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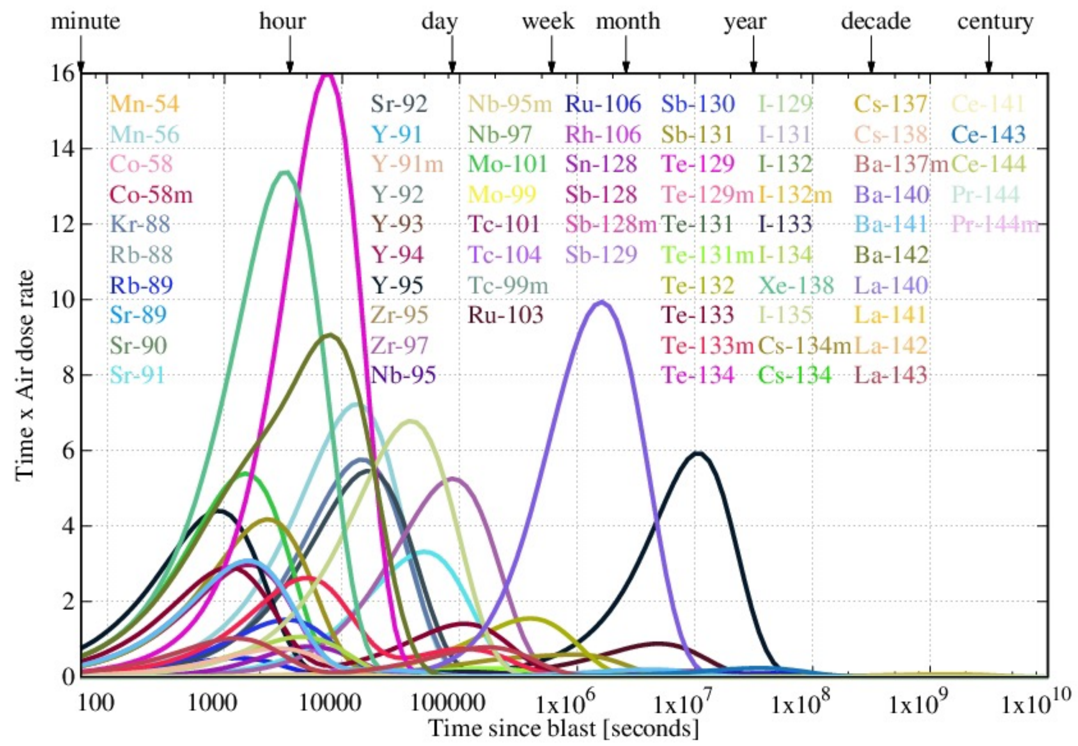

A novel method to estimate the radiological effects of fallout from nuclear detonation

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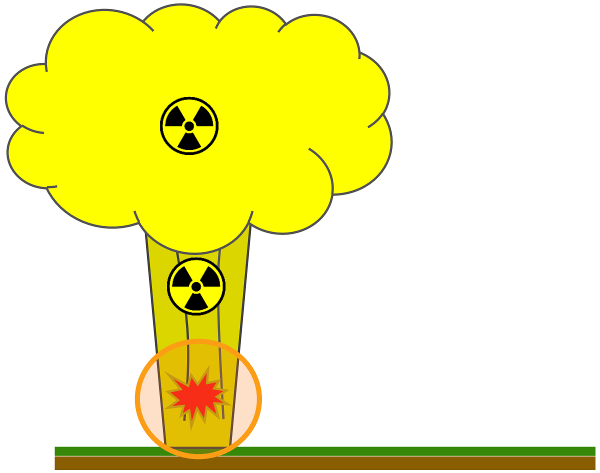
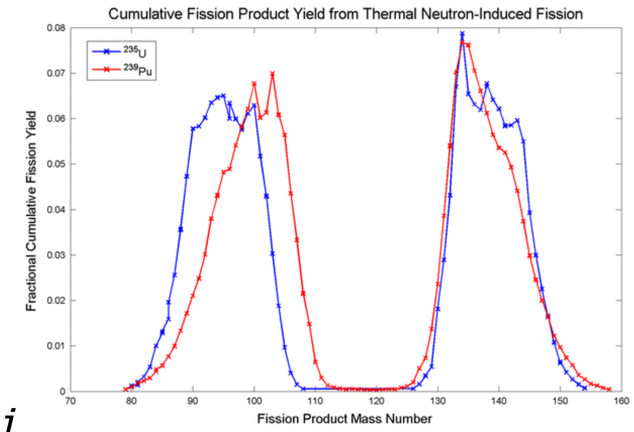
Challenges in modelling dispersion and dose of fallout from nuclear detonation

- **Radionuclide composition**
  - initial composition
  - decay and ingrowth of progeny
  - dose calculation for a large number of radionuclides
- **Stabilized cloud characteristics**
  - geometry based on yield, height of burst, etc.
  - particle size distribution
  - distribution of radioactivity
- **Dispersion over large distance and large height**
  - dispersion above mixing layer
  - availability of meteorological data for emergency response





Decay and ingrowth of progeny

$$\frac{d}{dt}A_i(t) = \sum_j M_{ij}A_j(t), \qquad M_{ij} = \nu_{ij}\lambda_i, \quad \lambda_i = \ln(2)/T_{1/2,i}$$

ν_{ij}=yield if $i \neq j$

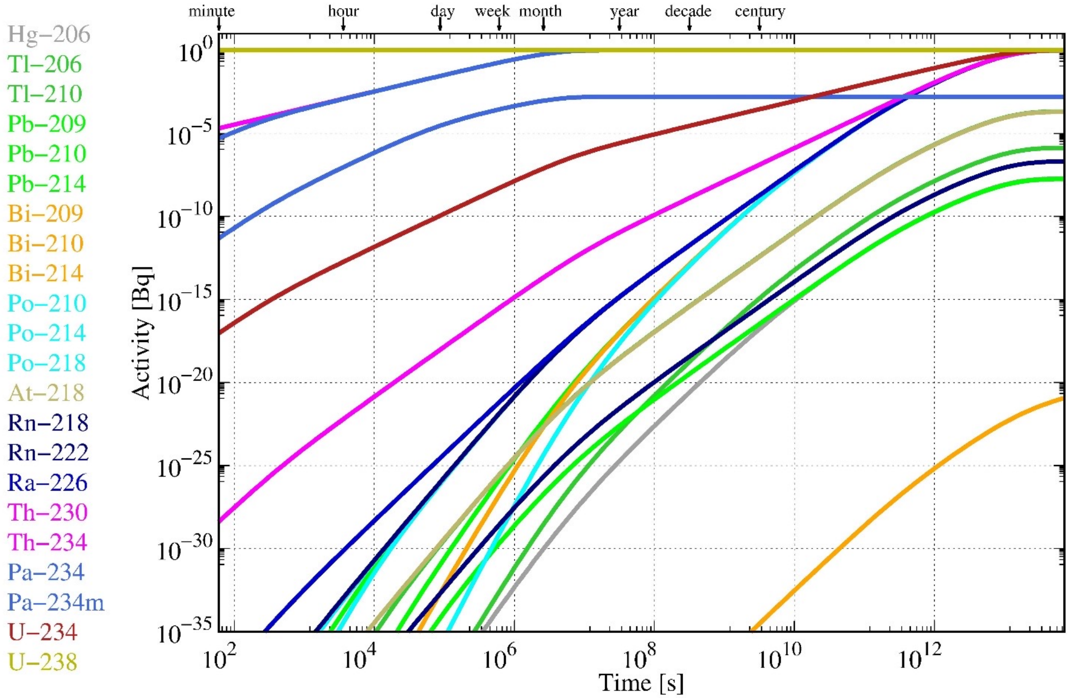
ν_{ij}=-1 for $i=j$ (clean decay)

$$A_i(t) = \sum_j H_{ij}(t) \cdot A_j(0),$$

with $H_{ij}(t)$ the components of matrix-exponential $H(t) = e^{Mt}$

- Matrix-exponential solved numerically (once) using 3821 radionuclides from Evaluated Nuclear Data File (ENDF) from IAEA (Brown et al., 2018).
- Human life in 1-minute steps: 42 million pinpoints... → not feasible...
- However, eigen values of matrix exponential $H(t) = e^{Mt}$ are decaying: this allows for using exponentially growing timesteps.
- → shortest delay: 60 sec, growth factor of 1.15 → 2.6 million year assessment using only 200 timesteps!

Example 1: daughters of 1 Bq ^{238}U

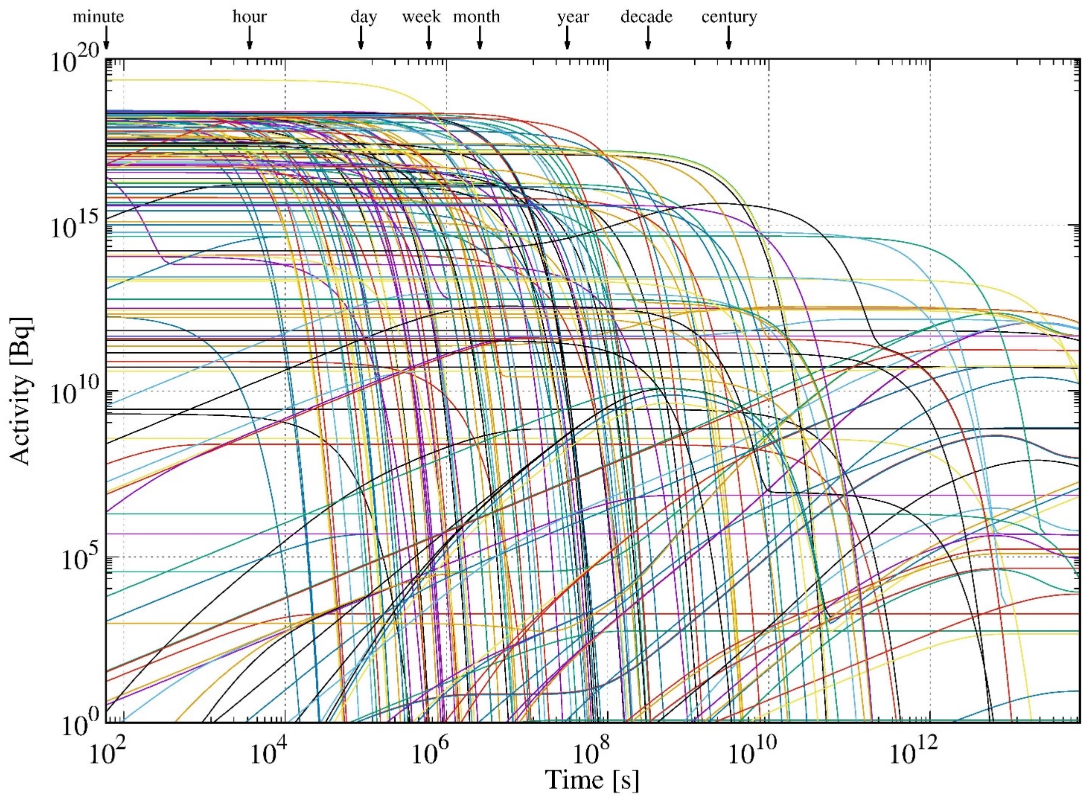


$$A_i(t) = \sum_j H_{ij}(t) \cdot A_j(0)$$

(The only element in $A_j(0)$ that is non-zero is ^{238}U: 1 Bq.)

$$T_{1/2}^{238U} = 1.41 \cdot 10^{17} \text{ sec}$$

Example 2: core inventory of Borssele NPP after shutdown



Dose calculation

E.g. external radiation in cloud:

$$D_{\mathrm{ext,air}}(\boldsymbol{x}, t_1 \rightarrow t_2) = \int_{t_1}^{t_2} \sum_i DCC_{\mathrm{ext,air},i}\, \rho_i(\boldsymbol{x}, \tau)\, \mathrm{d}\tau$$

Bq m^{-3}

Sv h^{-1} Bq^{-1} m^{3}

Common method: reduction of considered radionuclides:

- requires prior assessment of the source term for each pathway;
- is always an approximation of the dose;
- is computationally expensive: for a better approximation of dose, more nuclides should be considered;
- is prone to error; e.g. when considering another exposure interval, it's easy to forget to perform a new nuclide reduction assessment.

Dose conversion factors (DCCs) from:
<u>Inhalation:</u>
ICRP Publication 119 (2012)
Kawai et al. (2002)
<u>External radiation:</u>
EDC-Viewer, conform ICRP Publication 144 (ICRP, 2020)

Dose calculation revisited

$$D_{\text{ext,air}}(\boldsymbol{x}, t_1 \to t_2) = \int_{t_1}^{t_2} \sum_i DCC_{\text{ext,air},i}\, \rho_i(\boldsymbol{x}, \tau)\, \mathrm{d}\tau$$

$$DCC_{\text{air,cocktail}}(t) = \sum_i DCC_{\text{air},i} \sum_j H_{ij}(t) A_j(0)$$

Radioactivity
1. has same origin in time
2. does not 'unmix'

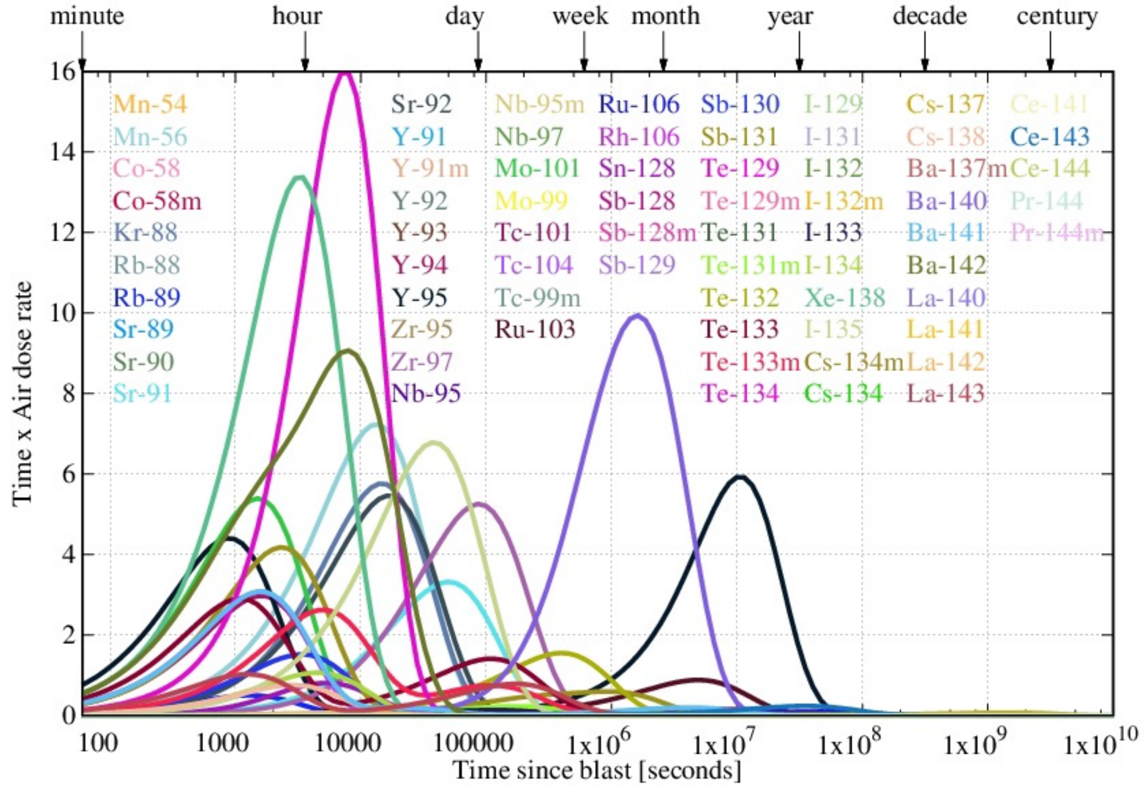
$$D_{\text{ext,air}}(\boldsymbol{x}, t_1 \to t_2) = \int_{t_1}^{t_2} DCC_{\text{ext,air,cocktail}}(\tau)\, T_{\text{air}}(\boldsymbol{x}, \tau)\, \mathrm{d}\tau$$

$$T_{\text{air}}(\boldsymbol{x}, \tau) = \rho_{\text{passive}}(\boldsymbol{x}, \tau) / A_{\text{passive}}(0)$$

- Dose contribution of *all* nuclides included in a single 'cocktail DCC',
- including effects of decay and ingrowth of nuclide 'cocktail' $A_j(0)$.
- The cocktail-DCC is thus time-dependent → can be pre-calculated and saved in look-up tables.
- The dispersion calculation is reduced to a *single* non-decaying tracer to determine 'thinning coefficients'. $T_{\text{air}}(\boldsymbol{x}, \tau)$ and $T_{\text{ground}}(\boldsymbol{x}, \tau)$.

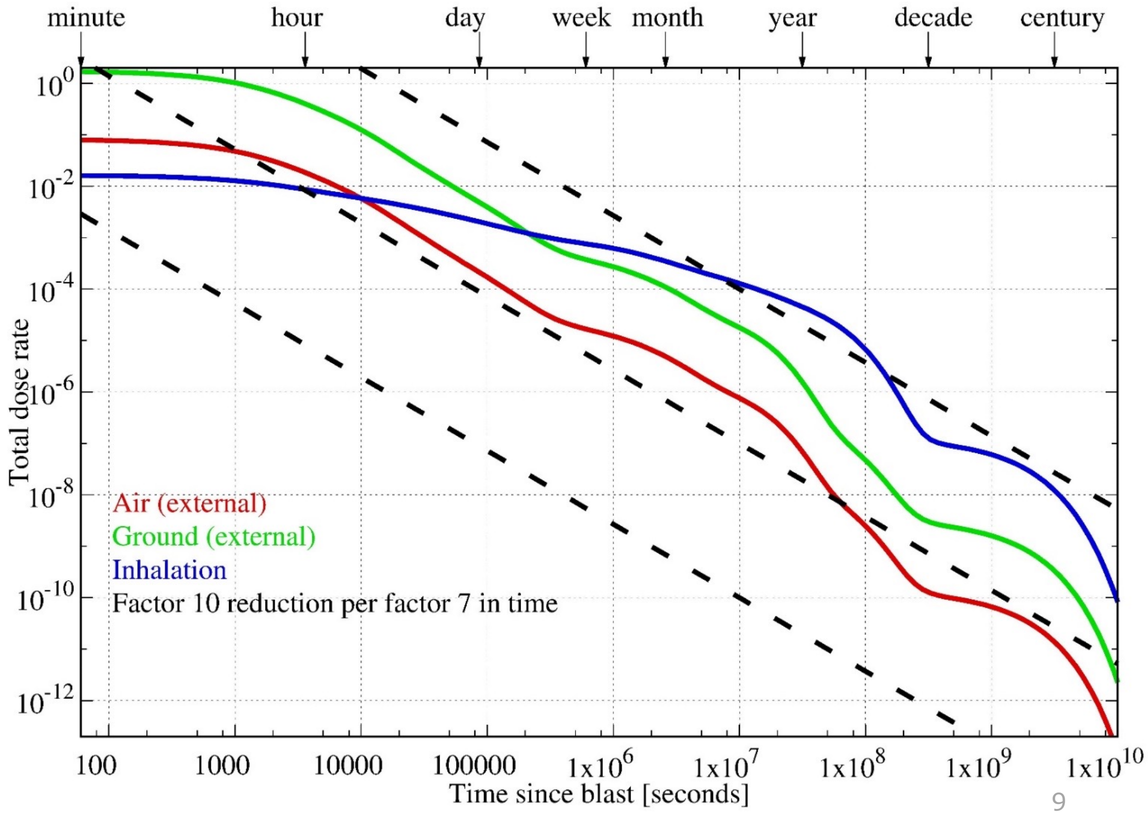
Application to nuclear detonation source term

- Initial nuclide composition: uranium weapon $A_j(0)$: 69 radionuclides, t=2.5 minutes after detonation (Kraus & Foster, 2014).
- The figure shows the contribution to the external dose rate in air of head-of-chains *including* progeny.



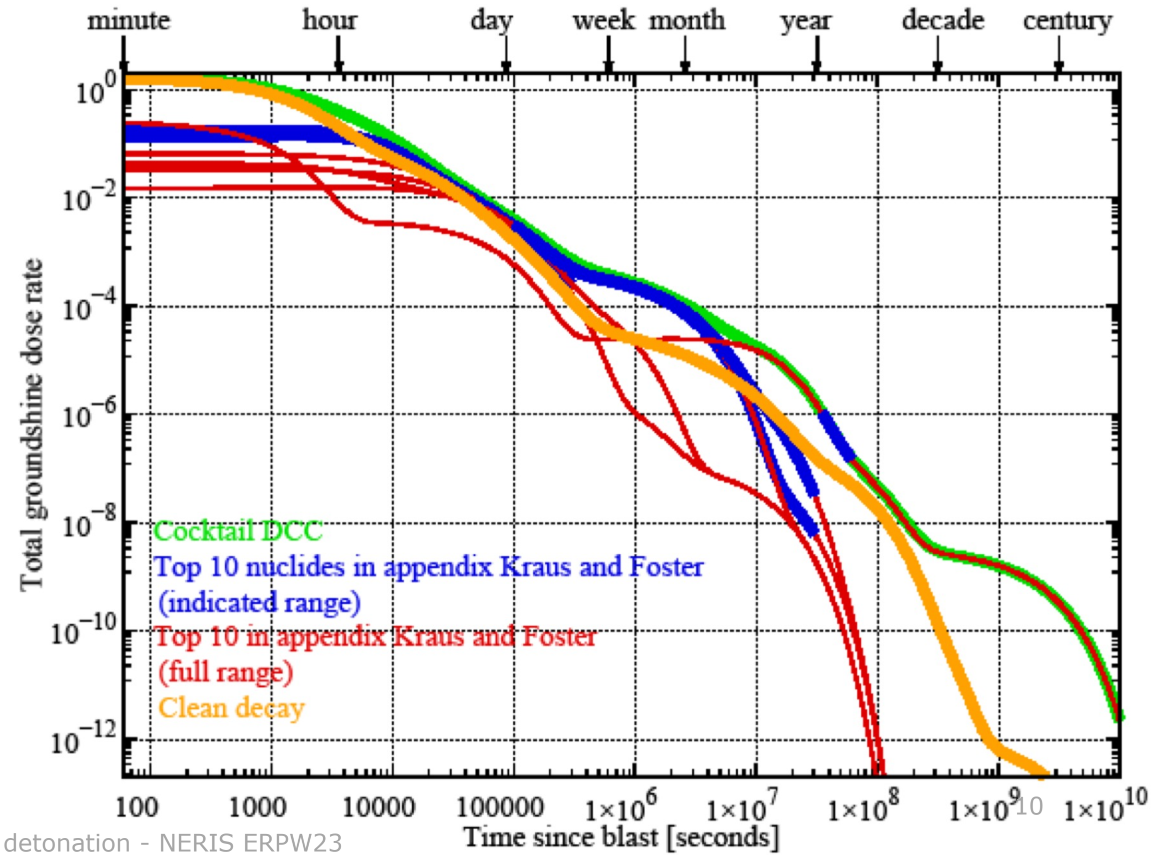
Application to nuclear detonation source term

- Initial nuclide composition: uranium weapon $A_j(0)$: 69 radionuclides, t=2.5 minutes after detonation (Kraus & Foster, 2014).
- The figure shows the total dose rate over time compared to rule-of-thumb by Glasstone & Dolan (1977).



Application to nuclear detonation source term

- Effect of ingrowth of progeny vs. clean decay.
- Effect of nuclide selection based on exposure interval.

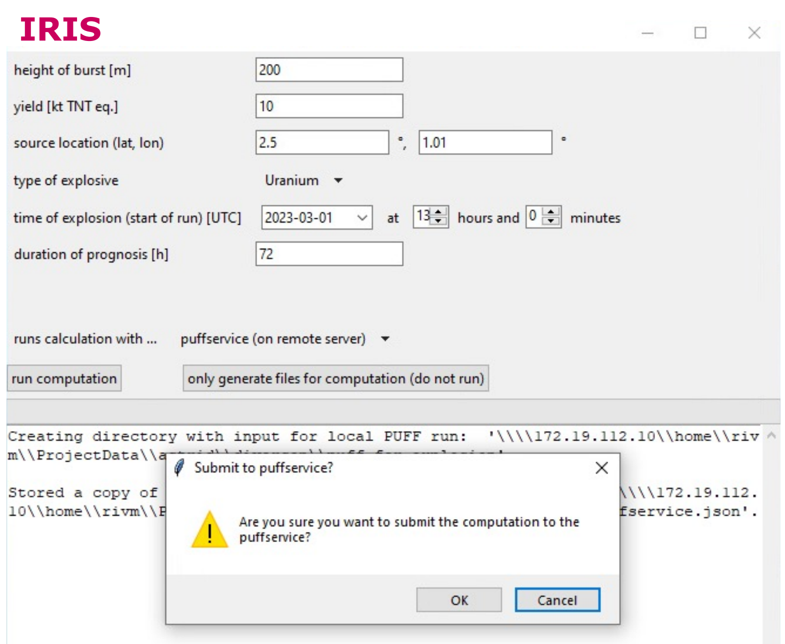


Application in tool IRIS

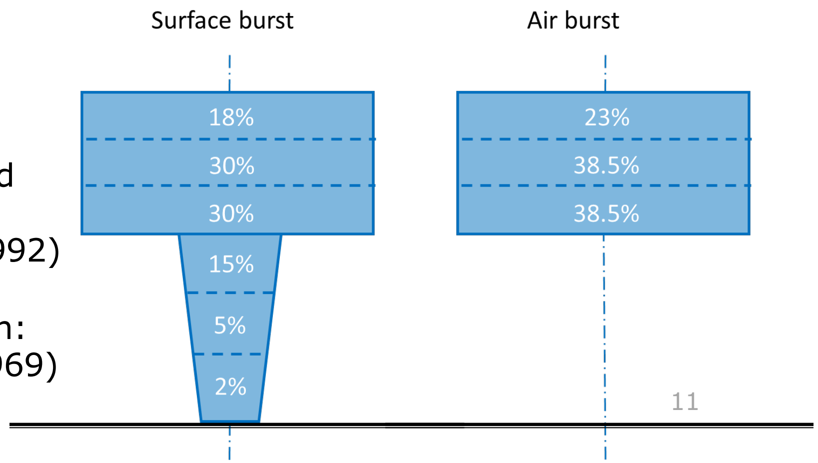
- 100 kT yield uranium weapon, source term Kraus & Foster (2014) (69 initial nuclides).
- Dispersion model NPK-Puff, 48h prognosis.
- Meteorology: ECMWF-HRES, resolution 0.1°, 15 levels up to 11.5 km height.
- Instantaneous plume: 1491 puffs.
- Particle size distribution:

Interpretation of Baker (1987)

Particle radius	Median radius	Surface burst	Air burst
(in µm)		fraction of total activity (in %)	
< 0.1	0.05	0.44	1.63
0.1-1	0.55	22.47	76.05
1-5	3	20.11	9.30
5-10	7.5	12.63	0.02
10-50	30	23.96	0
> 50	100	7.38	0
Gaseous	-	13	13
	Total	100.00	100.00

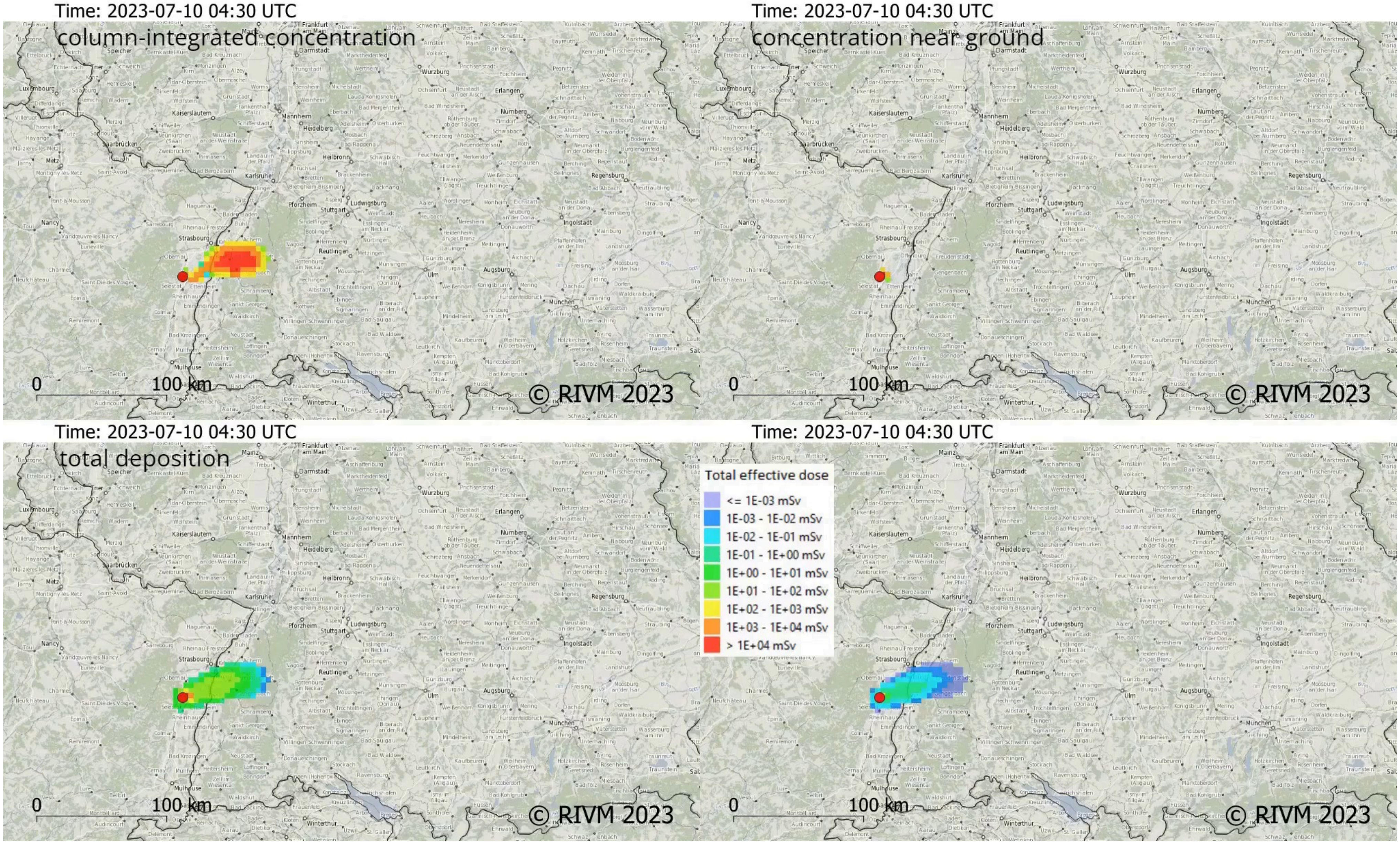


Vertical distribution of radioactivity:



Initial cloud geometry: Harvey (1992)

Distribution: Heffter (1969)


Time: 2023-07-10 04:30 UTC
column-integrated concentration
0
100 km
© RIVM 2023
Time: 2023-07-10 04:30 UTC
concentration near ground
0
100 km
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Time: 2023-07-10 04:30 UTC
total deposition
0
100 km
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Time: 2023-07-10 04:30 UTC
Total effective dose
<= 1E-03 mSv
1E-03 - 1E-02 mSv
1E-02 - 1E-01 mSv
1E-01 - 1E+00 mSv
1E+00 - 1E+01 mSv
1E+01 - 1E+02 mSv
1E+02 - 1E+03 mSv
1E+03 - 1E+04 mSv
> 1E+04 mSv
0
100 km
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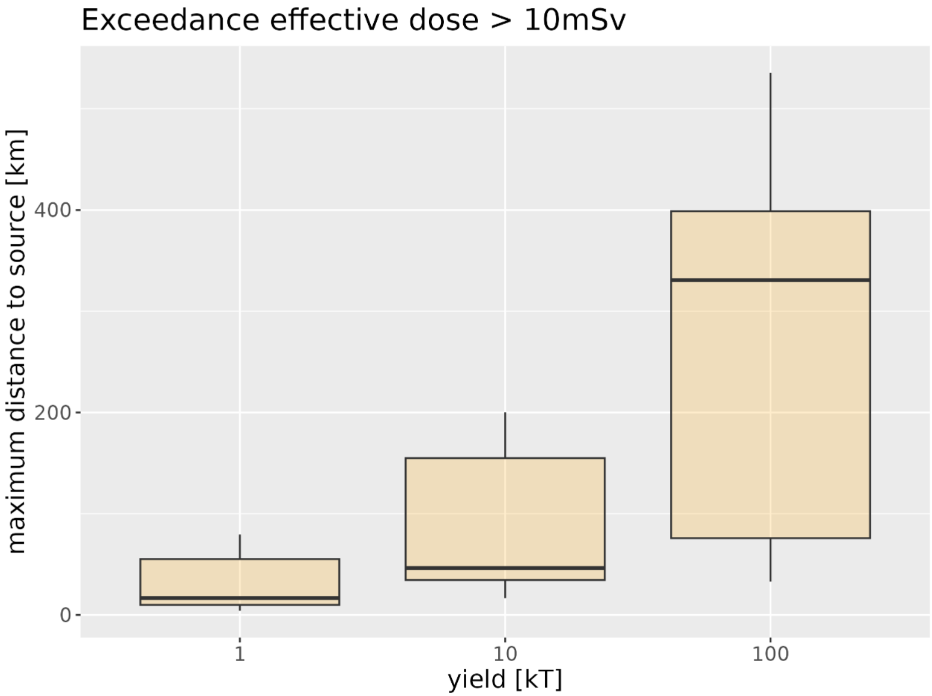
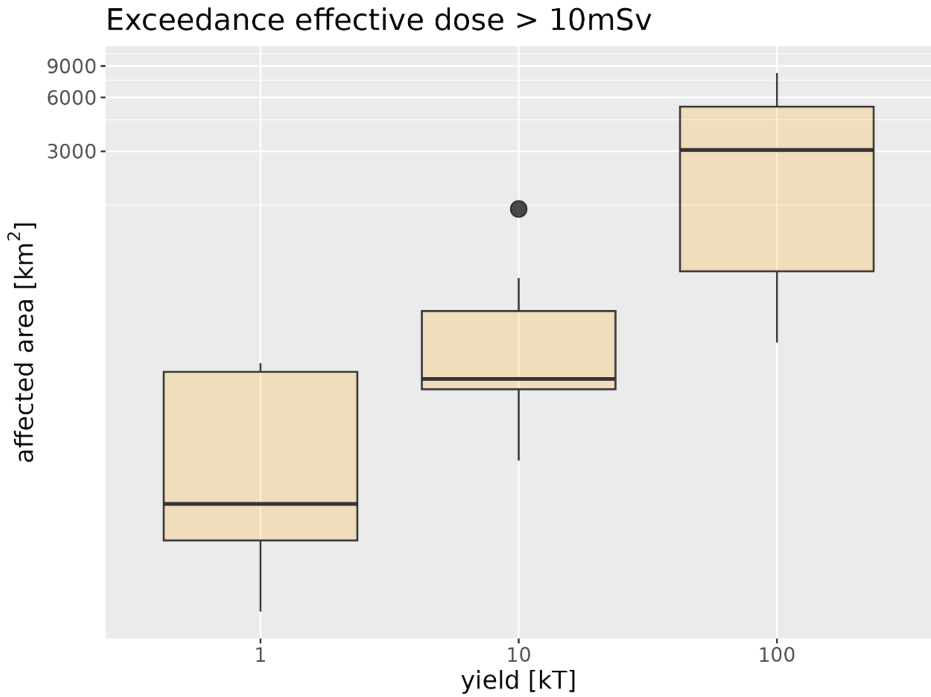
Outlook: gathering statistics





Conclusions (1/2)

- We have developed a fast method to compute decay and progeny for *all* 3821 radionuclides.
- We introduce the concept of a precalculated ‘cocktail-DCC’ for each exposure pathway that only requires multiplication with thinning factors (computed by a dispersion model) to compute the dose rate.
- Complete dose assessment is now possible, because it is not needed anymore to preselect a limited number of radionuclides for specific exposure intervals.
- The method is computationally much more efficient than traditional dispersion+dose assessment method.
- It is easily extendable with additional cocktail-DCC(s) and tracer(s) for e.g. nuclide group(s) with different dispersion characteristics and/or different reference time(s).

Conclusions (2/2)

- Nuclides that contribute less to dose are *also* included in modelling result: useful for measurement campaigns and detection of nuclear weapon tests.
- The method can be applied to *any* type of release as long as 1) no-unmixing principle holds and 2) released radioactivity has the same reference time. (e.g. instantaneous release from a reactor, or (dis)continuous release from reactor after shutdown).

Thank you for your attention!

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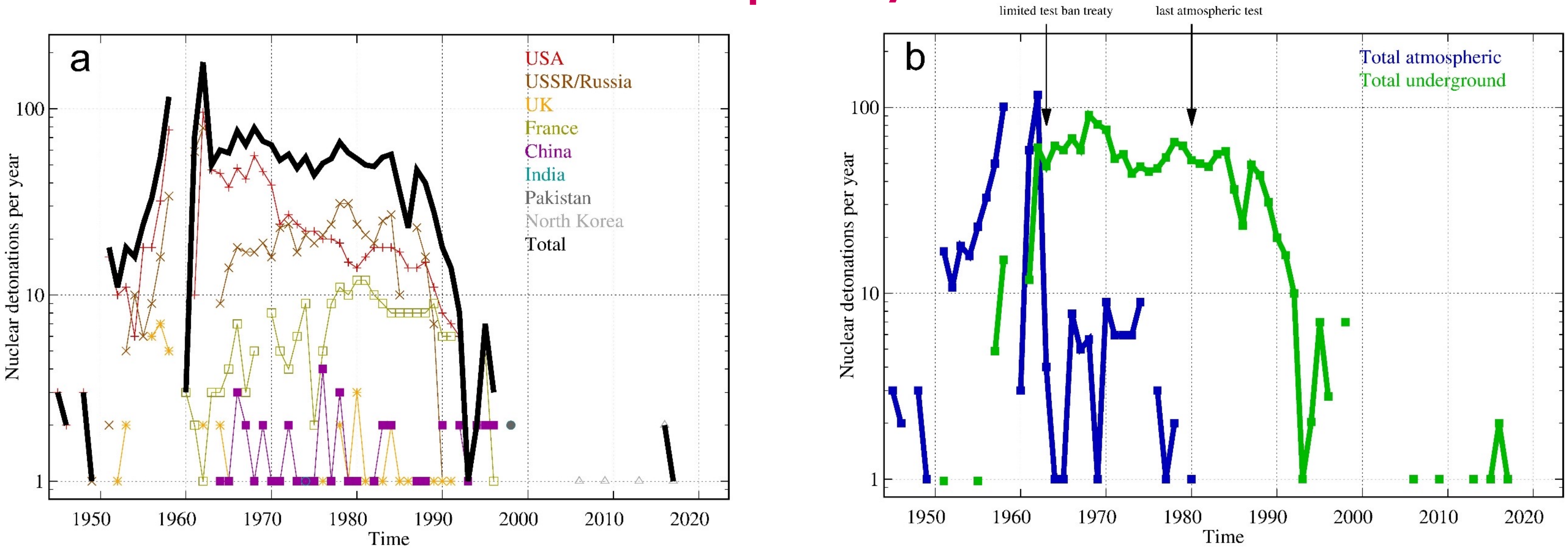
Nuclear detonations per year



Nuclear detonations in the course of time. Left: per country (data from Kimball (2022)) and right: atmospheric and underground (data from Reuters (2017))

Surface burst when:
$HOB < 180 * W^{0.4}$
HOB in [feet]
W in [kT TNT-eq]

Yield [kT TNT]	Surface burst when HOB < [m]
10	138
20	182
30	213
50	262
75	309
100	346

“Height of burst”

‘(Near) surface burst’
- Fission products
- Activation products
- Larger particles

‘Free Air burst’
- Fission products
- Few/no activation products
- Smaller particles