Report from NKS-B REMSEM: the 1st Nordic seminar regarding modelling of radionuclide transfer from fallout after a nuclear explosion

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Abstract

A two-day seminar regarding modelling of radionuclide transfer from fallout after a nuclear explosion was held in Sigtuna, Sweden, at 9-10 September 2025. There were 33 participants divided over 18 organisations and 5 countries. During the two days, 13 presentations were held and finally the work presented were discussed. Discussions also focused on future possibilities of joint work and possible research applications in order to continue to share knowledge and views related to food-chain transfer models.

Key words

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1. Introduction

Since the Russian invasion of the Crimean peninsula in 2014 the geopolitical tensions have increased, and even more so since February 2022. During the on-going war between Russia and Ukraine, threats of the use of nuclear weapons have been expressed. In addition, nuclear power plants in the area have been weaponized. If a radiological emergency would occur with dispersion of radionuclides, the most dominating radiological impact in the Nordic countries would be on food production, as land areas might be contaminated with radionuclides from the nuclear fallout. For a prompt assessment of the contamination of crops and animals, modelling tools can be used to estimate the transfer of radionuclides to these from the nuclear fallout. To increase the awareness of the work that has been done within the Nordic countries until now, and to identify further improvements, a two-day workshop was held with focus on discussions about modelling of radionuclide transfer from a nuclear fallout to man via food intake. The two-day seminar, NKS-B REMSEM, took place 9-10 September 2025 at Stora Brännbo, Sigtuna, Sweden. The participants of the seminar shared knowledge and described assessment models used in their work.

The key topics discussed during the seminar were: source terms from nuclear explosions; radioecological modelling for assessment of contamination to man via food; and conditions specific for Nordic environments. The programme of the seminar, the extended abstracts of the presentations held at the seminar will follow in this report, and finally, the discussions on possible future joint research projects are summarized.

2. Programme of the seminar

The programme of 2-day seminar NKS-B REMSEM, which took place 9-10 September 2025 at Stora Brännbo, Sigtuna, Sweden, is presented below.

Day 1: Tuesday 9 September 2025

Session 1: 10:00 – 12:00
Seminar opening – Petra Appelblad, FOI
Differences between fallout from nuclear explosions and fallout from NPP releases (30 min) - Anders Axelsson, SSM
Radioecology in general including modelling and transfer (30 min) – Justin Brown, DSA
Transfer of radionuclides to crops – An indoor pot experiment (25 min) - Marcus Östman, FOI
LUNCH 12:00-13:00
Session 2 13:00 – 14:30
Radioactivity in the environment and in food: examples from Chernobyl and Fukushima accidents (30 min) – Pål Andersson
Source terms from nuclear explosions (25 min) - Annika Tovedal, FOI
Environmental behaviour of radioactive particles originating from nuclear detonations (25 min) - Ole Christian Lind, NMBU
COFFEE BREAK 14:30-15:00
Session 3: 15:00 – 16:30
Monitoring and management of radionuclides in food (25 min) – Karin Neil Persson and Daniel Edgar, SLV
Future considerations for radioecological research from Finnish perspective (25 min) - Päivi Roivainen, STUK
Summary and discussions of the day (30 min) – Jenny Aasa, SLV
DINNER 18:30

Day 2: Wednesday 10 September 2025

Session 4: 08:30 – 10:00
FDMT food modelling (25 min) – Ali Hosseini, DSA
Ingestion doses and possible food intervention levels following fallout from a nuclear explosion (25 min) - Anders Axelsson, SSM
Discussions (30 min) – Anna Maria Blixt Buhr, SSM
COFFEE BREAK 10:00-10:30
Session 2 10:30 – 12:00
Long-term monitoring of radioactivity in food and the environment in Iceland: implications of fallout from nuclear weapons testing (25 min) - Henrik Öberg, IRSA
Nuclear bomb fallout and clean-up of agricultural areas - Kasper Grann Andersen, NKS
LUNCH 11:30-12:30
Session 3: 12:30 – 14:30
Discussion and work on the REMSEM report - Petra Appelblad, FOI
Discussions about the need of future radioecology research and applications in the Nordic countries and possible collaboration and/or joint research application - Anna Maria Blixt Buhr, SSM
Wrapping up of the seminar – Petra Appelblad, FOI
COFFEE BREAK 14:30-15:00

3. Extended abstracts of the presentations held at the seminar

The extended abstracts of the presentations, which were held at the seminar, are presented in this section of the report. For any questions regarding a specific presentation, contact the presenter's organisation.

3.1 Differences between fallout from nuclear explosions and fallout from nuclear power plant releases

Anders Axelsson

Swedish Radiation Safety Authority (SSM)

Fallout from nuclear explosions and fallout from nuclear power plant (NPP) severe accident releases were surveyed with respect to differences in formation and release mechanisms and resulting differences in essential characteristics.

Differences in formation and release mechanisms include characteristics of the irradiation (extended irradiation at moderate flux compared to instantaneous exposure to enormous flux for the NPP accident and the nuclear explosion, respectively), prevailing temperatures (some thousands of degrees compared to tens to hundreds of millions of degrees), and the role of barriers (differential release of radionuclides through multiple containment barriers and mitigating systems, compared to instantaneous, complete and indiscriminate release of all radionuclides to the environment).

As a result of the differences in formation and release of radioactive aerosols and gases in the near-ground nuclear explosion compared to the severe NPP accident, as well as differences in the source geometry, the size distributions and other physico-chemical properties of the fallout will be very different in the two cases. For example, whereas the radioactivity released in a severe NPP accident is usually modelled as gases and very small (micron or sub-micron-sized) particles, early fallout from a near-ground nuclear explosion is expected to be dominated by considerably larger particles (up to and above 100 microns in diameter). See *e.g.* Glasstone and Dolan, 1977.

Specific examples were used to highlight some of the fallout differences between a severe NPP accident and a nuclear explosion:

- A severe NPP accident resulting in the core melting and a large, unfiltered release of radionuclides starting about 4 hours after the initiating event. This scenario has been used as a "conceivable worst-case scenario" for a Swedish NPP accident in the 2017 review of Swedish emergency planning zones and distances (SSM, 2017).

- A nuclear explosion at ground level, with a sizeable fusion yield and resulting in extensive early fallout containing fission products and activation products from weapon and ground materials. This scenario has been used as the "main scenario" in a recent SSM study on radiological consequences of fallout from nuclear explosions (Axelsson et. al., 2023).

Comparing the examples, notable characteristics of the severe NPP accident include the prominence of iodine isotopes in the early phase, and the prominence of ^{134}Cs and ^{137}Cs in the longer term. Notable characteristics expected in nuclear explosion fallout are a very rapid initial decay of radioactivity and dose rate, and longer-term prominence of some other nuclides compared to the severe NPP accident release. For example, while ^{137}Cs is expected to be important in the long term in both cases, ^{90}Sr may be present to a similar extent as ^{137}Cs in the fallout from a nuclear explosion but is expected to be less prominent than ^{137}Cs by several orders of magnitude in the severe NPP accident release.

The role of neutron activation products can be important in the nuclear explosion fallout, but are difficult to predict for a generic case since their production depends on what target materials are present in weapon components and in the surroundings of the explosion. In the nuclear explosion example used for the comparison, ^{54}Mn (a possible weapon activation product) dominates the fallout activity two years after the explosion. In contrast, neutron activation products (excluding from this definition fission "by-products" such as ^{134}Cs) are not important to doses from the release used as a NPP accident example.

In conclusion, radioactive fallout from nuclear explosions and releases of radioactivity in severe NPP accidents differ in many respects that may be important to radioecological modelling and consequence assessments.

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3.2 Radioecology, Modelling, and Radionuclide Transfer

Justin Brown

Norwegian Radiation and Nuclear Safety Authority (DSA)

A key focus area for Radioecology is on the transfer of radionuclides in the environment and the resulting exposures to humans and ecosystems. This extended abstract synthesises key concepts on the characterisation of transfer processes, with an emphasis on the mechanisms of radionuclide behaviour and the modelling approaches available.

Transfer of radionuclides in the environment
The transfer of radionuclides through the environment is governed by both physical and biological processes. Following a release, transport occurs through advection and dispersion, with the physicochemical form of the radionuclide determining its bioavailability and degree of interaction with solid phases. In terrestrial systems, interception by vegetation and deposition from the atmosphere are critical initial processes. Subsequently, post-depositional processes such as weathering, wash-off, abrasion, and incorporation into soil become important. Further radionuclide migration occurs through runoff, sedimentation, leaching, and resuspension. Biological transfer through food chains, such as ingestion of contaminated plants by herbivores and subsequent predation by carnivores, constitutes a major route of radionuclide transfer through the food-chain. These processes are represented in Figure 1.

Human exposure pathways are primarily (i) internal, arising from the consumption of contaminated foodstuffs and water, inhalation of radioactive particles or gases, and (ii) external, arising due to irradiation from contaminated soils and sediments. Increasingly, assessments also consider non-human biota, using approaches such as the ICRP's reference animals and plants (ICRP, 2009). Environmental exposures are diverse, encompassing internal uptake, external irradiation, ingestion of lower trophic organisms, and dermal contamination. While commonly-used assessment methods often only apply simplified internal and external exposure models, the reality is considerably more complex.
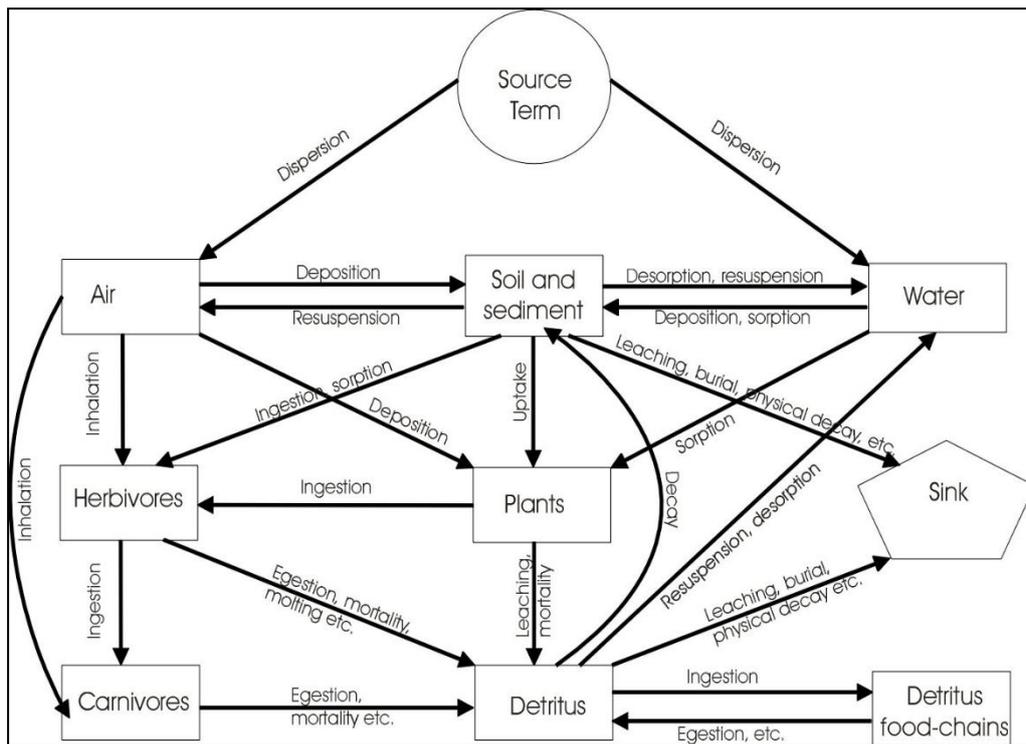
Figure 1. Radionuclide transfer in the environment. Based upon Whicker & Schultz (1982)

Modelling radionuclide transfer

The modelling of radionuclide transfer following deposition involves characterising both immediate and longer-term processes. A comprehensive overview is provided in IAEA (2010). Initial deposition is typically modelled through dry and wet deposition mechanisms, often through application of interception fractions, with radionuclide retention on vegetation subsequently determined by empirically-based weathering rates. For crops (where only part of plant consumed), contamination of edible parts is often estimated using translocation factors that depend on radionuclide type, plant species, and the time between deposition and harvest. Longer-term processes are frequently modelled through soil-to-plant concentration ratios (CRs), which provide empirical measures of transfer based on equilibrium assumptions.

In natural and semi-natural ecosystems, where radionuclide heterogeneity in soil complicates root uptake patterns, aggregated transfer factors (Tag) are employed as a pragmatic alternative to CRs. Tags normalise radionuclide accumulation in vegetation and animal products to a unit deposition (Bq/m^2) of the radionuclide. Similarly, for livestock, transfer coefficients describe the relationship between radionuclide intake (Bq/day) and activity concentrations in tissues (Bq/kg) or products such as milk (Bq/L). While these approaches provide broad coverage and are empirically grounded, they are limited by assumptions of equilibrium and neglect of key processes such as soil chemistry and radionuclide speciation. To address these limitations, supplementary approaches have been developed. The use of effective ecological half-lives allows dynamic situations to be approximated more realistically, reflecting temporal declines in contamination due to both physical decay and ecological processes. Alternatively, kinetic and biokinetic models, which represent ecosystems as compartmental structures with transfer rates between abiotic and biotic components, provide further insight into temporal dynamics. These models can incorporate dietary assimilation efficiencies, ingestion rates, and loss processes to simulate radionuclide kinetics within organisms. Allometric approaches, which

scale biological transfer parameters according to body mass, offer an additional predictive framework that has reasonable empirical support.

Although equilibrium-based models such as CRs and Tags have well-recognised limitations, they remain valuable due to their comprehensive data coverage and relative simplicity. More complex dynamic models often require parameters that are poorly characterised or unavailable. Thus, a balance is required between empirical pragmatism and the need for process-based understanding. In emergency scenarios involving rapidly changing conditions, kinetic approaches may be essential, whereas in long-term assessments of routine releases, equilibrium models offer a proportionate and practical solution.

Conclusion

Radioecological modelling integrates diverse approaches to represent the transfer of radionuclides across environmental and biological systems. Physical transport and deposition of radionuclides provide the input for subsequent biological uptake, with transfer occurring through multiple exposure pathways. While equilibrium-based methods provide wide applicability and empirical grounding, dynamic and allometry-based models offer a more process-based approach in specific contexts. Together, these methods support the assessment of radiological impacts on both humans and the environment, ensuring that regulatory and protective measures are informed by a scientifically robust understanding of radionuclide behaviour.

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3.3 Transfer of radionuclides to crops – an indoor pot experiment

Marcus Östman, Petra Appelblad and Annika Tovedal

Swedish Defence Research Agency (FOI), Umeå, Sweden

This presentation describes the ongoing work to collect transfer data of several radionuclides into crops, through a pot experiment.

One of the simplest empirical models of radioecology is the soil-to-plant transfer factor. The uptake of radionuclides to plants from soil, through the root system, has been studied around the world for about seventy years (IAEA TECDOC-1616). The subject was of great interest in Sweden for a long time and many reports have been published over the years, for example the work by Fredriksson (Fredriksson et al. 1969) and Rosén (Rosén 1996).

One limitation of the transfer factors is that they tend to span over several orders of magnitude due to variation in the experimental condition, such as type of soil, time, and chemical form of the radionuclide (Almahayni et al. 2019). For good reasons, a large part of the existing data covers Cs and Sr. For many of the other radionuclides, the data is much scarcer.

In order to test the uptake into crops from a Swedish soil for some of the less studied radionuclides, an indoor pot-experiment was performed. Each of 24 large pots were filled with approximately 20 litres of soil (silt), sampled from a field outside of Umeå, Sweden. The pots were sawn with rye grass (*Lolium perenne*), kale (*Brassica oleracea var. sabellica*) and red clover (*Trifolium pratense*).

To simulate a radioactive fallout, four radionuclides (^{134}Cs, ^{85}Sr, ^{88}Y and ^{139}Ce) were mixed into a synthetic rain water and applied to the pots after sawing of the seeds, but before any leaves had formed.

All crops were harvested after 40-68 days with subsequent soil-sampling. The radionuclides in soil and plants were measured with gamma spectrometry. ICP-MS/MS will be used to measure the stable isotopes of the element of interest as a comparison. Data evaluation is still ongoing.

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3.4 Radioactivity in the environment and food: examples from Chernobyl and Fukushima accidents

Pål Andersson

Swedish Radiation Safety Authority (SSM)

Modelling relevant for nuclear explosions should, like all modelling, be tightly connected to real world observations. Observations from earlier events or experiments may help to prioritise important aspects that need attention by modellers in planning and in initial handling of a situation as well as longer term modelling to increase the understanding of the specific situation, production of long-term prognosis, prospective and retrospective dose assessment. Such aspects could be in regard to important radionuclides, processes, exposure pathways, or specific circumstances. Earlier observations may also help to identify challenges for modelling.

It is important to be aware that there will always be many differences between the specific situations that has been observed and the modelling of any other situation. This is true not only for physical differences like differences in source term between nuclear explosions and nuclear power plant accidents (not least including very large variability in expected source term for different nuclear explosions), and differences in environmental factors between geographical areas, but also other differences like dietary and other habits, societal perceptions, requirements and expectations that might focus available observations differently compared to the current actual need.

Observations of environmental concentrations of radionuclides after the Chernobyl and Fukushima accidents can thus for example be used to inform modellers of important specific exposure routes that need consideration (or the opposite). Observations can also remind modelers of potential high variability in seemingly very similar samples as shown in an example for wild boar in Sweden (SSM, 2025) where activity concentrations of ^{137}Cs in individual animals were commonly observed both as low as 10 Bq/kg f.w. and as high as >10 000 Bq/kg f.w. all-over an area with an initial ground deposition between 20 and 60 kBq/m^2. The exposure from that specific pathway may thus be more affected by how hunters in the region handle meat with various concentrations of ^{137}Cs rather than for example the average concentration. This and other examples, e.g. observations of activity concentrations in roe deer and reindeer (Andersson et al., 2007), also indicate that there might be substantial seasonal variation that would need to be considered in certain types of modelling.

Observed activity concentrations of ^{137}Cs in perch from a Swedish lake also indicate a correlation with the size of the perch (Andersson et al., 2007) which then would be another aspect that might need to be considered by modellers. Such temporal or trophic variations need of course to be considered also when planning for further observations to support modelling.

Another example regarding concentration ratios (CR) for various plants growing on the floodplains of the river Dniepr (Lukash et al., 2025) highlights that not only could the CR for a certain radionuclide vary substantially between species, but also that this variation between species is radionuclide specific so that, in that example, *Berteroa incana* had the lowest CR

for ^{90}Sr among the studied species, but at the same time had the highest CR for ^{137}Cs. This is a reminder that it is a great challenge to extrapolate data from observed radionuclides and sample types to new ones that need to be modelled. It also highlights the obvious point that observations and modelling are tightly linked in that observations are needed for assigning parameter values as well as for validation of models.

Regarding drinking water, observations show that initially after a fallout surface water could pose a problem in that if those activity concentrations were to prevail, the drinking water pathway could give a substantial exposure. A positive is that surface water concentrations generally seem to decrease quickly the first weeks and months (Smith et al., 2001). Although long-term exposure thus might be considerably less than first impression given by initial activity concentration, there is still a wish and possibility to decrease exposure from drinking water if alternative water supplies can be used temporarily, e.g. if there is a possibility to use ground water for a certain period.

The example with drinking water points at one very important type of modelling, namely the modelling that can be done here and now in order to explore various scenarios and act as input to emergency preparedness planning, e.g. for the municipalities to evaluate how it could be possible to use ground water supplies with some knowledge of for how long such supplies would need to be sustainable, which could be informed by modelling. Modelling as part of the decision support system would naturally be very important in the early phase of a situation, but observations will also start to play a key role, together with further modelling, as soon as these become available to decision makers and modellers. In the long term, more detailed and complex evaluation of the situation would be required using both modelling and observations tightly connected.

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3.5 Source terms from nuclear weapon explosions - present research at FOI

Annika Tovedal and Peder Arvidsson

Swedish Defence Research Agency (FOI)

In order to adequately assess and plan for actions related to the fallout and other remaining radiation after nuclear weapon explosions, there is a need to describe possible source terms as accurately as possible.

The Swedish Defence Research Agency has developed a model, which utilizes a series of calculations and databases, that produces nuclide vectors for any kind of nuclear weapon explosions, fractionate the vectors based on particle production related to *e.g.* height of burst and finally describe the fallout using dispersion models.

The model will consist of a set of in-house computer codes and commercial software. The model will rely on input data, that describe the element composition of the weapon as well as the ground where the explosion might occur, for example a typical city or an airport.

So far, most of the software as well as the element compositions are in place. The next step in this work will be to, in some sense, validate the results towards existing historical data, measured and/or calculated (Spriggs 2017).

After the validation, the idea is to calculate nuclide vectors for a set of typical nuclear weapons explosion scenarios described by Goliath (Goliath 2019).

The calculated nuclide vectors expressed as fallout using dispersion models will produce a set of realistic source terms into radioecology modelling.

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3.6 Future considerations for radioecological research from Finnish perspective

Päivi Roivainen

STUK-Radiation and Nuclear Safety Authority, Department of Measurements and Environmental Monitoring, Vantaa, Finland

This presentation summarizes the current environmental monitoring programmes carried out by Finnish Radiation and Nuclear Safety Authority, and software used for atmospheric dispersion and radioecological modelling. The presentation describes activities of STUK related to modelling of the dispersion of radionuclides from nuclear explosions. It is extended to cover also more general considerations related to radioecological research from technological, environmental and legislative perspectives.

Current monitoring programmes and software
The laboratory of Environmental Surveillance monitors environmental radioactivity at the national level and around domestic nuclear power plants, planned spent nuclear fuel repository and uranium recovery facility. The laboratory also develops and maintains dispersion and dose calculation tools and decision support software and is responsible for Nuclear Test Ban Treaty Radionuclide Laboratory FIL07.

Monitoring programmes include long time series, which facilitate environmental surveillance and can also be used in research. The results show steady decrease of radioactive substances in the environment. The latest results are summarized in Virtanen and Inkinen (2025) and Virtanen et al. (2025). Additional projects can also be launched to support monitoring. In 2025 STUK carries out a citizen science campaign to investigate how Cs-137 concentration in edible mushrooms varies by region and species. Participation of citizens and media coverage has been good, which shows the importance of forest food to Finnish people.

STUK uses SILAM (System for Integrated modelLing of Atmospheric composition) and JRODOS (Real-time Online DecisiOn Support) for atmospheric dispersion modelling. JRODOS also includes a Food Chain and Dose Module (FDMT).

Modelling work related to nuclear explosions
STUK has carried out calculations related to atmospheric dispersion after a nuclear explosion. Data from these projects has been saved to facilitate further radioecological studies.

Considerations from technological, environmental and legislative perspectives
New activities such as final disposal of spent nuclear fuel and uranium recovery require monitoring in Finland and need to be taken into account in emergency preparedness. The means that e.g. new nuclides need to be considered in calculations. Progress related to small nuclear reactors also requires development of atmospheric dispersion modelling and considerations of potential new transfer routes in the environment.

Changing environmental conditions, agricultural practices and dietary habits can affect food-chain transfer of radionuclides. It is important to check the parameters of the models, such as FDMT. Changes also affect the monitoring programmes as some previously collected species have disappeared from the monitored areas and new species have been observed.

The on-going reform of nuclear energy legislation can have some effects on environmental monitoring programmes in Finland as these programmes will be on more responsibility of licence holders. Continuation of time series is important, also from the perspective of radioecological research. No change is expected in legislation related to nuclear explosives; they continue to be prohibited in Finland.

Conclusion
STUK will continue to develop atmospheric dispersion modelling, and the results can be utilized to study food chain transfer. The datasets collected through monitoring can support this work.

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3.7 Environmental behavior of radioactive particles originating from nuclear detonations

Ole Christian Lind

Norwegian University of Life Sciences

A significant fraction of radionuclides released from nuclear weapon detonations will be associated with particles ranging in size from submicron particles to fragments (Geckeis et al., 2019; Heft, 1970; Salbu et al., 2015). The characteristics of such radioactive particles (Fig. 1), including particle size distributions, surface and particle matrix elemental composition, morphology, crystalline structure, density, and oxidation state influence environmental transport, particle weathering rates, mobilization, ecosystem transfer and dosimetry (Salbu and Lind, 2020). To assess the environmental impact of radioactive particles released from nuclear explosions and subsequently deposited in ecosystems, detailed information on the particle properties is required.
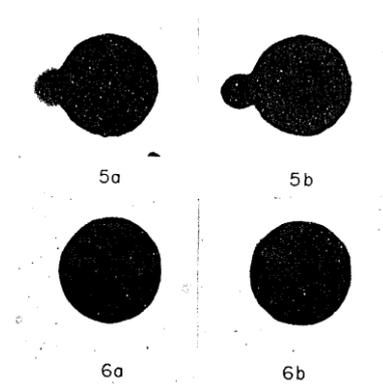

Figure 1.USSR air burst single fallout particles (size range 7.7 – 13.5 μm) deposited in Japan in 1962 (Mamuro et al. 1965).

Mobility and potential bioavailability of particle associated radionuclides
The mobility and potential bioavailability of particle-associated radionuclides will change over time. In principle, radioecological models have the capacity to describe dynamic particle weathering and subsequent transfer processes, which are required to reduce uncertainties in model outputs (Kashparov et al., 2020; Salbu et al., 2018; Urso et al., 2019). In order to be able to do this, however, parametrisation would be needed and publicly available dynamic data (e.g., leaching rates) is scarce (Andersson et al., 2025). It should be noted in this regard that relevant archive sample material exists and adequate characterisation methods have been developed (Salbu et al., 2018; Salbu and Lind, 2020). Such characterisation methods include size fractionation of radionuclides in leachates from dynamic leaching studies. Preliminary results indicate that radionuclides, due to particle weathering or molecular growth processes, may occur as submicron or even nanoscale particles with biological uptake properties potentially very different from those of ions (Salbu et al., 2018).

Potential impact of radioactive particles on environment and health

Radioactive particles released from nuclear detonations carry a substantial amount of radioactivity thus acting as point sources of both short- and long-term significance for health and environment (Andersson et al., 2025). External exposures, inhalation, dermal absorption, skin exposure and ingestion of particles contribute to the risk. Retention of radioactive particles in plants, filter-feeders (e.g., molluscs) and soil-dwelling animals (e.g. gastropods) can occur and eventually also cause ingestion by man. Furthermore, grazing animals may ingest significant amounts of radioactive particles if they stay in particle-affected pastures. According to Yoschenko et al. (2009), bioavailability of particle associated radionuclides in the gastrointestinal tract may be orders of magnitude lower than for corresponding radionuclide species in water-soluble form. Particle characteristics such as size (Yoschenko et al., 2009), shape and structure may also influence the GI transport of radioactive particles, i.e. if they are retained or not.

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3.8 Monitoring and management of radionuclides in food

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Swedish Food Agency

The Swedish Food Agency works to ensure safe food and safe drinking water, transparency in food handling and sustainable food consumption, e.g. by setting limit values, giving dietary advice and by control activities.

Analysis of radionuclides in food

The Swedish Food Agency regularly conducts so-called market basket studies with the aim to get an overall picture of the amount of nutrients and potentially harmful substances in food items representative for the average Swedish consumption. The choice of food items was based on statistics on direct consumption (Swedish Board of Agriculture), market shares and dietary surveys, and homogenized into pooled samples of specific food categories (food groups).

In the latest market basket study, the Market Basket 2022 (Livsmedelsverket, 2024a), analyses of a broad range of radionuclides, both anthropogenic and naturally occurring, were included for the first time. In addition, food items not regularly consumed by the general population were also included in the study. Those food items mainly consisted of meat from game, reindeer and lamb, different species of fish and shellfish, wild berries and mushrooms. In total, ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra, ^{212}Pb, ^{235}U, ^{40}K, ^{137}Cs and ^{90}Sr were analyzed in 17 food groups and two subgroups from the market basket study and in 35 additional food types.

The occurrence data of the radionuclides in the market basket samples, combined with data on the general amount of consumption of each food per year, were used to estimate the mean radiological exposure dose from food for the average Swedish consumer. Some results are still lacking due to analytical concerns.

The levels of the radionuclides in the additional food items were summarized and used for scenario calculations, where the radiological dose for each specific food type at specific portions sizes was estimated. Further, the number of portions of each food type that could be consumed was estimated at the assumption that it would not exceed 0.1 mSv per year.

Another set of data that is available from the Swedish Food Agency is from a recent citizen science-based study were monitoring of ^{137}Cs was performed in samples of roe deer meat (*Capreolus capreolus*), mushrooms and cloudberries collected by the public (Livsmedelsverket, 2024b). In most samples, the activity concentration of ^{137}Cs was below the Swedish limit values for game meat, mushrooms and wild berries (1500 Bq/kg). The report from this study is available at the web page of the Agency.

Management of radionuclides in reindeer and wild boars

In Sweden, the consumer intake of radionuclides from food is managed both by maximum permitted values in the national regulation LIVSFS2012:3 (appendix table D) for products sold on the market, and dietary advice for household consumption (private consumption). Thus, these efforts complete each other with the goal of keeping the intake of radionuclides in food at a safe level for consumers.

The current Swedish maximum permitted levels of ^{137}Cs was established in 1987, about a year after the Chernobyl accident. The fallout from Chernobyl severely affected the food production in Sweden, and in the most affected areas the effect from fallout still lingers. It is worth noting that the levels in the Swedish legislation differs from those in the Commission regulation (Euratom) 2016/52 which will enter into force in case of a nuclear accident or any other kind of nuclear emergency.

The reindeer husbandry suffered badly from the consequences of the fallout, where 78% of the reindeer that was slaughtered in 1986 exceeded the permitted limits of ^{137}Cs, which at that time was 300 Bq/kg. The maximum permitted level for reindeer was rised to 1500 Bq/kg in 1987. The reindeers roam freely to graze/browse, and lichen is a vital part of their diet, especially in the winter season. The main ways of trying to lower the levels of ^{137}Cs in reindeer has been by changing the time of slaughter to earlier in the autumn and support feeding with clean feed. Previously, bentonite clay has also been used as a cesium-binding feed additive. ^{137}Cs has been measured in reindeer and in reindeer meat since the fallout in 1986, and a national control program was established. The program has adapted and changed with time, and as an increasing number of geographical areas has been cleared of risk, it was decided to terminate the control program in 2020. This went into effect in July 2022. The actions taken had had effect, and the half-life of ^{137}Cs of approximately 30 years had passed. However, as the risk of exceeding maximum permitted levels in meat from the most affected geographical areas still remain, the responsibility to ensure that reindeer meat that is put for sale on the market complies with the maximum permitted values of ^{137}Cs now lies with the producer in accordance with how other risks in food are handled. The costs of sampling and analysis, and compensation for carcasses exceeding maximum permitted levels are still covered by the government.

Wild boars went extinct in Sweden in the 18th century but has since then been reintroduced and are spreading from the south further north. There are now established populations in the areas around Uppsala and Gävle that were severely affected by the Chernobyl fallout. This has emerged to be an issue, since the wild boars root deep in the soil in search of food. Since they are omnivores they eat worms, insects and roots in the soil (ingesting a lot of soil in the process) but also other feed which may contain high levels of ^{137}Cs such as moss, lichen and mushrooms. This means that there is a now an issue with ^{137}Cs in wild boars that Sweden did not have in 1986, as barely any wild boars were present in the affected areas at that time. There is also a national incitement for hunting more wild boars to lower the population due to the damage they are causing. One approach is to facilitate the selling of meat from wild boars for hunters. A lot of work has been put into finding procedures of doing this without compromising food security (there are other issues with the meat from wild boars as well such as trichina parasites and bacteria), and since 2021 the analysis of ^{137}Cs is subsidized by the Swedish government. This, along with other actions, has led to the possibility for hunters to sell small amounts of meat from wild boars directly to restaurants and similar establishments, without undergoing controls at a game handling establishment.

These are two ways of handling the risk of ^{137}Cs for consumers. They are slightly different in the approach due to the different circumstances but there are also similarities; the costs for analysis are covered by the government and there are both dietary advice and legal limit values to apply both for products for sale on the market and for private consumption.

Conclusion

To get the complete picture of the occurrence of radionuclides e.g. in a food matrix, many analyses and different techniques are required. This, in turn, requires high standards of every analytical step to get reliable data. However, successful data from this type of studies could be valuable input in modelling efforts, and the Swedish Food Agency could support with such data if needed. Management of radionuclides in food can be done with different approaches. When planning for the setup of a national control program, it is important to have access to data to be able to determine what to sample, how, when, and where to take the samples. Modelling, along with other information, can be an important tool for priorities when planning for a control program.

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3.9 FDMT Food Chain Modelling

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Following the accidental release of radioactive substances into the environment, one of the primary pathways of human exposure is through the ingestion of contaminated food. This exposure can occur via the consumption of contaminated crops, plants, or animal products. To address the consequences of nuclear or radiological accidents, decision-makers employ Decision Support Systems (DSSs) to inform and justify their actions. The two principal European emergency management DSSs are ARGOS (Accident Reporting and Guiding Operational System; Hoe et al., 2008) and JRODOS (Real-time On-line Decision Support System; Levdin et al., 2010). Both systems utilise the FDMT (Food Chain and Dose Module for Terrestrial pathways) to simulate the transfer of radionuclides through terrestrial food chains.

FDMT
Developed in Germany in the early 1990s, the FDMT software is based on the radioecological model ECOSYS-87 (Müller & Pröhl, 1993). The module enables the prediction of radionuclide activity concentrations in various—primarily agricultural—food products and facilitates the derivation of doses to members of the public from all relevant exposure pathways, including internal exposure (from ingestion and inhalation) and external exposure (from plume passage and deposited radionuclides).

FDMT adopts a partly process-based approach, accounting for seasonality in agricultural practices, crop growth, and human dietary habits. The model represents the entire food chain as a series of interconnected compartments and calculates radionuclide concentrations over time in 18 plant species, 11 animal products, and 18 processed foods. The suite of radionuclides considered is limited and predominantly based on nuclear power plant (NPP) accidents, especially Chernobyl. In addition to accounting for dry and wet deposition, FDMT incorporates key radioecological transfer processes, including interception by vegetation, foliar uptake, translocation, weathering loss and bio-dilution, root uptake and resuspension, animal ingestion and metabolism, and food processing. (Figure 1).
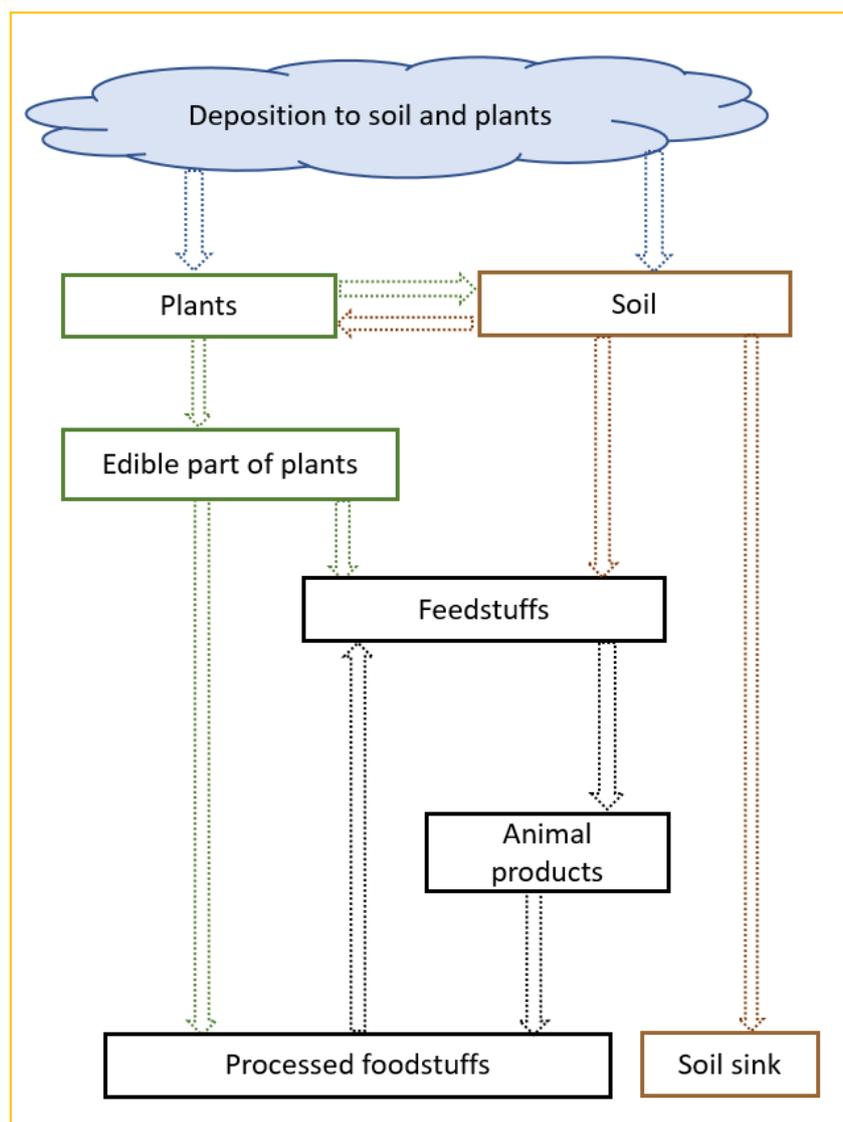
Figure 1. Important components in food-chain transfer modelling as considered by FDMT.

New FDMT and further development

Over many years of application in diverse scenarios, FDMT has demonstrated limitations in its original form, which can be grouped into three categories: structural, conceptual, and specificity-related (Hosseini et al., 2022). Structural limitations were identified by recognising that complex issues, such as human exposure through food chains, require modelling platforms flexible enough to allow for analysis of individual units without invoking the entire system. This flexibility has been incorporated into FDMT by its implementation within the AFRY Intelligent Scenario Modelling Platform[1].

After addressing structural limitations, further development of FDMT has focused on conceptual and specificity-related issues. This work exploits the model's enhanced flexibility to refine the FDMT framework through the incorporation of more detailed sub-models and increased specificity. The latter involves efforts to make the model more fit-for-purpose by integrating regional-specific parameters, adopting new and additional parameters, and employing updated, more relevant values (Hosseini et al., 2024).

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[1] https://www.intelligentscenariomodelling.com

Final remarks

Estimating internal dose from ingestion following a nuclear explosion involves a complex interplay of weapon design and composition, burst height, and environmental, biological, and behavioural factors. The aforementioned developments demonstrate the flexibility of the new FDMT module, which can be adapted to simulate and predict consequences arising from the fallout of a nuclear detonation. However, a shift in emergency preparedness and response paradigms is necessary—moving focus from nuclear power plant accidents to nuclear detonation events. This change requires identification and understanding of the differences in fallout mechanisms between reactor accidents and nuclear detonations. These differences may manifest as variations in source geometry, radionuclide production, release and dispersion patterns, physico-chemical properties of released particles, decay dynamics, and neutron activation products. Consequently, the default models, assumptions, and parameter values within FDMT should be thoroughly reviewed and revised to accurately reflect the specific characteristics of nuclear detonation events.

In summary, continual refinement of models like FDMT is crucial to ensuring that emergency preparedness and response strategies remain robust and aligned with evolving nuclear threats. By integrating new scientific insights and adapting to emerging scenarios, such systems can better protect public health in the face of unforeseen radiological challenges.

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3.10 Ingestion doses and possible food intervention levels following fallout from a nuclear explosion

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Based on radioecological modelling commissioned by SSM (Andersson, 2023, 2024), some initial analysis of doses from consumption of foodstuffs contaminated by fallout from nuclear explosions has been performed.

The analysis is based on unit contamination factors (Bq/kg per initially deposited Bq/m^2) in various foodstuffs for a number of key radionuclides, as modelled by Andersson (2023, 2024) using an Excel version of ECOSYS (Müller & Proehl, 1993) and nuclide vectors for nuclear explosion fallout supplied by SSM based on earlier work (Axelsson *et. al.*, 2023). The unit contamination factors represent the maximum concentration reached during the period of interest in each of the assessed foodstuffs for each assessed radionuclide. The periods of interest (modelling scope) have been the early phase, defined as the first two months (Andersson, 2023) after an explosion, and the late phase, defined as the second year (Andersson, 2024).

Unit contamination factors and nuclear explosion fallout nuclide vectors have been combined to produce indicative early-phase and late-phase doses from ingestion. In this analysis, annual and daily food consumption for adults and for small children were derived from the data (European Commission, 1998) that provide the basis for the limits set out in Council Regulation (Euratom) 2016/52 on maximum permitted levels of radioactive contamination of food and feed following a nuclear accident or any other radiological emergency.

As an example of results obtained, the analysis indicates that consumption during the early phase of foodstuffs produced in areas with substantial fallout (ground dose rate some millisieverts per hour after 24 hours) could result in very high committed effective doses of a sievert or more in the short term, in particular from dairy products and from directly-contaminated leafy vegetables. For intake over the longer term (late phase), the results indicate that annual committed doses of a few hundred millisieverts may be received from consumption of foodstuffs exclusively produced in areas with substantial fallout.

In order to explore the applicability of the limits set out in Council Regulation (Euratom) 2016/52 to the situation following fallout from a nuclear explosion, the doses resulting from application of those limits to contaminated foodstuffs have been estimated. The results indicate that consumption exclusively of foodstuffs contaminated up to the limits set out in the Council Regulation may result in committed doses of a few millisieverts in the early phase (first two months), and committed doses of a few millisieverts in the longer term (second year). The derivation of the Council Regulation limits assumes that only 10 % of food intake is contaminated to the level of the limits (and the remainder is not contaminated), and making the same assumption in the current analysis thus indicates that application of the limits could lead to restricting committed doses from food intake to below one millisievert.

The unit contamination factors, nuclear explosion fallout nuclide vectors, and food contamination limits set out in Council Regulation (Euratom) 2016/52 has also been used to

estimate possible intervention levels, *i.e.* levels of fallout that may lead to exceedance of contamination limits. Estimated intervention levels vary widely between different foodstuffs and between the early phase and the late phase. For exceedance of contamination limits during the early phase, intervention levels for certain foodstuffs imply that dose rates will soon fall below detection limits for dose rate instruments, indicating that contamination levels in foodstuffs need to be controlled by monitoring in the food production chain.

The conclusions from the analysis done so far are preliminary. They indicate that very high committed doses may be received in the short term by consumption of foodstuffs from areas with substantial fallout, and that high committed doses may be received over the longer term by consumption of foodstuffs produced in areas with substantial fallout. Further, the application of the limits set out in Council Regulation (Euratom) 2016/52 to foodstuffs contaminated by fallout from a nuclear explosion can lead to restricting committed doses from intake of foodstuffs to low levels.

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3.11 Long-term monitoring of radioactivity in food and the environment in Iceland: implications of fallout from nuclear weapons testing

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Icelandic Radiation Safety Authority (IRSA)

The Icelandic Radiation Safety Authority (IRSA) has maintained a systematic program for environmental and food monitoring of radioactivity since 1989, mandated under the Act on Radiation Protection (No. 44/2002). The program has focused on cesium-137 (^{137}Cs) as the principal fallout radionuclide of concern. Continuous surveillance addresses both routine environmental exposure and potential releases from global radiological events, while also providing critical input for national emergency preparedness.

An important aspect of the program is the long-term observation of residual fallout from atmospheric nuclear weapons testing conducted in the 1950s and 1960s. ^{137}Cs, with its 30-year physical half-life, persists in Icelandic soils, aquatic systems, and food chains at low levels detectable decades after deposition. Monitoring records demonstrate a clear exponential decline in activity concentrations across foodstuffs such as cow's milk and lamb meat, consistent with both physical decay and ecological redistribution processes. These data provide an important baseline for distinguishing between historic fallout and contributions from later events, including the Chernobyl accident (1986) and the Fukushima accident (2011).

The monitoring framework combines real-time external gamma dose rate measurements—currently operated at four permanent stations across Iceland, complemented by a CTBTO radionuclide station in Reykjavík—with an extensive sampling scheme of environmental and food matrices. Targeted media include aerosols, precipitation, seawater, seaweed, milk and milk powder, lamb meat, fish, and selected foodstuffs of local importance. Annual reports (Guðnason et al., 2016) summarize the results, which consistently show low activity concentrations in the samples, though seasonal and inter-annual variability is observed.

Analytical capacity is based on stationary and mobile HPGe detectors, supported by NaI detectors and air samplers. Until 2020, IRSA relied on the in-house Greina software for gamma-spectrometric analysis; since 2021, the transition to GammaVision has enabled both improved standardization and automation. A recent methodological study (Öberg et al., 2025) compared both software packages using datasets of lamb meat, milk, and milk powder spectra from the time-period 2013–2020, identifying systematic efficiency calibration differences that require harmonization for consistent time-series reporting. To enhance throughput, an automated analysis pipeline has been developed, significantly accelerating quantification while maintaining quality control.

The robustness of IRSA's program is further underpinned by institutional collaboration: *e.g.* the Icelandic Met Office maintains gamma stations and provides IRSA with precipation samples periodically, the Marine and Freshwater Research Institute contributes with seawater sampling, and food regulators and industry partners facilitate access to agricultural products. This long-standing network has created a resilient monitoring "supply chain," ensuring continuity and public engagement.

Conclusion

In summary, the Icelandic monitoring program represents a well-established, collaborative, and technically adaptive system for long-term assessment of environmental radioactivity. Through continuous optimization of analytical methods and sustained institutional partnerships, IRSA ensures reliable surveillance of radiological impacts on food and the environment, thereby strengthening both national radiation protection and regional emergency preparedness capacities.

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3.12 Nuclear bomb fallout and clean-up of agricultural areas

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Fallout contaminant formation and characteristics

In a ground based or near-ground nuclear bomb burst, temperatures may be extremely high - up to many millions of degrees. As a result, all matter in the vicinity of the fireball will be vaporized. As the temperature decreases over just tens of seconds to few minutes to about 3000⁰C, a formation of small liquid droplets will commence. Radionuclides of refractory elements that have evaporation temperatures in this region will typically become incorporated in the droplets. The droplets will solidify when the temperature declines to some 1500⁰C, which is the approximate melting point of the mineral soil and many other ground materials that were whirled up and vaporized in the blast. Some bomb or surface debris may consist of more or less refractory matter, which can solidify earlier or later in this process.

These 'refractory' radionuclides condensing at temperatures above approximately 1500⁰C tend to be mixed throughout the entire particle matrix, whereas the more volatile element radionuclides and/or their daughters condense later (at lower temperature) on the surface of the large mass of whirled-up soil/debris particles or existing solidified, or ambient particles. Such radionuclides as a rule of thumb should include most isotopes formed of the elements As, Ba, Br, Cd, Cs, I, Rb, Se, Sr, Te, Yb, and Zn. According to bomb test results (e.g., Russell, 1965), also Ru and ^{141}Ce should be volatile in at least some cases. The volatility of Ru is known from the Chernobyl accident to strongly depend on oxidation stage.

It will largely be the initial fission product element that determines the particle association. A chain of subsequent beta decays may cause a number of elemental transitions with retained mass number, but the entire mass chain should remain associated with particles in the same way.

Two distinctly different types of particles are thus formed: round (solidified droplet) particles with homogeneous specific radioactivity proportional to the cube of the radius, and irregular particles (to a great extent formed by physical fragmentation) with radioactive matter distributed only on the surface and therefore specific radioactivity proportional to the square of the radius.

The first particle type will tend to contain refractory element radionuclides, whereas the other will typically be coated by the more volatile.

The two particle types both have size distributions that span over several decades and overlap each other. The larger particles will deposit as gravity driven fallout over relatively short distances, whereas smaller particles, particularly in the 0.1-1 μm range, can travel with the wind over thousands of kilometres.

In-line with the observation of two different particle types, it has been found a good approach to approximate the observed particle size activity distributions from nuclear blast testing with a bi-modal lognormal distribution function of the following type (Baker, 1987):

$$F(r) = \frac{N1}{r\,\beta_1\,\sqrt{2\pi}} \exp\left(-\frac{(\ln(r)-\alpha_{n1})^2}{2\beta_1^2}\right) + \frac{N2}{r\,\beta_2\,\sqrt{2\pi}} \exp\left(-\frac{(\ln(r)-\alpha_{n2})^2}{2\beta_2^2}\right), \text{ where}$$

N1 is the fraction of spherical particles with specific activity proportional to r^3

N2 is the fraction of irregular particles with specific activity proportional to r^2

α_{n1} and α_{n2} : natural logarithm of resp. median particle radius, β_1 and β_2 : ln of respective standard deviation, taking into account radionuclide distribution.

In contrast, it should be noted that no N_2 type particles are observed in high air bursts, but N_1 type particles are there very similar with those from ground bursts.

Implications for mobility and choice of agricultural food countermeasures
It would be expected that the most refractory element radionuclides, which are mixed in a matrix such as high-temperature glassified soil, would not be readily soluble after atmospheric dispersion and deposition in the environment, whereas volatile element radionuclides deposited/condensed on the surface of carrier particles would be expected to be much more soluble and readily environmentally mobile.

The Chernobyl accident showed that the environmental solubility of low solubility fuel particles can greatly depend on contaminant oxidation and pH of the soil surface to which deposition occurred (Kashparov et al., 1997). It was here found that dissolution of Sr from deposited fuel particles might under some circumstances take several decades to complete. This implies that countermeasures for different types of contaminants may be needed at considerably different times, also following a bomb blast fallout deposition. The environmental dissolution might possibly take so long that the physical half-life has greatly reduced the concentrations of some relatively short-lived radionuclides before they become environmentally mobile to a significant extent. Sadly, there exists only extremely little information to judge these dynamical processes from.

The European handbook for recovery in food producing areas (Nisbet et al., 2011) contains descriptions of a total of 57 countermeasures for treatment of contaminated food producing areas and food products after deposition of fallout from a nuclear power plant accident. Many of these countermeasures would also be applicable for nuclear bomb fallout, as they are not contaminant or scenario specific (e.g., ploughing procedures, early removal of crops and topsoil removal). Preliminary ingestion dose calculations indicate that for example ^{137}Cs and [106]Ru, which are important to target for nuclear power plant scenarios would also be important for bomb blast fallout scenarios. However, there are indications that also previously unconsidered radionuclides may have importance in the bomb fallout scenarios, and it would be helpful to look into possible element specific countermeasures to minimise the consequences of environmental presence also of these.

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4 Discussions and future work

4.1 Discussions day 1

During day 1, all participants had an open discussion about the fallout and particle formation, radionuclides, measurements, sampling and modelling. These discussions can be summarised as:

The fallout and particle formation
It has been found that some glass particles in the fallout are leachable - not entirely inert as often stated in the literature. This shows that there is still more to learn about particles to be able to make better estimates on radionuclide transfer. The data in the literature is collected from different sources, for example the Maralinga tests; the Palomares incident; the Chernobyl accident; the Fukushima accident as well as laboratory tests.

Radionuclides
Which radionuclides will be important? Depending on the timescale, it will be different. For example, in long-term perspective, iodine will not be important for the human health risk whilst in a short-term perspective, iodine will be a major contributor to dose to man. In the long run there will be other radionuclides that will have more significant impact on the total dose to man.

In the 50's and 60's a lot of research on radionuclides was done in many countries. The measurement techniques used were less developed compared to today's instrumentation and the studies focused on a few radionuclides. Further, instead of performing nuclide-specific measurements, the researchers used dose rate data to do retrospective dose calculations. Scenario specific source terms would give more information on which radionuclides that will be more important. There is also a need to perform experiments on transfer of radionuclides as there are many radionuclides where this kind of data is missing.

Measurements and sampling
New species need to be included in the measurement programs as some are becoming rare, for example, bladder wrack will need to be replaced. In contrast, the wild boar population is expanding geographically and this adds an important exposure pathway to some Nordic countries which needs to be considered. Additionally, it was mentioned that citizen science is important as citizens can help with sampling for instance. There are on-going discussions in more than one Nordic country regarding sampling: how many samples need to be analysed to achieve a statistically significant answer? Further, there is a need for regular measurements of a broad range of radionuclides for the understanding of the ongoing background exposure. This information is important in the estimation of the additional risk in case of a radiological event. Standardised methods were also discussed and are also needed for an improved handling of an event. All this has to be in place beforehand as a preparedness step.

Radioecological modelling
It is highly unlikely that there will be enough measurement capacity in an early phase of a radiological event, thus modelling is necessary for decision-making. Would it be possible to use dose rate measurements further as input data to modelling?

Radioecological modelling can be used in the planning stage or in the early phase of an event to find out what we should measure in case of a radiological event. With models we can

perhaps find out what is most important to focus on. The more certain modelling, the more certain decisions can be taken regarding food intake from contaminated areas. However, a model can never replace observations totally. In the early phase, it might not be the model with the highest accuracy and predictive power (which likely would be a very complex model with high demands on input data) that is best suited model. In contrast, it may be more beneficial to use a model that quickly can give some indications about the situation. A simpler model may meet the needs for authorities in the early phases of an event whilst a more complex model may be needed by academia to answer specific research questions.

4.2 Discussions day 2

During day 2, breakout groups discussed the take-homes from the seminar. The discussions are summarised in bullet points below:

- We need to have some initial idea on where the concerns are about foodstuff and nuclear fallout. What is interesting to measure? Which elements, which nuclides and which food and feed?

- We need more information about characteristic properties of nuclear fallout particles. What is the biological availability? What can be achieved by environmental sampling?

- Conservative assumptions are applied by assuming that all nuclides are fully bioavailable.

- To develop models, we should narrow down the initial output of models with an iterative process

- Nuclear explosions are new to some in the room. What does the new source term mean to us? How should we evolve around this compared to NPP?

- Nuclear detonation is very scenario-specific. How do we treat this? Can we come up with a few scenarios to to highlight the existing uncertainties?

- How quickly can we know the nuclide vector in case of a release/explosion?

- Models: it is difficult to have all these complex models, we need simpler models for ease of use in case of an emergency.

- Uncertainty and sensitivity analyses are important in order to be able to make simpler models.

- What we do during this seminar is very important. To share knowledge is key to improve the situation. Regular meetings within the Nordic community are important.

- How important are the Nordic parameters for modelling? It might not be that big a difference compared to southern Europe? Experiments are needed to be able to find differences.

- Modelling: there are different needs of models. One for research and exploratory and one for advisory purposes.

- Source term and particle size are key parameters for further calculations.

- Do not forget data mining. Very little that hasn't been studied at some point. Maybe there is a potential for a joint comprehensive literature review of all work from the 50's and onward to find data that already exist? Perhaps catalogue report could be made.

- Sensitivity and uncertainty analyses to find which parameters that are important to study more. This needs to be iterated.

- Can archived samples be used to learn more of historical fallout? However, a lot of the radionuclides have most likely already decayed and the information might be gone. Perhaps it would be informative to look at analogues if the nuclides of interest may have decayed.

- Are the short-term or the long-term models most important? Perhaps it is most interesting in the beginning or beforehand of an event?

- The short-term modelling could help in steering the work to the most important areas.

- Would it be of interest to use modelling for retrospective dose calculations?

- What can AI (articificial intelligence) and IoT (Internet of Things) do to speed up data crunching?

4.3 Possible NKS applications or thoughts related to applications

During this part of the seminar, all participants had an open discussion about possible continuation after the seminar. These discussions are summarised below.

- Pulling together plans for what is needed to improve the nuclear emergency in the Nordic countries. For example, countermeasures in the agricultural, how should we make the measurements, do we have the required instrument and personnel and time that are required to fulfil the demands of the situations? It is not just dose rate that is interesting, there are many parameters in order to choose the correct countermeasures in early phase.

- Gap analysis for the Nordic countries regarding modelling: differences between nuclear power plant accidents *vs*. nuclear weapon explosion. Can this be combined with sensitivity analysis?

- In the future meetings we should talk about what research is needed.

- One possible application would be to have a seminar next year, IRSA will take the lead for a new project application.

- For this project, it was a quite closed invitation. Could we make a broader invitation?

- Remember to encourage young scientists to participate in future seminars.

5 Conclusions

These two days have been rewarding for the participants and it is important that we, as a Nordic community, continue to cooperate to enhance the knowledge about radioecological modelling further. It was decided that a new application for next year will be sent to NKS to continue the discussions on modelling of radionuclide transfer. Furthermore, in order to improve the models, there is a need to calculate scenario specific source terms, search out more information about physico-chemical characteristics of the particles, as well as perform experiments on radionuclide transfer to food and feed.

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7 Disclaimer

The views expressed in this document remain the responsibility of the authors and do not necessarily reflect those of NKS. In particular, neither NKS nor any other organisation or body supporting NKS activities can be held responsible for the material presented in this report.

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Abstract max. 2000 characters	A two-day seminar regarding modelling of radionuclide transfer from fallout after a nuclear explosion was held in Sigtuna, Sweden, at 9-10 September 2025. There were 33 participants divided over 18 organisations and 5 countries. During the two days, 13 presentations were held and finally the work presented were discussed. Discussions also focused on future possibilities of joint work and possible research applications in order to continue to share knowledge and views related to food-chain transfer models.
Key words	Radionuclide, transfer, modelling, fallout, nuclear explosion, food, feed,