3D radiological modelling techniques

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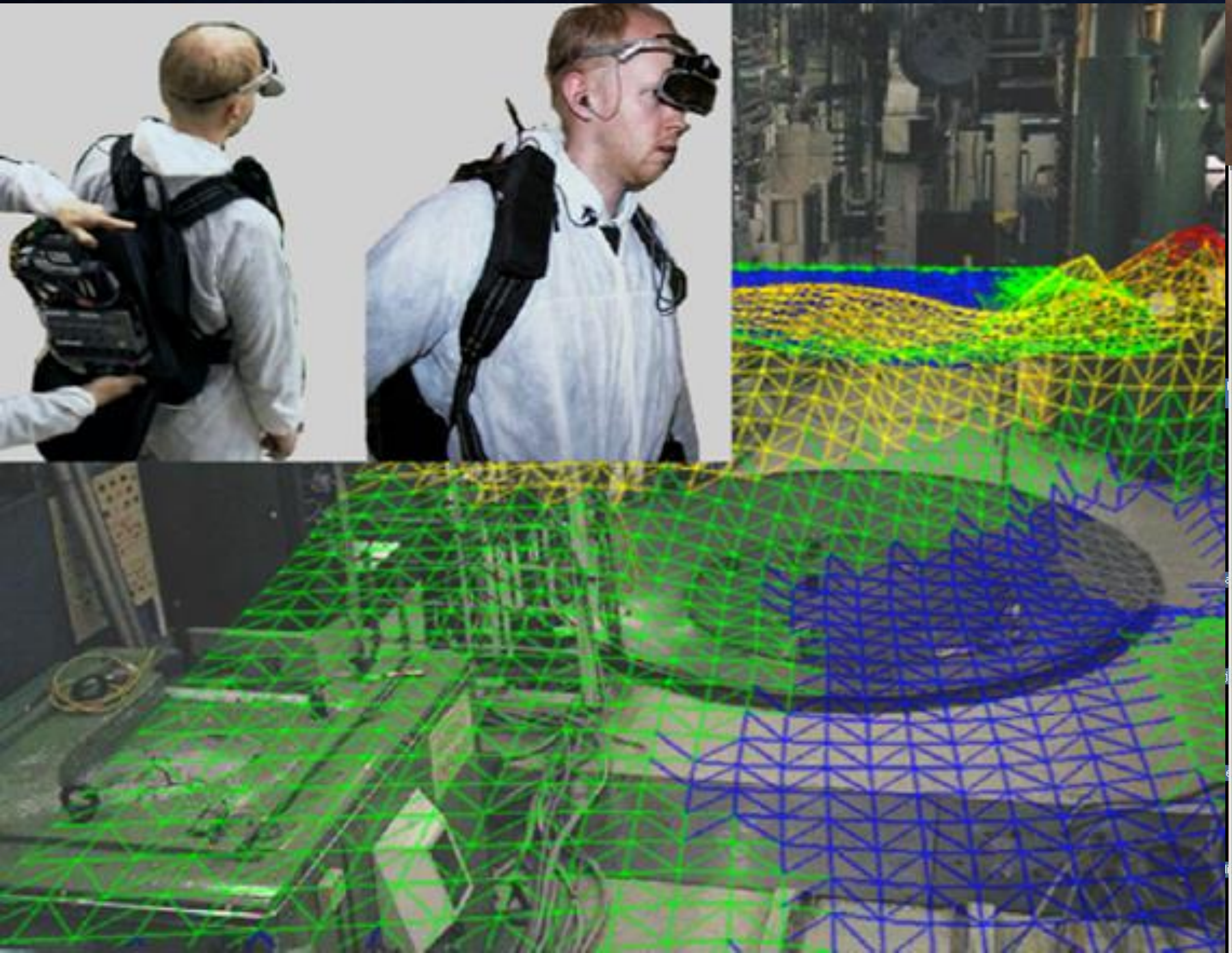
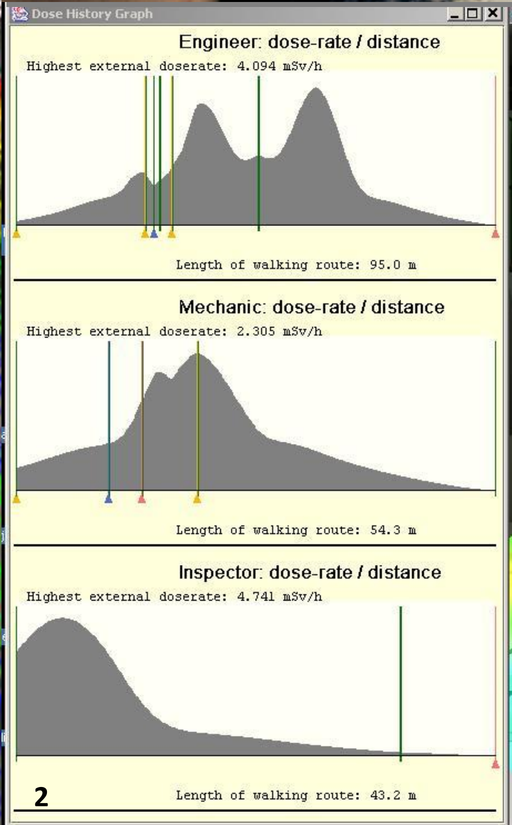
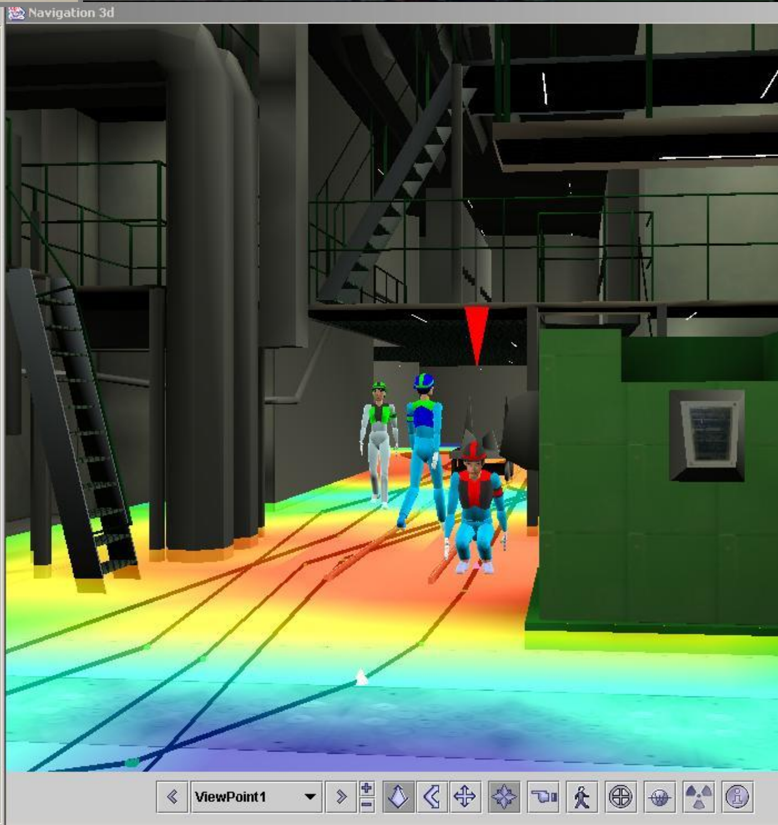
Digital support concepts in nuclear environments

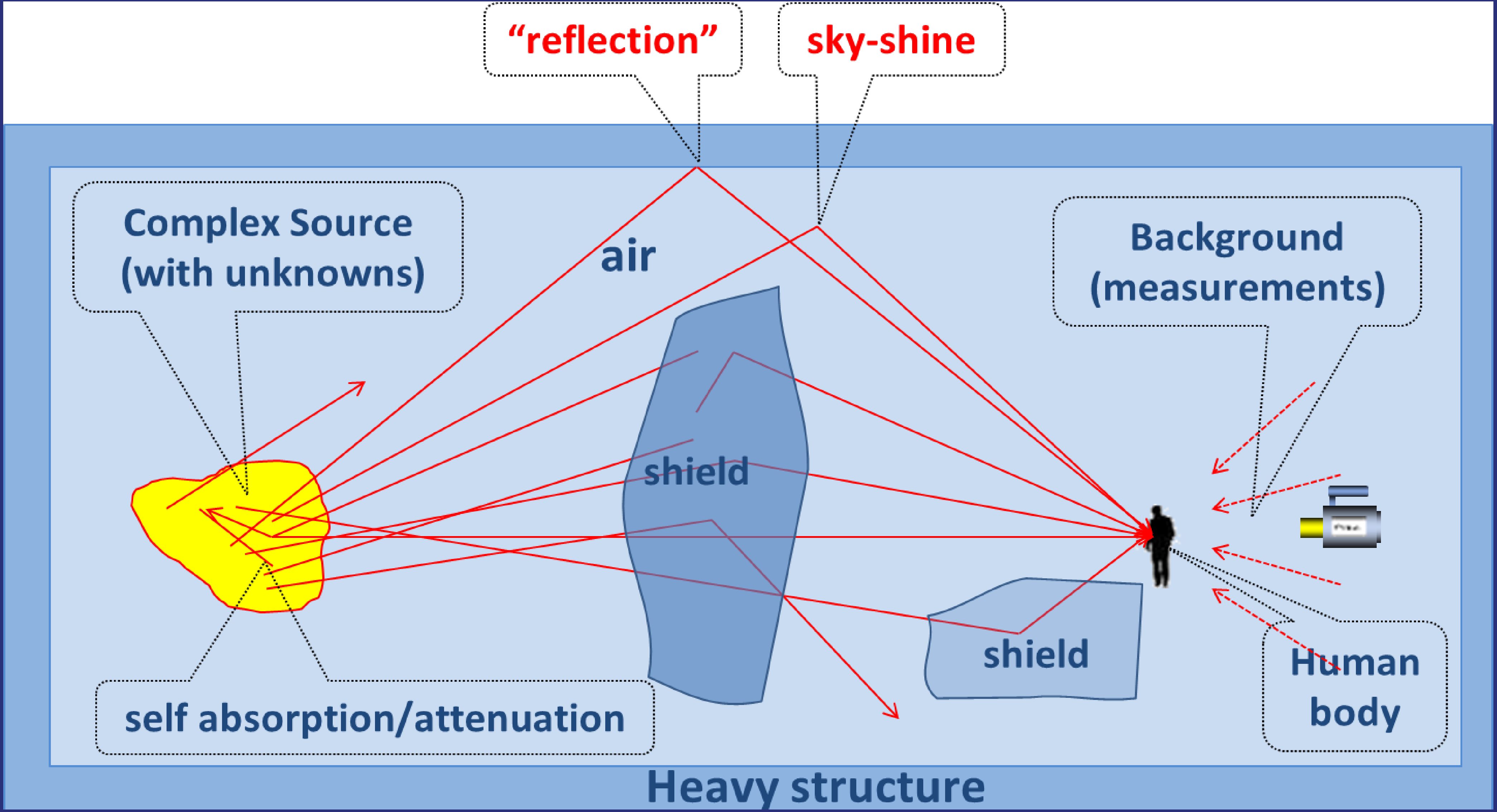
(since 1996 till today)



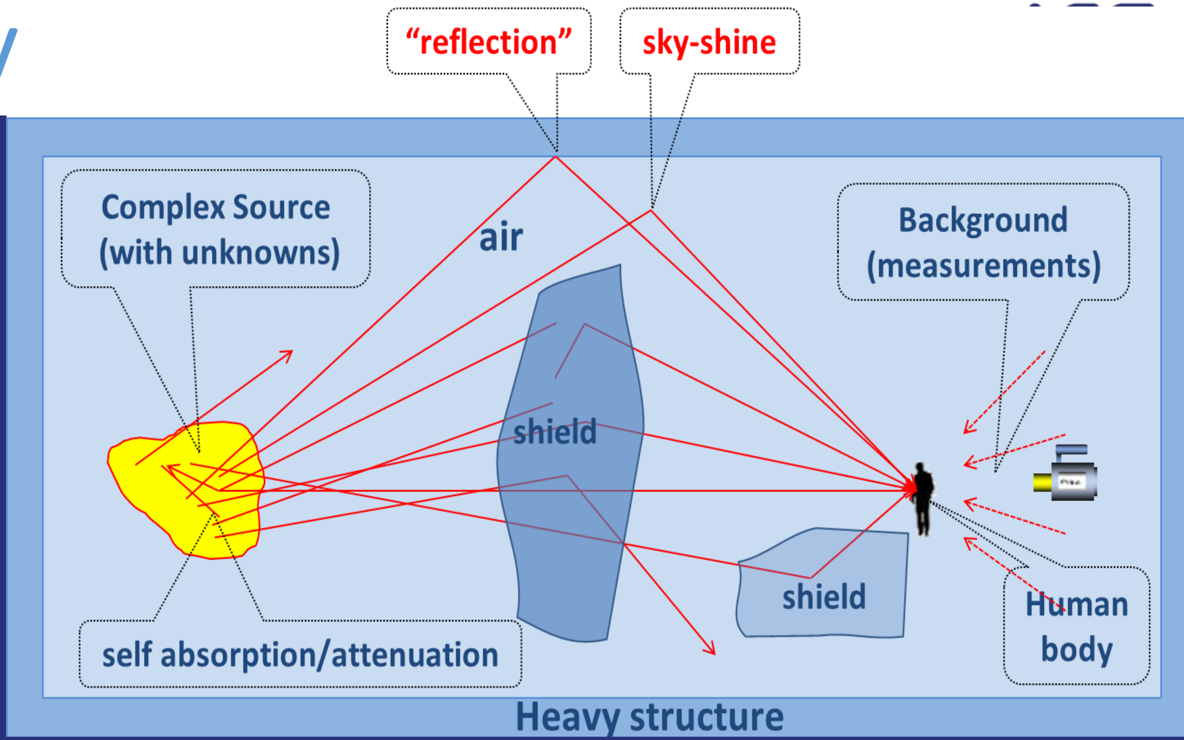




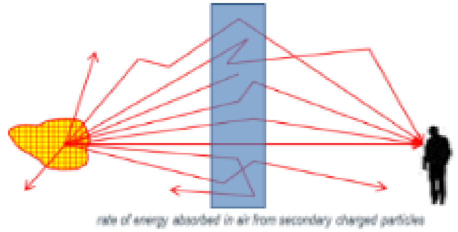
Radiation transport and dosimetry



Radiation transport and dosimetry



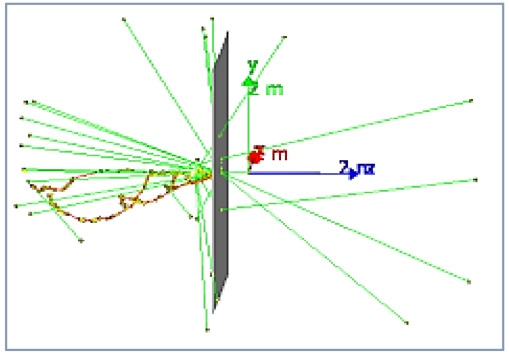
Real-time (Point Kernel) radiation transprot



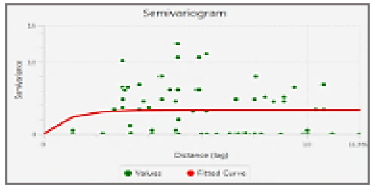
$$Dose = Const \times \sum_i \left(\frac{Ay_i}{4\pi d^2} \times e^{-\mu_i \times t} \times E_i \cdot (\mu_{en}/\rho)_i \times B_X(E_i, t) \right)$$

conversion of units $\Phi_i(natt)$ $\Phi_i(att)$ $\Psi_i(att)$ CF

MC radiation trasport (MCNP, GEANT4)

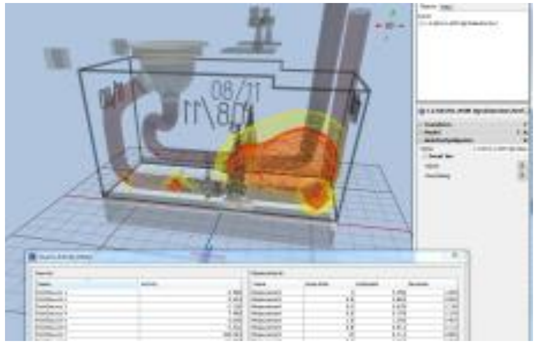


Interpolation, Geostatistics

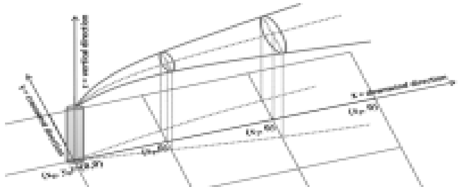


$$Z^*(\mathbf{u}) = m(\mathbf{u}) + \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_\alpha(\mathbf{u})[Z(\mathbf{u}_\alpha) - m(\mathbf{u})]$$
$$= \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_\alpha(\mathbf{u}) Z(\mathbf{u}_\alpha) + \left[1 - \sum_{\alpha=1}^{n(\mathbf{u})} \lambda_\alpha(\mathbf{u})\right] m(\mathbf{u})$$

Source deconvolution



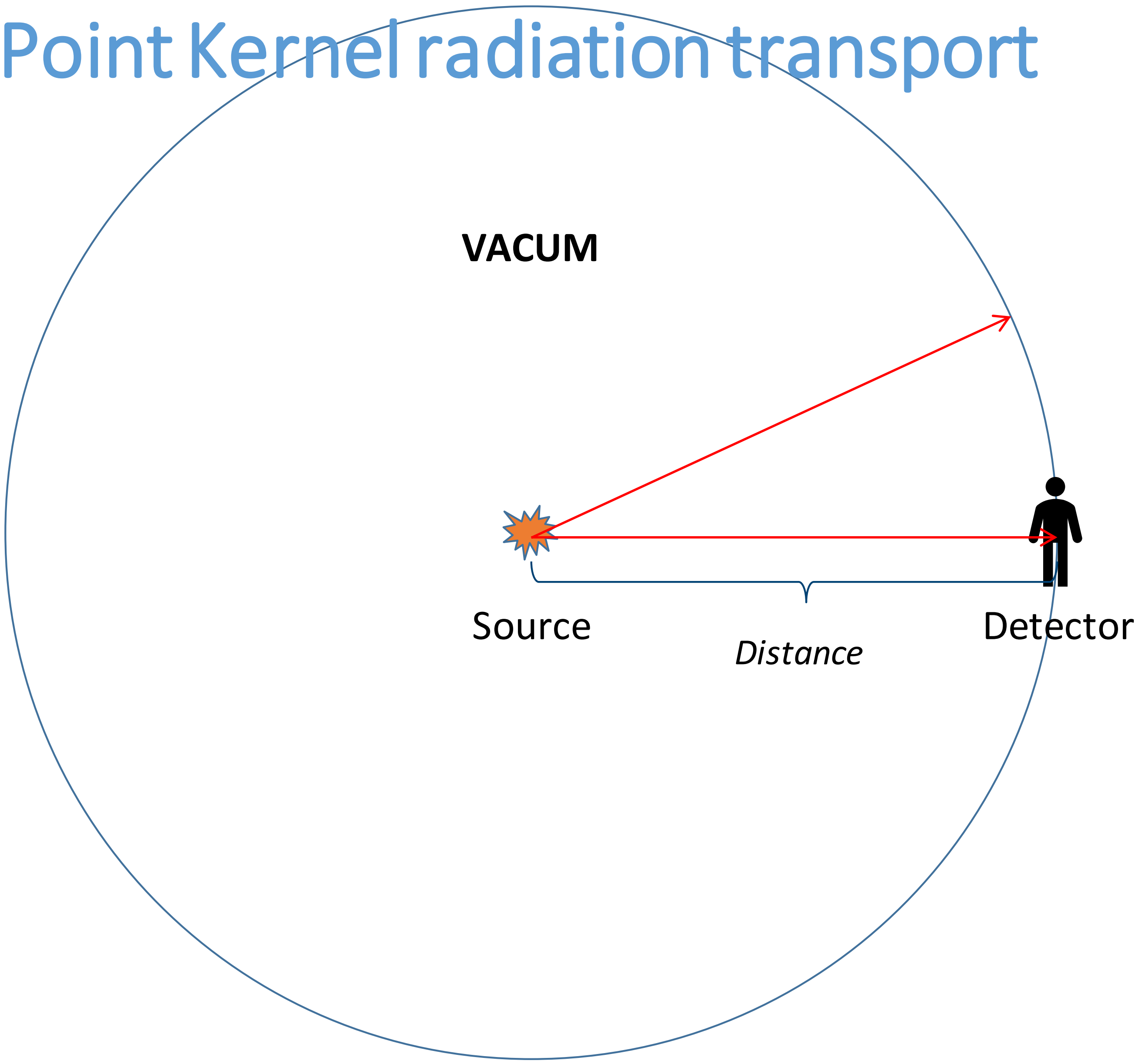
Atmospheric dispersion



$$C(x,y,z) = \frac{Q(x)}{2\pi \cdot \sigma_y(x) \cdot \sigma_z(x) \cdot u_{10}} exp\left[\frac{-y^2}{2\sigma_y(x)^2}\right] F(x,z)$$

$$C(x,y,z) = \frac{Q(x)}{\sqrt{2\pi} \cdot \sigma_y(x) \cdot A \cdot u_{10}} exp\left[\frac{-y^2}{2\sigma_y(x)^2}\right]$$

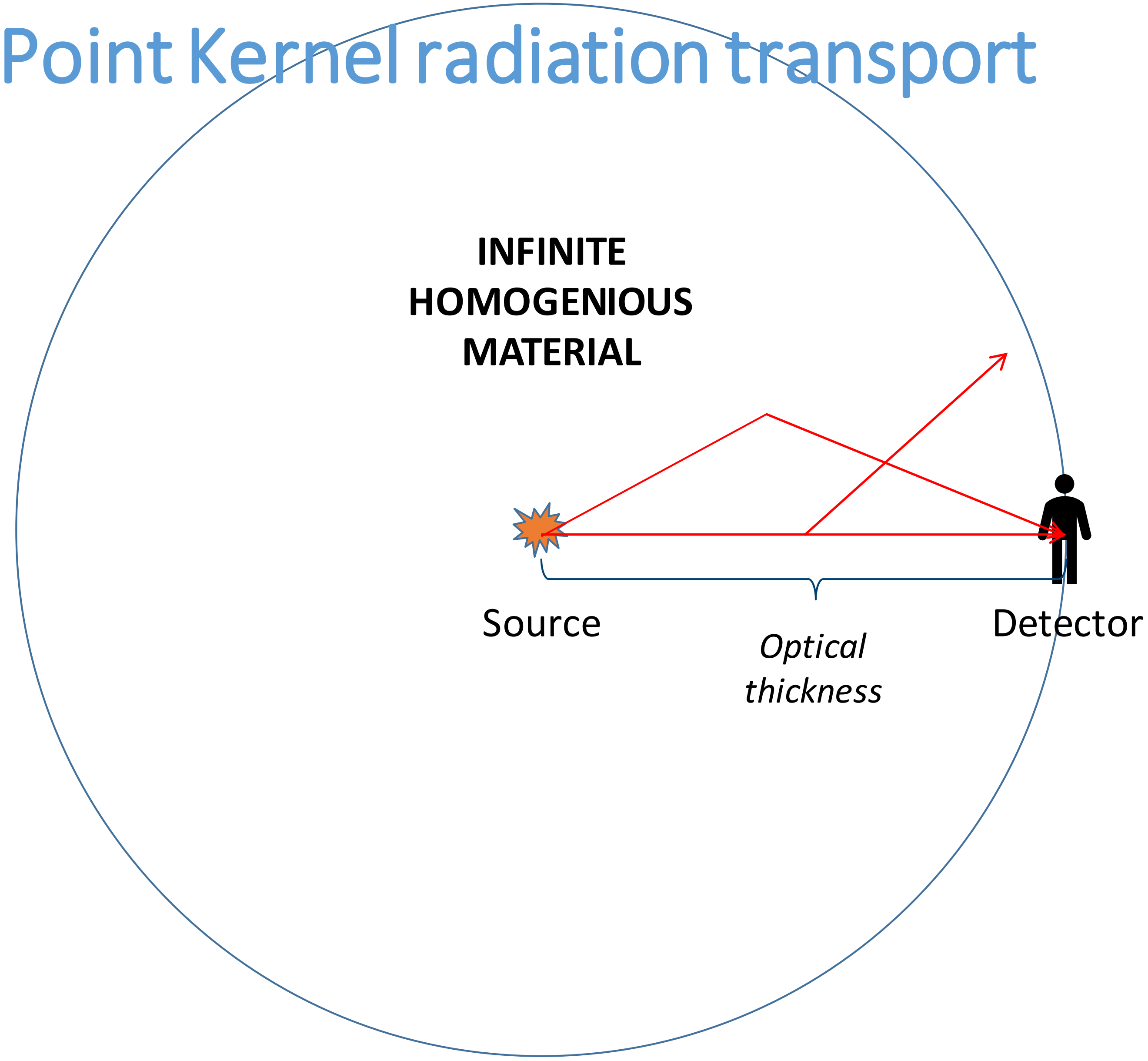
Point Kernel radiation transport



$$Dose = flux * conversion\ factor_{energy}$$

$$Flux = \frac{Number\ of\ particles}{Surface\ area\ of\ sphere\ (cm^2)}$$

Point Kernel radiation transport

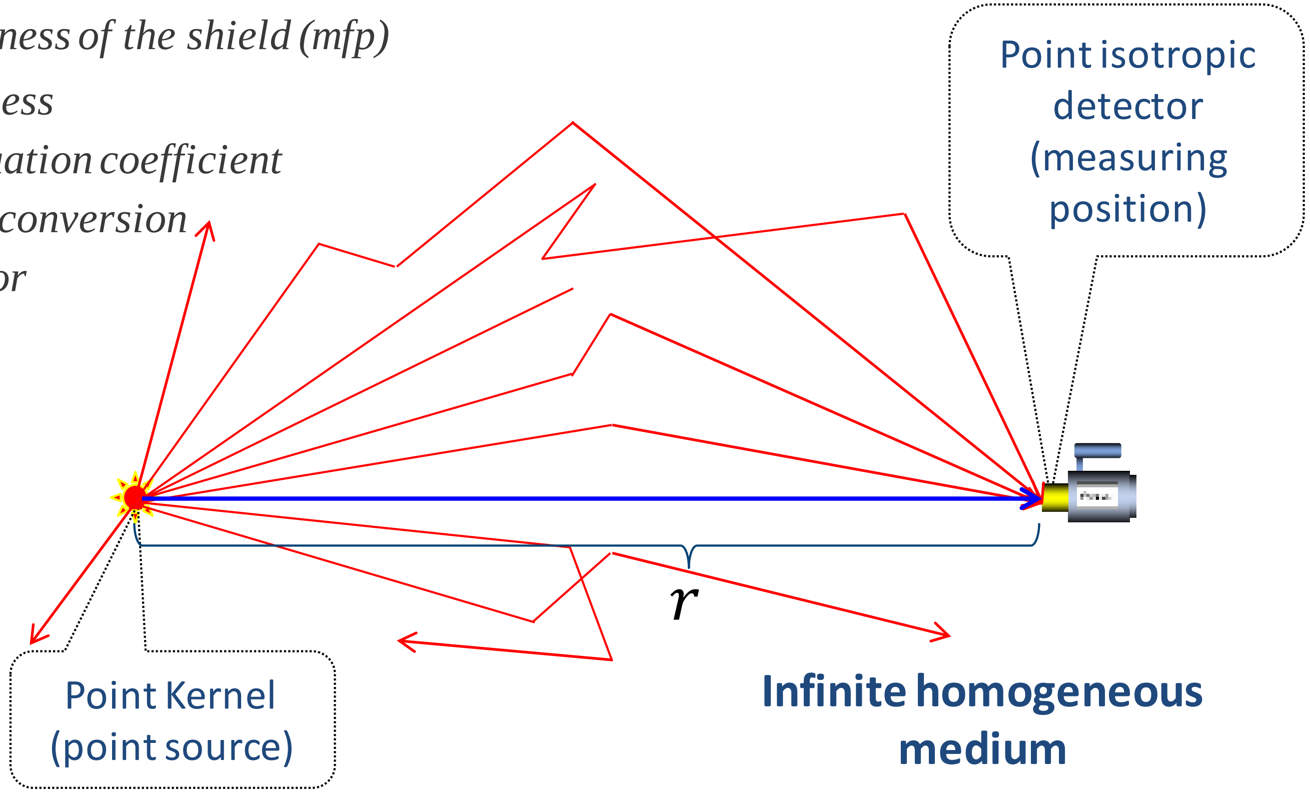


$$Dose = flux * conversion\ factor_{energy}$$
$* \ attenuation$
$* \ scatter\ (build\text{-}up)$

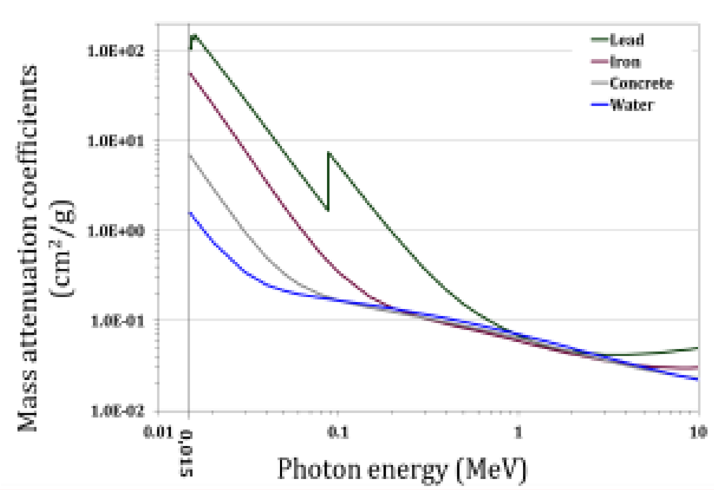
Point Kernel radiation transport

$$D(r,E) = Q(E) \cdot \frac{1}{4\pi r^2} \cdot e^{-\Sigma r} \cdot d(E) \cdot B_d(\Sigma r, E)$$

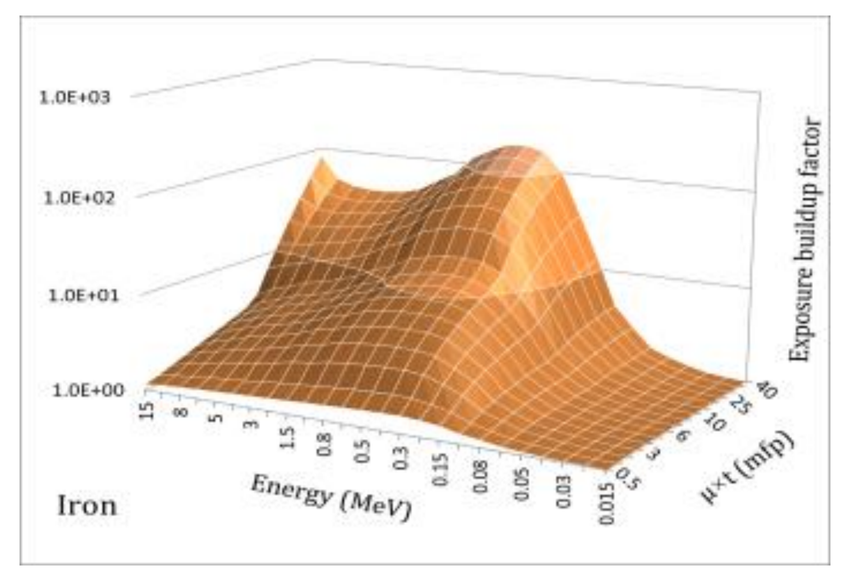
$Q(E)$	*source strength*
$\Sigma r = \mu \times r$	*optical thickness of the shield (mfp)*
r	*shield thickness*
μ	*linear attenuation coefficient*
$d(E)$	*flux-to-dose conversion*
$B_d(\Sigma r, E)$	*buildup factor*



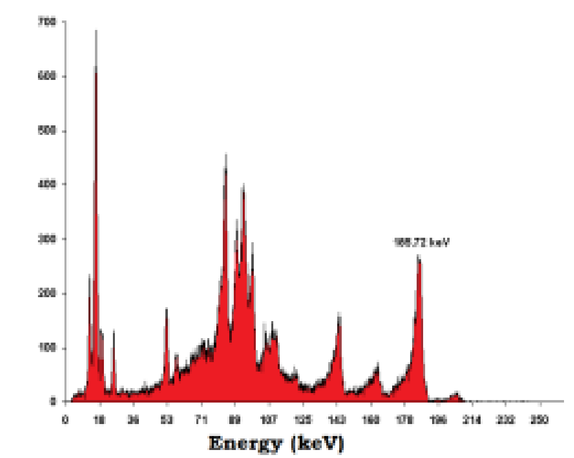
Our implementation

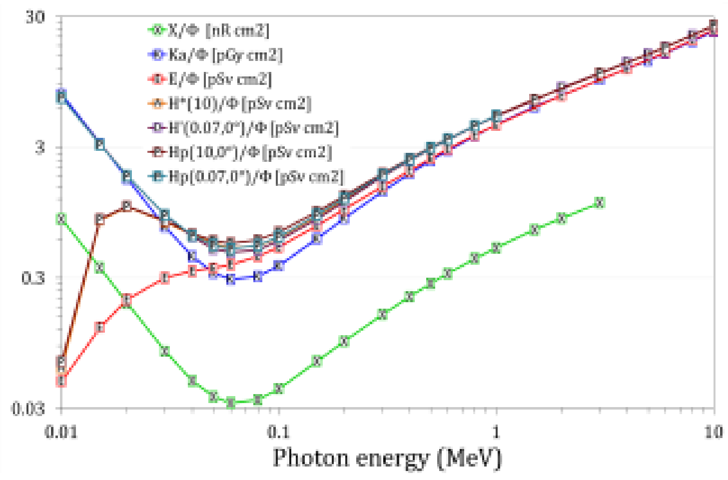


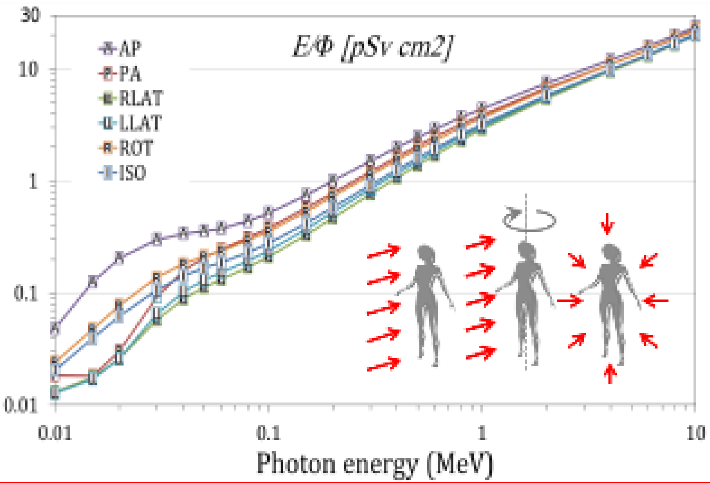
$const \cdot E \cdot (\mu_{en}/\rho)$

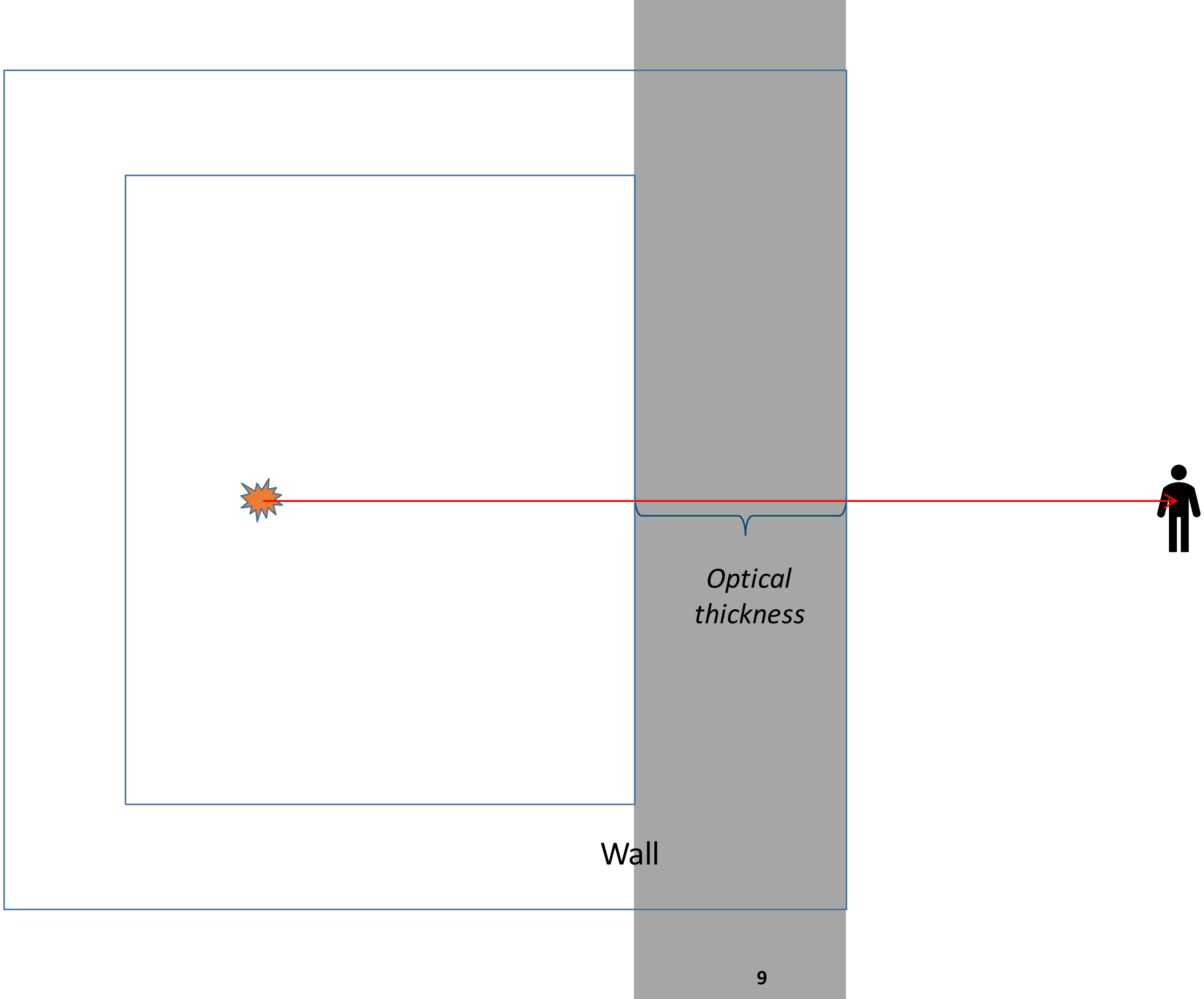


$$D(r,E) = Q(E) \cdot \frac{1}{4\pi r^2} \cdot e^{-\Sigma r} \cdot d(E) \cdot B_d(\Sigma r, E)$$





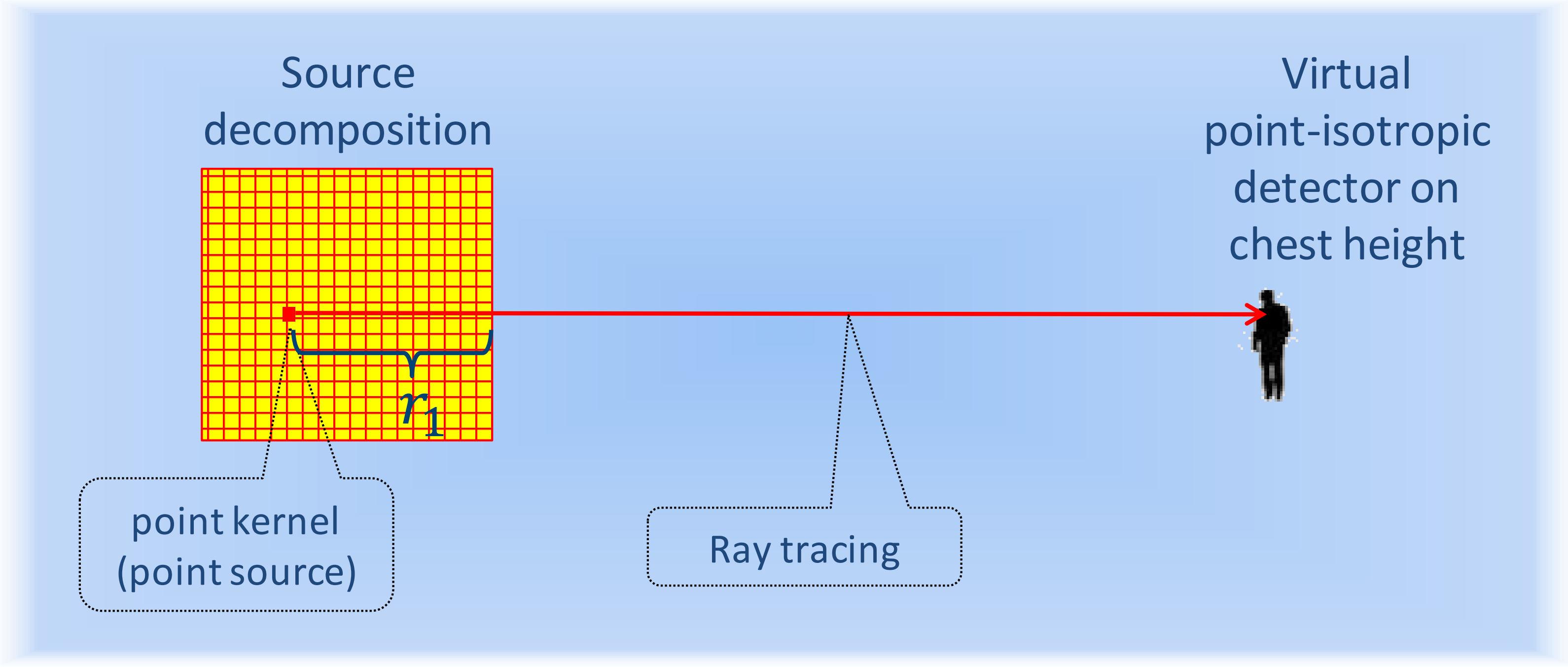



Optical
thickness
Wall

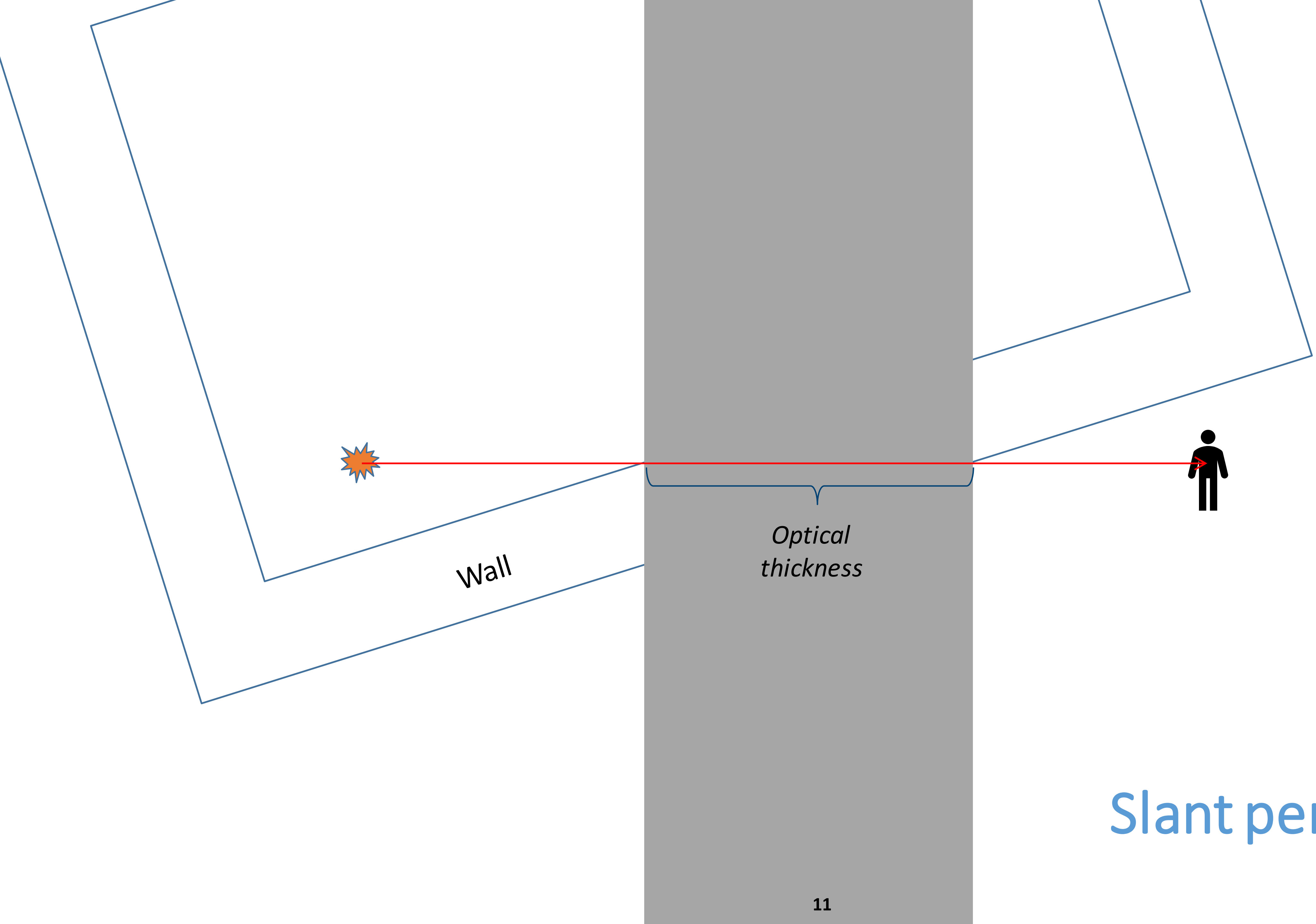
Our implementation – extended sources

A source can be considers as a point if distance to it’s centre is 10X longer than it’s diameter

- Extended sources are decomposed to point kernels – dose is summed up
  - Uniform decomposition vs. adaptive decomposition e.g. based on distance to the ‘detector’ – speed and accuracy trade-offs



Slant penetration



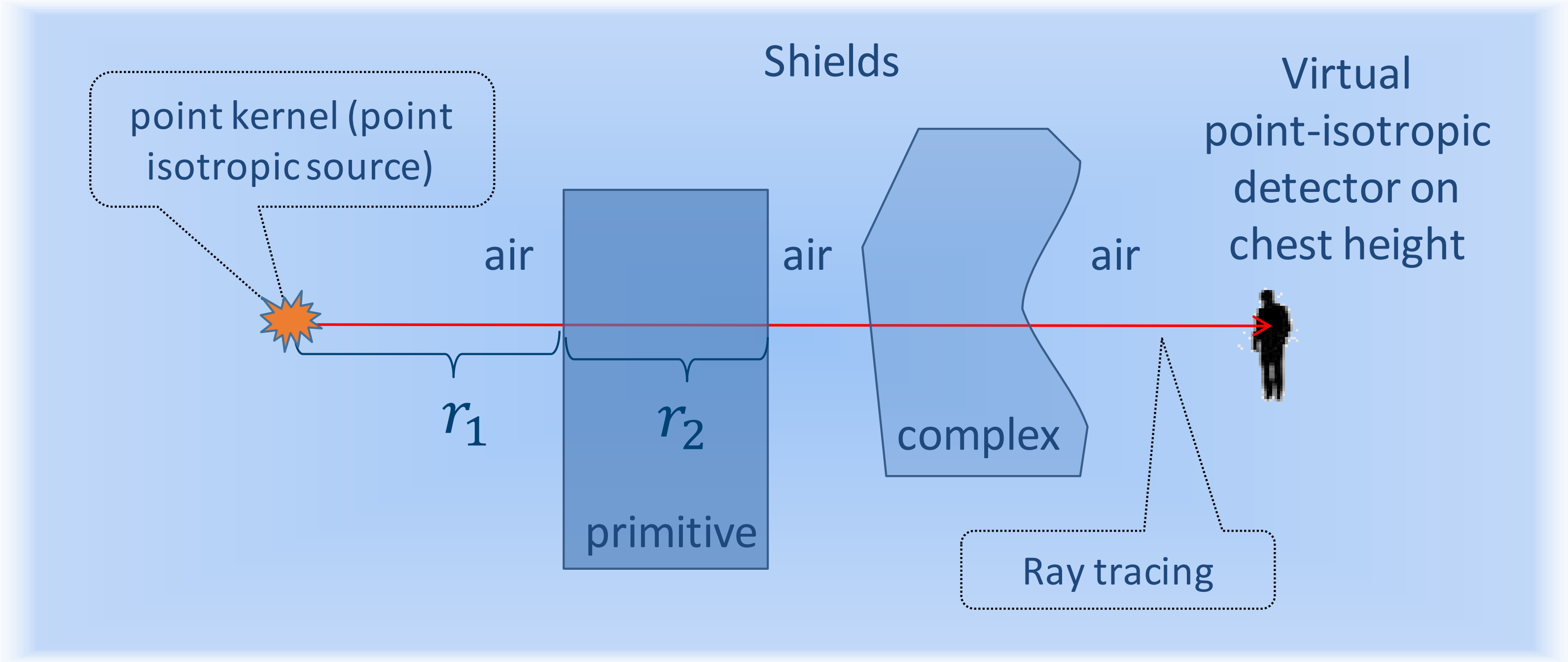
Multiple shields

$$D(r,E) = \frac{Q(E)}{4\pi r^2} \cdot e^{-\Sigma r} \cdot d(E) \cdot B_d(\Sigma r, E)$$

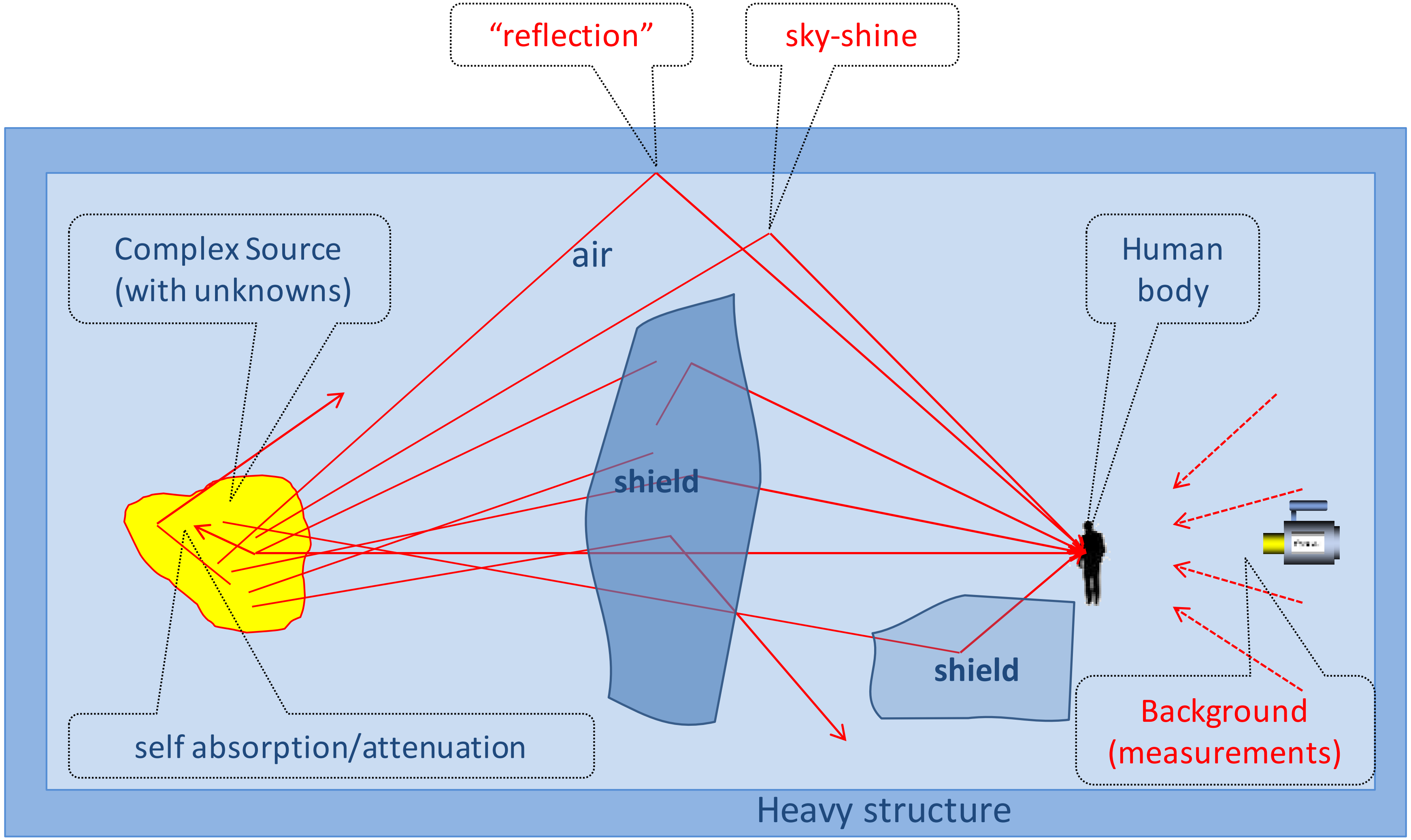
$$e^{-\Sigma r} = e^{-(\Sigma r_1 + \Sigma r_2 \dots)}$$

$$B_d(\Sigma r, E) = B_d(\Sigma r_1, E) + B_d(\Sigma r_2, E) \dots$$

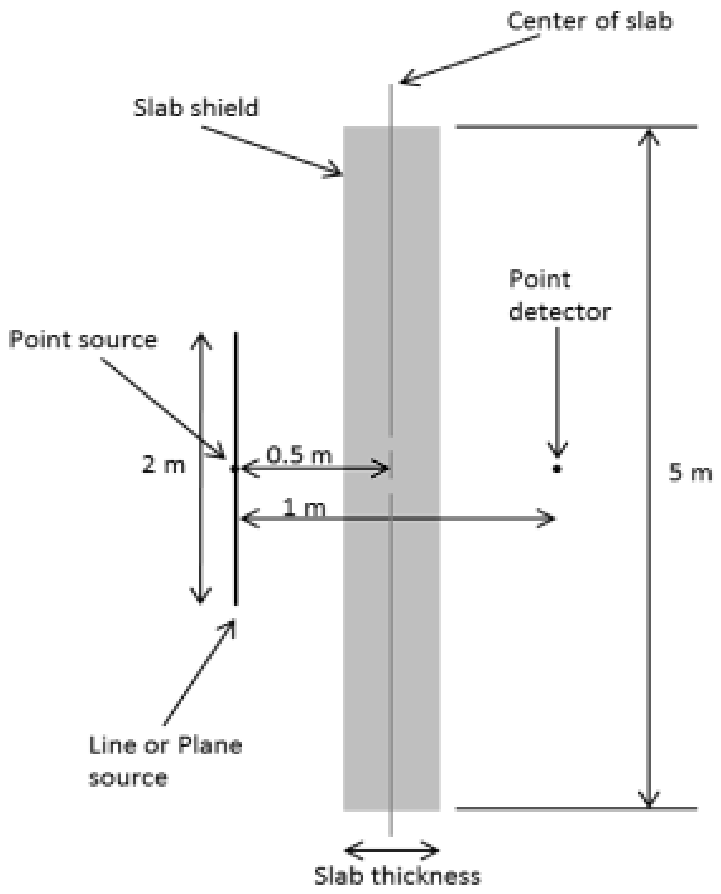
$$D = \sum_i (D(r, E_i))$$

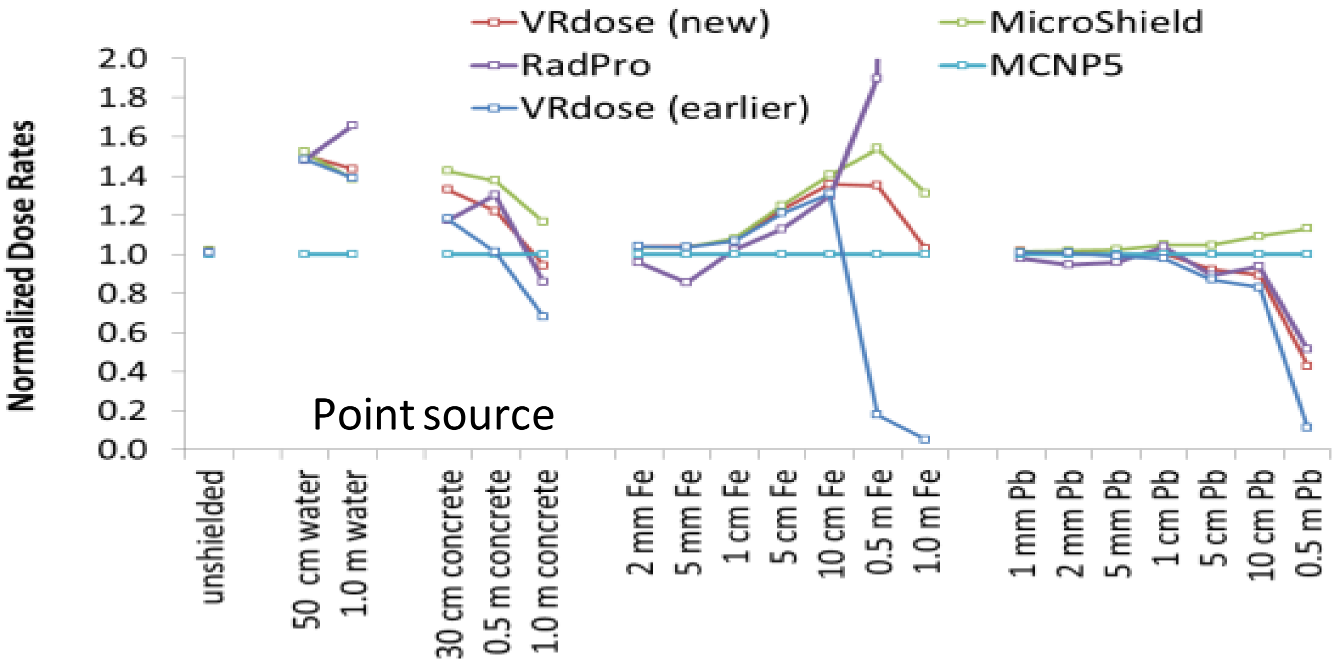


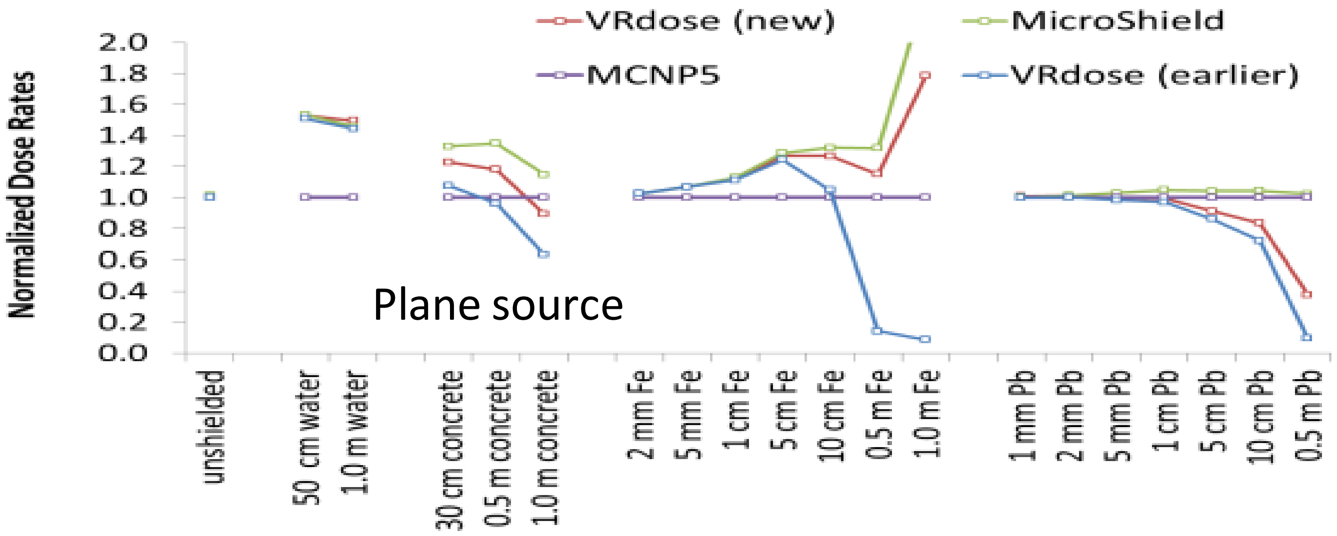
The real situation



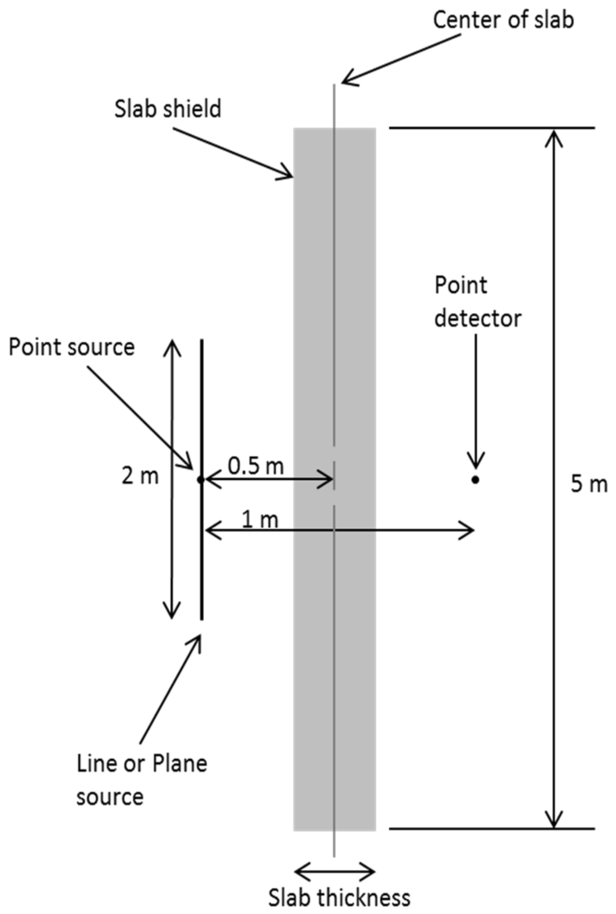
Benchmarking

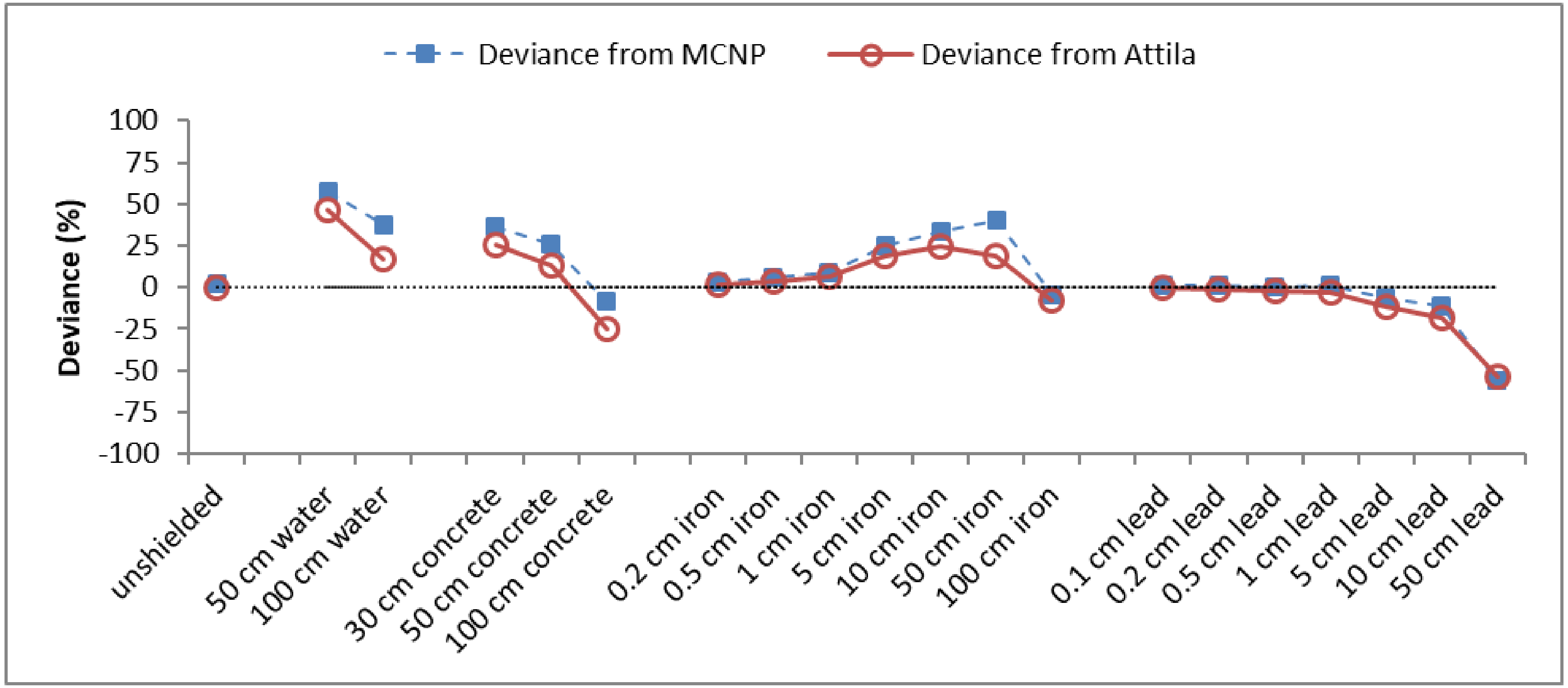






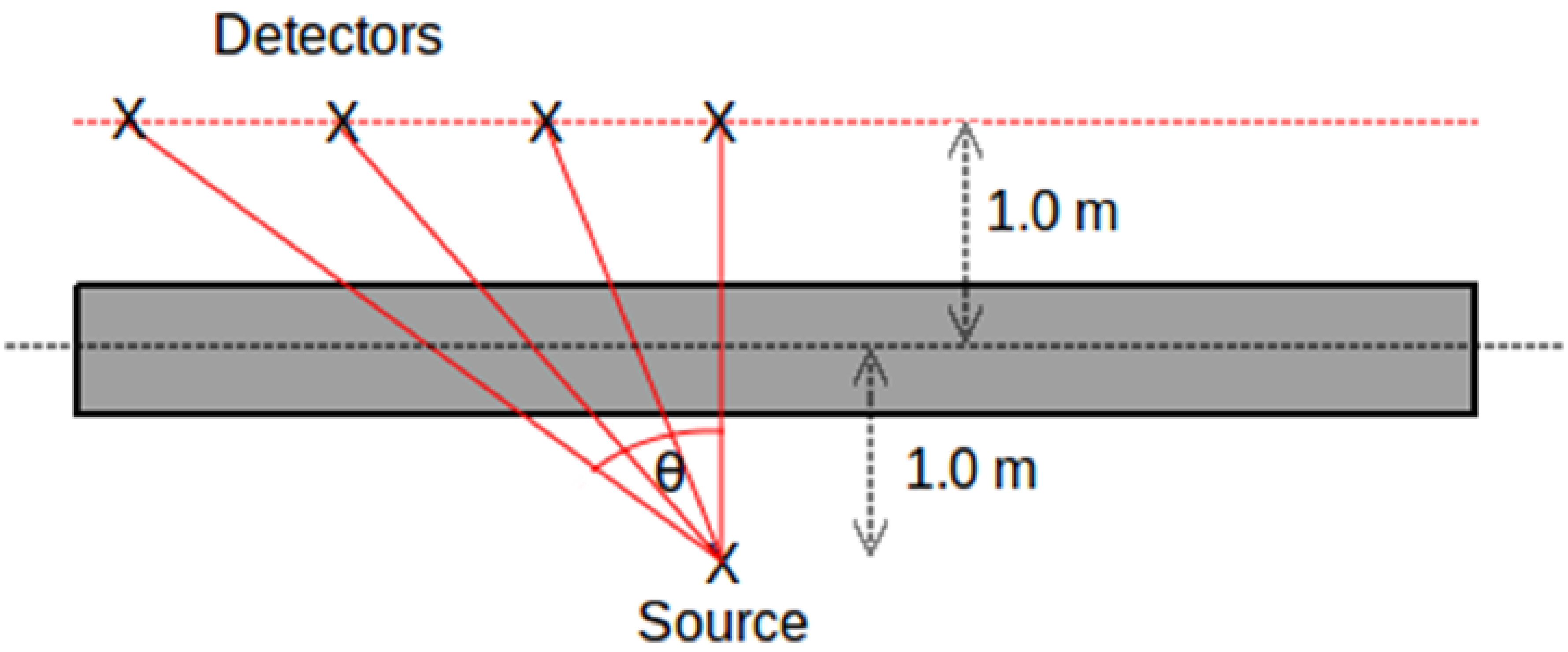
Normally incident radiation



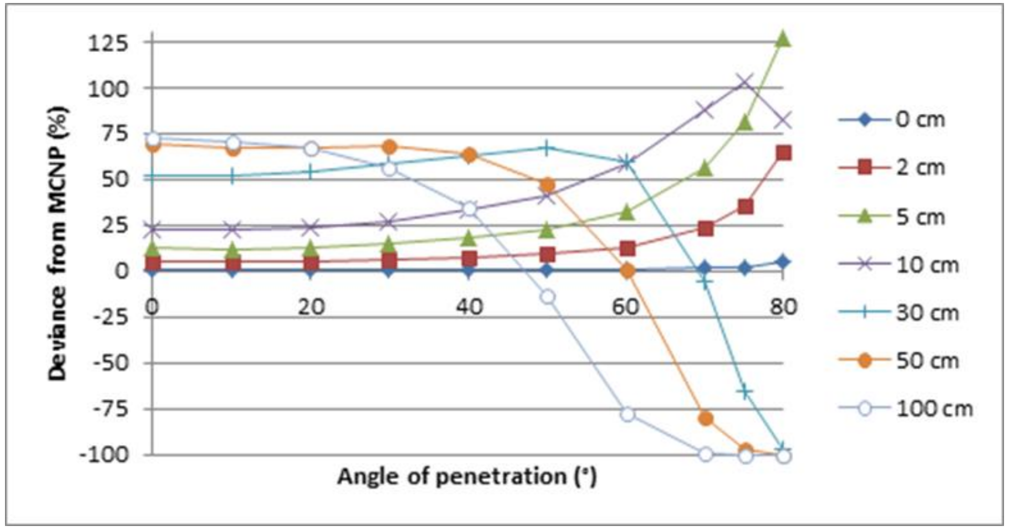


Positive numbers mean that point-kernel is overestimating the dose rate

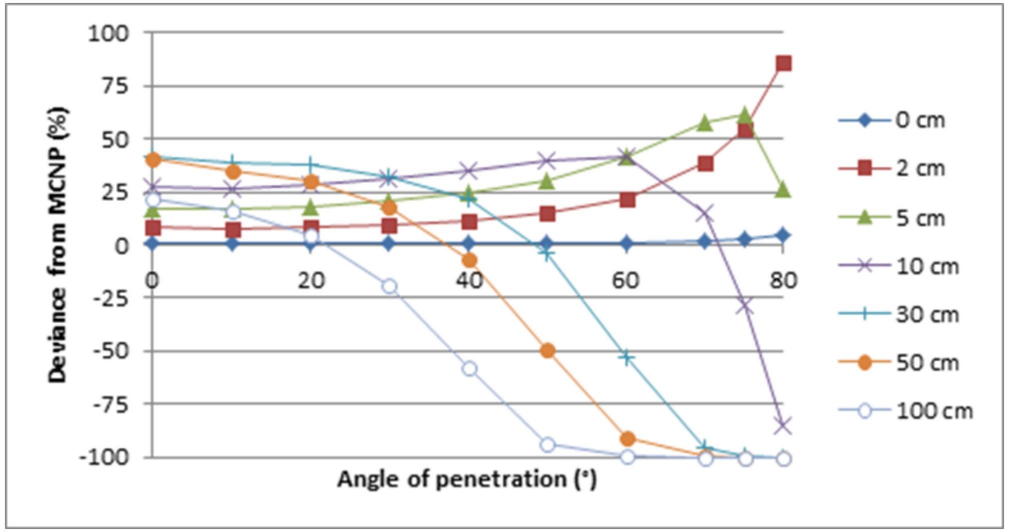
Obliquely incident radiation



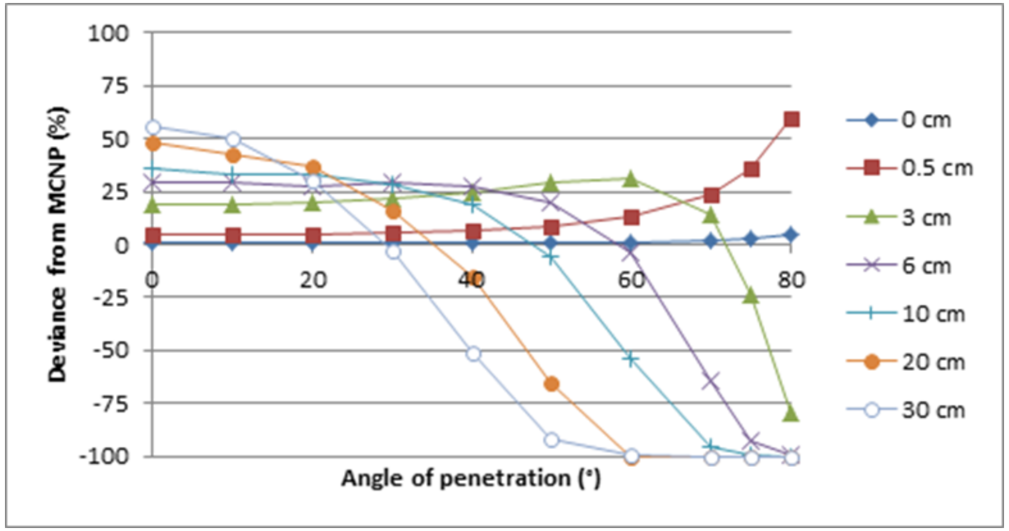
Water



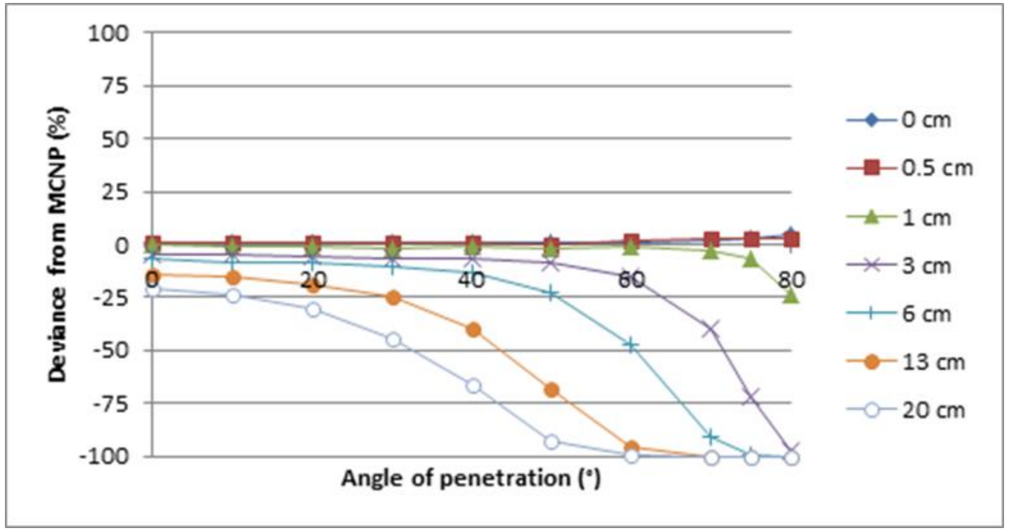
Concrete



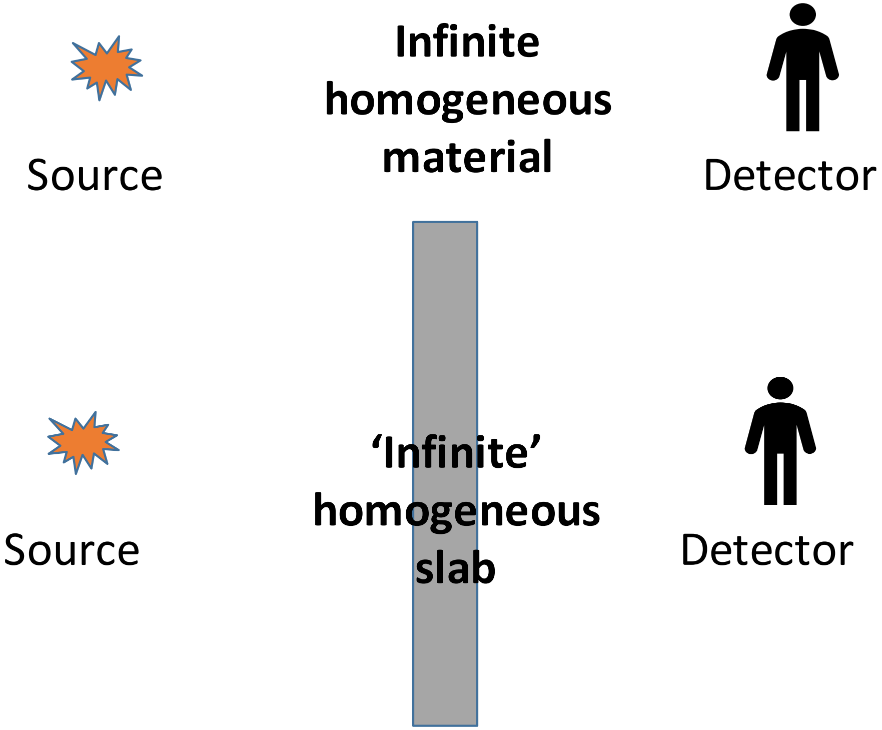
Iron

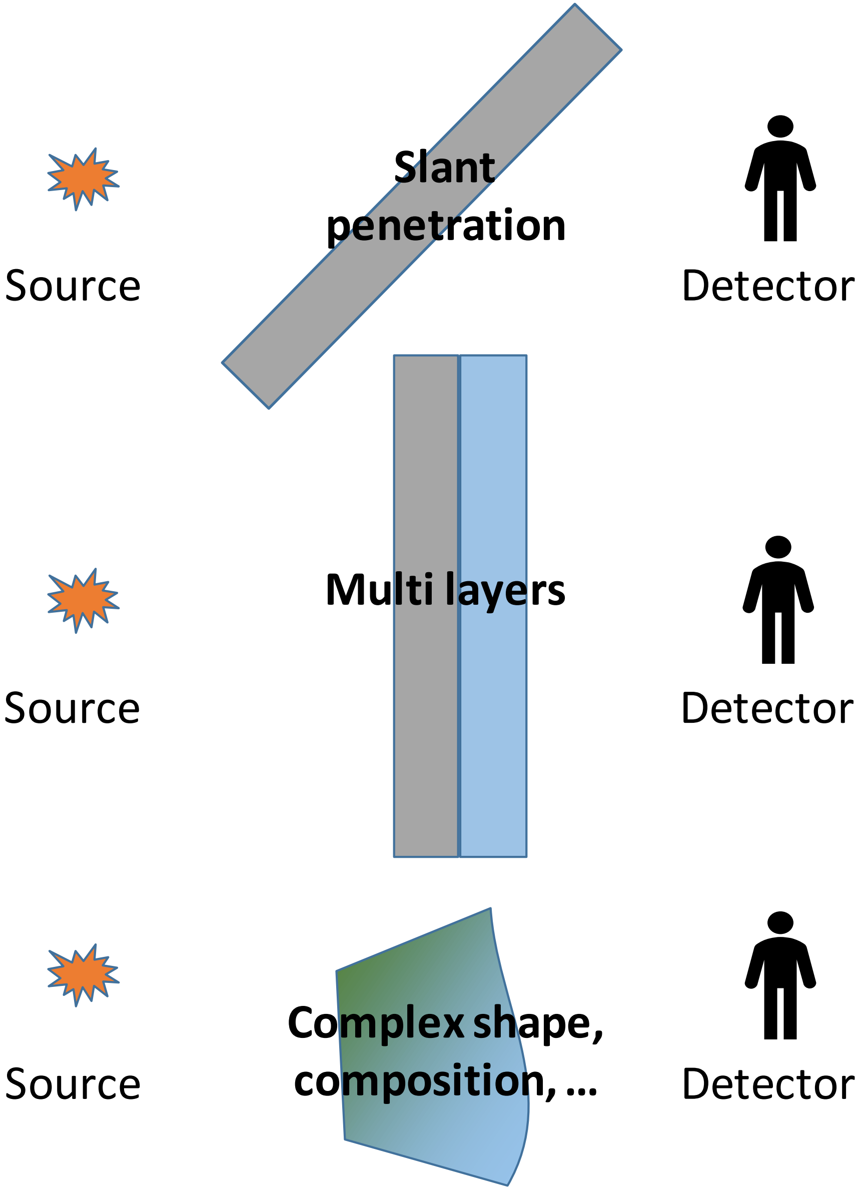


Lead



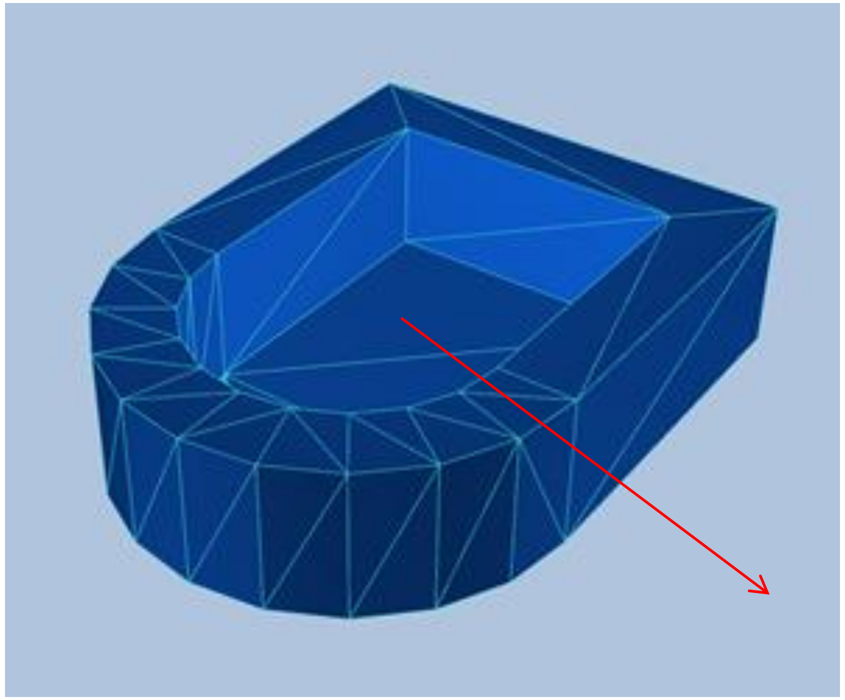
Shield modelling





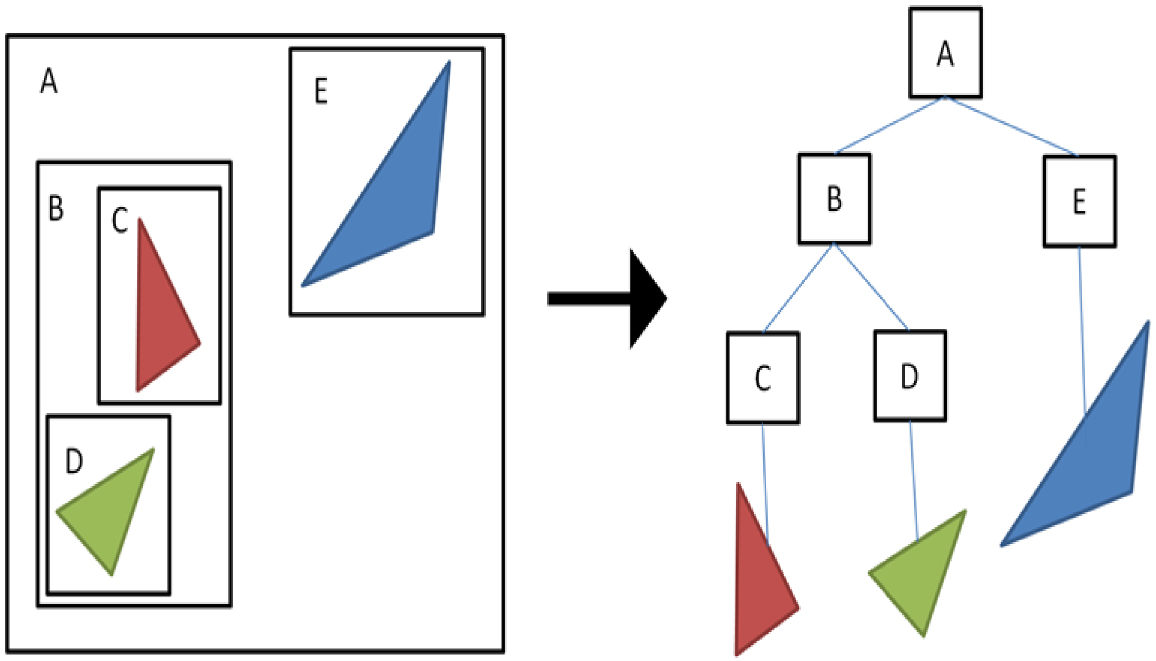
Evaluation of radiological shield intersection algorithms

Surface Mesh



- Based on Boundary Representation (B-rep) tech
- Triangles define the boundary between inside and outside of the model
- The set of faces must form a complete, closed skin of the model (with no intersecting faces)
- Must be tessellated for round objects => not 100 % accurate
- Brute force method - every triangle is checked against every ray

Bounding Volume Hierarchy (BHV)

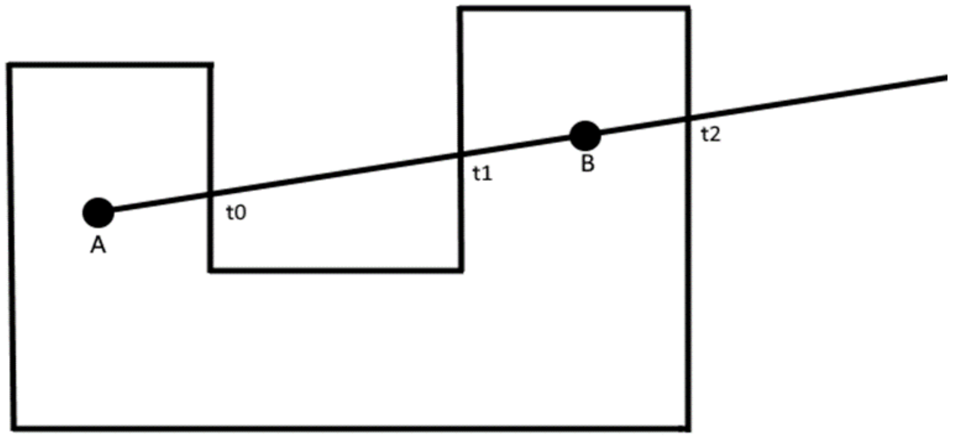


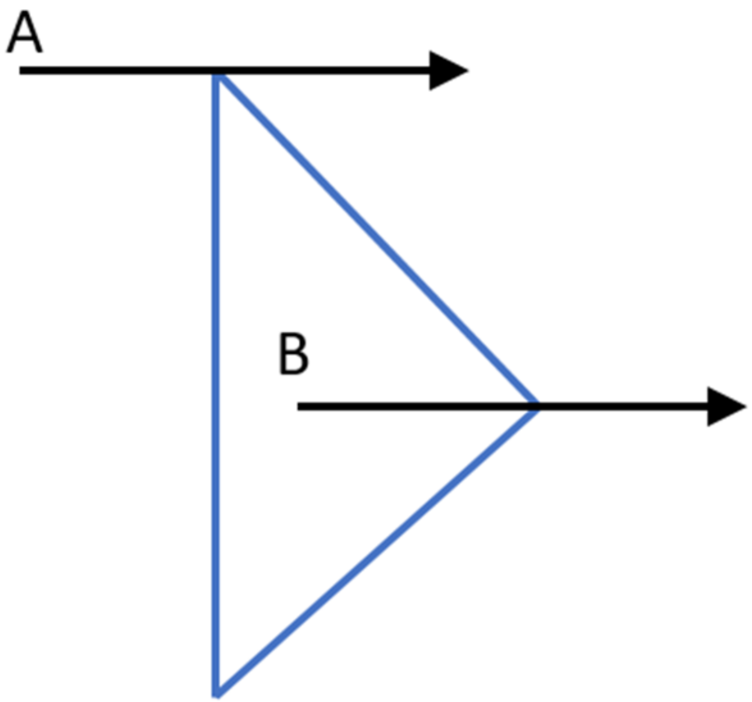
BV = Bounding Volume

Optimized version of the Surface Mesh

- A BV (in our case an axis aligned bounding box) is created around every triangle
- BVs are grouped under parent BVs - tree hierarchy
- If a ray does not hit a BV, all surfaces in the children BVs are skipped in the ray-tracing

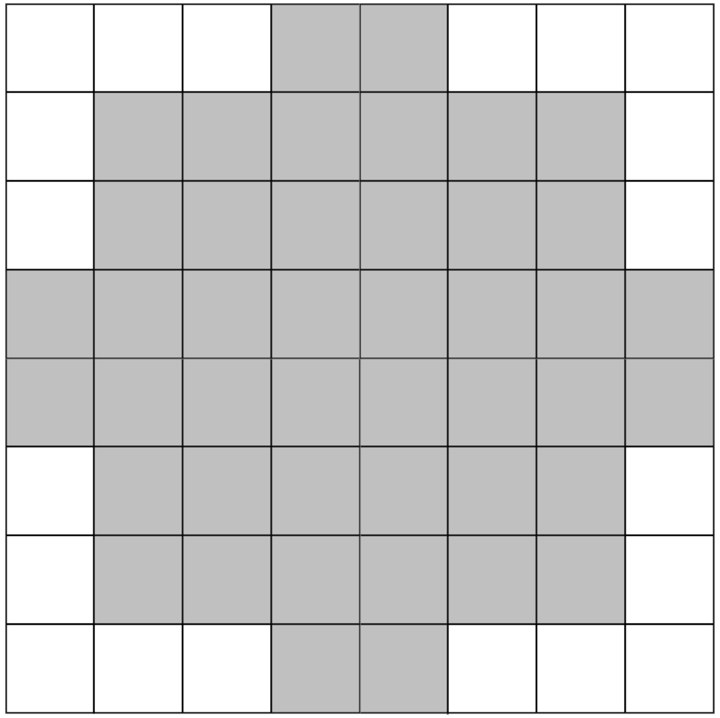
Error when intersecting edges or vertexes

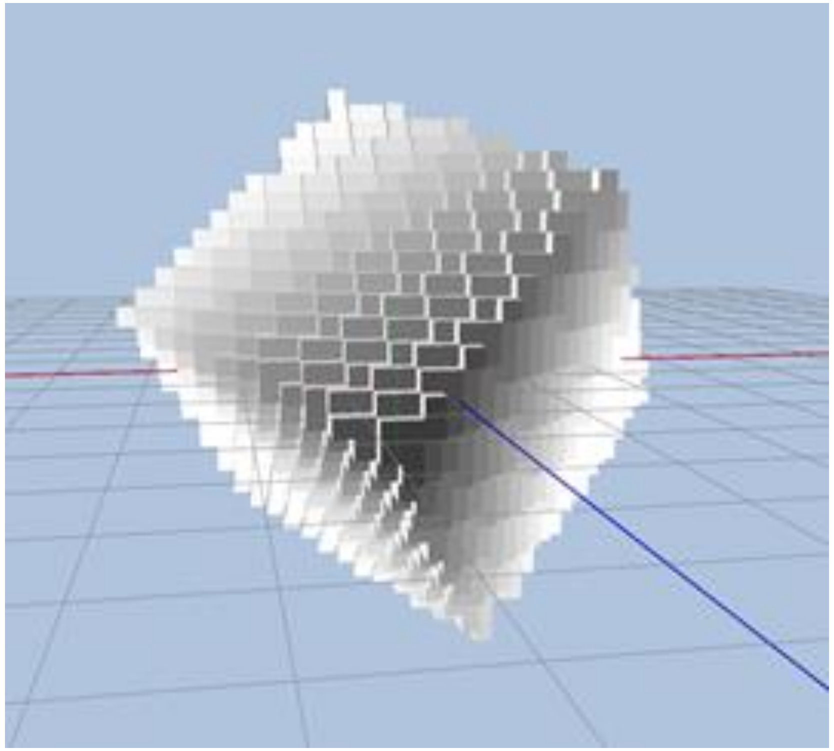




Both Surface Mesh and BVH uses the even-odd rule to determine if the particle is inside or outside the object.
The state is flipped between inside and outside when intersecting a surface of a mesh.
At edges and vertices multiple intersections can be detected when penetrating the skin of the model.

Voxel Grid

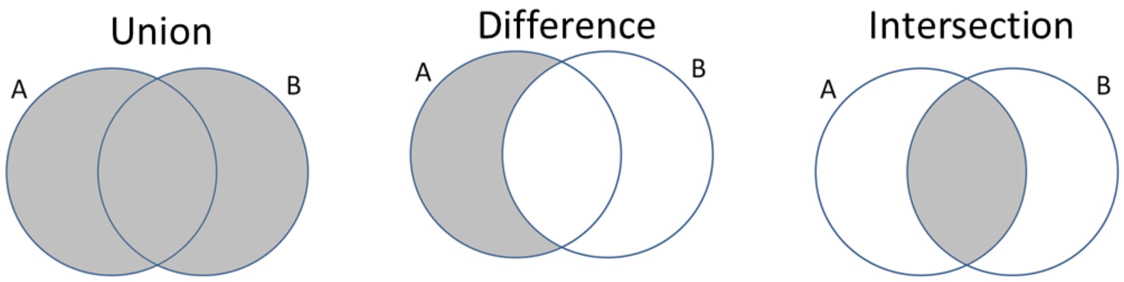


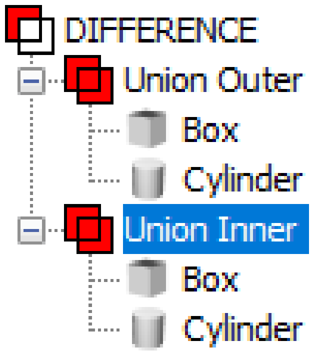


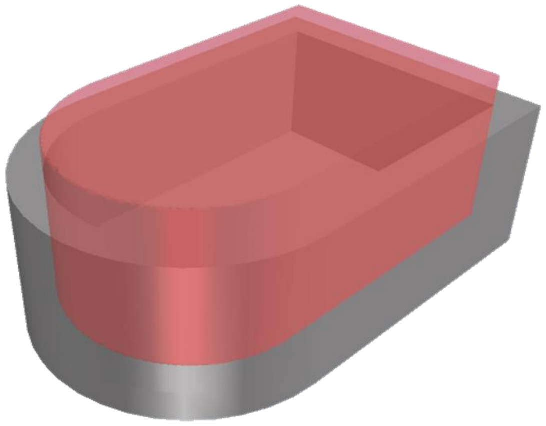
- Shields are modelled as a three-dimensional grid of voxels
- Each voxel defines if the volume is inside or outside the shield
- Compex (round) shapes need to be tesselated => not 100% accureate

Constructive Solid Geometry (CSG)

Boolean operations







- Combines primitives (spheres, cylinders, boxes,…) using Boolean operations.
- Boolean operations are organized in tree structure (results of an operation can be input to another operation)

Asymptotic analysis

Letter	Represents
n	the number of nodes in a CSG tree
c	the number of cells along the longest edge of a Voxel Grid
t	the number of triangles within a mesh
i	the number of triangles within a mesh that were intersected

Runtime complexity

Algorithm	Worst-case	Average-case	Best-case
CSG	$O(n^2)$		$\Omega(\mathrm{n})$
Voxel Grid	$O(c)$	$\Theta(\mathrm{c})$	$\Omega(c)$
Surface Mesh	$O(t \log t)$	$\Theta(t\,\mathrm{i} \log i)$	$\Omega(\mathrm{t})$
BVH	$O(t \log t)$	$\Theta(\log t + i \log i)$	$\Omega(1)$

Memory requirement

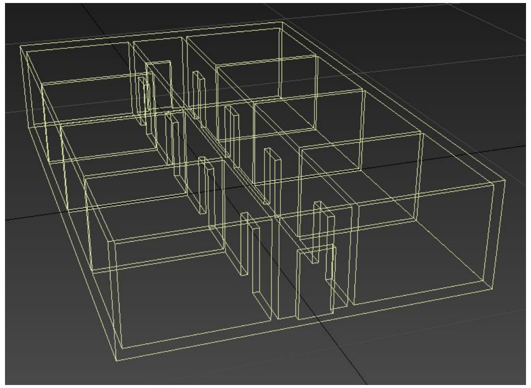
Algorithm	Worst-case
CSG	$O(n)$
Voxel Grid	$O(c^3)$
Surface Mesh	$O(t)$
BVH	$O(t)$

Benchmarking

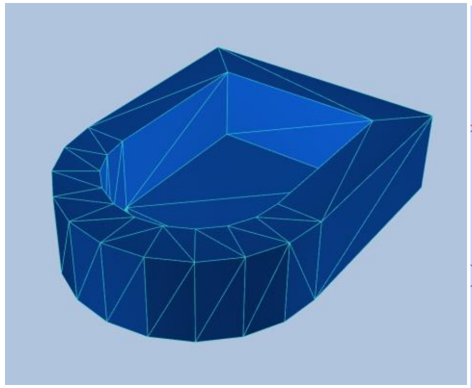
Shield shapes:

building

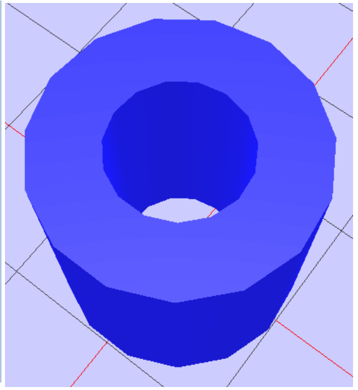
(rooms, hallway, door openings)



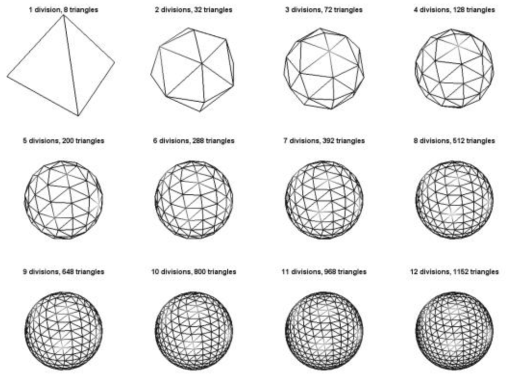
pool



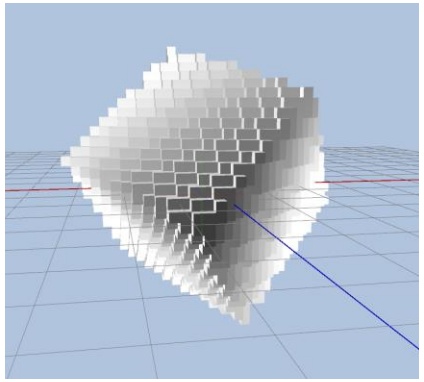
pipe

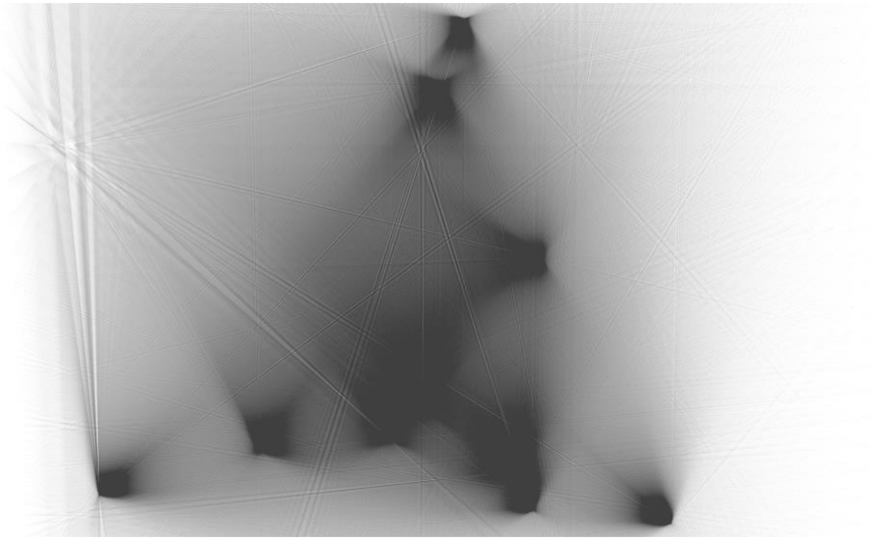


sphere



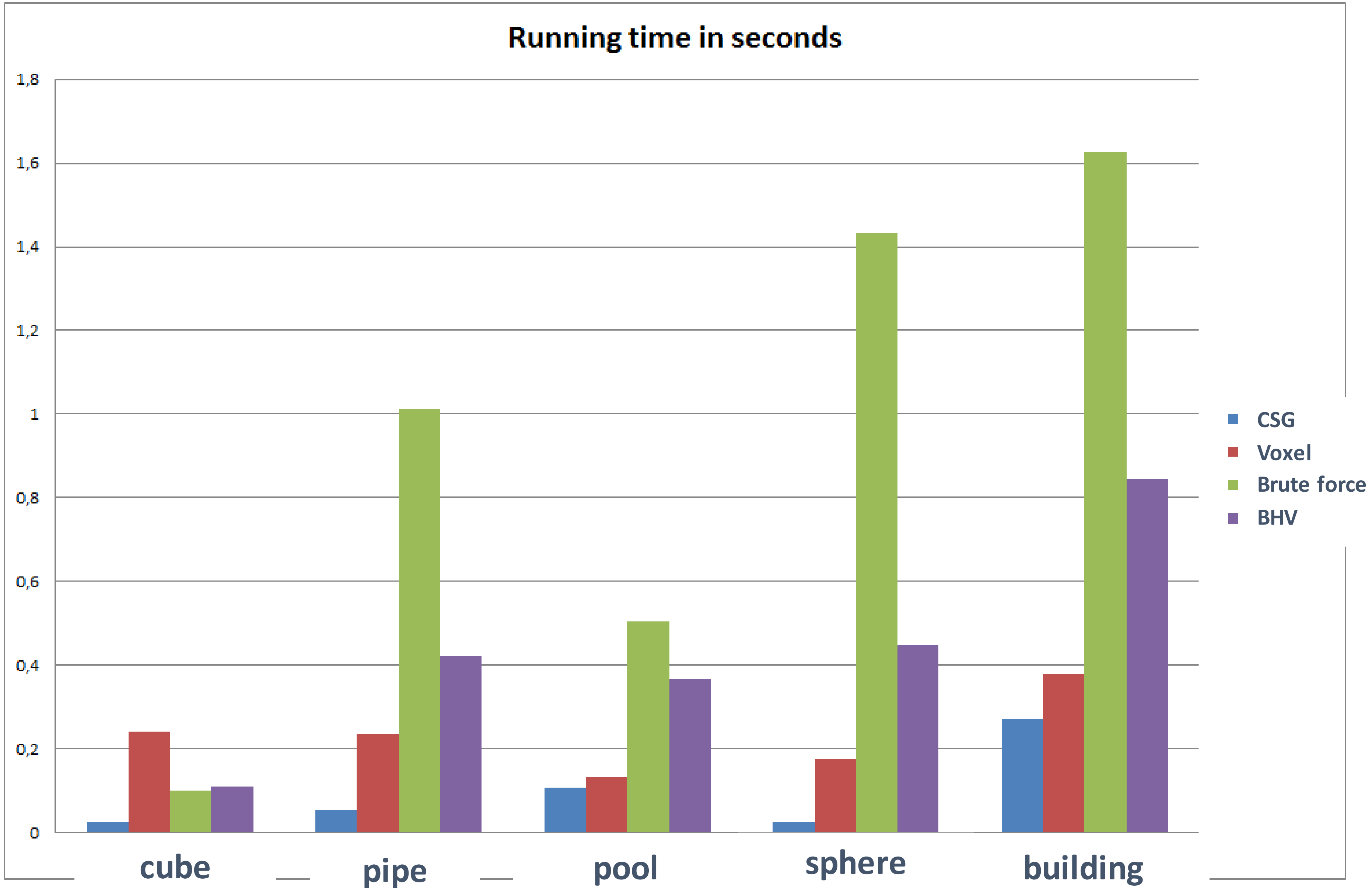
cube



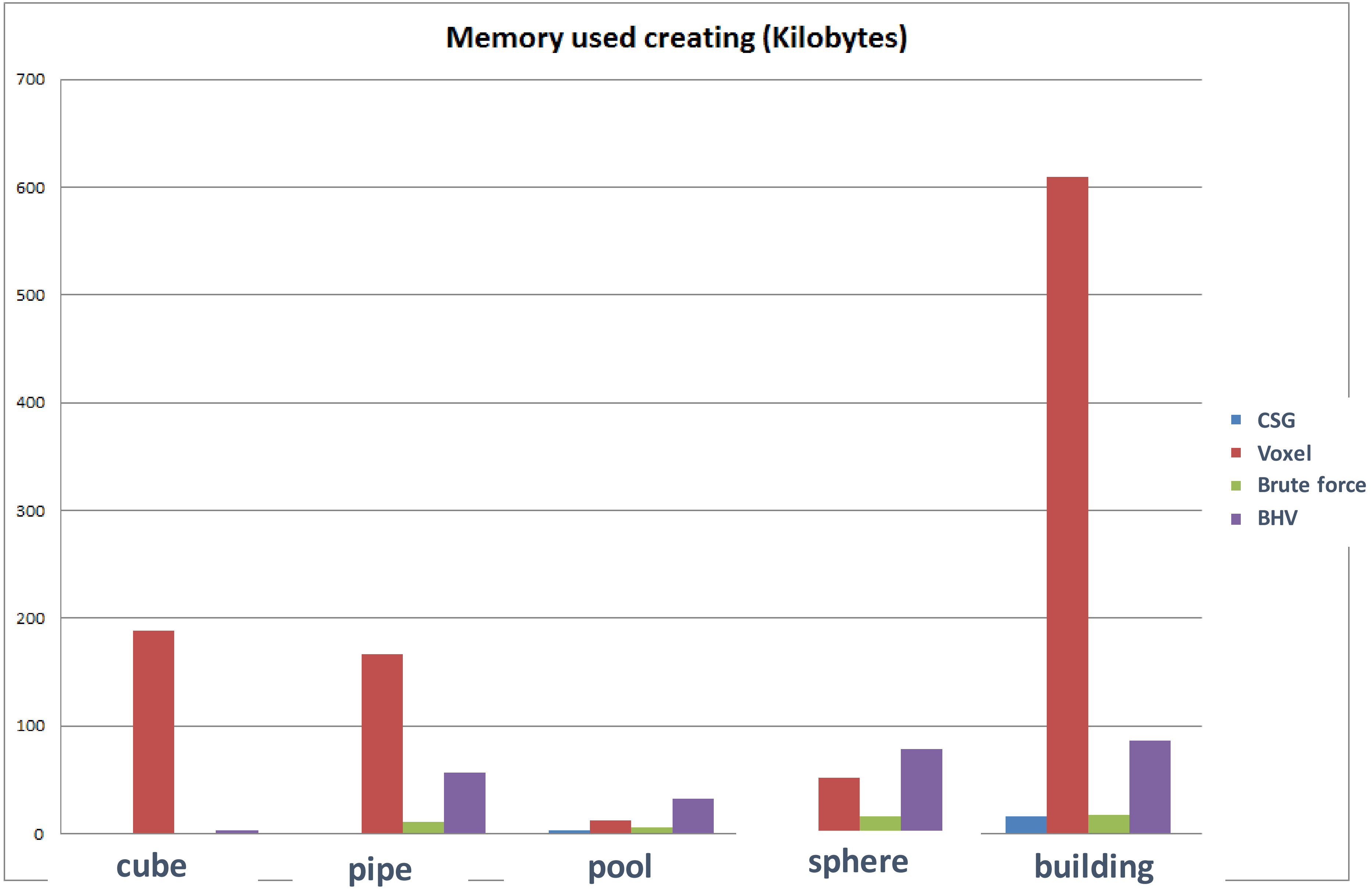


Test case:

- 30x30x30 grid
- 10 point isotropic source emitting 270 000 rays (lines) in total

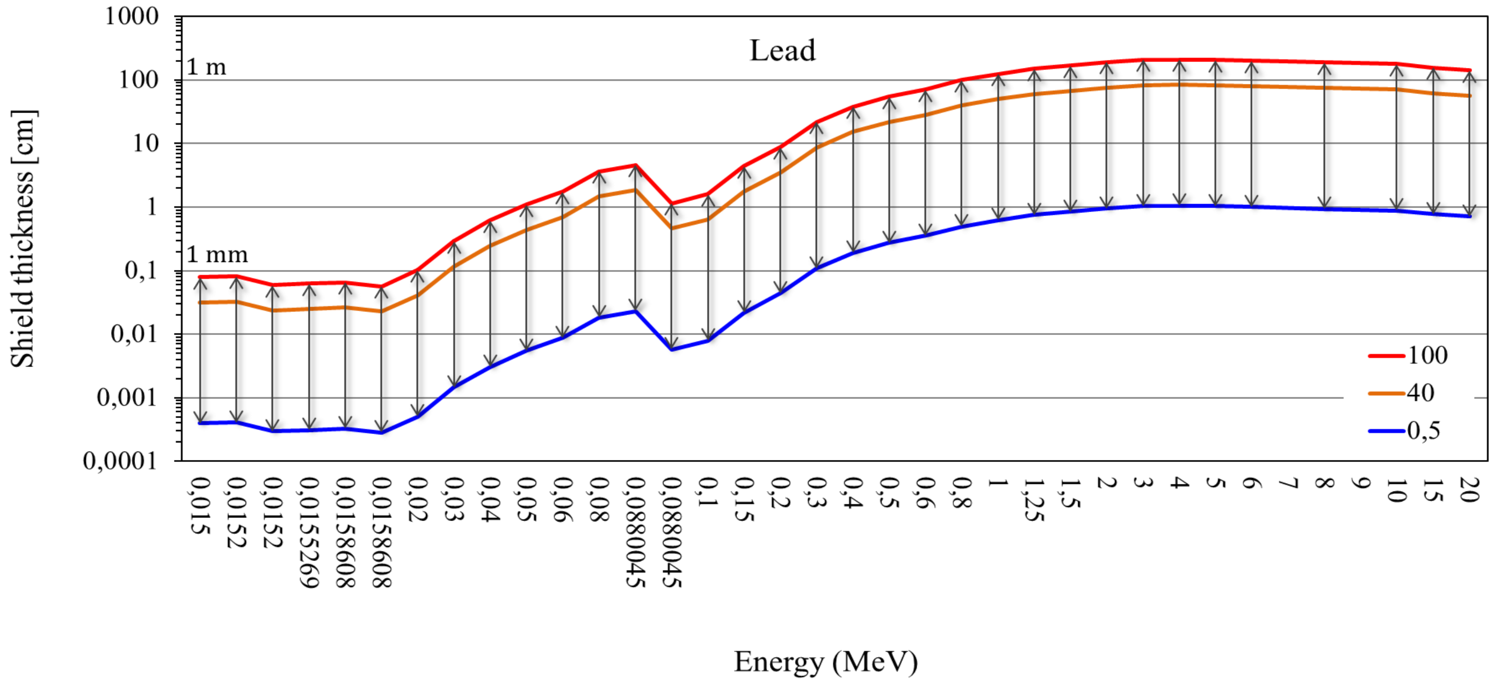


Mesh and voxel tessellated to give error less than 1%

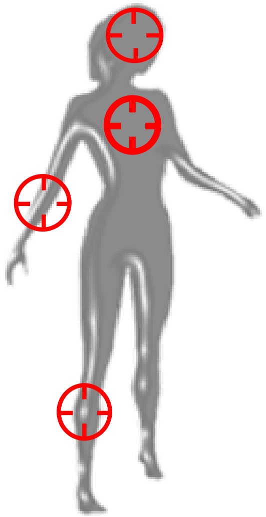


Memory used creating (Kilobytes)
700
600
500
400
300
200
100
0
cube
pipe
pool
sphere
building
CSG
Voxel
Brute force
BHV

Limitations

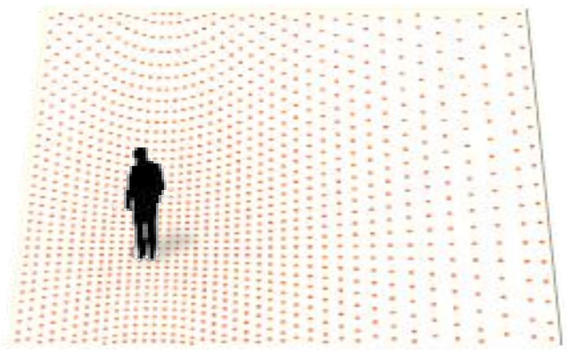


- Extreme <u>photons energies</u> (available input on energy absorption is for **10keV - 10MeV**)
- Extreme <u>optical thicknesses</u> (available input on buildup)
- <u>Shielding</u> composition (applied buildup data and calculation)
- High contribution of “<u>reflections</u>” (usually not considered in PK models)
- Complex <u>dose distribution</u> in the body (representation of human body)

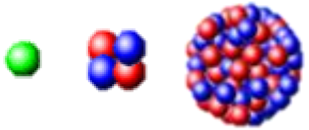


Limitations (cont'd)

- Variations in input data availability (model needs source description)
- Accuracy of dose calculations (model is designed for conservative estimations)
- Large extended sources and close detectors (model applies adaptive source decomposition, but needs verification)
- Complex source with high self scatter (model applies buildup for scatter inside the source)



- Type of radiation (model is applicable to gamma and X-ray only)



- Exposure pathways other than external – PK model is not applicable for inhalation, ingestion and skin dose from deposited material on clothing/skin)

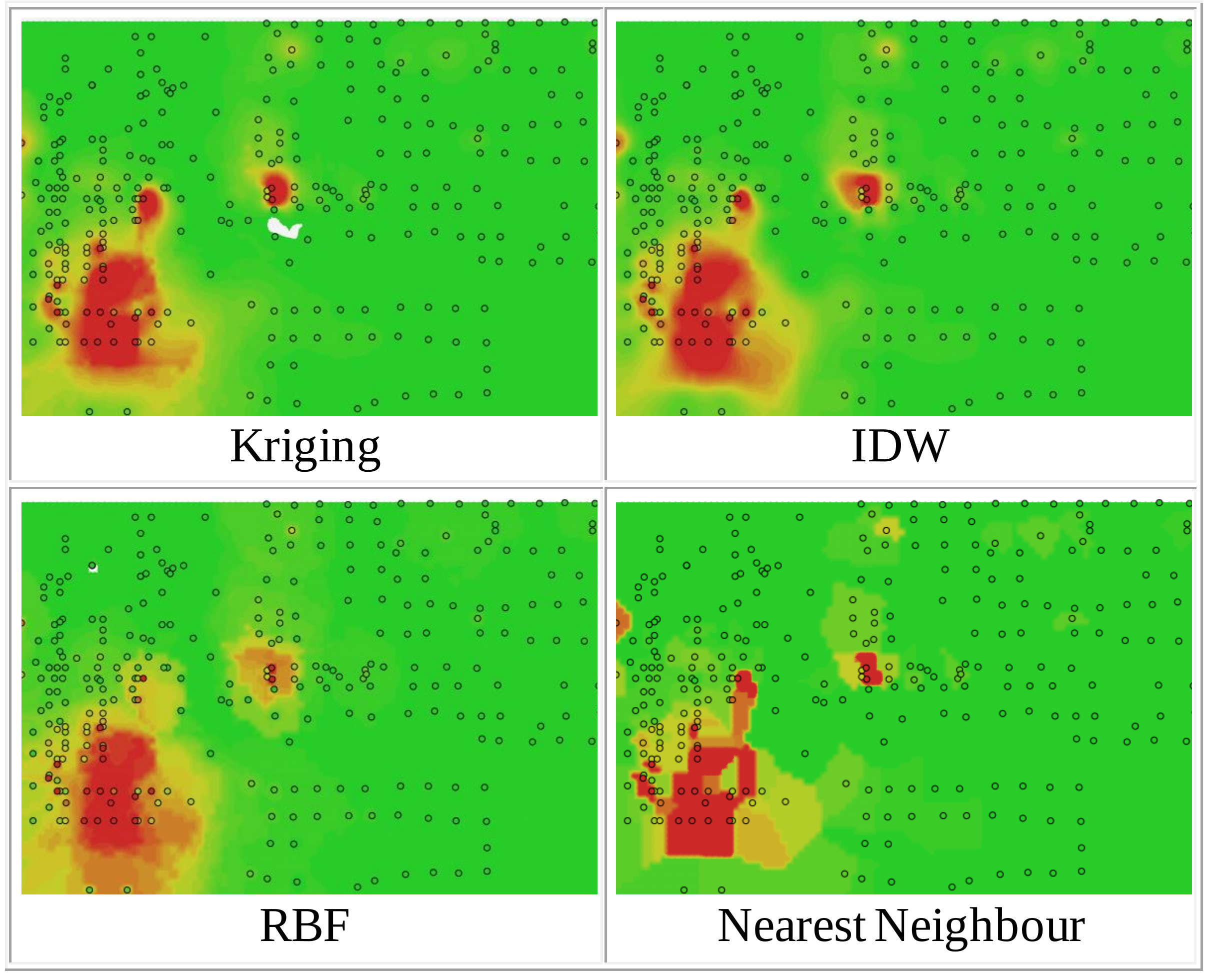
Some solutions

- Combination with MC (Mote Carlo) radiation transport for complex irradiation situations - Interface with **MCNP**
  - Easy production of input for MCNP simulations
  - Enables MC radiological assessments for whole jobs (not static)
- Geostatistical & other **interpolation** techniques & combination with rad. transport
- **Source deconvolution** techniques

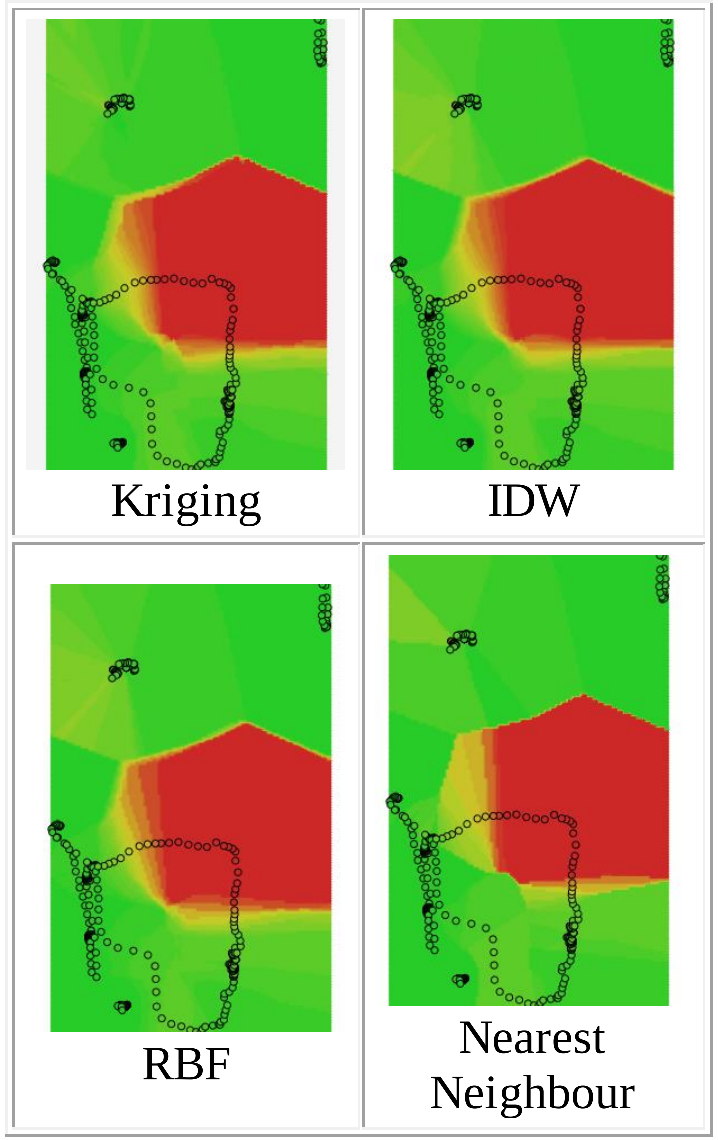
Interpolation

- Nearest Neighbour: Returns the value in the nearest point from the known measurement. Not really an interpolation method (included as reference)
- Inverse Distance Weighting (IDW): The result is the weighted average of the values in the surrounding points weighted with a function of the inverse distance of these points.
- Radial Basis Function Neural Net (RBF Net): The interpolation is done with a radial basis function neural net using the known points as centres for the radial basis function.
- Ordinary Kriging: Originating from geostatistics where the interpolated value is computed using a covariance function to give weights to the known points

Interpolation – test cases



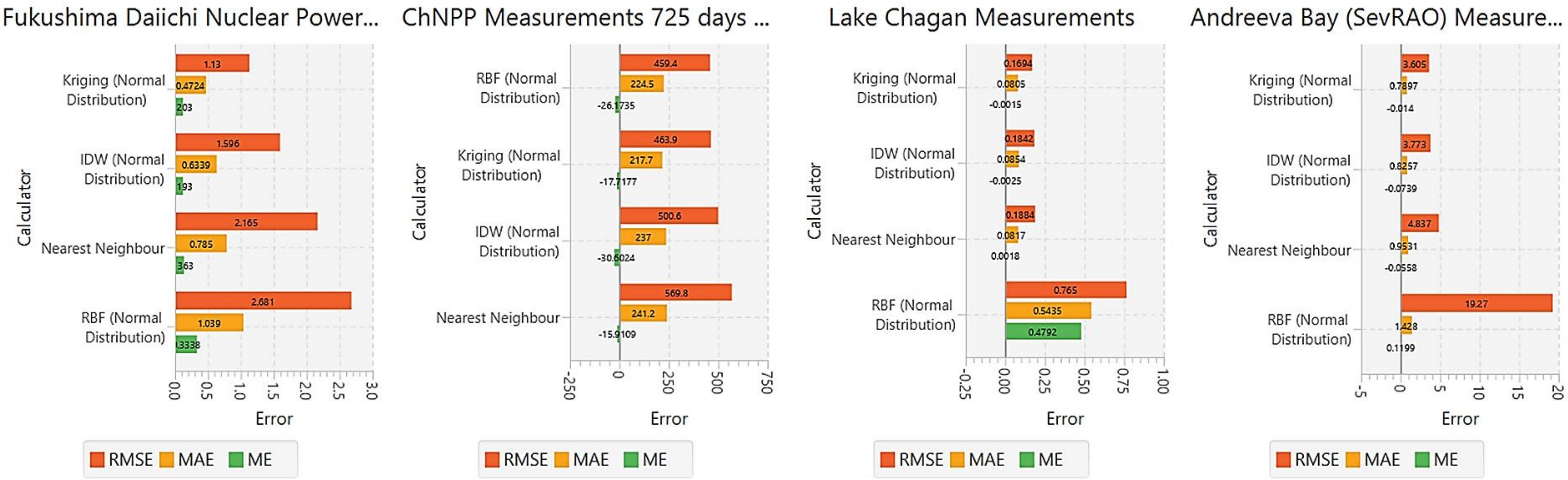
ChNPP 725 days after accident



Fukushima Daiichi NPP

Interpolation – Cross-validation

10 fold cross-validation repeated 10 times



RMSE = Root Mean Squared Error
MAE = Mean Absolute Error
ME = Mean Error

Iguchi method

(07/10/99 Yukihiro Iguchi, JAEA)

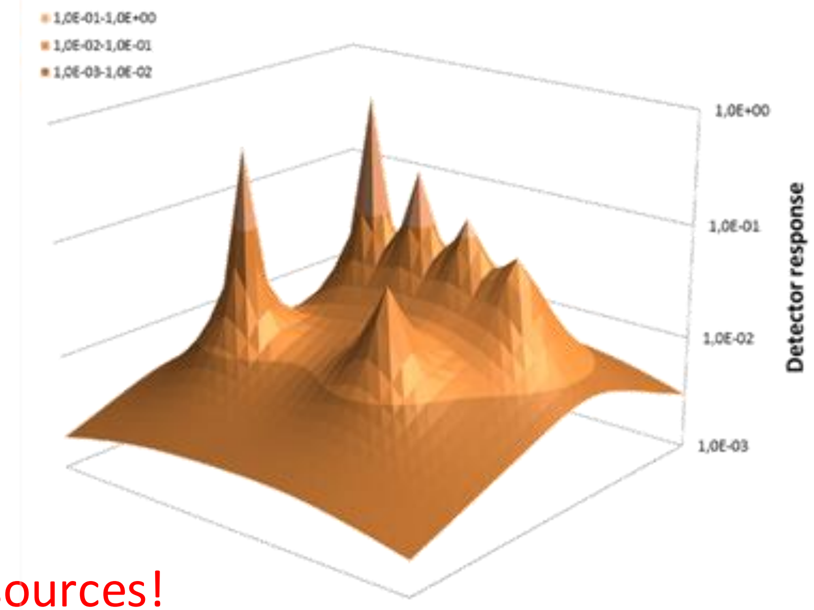
- Based on measures + *additional input information*:
- measuring positions =
  location of sources (hot spots) + 1 background measurement

1. $D_j = \sum_{i=1}^{n} \frac{S_i \times R}{(r_{ij} + \alpha)^2} \Rightarrow$ Linear equation system solved by Gaussian Elimination

2. $D_B = \sum_{i=1}^{n} \frac{S_i \times R}{(r_{iB} + \alpha)^2} \Rightarrow$ Use this to calculate α e.g. by Bisection Method

3. $\rightarrow D_P = \sum_{i=1}^{n} \frac{S_i \times R}{(r_{iP} + \alpha)^2}$ Equation for arbitrary points (P)

Sample mapping in an area containing 6 sources



Will give false information in case of unknown sources!

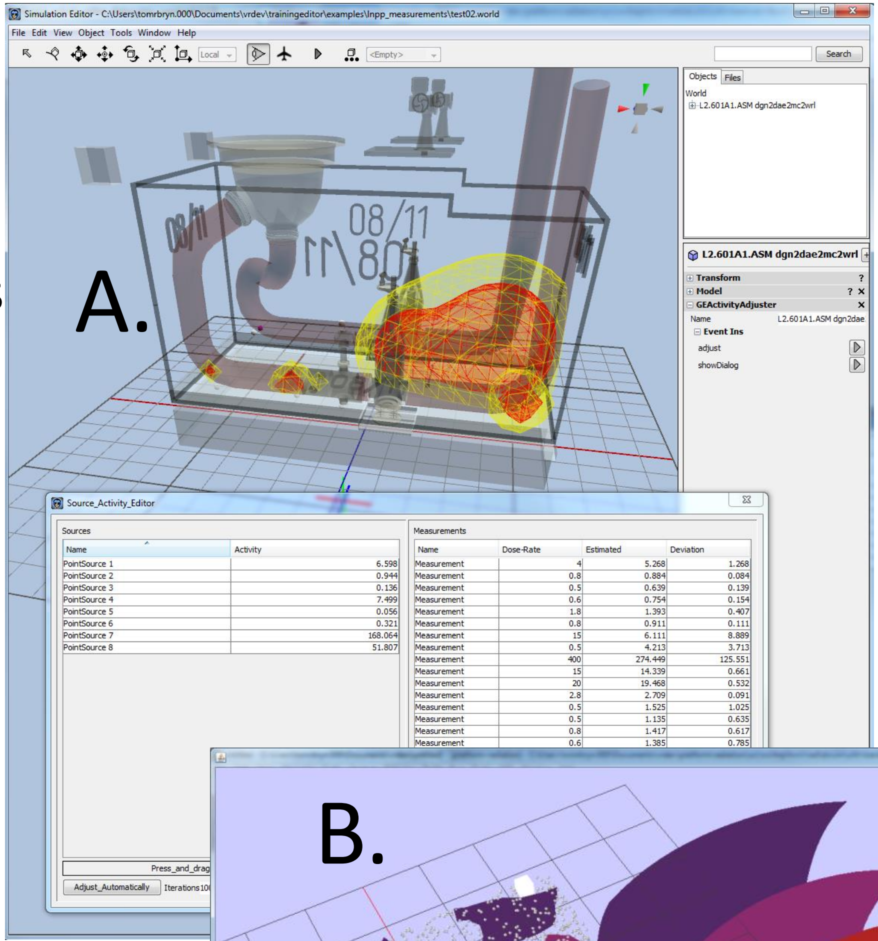
Source deconvolution

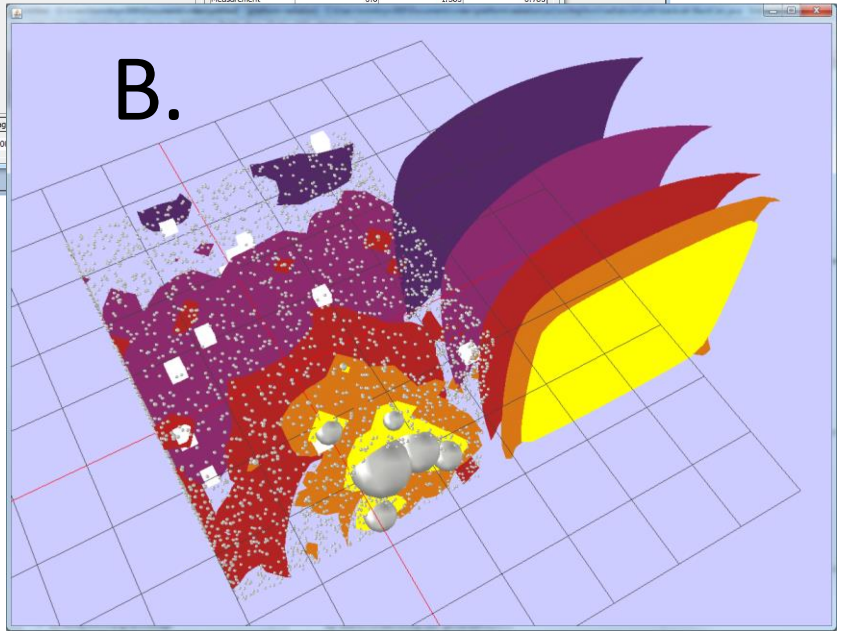
A. Input: 1. Set of shields (incl. air) 2. set of measurements 3. set of point sources (positions and isotope vectors)

- Method: Adjusts source strengths so that calculated values match measurements
- Tech: Custom genetic algorithm to solve a global optimisation problem where source strengths are found to optimise ‘cost’
  - cost = square sum of the absolute difference between the measured and calculated

B. Position of the sources are unknown (prototype)

- Method: Generate a high number of point sources along the surfaces (e.g. walls)
- Tech: Same global optimisation algorithm





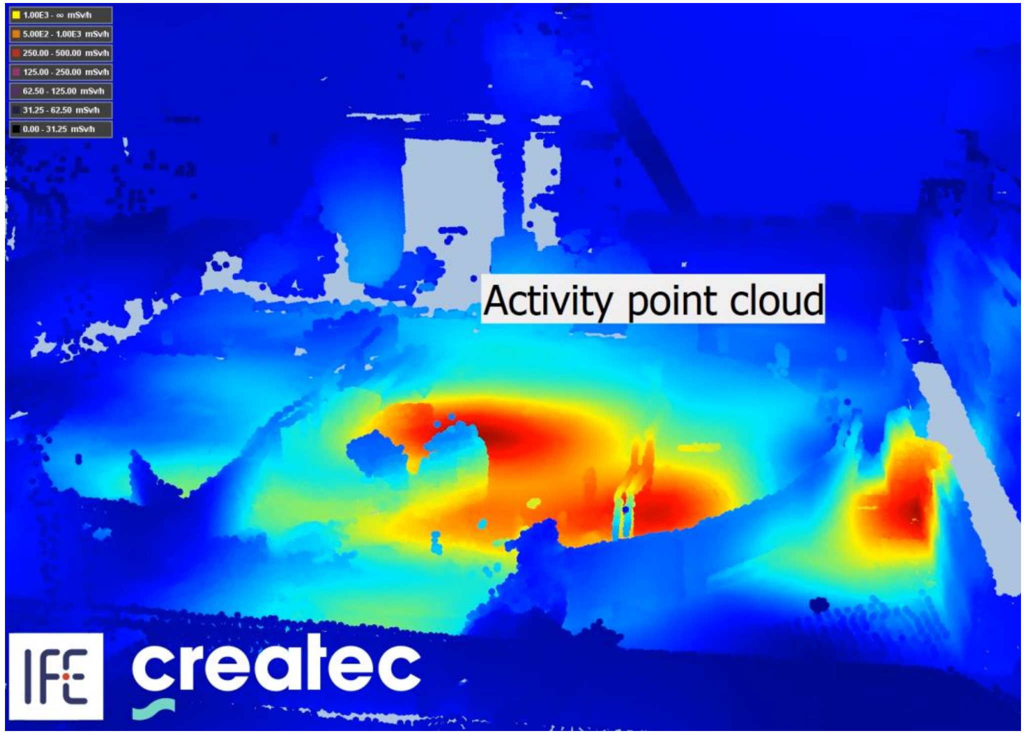
Source point clouds – gamma camera support

3D gamma scanners generate clouds of points with associated rad. properties (…)

How to use this in PK calculations?

- Oct tree to achieve (near) real-time speed
  - Sources are combined based on distance from ‘detector’
  - Inaccuracy if a combined source is detected as shielded while in reality it’s only partly shielded

Could be used to see simulate decontamination.



Single scatter ALBEDO

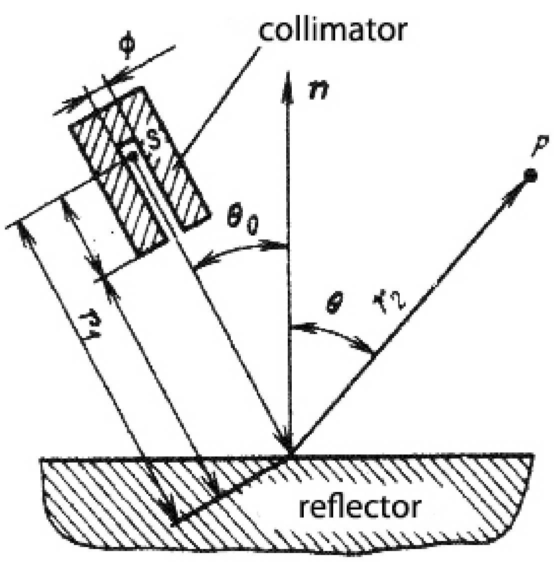
Method: Semi-empirical formula for single scatter albedo

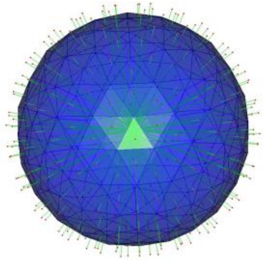
Gusev et. al. 198. Shielding from Ionizing Radiation. Vol.1. Physical Fundamentals for Shielding from Radiation (ISBN 5-283-02971-9)

Tech: R script

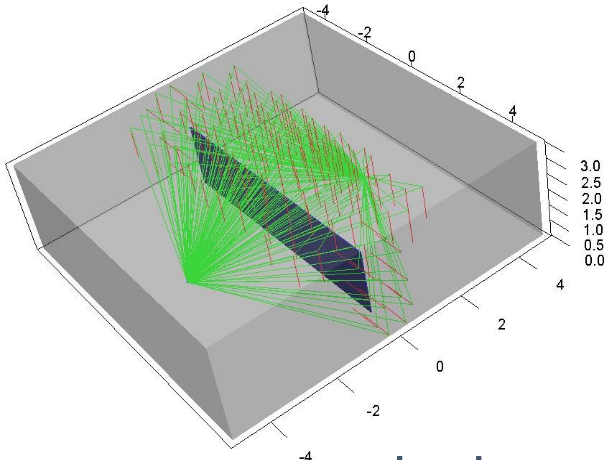
Conclusions:

- Dose from ‘reflection’ = 2% of direct dose with no shielding
- Dose from ‘reflection’ is comparable with direct dose with shields > cm lead
- Method is sensitive to resolution i.e. nr of faces of the polyhedron representing the source

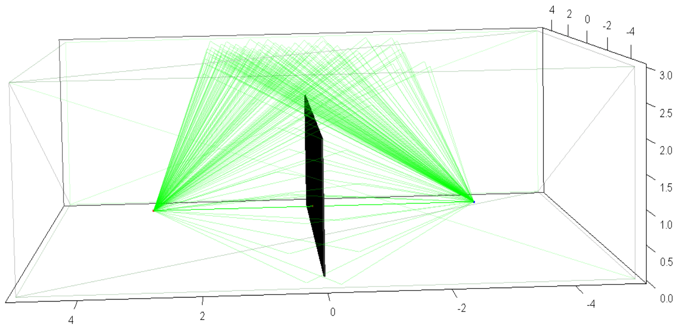




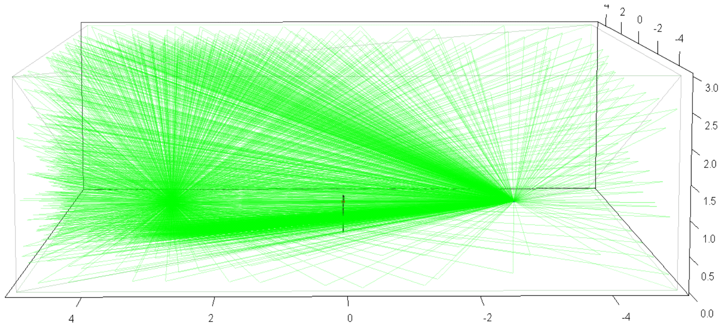
source



test case



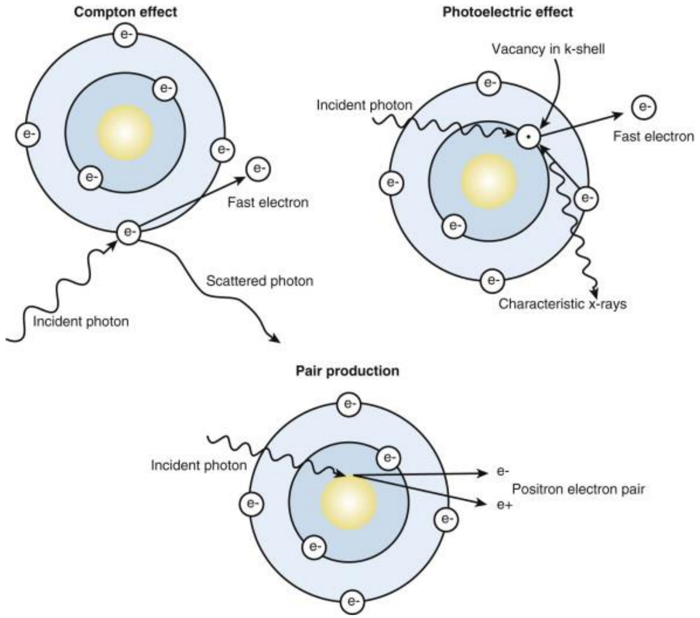
Albedo = 2.3*10 mSv/h
Direct dose rate = 5.5*10 mSv/h

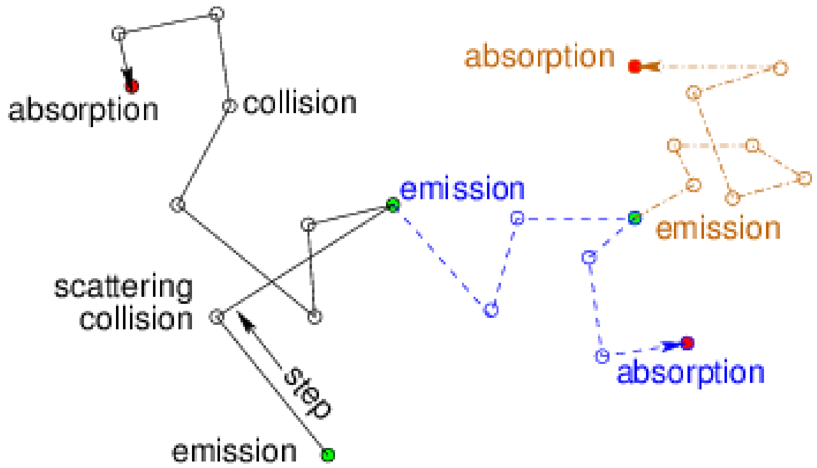


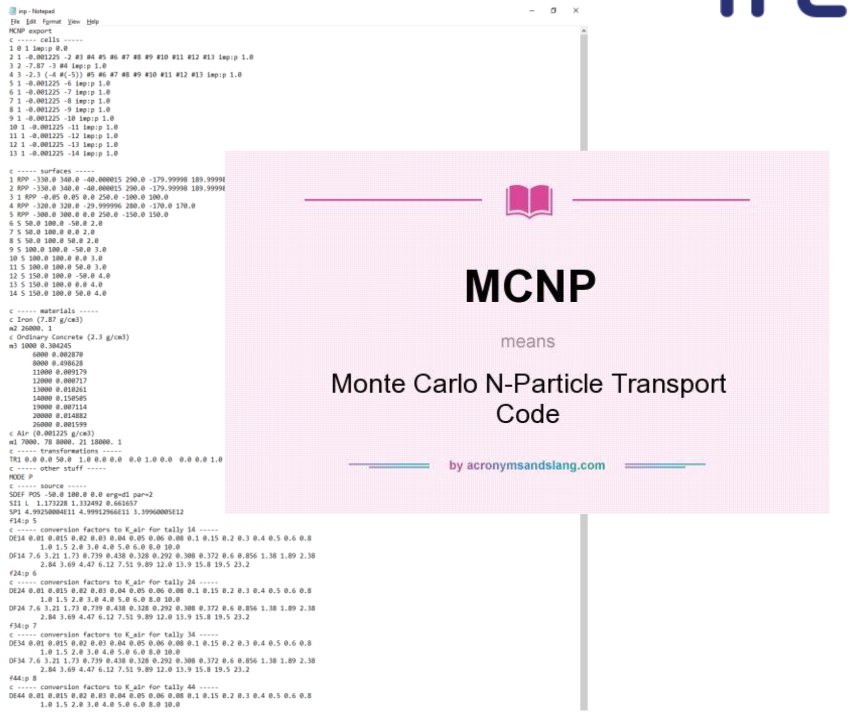
Albedo = 4.2*10 mSv/h
Direct dose rate = 5.5*10 mSv/h

K. Chizhov , I. Kudrin , I. Mazur , I. Tesnov , I. Szöke ,V. Kryuchkov

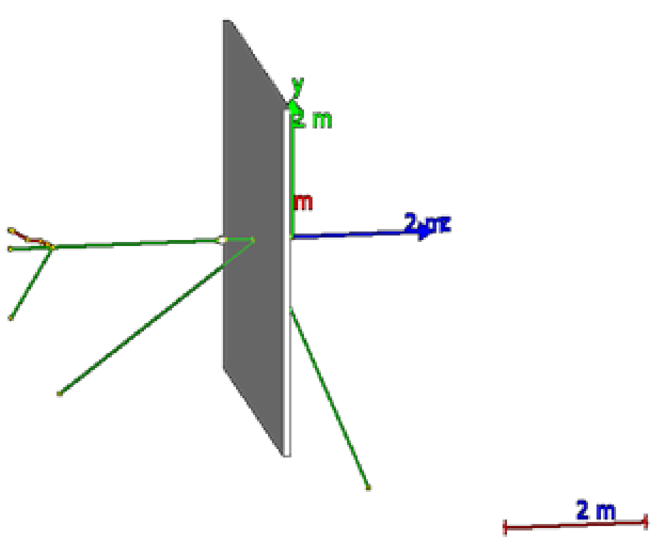
Monte Carlo radiation transport - MCNP

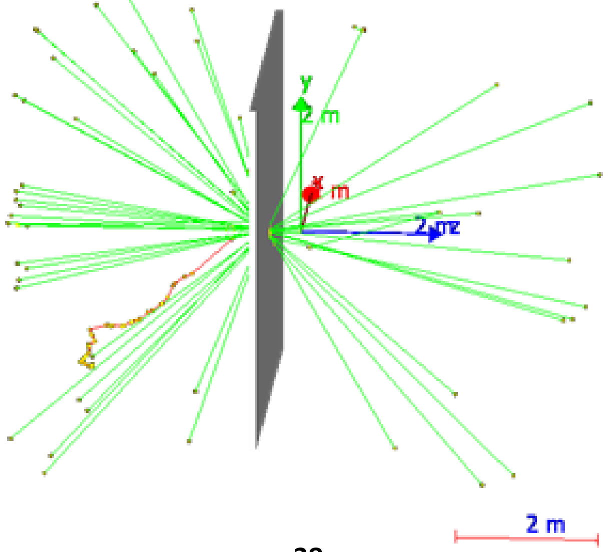


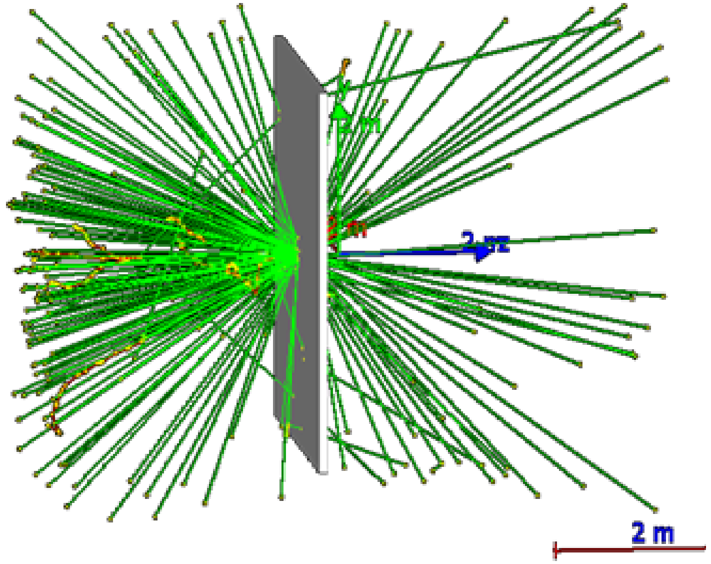




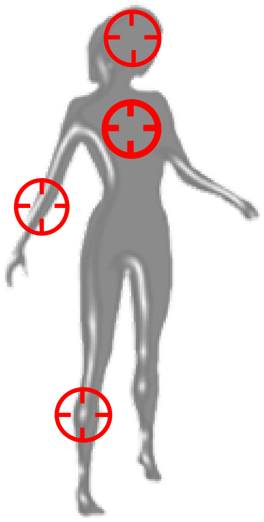

```
MCNP export
c ----- cells -----
1 0 1 imp:p 0.0
2 1 -0.001225 -2 #3 #4 #5 #6 #7 #8 #9 #10 #11 #12 #13 imp:p 1.0
3 2 -7.87 -3 #4 imp:p 1.0
4 3 -2.3 (-4 #(-5)) #5 #6 #7 #8 #9 #10 #11 #12 #13 imp:p 1.0
5 1 -0.001225 -6 imp:p 1.0
6 1 -0.001225 -7 imp:p 1.0
7 1 -0.001225 -8 imp:p 1.0
8 1 -0.001225 -9 imp:p 1.0
9 1 -0.001225 -10 imp:p 1.0
10 1 -0.001225 -11 imp:p 1.0
11 1 -0.001225 -12 imp:p 1.0
12 1 -0.001225 -13 imp:p 1.0
13 1 -0.001225 -14 imp:p 1.0

c ----- surfaces -----
1 RPP -330.0 340.0 -40.000015 290.0 -179.99998 189.99998
2 RPP -330.0 340.0 -40.000015 290.0 -179.99998 189.99998
3 1 RPP -0.05 0.05 0.0 250.0 -100.0 100.0
4 RPP -320.0 320.0 -29.999996 280.0 -170.0 170.0
5 RPP -300.0 300.0 0.0 250.0 -150.0 150.0
6 S 50.0 100.0 -50.0 2.0
7 S 50.0 100.0 0.0 2.0
8 S 50.0 100.0 50.0 2.0
9 S 100.0 100.0 -50.0 3.0
10 S 100.0 100.0 0.0 3.0
11 S 100.0 100.0 50.0 3.0
12 S 150.0 100.0 -50.0 4.0
13 S 150.0 100.0 0.0 4.0
14 S 150.0 100.0 50.0 4.0

c ----- materials -----
c Iron (7.87 g/cm3)
m2 26000. 1
c Ordinary Concrete (2.3 g/cm3)
m3 1000 0.304245
      6000 0.002870
      8000 0.498628
      11000 0.009179
      12000 0.000717
      13000 0.010261
      14000 0.150505
      19000 0.007114
      20000 0.014882
      26000 0.001599
c Air (0.001225 g/cm3)
m1 7000. 78 8000. 21 18000. 1
c ----- transformations -----
TR1 0.0 0.0 50.0  1.0 0.0 0.0  0.0 1.0 0.0  0.0 0.0 1.0
c ----- other stuff -----
MODE P
c ----- source -----
SDEF POS -50.0 100.0 0.0 erg=d1 par=2
SI1 L  1.173228 1.332492 0.661657
SP1 4.99250004E11 4.99912966E11 3.39960005E12
f14:p 5
c ----- conversion factors to K_air for tally 14 -----
DE14 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6 0.8
        1.0 1.5 2.0 3.0 4.0 5.0 6.0 8.0 10.0
DF14 7.6 3.21 1.73 0.739 0.438 0.328 0.292 0.308 0.372 0.6 0.856 1.38 1.89 2.38
        2.84 3.69 4.47 6.12 7.51 9.89 12.0 13.9 15.8 19.5 23.2
f24:p 6
c ----- conversion factors to K_air for tally 24 -----
DE24 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6 0.8
        1.0 1.5 2.0 3.0 4.0 5.0 6.0 8.0 10.0
DF24 7.6 3.21 1.73 0.739 0.438 0.328 0.292 0.308 0.372 0.6 0.856 1.38 1.89 2.38
        2.84 3.69 4.47 6.12 7.51 9.89 12.0 13.9 15.8 19.5 23.2
f34:p 7
c ----- conversion factors to K_air for tally 34 -----
DE34 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6 0.8
        1.0 1.5 2.0 3.0 4.0 5.0 6.0 8.0 10.0
DF34 7.6 3.21 1.73 0.739 0.438 0.328 0.292 0.308 0.372 0.6 0.856 1.38 1.89 2.38
        2.84 3.69 4.47 6.12 7.51 9.89 12.0 13.9 15.8 19.5 23.2
f44:p 8
c ----- conversion factors to K_air for tally 44 -----
DE44 0.01 0.015 0.02 0.03 0.04 0.05 0.06 0.08 0.1 0.15 0.2 0.3 0.4 0.5 0.6 0.8
        1.0 1.5 2.0 3.0 4.0 5.0 6.0 8.0 10.0
```

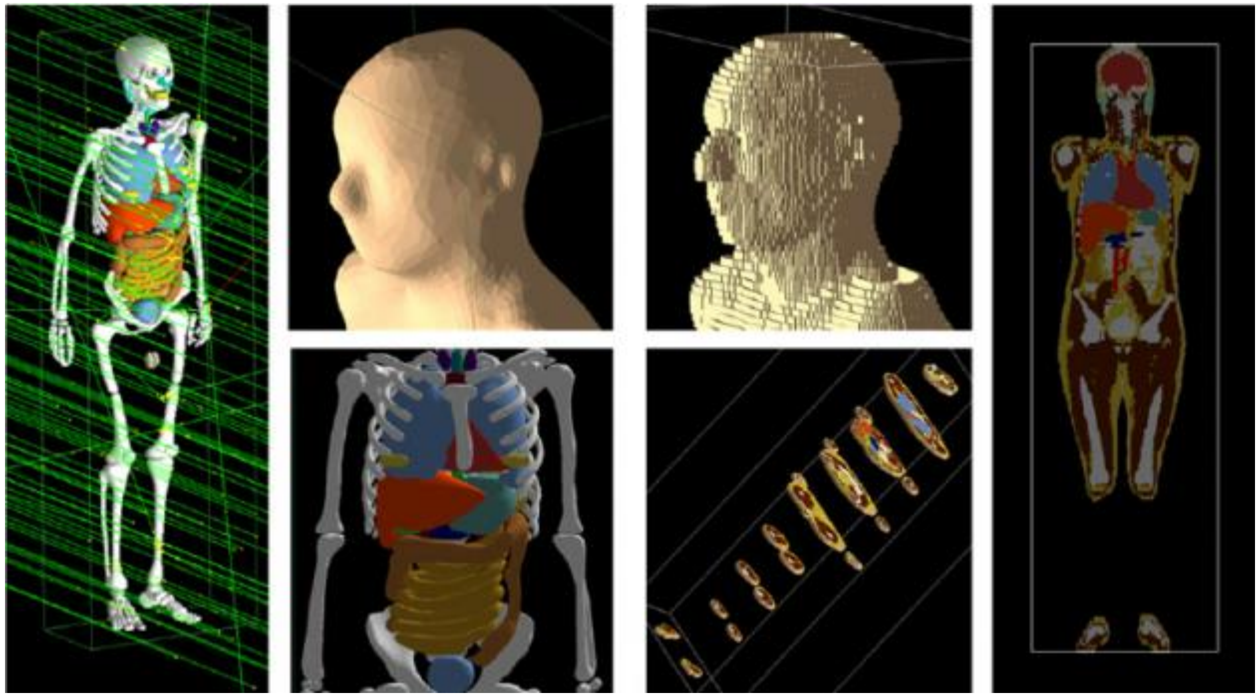




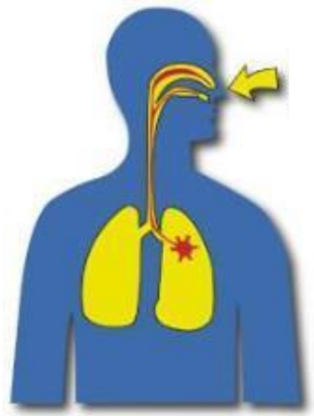


Human phantoms

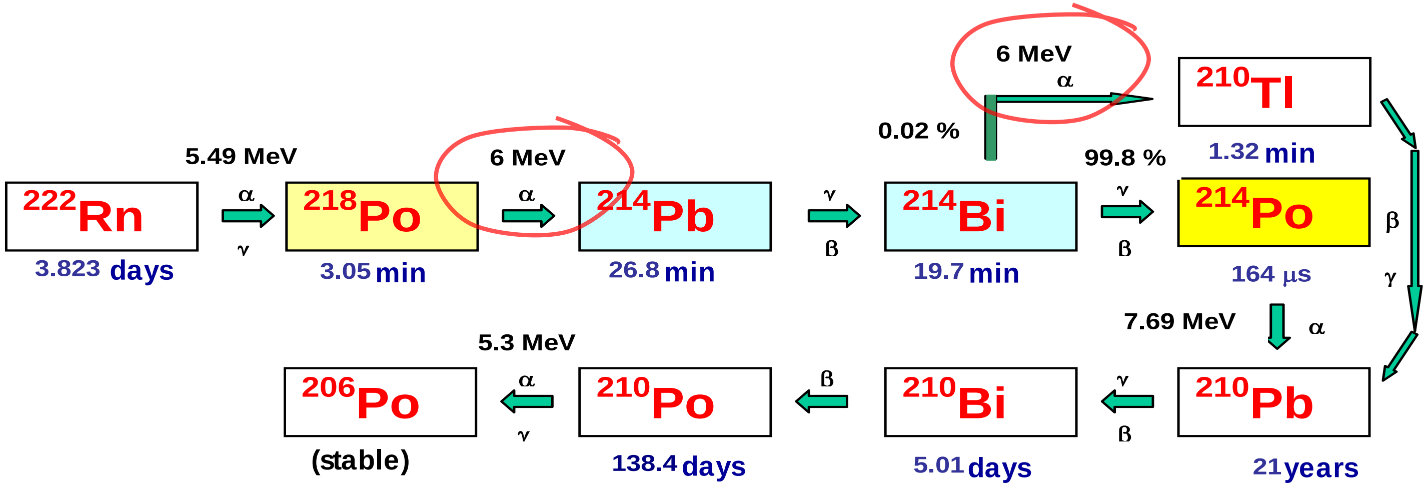




ICRP - Phys. Med. Biol. 58 (2013) 6985–7007



Inhalation



Overall dose

Effective dose

mSv

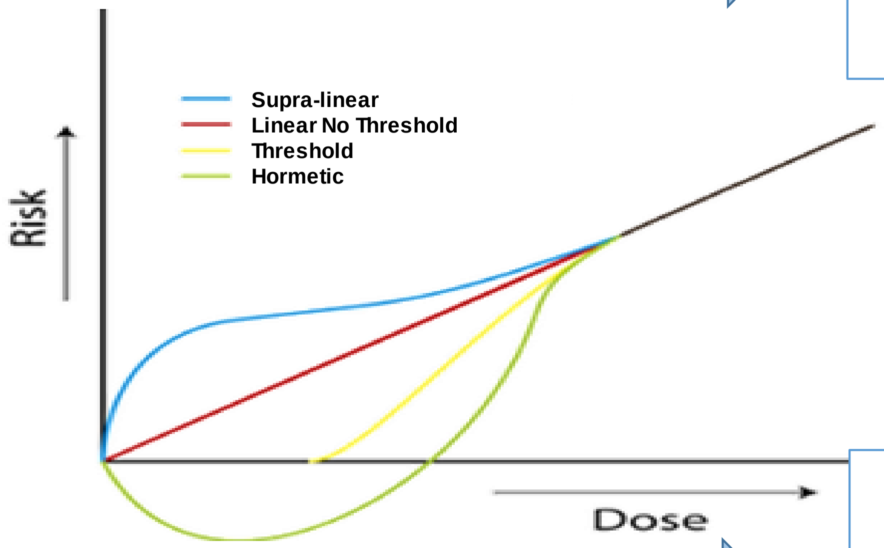
Details of rad. burden

Regional (e.g. lobe, airway specific) exposure rate, events on cellular level

Epidemiology

Risk

(e.g. cancer risk)

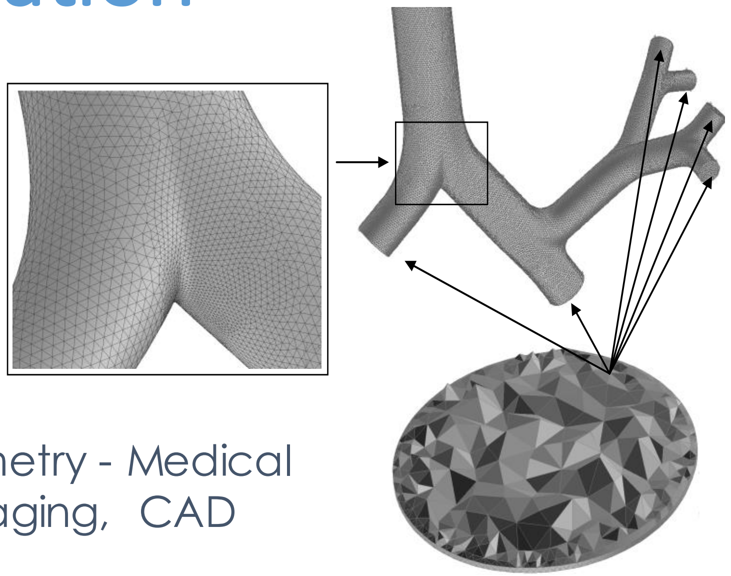


Risk

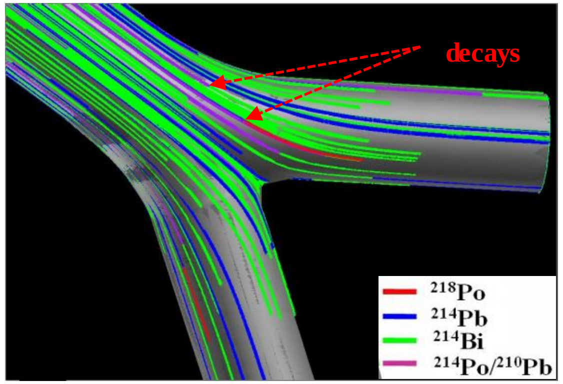
(e.g. cancer risk)

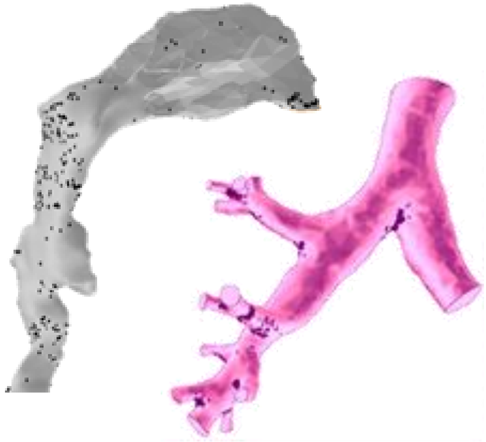
Modelling and in-vitro experiments

Inhalation



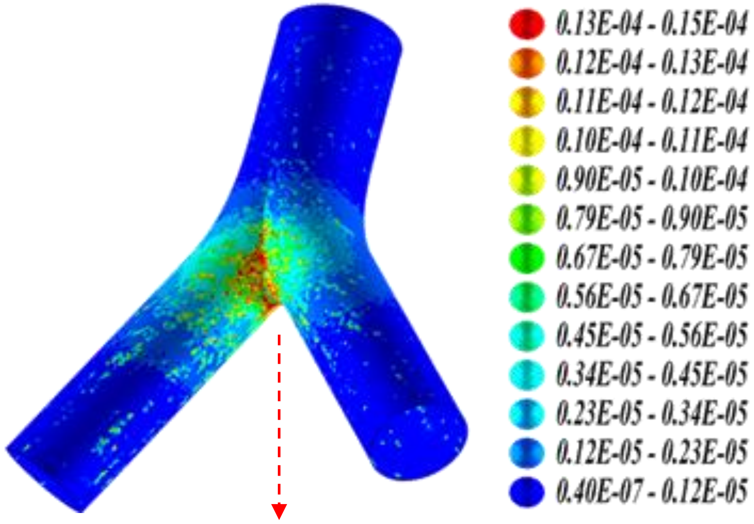
Geometry - Medical imaging, CAD

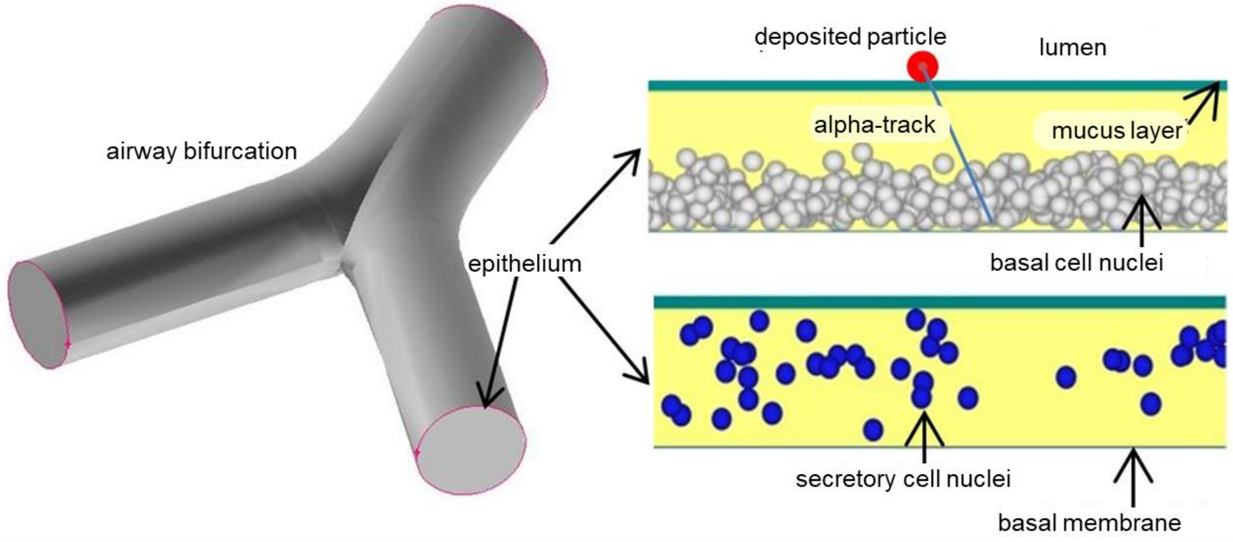




Air & particle transport (and deposition) – custom CFD

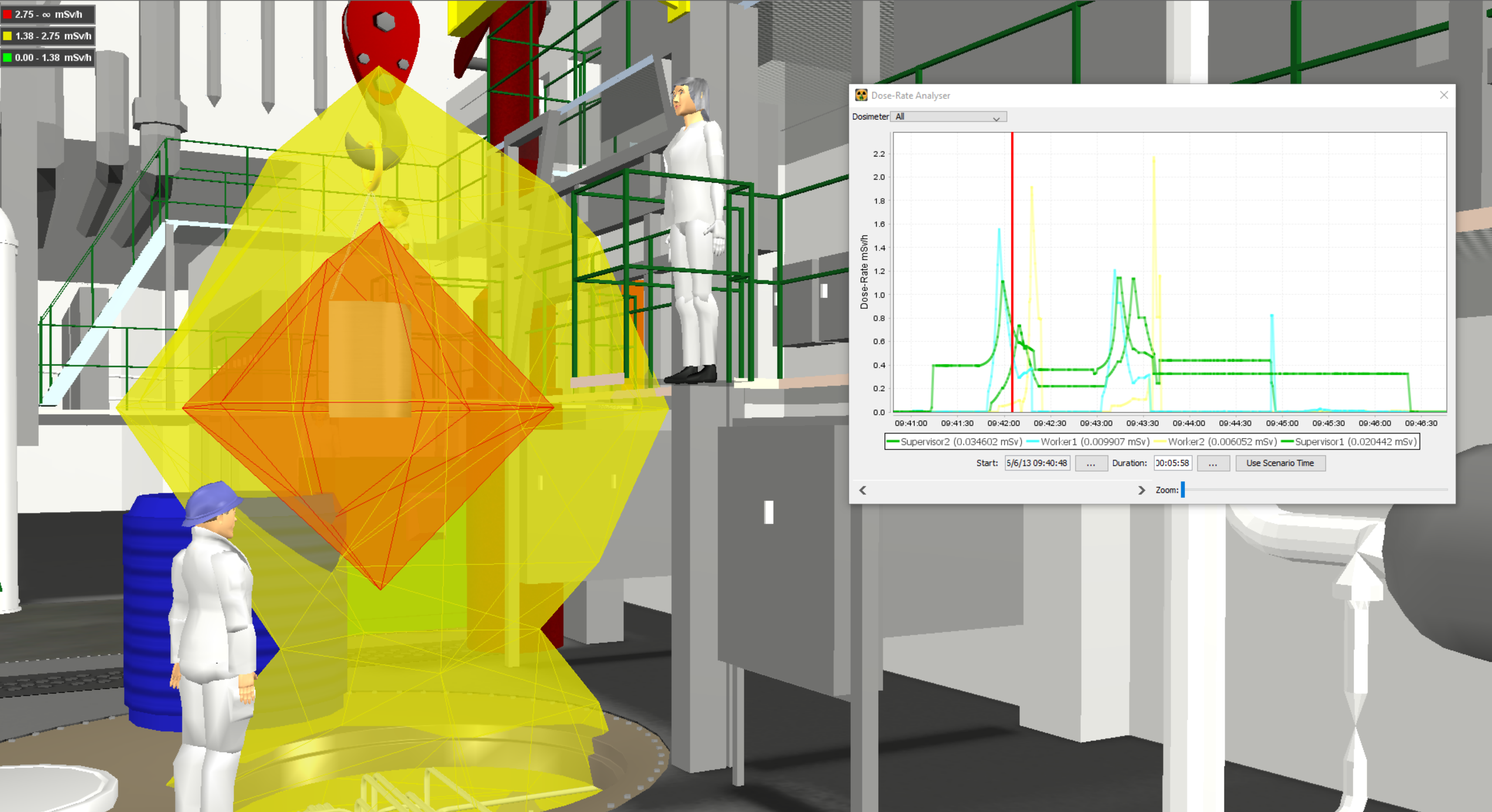
Cell transformation probability direct effect

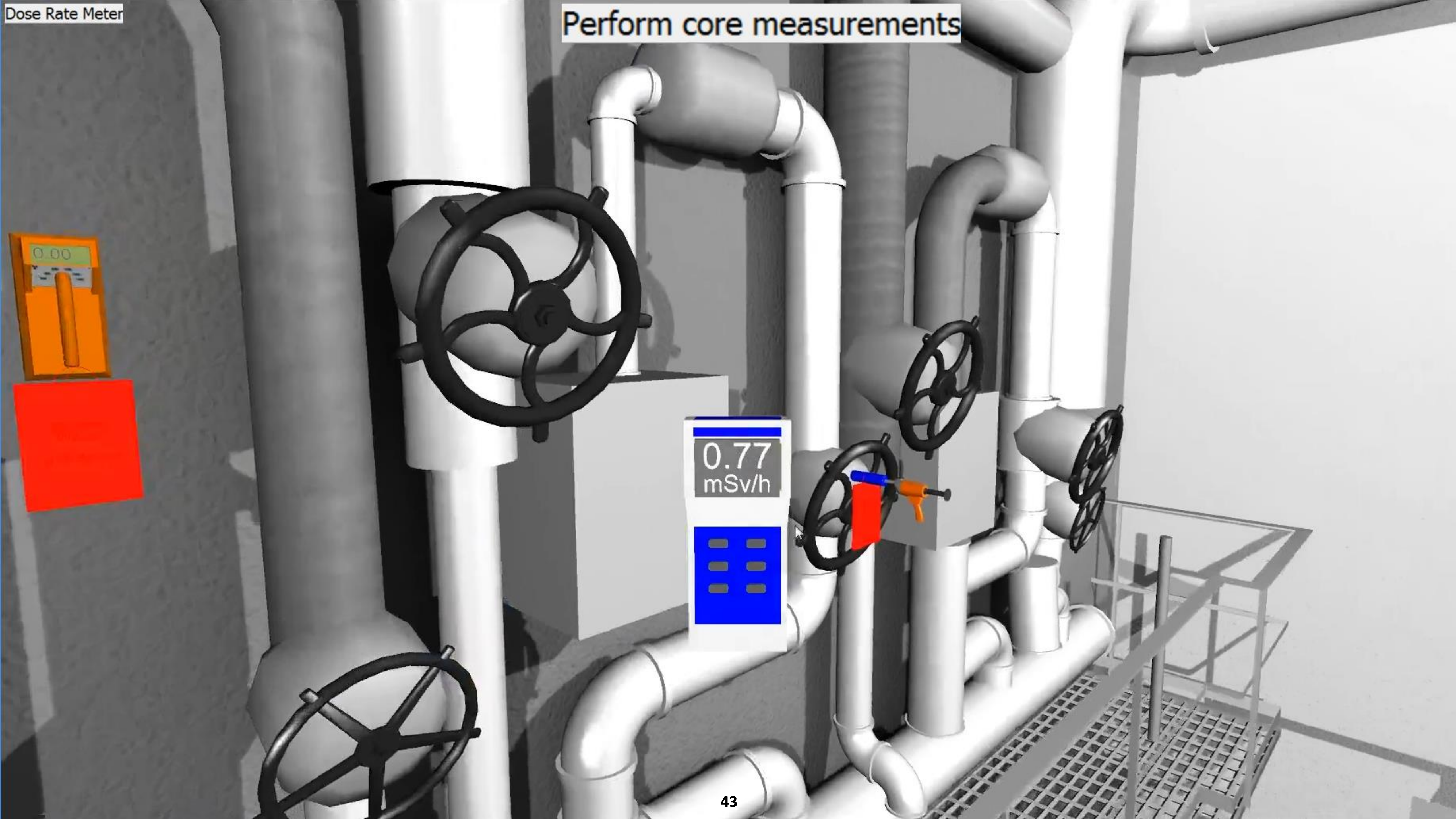


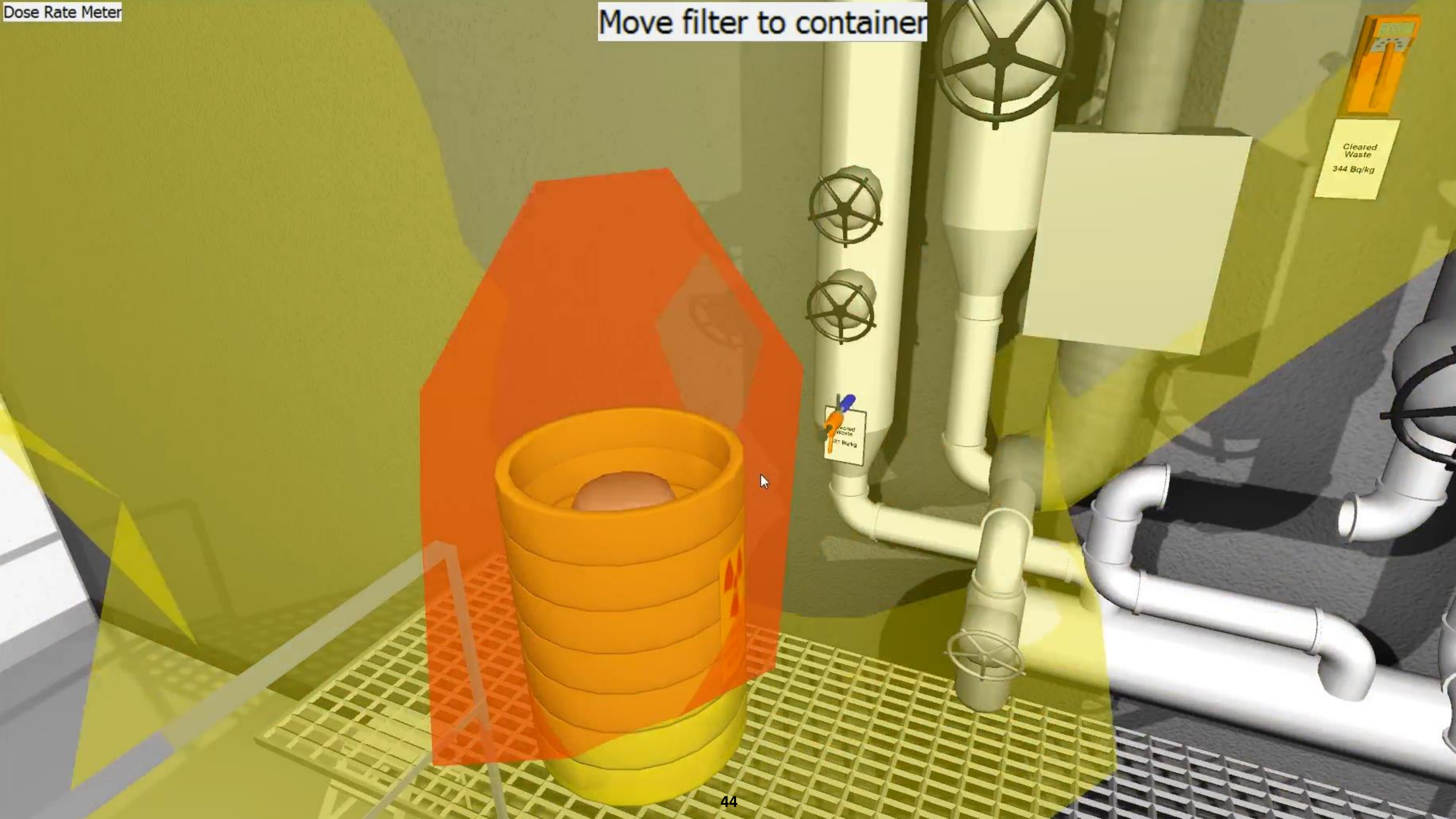


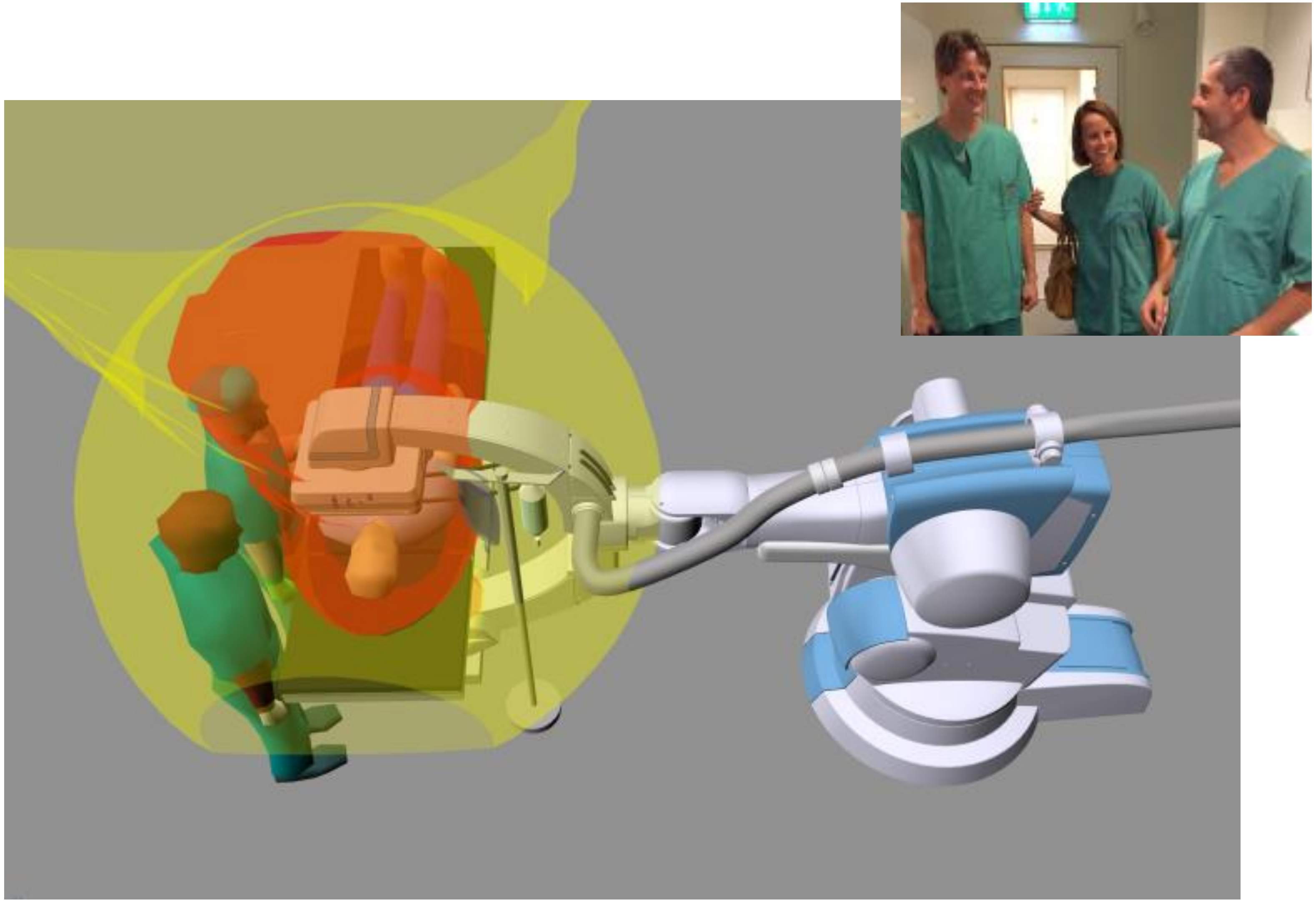
Epithelium modelling, Own-code

a – cell interactions - Own-code, lit. data


2.75 - ∞ mSv/h
1.38 - 2.75 mSv/h
0.00 - 1.38 mSv/h
Dose-Rate Analyser
Dosimeter All
Dose-Rate mSv/h
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
09:41:00 09:41:30 09:42:00 09:42:30 09:43:00 09:43:30 09:44:00 09:44:30 09:45:00 09:45:30 09:46:00 09:46:30
Supervisor2 (0.034602 mSv)
Worker1 (0.009907 mSv)
Worker2 (0.006052 mSv)
Supervisor1 (0.020442 mSv)
Start: 5/6/13 09:40:48
Duration: 00:05:58
Use Scenario Time
Zoom:


Dose Rate Meter
Perform core measurements
0.00
0.77
mSv/h


Dose Rate Meter
Move filter to container
Cleared Waste
344 Bq/kg



Publications

- Szőke et al. New software tools for dynamic radiological characterisation and monitoring in nuclear sites. Workshop on Radiological Characterisation for Decommissioning; 2012 April 17-19; Nyköping (Sweden). http://www.oecd-nea.org/rwm/wpdd/rcd-workshop/
- Szőke et al. Human-centred technologies for nuclear decommissioning. NKS-R Decommissioning Seminar; 2013 November 6-7; Halden http://projects.hrp.no/nks-decom-2013/files/2013/01/Human_centred_techologies_for_nuclear_decommissioning_ife_szoeke_ppt_nks2013.pdf
- Szőke & Johnsen Human-centred radiological software techniques supporting improved nuclear safety. Nuclear Safety and Simulation. 2013; 4 3: 219-25. http://www.ijnsweb.com/?type=subscriber&action=articleinfo&id=176
- Szőke et al. Real-time 3D radiation risk assessment supporting simulation of work in nuclear environments. Journal of Radiological Protection. 2014; 34 2: 389–416. http://iopscience.iop.org/0952-4746/34/2/389/
- Szőke et al. Comprehensive support for nuclear decommissioning based on 3D simulation and advanced user interface technologies. Journal of Nuclear Science and Technology. 2014; http://www.tandfonline.com/doi/full/10.1080/00223131.2014.951704
- Chizhov et al. 3D simulation as a tool for improving safety culture during the remediation work in the Andreeva Bay. Journal of Radiological Protection. 2014; 34(4): 755-73. http://iopscience.iop.org/0952-4746/34/4/755/ - Winner of 2014 Bernard Wheatley Award!