Federal Office for
Radiation Protection

Assessment of potential radiological consequences of nuclear detonations using dispersion modeling

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NERIS workshop, ERPW

2023-10-09, Dublin

Overview

1. Dispersion modeling at BfS

    → RODOS

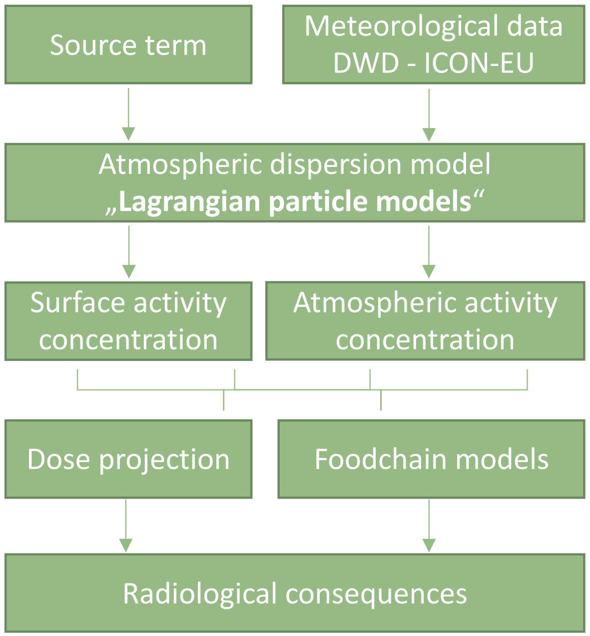
2. Source term
    - Geometry
    - Aerosol particles / sizes
    - Radioisotopes

3. Statistical assessment: Radiological consequences of 10 kt yield detonation

    → Typical distances for protective measures

Dose projection tools

- at BfS: Routine operation of „RODOS“ (**R**ealtime **O**nline **D**ecisi**o**n **S**upport System)
- Other countries/organizations also use „ARGOS“ or own developments



- Source term:
  - Activity per radionuclide
  - Release height/location/geometry
  - Particle size distribution

- Meteo-data: ICON-EU in 24 height-levels up to 10 km ca.: 10, 41, 95, 165, 250, 350, 470, 590, 730, 890, 1050, 1200, 1400, 1600, 1810, 2030, 2260, 2750, 3560, 4430, 5470, 6800, 8150, 9200 meters above surface
- Dose projection tools can be used to assess typical radiological consequences:

  Statistical calculations for many different meteo. conditions (e.g. for 365 days)

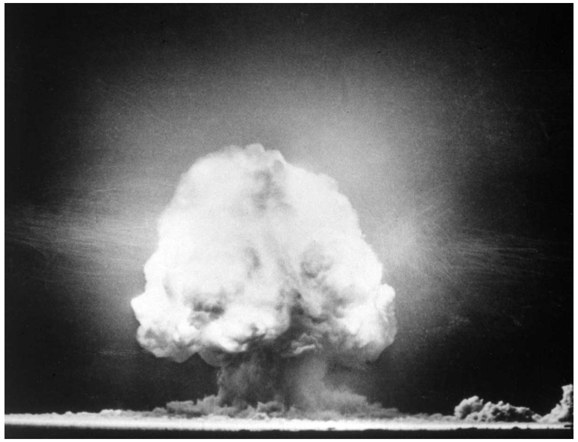
  → Compare dose projections to predefined/legal threshold levels

  → Statistics over e.g. distance up to which countermeasures typically have to be applied

Source term - Geometry

- Nuclear detonations cause an initial fireball, inside of which all matter is vaporized
- As the fireball expands, it cools down quickly
- This results in a typical formation of winds that lead to the stabilization into the typical mushroom cloud
- Materials in the cloud subject to upward motion
- Stable cloud after around 10 minutes

  → Starting point of dispersion modeling
- Dimension of the cloud ∝ yield



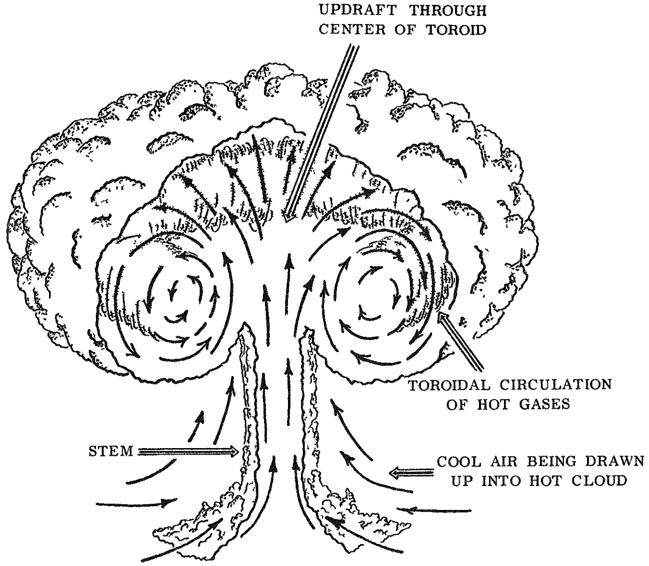


Image: Glasstone and Dolan, 1977

Source term - Geometry

- Updraft causes most activity to be in the head of the cloud
- Total cloud height can be much larger than 10 km
- Activity/Height distribution parametrized in 6 layers (Rolph et. al., 2014)
- Total height, layer heights, cloud radius, and head/stem ratio are parametrized and determined by user input of the detonation yield

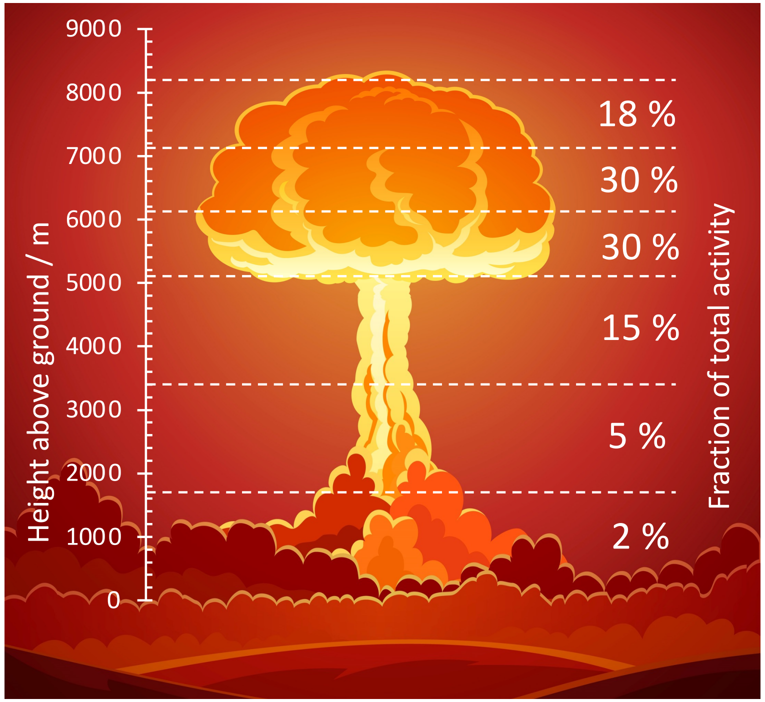


Table 1
Model cloud layer heights (meters above ground level) based on nuclear yield in kilotons (kT).

Yield (kT)	≤2.5	≤7.5	≤12.5	≤17.5	≤22.5	≤27.5	≤32.5	≤37.5	≤42.5	≤45.0
Level 7	3700	6300	8200	9700	10800	11200	11600	11900	12200	12500
Level 6	3132	5434	7166	8532	9532	9900	10232	10500	10766	11000
Level 5	2566	4567	6130	7366	8266	8600	8866	9100	9333	9500
Level 4	2000	3700	5100	6200	7000	7300	7500	7700	7900	8000
Level 3	1334	2466	3400	4132	4666	4866	5000	5132	5266	5332
Level 2	667	1233	1700	2066	2333	2433	2500	2566	2633	2666
Level 1	0	0	0	0	0	0	0	0	0	0

Table: Rolph G.D., Ngan F., Draxler R.R., 2014
http://dx.doi.org/10.1016/j.jenvrad.2014.05.006

Source term – Particle size distributions

- As vaporized radioisotopes cool down, they condense, typically onto debris particles
- The distribution of available particles depends strongly on the type of the detonation. Most notable are surface detonations, which suck in a vast amount of dirt

  → Assumptions for modeling: surface burst

  with Glasstone's distribution
- Activity-particle size distribution is well known to be **log-normal**, but quite different distributions have been observed
- **Simplification: All isotopes have the same distribution**
- **Simplification: All particles contribute equally to inhalation dose (→ overestimation)**
- Physically: Different condensation temperatures or decay properties cause Element-/Isotope-specific particle size distributions

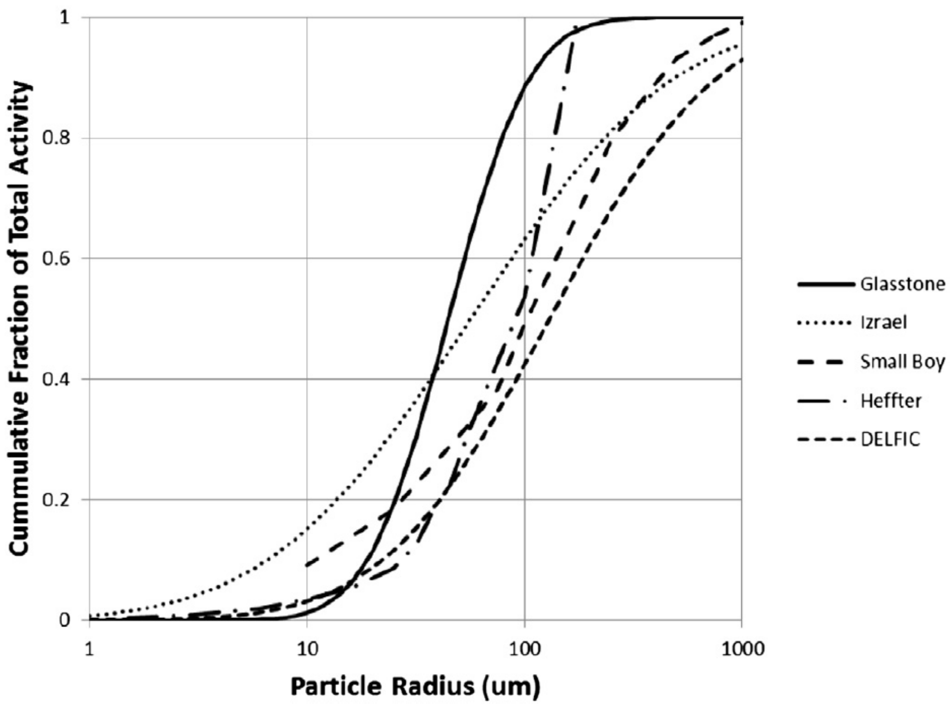


Image: Rolph G.D., Ngan F., Draxler R.R., 2014

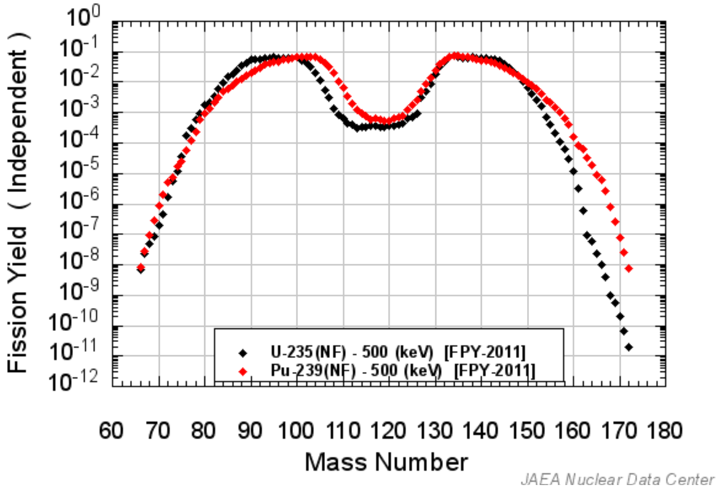
Source term – Radioisotopes

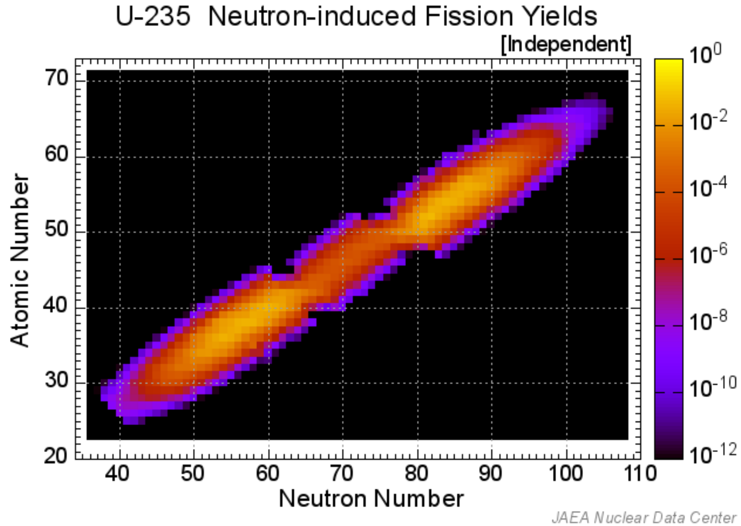
- Nuclear detonation has different means of producing radioactive isotopes:
  - **Fission products**
  - Activation products of the weapon materials
  - Activation products of surrounding soil and air
  - Unfissioned fuel

- The amount of initially produced different nuclides during a detonation can be estimated to be on the order of 1000

  → Selection of radionuclides is neccessary for modeling

  → Identify those, which are most dose-relevant (Kraus T., Foster K., 2014)



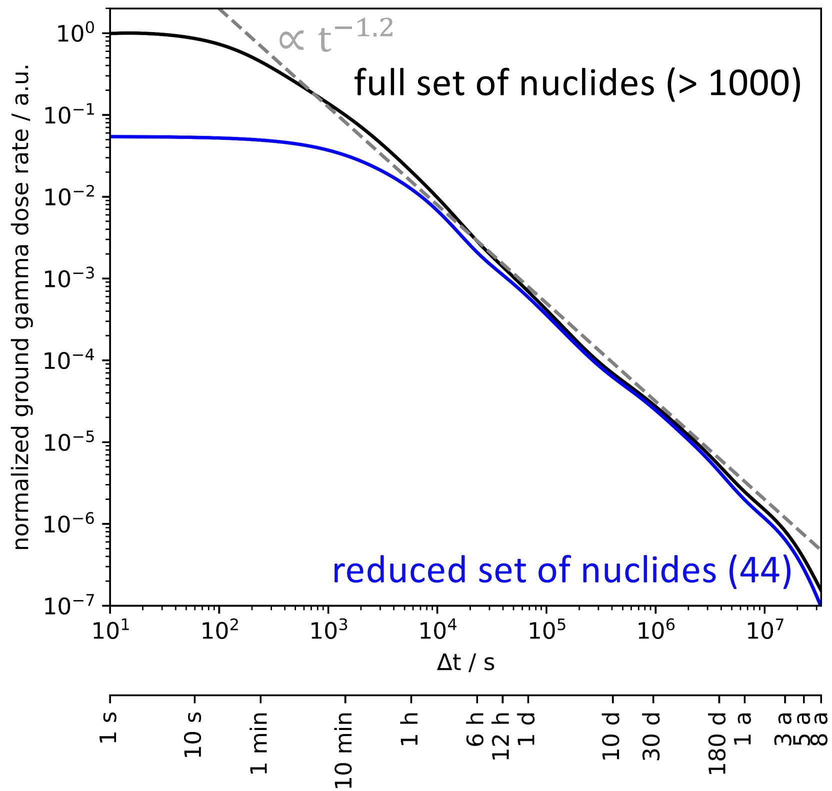


Kraus T., Foster K., Health Physics, 2014 DOI: 10.1097/HP.0000000000000086
Images: JAEA Nuclear Data Center

Source term – Radioisotopes

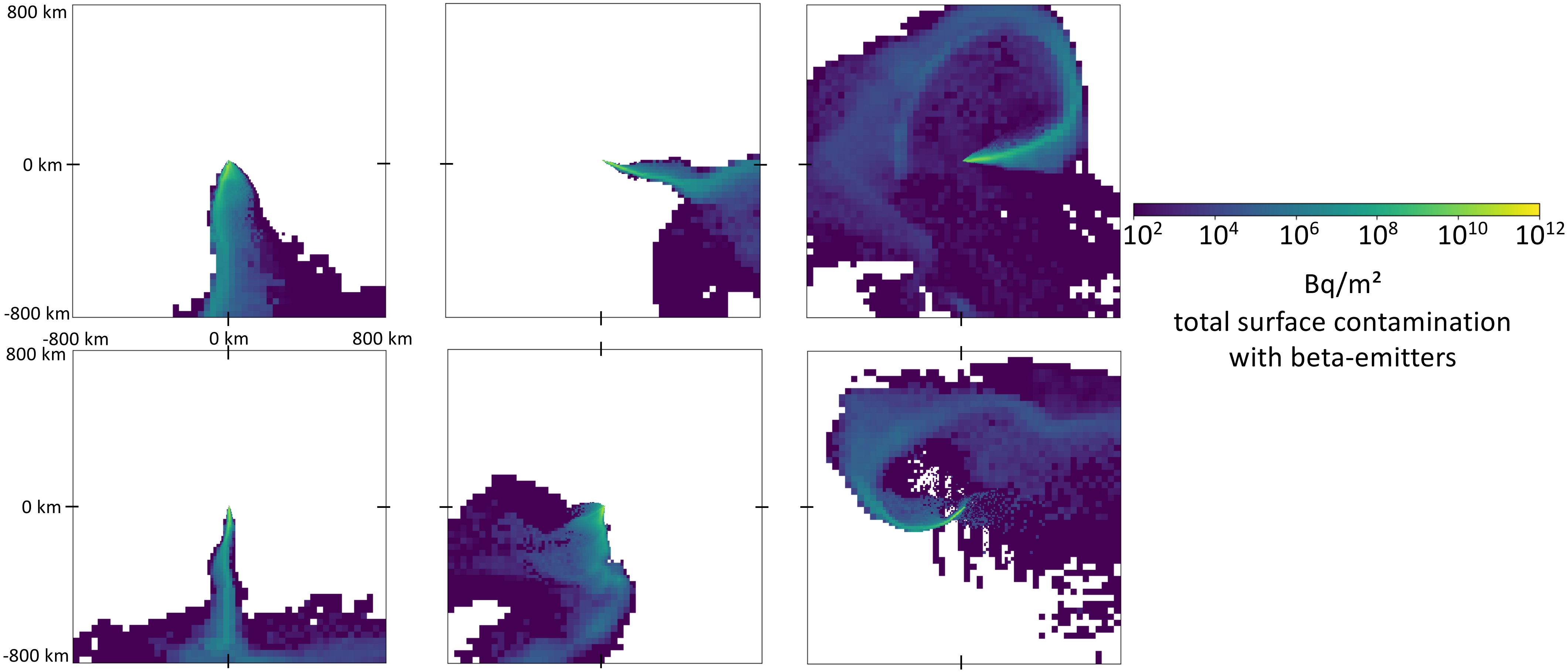
- Source-Term estimation combining information from
  - ENDF-B/VIII fission yields and decay data
  - Kraus and Foster, 2014
  - Spriggs and Egbert (2020, Hiroshima estimation, LLNL)
- **Limitation: 44 Total nuclides can be considered in RODOS**
  - → Select subset of nuclides, such that projected activity at 10 minutes after burst best matches theoretical projection (starting from fission yields)
  - → Includes most dose-relevant nuclides (> 95 % of dose) per Kraus/Foster
  - → scale activity with yield

- Physically: Vast amount of very short-lived nuclides cause very high dose in the initial phase: **Underestimation of dose in close proximity (on the few km scale)**

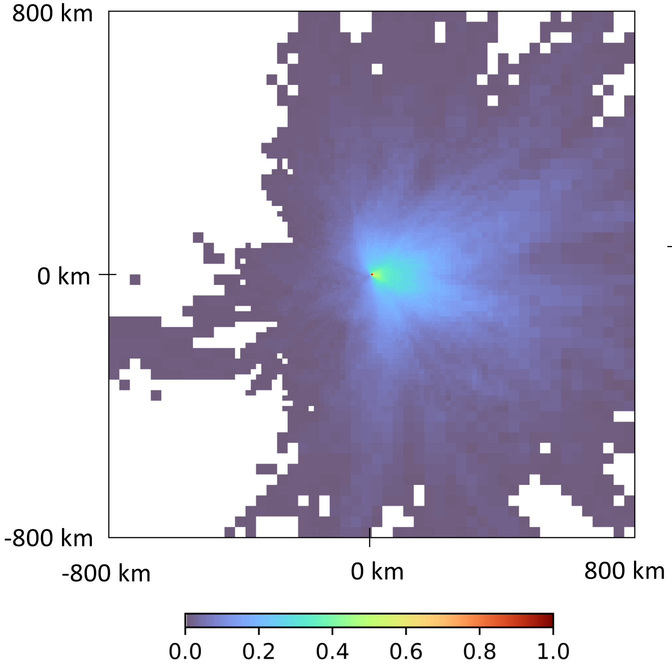


Spriggs, Egbert, LLNL technical report, 2020
https://doi.org/10.2172/1668494

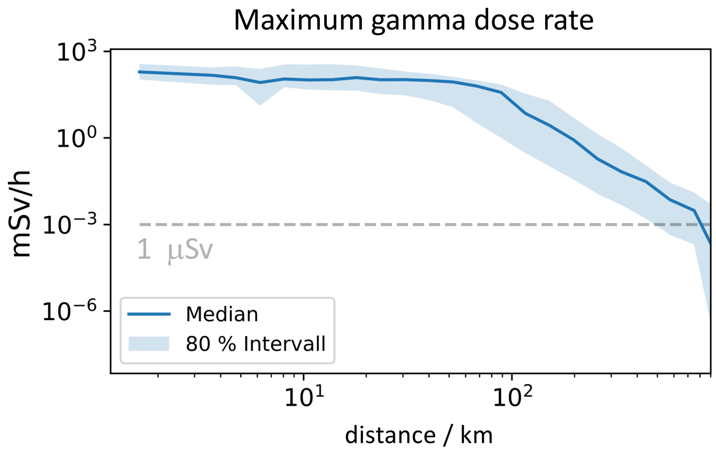
Fallout modeling – Examples – total surface Beta contamination (temporal maximum)



Statistical assessments – 10 kT yield – Example: Gamma dose rate (GDR)



„Heatmaps“:
Relative frequency
of maximum GDR > 1 µSv/h
in N computational cases
(N = 365)



Typical assessments: Distances in which certain radiological criteria are exceeded (e.g. in the 90 % overlapping interval/percentile)

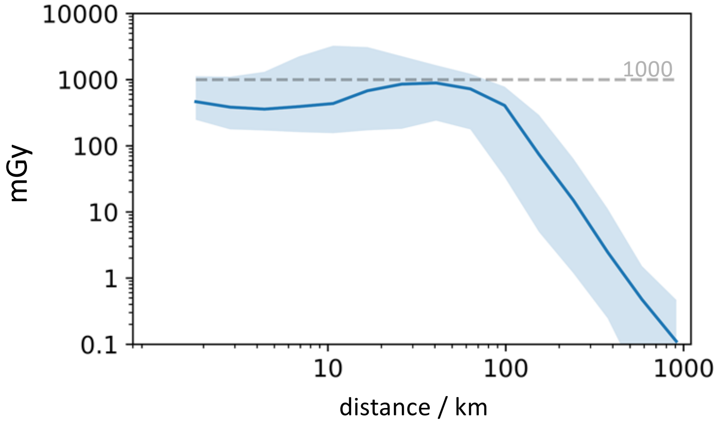
→ **„in 90 % of cases, the criteria for countermeasure X are fulfilled in a distance less than Y km“**

→ here: Gamma-dose rate > 1 µSv/h is a general criterion for the appropriateness of recommendations to the public (e.g. to avoid incorporation)

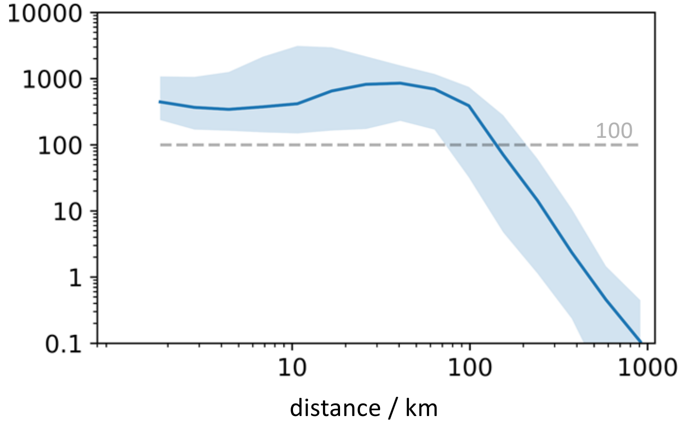
→ can be exceeded up to a distance of more than 800 km

Statistical assessments – 10 kT yield – deterministic effects

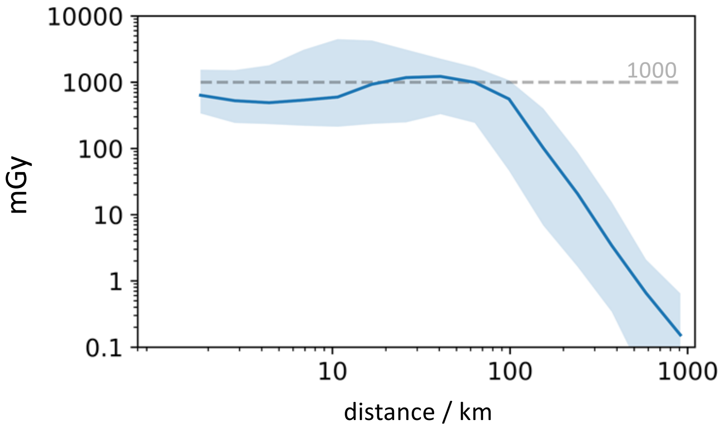
Dose 7d red bone marrow, adults



Uterus/Fetus dose, 7 d, adults



Dose 7d red bone marrow, children



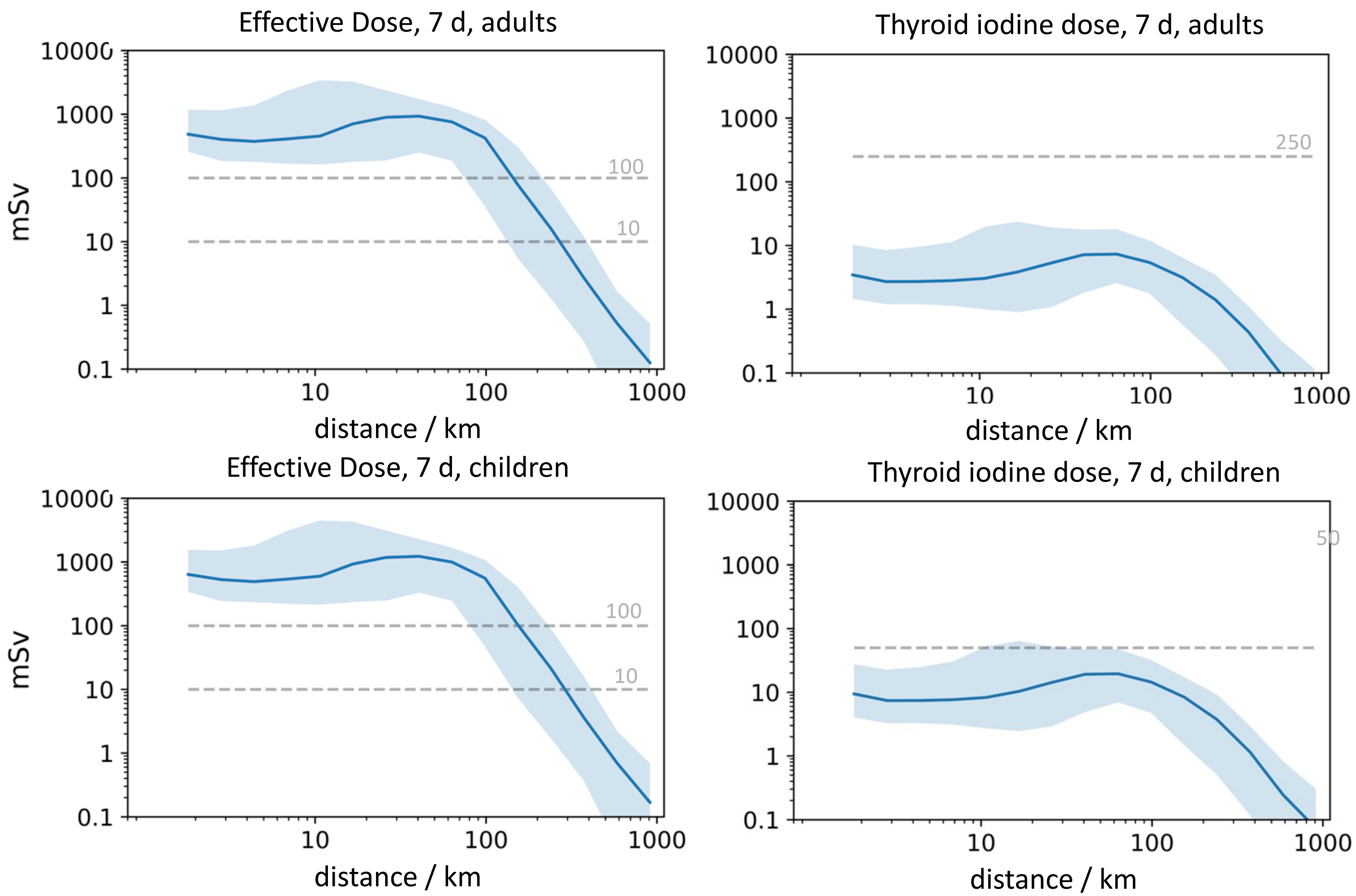
Deterministic effects:

- Onset roughly at 1 Gy dose for the red bone marrow (RBM)
- Uterus dose of 100 mGy as proxy for the fetus dose

Deterministic effects from fallout from at 10 kT burst possible in up to

- **70 km** (RBM)
- **200 km** (uterus/fetus)

Statistical assessments – 10 kT yield – urgent actions



thresholds based on German legislation

7 d effective, unprotected dose:
> 100 mSv up to 160 km (evacuation)
> 10 mSv up to 270 km (sheltering)

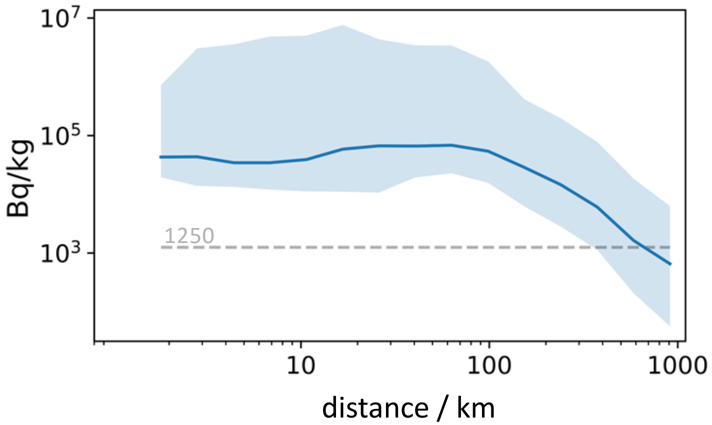
→ evacuation can likely not be applied in event; **resort to sheltering**

Thyroid doses due to inhalation of iodines do not exceed threshold levels for iodine thyroid blocking (250 mSv adults, 50 mSv for children)

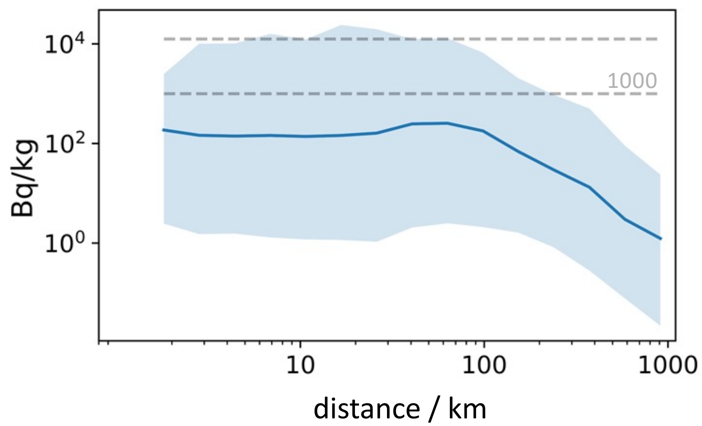
→ **Iodine thyroid blocking not recommended**

Statistical assessments – 10 kT yield – radiological impact on agriculture

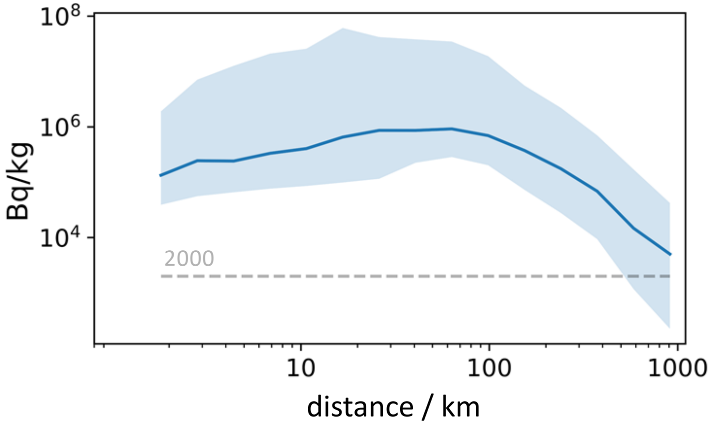
Cesium contamination – leafy vegetables



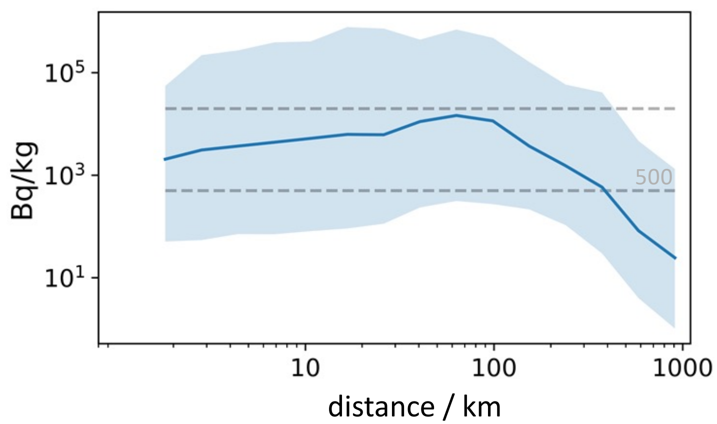
Cesium contamination – cow's milk



Iodine contamination – leafy vegetables



Iodine contamination – cow's milk



thresholds based on EU limits (EURATOM 2016/52)

Leafy vegetables:

Marketing bans due to Cs contamination up to 800 km, due to Iodines more than 800 km

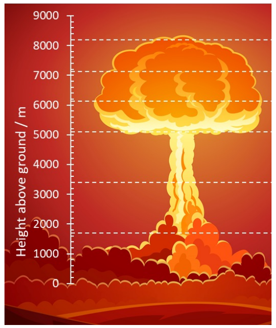
Cow's milk:

Marketing bans due to Cs contamination up to 300 km, due to Iodines up to 750 km

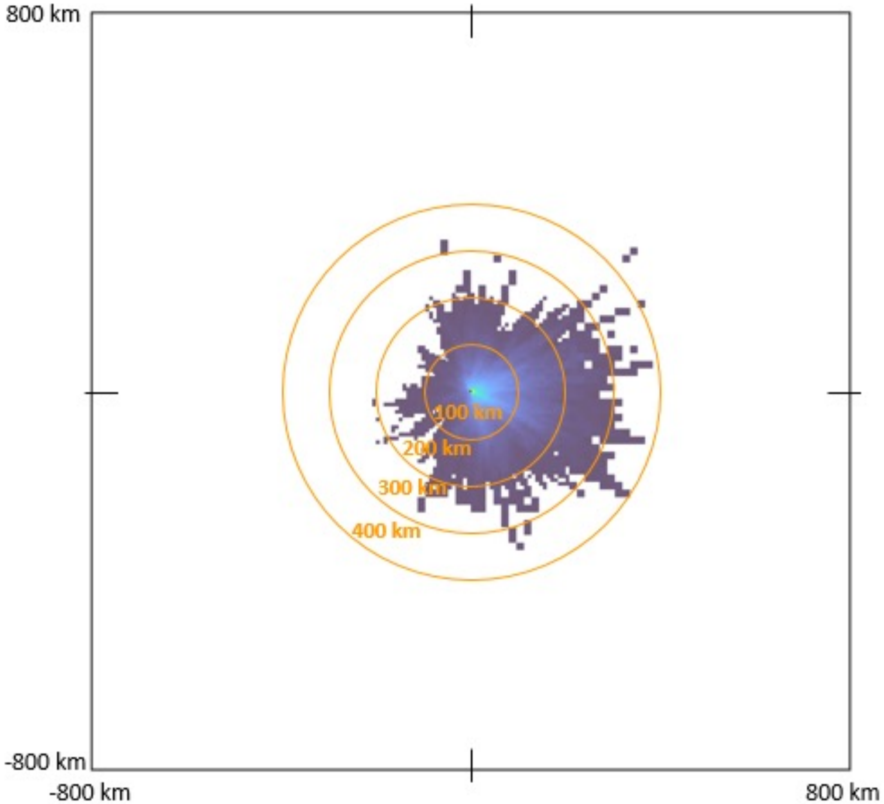
→ Agricultural countermeasures in more than 800 km distance

Overview consequences for 10 kT yield

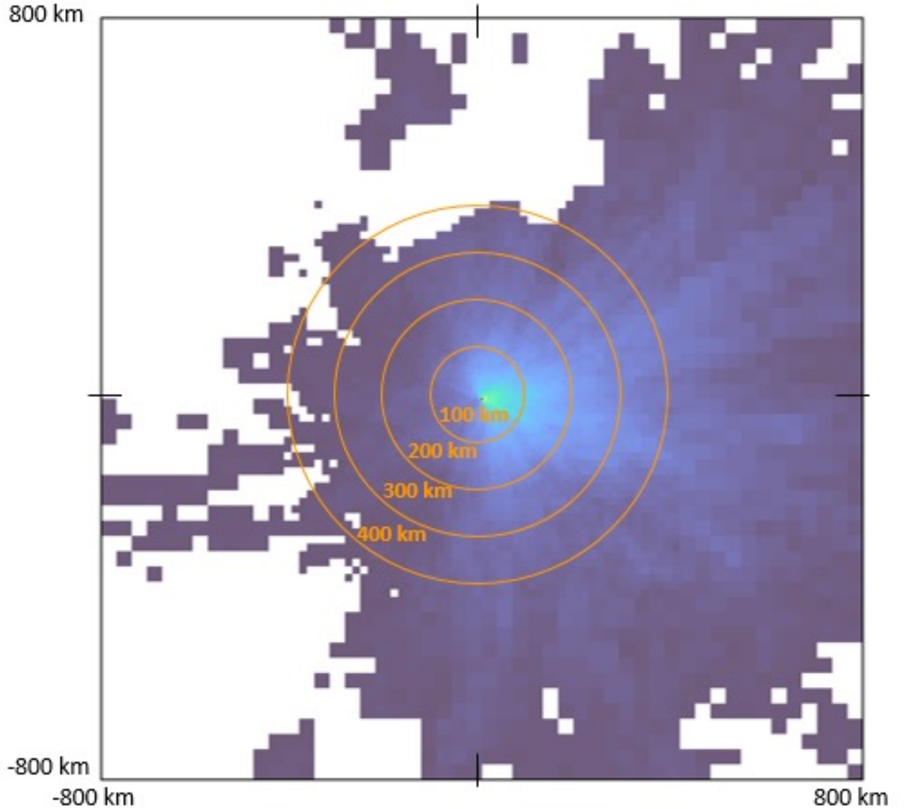
potential **radiological consequences** of a nuclear detonation of 10 kT yield

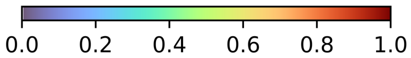


Sheltering of children



Iodine contamination leafy vegetables > threshold





Statistical assessments – Predominant early exposure pathway and protective measures

- In the overwhelming number of cases (weather + location):
  - Inhalation dose is only a minor contributor
  - Ground dose is most important
- Temporal evolution of dose-rate:

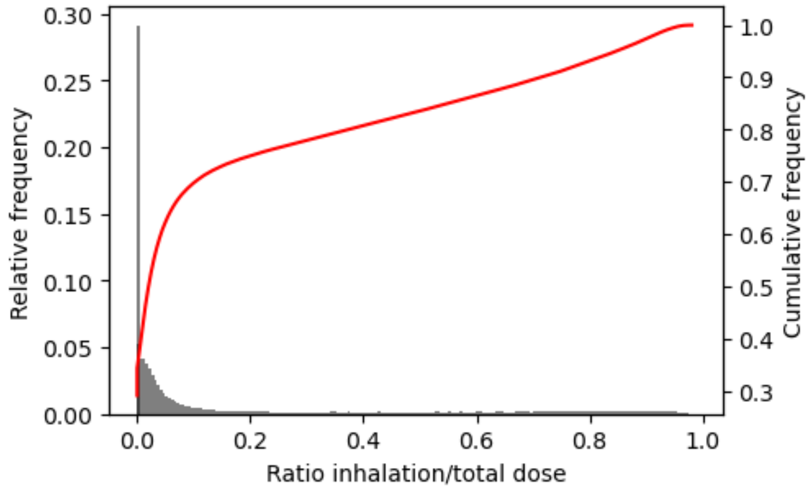
  Power law decline of dose-rate makes **early/immediate** protective measures very important and effective:

  „For every 7-fold increase in time, dose-rate decreases by a factor of 10"

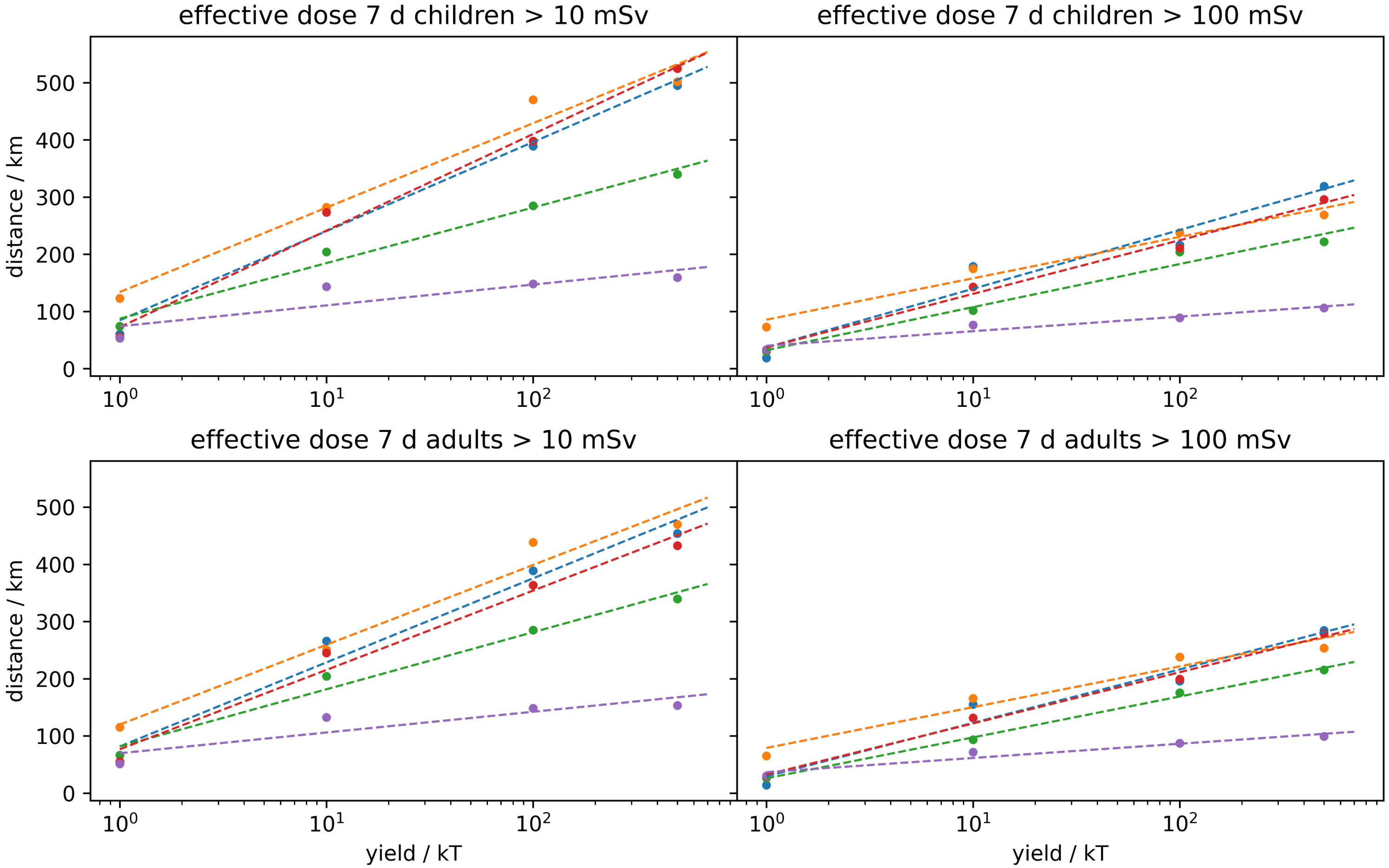
  Recommended actions need to be such that they can be applied by everyone, ideally, without external support

  → **Sheltering!**

Statistics over dose ratios over all locations and 365 weather situations



Dependance on yield – Examples for distinct weather scenarios



Distances for countermeasures scale approximately as

$$\propto a \ln\left(\frac{yield}{\mathrm{kT}}\right) + b$$

but the details depend strongly on weather conditions

Outlook – future work

- Limitations of current dispersion model / implementation using proprietary LASAT atmospheric dispersion model (ADM):
  - calculations only up to 10 km, not validated for high altitudes
  - refined/customizable particle-size distributions
  - enhanced decay-chain calculations (e.g. noble-gas → aerosol decays)

→ Implementation and adaptation of FLEXPART ADM

- Modeling of initial radiation → calculation of ATP-45 zones
- Comparison with historical events (e.g. surface level tests) using reanalysis weather data and unclassified measurements

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Thank you for your attention!

Questions?

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Source term - Geometry

- Parametrizations taken from literature: Glasstone and Dolan, NATO ATP-45

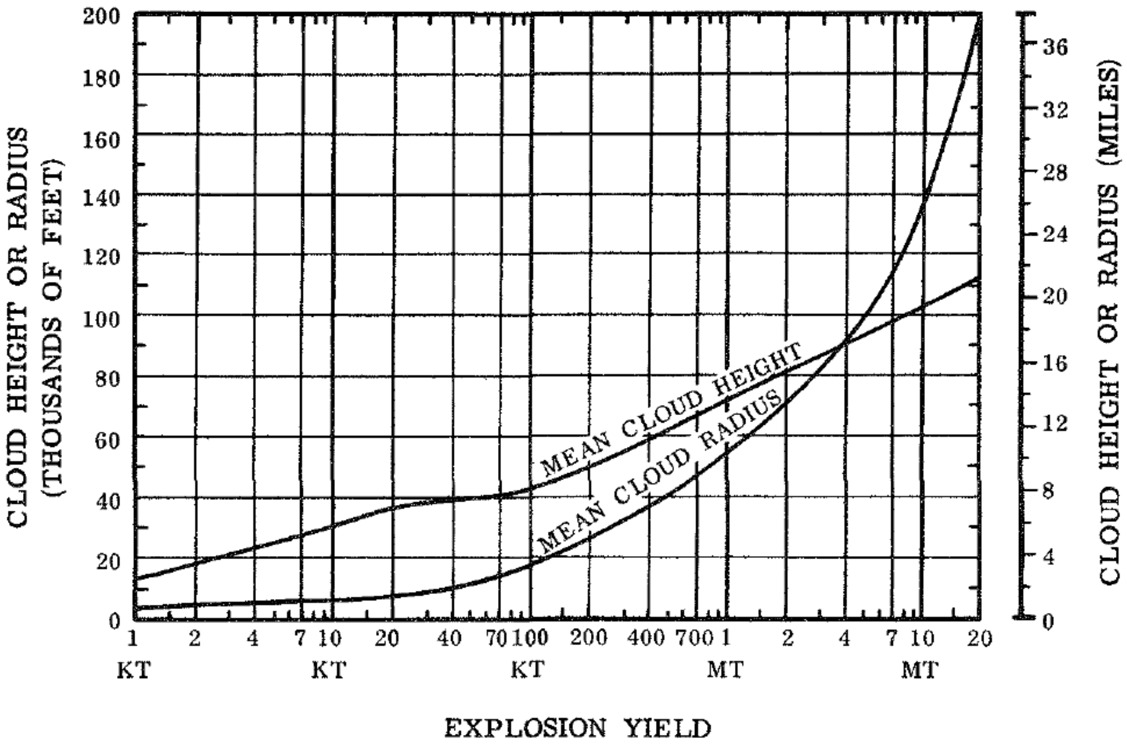


Image: Glasstone and Dolan, 1977

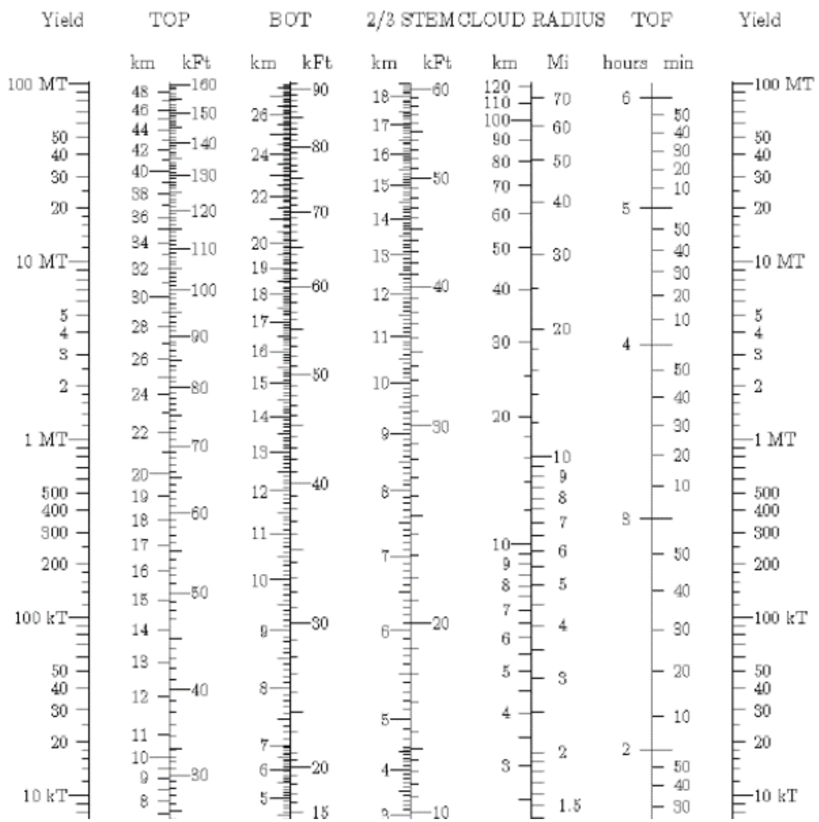
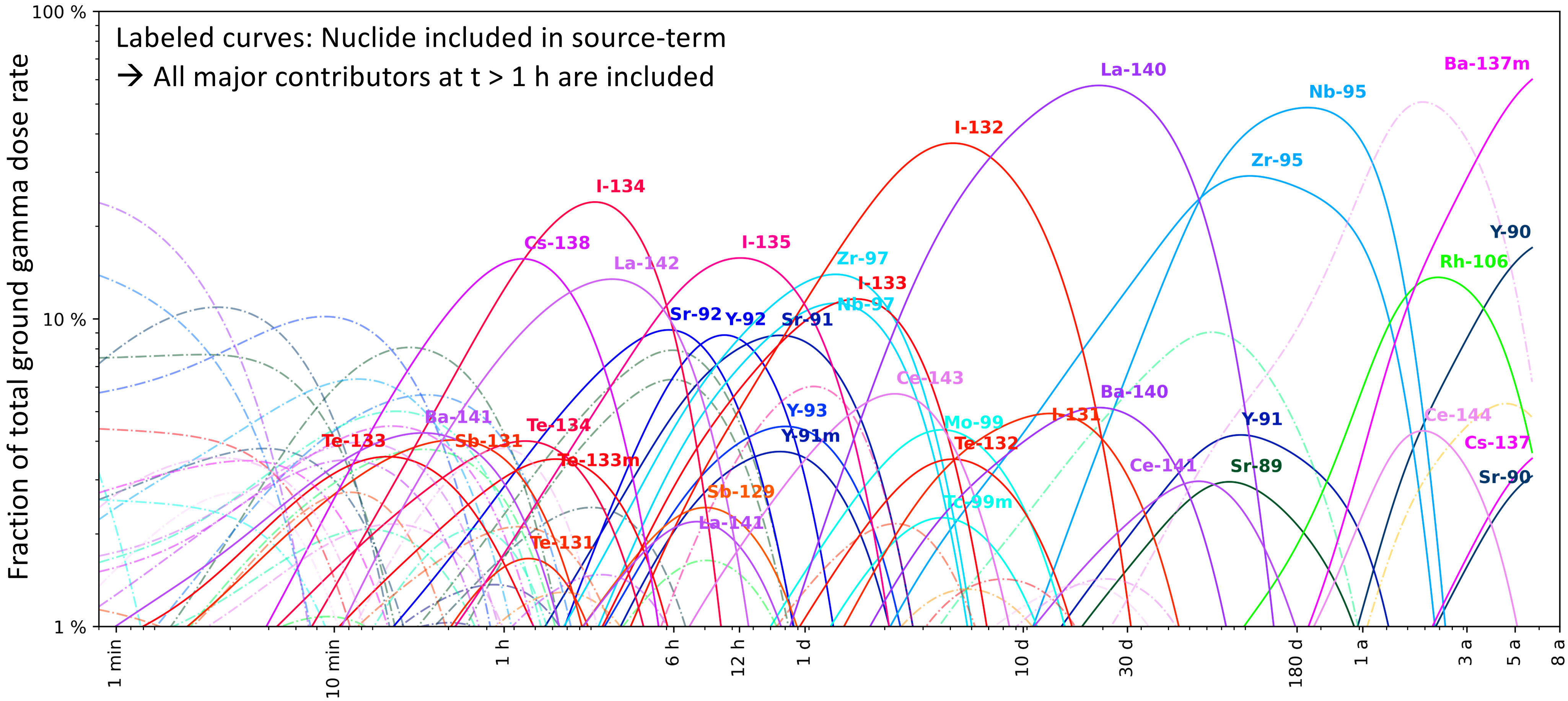


Image: NATO ATP-45, unclassified

Source term – Radioisotopes



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