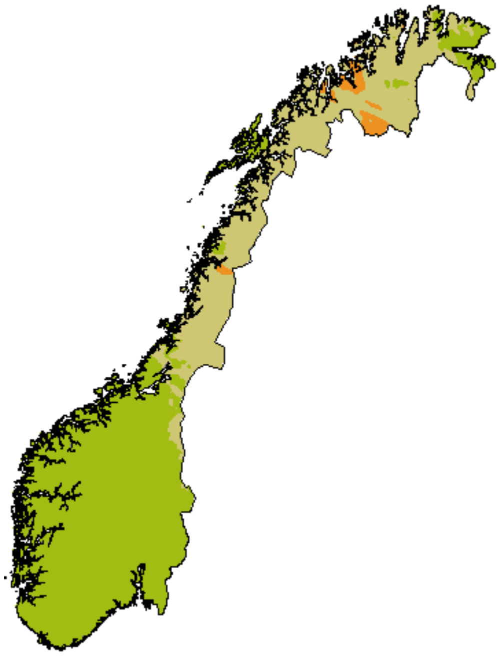


Figure 10: *Predictions for wild berries. Areas above intervention levels for expected (orange) and max (khaki) transfer. Green areas are likely to be clean in all phases after the hypothetical accident.*

8.1.2 Mushrooms

The transfer of radioactive caesium to mushrooms show a high degree of variability between species. The coloured areas in Figure 12 are therefore attributed to type of mushroom (see section 7.3 and [11] for more on this topic).

High accumulator fungi such as *Cortinarius caperatus* (the Gypsy / rimsopp) will probably be above the intervention level for the northern, central and south-eastern parts of Norway (as represented by the orange and khaki areas in Fig. 12), whereas more popular species such as *Cantharellus cibarius* (chantarelle / kantarell) and *Boletus edulis* (penny bun / steinsopp) are likely to be above only in some areas in the northern parts of the country (i.e. orange areas).

Figure 11: *Orange Birch bolete / Rødskrubb (Leccinum versipelle) (photo: Håvard Thørring)*

Low accumulators, such as *Coprinus comatus* (whig/matblekksopp) should be below the intervention level of 600 Bq/kg – even in the most contaminated areas. Consequently, there are no red areas in Figure 12.

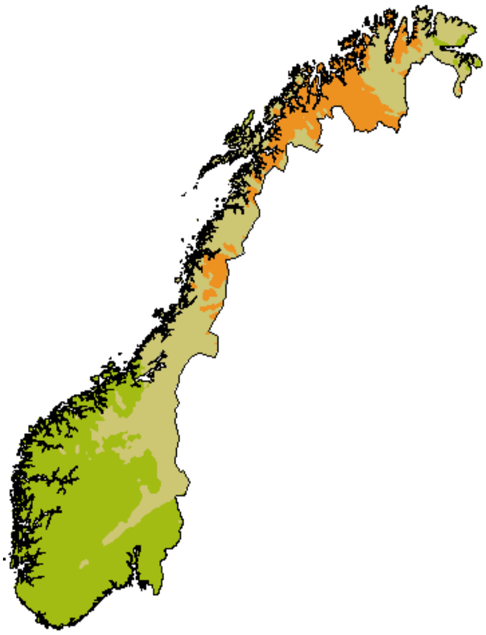


Figure 12: *Predictions for mushrooms. Areas above intervention levels for expected (orange) and max (khaki) transfer. Green areas are likely to be clean in all phases after the hypothetical accident.*

8.2 Radiocaesium in animals and animal products (scenario BIII)

Contamination maps for game, reindeer and domestic animals are shown in Figures 15-17. Based on these data and the regional distribution data [11, Appendix 1], the number of affected animals (per year) has been calculated for minimum, expected and maximum transfer. Results are shown in Table 6.

The predicted overall trend is that the most affected animals/products are semi-domesticated reindeer, lamb and brown whey cheese from goats, whereas game such as roe deer and red deer will be less affected. In the following sections, results for each category of animals will be discussed in more detail.

Table 6: *Animals affected per year according to scenario BIII.*

Type	**Number of animals affected** Expected (min-max)	**Total animals**	**% of total** Expected (min-max)
Semi-domesticated reindeer*	40000 (14000-62000)	70000	57 (20-89)
Lamb**	110000 (17000-310000)	890000	12 (2-35)
Goats (whey cheese)	12000 (3900-16000)	35000	34 (11-45)
Goats (milk production)	3400 (0-12000)	35000	10 (0-33)
Moose	1 (0-7300)	36000	0 (0-21)
Roe deer	0 (0-1800)	30000	0 (0-6)
Red deer	0 (0-240)	33000	0 (0-0.7)
Wild reindeer	0 (0-880)	5200	0 (0-17)

* Based on current practice in all herding districts concerning slaughter. Due to lack of information regarding the exact geographical location of 3000 slaughtered reindeer, the total has been reduced from 73 to 70 thousand in the assessment. The missing reindeer are mainly located in Oppland County – a region not very affected by the predicted fallout from the hypothetical accident at LNPP.

** Numbers refer to registered lamb (ca. 80 % of the total). Real slaughter numbers will be higher [11].

Figure 13: *Semi-domesticated reindeer (photo: Lavrans Skuterud)*

8.2.1 Game

Most of the game included in our assessment is found in the southern and central parts of Norway. Particularly red deer and roe deer are hunted in areas that would hardly be affected by the hypothetical fallout. This explains the low numbers of affected animals for these species (Table 6). In contrast, moose – as evident from Figure 15a, is distributed further north compared to the other two species, and are also more numerous in the eastern (more contaminated) parts of Norway.Limited impact from a hypothetical accident at LNPP was predicted even for moose – except under assumption of max transfer (khaki areas), which may apply to the first years – or in particularly vulnerable areas (i.e. with high transfer of radioactive caesium to feed plants).

Figure 14: *Moose (Photo: Malene Thyssen / Wikimedia commons)*

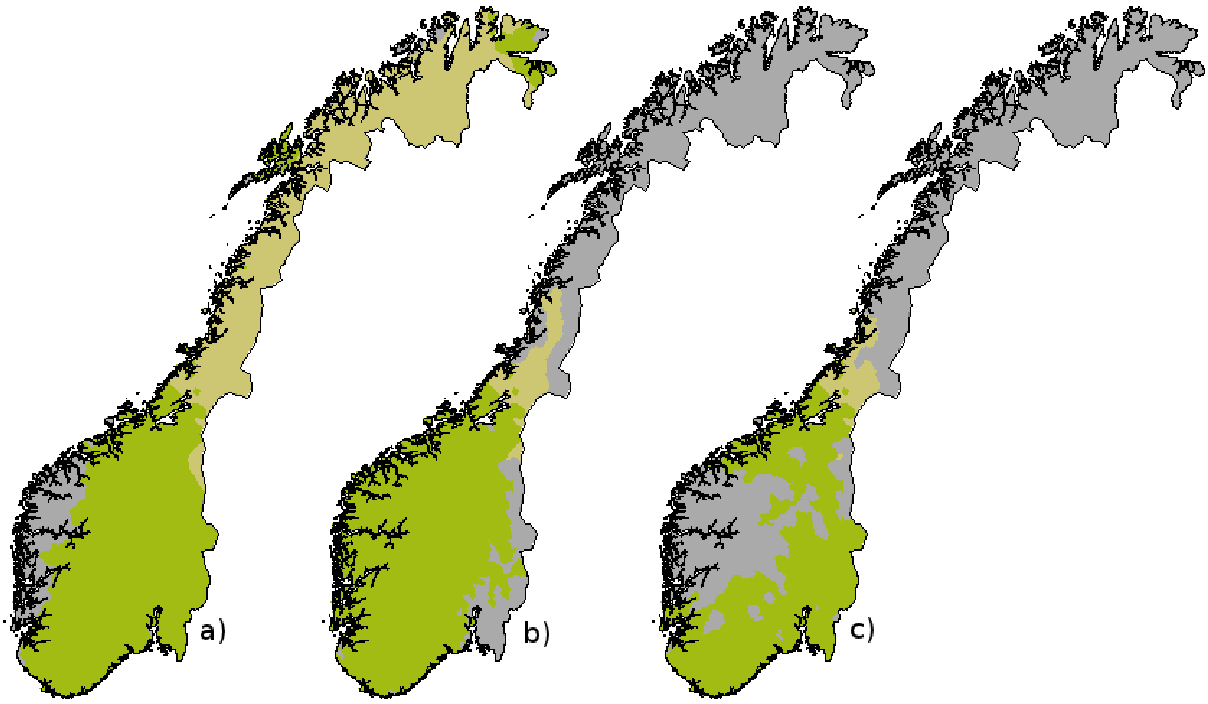


Figure 15: *Predictions for game: (a) Moose, (b) Red deer and (c) Roe deer. Areas above intervention levels for expected (orange), min (red) and max (khaki) transfer. Green areas are likely to be clean in all phases after the hypothetical accident. No hunting data for grey regions – either due to no animals present or lack of hunting data for the period considered.*

8.2.2 Reindeer

Due to the predicted fallout patterns (Figure 4a) and the general high transfer of radioactive caesium to reindeer (Table 4), semi-domesticated reindeer is by far the animals most affected, on a percentage basis, by the hypothetical accident at LNPP (Table 6, Figures 16a-b). In the first years after the hypothetical accident (khaki areas), just about every herding district in central and northern Norway will have to cope with reindeer exceeding the intervention level of 3000 Bq/kg. Even when using the minimum transfer (red areas), as many as 20 % of the animals will be above the intervention level (Table 6).

To avoid condemnation and to reduce contamination levels in meat, there will, consequently, be a need for extensive countermeasures in years or even decades to come. Such measures might include live monitoring of animals before slaughter, change of slaughter time (from winter to autumn), clean feeding, and grazing in less contaminated areas.

From Figures 16a and b, the herding districts in southern central parts of Norway are less affected than the areas further north. However, it should be noted that these areas were heavily contaminated by the Chernobyl accident and some herding districts are still in need of countermeasures; an accident at LNPP would therefore add to already existing problems.

As evident from Table 6, wild reindeer will be considerably less affected than the semi-domesticated animals. Based on our predictions, the consequences will be confined to the first years after the fallout – mainly in the northern parts of the wild reindeer distribution area (see Figure 16c).

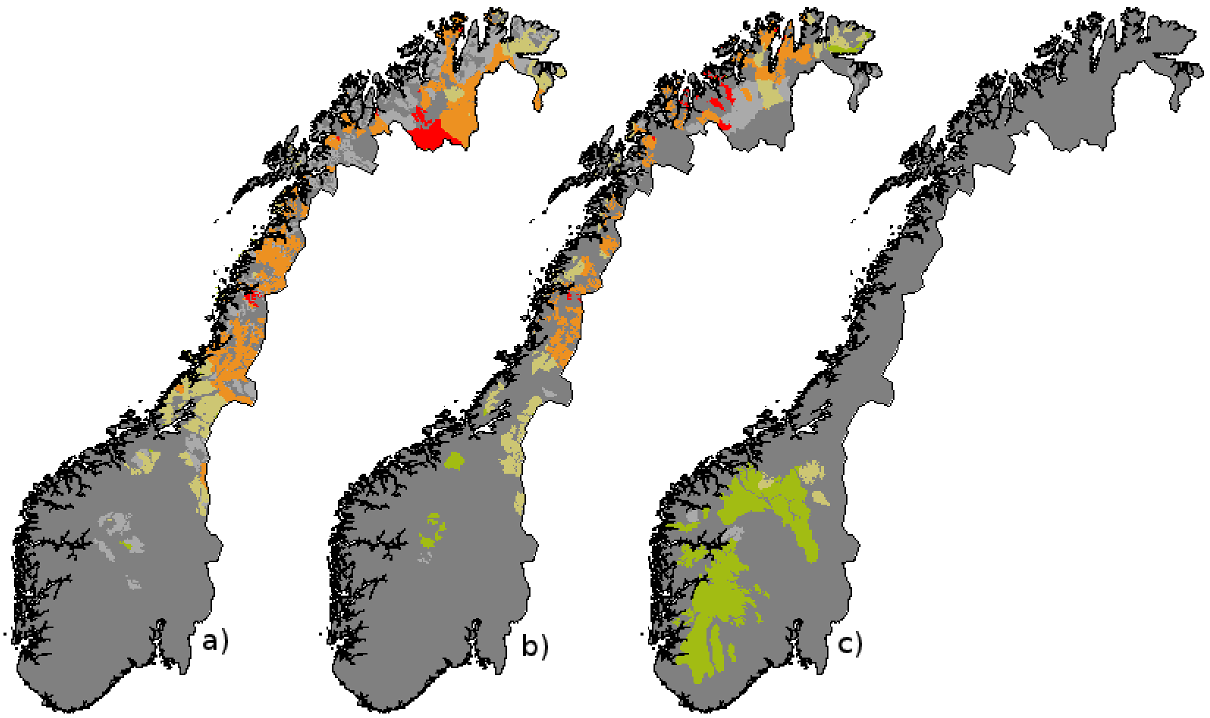


Figure 16: *Predictions for reindeer: (a) Semi-domesticated, winter pasture; (b) Semi-domesticated, autumn pasture; (c) Wild reindeer, autumn. Areas above intervention levels for expected (orange), min (red) and max (khaki) transfer. Green areas are likely to be clean in all phases after the hypothetical accident. No slaughter/hunting data for grey regions.*

8.2.3 Domestic animals

The most serious consequences of the hypothetical fallout on domestic production will be in the central and northern parts of Norway.

Particularly production of brown whey cheese will be seriously affected. Even using the minimum transfer a considerable fraction of the brown cheese will be above the intervention level (11 %, Table 6). As shown in Figure 17c the problem will be largest in Troms County, and there will be a need for extensive countermeasures in this region for years or even decades to come. In contrast, most production in western/south-western Norway will be outside the contaminated areas, as evident from the green areas in 17c. Consequently, these important areas for sheep and goat products are likely to remain uncontaminated provided Scenario BIII.

The effects on sheep production will follow the same geographical pattern as goat cheese, with large potential consequences in central and particularly northern Norway (as indicated by the red and orange areas). Total numbers of affected animals will reach hundreds of thousands, even though lamb are less affected than semi-domesticated reindeer and whey cheese on a percentage level (Table 6).

Goat milk production will be less affected than sheep and goats cheese; only in Troms County long-term consequences are to be expected. Milk from free grazing cows is not directly considered in this impact assessment. It may, however, be assumed that cow milk from certain parts of Troms County (i.e. orange areas for goat milk production) are likely to be above the intervention level of 370 Bq/l. This is a conservative assumption since transfer to cow milk is generally 3-5 times lower than to goat milk from the same grazing area. 95 % of all cows in Norway graze on home fields, which are considerably less vulnerable to radioactive caesium contamination than natural pastures, due to common practices such as ploughing and fertilising.

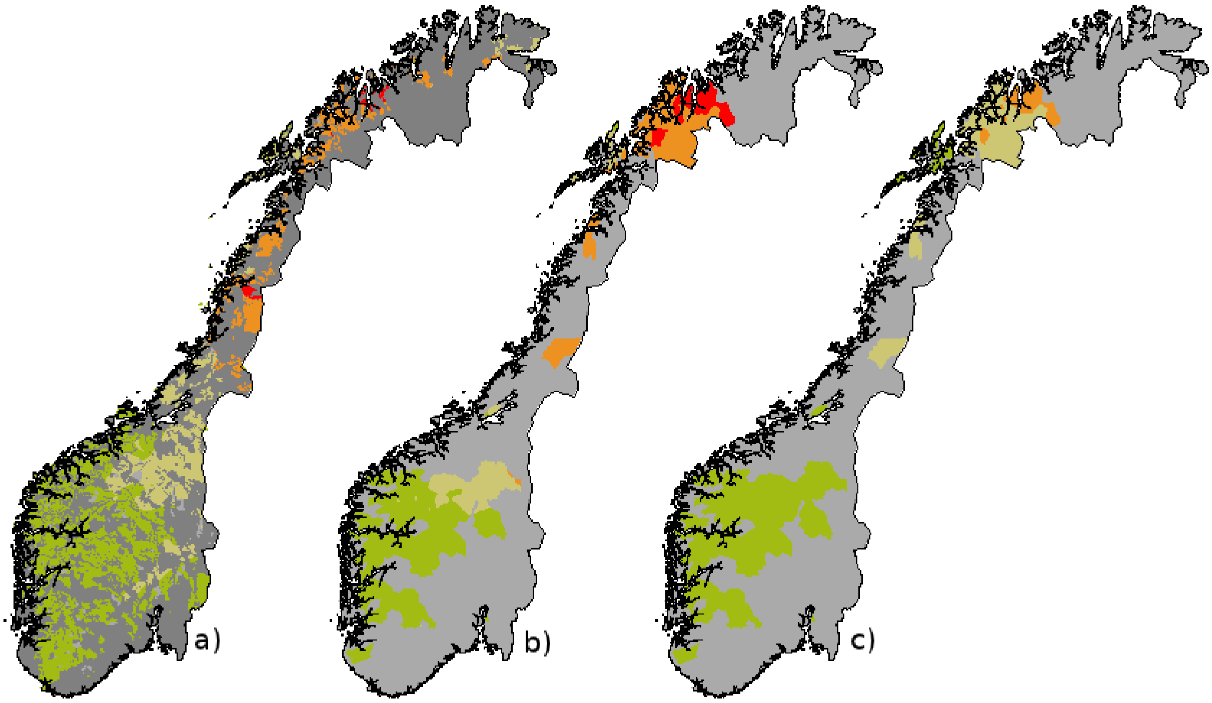


Figure 17: *Predictions for (a) lamb meat, (b) goat milk and (c) whey cheese from goat. Areas above intervention levels for expected (orange), min (red) and max (khaki) transfer. Green areas are likely to be clean in all phases after the hypothetical accident. No sheep or goats in grey regions.*

Table 7: *Animals affected per year according to scenario BII.*

Type	Number of animals affected Expected (min-max)	Total animals	% of total Expected (min-max)
Semi-domesticated reindeer*	6700 (200-23000)	70000	10 (0-34)
Lamb**	62000 (7300-210000)	890000	7 (1-24)
Goats (whey cheese) production)	1100 (3-10000)	35000	3 (0-28)
Goats (milk production)	2 (0-450)	35000	0 (0-1)
Moose	0 (0-8800)	36000	0 (0-24)
Roe deer	900 (0-4900)	30000	3 (0-16)
Red deer	0 (0-1300)	33000	0 (0-4)
Wild reindeer	0 (0-1100)	5200	0 (0-22)

* Based on current practice in all herding districts concerning slaughter. Due to lack of information regarding the exact geographical location of 3000 slaughtered reindeer, the total has been reduced from 73 to 70 thousand in the assessment. The missing reindeer are mainly located in Oppland County – a region not very affected by the predicted fallout from the hypothetical accident at LNPP.

** Numbers refer to registered lamb (ca. 80 % of the total). Real slaughter numbers will be higher [11].

8.3 Radiocaesium in animals and animal products (Scenario BII)

To demonstrate the importance of weather conditions on the consequences of one particular accident scenario (Chernobyl type catastrophic release), we have also calculated the number of affected animals for scenario BII (Table 7). As described in section 6.2, the total fallout in Norway from this accident/weather scenario was about 40% of BIII. Still, serious consequences are predicted, affecting about 30 % of annual production of semi-domesticated reindeer, lamb and whey cheese production, provided max transfer is assumed (i.e. the first years after the fallout). For scenario BIII the corresponding numbers were 2-3 times higher.

As for BIII, long-term consequences are also to be expected for BII – e.g. up to 10 % of the production of semi-domesticated reindeer is likely to be above the specified intervention level of 3000 Bq/kg for years or decades. The corresponding figure for BIII is about 60 %.

Contrary to expectation, the number of affected game is slightly higher in scenario BII. This is likely due to the different fallout pattern described in section 6.2: A large fraction of the deposition in BIII occurred in the northernmost counties Troms and Finnmark, where no red deer or roe deer are hunted/present (Figure 15; [11]). Anyhow, the consequences for game are limited in both meteorological scenarios II and III.

9 Conclusions

The consequences for Norway following a hypothetical accident at Leningrad NPP will depend on factors such as the reactor type (RBMK or VVER), accident scenario (design basis or catastrophic accident) and the weather conditions at the time. An accident at LNPP does not necessarily entail radioactive fallout in Norway. The predicted release from the new VVER reactor will hardly give any fallout in Norway, while a catastrophic accident at the RBMK reactor could lead to serious consequences. If the weather conditions are unfavourable, a radioactive cloud released due to an accident could be transported to Norway. The probability of such weather conditions is around 20%, and it is more likely that the cloud will be transported to the northern part of Norway than to the southern part [7].

In the worst case, the radioactive cloud can reach almost any point in Norway within one, maximum two days. The shortest arrival time is around 18 hours.

Of the four scenario combinations considered in this report, scenario BIII resulted in the most serious impacts for Norway. For this scenario, the largest consequences were predicted for semi-domestic reindeer, sheep and goat cheese production.

Up to 90 % of all semi-domestic reindeer could be exceeding the food intervention level for radioactive caesium the first couple of years after the fallout, and 20-60 % likely to be above for years or even decades to come.

For lamb the number of affected animals in the first years could reach 300 000 (35 % of the country total production), and as many as 100 000 animals could be above the intervention level in the following years.

There will, consequently, be a need for extensive countermeasures in large areas for many years involving more than one hundred thousand animals each year.

The consequences for game in general are predicted to be low, but will to some extent depend on the regional distribution of the different species. For instance, red deer and roe deer are virtually absent in the most contaminated northern parts of Norway, whereas a considerable fraction of moose is found in these areas.

Berries from the southern part of Norway are not likely to be subject to gathering restrictions while berries in the northern part of Norway are at risk of being above the intervention level.

The consequences for mushrooms will depend on species and affected areas. High accumulator species will probably be above the intervention level in the northern and south-eastern parts of Norway, while more popular species are likely to be above limits in some northern areas only.

The deposited amount of Cs-137 in scenario BIII is about 2 times larger than the fallout from the Chernobyl accident over Norway. So far, the direct costs for mitigating actions in agriculture and reindeer husbandry due to the Chernobyl accident in Norway are estimated at around 700 million NOK. The annual costs for countermeasures are still around 15 million NOK per year and we foresee the need for countermeasures for another decade. In addition, there are other costs not included in the above estimates (monitoring, voluntary work, psychosocial effects, loss in production etc.), so the total predicted cost to society from a worst case hypothetical accident at Leningrad NPP could be considerable. Moreover, a real accident would also give fallout of e.g. radioactive strontium which would add to the consequences described in this report.

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Appendix 1

Regional distribution of reindeer in different seasons

The reindeer are being moved within or between herding districts in different seasons of the year. So, the regional distribution of reindeer is largely season-dependent as evident from the figure below. The moving of herds does not follow strict calendar dates; other factors such as the weather conditions also play a role (e.g. if there is too much snow early in the season, reindeer have to be moved to the winter areas earlier). It is thus difficult to predict exact grazing times in different districts throughout the year. For modelling purposes, we assume that the reindeer have been fed solely in the district where they are reported slaughtered. For more info on reindeer we refer to the appendix in [11].

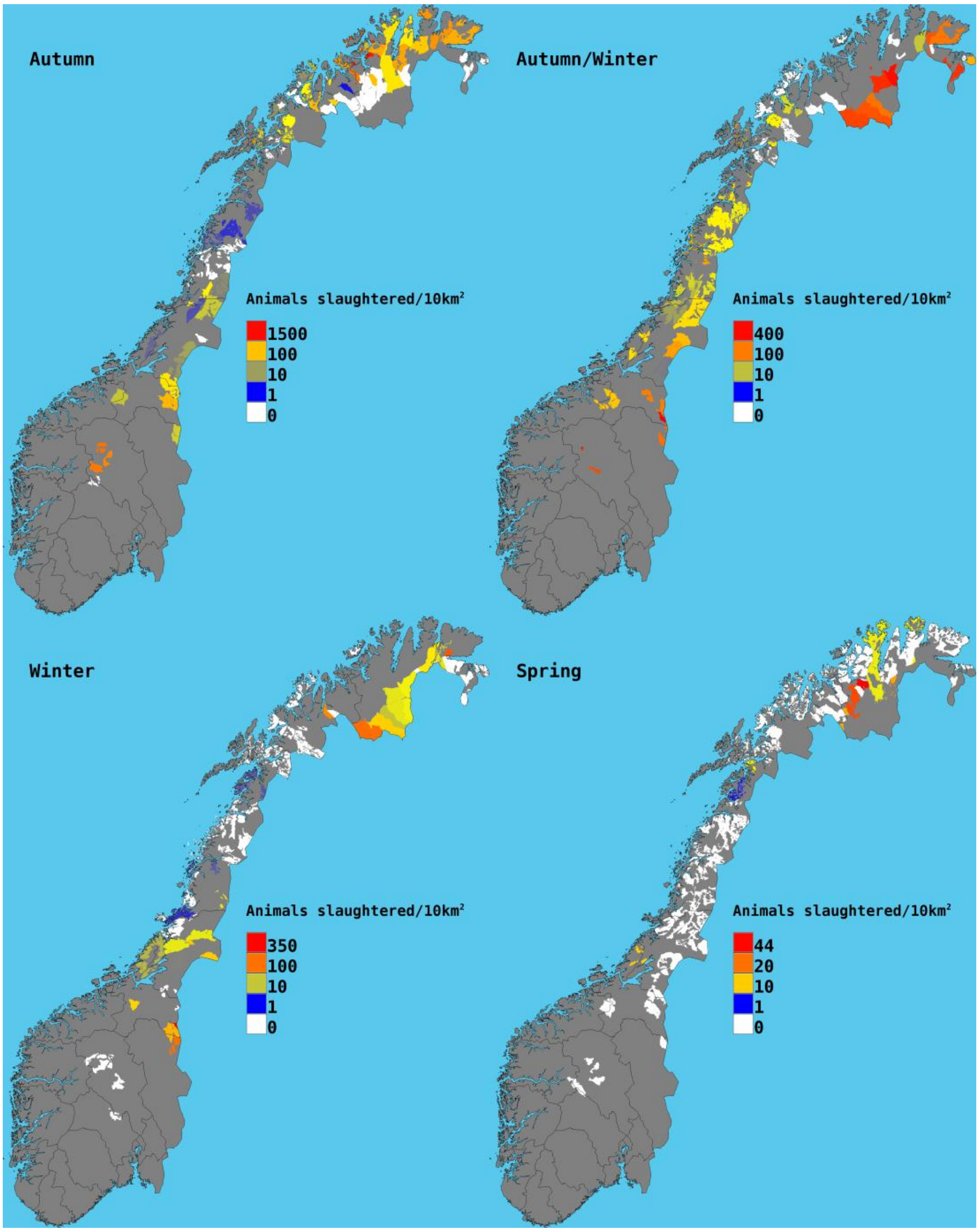

Figure A1: *Regional distribution of slaughtered reindeer (Autumn: September-October; Autumn/Winter: November-December; Winter: January-February; Spring: March-April).*

Appendix 2

ENCO FR-(08)-35 Report on Source Term data for Leningrad NPP site

Norwegian Radiation Protection Authority

Source Term data for the Leningrad NPP site

ENCO FR-(08)-35

May 2008

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Source Term data
for Leningrad NPP site

Report
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TABLE OF CONTENTS

1. Introduction

1.1. Objectives and scope

The aim of this report is to establish the amounts of radionuclides that could be released to the atmosphere during an accident of a nuclear power plant (source term) located at Leningrad NPP site (at Sosnovy Bor, Russia). These data are intended to be used for the assessment of consequences of such an release in Norway.

The source term (ST) data are derived for two typical NPPs: (i) RBMK plant (one of four RBMK plants that are operating at the Leningrad site) and (ii) WWER-1000 plant (a hypothetical plant that could be built at the same site).

The source terms estimated for the RBMK plant include three different categories:

- Catastrophic release (beyond design-basis accident with a large fraction of fuel destroyed - release of the Chernobyl accident)
- A severe accident (beyond design basis accident with the destruction of several channels and an immediate release)
- A design Basis Accident (such as the overheating of channels with a filtered release).

The source term provided for a hypothetical WWER plant is intended to represent the most severe (catastrophic) radiological consequences that could occur as a result of a 'credible' accident scenario in a nuclear power plant of the most recent design. The estimated source term data correspond to postulated severe accidents that are associated with the highest radiological impact. The STs are estimated based on a number of representative accident scenarios. These scenarios are selected among 'credible' accident scenarios, i.e. those that are estimated to be beyond the specific frequency (e.g. the limit of 10E-7 per year recommended by IAEA for accidents with a large early release).

For RBMK catastrophic release scenario, the ST data are based on a measured/calculated releases in the real accident (Chernobyl accident in 1986). Other ST data are derived based on a selection of specific postulated accidents - both design basis and beyond design basis accidents.

For each of the source terms, a brief technical description of the release scenarios (the rate of release for each of the important radionuclides) and their likelihood is provided. Other data relevant needed for the simulation of off-site consequences (such as the timing of release and the height of release) are also estimated.

1.2. Technical characteristics of RBMK reactors

The RBMK 1000 reactor (1000 MWe, 3200 MWth power; there are also 1500 MWe types, e.g. Ignalina NPP) is graphite moderated, light water cooled reactor with the UO_2 fuel in 1660 individual vertical channels. The fuel inventory in the core is equal to approximately 190 t of uranium.

The RBMK core consists of graphite blocks (250 mm x 250 mm, 600 mm high) stacked together to form a cylindrical structure 12 m in diameter and 7 m high. It is located in a leaktight cavity formed by a cylindrical shroud, the bottom support structure and the upper steel cover. Each graphite block (except those forming the radial reflector) has a central hole which provides the space for the fuel channels or one of the absorber rod channels.

Fuel and control rod channels penetrate the lower and upper steel structures. Each of the fuel channels is connected to one of the two cooling loops below and above the core. The drives of the control rods are located above the core below the operating floor shield structure.

The fuel, in the form of UO_2 pellets, is sheathed with a cladding tubes made of zirconium-niobium alloy. Eighteen fuel pins approximately 3.5 m in length are arranged in a cylindrical cluster (subassembly). Each fuel channel contains two subassemblies connected in series.

The RBMK reactor is cooled by circulating light water that boils in the upper parts of the vertical tubes, to produce steam. Each of the two cooling loops includes 840 fuel channels, two steam separators, four coolant pumps and associated equipment. The steam separators supply steam directly to two 500 MW(e) turbogenerators, each with a condenser and feedwater system. The reactor is refuelled on-load using a special machine.

The RBMK reactor has a positive void reactivity coefficient. However, the fuel temperature coefficient is negative and the net effect of a power change depends upon the power level. Under normal operating conditions the net effect (power coefficient) is negative at full power and becomes positive below approximately 20% of full power. Therefore, the operation of the reactor below 700 MW(th) is restricted.

The RBMK plants have a special system for emergency steam condensation in case of a pipe break in the cooling circuit. These systems (called accident localization systems - ALS) significantly vary in different generations of RBMK plants [29]. Table 1.1 provides information regarding ALS type in various plants.

The first generation of RBMK did not have any system for localization of accidental radioactive steam discharge (ALS). In these plants any accident with coolant losses (except of fuel channel break inside the core envelope) leads to a radioactive release to the environment. In the case of fuel channel break inside the core envelope radioactive steam can be condensed in the accident localization condenser and further filtered to partially localize the release. It should be noted that these systems were slightly modified and improved after the Chernobyl accident.

Table 1.1. Generations of NPP Units of RBMK type

NPP Unit	Entry into service	Generation/design features
Leningrad 1	21.12.73	First generation (no ALS)
Leningrad 2	11.07.75	
Chernobyl 1	26.09.77	
Chernobyl 2	21.12.78	
Kursk 1	12.12.76	
Kursk 2	28.01.79	
Leningrad 3	07.12.79	Second generation (version A)
Leningrad 4	09.02.81	
Ignalina 1	31.12.83	
Ignalina 2	20.08.87	
Chernobyl 3	03.12.83	
Chernobyl 4	20.08.87	
Smolensk 1	09.12.82	Second generation (version B)
Smolensk 2	31.05.85	
Kursk 3	17.10.83	
Kursk 4	02.12.85	
Smolensk 3	17.01.90	Third generation
Kursk 5	Under construction	

Notes: Chernobyl NPP, and Ignalina NPP Unit #1 are permanently shut-down.

The RBMK plants of the second and third generation have two different ALS configurations. Namely:

- The ALS system is housed in accident localization towers (ALT). This design was used in Leningrad 3 & 4 and Ignalina 1 & 2 NPPs;
- The ALS system is located at special compartments at bottom of the reactor hall. The main feature of this design is a large water vessel to condenses an accidental (radioactive) steam discharge. This design was used in all other plants of the second and third generations.

The further analyses of radiological releases this report is conservative, i.e. based on calculations relevant for the or the first generation of RBMK reactors.

1.3. Technical characteristics of WWER-1000 reactors

The WWER-1000 design was commercially introduced in the 1980s. The first prototype model, referred to as V-187, was put into operation in 1981 in Novovoronezh (Unit 5). It was followed by more advanced models V-302 (South Ukraine Unit 1 operational from 1982) and V-338 (Kalinin Units 1 and 2 put into operation in 1984 - 1986). The next model, known as V-320, was introduced starting from 1985 in several plant sites. NPP units with V-320 reactor were constructed and put into operation in 1990s and early 2000s in Russia (Kalinin Units 3 and 4, Balakovo Units 1-4, Volgodonsk Unit 1), Ukraine (Zaporoshe Unit 1-6, Khmelnitskyj Units 1-4, Rovno Units 3 and 4, and South Ukraine Unit 3 and 4,), Czech Republic (Temelin Units 1 and 2), and Bulgaria (Kozloduy Units 5 and 6).

It should be noted that all WWER-1000 units are similar to PWRs used in western countries. The nuclear steam supply system of all WWER-1000 units is completely enclosed by a full pressure dry containment. All design versions have a steel lined, pre-stressed, reinforced concrete containment shell. The containment is designed to accommodate the double-ended rupture of any single primary system pipeline with 850 mm diameter. Corresponding design overpressure is 0.41 MPa.

The next generation of WWER-1000 reactor developed in 1990s is the model known as V-392. There are several modifications of this model that have been designed to the specific needs of the customers. These include V-428 designed for China (Tianwan Units 1 and 2 operable from 2006/2007), V-412 designed for India (Kundankulan Units 1 and 2 expected completion in 2009), and V-446 designed for Iran (Bushehr Unit 1 expected completed in 2009) and for Bulgaria (Belene Units 1 and 2 scheduled for 2012/2013). If a decision to replace RBMKs at Leningrad site is taken soon, it is reasonable to expect a V 446 to be constructed there.

The new models are an evolutionary concept, i.e. the design used all the processes, systems and components as well as all experience accumulated in designing, manufacturing and operating of the WWER-1000 plants of the previous generation.

The basic difference of this design as compared to other earlier designs is in applying more advanced equipment and implementation of additional safety systems that focus on preventing and mitigating consequences of accidents both

DBA and BDBA. Spectrum of accidents considered in the design was increased. The plant is designed for seismic impact under operating basis earthquake (OBE) of magnitude 7 and under safe shutdown earthquake (SSE) of magnitude 8 according to MSK 64 scale.

The most relevant improvements of the new designs (V-392) as compared to older design (V-320) include the following features [40]:

- Advanced, more economical and reliable core, including elimination of positive reactivity effects
- Advanced steam generator
- Reactor coolant pump with advanced design of seals
- Passive heat removal system
- Additional system of filling the core
- Passive system of quick boron injection
- Advanced I&C, including diagnostics system complex
- The application of the ‘leak before break’ concept.

Introducing passive elements and increased diversity in the essential safety systems significantly increased their reliability. The use of advanced equipment (RCP, SG, SG safety valves) and the application of the “leak-before-break” also decreased the frequency of LOCA IEs.

The differences in the relevant characteristics of the core that can affect the initial inventory of radionuclides in the core (such as the average power rate and fuel burnup) are not significant. The main characteristics of the WWER-1000 reactor core (V-392 type) are given in Table 1.2.

Table 1.2. Characteristics of the WWER-1000 reactor core (V-392)

Parameter	Unit	Value
Nominal thermal power	MW	3000
Duration of reactor operation at nominal power between refueling	hrs	7000
Nominal time of fuel assemblies (FA) in the core (fuel service life)	yrs	3
Number of fuel assemblies in the core	-	163
Fuel mass in FA	kg	490
Nominal fuel loading of the core	kg UO_2	79 870
Fuel burn-up fraction (for refueling stationary condition)	MWd/kg (U)	
Average for FA		43.0
Maximum for FA		44.0
Nominal time of FA in the core (fuel life cycle)	yrs	3
Maximum allowable time of fuel in the core	effective hrs	3000
Average fuel power density	kW/kgU	42.6
Effective moderator temperature	°C	305

It should be noted that some other improvements are of relevance for radiological releases:: (i) the probability of a failure of a safety feature is decreased, which can result in the reduction of the likelihood of core damage as well as the frequency of certain class of accidents, (ii) the delay to failure of a safety feature is increased, which means more deposition and retention of fission products with the corresponding reduction of the source term.

These modifications that reduce the frequency of the most severe accident to very low values are taken into account in the selection of representative accident scenarios for which the ST is estimated. The other impacts are considered, to the extent practicable, in estimating the release fractions and associated ST.

2. Accident scenarios an overview

Provision of source term data for the Leningrad site covers a range of selected accident scenarios. These scenarios are selected for the specific reference plants of RBMK and WWER type.

2.1. Selection of reference plants

2.1.1. RBMK-1000 plant

From two types of RBMK plants in operation at Leningrad, the older design, first generation of RBMK-1000 was considered a reference plant. This is a conservative assumption, that is deemed appropriate for an enveloping assessment.

2.1.2. WWER-1000 plant

Hypothetical plant with WWER-1000 reactor considered in this project is assumed to represent the current design, that being the V-392 reactor model.

2.2. Estimation of source term

The ST data provided in this project are mainly based on the existing information sources. No additional, code-based calculations were performed within the framework of this project.

2.2.1. RBMK plant

The radiological characteristics of the catastrophic scenario for RBMK are based on observations from a real accident (Chernobyl in 1986). The characteristics of the radiological releases resulting from the Chernobyl accident were derived mainly from post-accident measurements and should be considered the best estimate data.

Characteristics for other scenarios considered for the RBMK plant are based on computer simulation by SA codes for postulated scenarios, as a part of the design of the plant. They are defined with a relatively high conservatism.

2.2.2. WWER plant

A realistic estimation of the source term is normally made within plant specific Level 2 PSA. However, for the new designs (such as V-392 or V-446) the availability of Level 2 PSAs is limited.

The source term data for the purpose of this project have been determined for a hypothetical plant with WWER-1000 reactor using the existing analyses and data that have been derived for the plant with the reactor of V-320 model. The WWER-1000 plant with the reactor of V-320 model is relatively well covered in the existing analyses (both the probabilistic and deterministic). The approach to estimating the ST data that is intended to consider the effect of design changes of the new reactor models is described below.

The radionuclide inventory of the core is based on Russian data derived for the original Soviet fuel [37]. It is worth noting that all the differences in the core design of various WWER-1000 reactor models (such as the material composition, maximum average burnup, power output and rate, etc.) have only small impact on the initial inventory of radionuclides in the core considered at the onset of an accident.

The next step of the process include selecting representative accident scenarios that are the most severe from the point of view of radiological releases (source term) but at the same time can be considered the ‘credible’ scenarios. Input to this evaluation is provided from Level 2 PSA for a standard WWER-1000 plant (V-320) similar to those currently under operation.

The scenarios of very high consequences and a very low frequency are not taken into account. Consistently with the current international practice, it is assumed that accident scenarios, which have the frequencies lower than 1E-7, are not considered ‘credible’. The frequencies of accident scenarios predicted in the PSA for the V-320 model, which are considered ‘credible’ accident scenarios, were re-evaluated taking into account the technical features of the most current designs. The release fractions derived in PSA for V-320 were conservatively assumed applicable to the new designs.

The definition of the Release Categories (RC) for the selected accident scenarios and the associated source term data are based on simulations conducted as part of the Level 2 PSA for a typical WWER-1000/V-320 plant. These analyses have been conducted using the STCP code package and MELCOR code, supported by engineering judgement.

2.3. Representative accident scenarios

2.3.1. RBMK plant

The accident scenarios selected for RBMKs plant cover a broad range of radiological consequences and include a catastrophic accident with a large fraction of fuel damage, partial destruction of fuel with immediate release, and overheating of fuel with limited (filtered) release. Therefore the accident scenarios considered cover a range of design basis accidents (DBAs) and beyond design basis accidents (BDBA)[1].

According to the requirements of Russian nuclear regulatory authority ROSTECHNADZOR, the BDBAs should be analyzed by deterministic and probabilistic methods. In compliance with requirements of the General Regulation for NPP Safety (OPB 88/97) [33], the estimated probability of an event with a large radioactive release should be less than 10^{-7} per reactor year.

List of postulated accidents considered mandatory in the RBMK safety assessment has been increased continually and now it includes more than 30 events [30]. Depending on the type of initiating events the following major groups of DBAs are considered:

- Operational transients,
- Deterioration of core cooling,
- Loss-of-coolant accidents,
- Reactivity-initiated accidents.
- Accidents with fuel transport operations
- Accidents initiated by internal or external hazards

For the purpose of this report the following accident scenarios are taken into account as representative with regard to the radioactive releases (Source Term):

Loss of coolant accidents

(1) Break of a fuel channel (FC) tube inside the reactor cavity
(2) Guillotine break of a downcomer pipe
(3) Guillotine break of a distributing group header (DGH)
(4) Simultaneous break of 9 FCs

---

[1] DBAs are used in the design of a nuclear power plant to establish the performance requirements for reactor structures, systems and components. They are postulated accidents to which a nuclear plant, its systems, structures and components must be designed (considering the single failure criterion) and built to withstand loads during accident conditions without releasing the harmful amounts of radioactive materials to the outside environment. Any DBA is controlled by the reactor safety systems. DBA should have insignificant off-site consequences, but may require long shutdown for correction or repair.

More serious accidents that may involve significant core degradation and/or pose the real danger of a significant release of radiation to the environment are classified as beyond DBA or severe accidents.

Accidents with fuel transport operations

(5) Dropping a spent fuel basket when reloading from a cooling pond to a railcar

(6) Dropping a fuel assembly during its handling by the central hall crane.

2.3.2. WWER-1000 plant

The most significant release scenario is selected based on Level 2 PSA for a typical WWER-1000 plant taking into account only those that are considered 'credible'.

In terms of the core damage frequency the risk of a typical plant of V-320 model for at-power conditions is dominated by the following three accident initiators: large primary to secondary LOCA (PRISE), loss of station power (LOSP) followed by blackout, and small break LOCA. Typically, these IEs contribute to more than 70-80% of the overall CDF for at-power conditions.

The most frequent types of the release categories (RCs) are associated with accident scenarios that involve failures of core cooling function either for a short term (blackout with off-site power recovered) or a long term followed by release of FPs through the containment (intact or failed).

The RC with the highest frequency (dominated by LOSP IE) involves the release from an intact containment (due to leakage) and the core melt arrested in vessel (RC1). Other RCs of a high likelihood involve a failure of the vessel in combination with a failure of the containment function either due to bypass initiated by PRISE IE (RC2) or failure due to the overpressurisation (RC3) or basemat melt in the long term (RC4).

Each of the above mentioned RCs has a relatively high frequency (1E-6 - 1E-5/year) but a relatively low contribution to the overall release of radioactive materials to the environment (source term). The RCs with the containment intact or containment failure in the long term have relatively high frequencies but the potential radiological consequences are very low.

The accident scenario that has a relatively high likelihood and a larger source term is the scenario initiated by a large break in SG (RC2). In this scenario HP ECCS and auxiliary feedwater systems are available, but the operator failed to perform a fast cooldown and stabilization of the unit. The releases to the environment take place through the SG relief valve that is normally cycling.

The more severe accident scenarios (in terms of associated ST) include those that involve further deterioration of safety systems as compared to scenarios mentioned above. This includes, for example, the PRISE scenario with SG relief valve stuck open, scenario with early containment failure at the vessel failure due to the direct containment heating (DHC), or failure of sprays in the scenarios with the containment failure in the long term. However, the frequencies of these scenarios are typically 1E-7 –5E-7 or lower. This also applies to the scenario initiated by interfacing system LOCA. It can be noted that in the plants of new designs the likelihood of such RCs will be further decreased.

The likelihood of such severe accident scenarios for the new designs is expected to be lowered by 1 to 2 orders of magnitude [44]. It is worth noting that in the Level 1 PSA study performed for an advanced WWER-1000 (V-392) [44] the CDF is estimated below 1E-7/yr.

Reflecting the above consideration, the following representative RCs are selected as the basis for a ‘catastrophic’ release for a WWER-1000 plant:

- RC4 associated with station blackout with late basemat melt-through (initiated by LOSP with off-site power recovered before the containment failure and with sprays operable)
- RC2 associated with the containment bypass following PRISE IE (with SG relief valve normally cycling).

For the new designs, the RC2 associated with the containment bypass (e.g. following PRISE IE) is not considered credible, due to the design improvements introduced for V-392 type. Nevertheless, a corresponding ST is provided for comparison.

The ST data are additionally provided for the C1 (core melt arrested in vessel and intact containment) which is dominated by a small break LOCA or LOSP IEs. This RC represents the lowest releases that is expected in a severe core damage accident..

3. The Chernobyl Accident

3.1.1. Description

The accident happened on 26 April 1986 at Unit 4 of Chernobyl RBMK 1000 NPP. The Unit 4 was started up in December 1983 and until 26 April 1986 it was operated for 715 effective full power days. The averaged fuel burnup at the time of the accident was estimated to be equal to approximately 11000 MWd/t.

In view of the particular design characteristics (the positive power coefficient at low power levels) the reactor was operated in an unsafe (and forbidden) regime. The operators deliberately and in violation of rules withdrew most control and safety rods from the core and switched off some important safety systems.

The subsequent events led to generation of an increasing amount of steam voids in the reactor core, thereby introducing a positive reactivity. This increased reactivity of the core led to a critical power excursion. Rapid release of energy into the fuel resulted in the thermal burst, which resulted in an explosion destroying the facility. Radioactive release was enhanced by an exceptionally energetic plume leading to a very high elevations. Resulting graphite fire maintained the energetic plume for 4 days, vastly contributing to the overall release quantities.

3.1.2. Source term data

The releases data were, over the years, estimated by analyses of the radiation measurements and samples from the area around Chernobyl NPP and wider. The first detailed information on the Chernobyl accident including data on the radionuclide releases was provided at the International Atomic Energy Agency (IAEA) in August 1986 [1], [2]. At International Conference “One decade after Chernobyl: Summing up the consequences of the accident”, the results of studies and analyses made during 10 years after the accident were summarized.

The ST for the Chernobyl type is based on those and on the results of studies and analyses of the subsequent years [3-21].

3.1.2.1. Radionuclide Inventory of the Core

The Chernobyl Unit 4 core inventory at the time of the accident was estimated to be about 10^{19} – 10^{20} Bq. Those estimates are listed in column 3 of the Table 3.1.

Subsequent studies [3] refined the burn-up to about 10910 MWd/t. With this, a more precise estimation of the core inventory could be established (column 4 of the table).

3.1.2.2. *Material Released*

The physical conditions and in particular the duration of the release is unique for RBMKs, and not comparable with any other reactor type. Furthermore, the isotopic content of the materials released was found to be different that predicted by the analysis.

Considering local and wider measurement and sampling, it was originally estimated that about $1{\cdot}10^{18}$ to $2{\cdot}10^{18}$ Bq were released [1, 2]. These are shown in the Table 3.1, in column 5. Noble gases are thought to have been completely expelled from the fuel into the environment. Releases of other radionuclides were estimated to be equal to about 10-20 % of the volatile radionuclides - iodine, cesium and tellurium, and to ~3 – 6 % of the more refractory radionuclides - barium, strontium, plutonium, cerium, etc.

Table 3.1. Different estimates of radionuclide inventory release

Radio-Nuclide	*T1/2, d*	*Q*, Bq [1,2]	*Q*, Bq [3]	*RQ, %,* [1,2]	*RQ*, % [3,8]
^{85}Kr	3930	3.3E16	3.3E16	100	100
^{133}Xe	5.27	7.3E18	6.3E18	100	100
^{131}I	8.05	3.1E18	3.2E18	20	50 - 60
^{134}Cs	750	1.9E17	1.8E17	10	33 ± 10
^{137}Cs	1.1E04	2.9E17	2.8E17	13	33 ± 10
^{132}Te	3.27	3.3E18	2.7E18	15	10 - 60
^{89}Sr	53	2.3E18	2.3E18	4	3.5 – 4.5
^{90}Sr	1.02E04	2.0E17	2.0E17	4	3.5 – 4.5
^{140}Ba	12.8	5.3E18	4.8E18	5.6	3.5 – 6.0
^{95}Zr	65.5	5.6E18	5.6E18	3.2	3.5
^{99}Mo	2.8	7.3E18	4.8E18	2.3	3.5 – 6.0
^{103}Ru	39.5	5.0E18	4.8E18	2.9	3.5 – 6.0
^{106}Ru	368	2.0E18	2.1E18	2.9	3.5 – 6.0
^{141}Ce	32.5	5.6E18	5.6E18	2.3	3.5
^{144}Ce	284	3.2E18	3.3E18	2.8	3.5
^{238}Pu	3.15E04	1.0E15	1.0E15	3	3.5
^{239}Pu	8.9E06	8.5E14	8.5E14	3	3.5
^{240}Pu	2.4E06	1.2E15	1.2E15	3	3.5
^{241}Pu	4800	1.7E17	1.7E17	3	3.5
^{239}Np	2.35	3.6E19	2.7E19	3	3.5
^{242}Cm	164	2.5E16	2.6E16	3	3.5
^{241}Am	1.58E05	-	1.4E14	3	3.5
^{243}Am	2.69E06	-	5.4E12	3	3.5

Considerable amount of data were collected in a decade after the accidents and used for improved estimates of the release. In release quantities presented in the Table 3.1, 6th column could be seen as the actual source term from the Chernobyl accident.

Variations in the release quantity and its radionuclide composition were explained by the behavior of core debris. Vigorous natural circulation of air up through the damaged portion of the reactor provided an efficient transport of radionuclides released. Significant uncertainties related with the behavior of the graphite moderator and the effects of many tons of lead, borax, clay, and sand dropped into the reactor vault to extinguish the graphite fire were reduced after samples were collected and additional measurements undertaken [8-10].

3.1.2.3. Releases height

Initially, radioactive material was released in an energetic plume to a high elevation (more than 1000, possibly up to 3000 meters). Reference [1] indicate that the “observed height” of the plume was more than 1200 m. In the following days, with fire being gradually extinguished, the plume height was not higher than 200 – 400 m.

3.1.2.4. Release mechanisms

The two main release mechanisms took place during the Chernobyl accident [1, 2]:

- **Mechanical release**. During the initial phase (explosion) and the fuel fragmentation later.
- **Vaporization release.** During the initial phase, volatile radionuclides and noble gases evaporated from the fragmentized fuel. Later, at elevated temperatures radionuclides re-vaporized.

The particles had, initially, exactly the same chemical composition as the fuel. The volatile constituents quickly vaporized as the aerosols have high surface area to volume ratios. Consequently, mechanically-produced aerosols differed from original fuel composition. As the mixture of vapors and mechanically-produced aerosols cooled, its surface became the point for condensation.

3.1.2.5. Iodine release

An important element of post-Chernobyl analysis was the identification of amount and chemical form of iodine released. Much of the iodine was released in gaseous form (I_2 or CH_3I), but it varied in time. The gaseous fraction of the iodine made up 60 to 80 % during the two weeks after the accident. At later stages 40 % of the iodine was aerosols, 35 % gaseous elemental iodine, and 25 % was organic iodide [26].

3.1.2.6. Timing of the release

The release of radionuclides from the Chernobyl plant did not occur in a single massive event. About 25 % of the release took place during the first day of the accident. The rest of the release of radioactivity occurred as a protracted process over a nine-day period:

- Within 5 days after the accident (days 2 to 6 of the release) the release rate declined to a minimum value of about one sixth of the initial release rate;
- In next 4 days, the release rate increased to a value about 70 % of the initial release rate;

After 10 days after the accident, the release rate dropped to less than 1 % of the initial rate and a continued to decline thereafter.

Table 3.2. The Chernobyl accident daily releases (in % of the total release)

Date	26.04	27.04	28.04	29.04	30.04	01.05	02.05	03.05	04.05	05.05
RQ, %	25	8	6	5	4	4	7	11	14	16

4. Postulated accidents - RBMK plant

4.1. *Break of a FC tube*

4.1.1. Description of the scenario

Break of the Fuel Channel (FC) was postulated to occur inside the reactor cavity, while the reactor is operating at nominal power. Two scenarios were analysed: (a) spontaneous guillotine break of a FC pipe and (b) a consequential FC break following thermo-mechanical deformation due to a failure of cooling. The scenario (b) has been shown to be more severe with regard to ST than the scenario (a) [29]. Therefore, ST data are provided for the scenario (b).

In this scenario, a loss of the coolant flow in the channel results in a significant heating up of the fuel and fuel claddings leading to overheating and break of the FC in the maximum temperature zone. It is assumed in the analysis that claddings of all 36 fuel rods in the FA are damaged as a result of the accident.

4.1.2. Source term data

The fission products released into the reactor cavity include the FPs released to the coolant before the accident (from leaking FAs) and during the accident both from the gaps of the damaged FAs and from the fuel due to overheating in the early phase and partial fragmentation of the fuel in the later phase of the accident. Table 4.1 provides a conservative estimate of the amount of fission products released into the reactor cavity. It is estimated that 100% of noble gases and 10% of iodine and cesium are released.

It is estimated that about 90 % of iodine and cesium is absorbed in the emergency condenser and downstream condensing systems (such as SOVA-TK used in Units 1 and 2 of the Kursk NPP). The condensing system water is fed to the active sewage tanks and treatment facilities.

Results of calculations of FP releases to the environment are presented in Table 4.2. These data are provided for two cases: (i) the emergency condenser (EC) is operable and (ii) EC is not operable.

Table 4.1. FP release following a break of a FC

Radio-nuclide	Radioactivity, TBq				
	From gaps of rods, non-hermetic before the accident	From gaps of 36 rods in a failed channel	From overheated fuel of 36 rods in a failed channel	From surface of fuel particles in 36 rods after their fragmentation	**Total**
^{131}I	17.7	26.4	6.5	139.9	190.5
^{132}I	39.5	47.6	9.3	197.3	293.6
^{133}I	14.7	19.2	13.2	282.7	329.8
^{134}I	7.4	9.0	16.1	342.6	375.0
^{135}I	7.5	9.4	12.7	270.2	300.0
^{85m}Kr	1.7	2.3	1.1	60.8	65.9
^{87}Kr	1.6	2.0	2.1	108.7	114.4
^{88}Kr	6.3	2.6	2.9	151.6	163.3
^{133}Xe	30.7	37.8	5.6	267.5	341.7
^{135}Xe	2.7	4.0	0.9	46.1	53.7
^{134}Cs	7.6	1.1	0.07	1.7	10.5
^{137}Cs	16.0	3.8	0.3	5.7	25.93

Table 4.2. FP release following a break of a FC, depending on system operation

Radionuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs
EC doesn't operate	19.1	29.3	33.0	37.5	30.0	65.9	114.4	163.3	341.7	53.7	1.0	2.6
EC operates (K_r =98 %)*	0.38	0.59	0.66	0.75	0.60	65.9	114.4	163.3	341.7	53.7	0.021	0.052

*) Coefficient of radionuclides' retention - K_r = 98 %.

4.2. Break of a downcomer pipe

4.2.1. Description of the scenario

The downcomer connects the steam separators and the main coolant pump (MCP) suction header. The following three cases were analyzed:

(a) Accident with normal operation of all systems
(b) Accident with loss of auxiliary power and failure of a reverse valve in one distributing group header
(c) Accident with loss of auxiliary power and one auxiliary feedwater pump.

No fuel claddings is expected to occur in al of those cases. The ST reflects the fission products in the main circulation circuit (MCC) and in the gap of fuel rods that were leaking before the accident.

4.2.2. Source term data

It is estimated that 100% of noble gases and the iodine and cesium in hydrosol form (i.e. 10 %) is released into the environment.

Table 4.3. FP release following a downcomer pipe break

Radionuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs
Release into the MCC	17.7	39.5	14.7	7.4	7.5	1.7	1.6	6.3	30.7	2.7	7.6	16.0
Release into the environment	1.8	3.9	1.5	0.74	0.75	1.7	1.6	6.3	30.7	2.7	0.77	1.6

4.3. Break of a distributing group header

4.3.1. Description of the scenario

The break of the distributing group header (DGH) is the most severe DBA. Thermal-hydraulic analysis of this accident was performed for the following three accident scenarios:

(a) Accident with normal operation of all systems
(b) Accident with loss of auxiliary power and failure of a reverse valve in one distributing group header
(c) Accident with loss of auxiliary power and one auxiliary feedwater pump.

The analysis showed that additional damages of fuel claddings could occur only in the case of the third accident scenario (c). The ST in the table 4.4 is applicable to this scenario.

4.3.2. Source term data

It is estimated that 100% of noble gases and iodine and cesium in hydrosol form (i.e. 10 %) is released into the environment.

Table 4.4. FPs release following a DGH break

Radionuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs
Release into the MCC	42.1	83.5	32.4	15.8	16.2	2.0	3.5	8.7	65.7	6.4	8.6	19.6
Release into the environment	4.2	8.4	3.3	1.6	1.6	2.0	3.5	8.7	65.7	6.4	0.86	1.96

4.4. *Simultaneous break of 9 FCs*

4.4.1. Description of the scenario

A simultaneous break of 9 FCs is the maximum to which the reactor space is expected to remain intact. The integrity is maintained by releasing the steam from the reactor space to the atmosphere to prevent the overpressurization. The FP release takes place at the level of about 30 m above the ground.

4.4.2. Source term data

It is assumed that the total amount of radionuclides discharged into the reactor space is released into the atmosphere.

Table 4.5. FPs release following a break of 9 FC

Radionuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs
Release, TBq	23.6	42.8	17.2	8.1	8.4	20.5	18.1	234.4	342.8	36.2	1.0	3.5

4.5. *Dropping of a spent fuel cask*

4.5.1. Description of the scenario

The accident scenario involving the Spent fuel cask is is assumed to contain spent fuel with the maximum burnup of 30 MWd/kg U at the time of discharge from the reactor that had been kept in the spent fuel pond for 1.5 years. For the analysis of a drop of the basket it is conservatively assumed that of 9 fuel assemblies and all 324 fuel elements are damaged.

4.5.2. Source term data

It is assumed that all of the Cs and Kr contained in the gap is released into the environment and that Cs is released as aerosol and Kr in a gaseous form. In this accindet, the radioactivity is released into the environment via aerosol filters at the ventilation stack. The efficiency of the filters is 95 %.

Table 4.6. FP release following a drop of the spent fuel cask

Radionuclide	^{85}Kr	^{134}Cs	^{137}Cs
Activity in the gap at the extract from the core, TBq	8.3	102.5	115.7
Activity in the gap at the time of accident, TBq	7.5	61.8	111.8
Activity released to the environment, TBq	7.5	3.1	5.6

4.6. Dropping of a fuel assembly

4.6.1. Description of the scenario

The selected accident is a drop of one fuel assembly (heated up to ~ 340°C) during transfer. It is assumed that all 36 fuel rods will be damaged by mechanical impact and all fission products in the gap is reelased.

4.6.2. Source term data

The activity of FPs in the gap is reduced by a decay during 10 hours. All nuclides are released to the environment via aerosol filters on the ventilation stack> the reelase height is 150 m. 100% of the cesium and iodine is reelased as aerosol

Table 4.7. FP release following a drop of a FA

Radionuclide	^{131}**I**	^{132}**I**	^{133}**I**	^{134}**I**	^{135}**I**	^{85m}**Kr**	^{87}**Kr**	^{88}**Kr**	^{133}**Xe**	^{135}**Xe**	^{134}**Cs**	^{137}**Cs**
Release, TBq	1.3	0.1	0.7	0.0001	0.16	0.5	0.009	0.2	35.8	1.9	0.06	0.2

5. Postulated accidents – WWER plant

5.1. Description of the selected accident scenarios

5.1.1. Catastrophic scenario

The accident scenarios considered as the basis for catastrophic release include the scenarios with the highest potential for off-site consequences. Two most severe accident scenarios were selected based on Level 2 PSA for WWER-1000 reactor (V-320 model) are:

(a) Station blackout with late basemat melt-through

(b) Containment bypass following PRISE IE.

The accident scenario (a) is initiated by a loss of station power (LOSP) followed by a total blackout. The reactor vessel fails, debris remains in cavity and is not cooled in the long term. Off-site power is recovered before the containment failure and the spray system is operable. Similar scenario may also be initiated by a small break LOCA with ECCS not available. The associated source term category is RC4.

The accident scenario (b) is initiated by a large break in the steam generator (40 mm). The ECCS and AFW systems are assumed operable and operator is successful in preventing SG overfilling and the SG relief valve is normally cycling. However, fast cooldown and stabilisation of the unit fails, leading to core melt. This is accident sequence with bypass of the containment that involves early and late releases directly to the environment. Corresponding release category is RC2. It should be noted that for the plants of the new designs the frequencies of accident scenarios that contribute to this RC are expected to be significantly reduced (below the frequency threshold of 1E-7/yr). In this report the accident scenario (b) is considered only for comparison with scenario (a).

5.1.2. Accident scenario of lower severity

The accident scenario that involves core melt arrested in vessel and release through an intact containment due to leakage is provided in this report for comparison.

The corresponding RC1 represents one of the severe accident scenarios of relatively high frequencies but the low radiological consequences. The dominant accident scenario contributing to this RC is LOSP sequence followed by station blackout with off-site power recovered before containment failure.

5.2. Radionuclide inventory of the core

The inventory of radionuclides in the reactor core is based on data provided in Ref [37].

Table 5.1. Inventory of the core in WWER-1000, V-320

Radionuclide group	Representative specie	Activity, Ci	Activity, Bq
Noble gases	^{85m}Kr	1,80E+07	6,66E+17
	^{87}Kr	3,80E+07	1,41E+18
	^{88}Kr	5,40E+07	2,00E+18
	^{133}Xe	1,70E+08	6,29E+18
	^{135}Xe	3,80E+07	1,41E+18
Halogens	^{131}I	8,50E+07	3,15E+18
	^{132}I	1,20E+08	4,44E+18
	^{133}I	1,70E+08	6,29E+18
	^{134}I	1,80E+08	6,66E+18
	^{135}I	1,60E+08	5,92E+18
Platinoids	^{103}Ru	1,30E+08	4,81E+18
	^{106}Ru	4,50E+07	1,67E+18
Alkali metals	^{134}Cs	1,40E+07	5,18E+17
	^{137}Cs	8,90E+06	3,29E+17
Tetravalents	^{144}Ce	1,00E+08	3,70E+18
Trivalents	^{140}La	1,50E+08	5,55E+18
Alkaline earths	^{90}Sr	6,60E+06	2,44E+17

5.3. Source term data

The main groups of fission products released into the environment (source terms) are estimated based on simulations by the use of severe accident code MELCOR.

5.3.1. Catastrophic scenario

In the RC 4, the time of basemat failure is expected about 100 hours after the initiation. At this time, although the cumulative release of aerosols increases significantly, more than 99% of the released aerosols are inactive particles. The decontamination factor is conservatively assumed to be about 100. The decontamination factor of 0.7 is used for taking into account retention of aerosols in the auxiliary building.

The RC2 involves a direct release to the environment. Nevertheless, the ST is limited due to retention in the primary system caused by a high flow in intact legs and intensive heat exchange and condensation in SG.

5.3.2. Accident scenario of lower severity

The RC1 has a relatively high likelihood and with limited (minimum) release as the containment remains intact [47]. The ST reflects that the design leakage (through intact containment) is about 0.01% of the full containment volume per 24 hrs period.

Table 5.2. FP release for Release Categories RC1, RC2, RC4

Radionuclide	Inventory	RC4		RC2		RC1	
	Bq	%	Bq	%	Bq	%	Bq
^{85m}Kr	6,66E+17	9,2E+01	6,13E+17	8,8E+01	5,86E+17	9,20E-02	6,13E+14
^{87}Kr	1,41E+18	9,2E+01	1,29E+18	8,8E+01	1,24E+18	9,20E-02	1,29E+15
^{88}Kr	2,00E+18	9,2E+01	1,84E+18	8,8E+01	1,76E+18	9,20E-02	1,84E+15
^{133}Xe	6,29E+18	9,2E+01	5,79E+18	8,8E+01	5,54E+18	9,20E-02	5,79E+15
^{135}Xe	1,41E+18	9,2E+01	1,29E+18	8,8E+01	1,24E+18	9,20E-02	1,29E+15
^{131}I	3,15E+18	1,0E-03	3,15E+13	8,5E-01	2,67E+16	1,00E-03	3,15E+13
^{132}I	4,44E+18	1,0E-03	4,44E+13	8,5E-01	3,77E+16	1,00E-03	4,44E+13
^{133}I	6,29E+18	1,0E-03	6,29E+13	8,5E-01	5,35E+16	1,00E-03	6,29E+13
^{134}I	6,66E+18	1,0E-03	6,66E+13	8,5E-01	5,66E+16	1,00E-03	6,66E+13
^{135}I	5,92E+18	1,0E-03	5,92E+13	8,5E-01	5,03E+16	1,00E-03	5,92E+13
^{103}Ru	4,81E+18	4,5E-07	2,16E+10	1,1E-05	5,29E+11	4,00E-07	1,92E+10
^{106}Ru	1,67E+18	4,5E-07	7,49E+09	1,1E-05	1,83E+11	4,00E-07	6,66E+09
^{134}Cs	5,18E+17	1,0E-03	5,18E+12	8,5E-01	4,40E+15	1,00E-03	5,18E+12
^{137}Cs	3,29E+17	1,0E-03	3,29E+12	8,5E-01	2,80E+15	1,00E-03	3,29E+12
^{144}Ce	3,70E+18	2,3E-03	8,51E+13	1,8E-04	6,66E+12	1,80E-05	6,66E+11
^{140}La	5,55E+18	1,1E-03	6,11E+13	2,5E-05	1,39E+12	3,70E-06	2,05E+11
^{90}Sr	2,44E+17	1,7E-02	4,15E+13	1,8E-02	4,40E+13	1,60E-04	3,91E+11

6. Conclusion

The FP releases into the environment were determined for relevant accident scenarios for RBMK and for WWER-1000 (hypothetical plant) at the location of current Leningrad NPP in Sosnovy Bor in Russia.

For catastrophic (limiting) release from RBMK, Chernobyl accident was considered. Other releases described in this report are estimated with conservative assumptions. The exception is the BDBA accident scenario with break of 9 FCs where best estimate approach was chosen.

The isotopic inventory of the core is set at the end of the fuel cycle. It is worth noting that for the Chernobyl accident in 1986 the radionuclide inventory of the reactor at the time of accident corresponds to the average burnup of about 11000 MWD/t, which is lower than the equilibrium for an RBMK.

An important assumptions when considering releases from the fuel include: (i) the level of damages of fuel, prior to accident, is maximum allowed per regulations, (ii) the total loss of integrity of fuel cladding occurs at 700^{o}C, (iii) the release of FPs from the gap to the coolant is complete and instantaneous, and (iv) all FPs in the coolant are instantaneously released at the time of the break of the reactor cooling system.

The DBAs with the limiting radiological consequences include breaks in the reactor cooling system (FC pipe, DGH, and downcomer pipe) and fuel transport accidents including a drop of the spent fuel cask and a drop of a ‘hot’ fuel assembly. The ST data for RBMK for all accident scenarios are summarized in Table 6.1, which also provides a simple grouping into the release categories.

The ST data to be used for the estimation of the off-site consequences for representative scenarios for RBMK and WWER reactors are summarized (in a normalized form) in Table 6.2. For the RBMK, the ST data are provided for (i) catastrophic release (RC - Large), (ii) BDBA (RC – Medium), and (iii) DBA (RC – low). Items (ii) and (iii) correspond to the scenarios associated with the limiting releases within specific RC (see Table 6.1). For the WWER-1000 plant the ST data are provided for the catastrophic release assumed representative for the new plant designs (RC2). Two additional RCs that are provided for comparison, includes a higher ST corresponding to the older WWER-1000 plants (RC4), and a representative ST for a severe core melt scenario (RC1).

Table 6.2 includes summarizes other information that are normally required for the dispersion estimates, such as the height and timing of a release.

Table 6.1. Summary of ST data for postulated accident scenarios in the RBMK plant

Radionuclide	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	^{85m}Kr	^{87}Kr	^{88}Kr	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs	Total, TBq	RC*
Break of a FC tube - EC doesn't operate (Table 4.2)	19,1	29,3	33,0	37,5	30,0	65,9	114,4	163,3	341,7	53,7	1,0	2,6	891,5	Medium
Break of a FC tube - EC operates (Table 4.2)	0,38	0,59	0,66	0,75	0,60	65,9	114,4	163,3	341,7	53,7	0,021	0,052	742,1	Medium
Break of a downcomer pipe (Table 4.3)	1,8	3,9	1,5	0,74	0,75	1,7	1,6	6,3	30,7	2,7	0,77	1,6	54,1	Low
Break of a distributing group header (Table 4.4)	4,2	8,4	3,3	1,6	1,6	2,0	3,5	8,7	65,7	6,4	0,86	1,96	108,2	Low
Simultaneous break of 9 FCs (Table 4.5)	23,6	42,8	17,2	8,1	8,4	20,5	18,1	234,4	342,8	36,2	1,0	3,5	756,6	Medium
Dropping of a spent fuel basket (Table 4.6)						7,5					3,1	5,6	16,2	Low
Dropping of a fuel assembly (Table 4.7)	1,3	0,1	0,7	E-4	0,16	0,5	0,009	0,2	35,8	1,9	0,06	0,2	40,9	Low

*) See Table 6.2 for the definition of RCs.

Table 6.2. Release Summary for the considered accident scenarios in the WWER-1000 plant

Accident scenario	RBMK Catastrophic scenario (Chernobyl 1986); RC - Large	RBMK - Beyond Design Basis; RC – Medium	RBMK - Design Basis Accident; RC – Low	WWER-1000 Catastrophic release (PRISE)	WWER 1000 Late basemat melt-through	WWER-1000 Core melt in-vessel, intact CT
Reference **Radionuclides**	Table 3.1	Table 4.5	Table 4.4	Table 5.2 - RC2	Table 5.2 - RC4	Table 5.2 – RC1
^{131}I	3,20E+18	2,36E+13	4,20E+12	2,67E+16	3,15E+13	3,15E+13
^{132}I	-	4,28E+13	8,40E+12	3,77E+16	4,44E+13	4,44E+13
^{133}I	-	1,72E+13	3,30E+12	5,35E+16	6,29E+13	6,29E+13
^{134}I	-	8,10E+12	1,60E+12	5,66E+16	6,66E+13	6,66E+13
^{135}I	-	8,40E+12	1,60E+12	5,03E+16	5,92E+13	5,92E+13
^{134}Cs	8,17E+16	1,00E+12	8,60E+11	4,40E+15	5,18E+12	5,18E+12
^{137}Cs	1,25E+17	3,50E+12	1,96E+12	2,80E+15	3,29E+12	3,29E+12
^{85m}Kr	3,30E+16	2,05E+13	2,00E+12	5,86E+17	6,13E+17	6,13E+14
^{87}Kr	-	1,81E+13	3,50E+12	1,24E+18	1,29E+18	1,29E+15
^{88}Kr	-	2,34E+14	8,70E+12	1,76E+18	1,84E+18	1,84E+15
^{89}Sr	9,89E+16	-	-	-	-	-
^{90}Sr	9,00E+15	-	-	4,40E+13	4,15E+13	3,91E+11
^{133}Xe	7,30E+18	3,43E+14	6,57E+13	5,54E+18	5,79E+18	5,79E+15
^{135}Xe	-	3,62E+13	6,40E+12	1,24E+18	1,29E+18	1,29E+15
Elevation of release	conservatively 1200m	30m above ground	Stack release, 150 m above ground	30m above ground	Ground level	Stack release, 100 m above ground
Time delay (form accident initiation)	see Table 2.2	instantaneously	instantaneously	Instantaneously	Instantaneously	1 day
Frequency of occurrence per year	1,00E-07	6,20E-06	1,50E-02	< 5E-6* << 1E-7**	< 5E-6* << 1E-7**	< 5E-6* << 1E-7**

*) Frequency for older design (V320)
**) Frequency for new designs (V392)

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ABBREVIATIONS

AFW	Auxiliary Feedwater
ALS	Accident Localization System
ALT	Accident Localization Tower
BDBA	Beyond Design Basis Accident
CT	Containment
DBA	Design Basis Accident
DGH	Distribution Group Header
EC	Emergency Condenser
ECCS	Emergency Core Cooling System
FA	Fuel Assembly
FC	Fuel Channel
FP	Fission Product
IE	Initiating Event
INES	International Nuclear Event Scale
LOCA	Loss of Coolant Accident
LOSP	Loss of Station Power
MCC	Main Cooling Circuit
NPP	Nuclear Power Plant
PRISE	Primary to Secondary LOCA
PSA	Probabilistic Safety Assessment
PT	Pressure Tube
RC	Release Category
SG	Steam Generator
ST	Source Term

Statens strålevern
Norwegian Radiation Protection Authority

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