



Nordic nuclear safety research

NKS-512
ISBN 978-87-7893-612-7

DispeRasion Analysis of early nuclear WeapoN tests (DRAWN)

Jens Havskov Sørensen¹ (co-ordinator)
Henrik Feddersen¹
Kristian Holten Møller¹
Magnuz Engardt²
Lennart Robertson²
Jan Pehrsson³
Henrik Roed⁴
Elias Pagh Senstius⁴
Naeem Ul Syed⁵
Anders Axelsson⁶
Jan Burman⁶
Jonas Lindgren⁶
Mikael Moring⁷
Tuomas Peltonen⁷
Mikko Voutilainen⁷

¹Danish Meteorological Institute (DMI)

²Swedish Meteorological and Hydrological Institute (SMHI)

³PDC-ARGOS

⁴Danish Emergency Management Agency (DEMA)

⁵Norwegian Radiation and Nuclear Safety Authority (DSA)

⁶Swedish Radiation Safety Authority (SSM)

⁷Radiation and Nuclear Safety Authority (STUK)

February 2026

Abstract

The geopolitical situation involves an increased risk for use of nuclear weapons. Detonation of such weapons implies atmospheric dispersion of radioactivity posing a risk to the public also at longer distances from the detonation. Thus, there is a need for developing new, or improving existing, prediction model tools for such events aiming at enhanced civil protection.

The model systems describe the initial spatial distribution of radioactive matter, when stabilization has occurred around ten minutes after detonation, as observed in the field. This distribution is taken over by an operational atmospheric dispersion model complying with this description. In the previous NKS-B project DISARM, methods have been developed for describing this distribution as a mushroom cloud.

In DRAWN, the methods developed have been applied to and validated against selected atmospheric nuclear tests in the Nevada desert in the 1940s, 1950s, and early 1960s.

The non-hydrostatic Harmonie numerical weather prediction model has been set up and run at high resolution using ERA5 reanalysis data of the European Centre for Medium-Range Weather Forecasts describing the boundary conditions.

The KDFOC3 pseudo-nuclide approach describing the released radioactivity has been applied, and the resulting gamma dose rates compared with observations. In addition, the detailed SSM nuclide vector approach has been compared with the results of KDFOC3. The overall conclusion of this study is that the parametrized decay law very accurately reproduces the total dose rate resulting from using the nuclide vector, especially between 1 and 10^4 hours after detonation.

The predicted plumes are imported to the ARGOS nuclear decision-support system for presentation and dose assessment, and optimum presentation for nuclear emergency management and decision making are considered.

Key words

nuclear emergency preparedness, atmospheric dispersion modelling, nuclear weapons, detonation, stabilized cloud, particle size distribution

NKS-512

ISBN 978-87-7893-612-7

Electronic report, February 2026

NKS Secretariat

P.O. Box 49

DK - 4000 Roskilde, Denmark

Phone +45 4677 4041

www.nks.org

e-mail nks@nks.org

DispeRSION Analysis of early nuclear WeapoN tests (DRAWN)

Report of the NKS-B DISARM activity (Contract: AFT/B(25)3)

Jens Havskov Sørensen¹ (co-ordinator)

Henrik Feddersen¹

Kristian Holten Møller¹

Magnuz Engardt²

Lennart Robertson²

Jan Pehrsson³

Henrik Roed⁴

Elias Pagh Senstius⁴

Naeem Ul Syed⁵

Anders Axelsson⁶

Jan Burman⁶

Jonas Lindgren⁶

Mikael Moring⁷

Tuomas Peltonen⁷

Mikko Voutilainen⁷

¹Danish Meteorological Institute (DMI)

²Swedish Meteorological and Hydrological Institute (SMHI)

³PDC-ARGOS

⁴Danish Emergency Management Agency (DEMA)

⁵Norwegian Radiation and Nuclear Safety Authority (DSA)

⁶Swedish Radiation Safety Authority (SSM)

⁷Radiation and Nuclear Safety Authority (STUK)

Table of contents

Introduction	5
Selected Nuclear Test Cases	6
Numerical Weather Prediction model data	7
ERA5.....	7
Harmonie.....	7
Atmospheric Dispersion Models.....	8
Danish Emergency Response Model of the Atmosphere (DERMA)	8
Description of Stabilized Cloud	9
Source Term.....	11
Application to Selected Cases.....	12
Trinity.....	13
Nancy	14
Harry	14
Smoky	15
Small Boy.....	15
Multi-scale Atmospheric Transport and Chemistry model (MATCH).....	16
Application to Selected Cases.....	16
Trinity.....	17
Nancy	19
Harry	20
Smoky	23
Small Boy.....	25
Dose rate calculation using the KDFOC3 method compared to a nuclide-vector approach	27
Description of the nuclide vector	27
Description of the KDFOC3 approach.....	27
Comparison of the results from the two methods	27
Observations.....	28
Nuclear Decision-Support System ARGOS.....	30
Vertical Distribution.....	31
Dose calculation in ARGOS for pseudo nuclides	32
Decay calculation	32
Dose calculation.....	33

Integration Time.....	33
Gamma Dose from (deposition on) Ground.....	34
Validation against radiological data.....	35
Trinity.....	35
Nancy.....	36
Harry.....	37
Smoky.....	38
Small Boy.....	39
Comparison of DERMA model results to measurements.....	40
Summary, Conclusions, and Outlook.....	43
References.....	44
Appendix A – DERMA modelled deposition patterns 48 hours post detonation.....	49
Trinity.....	49
Nancy.....	49
Harry.....	50
Smoky.....	50
Small Boy.....	51
Appendix B – DERMA-modelled puff-center locations at selected times.....	52
Trinity.....	52
Nancy.....	53
Harry.....	53
Smoky.....	54
Small Boy.....	54

Introduction

The current geopolitical situation involves an increased risk for use of nuclear weapons. Detonation of such weapons implies atmospheric dispersion of radioactivity posing a risk to the public also at longer distances from the detonation. Thus, there is a need for developing new, or improving existing, prediction model tools for such events aiming at enhanced civil protection.

The model systems describe the initial spatial distribution of radioactive matter, when stabilization has occurred around ten minutes after detonation, as observed in the field. This effective initial spatial distribution is taken over by an operational atmospheric dispersion model, which will have to be further developed in order to comply with such description.

The atmospheric dispersion model which can be based on existing descriptions, e.g. the KDFOC3 approach by Harvey *et al.* (1992), are implemented on the supercomputer at the national meteorological service and interfaced with the nuclear decision-support system (DSS) in use.

In the previous NKS-B project DISARM (DISpersion of radioActivity fRom nuclear boMbs), methods have been developed for description of the initial spatial distribution of radioactive matter after the detonation of a nuclear weapon. This effective spatial distribution of the stabilized mushroom cloud is taken over by the atmospheric dispersion model which has been improved in order to comply with the description.

The objectives of DRAWN are twofold: (1) to apply and validate the methods developed in DISARM to selected atmospheric nuclear tests in the Nevada desert in the 1940s, 1950s, and early 1960s, and (2) to continue the improvement of the methods describing the mushroom cloud after stabilization.

Regarding validation, we have selected detonations of different yields and detonation heights. For each of the selected cases, the non-hydrostatic Harmonie numerical weather prediction (NWP) model has been set up and run at high resolution using ERA5 reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) to describe the boundary conditions. The Harmonie model was set up on a supercomputer for a geographic domain of sufficient size to represent the dispersion of the radioactive plume.

In DRAWN, deterministic model simulations have been performed with the DERMA and MATCH models for the nuclear tests of Trinity (1945), Nancy (1953), Harry (1953), Smoky (1957), and Small Boy (1962). The simulations have been performed with both Harmonie and ERA5 meteorological data.

The KDFOC3 pseudo-nuclide approach describing the released radioactivity (Harvey *et al.*, 1992) has been applied, and the resulting gamma dose rates are compared with observations. In addition, a detailed nuclide vector approach has been examined and compared with the results of KDFOC3.

The predicted plumes, both deterministic and using ensemble-statistical methods, are imported to the ARGOS nuclear decision-support system (DSS) for presentation and dose

assessment, and optimum presentation for nuclear emergency management and decision making are considered.

As a continuation of the work initiated and carried out in the DISARM project, the updated implementation of KDFOC3 will be evaluated against the cases that are behind the formulations from the beginning.

Collaboration has taken place with the ongoing project PREDICT (imPRovements in atmospheric dispErSION moDelling and proteCTive action strategies in case of nuclear detonation) in the EU PIANOFORTE programme such that there will be no duplication of efforts, and the two projects will exchange information and data, and they will complement each other.

Selected Nuclear Test Cases

Five historical nuclear weapon detonation tests from the Western US in the period 1945–1962 have been selected for the comparison between simulations and measurements. For this project, we chose the same cases as chosen for the PIANOFORTE project PREDICT (ImPRovements in atmospheric dispErSION moDelling and proteCTive action strategies in case of nuclear detonations) to enhance the synergy between the two projects. The five selected cases are given in Table 1. The cases were selected to encompass different yields ranging from 1.65 kT to 44 kT and different points in time from 1945 to 1962. Additionally, the cases were chosen based on the availability of detailed measurements. All five detonations occurred with nuclear devices affixed to a tower in relative proximity to the ground with heights ranging from 3 m to 210 m.

Table 1 Data for the five historical nuclear detonation tests studied here. Names in bold are the ones that will be used throughout this study.

Name [Reference]	Time of detonation	Location	Yield (kT equivalent)	Tower height (m, converted)
Trinity [Quinn, 1987]	July 16 1945, 12.30 UTC	33° 40' 31" N, 106° 28' 29" W	21	30
Upshot-Knothole 2 (Nancy) [Steadman et al., 1984]	March 24 1953, 13.10 UTC	37° 5' 44" N, 116° 06' 10" W	24	91
Upshot-Knothole 9 (Harry) [Quinn et al., 1981]	May 19 1953, 12.05 UTC	37° 02' 25" N, 116° 01' 31" W	32	91
Plumbbob Smoky [Quinn et al., 1982]	August 31 1957, 12.30 UTC	37° 11' 14" N, 116° 04' 04" W	44	210
Dominic II/Sunbeam Small Boy [Quinn et al., 1984]	July 14 1962, 18.30 UTC	36° 48' 09" N, 115° 55' 59" W	1.65*	3

* Unverified value. Reported as “low range yield” by Quinn et al. (1984). Modelled as 1.65 kT throughout this work.

Numerical Weather Prediction model data

The atmospheric dispersion modelling for the five selected cases was carried out using forcings from both the ERA5 numerical weather prediction model reanalysis (Hersbach et al., 2003) and from high-resolution non-hydrostatic Harmonie data (Bengtsson et al., 2017). The Harmonie model was set up and run for the selected cases using ERA5 reanalysis data acquired from ECMWF as part of this project using ERA5 for the boundary conditions. Table 2 summarizes selected key differences between the two forecast models with details given in the subsequent sections.

Table 2 Key differences between the ERA5 and Harmonie forecasts used as forcing data in this study.

	ERA5	Harmonie
Model physics	Hydrostatic	Non-hydrostatic
Horizontal resolution	31 km (0.25°)	2 km (0.018°)
Vertical layers	137	90
Area	Global Model*	Limited-Area Model (LAM) 2400 km x 2400 km (1200 x 1200 points) centred around detonation site
Model time step	12 minutes	60 seconds
Data assimilation	Yes	No (but using ERA5 with data assimilation as boundaries)

*A unique 713 km × 527 km area is extracted here for modelling the Trinity case, while the remaining four cases are modelled using the same 744 km × 620 km extracted area.

ERA5

ERA5 is the fifth generation of global NWP reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and spans the period from 1940 to today (Hersbach et al., 2003; ERA5). The ERA5 reanalysis is based on cycle CY41R2 of the ECMWF Integrated Forecast System (IFS) using 137 vertical levels and 31 km (0.25°) horizontal resolution. The IFS model is hydrostatic. The forecast uses 4D-Var data assimilation every 12 hours (06 and 18 UTC) by merging of the existing calculated model state and available observations. The subsequent forecast has a 12-minute internal time step and output is produced with hourly resolution.

Harmonie

To improve the meteorological forcings for the dispersion models and assess the effect of the differences, high-resolution Limited-Area Model (LAM), non-hydrostatic Harmonie forecasts (Bengtsson et al., 2017) were carried out for all five cases as part of this study. The Harmonie forecasts were done on the ATOS Bologna HPC using Harmonie cycle 43h22. For each of the five cases, seven days of spin-up was used prior to the time of detonation to ensure correct initialization, and the forecast was continued for three days past the detonation. As opposed to the global IFS model, the Harmonie model is a Limited-Area Model, modelling only for a selected area, which allows for much higher resolution in the area of interest. For the runs conducted here, a horizontal resolution of 2 km (0.018°) was used covering an area of 1200 × 1200 points centred near the detonation site. The Harmonie runs done here use data from the ERA5 reforecast as boundary conditions and was run without internal data assimilation. The internal model time step was 60 s and, as for ERA5, output was produced every hour. For the Harmonie forecasting, 90 vertical levels were used.

Atmospheric Dispersion Models

Danish Emergency Response Model of the Atmosphere (DERMA)

The Danish Emergency Response Model of the Atmosphere (DERMA) (Tølløse and Sørensen, 2025, 2022; Tølløse *et al.*, 2021; Sørensen *et al.*, 2007; Sørensen, 1998) is a comprehensive numerical regional and meso-scale atmospheric dispersion model developed at the Danish Meteorological Institute (DMI). The model is used operationally for the Danish nuclear emergency preparedness, for which the Danish Emergency Management Agency (DEMA) is responsible (Hoe *et al.*, 2002). The model is also employed for veterinary emergency preparedness (Sørensen *et al.*, 2000; 2001; Mikkelsen *et al.*, 2003; Gloster *et al.*, 2010a; 2010b), where it is used for assessment of airborne spread of animal diseases, e.g. foot-and-mouth disease. DERMA may also be used to simulate atmospheric dispersion of chemical substances, biological warfare agents and ashes from volcanic eruptions, and it has been employed for probabilistic nuclear risk assessment for nuclear reactor accidents (Lauritzen *et al.*, 2006; 2007; Baklanov *et al.*, 2003; Mahura *et al.*, 2003; 2005).

The main objective of DERMA is to predict the dispersion of a radioactive plume and the accompanied deposition. However, the model may also be used in situations where increased levels of radioactivity have been measured but no information is available on a radioactive release. In such cases, inverse (adjoint) modelling may be applied whereby potential sources of radioactivity may be localised and release rates estimated.

The three-dimensional model is of Lagrangian type making use of a hybrid stochastic particle-puff diffusion description, and it is currently capable of describing plumes at downwind distances up to the global scale (Sørensen *et al.*, 1998). The model utilizes aerosol size dependent dry and wet deposition parameterisations as described by Baklanov and Sørensen (2001). The current version of the DERMA model does not include the effect of gravitational settling. For nuclear detonations, the vast energy released imply that large particles may reach high altitudes, e.g. in the stratosphere, as a result of the detonation. These particles may deposit several hundred kilometres from the detonation site due to the effect of gravitational settling and thus contribute substantially to gamma doses in this range. Work is underway to include gravitational settling in DERMA.

Currently, the operational version of DERMA makes use of analysed and forecasted meteorological data of various deterministic versions at DMI of the NWP model Harmonie (Bengtsson *et al.*, 2017) covering North-western Europe, Greenland and the Faeroes, and from the global model developed and operated by the European Centre for Medium-range Weather Forecasts (ECMWF).

Description of Stabilized Cloud

Because of the energy released on detonation, nuclear explosions close to the surface form characteristic mushroom shaped clouds. These clouds contain radioactive material which will be dispersed in the atmosphere. To model the atmospheric dispersion as accurately as possible, we need to be able to approximate the initial three-dimensional structure of the stabilized mushroom cloud to serve as a starting point for our atmospheric dispersion model.

The initial description of the stabilized cloud for the DERMA code is based on the “K-Division Defense Nuclear Agency Fallout Code” (KDFOC3, Harvey *et al.*, 1992). In this description, the stabilized cloud can be approximated as a cylindrical main cloud, a tapered stem and an optional cylindrical base surge, whose presence depends on the altitude of detonation. Given the yield and altitude of detonation, KDFOC3 can provide a full empirical description of the stabilized cloud. Via the decision support program ARGOS, the Danish Emergency Management Agency (DEMA) provides this input to generate the KDFOC3 description of the stabilized cloud. However, additional flexibility is built into the system to allow modifications beyond the KDFOC3 description based on e.g. observations. This includes potential gaps between the different parts of the cloud (main, stem and base surge). Additionally, the KDFOC3 description is extended to allow for free air bursts (i.e. explosions without significant interaction with the surface), which is not originally included in the description.

Based on the input from DEMA, ARGOS provides DERMA with the following nine geometrical parameters which fully describe the stabilized cloud within the implemented framework:

- Radius of the main cloud
- Altitude of the top of the main cloud
- Altitude of the bottom of the main cloud
- Altitude of the top of the stem
- Altitude of the bottom of the stem
- Radius of the top of the stem
- Radius of the bottom of the stem
- Height of the base surge (if present)
- Radius of the base surge (if present)

In addition, ARGOS provides the following required for modelling of the initial state:

- Latitude and longitude of detonation
- Time of formation of the stabilized cloud (postulated to be 10 minutes after detonation)
- Source term specifying the (pseudo)nuclides and activity

For the dispersion modelling, the stabilized cloud is described by a set of identical spheroids distributed in three-dimensional space. Initially, based on the geometrical parameters received, a two-dimensional structure of the cloud is generated showing the radius of the cloud as a function of altitude, Figure 1. Radii smaller than the spheroid radius are modelled as the spheroid radius. This continuous description is discretized by dividing the structure into

a number of vertical layers, each with a fixed separation of 20 m. In each vertical layer, the spheroids are distributed based on closest packing to best reproduce the radius of the cloud at the given altitude, Figure 2. Each alternating layer is rotated by 30 degrees relative to each other to better represent the overall circular geometry. The centres of neighbouring spheroids in the same layer are separated by a horizontal distance related to the grid size of the meteorological model used for the simulation and thus varies from model to model.

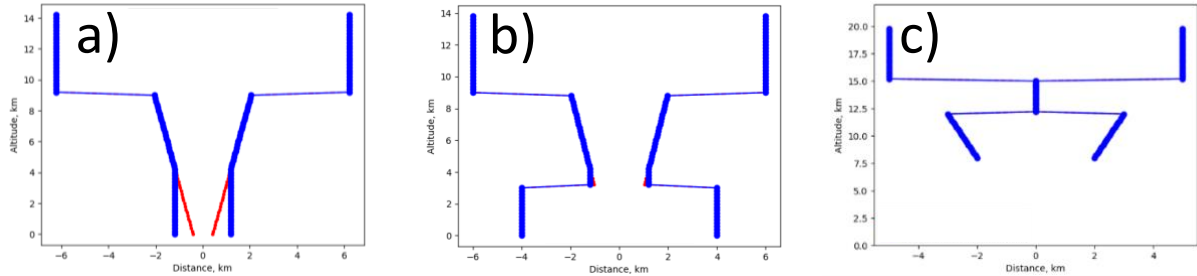


Figure 1. Illustration of the altitude-radius structure of three modelled clouds: a) the KDFOC3 description of the stabilized cloud from detonation of a 100 kt nuclear device, b) a comparable cloud but including a base surge, and c) a non-continuous cloud not reaching the surface representing a free air burst. Red shows the KDFOC3 calculated radius, and blue the actually modelled radius which is limited by the spheroid radius.

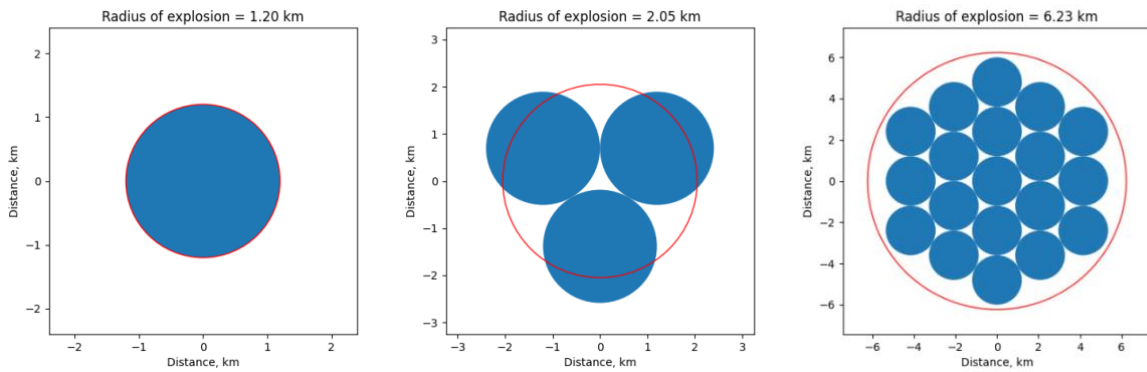


Figure 2. Examples of the closest packing of circles in the bottom of the stem (left), the top of the stem (middle) and the main cloud (right) of the mushroom cloud shown in panel a) of Figure 1.

The total activity is distributed vertically in the cloud according to Rolph *et al.* (2014), based on Heffter (1969). Specifically, the stem and main cloud are each divided into three parts, each part containing a fixed amount of the total activity. From the bottom-up, this distribution is [2.5, 5, 15, 30, 30, 17.5]%. Within each of these six sections of the cloud, the activity is distributed evenly between all puffs, translating to a homogeneous distribution horizontally, cf. Figure 3 and Figure 4.

If a base surge is present, this is given a fixed fraction of the total activity of 20% (Knox, 1964). For free air bursts without stems and base surges, the activity is distributed evenly in the whole cloud.

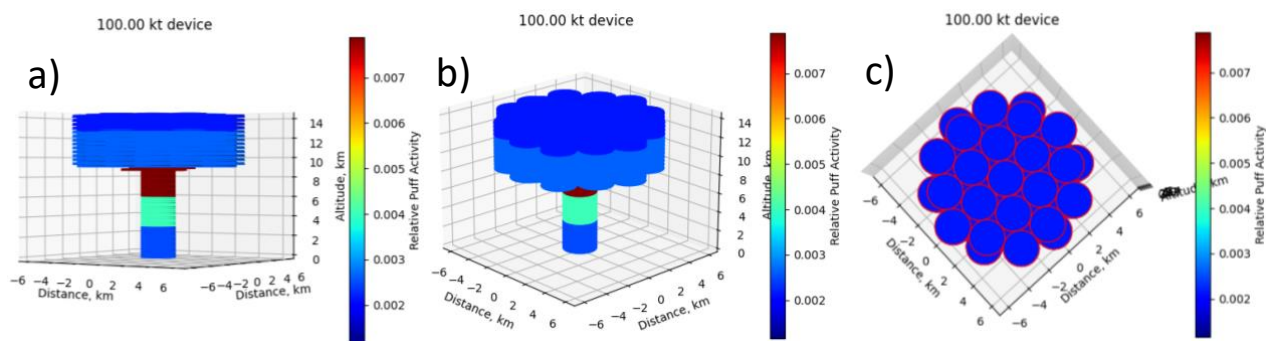


Figure 3 Different views of the three-dimensional structure of cloud a) in Figure 1. Illustration of the altitude-radius structure of three modelled clouds: a) the KDFOC3 description of the stabilized cloud from detonation of a 100 kt nuclear device, b) a comparable cloud but including a base surge, and c) a non-continuous cloud not reaching the surface representing a free air burst. Red shows the KDFOC3 calculated radius, and blue the actually modelled radius which is limited by the spheroid radius.. For the top view, c), the spheroids are outlined in red for visual clarity. Each spheroid is represented as a cylinder of uniform activity for this visualization.

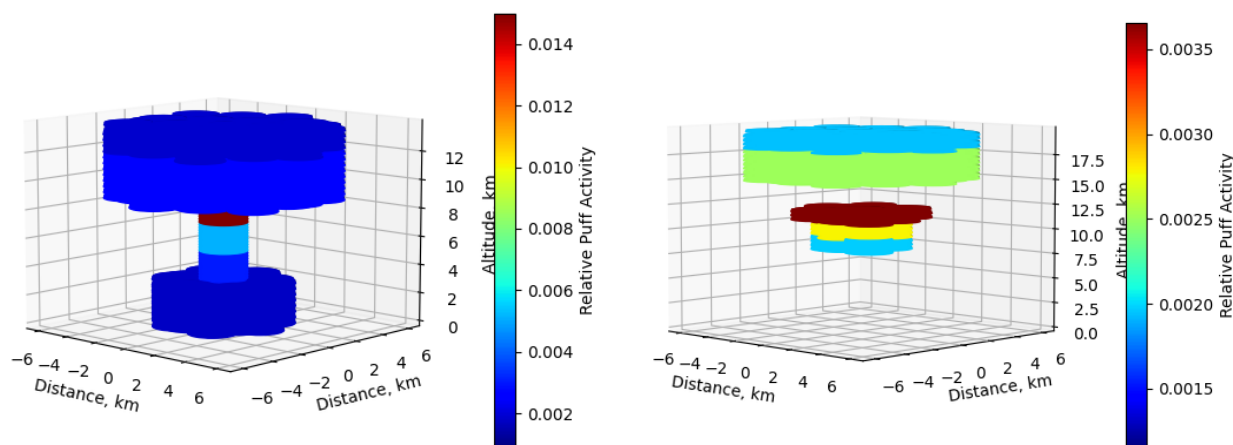


Figure 4 Three dimensional structures of the clouds b) and c) in Figure 1. Illustration of the altitude-radius structure of three modelled clouds: a) the KDFOC3 description of the stabilized cloud from detonation of a 100 kt nuclear device, b) a comparable cloud but including a base surge, and c) a non-continuous cloud not reaching the surface representing a free air burst. Red shows the KDFOC3 calculated radius, and blue the actually modelled radius which is limited by the spheroid radius.

Source Term

The isotopic composition of the radioactive material released during a nuclear detonation is highly complex involving decay chains and rapidly changing (Kraus et al. 2014). Instead, as is done by e.g. DERMA, the emission from the nuclear device can be modelled by the KDFOC3 approach (Harvey *et al.*, 1992) with a single non-decaying pseudo-nuclide labelled Ps-1. The pseudo-nuclide can be considered a tracer for the activity from which the actual doses can subsequently be calculated using empirical relations. In this report, we present the activity of the pseudo-nuclide with a unit of pseudo-Becquerels (pBq) to distinguish it from an actual activity.

Application to Selected Cases

The figures below show the output from DERMA when run using both ERA5 and Harmonie forcings for the five selected cases (Table 1) at 12 hours post detonation. The calculated total deposition is converted from pBq/m² to ground gamma dose rates in ARGOS. Finally, the units of Sievert/hour (Sv/h) are converted to milliRöntgen/hour (mR/h) using a conversion factor of 115 mR/Sv. For all figures, the same range of 10⁻² to 10³ mR/h is shown on a logarithmic scale. For each set of figures, the same geographical extent is shown to allow direct comparison.

The DERMA output based on the two different NWP models agree on the overall large-scale result for all five cases. This is expected, as both are modern NWP models with a good ability to predict and describe the weather. Additionally, as the Harmonie runs use the ERA5 data for its boundary conditions, and therefore it is naturally informed by the ERA5 model.

However, despite the overall agreement, the results are quite different, most notably in the resolution of the ground gamma dose rates. While DERMA is a Lagrangian model and thus internally independent of the grid of the NWP data, it has the convention of providing output on the same grid as the input NWP data, to illustrate to the user the accuracy of the underlying forcing data. This is very clear when comparing the model runs based on ERA5 and Harmonie. The difference in resolution between the two NWP models used as input to DERMA is about a factor of 15 (see Table 2) and thus the model output based on Harmonie has significantly more fine structure when compared to the output based on ERA5. An additional effect contributing to this is that the initial size of the puffs is governed by the resolution of the NWP grid, so each puff is also much larger initially for the ERA5-based model runs. Naturally, the much higher-resolution output based on Harmonie data shows a lot of fine structure which is not possible with the coarser ERA5-based runs. However, given the uncertainty in the NWP forecasts, the details of this fine structure is not expected to be exact. In the next phase of the DRAWN project, the effects of the inherent meteorological uncertainties on the calculated gamma doses will be quantitatively assessed.

In addition to the differences resulting from the differences in resolution, other more important differences can be seen in the geographical extent of the deposition 12 hours after detonation. Most noticeable for the Nancy test case, the area affected by the detonation is significantly larger for the model run on Harmonie data. Given the short-lived nature of the stabilized mushroom cloud, the dispersion is very sensitive to the uncertainties of the meteorological conditions at the time of detonation as also found by the comparison between different NWP ensemble members in the NKS-B project DISARM (Sørensen et al., 2025). Also, the Smoky and Harry results show larger extent of the deposition for the Harmonie case as opposed to the ERA5-based runs.

Figure 36-Figure 40 show the deposition from the DERMA Harmonie runs 48 hours post detonation.

Trinity

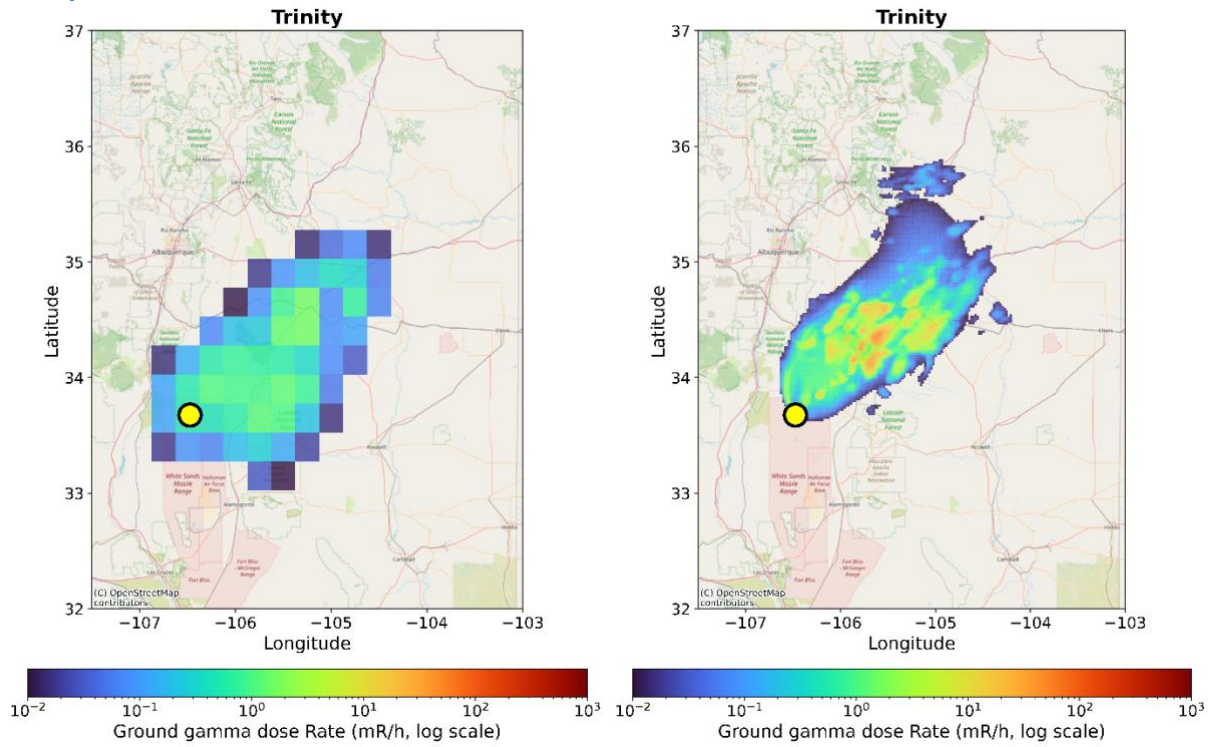


Figure 5 Modelled ground gamma dose rate (mR/h) 12 hours post detonation for the Trinity experiment based on DERMA modelling using ERA5 (left) and Harmonie (right) forcing data.

Nancy

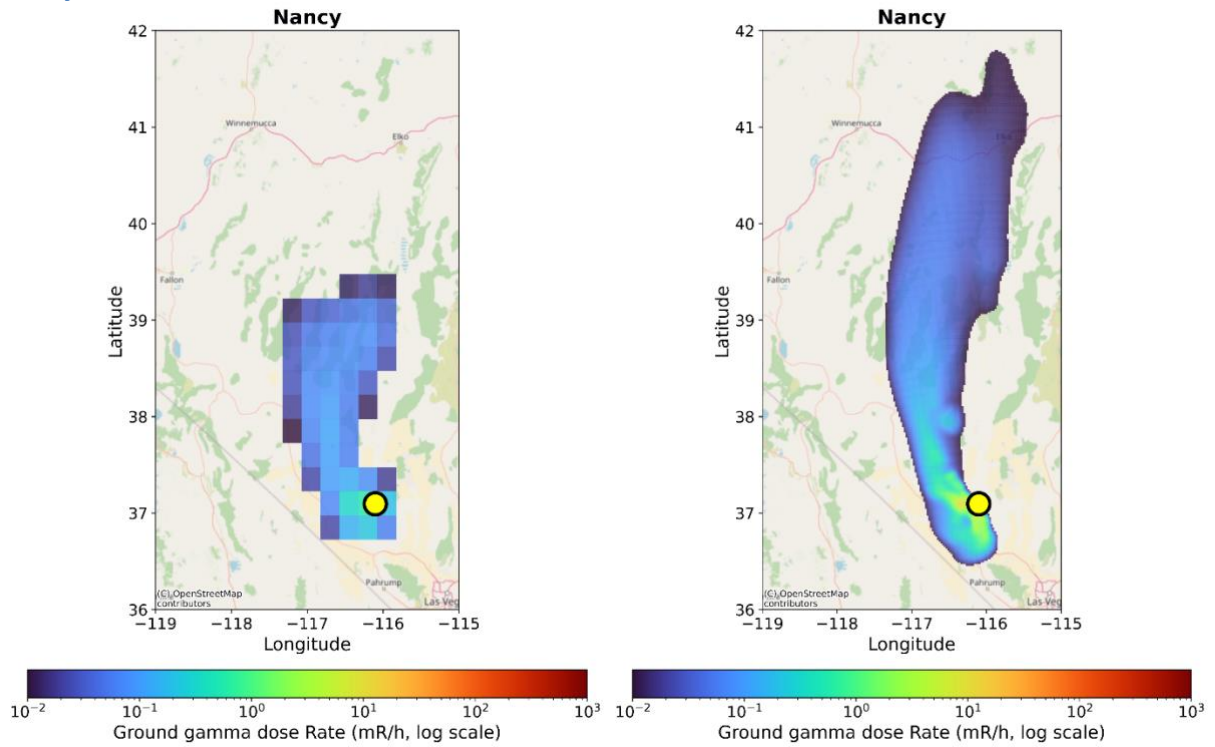


Figure 6 Modelled ground gamma dose rate (mR/h) 12 hours post detonation for the Nancy experiment based on DERMA modelling using ERA5 (left) and Harmonie (right) forcing data.

Harry

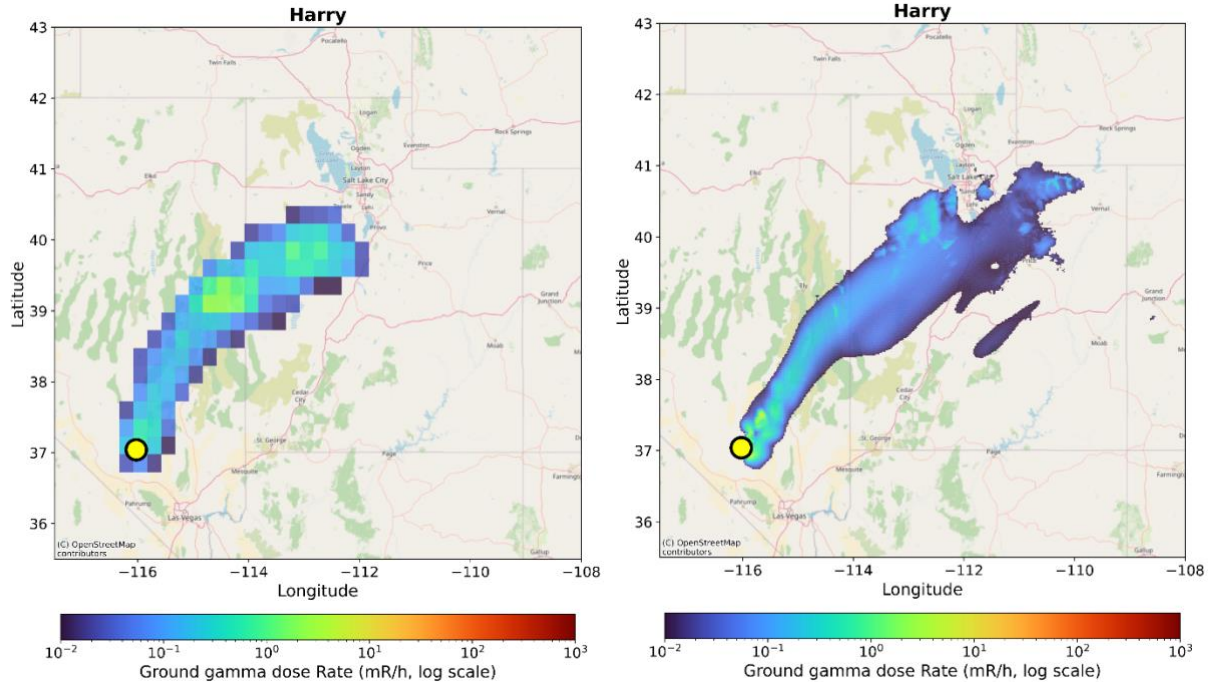


Figure 7 Modelled ground gamma dose rate (mR/h) 12 hours post detonation for the Harry experiment based on DERMA modelling using ERA5 (left) and Harmonie (right) forcing data.

Smoky

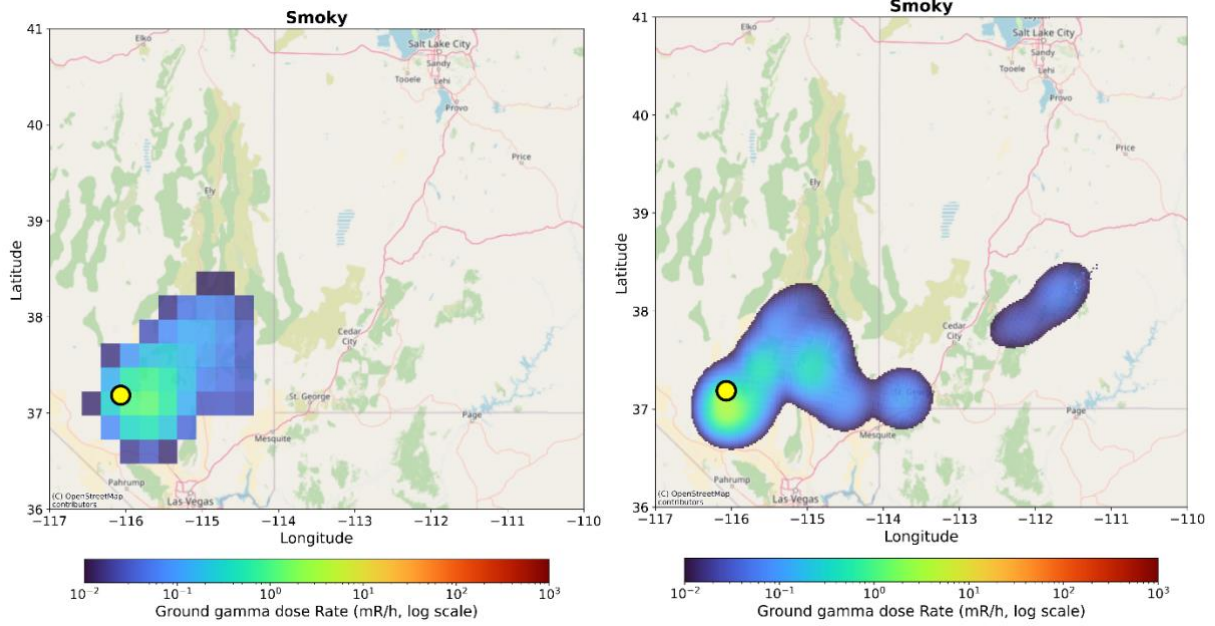


Figure 8 Modelled ground gamma dose rate (mR/h) 12 hours post detonation for the Smoky experiment based on DERMA modelling using ERA5 (left) and Harmonic (right) forcing data.

Small Boy

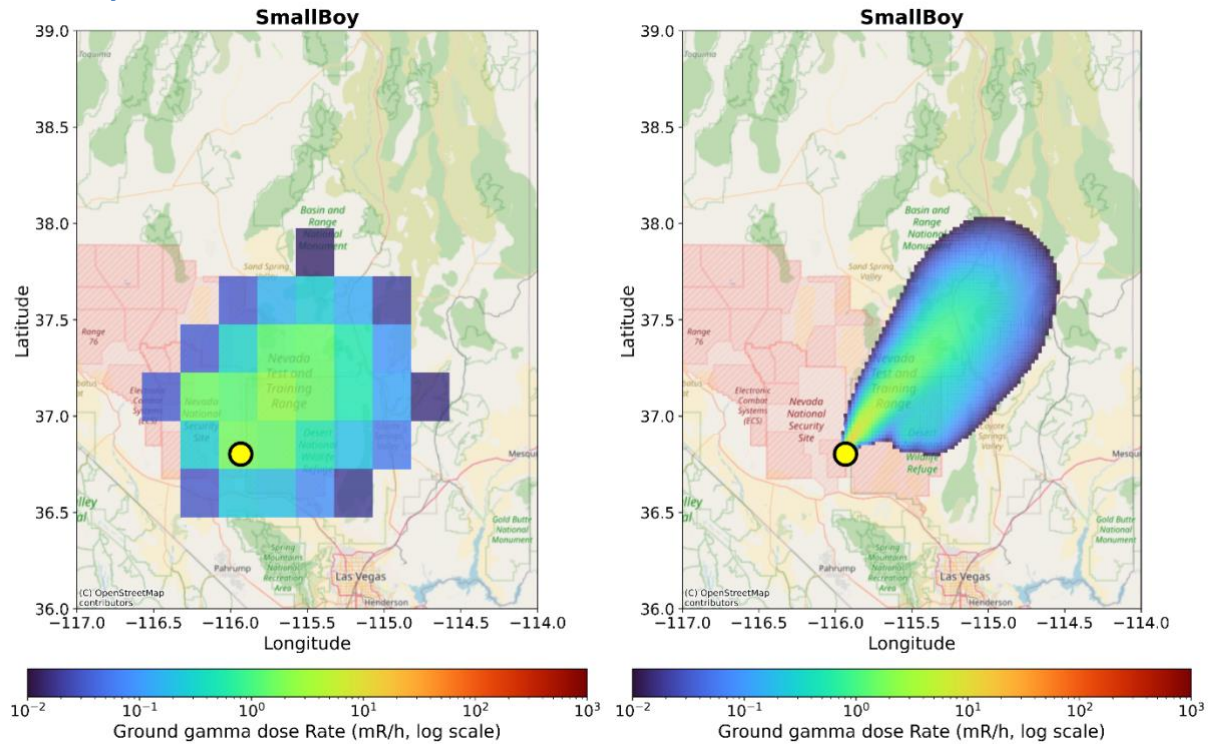


Figure 9 Modelled ground gamma dose rate (mR/h) 12 hours post detonation for the Small Boy experiment based on DERMA modelling using ERA5 (left) and Harmonic (right) forcing data.

Multi-scale Atmospheric Transport and Chemistry model (MATCH)

The Multi-scale Atmospheric Transport and Chemistry model (MATCH) (Robertson *et al.*, 1999) is multi-purpose Eulerian chemical transport model (CTM) developed by the SMHI. The model is used for emergency applications such as nuclear and natural events (volcanoes), aerosol dynamics and optics (Andersson *et al.*, 2015), complex chemistry, and data assimilation (Robertson and Langner, 1998; Kahnert, 2008; Kahnert, 2018). The MATCH model is used operationally for chemical forecasts in CAMS (Copernicus Atmospheric Monitoring Service) and for SSM (Swedish Radiation Safety Authority) serving the ARGOS system needs (Hoe *et al.*, 1999; 2002). Other applications are studies for air quality and health issues in climate projections. In most applications MATCH is used as a limited-area model on various possible scales, but also for global applications.

The MATCH model is basically an Eulerian model, but for emergency preparedness and response applications a Lagrangian particle model is used in the near field of the emission location.

A wide range of possible driving meteorological data is applicable like analyses and forecasts from HARMONIE, IFS (Integrated Forecasting System) developed and run by ECMWF (European Centre for Medium-Range Weather Forecasts), and WRF (Weather Research and Forecasting).

For nuclear weapon simulations, the operational MATCH model is initialised based on KDFOC3 (Harvey *et al.*, 1992) with procedures developed at FOI. The procedures handle underground detonations, as well as upper air detonation with or without surface contact (Winter *et al.*, 2008).

Application to Selected Cases

The MATCH results are presented for each case with first a graphical description of the KDFOC stabilised cloud in terms of vertical and horizontal extent and the assumed distribution of aerosol bins for different parts of the cloud. Two runs are made for each case 1) having Harmonie meteorological data in 2.5 km resolution provided by DMI, and 2) having ERA5 data derived from ECMWF MARS system. The ERA5 model was run at 0.25 degree resolution; however, here the data have been interpolated to 0.1 degree resolution. In the cases of Harry and Smoky a tentative comparison is made from Rolph *et al.* (2014), only for the extent of the fallout region not trying to compare dose rates. The model results are presented by the temporally and vertically integrated total column of H+1, aka Ps-1, activity showing the general transport picture for all parts of the cloud in the vertical, near surface H+1 accumulated activity concentration, and H+1 accumulated activity deposition. Here, activity is expressed in pseudo-Becquerels.

The Trinity case appears to be a case with moderate wind conditions showing moderate extension of the transport. Simulations with Harmonie and ERA5 are very similar.

The Nancy case show faster transport while the main fallout remains inside the model area. The overall transport picture is the same for the two meteorological data sets. Details of mainly resolution origin are shown,

The Harry case shows a spread in a 90 degree segment where the upper layers transport is directed towards the south-east while lower layers towards east to north-east. A tentative comparison with Rolph *et al.* (2014) shows that the model fallout encloses the measured area but extends also to a larger area of fallout. The model exhibits finger like transport patterns that at first attributed to the

Lagrangian entry model. However, also a run with the entry Lagrangian model switched off (injection grid-point wise) has the similar feature even though more diffused. The different parts of the cloud in the vertical appears to be spread in various directions in a less smooth way.

The Smoky case shows also a rapid transport pattern but again the major fallout is found inside the model area. The runs using Harmonie or ERA5 meteorological data appears to be rather similar. In comparison with Rolph et al. (2014) it fits rather well while a northwards deposition area is not shown in Rolph et al. (2014).

The Small Boy case seems to be in moderate wind conditions. Although the general picture is the same using Harmonie or ERA5 weather data, there are details that differ.

In summary, the ambition to run for five nuclear test cases were challenging not the least to derive the Harmonie data for these cases. Retrieving ERA5 data only followed standard procedures and we benefit from that ERA5 re-analyses were made all the way back to 1945. Very much thanks to DMI for the effort to provide the Harmonie data at the ECMWF premisses. The benefit of having more detailed meteorology has though to be confirmed. In general, we could see that using Harmonie or ERA5 gave very much similar results but differs on details. Conclusion from the tentative comparisons for the cases of Harry and Smoky with Rolph et al. (2014) is that modelled fallout regions falls into measured fallout regions while some other fallout areas are not confirmed having Rolph et al. (2014). More detailed comparisons for dose rates and arrival times would give some hints on how well we have implemented the KDFOC description in the first place, and secondly how well the fallout processes are described. The outcome so far is that a continuation into phase 2 of DRAWN would at least not fail having the indication that our modelled fallout are right in an indicative manner.

Trinity

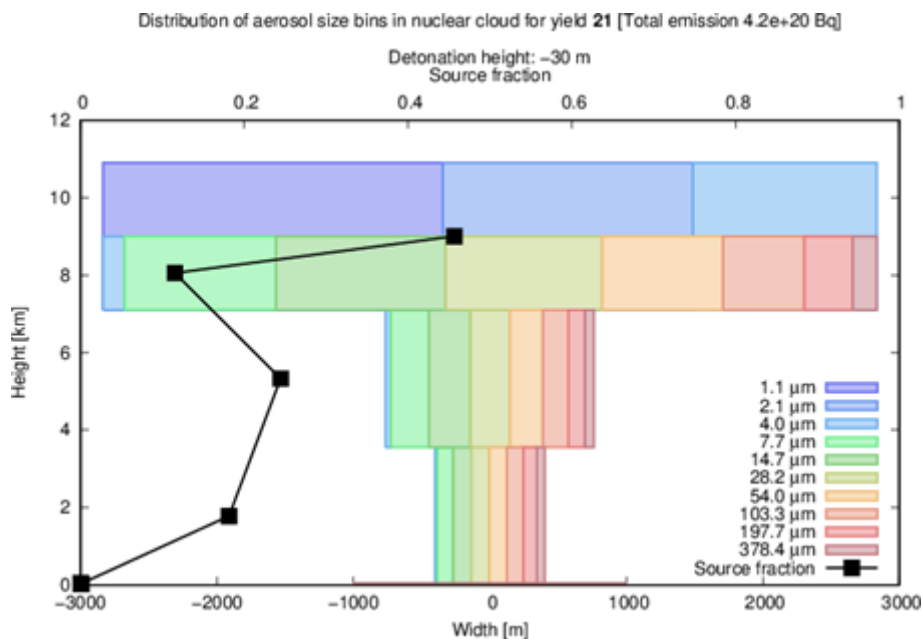


Figure 10 Vertical and horizontal extension of the stabilized cloud for the Trinity case of 21 kton yield. The distribution of aerosol bins are shown as shaded fields, and the activity of different parts of the cloud is shown as a black line.

Runs for nuclear experiment Trinity (HARMONIE) at 12:30 GMT July 16 1945
Wed 18 Jul 1945 01:00

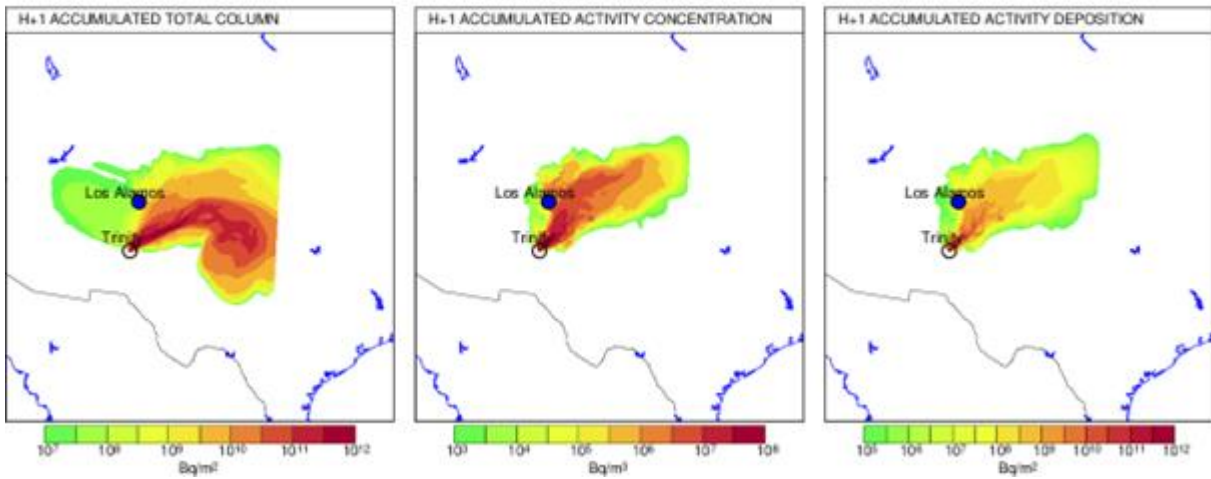


Figure 11 The Trinity case for Harmonie data. The left panel shows the H+1 total column and thus an image of the general transport, the middle panel shows the H+1 integrated activity near ground, and the right panel shows the H+1 total activity deposition.

Runs for nuclear experiment Trinity at 12:30 GMT July 16 1945
Wed 18 Jul 1945 00:00

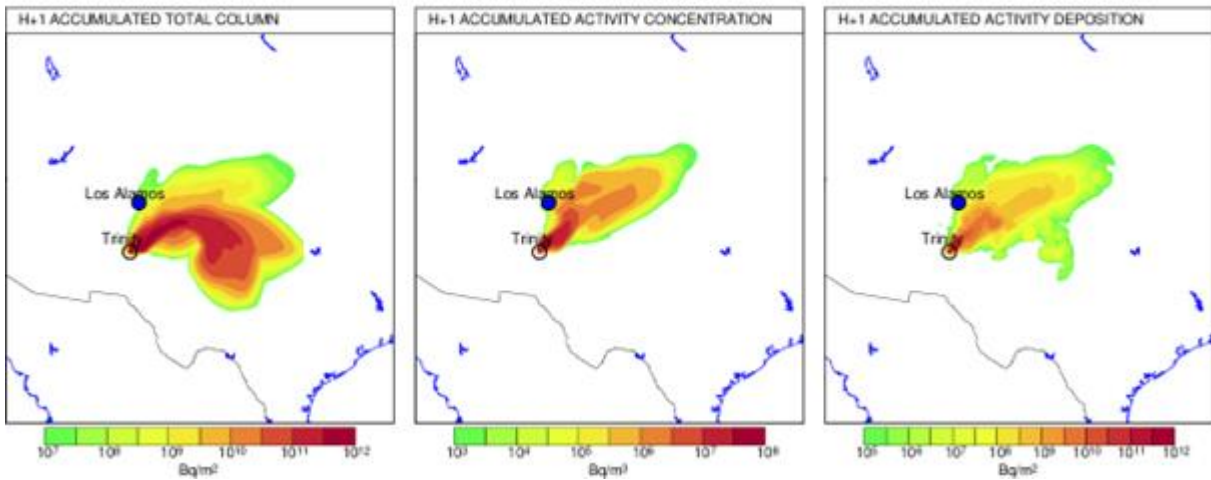


Figure 12 The Trinity case for ERA5 data. Panel description as for Figure 11.

Nancy

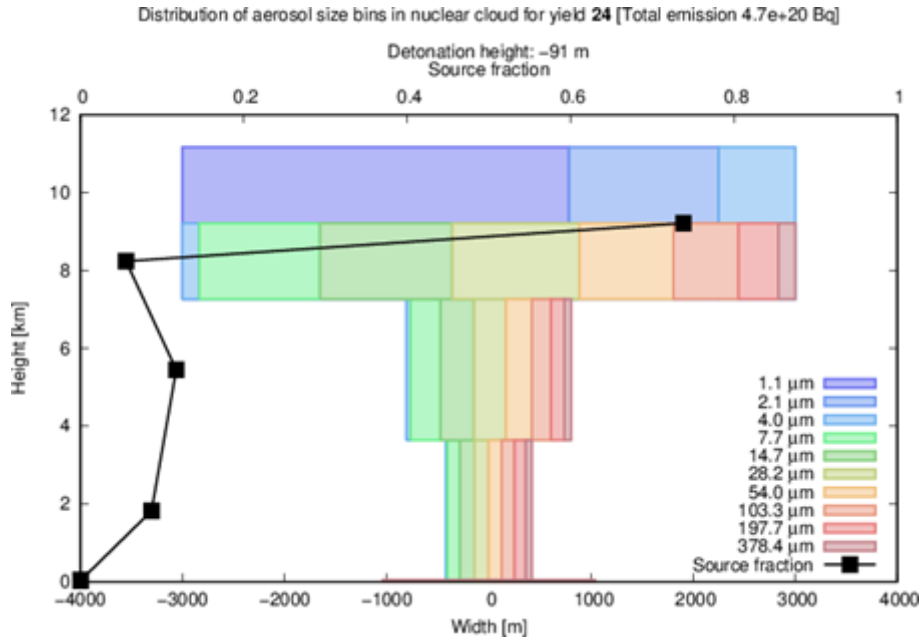


Figure 13 Vertical and horizontal extension of the stabilized cloud for the Nancy case of 24 kton yield. The distribution of aerosol bins are shown as shaded fields, and the activity of different parts of the cloud is shown as a black line.

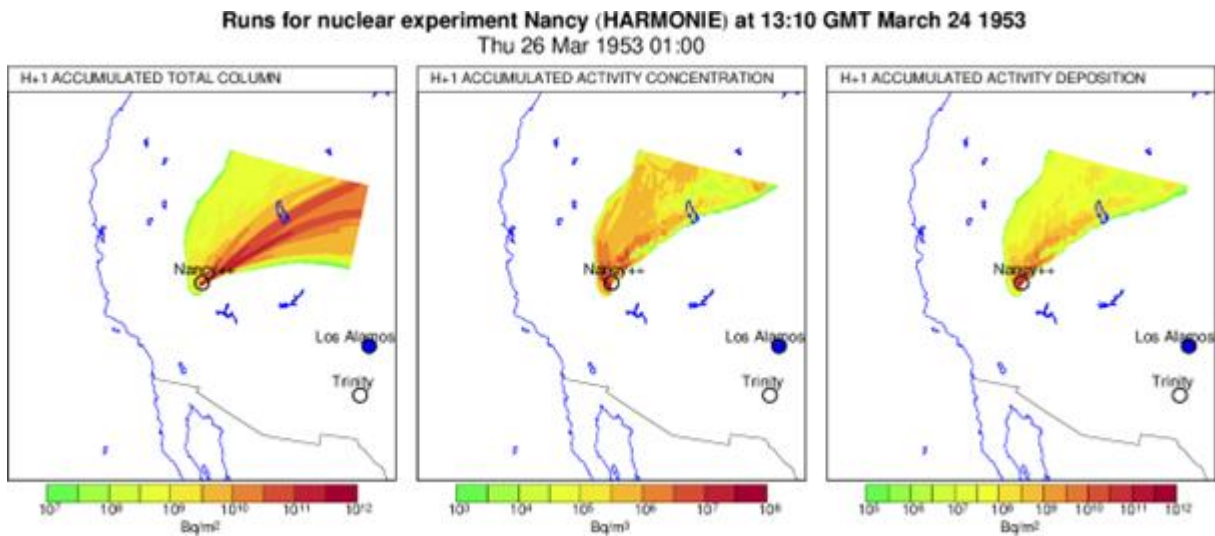


Figure 14 The Nancy case for Harmonie data. Panel description as for Figure 11.

Runs for nuclear experiment Nancy at 13:10 GMT March 24 1953
Thu 26 Mar 1953 00:00

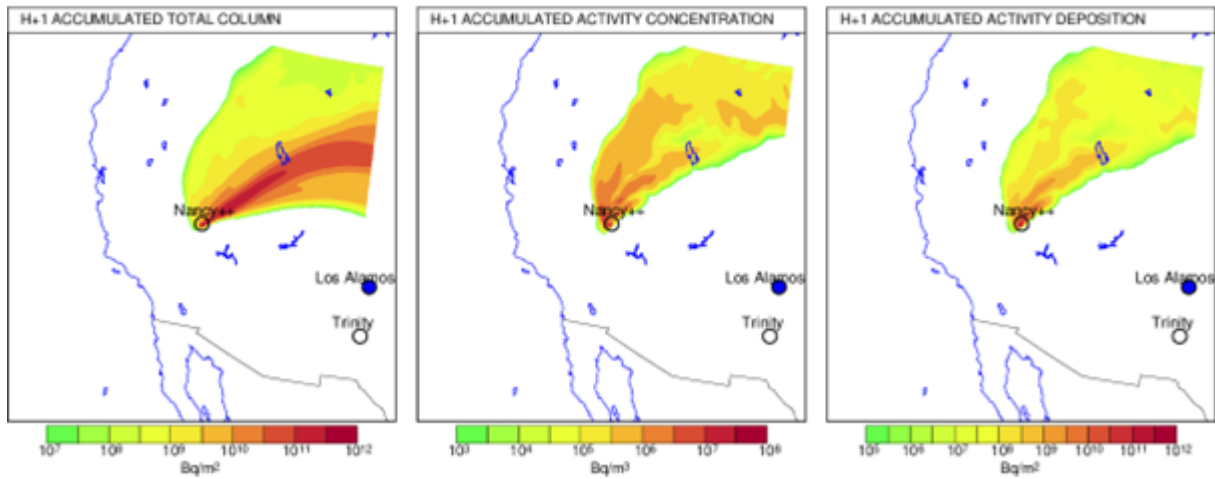


Figure 15 The Nancy case for ERA5 data. Panel description as for Figure 11.

Harry

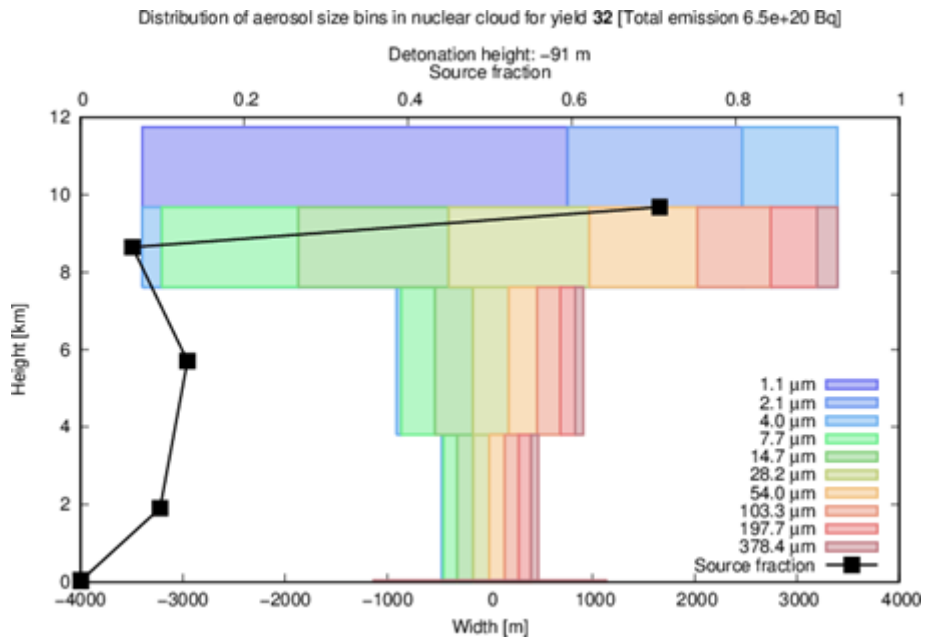


Figure 16 Vertical and horizontal extension of the stabilized cloud for the Harry case of 32 kton yield. The distribution of aerosol bins are shown as shaded fields, and the activity of different parts of the cloud is shown as a black line.

Runs for nuclear experiment Harry (HARMONIE) at 12:05 GMT May 19 1953
Thu 21 May 1953 01:00

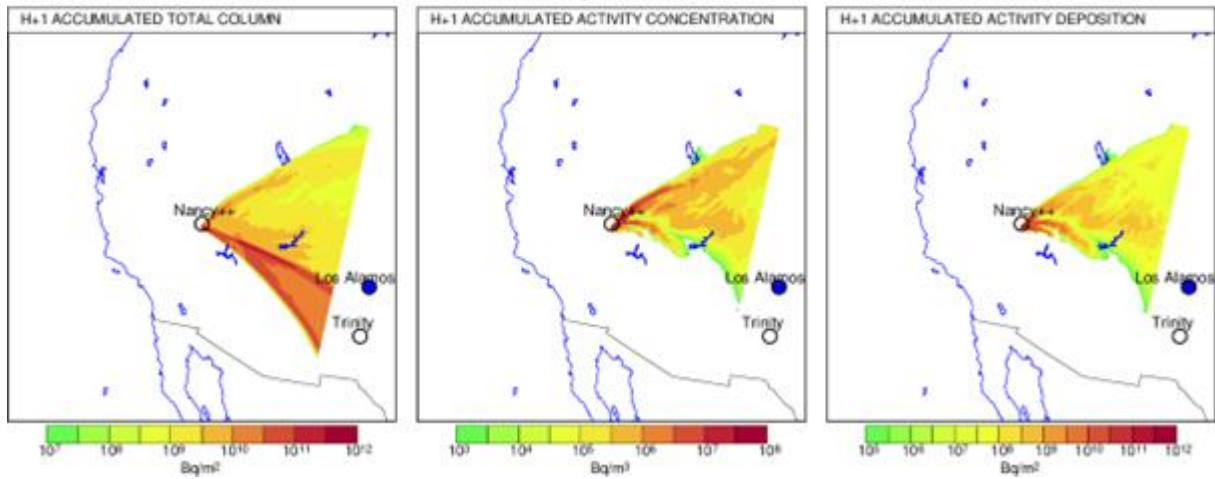


Figure 17 The Harry case for Harmonie data. Panel description as for Figure 11.

Runs for nuclear experiment Harry at 12:05 GMT May 19 1953
Thu 21 May 1953 00:00

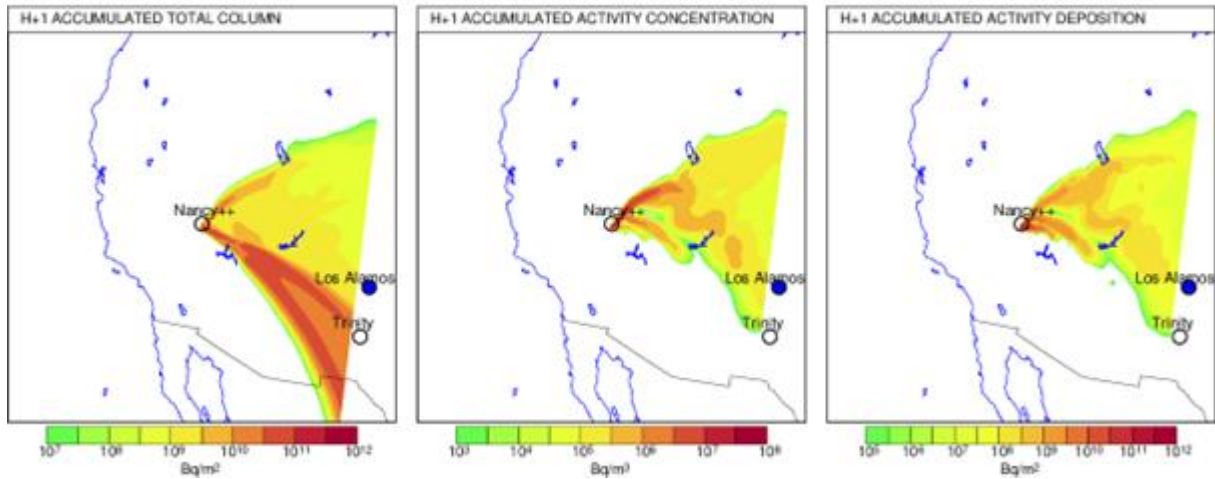


Figure 18 The Harry case for ERA5 data. Panel description as for Figure 11.

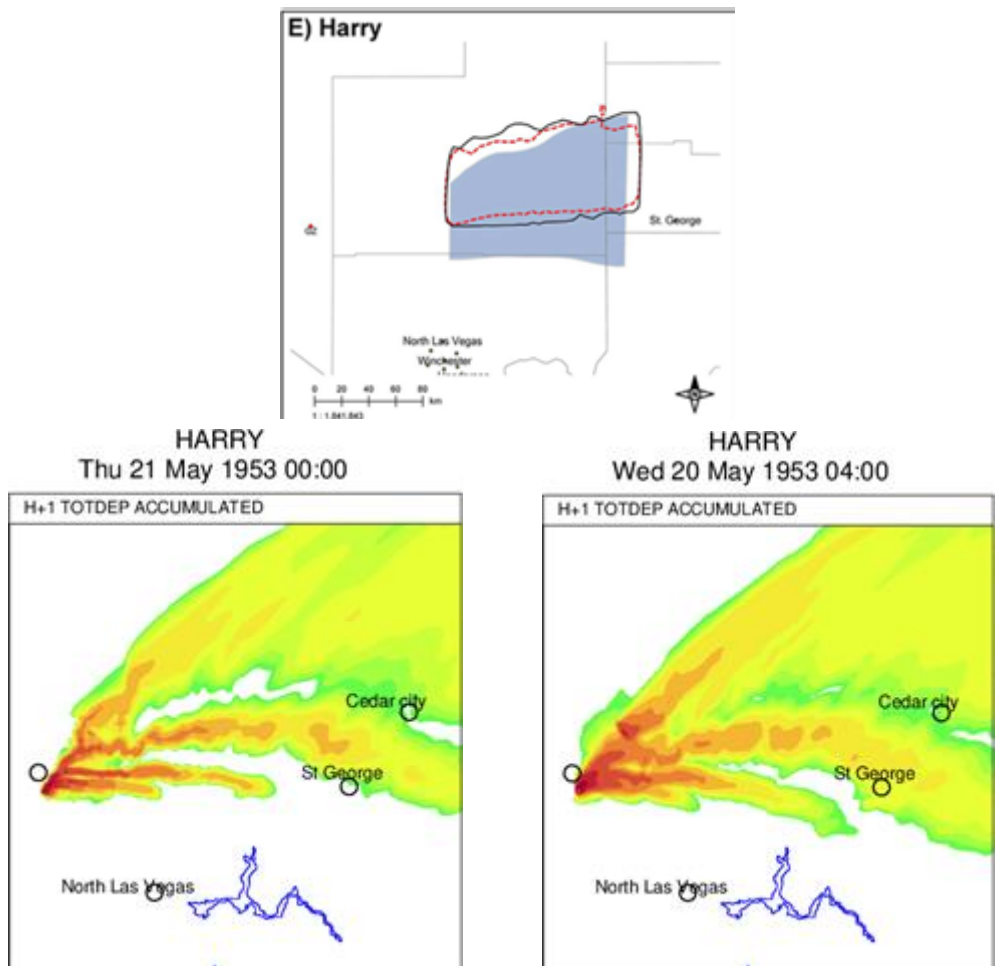


Figure 19 An attempt for verification using extension zone from Rolph et al. (2014) (top) and MATCH model with Lagrangian entry model (bottom left) and without (bottom right).

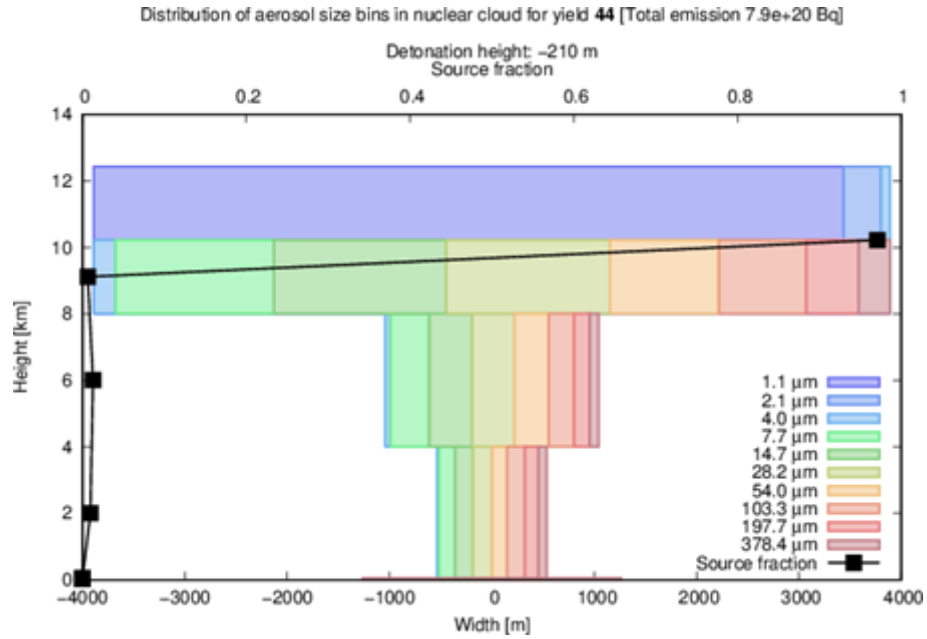


Figure 20 Vertical and horizontal extension of the stabilized cloud for the Smoky case of 44 kton yield. The distribution of aerosol bins are shown as shaded fields, and the activity of different parts of the cloud is shown as a black line.

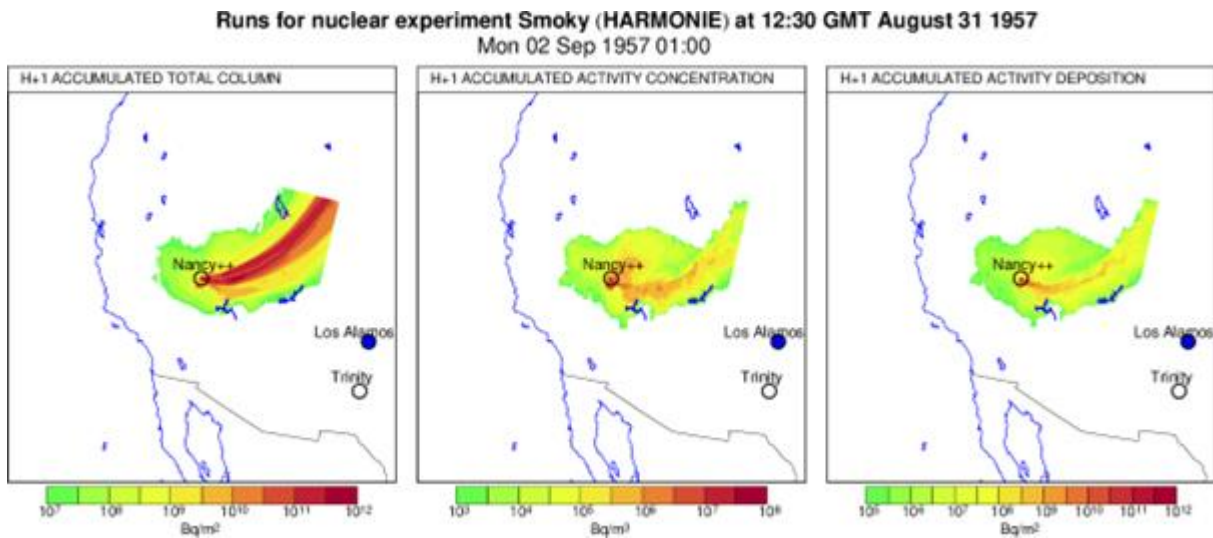


Figure 21 The Smoky case for Harmonie data. Panel description as for Figure 11.

Runs for nuclear experiment Smoky at 12:30 GMT August 31 1957
 Mon 02 Sep 1957 00:00

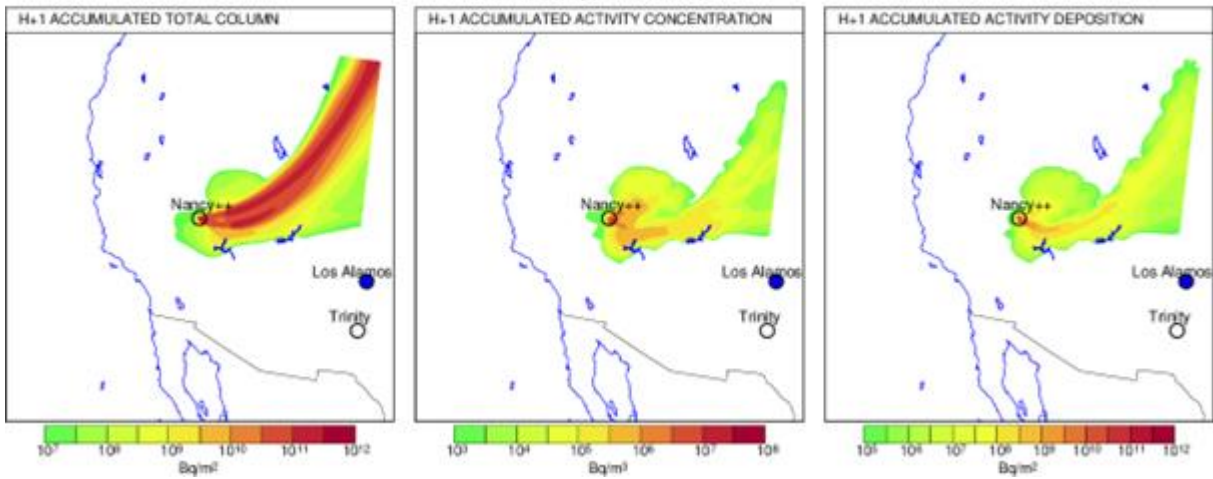


Figure 22 The Smoky case for ERA5 data. Panel description as for Figure 11.

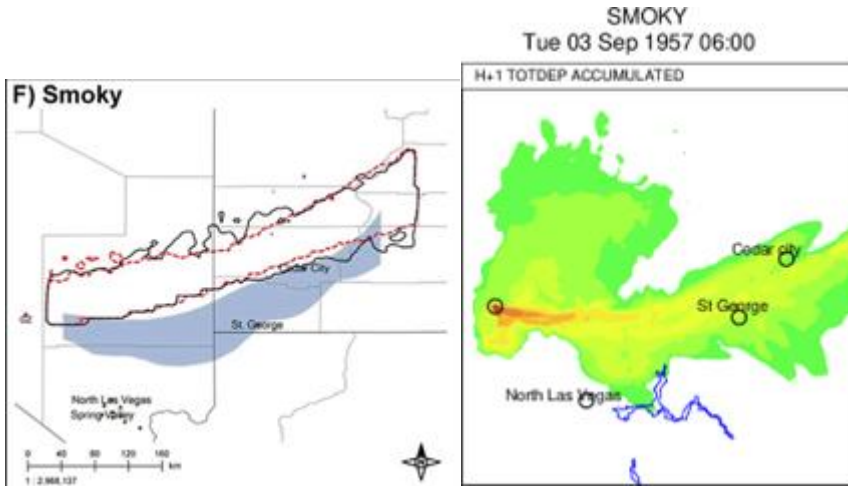


Figure 23 An attempt for verification using extension zone from Rolph et al. (2014) (left) and MATCH model using Harmonie (right).

Small Boy

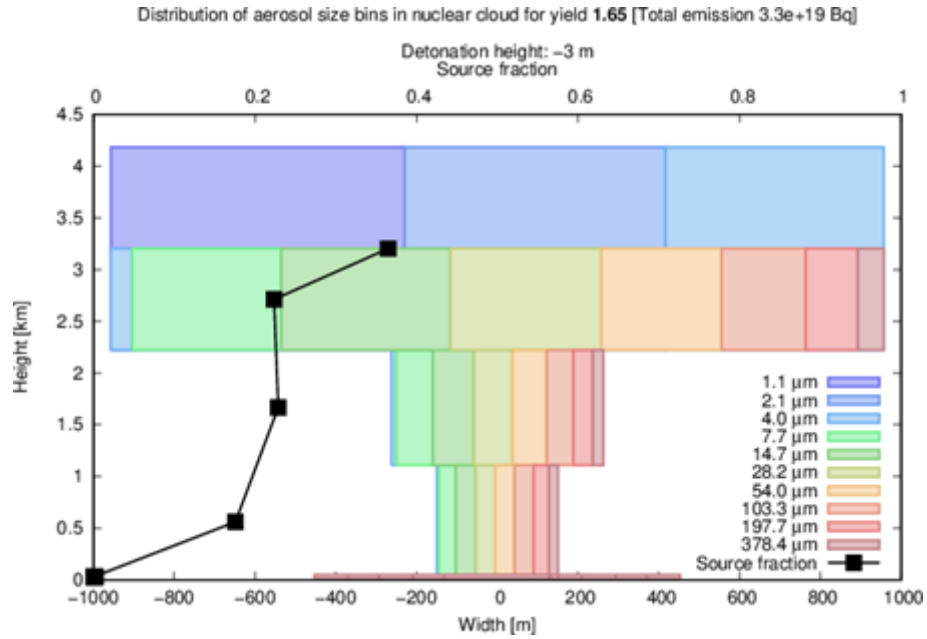


Figure 24 Vertical and horizontal extension of the stabilized cloud for the Small Boy case of 1.65 kton yield. The distribution of aerosol bins are shown as shaded fields, and the activity of different parts of the cloud is shown as a black line.

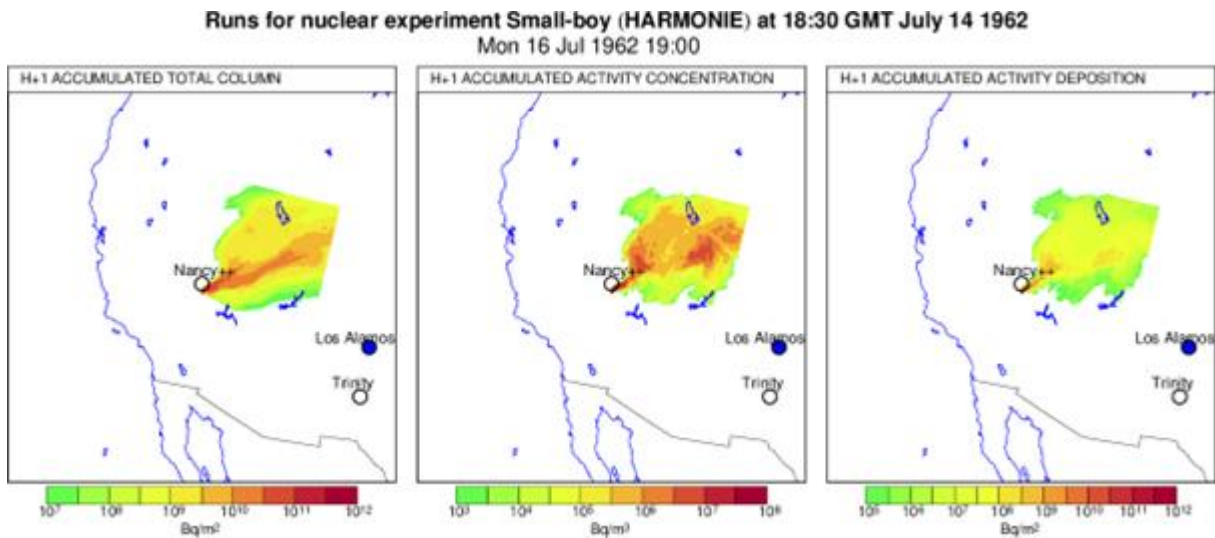


Figure 25 The Small Boy case for Harmonie data. Panel description as for Figure 11.

Runs for nuclear experiment Small-boy at 18:30 GMT July 14 1962
Mon 16 Jul 1962 18:00

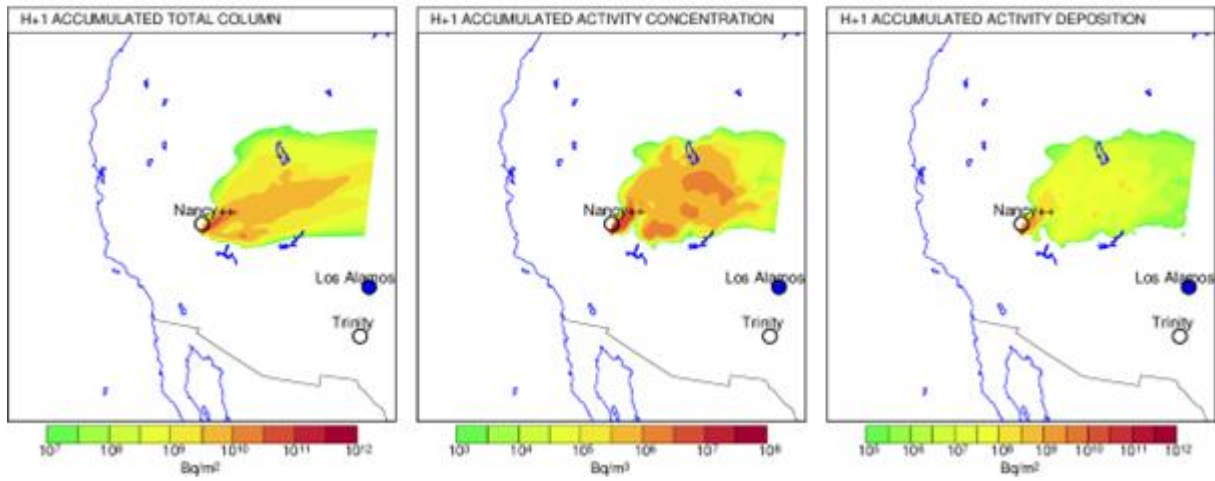


Figure 26 The Small Boy case for ERA5 data. Panel description as for Figure 11.

Dose rate calculation using the KDFOC3 method compared to a nuclide-vector approach

A comparison is made of dose-rate calculation by the nuclide-vector approach developed by the Swedish Radiation Safety Authority (SSM) (Axelsson et al., 2023) and the KDFOC3 approach (Harvey et al., 1992) estimating dose rate from deposited radioactive material.

Description of the nuclide vector

The SSM nuclide vector is a vector that is used for nuclide specific calculations relevant for estimating radiological consequences and developed for that purpose.

In the report by Axelsson et al. (2023), it is described how the vector is developed to make the effective dose estimation to be at least 95% of the effective dose from ground deposition during the first day, week, month and year respectively, after a nuclear detonation.

The development of the nuclide vector, is derived from representative reactions on U-235, Pu-239, and U-238. SSM has calculated decay and ingrowth for the initial unit vectors during 10 minutes from the time of the explosion to be used as input values in the source description. The resulting unit vectors can be scaled linearly to model fission products from the desired fission yield. More details in the references.

Description of the KDFOC3 approach

The pseudo-nuclide (H+1 or Ps-1) approach is presented in the KDFOC3 report (Harvey et al., 1992) where it is stated that “(...) it deals only with gross fission products, not individual nuclides.” Hence it uses a gross fission product decay law to calculate doses. In the KDFOC3 report, the $t^{-1.2}$ decay law is described. See also the report by Glasstone and Dolan (1977).

Comparison of the results from the two methods

Starting with the nuclide vector for fission only, the decay for each of the nuclides is calculated from 1 to 10^5 hours, using the SSM software DosCalc¹ that keeps count of the mother-daughter processes together with the emitted radiation.

In Figure 27 Dose rates from the individual nuclides (coloured curves) in the SSM nuclide vector from fission reaction, as well as their sum (dashed black curve), from 10 minutes up to 10^5 hours., the dose rate from each of the nuclides from the SSM nuclide vector is plotted. It is obvious that the decay varies a lot between the nuclides. The dashed line is the sum of the dose rate and that is what we want to compare with the $t^{-1.2}$ decay law. By using the dose rate from the nuclide vector at 1 hour after detonation, we use the same value for the one-hour value while plotting the $t^{-1.2}$ decay curve. In Figure 28, the sum of the dose rate from all the nuclides is plotted together with the curve given by the $t^{-1.2}$ decay law. The curves are quite similar between 1 hour up to 10 000 hours.

In this study only decay is observed. In a case of a nuclear detonation, fractionation would appear and to some extent separate nuclides on particles of different size which can be observed in the deposition pattern.

¹DosCalc64 is a stand-alone software used to calculate effective dose from ground shine, developed by the Swedish Radiation Safety Authority (SSM). DosCalc v 1.0 (Manual 20-914)

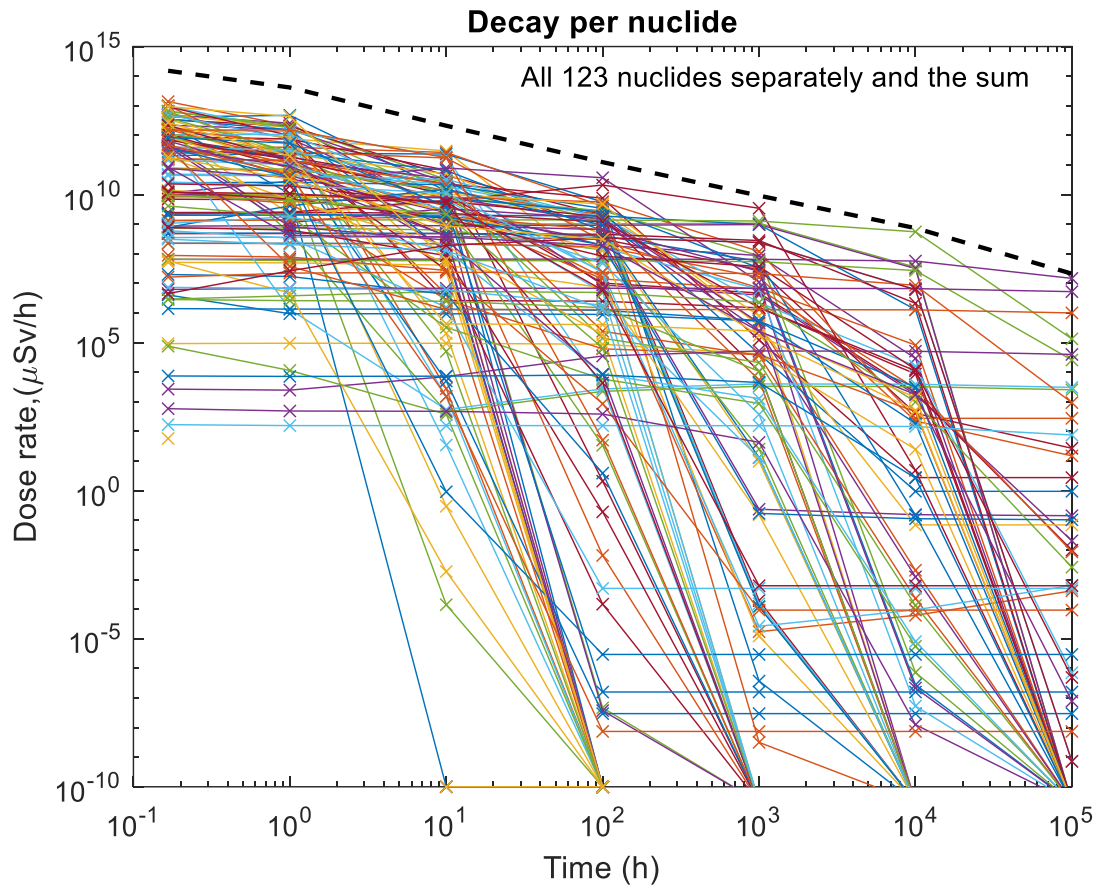


Figure 27 Dose rates from the individual nuclides (coloured curves) in the SSM nuclide vector from fission reaction, as well as their sum (dashed black curve), from 10 minutes up to 10^5 hours.

Observations

In Figure 28, a comparison is shown between the sum of dose rates from all nuclides in the SSM nuclide vector and the decay law of dose rate as presented in the KDFOC3 report. The decay curve value for dose rate is set equal to the sum of all nuclides from the SSM vector at the time 1 hour.

The two methods studied to predict dose rate over time indicate that the SSM nuclide vector here used will show much the same decay of dose rate as the $t^{-1.2}$ decay law used in the KDFOC3 model, notably between 1 and 10^4 hours. Note that fission products only are studied in this case. Especially if a scenario includes fusion parts, activation may be needed to consider. More details are found in the SSM report (Axelsson et al., 2023).

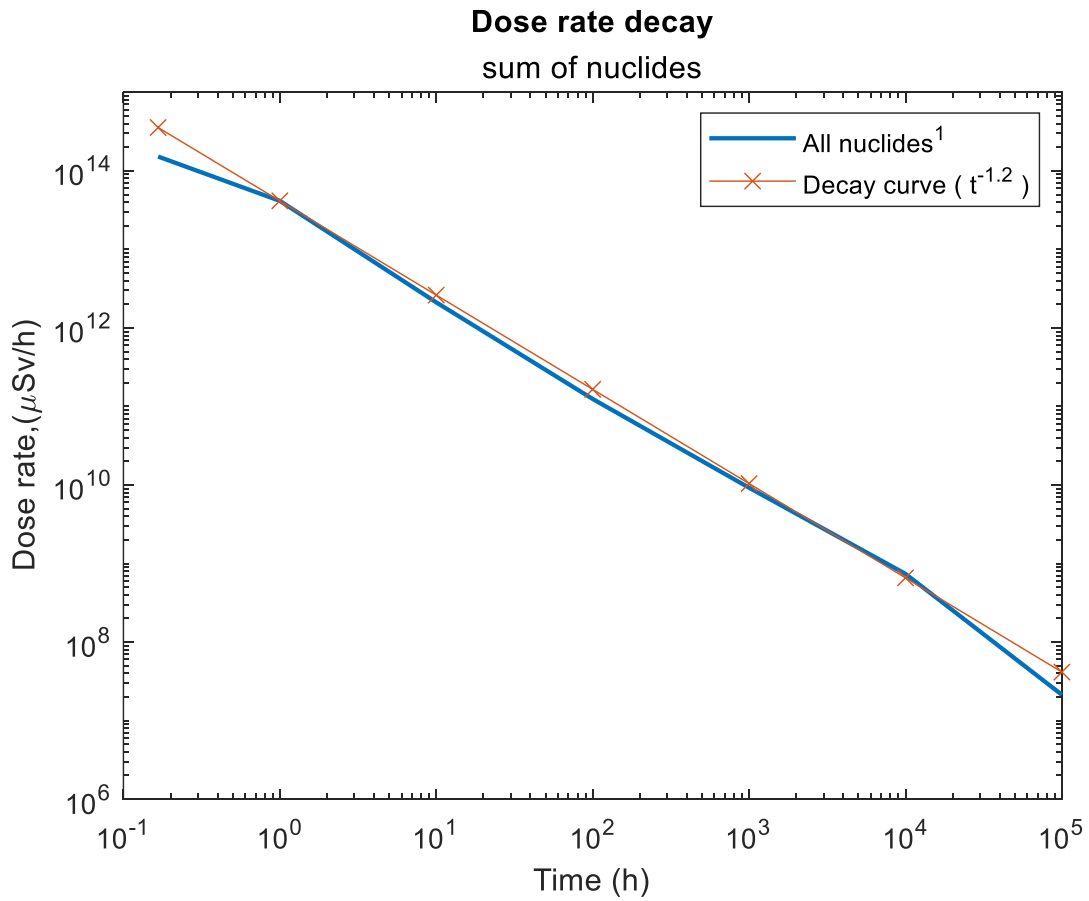


Figure 28 Comparison between the sum of dose rates from all nuclides in the SSM nuclide vector and the decay law of dose rate as presented in the KDFOC3 report. The decay curve value for dose rate is set equal to the sum of all nuclides from the SSM vector at time 1 hour.

Nuclear Decision-Support System ARGOS

The Long-Range dispersion model interface in ARGOS has been developed in close cooperation with the different model providers through a number of years. The default interface is capable of handling forward deterministic Atmospheric Dispersion Modelling (ADM). In addition, specific interfaces have been developed for specific modelling needs such as handling ensemble calculations (developed in cooperation with DMI) and Adjoint modelling results (developed in cooperation with SMHI and SSM). Likewise, new interfaces will have to be developed in order to handle ADM from nuclear detonations. The implications of such interfaces will be discussed in this section.

A big issue in dealing with ADM-results based on nuclear explosions is the large number of nuclides, especially very short-lived nuclides, that is needed to represent the main contribution to the dose resulting from a nuclear explosion.

One solution to this problem is to simply use brute force and perform dose assessment for nuclear explosions in exactly the same way as it is done for (normal) nuclear and radiological releases, performing specific dose calculations for each individual nuclide in the specific run. Accepting that the dose assessment for hundreds of individual nuclides might be quite time consuming.

An alternative solution is to introduce the concept of pseudo nuclides where a single, or a very limited number of pseudo nuclides, represent the dose contribution of a larger set of individual nuclides. This approach obviously limits the number of calculations for activity and deposition on the ADM-model side but also the number of calculations needed on the dose assessment side, in ARGOS.

The concept of pseudo nuclide activity should be interpreted as bulk (gamma) activity – the activity of all the nuclides released in the explosion combined into one (or more) "pseudo-nuclide(s)".

The activity from the pseudo nuclides is anticipated to be presented to ARGOS from the ADM-model as the bulk gamma activity one hour after detonation. But the modelling start of nuclear explosions is not done at the moment of detonation, but rather at the time when a stabilized cloud prevails. This stabilized cloud constitutes the source term from a geometrical point of view.

The above is to be taken into account when calculating the “decayed pseudo nuclide dataset”, presenting the basis for performing dose assessments in this situation.

A setting in ARGOS specifies the minutes between detonation and start of ADM, this setting is called FSC (Forming of Stabilized Cloud).

ARGOS will then use this information when calculating decayed pseudo nuclides.

Vertical Distribution

For nuclear emergency preparedness and in associated decision-support systems, one typically presents calculated concentrations and doses at ground level since this level is of prime interest. However, especially for detonated nuclear weapons, large quantities of radioactivity may reside at high levels above ground, even up in the stratosphere, and it may be of interest to the experts guiding decision makers to have some knowledge on the position of the radioactivity aloft. Obviously, one may extend the concentration calculations to a number of vertical levels as it is usually done for calculation of volcanic ash concentrations in case of volcanic eruptions. However, a simpler, and quicker approach, may be to simply plot the positions of particles or puff centres making up the three-dimensional model plume.

In Figure 29 an example of this is given. The total effective dose in Sv at ground level is shown as calculated by DERMA using Harmonie NWP model data. On top is plotted the positions of the centres of the puffs making up the model plume, the height of which is given in meters above ground. Note that the dose is a time-integrated quantity whereas the puff-centre positions are instantaneous.

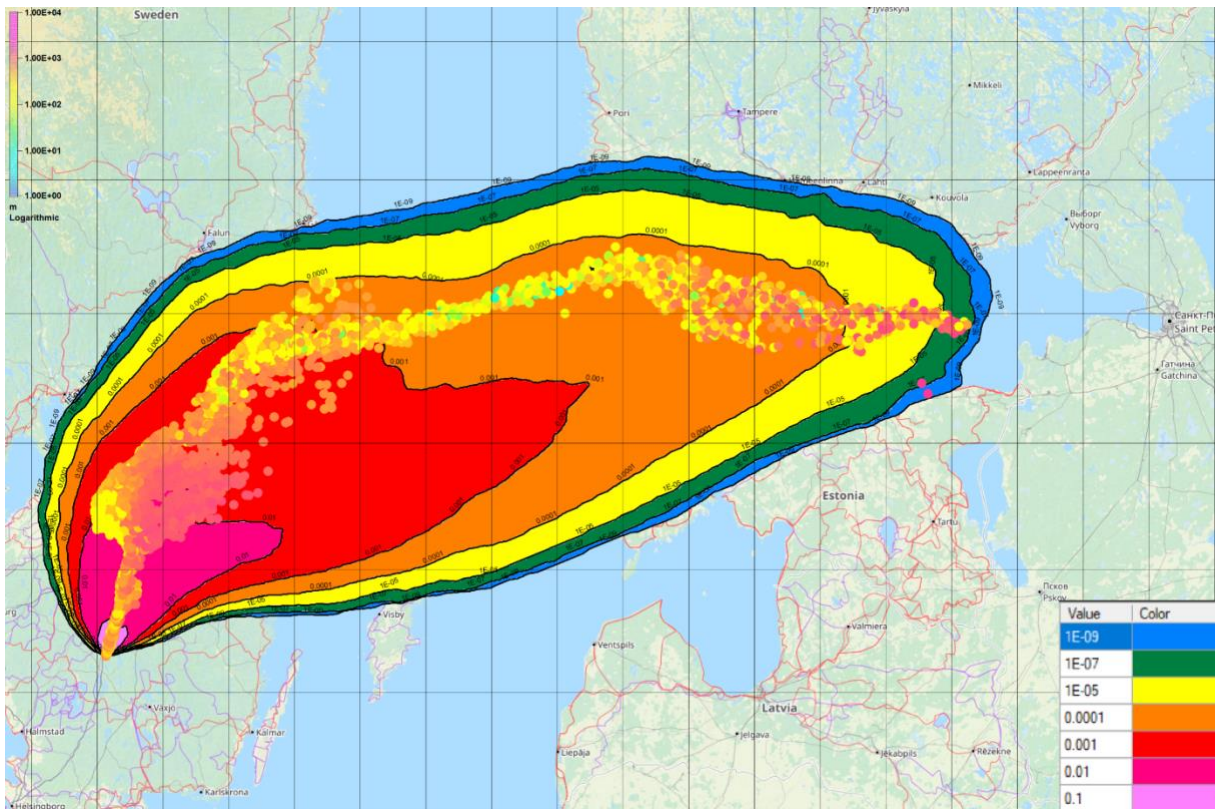


Figure 29 Total effective dose in Sv at ground level according to the legend in the lower-right corner as calculated by DERMA using Harmonie NWP model data at 2.5 km horizontal resolution. On top is plotted the positions of the centres of the puffs making up the model plume, the height of which is given in meters above ground according to the logarithmic axis in the upper left corner.

Dose calculation in ARGOS for pseudo nuclides

Decay calculation

The concept of Ps-1, aka H-1, activity should be interpreted as bulk (gamma) activity – the activity of all the nuclides released in the explosion combined into one (or more) "pseudo-nuclide(s)".

The activity of Ps-1 (and other "BombCalc-nuclides) is anticipated to be presented to ARGOS from the ModelServer as the bulk gamma activity one hour after detonation. But the modelling start of nuclear explosions is not done at the moment of detonation, but rather at the time when a stabilized cloud has formed around 10 minutes after detonation. This stabilized cloud constitutes the source term from a geometrical point of view.

The above is to be taken into account when calculating the "decayed Ps-1 dataset".

The user can specify the minutes between detonation and start of ADM (forming of the stabilized cloud) in DB-Editor, this setting is called FSC.

ARGOS will then use this information when calculating decayed Ps-1.

Example:

If FSC = 10 mins then the time step T0 + 1 h in fact represents the time 1 h + 10 mins after detonation.

In order to derive decayed Ps-1 activity for this time step, the Ps-1 activity should in fact be decayed by another 10 mins.

Likewise, the time step T0 + 30 mins in fact represents the time 40 mins after detonation.

In order to derive decayed Ps-1 activity for this time step, the Ps-1 activity should in fact be "undecayed" by 20 mins.

Decay of "bomb dose calc" nuclides (Ps-1) is handled with this formula:

$$A(t) = A(1) t^{-r}$$

where

- $A(t)$: Activity at time t [hours]
- $A(1)$: Activity at t = 1 [hours]
- t : Time after detonation [hours] – taking FSC into account
- r : Bomb Decay factor

Example of calculation with $r = 0.1$ and FSC = 12 min:

We have a result-set with seven timesteps for Air concentration, instantaneous (un-decayed) from the Model-server:

- 12:00 2000 Bq
- 12:30 1500 Bq
- 13:00 1000 Bq
- 13:30 825 Bq
- 14:00 750 Bq

When we now should produce the decayed Air concentration, we do this:

- 12:00 $2000*(0+0.2)^{-0.1}$ = 2349 Bq
- 12:30 $1500*(0.5+0.2)^{-0.1}$ = 1554 Bq
- 13:00 $1000*(1+0.2)^{-0.1}$ = 982 Bq
- 13:30 $825*(1.5+0.2)^{-0.1}$ = 782 Bq
- 14:00 $750*(2+0.2)^{-0.1}$ = 693 Bq

The resulting “decayed” activity (for Ps-1) will be presented as a special nuclide on the Air concentration and deposition endpoints.

Dose calculation

For ”Bomb dose calc” runs, only doses from deposition are taken into account.

Extended dose calculation is performed through the use of the special decay calculation for “bomb dosecalc” nuclides (Ps-1).

Dose calculations are only performed for the “decayed” version of the “Bomb dosecalc” type nuclides (Ps-1). All other nuclides are omitted from the dose calculations in “Bomb dose calc” mode.

For “Bomb dose calc” runs only doses from Deposition are shown in the result tree – other (dose) endpoints will be hidden in the result tree.

All endpoints related to activity and timing (e.g. TOFA, SOFA, etc.) remain unchanged.

Integration Time

When radiation from ground is estimated, it is relevant to calculate time-integrated values because the deposited material (if not removed) will expose people to external radiation over time.

In the ARGOS system, this integration is calculated in ‘automatic’ intervals of 1 day as long as the prognosis lasts and thereafter at user defined intervals – starting at the time of (first) release. The domain of integration periods is the union of ‘automatic’ interval periods and user defined periods.

A special page in the ARGOS Database Editor should be used for entering the user defined integration periods (days). One user defined period (1 day) should always exist in the database and can therefore not be deleted from within the ARGOS Database Editor.

The integration time for each period can be described by the following formula:

$$T_N = T_0 + P_N * 86400 [s]$$

where:

- N is the period number, $N \in [1..n[$
- T_N is the time at integration period N
- T_0 is the time at the (first) release
- P_N is the number of (full) days for period N

Integration Time is considered for these pathways: “External Gamma dose from Ground” and “Total Effective dose”.

Gamma Dose from (deposition on) Ground

The Gamma Dose from deposition is calculated from:

$$D_{Gamma,dep,Air\ kerma} = \sum_{t=1}^n \int_{t-1}^t A_{Ground,t} \cdot F_{Depo,Gamma,i} \cdot \Delta t \ [Gy]$$

$$D_{Gamma,dep,Ambient} = \sum_{t=1}^n \int_{t-1}^t A_{Ground,t} \cdot F_{Depo,Gamma,i} \cdot \Delta t \cdot K_{Ground,i} \ [Sv]$$

where:

- $D_{Gamma,dep,Air\ kerma}$ is the Gamma dose from deposition (as air kerma), [Gy]
- $A_{Ground,t}$ is the (instantaneous) deposition on ground for a given nuclide at time t, $\left[\frac{Bq}{m^2}\right]$
- $F_{Depo,Gamma,i}$ is depo-gamma factor for a given nuclide, $\left[\frac{Gy\ m^2}{s\ Bq}\right]$
- ΔT is the time interval of each timestep, [s]
- $D_{Gamma,dep,Ambient}$ is the Gamma dose from deposit (as ambient dose equivalent), [Sv]
- $K_{Ground,i}$ is the Ambient Dose Equivalent Ground conversion factor for a given nuclide $\left[\frac{Sv}{Gy}\right]$

For the pseudo-nuclide used in the DRAWN-project a value of $1e-15 \left[\frac{Gy\ m^2}{s\ Bq}\right]$ is used.

As we only consider ground doses External Gamma Dose, Ground is equal to the Total Effective Dose.

Validation against radiological data

For each of the five selected historical detonations, maps with isocurves of the measured gamma dose rates 12 hours post detonation (H+12 hours) have been presented in the literature (Quinn, 1987; Steadman et al., 1984; Quinn et al., 1981; Quinn et al., 1982; Quinn et al., 1984). These maps, which are reproduced in the sections below, form the basis for the comparison between the measurements and the modelling done here. It should be noted that the maps are compiled from data measured at different times post detonation, but with gamma doses normalized to H+12 hours. This is the reason for measurements in regions beyond 12 hours time-of-arrival time in some of the measurement data sets. This also has implications for the comparison to model results, as the DERMA model output in Figure 5 - Figure 9 are based solely on the output at 12 hours post detonation. For comparison, DERMA deposition patterns 48 hours post detonation are given in “Appendix A – DERMA modelled deposition patterns 48 hours post detonation”.

Trinity

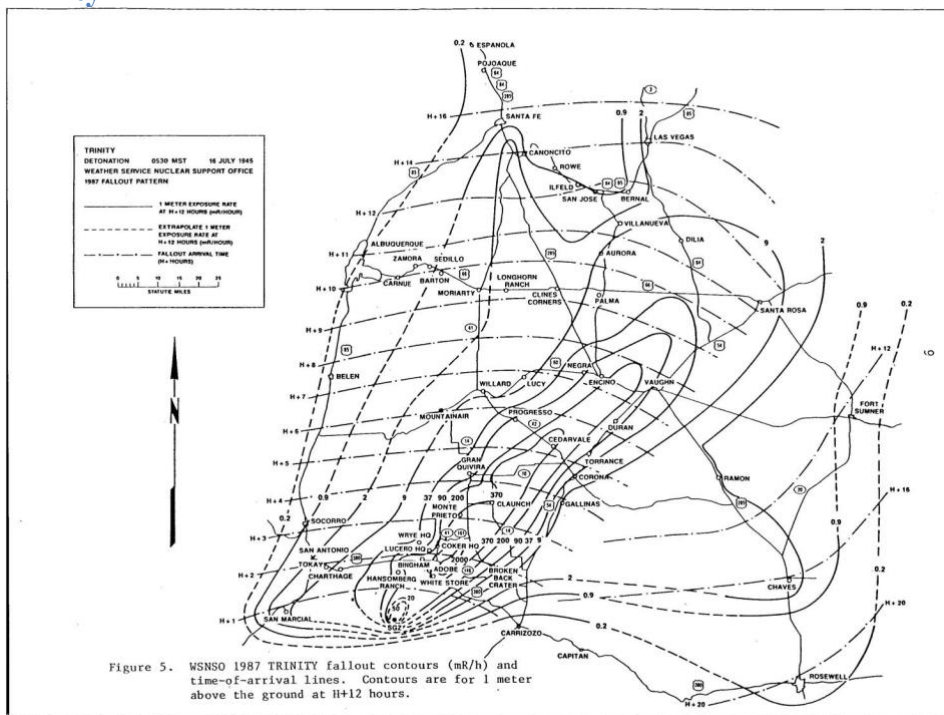


Figure 30 Measured (solid) and extrapolated (dashed) exposure rates normalized to 12 hours post detonation for the Trinity nuclear test detonation on July 16 1945, 12.30 UTC. Dashed lines show the time-of-arrival. Reproduction of Figure 5 from (Quinn, 1987).

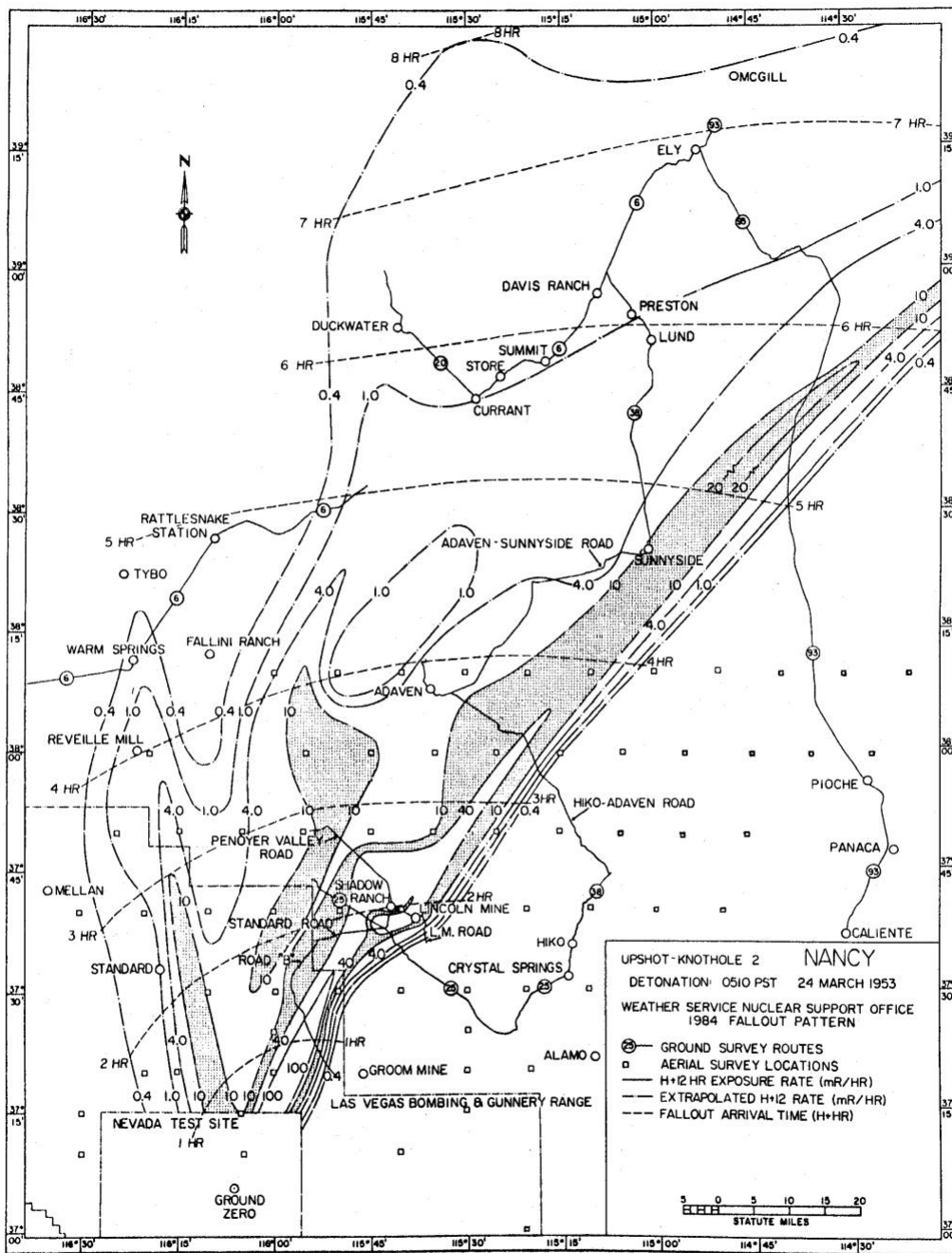


FIGURE 3. THE WSNSO 1984 NANCY FALLOUT PATTERN

Figure 31 Measured (solid) and extrapolated (long dashed) exposure rates normalized to 12 hours post detonation for the Nancy nuclear test detonation on March 24 1953, 13.10 UTC. Dashed lines show the time-of-arrival. Reproduction of Figure 3 from (Steadman et al., 1984).

Harry

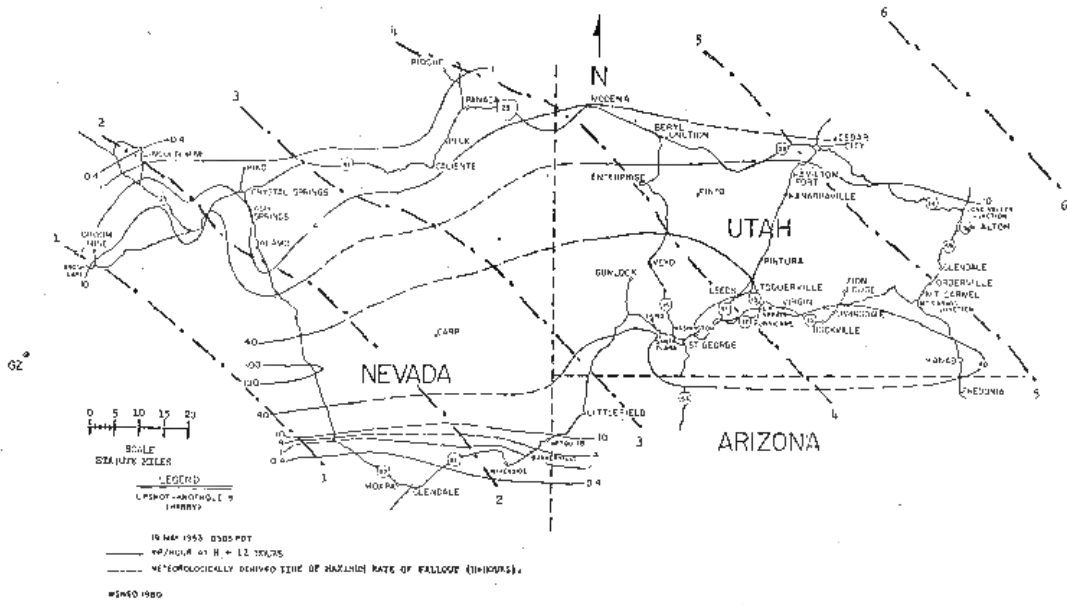


Figure 9. Extended range fallout pattern contours (mR/hr at H + 12 hours) and meteorologically derived time of maximum rate of fallout (H + Hours) at 4000 feet MSL.

Figure 32 Measured (solid) and extrapolated (dashed) exposure rates normalized to 12 hours post detonation for the Harry nuclear test detonation on May 19 1953, 12.05 UTC. Reproduction of Figure 9 from (Quinn et al., 1981).

Smoky

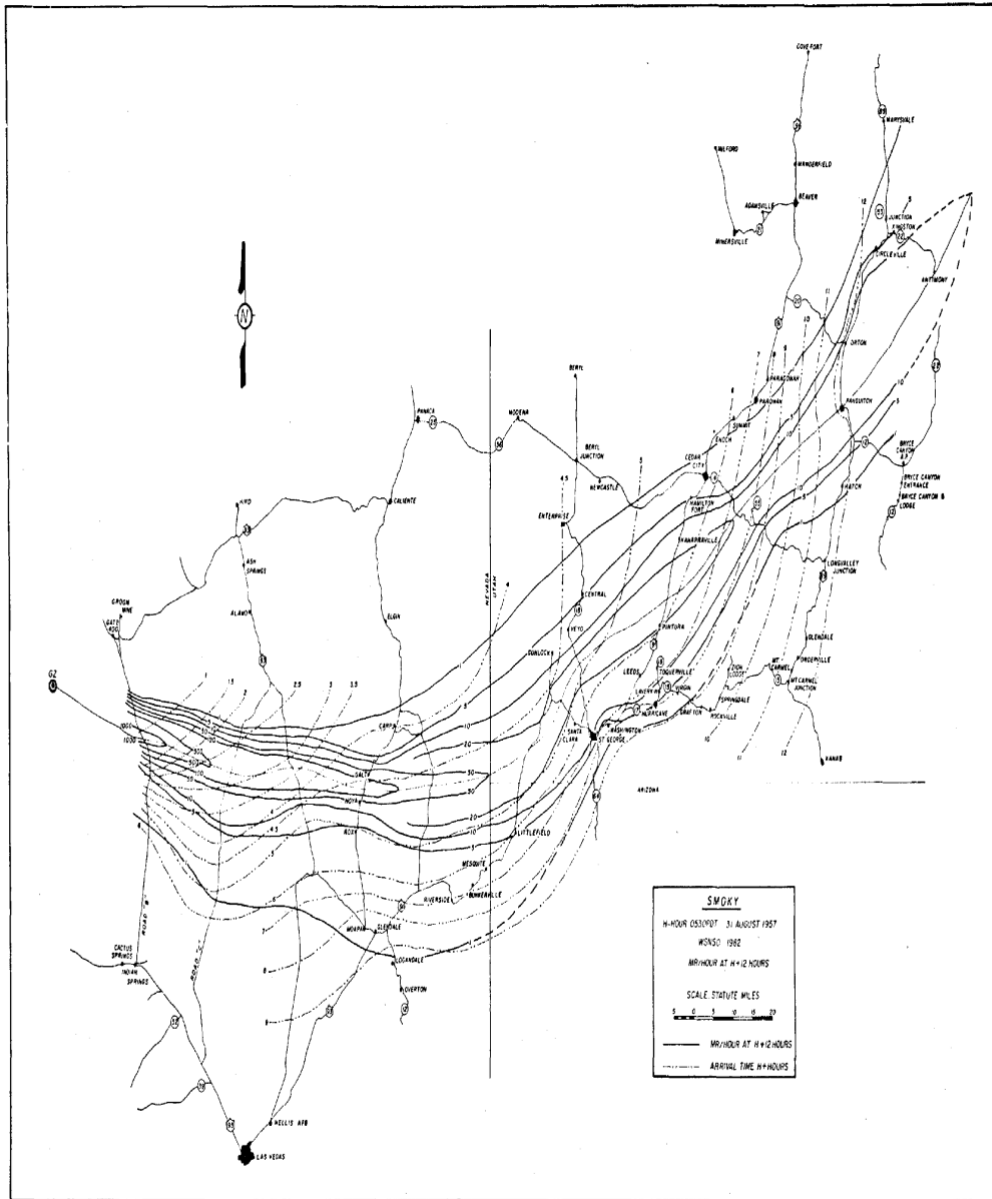


Figure 19. WSNSO 1982 fallout pattern and fallout arrival time lines.

Figure 33 Measured (solid) exposure rates normalized to 12 hours post detonation for the Smoky nuclear test detonation on August 31 1957, 12.30 UTC. Dotted lines show the time-of-arrival. Reproduction of Figure 19 from (Quinn et al., 1982).

Small Boy

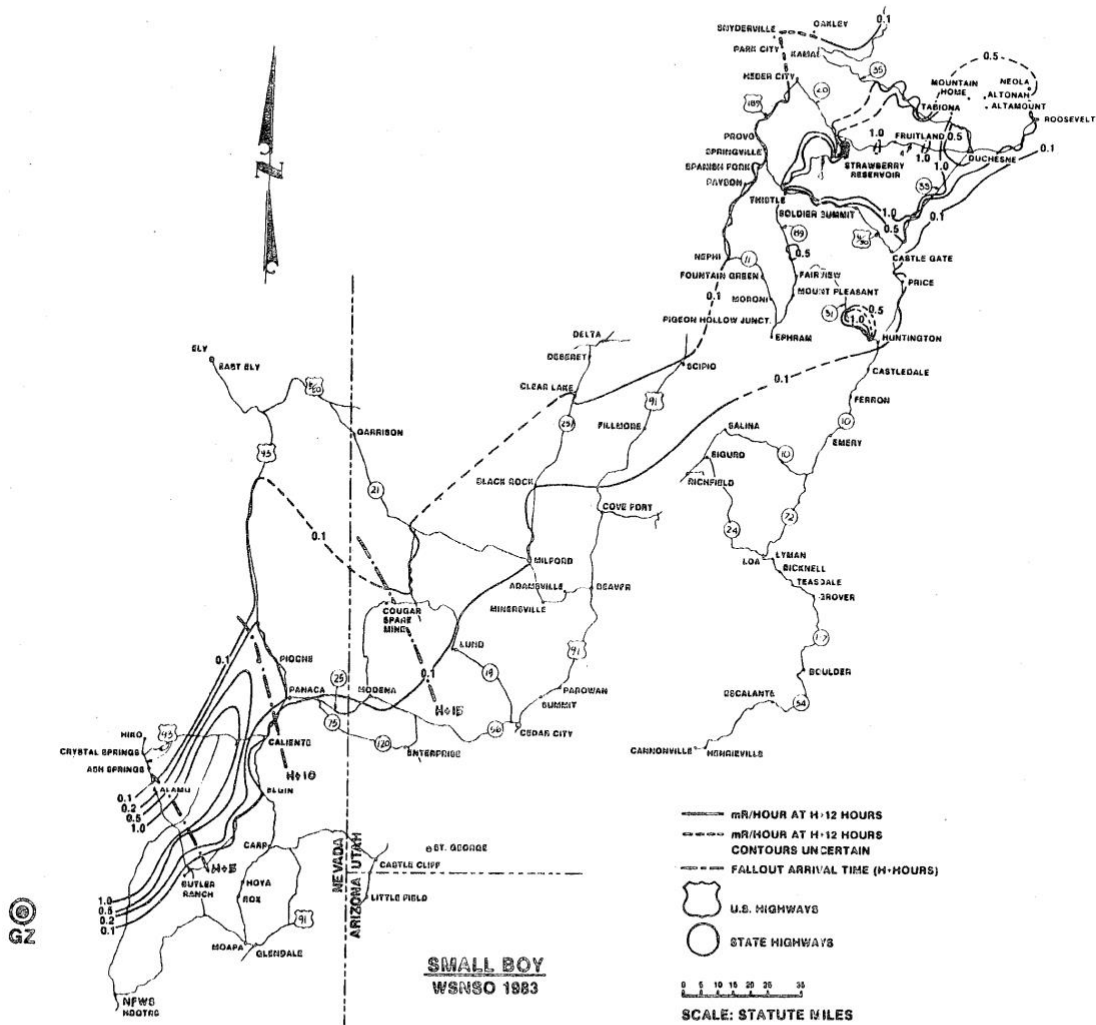


Figure 2. Weather Service Nuclear Support Office H+12 hour fallout-pattern contours and time of arrival lines.

Figure 34 Measured (solid) and extrapolated (dashed) exposure rates normalized to 12 hours post detonation for the Small Boy nuclear test detonation on July 14 1962, 18.30 UTC. Dash-dotted lines show the time-of-arrival. Reproduction of Figure 2 from (Quinn et al., 1984).

Comparison of DERMA model results to measurements

With the post-processing done in ARGOS and the unit conversion applied, the DERMA model output in Figure 5 - Figure 9 is directly comparable to the measurement results given in Figure 30- Figure 34.

Comparing firstly the magnitude of the exposure rates, a clear result presents itself. For all five cases, the exposure rates modelled using DERMA are lower than the measurements by about a factor of 10 in the regions of highest exposure close to the detonation site. This is not too surprising, given the currently-known deficiencies of the DERMA model in the context of modelling nuclear detonations. As described in the section on DERMA, in its current form, it does not include the effect of gravitational settling. Especially for a nuclear weapon modelling, this is important, as even large, heavy particles are flung to high altitudes by the forces of the detonation. Due to gravity, most of these are expected to deposit relatively close to the detonation site, and due to the Coriolis effect mainly to the right on the northern hemisphere, resulting in large exposure rates. In the DERMA model, on the other hand, these remain suspended for longer time allowing transport away from the detonation site, thus reducing the modelled exposure rate close to the detonation site. Thus, the planned update to include this effect in DERMA is expected to increase the deposition close to the detonation site, and thus yield better agreement with the measurements. This development is complicated by the fact that the gravitational settling depends on the particle size distribution of the material emitted by the detonation, which may not be well-known.

For the geographical extent of the exposure, the comparison between model output and measurements is less clear and more case-dependent. For the Trinity case, the model and measurements seem to be in good agreement that the exposure is centered around a line extending in a northwesterly direction from the detonation site, see Figure 5 and Figure 30.

The same agreement (and incidentally, direction of deposition relative to the detonation) is found close to the detonation site for the Small Boy test, as seen by comparing Figure 9 and Figure 34. Also in this case, the fallout is covering a region northwest of the detonation site. However, looking at the measurements (Figure 34), an additional region of large exposure rates is seen much further northwest, isolated from the region of large activity close to the detonation site, not present in the model results in Figure 9. But as this region is well beyond the 15 hour time-of-arrival, the exposure rates in this region must be based on measurements done at a later time, which have then been normalized to the exposure rate 12 hours post detonation. Figure 40 shows the deposition modelled with DERMA 48 hours post detonation, and this shows that also in the model, deposition is found in this region at a time later than the 12 hours shown in Figure 9, further highlighting the agreement between model and measurements for this detonation.

For the three remaining cases, Harry, Nancy and Smoky, the agreement in the direction of deposition relative to the detonation site is worse than for the two cases described above. In all three of these cases, the measurements are dominated by exposure rates in areas that are in a more eastward direction than modelled. One option for this discrepancy is that the NWP data providing the forcing for the model might not accurately reflect the actual weather conditions during the time of these three test detonations. As the stabilized cloud is so short-lived, the exact deposition patterns are highly sensitive to the meteorological conditions at the time of detonation. Thus, even small temporal shifts in the timing of e.g. the change of wind

direction in the model can result in quite different deposition patterns, as also found in the NKS project DISARM (Sørensen et al., 2025).

However, the systematic western bias in the model results compared to the measurements could point towards a more physical explanation. As mentioned above, the DERMA model does not currently account for the gravitational settling of the heavy particles and thus the modelled deposition is governed by the material close to the surface. On the northern hemisphere, the Coriolis effect acts to shift the air to the right, and this effect is larger at greater altitudes. Thus, radioactive material effectively released at higher altitudes is generally moved more eastwards than that released near the surface. In reality, this material deposits in this more eastward direction via gravitational settling, but as this effect is currently missing in the DERMA model, less eastwards deposition is expected.

The bias towards more eastward movement at higher altitudes can be seen in Figure 35 **Error! Reference source not found.** and Figure 44. In these figures, both the instantaneous puff-center positions are shown and the ground-level gamma dose rate, the latter depending on the accumulated deposition on ground and thus an integrated quantity. As can be seen, the mushroom cloud is already substantially distorted after three hours; however, the stem and the main cloud can still be identified. It is clear, that the particles at higher altitudes are moving in a more eastern direction than those near the surface, and if the activity from these particles was to more efficiently reach the surface in the model, deposition patterns in better agreement with the measurements are expected. The reason that the model and measurements are in agreement despite this model deficiency for the Small Boy case is likely due to the small size of this device resulting in a much smaller vertical extent of the mushroom cloud. The agreement for Trinity may be more fortuitous. In both of these cases, it is seen that the material moves in a consistent direction at the different altitudes modelled (Figure 41 and Figure 45), possibly due to the specific meteorological conditions on those dates.

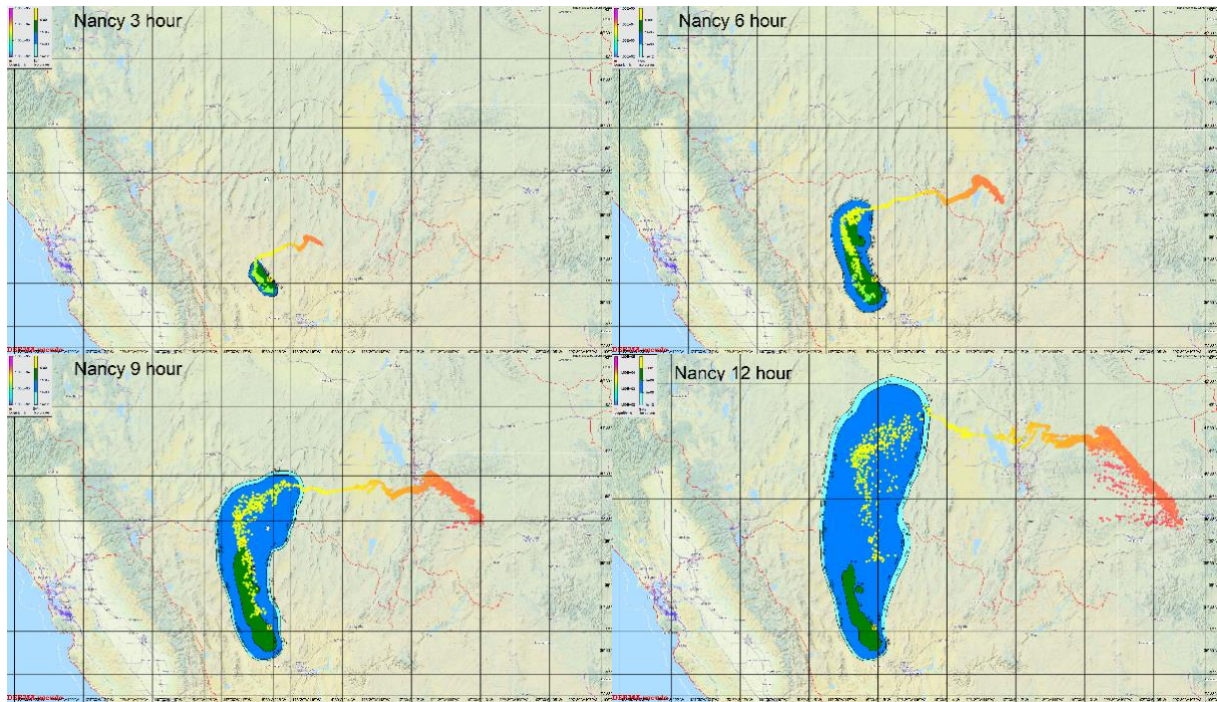


Figure 35 Instantaneous puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of the ground-level gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Nancy nuclear detonation test.

Summary, Conclusions, and Outlook

The current geopolitical situation involves an increased risk for use of nuclear weapons. Detonation of such weapons implies atmospheric dispersion of radioactivity posing a risk to the public also at longer distances from the detonation. Thus, there is a need for developing new, or improving existing, prediction model tools for such events aiming at enhanced civil protection.

The model systems describe the initial spatial distribution of radioactive matter, when stabilization has occurred around ten minutes after detonation, as observed in the field. This effective distribution is taken over by an operational atmospheric dispersion model, which is developed in order to comply with such description. In the previous NKS-B project DISARM, methods have been developed for describing the initial spatial distribution of radioactive matter after the detonation of a nuclear weapon. This effective distribution described as a mushroom cloud is taken over by the atmospheric dispersion model.

In DRAWN, the methods developed have been applied to and validated against selected atmospheric nuclear tests in the Nevada desert in the 1940s, 1950s, and early 1960s.

The non-hydrostatic Harmonie numerical weather prediction model has been set up and run at high resolution using ERA5 reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) to describe the boundary conditions.

The KDFOC3 pseudo-nuclide approach describing the released radioactivity has been applied, and the resulting gamma dose rates compared with observations. In addition, the detailed SSM nuclide vector approach has been compared with the results of KDFOC3. The overall conclusion of this study is that the parametrized decay law very accurately reproduces the total dose rate resulting from using the nuclide vector, especially between 1 and 10^4 hours after detonation.

The predicted plumes are imported to the ARGOS nuclear decision-support system for presentation and dose assessment, and optimum presentation for nuclear emergency management and decision making are considered.

As an outlook, the effect of the inherent meteorological uncertainties on the dispersion patterns should be quantified by applying a statistical ensemble model system to each of the selected nuclear tests in the Nevada desert. Here, methodologies developed in the previous NKS projects MUD, AVESOME, and DISARM should be utilized.

References

- Andersson, C., Bergström, R., Bennet, C., Robertson, L., Thomas, M., Korhonen, H., Lehtinen, K.E.J., and Kokkola, H. 2015. MATCH-SALSA – Multi-scale Atmospheric Transport and CHemistry model coupled to the SALSA aerosol microphysics model – Part 1: Model description and evaluation. *Geosci. Model Dev.* **8**, 171–189. doi:10.5194/gmd-8-171-2015
- Arthur, S.R., Lundqvist, K.A., Mirocha, J.D., Neuscamman, Kanarska, Y., and Nasstrom J.S. Simulating nuclear cloud rise within a realistic atmosphere using the Weather Research and Forecast model. *Atmos. Environ.* **254** (2021) 118363, 1-17
- Axelsson, A., P. Kock, J. Johansson, J. Lindgren, A. M. Blixt Buhr, J. Boson, U. Bäverstam, S. Karlsson. Radiological Consequences of Fallout from Nuclear Explosions. *SSM report 2023:05e* (2023) <https://www.stralsakerhetsmyndigheten.se/en/publications/reports/radiation-protection/2023/202305e/>
- Baker, G. H. Implications of Atmospheric Test Fallout Data for Nuclear Winter, report AD-A182607, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, U.S.A., 1987
- Baklanov, A. and J. H. Sørensen. Parameterisation of radionuclide deposition in atmospheric dispersion models. *Phys. Chem. Earth* **26** (2001) 787–799
- Bengtsson, L., U. Andrae, T. Aspelien, Y. Batrak, J. Calvo, W, de Rooy, E. Gleeson, B. H. Sass, M. Homleid, M. Hortal, K.-I. Ivarsson, G. Lenderink, S. Niemelä, K. P. Nielsen, J. Onville, L. Rontu, P. Samuelsson, D. S. Muñoz, A. Subias, S. Tijn, V. Toll, X. Yang, and M. Ø. Køltzow. The HARMONIE–AROME Model Configuration in the ALADIN–HIRLAM NWP System. *Monthly Weather Review* (2017) **145** No. 5 <https://doi.org/10.1175/MWR-D-16-0417.1>
- Bouttier, F., Raynaud, L., Nuissier, O. and Ménétrier, B. (2016) Sensitivity of the AROME ensemble to initial and surface perturbations during HyMeX. *Quart. J. Roy. Meteor. Soc.* **142** 390-403, <https://doi.org/10.1002/qj.2622>
- Daubechies, I. Ten Lectures On Wavelets. SIAM, 1992
- ERA5. Copernicus Climate Data Store, <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>
- Glasstone, S., and P. H. Dolan. The Effects of Nuclear Weapons. *The United States Department of Defense and the United States Department of Energy, third edition* (1977) <https://atomicarchive.com/resources/documents/effects/glasstone-dolan/>

Gloster, J., A. Jones, A. Redington, L. Burgin, J. H. Sørensen, R. Turner. International approach to atmospheric disease dispersion modelling. *Veterinary Record* 03 (2010a) **166** (12):369. DOI:10.1136/vr.166.12.369a

Gloster, J., A. Jones, A. Redington, L. Burgin, J. H. Sørensen, R. Turner, P. Hullinger, M. Dillon, P. Astrup, G. Garner, R. D'Amours, R. Sellers and D. Paton. Airborne spread of foot-and-mouth disease – model intercomparison. *Veterinary Journal* **183** (2010b) 278–286

Harvey, T., Serduke, F., Edwards, L., Peters, L. 1992, KDFOC3: A Nuclear Fallout Assessment Capability". Lawrence Livermore National Laboratory. UCRL-TM-222788

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N. (2023): ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47

Hoe, S., J. H. Sørensen and S. Thykier-Nielsen. The Nuclear Decision Support System ARGOS NT and Early Warning Systems in Some Countries around the Baltic Sea. In: Proceedings of the 7th Topical Meeting on Emergency Preparedness and Response, September 14–17, 1999, Santa Fe, New Mexico, USA

Hoe, S., H. Müller, F. Gering, S. Thykier-Nielsen and J. H. Sørensen. ARGOS 2001 a Decision Support System for Nuclear Emergencies. In: Proceedings of the Radiation Protection and Shielding Division Topical Meeting, April 14–17, 2002, Santa Fe, New Mexico, USA

Knox, J B. 1964. "Prediction of Fallout from Subsurface Nuclear Detonations". United States. <https://doi.org/10.2172/4677749>. <https://www.osti.gov/servlets/purl/4677749>

Kraus, T. and Foster, K., 2014. Analysis of fission and activation radionuclides produced by a uranium-fuelled nuclear detonation and identification of the top dose-producing radionuclides. *Health Phys.* 107(2):150-63. doi: 10.1097/HP.0000000000000086.

Lindqvist, J. En stokastisk partikelmodell i ett icke-metriskt koordinatsystem., in: FOA-R-99-01086-862, FOA, 1999

Mikkelsen, T., S. Alexandersen, H. Champion, P. Astrup, A. I. Donaldson, F. N. Dunkerley, J. Gloster, J. H. Sørensen and S. Thykier-Nielsen. Investigation of Airborne Foot-and-Mouth Disease Virus Transmission during Low-Wind Conditions in the Early Phase of the UK 2001 Epidemic. *Atmos. Chem. Phys. Disc.* **3** (2003) 677–703

Molenkamp, C.R. Octet user's manual. National Laboratory. Technical Report UCRL-SM-226802. (2006)

Murray, F.W. Numerical models of tropical cumulus cloud with bilateral and axial symmetry. *Mon. Weath. Rev.* **98** No 1:14–28 (1970)

NATO Standard ATP-45. Warning and reporting and hazard prediction of chemical, biological, radiological and nuclear incidents. Edition F Version 2, March 2020

Ollinaho, P., Lock, S. J., Leutbecher, M., Bechtold, P., Beljaars, A., Bozza, A., Forbes, R. M., Haiden, T., Hogan, R. J. and Sandu, I. (2017). Towards process-level representation of model uncertainties: Stochastically perturbed parametrisations in the ECMWF ensemble. *Quart. J. Roy. Meteor. Soc.* **143** 408–422, <https://doi.org/10.1002/qj.2931>

PDC-ARGOS. <http://www.pdc-argos.com>

PREDICT. ImPRovements in atmospheric dispErsion moDellIng and proteCTive action strategies in case of nuclear detonations. <https://pianoforte-partnership.eu/predict/>

Quinn, V.E., Urban, V.D. & Kennedy, N.C. (1981). Analysis of Upshot-knothole 9 (Harry) radiological and meteorological data (No. NVO-233). National Oceanic and Atmospheric Administration, Las Vegas, NV (USA). Weather Service Nuclear Support Office.

Quinn, V.E., Kennedy, N.C. and Urban, V.D., 1982. Analysis of Operation Plumbbob nuclear test SMOKY radiological and meteorological data (No. NVO-249). National Oceanic and Atmospheric Administration, Las Vegas, NV (USA). Weather Service Nuclear Support Office.

Quinn, V.E., Kennedy, N.C. and Steadman C.R., 1984. Analysis of Operation Dominic_II Small Boy radiological and meteorological data (No. NVO-285). National Oceanic and Atmospheric Administration, Las Vegas, NV (USA). Weather Service Nuclear Support Office.

Quinn, V.E. (1987). Analysis of nuclear test Trinity, Radiological and meteorological data. NVO-313. National Oceanic and Atmospheric Administration, Las Vegas, NV (USA). Weather Service Nuclear Support Office.

Robertson, L., Langner, J. and Engardt, M., An Eulerian limited-area atmospheric transport model, *J. Appl. Met.* **38**, 190-210, 1999

Rolph, G.D., F. Ngan, R.R. Draxler. Modeling the fallout from stabilized nuclear clouds using the HYSPLIT atmospheric dispersion model. *J. Environ. Radioact.*, **136** (2014), pp. 41-55

Steadman Jr, C.R., Kennedy, N.C. and Quinn, V.E., 1984. Analysis of Operation Upshot-Knothole nuclear test NANCY radiological and meteorological data (No. NVO-282). National Oceanic and Atmospheric Administration, Las Vegas, NV (USA). Weather Service Nuclear Support Office.

Sørensen, J. H. Sensitivity of the DERMA Long-Range Dispersion Model to Meteorological Input and Diffusion Parameters. *Atmos. Environ.* **32** (1998) 4195–4206

Sørensen, J. H., D. K. J. Mackay, C. Ø. Jensen and A. I. Donaldson. An integrated model to predict the atmospheric spread of foot-and-mouth disease virus. *Epidemiol. Infect.* (2000) 124, 577–590

Sørensen, J. H., C. Ø. Jensen, T. Mikkelsen, D. Mackay and A. I. Donaldson. Modelling the atmospheric spread of foot-and-mouth disease virus for emergency preparedness. *Phys. Chem. Earth* **26** (2001) 93–97

Sørensen, J. H., A. Baklanov and S. Hoe. The Danish Emergency Response Model of the Atmosphere. *J. Envir. Radioactivity* **96** (2007) 122–129

Sørensen, J. H., B. Amstrup, H. Feddersen, U. S. Korsholm, J. Bartnicki, H. Klein, P. Wind, B. Lauritzen, S. C. Hoe, C. Israelson, and J. Lindgren. Meteorological Uncertainty of atmospheric Dispersion model results (MUD). NKS-307, (2014)
http://www.nks.org/en/nks_reports/view_document.htm?id=111010212220490

Sørensen, J. H., B. Amstrup, H. Feddersen, J. Bartnicki, H. Klein, M. Simonsen, B. Lauritzen, S. C. Hoe, C. Israelson and J. Lindgren. Fukushima Accident: UNcertainty of Atmospheric dispersion modelling (FAUNA). NKS-360 (2016),
<http://www.nks.org/scripts/getdocument.php?file=111010213440189>

Sørensen, J. H., B. Amstrup, T. Bøvith, H. Feddersen, R. Gill, M. Sørensen, F. Vejen, P. Astrup, N. Davis, B. Lauritzen, S. C. Hoe, J. E. Dyve, P. Lindahl. MEteorological uncertainty of ShOrt-range dispersion (MESO). NKS-380 (2017)
http://www.nks.org/en/nks_reports/view_document.htm?id=111010214043891

Sørensen, J. H., F. Schönfeldt, R. Sigg, J. Pehrsson, B. Lauritzen, J. Bartnicki, H. Klein, S. C. Hoe, and J. Lindgren. Added Value of uncertainty Estimates of SOURCE term and Meteorology (AVESOME) – final report. NKS-420 (2019)
http://www.nks.org/en/nks_reports/view_document.htm?id=111010214696230

Sørensen, J.H., Bartnicki, J., Blixt Buhr, A.M., Feddersen, H., Hoe, S.C., Israelson, C., Klein, H., Lauritzen, B., Lindgren, J., Schönfeldt, F., Sigg, R. Uncertainties in atmospheric dispersion modelling during nuclear accidents. *J. Environ. Radioact.* **222** (2020) 1-10
<https://doi.org/10.1016/j.jenvrad.2020.106356>

Sørensen, J.H., Møller, K.H, Tølløse, K.S., Robertson, L., Persson, L.Å., Vågberg, D., Pehrsson, J., Roed, H., Senstius, E.P., Syed, N.U., Axelsson, A., Buhr, A.M.B., Burman, J., Lindgren, J., Moring, M., Peltonen, T., Voutilainen, M. DISpersion of radioActivity fRom nuclear boMbs (DISARM) – final report. NKS-498 (2025)
https://www.nks.org/en/nks_reports/view_document.htm?id=111010214699052

Tølløse, K. S., and Sørensen, J. H. A New Hybrid Particle-Puff Approach to Atmospheric Dispersion Modelling, Implemented in the Danish Emergency Response Model of the

Atmosphere (DERMA). *Geosci. Model Dev.*, Vol. 18, 7763–7779 (2025)
<https://doi.org/10.5194/gmd-2024-173>

Tølløse, K. S., J. H. Sørensen. Bayesian Inverse Modelling for Probabilistic Multi-Nuclide Source Term Estimation Using Observations of Air Concentration and Gamma Dose Rate. *Atmosphere* (2022) 13, 1877;

<https://doi.org/10.3390/atmos13111877><https://doi.org/10.3390/atmos12121567>

Tølløse, K. S., E. Kaas, J. H. Sørensen. Probabilistic Inverse Method for Source Localization Applied to ETEX and the 2017 Case of Ru-106 including Analyses of Sensitivity to Measurement Data. *Atmosphere* (2021) 12(12), 1567; <https://doi.org/10.3390/atmos12121567>

Winter, S., P.v. Schoenberg, L. Thaning, FOI Memo 2339. Utvecklingsarbete av systemet för spridningsberäkningar i den nationella strålskyddsberedskapen, in: FOI Memo 2339, Swedish Defence Research Agency FOI, 2008

Appendix A – DERMA modelled deposition patterns 48 hours post detonation

Trinity

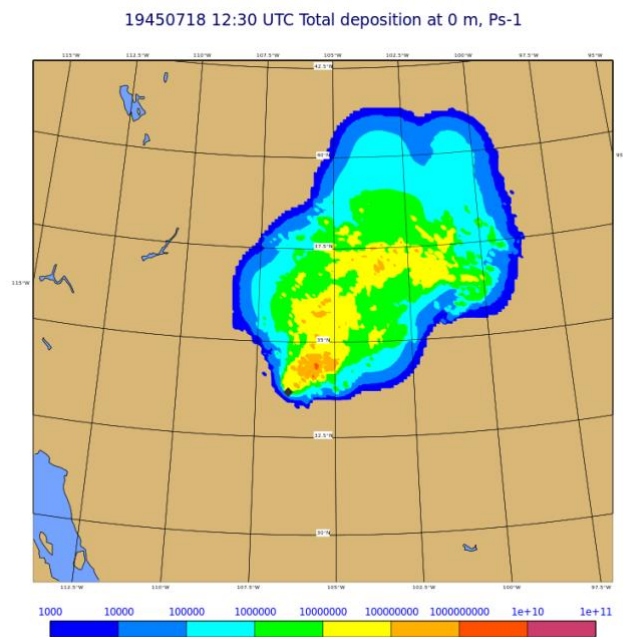


Figure 36 Total accumulated ground deposited activity (pBq/m^2) 48 hours post detonation for the Trinity case. The detonation site is indicated by the black diamond.

Nancy

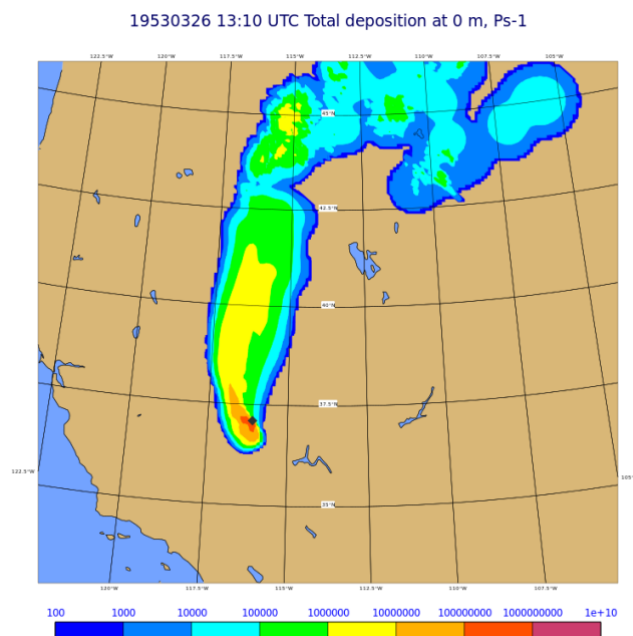


Figure 37 Total accumulated ground deposited activity (pBq/m^2) 48 hours post detonation for the Nancy case. The detonation site is indicated by the black diamond.

Harry

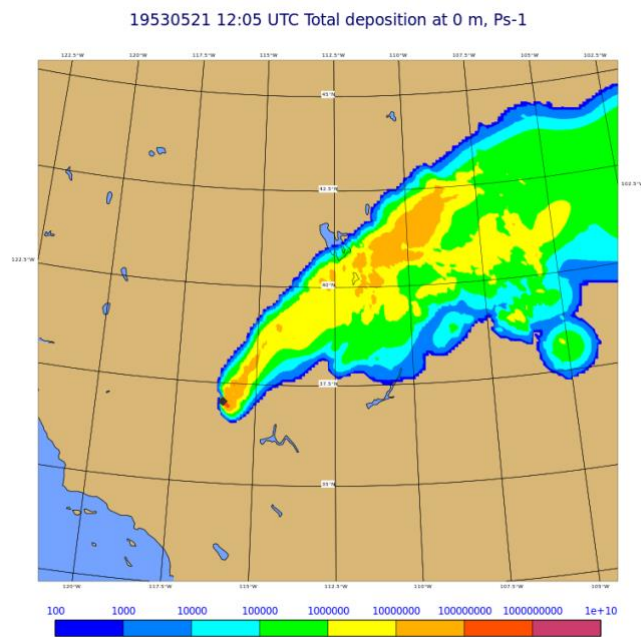


Figure 38 Total accumulated ground deposited activity (pBq/m²) 48 hours post detonation for the Harry case. The detonation site is indicated by the black diamond.

Smoky

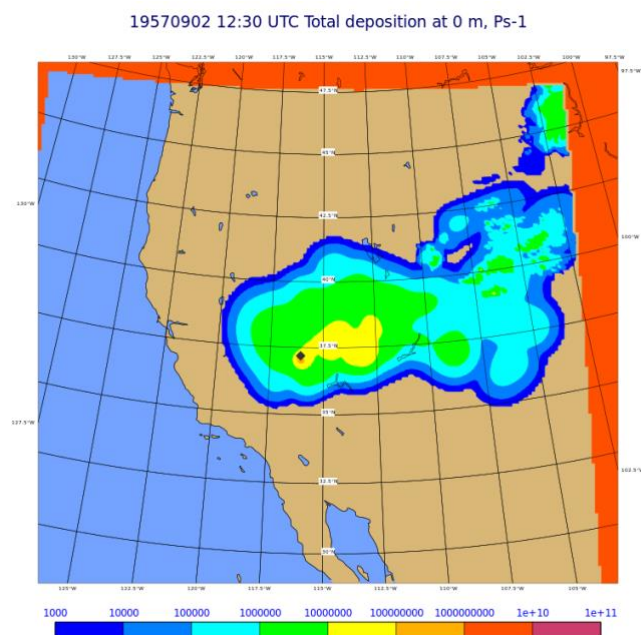


Figure 39. Total accumulated ground deposited activity (pBq/m²) 48 hours post detonation for the Smoky case. The detonation site is indicated by the black diamond. The colored box surrounding the figure shows the outline of the NWP domain used.

Small Boy

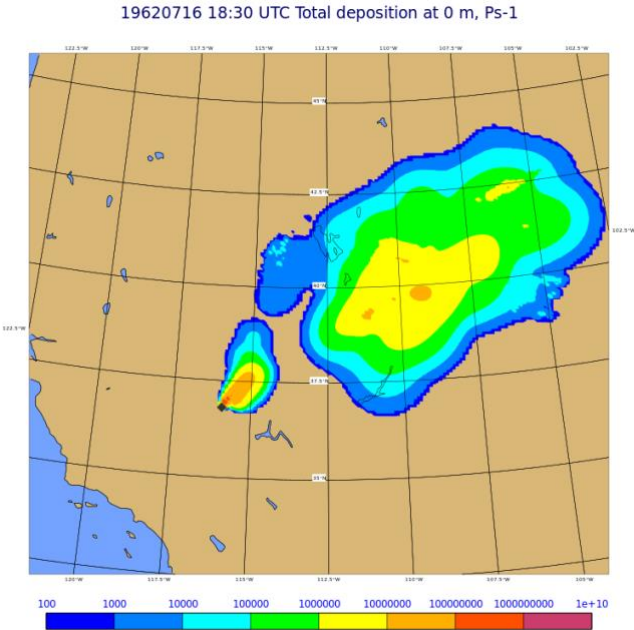


Figure 40 Total accumulated ground deposited activity (pBq/m²) 48 hours post detonation for the Small Boy case. The detonation site is indicated by the black diamond.

Appendix B – DERMA-modelled puff-center locations at selected times

Trinity

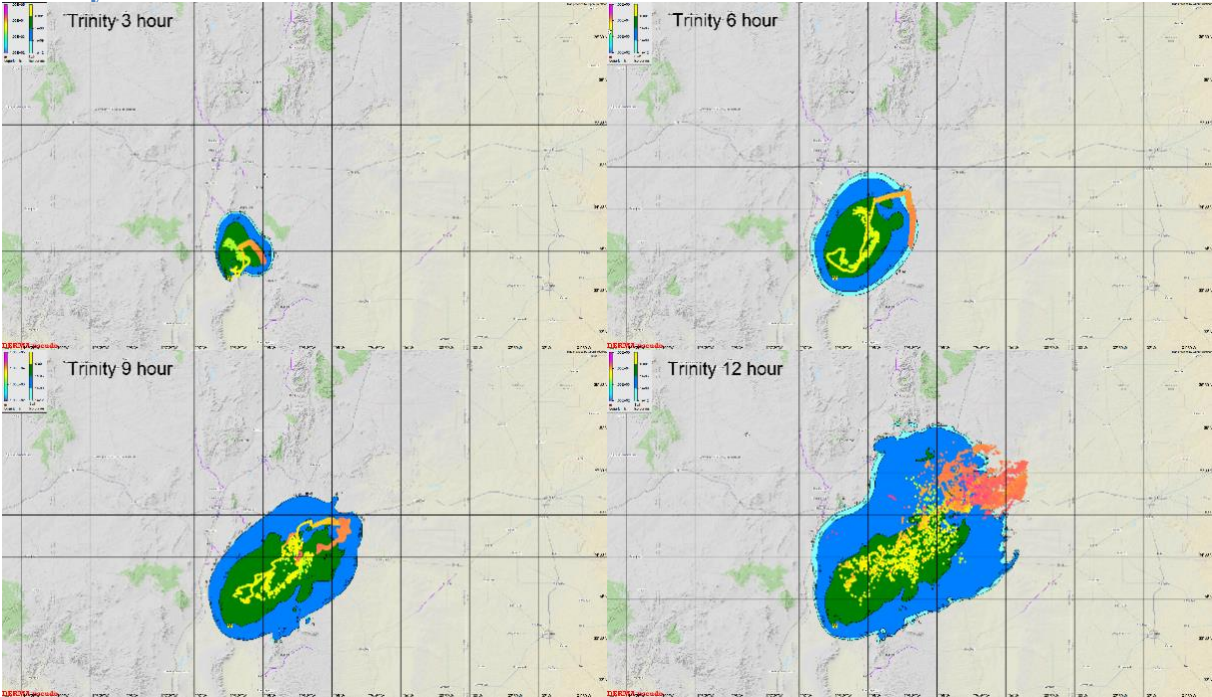


Figure 41 Puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of ground-level gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Trinity nuclear detonation test.

Nancy

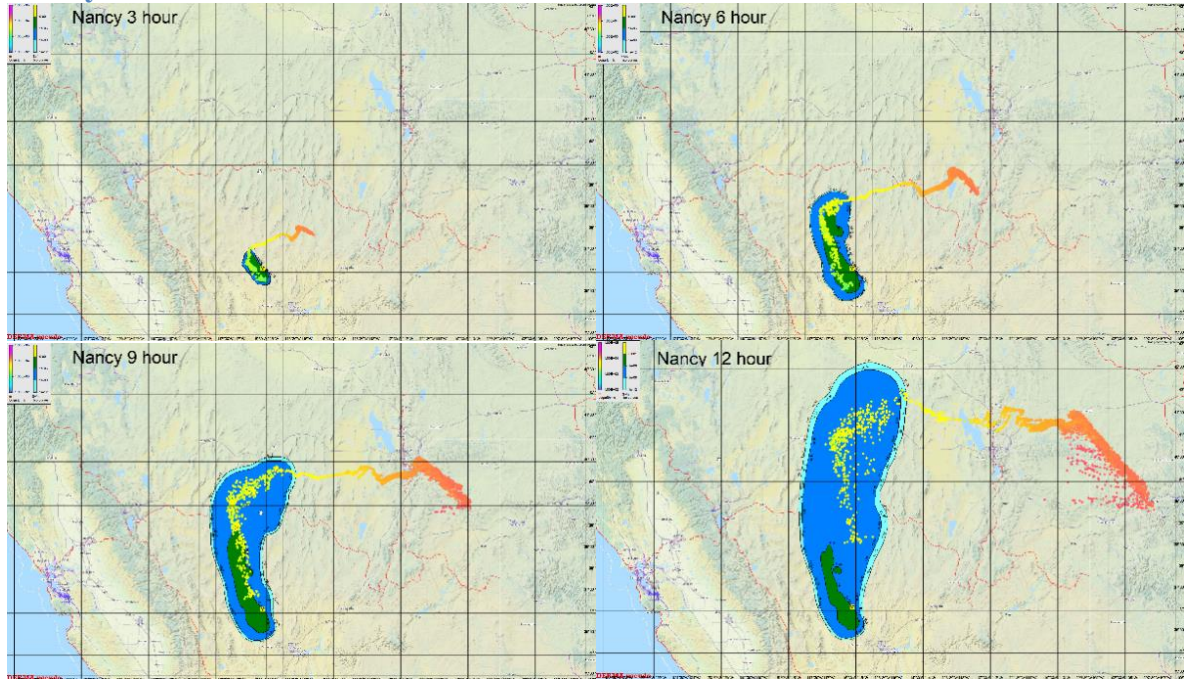


Figure 42 Replicate of Figure 35 included here for completeness. Puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of ground gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Nancy nuclear detonation test.

Harry

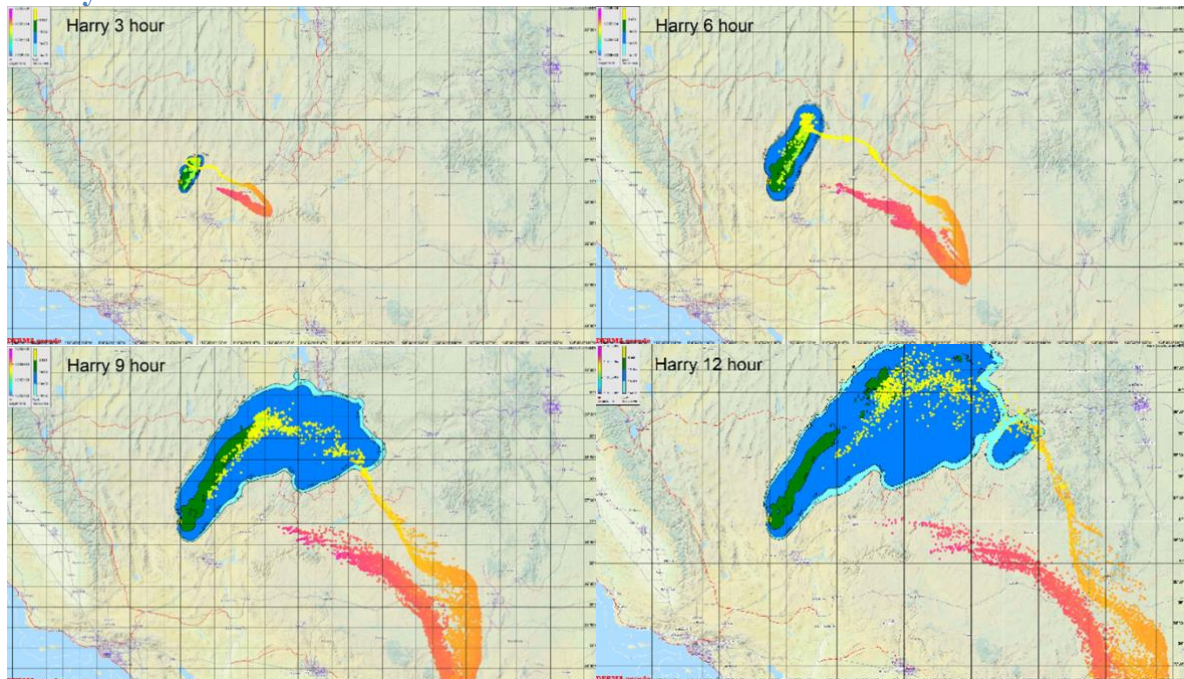


Figure 43 Puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of ground gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Harry nuclear detonation test.

Smoky

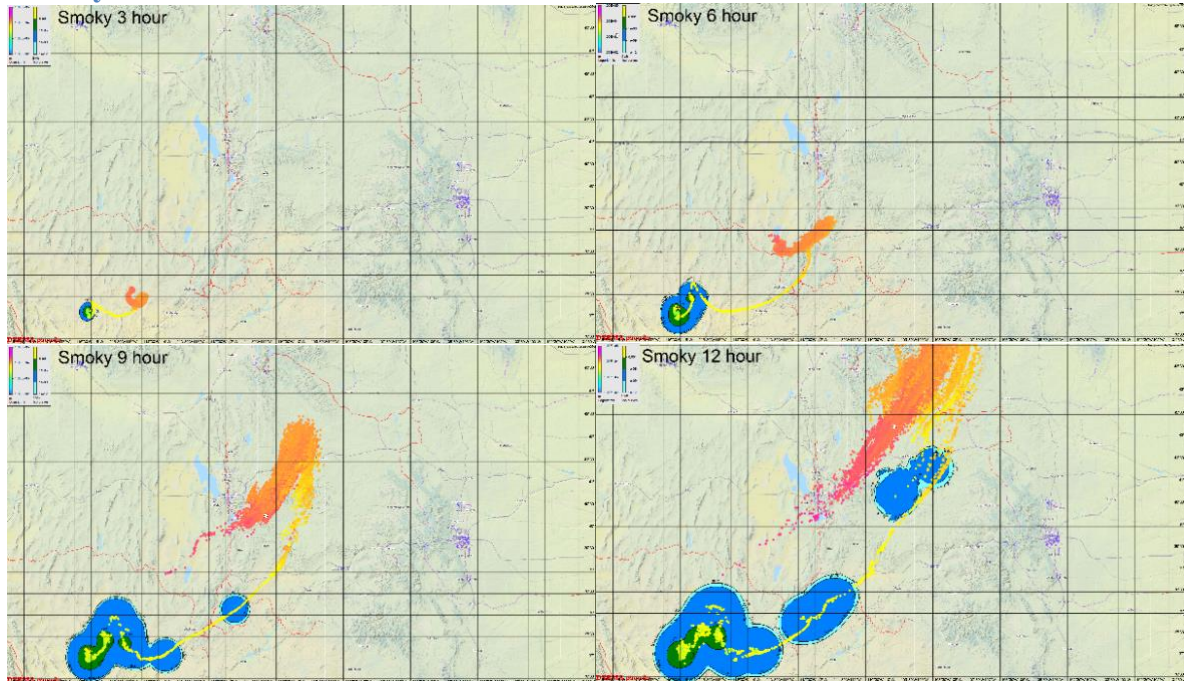


Figure 44 Puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of ground gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Smoky nuclear detonation test.

Small Boy

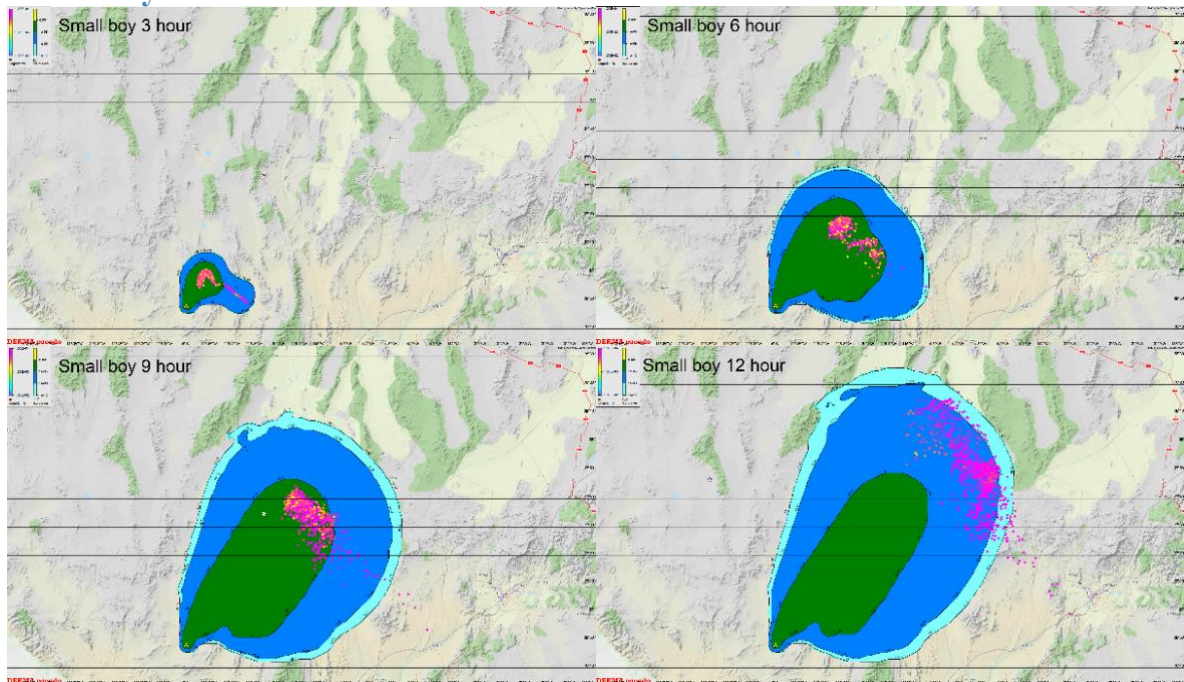


Figure 45 Puff-center positions (dots) color-coded with altitude (yellow at the surface and red at highest altitudes) overlaid on top of ground gamma dose rate isocurves (Sv/h) as modelled with DERMA at 3, 6, 9 and 12 hours post detonation for the Small Boy nuclear detonation test.

Acknowledgements

NKS conveys its gratitude to all organizations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

Disclaimer

The views expressed in this document remain the responsibility of the author(s) 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.

Bibliographic Data Sheet

NKS-512

Title	DispeRision Analysis of early nuclear WeapoN tests (DRAWN)
Author(s)	Jens Havskov Sørensen ¹ (co-ordinator) Henrik Feddersen ¹ Kristian Holten Møller ¹ Magnuz Engardt ² Lennart Robertson ² Jan Pehrsson ³ Henrik Roed ⁴ Elias Pagh Senstius ⁴ Naeem Ul Syed ⁵ Anders Axelsson ⁶ Jan Burman ⁶ Jonas Lindgren ⁶ Mikael Moring ⁷ Tuomas Peltonen ⁷ Mikko Voutilainen ⁷
Affiliation(s)	¹ Danish Meteorological Institute (DMI) ² Swedish Meteorological and Hydrological Institute (SMHI) ³ PDC-ARGOS ⁴ Danish Emergency Management Agency (DEMA) ⁵ Norwegian Radiation and Nuclear Safety Authority (DSA) ⁶ Swedish Radiation Safety Authority (SSM) ⁷ Radiation and Nuclear Safety Authority (STUK)
ISBN	978-87-7893-612-7
Date	February 2026
Project	NKS-B / DRAWN
No. of pages	56
No. of tables	2

No. of illustrations 46

No. of references 47

Abstract
max. 2000 characters

The geopolitical situation involves an increased risk for use of nuclear weapons. Detonation of such weapons implies atmospheric dispersion of radioactivity posing a risk to the public also at longer distances from the detonation. Thus, there is a need for developing new, or improving existing, prediction model tools for such events aiming at enhanced civil protection.

The model systems describe the initial spatial distribution of radioactive matter, when stabilization has occurred around ten minutes after detonation, as observed in the field. This distribution is taken over by an operational atmospheric dispersion model complying with this description. In the previous NKS-B project DISARM, methods have been developed for describing this distribution as a mushroom cloud.

In DRAWN, the methods developed have been applied to and validated against selected atmospheric nuclear tests in the Nevada desert in the 1940s, 1950s, and early 1960s.

The non-hydrostatic Harmonie numerical weather prediction model has been set up and run at high resolution using ERA5 reanalysis data of the European Centre for Medium-Range Weather Forecasts describing the boundary conditions.

The KDFOC3 pseudo-nuclide approach describing the released radioactivity has been applied, and the resulting gamma dose rates compared with observations. In addition, the detailed SSM nuclide vector approach has been compared with the results of KDFOC3. The overall conclusion of this study is that the parametrized decay law very accurately reproduces the total dose rate resulting from using the nuclide vector, especially between 1 and 10^4 hours after detonation.

The predicted plumes are imported to the ARGOS nuclear decision-support system for presentation and dose assessment, and optimum presentation for nuclear emergency management and decision making are considered.

Key words

nuclear emergency preparedness, atmospheric dispersion modelling, nuclear weapons, detonation, stabilized cloud, particle size distribution