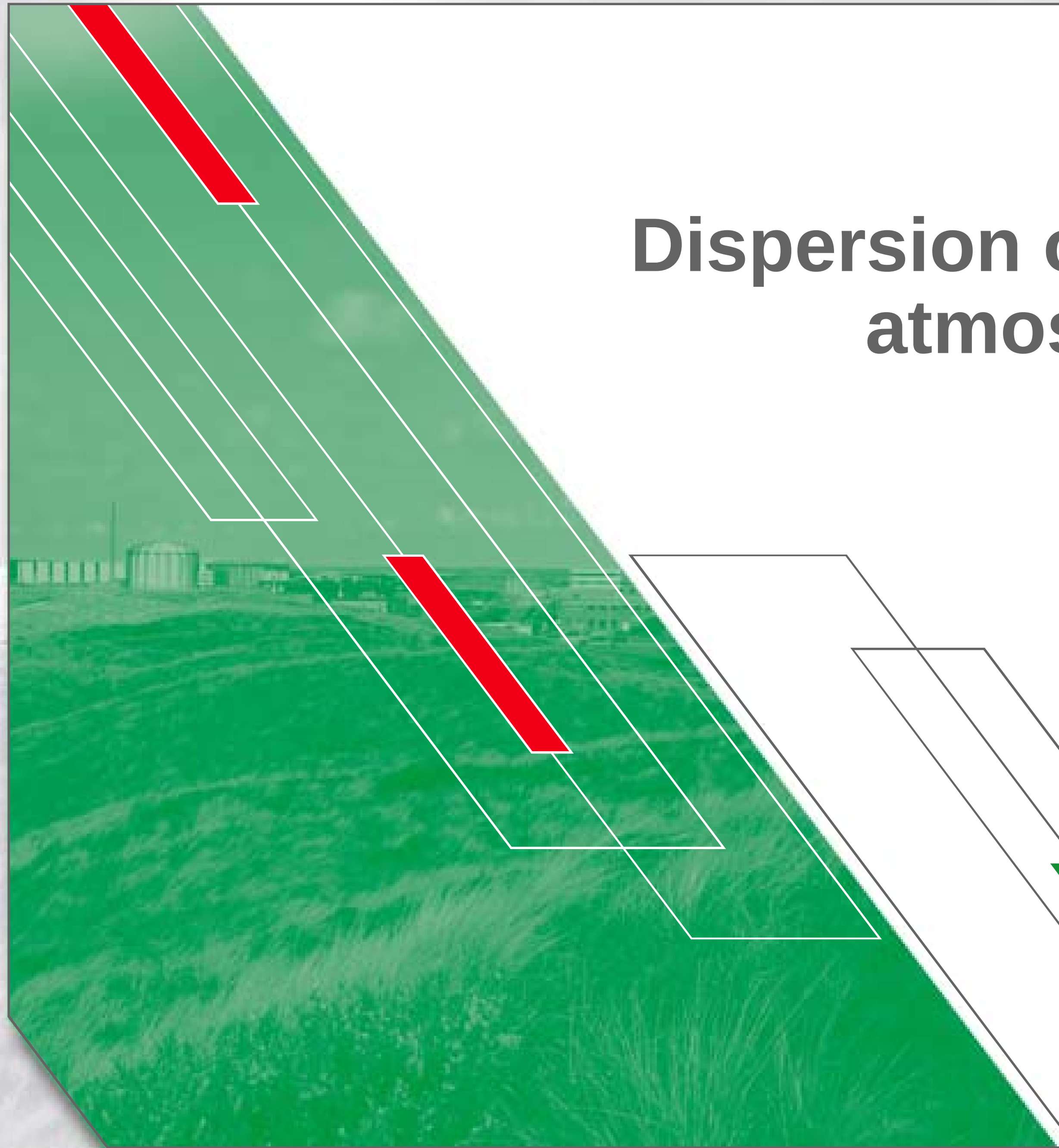

Dispersion of ^{99m}Tc in the atmosphere from a detonation

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Contents

1. Introduction

- Field experiments at NINCBS in Pribram
- Explosion of ^{99m}Tc in the atmosphere
- Explosion carried out on a helicopter landing side surrounded by forest
- Tests side is surrounded by forest and hills.

- Measurements include:
  - Atmospheric conditions e.g. wind speed, direction temperature etc.
  - Droplet specifications, like droplet size and volume activity.
  - Surface contamination and subsequent dose rates.:
  - Radioactive concentrations in the air.

Test side at NINCBS in Pribram

2. Mathematical background

- Computational Fluid Dynamics (CFD)

  The calculations are based on the CFD software Fluent©, in-house algorithms are included to take account of nuclear decay, deposition and dispersion.

- Navier-Stokes equations

  The atmospheric flow is modelled using conservation equations for mass, momentum and energy.

- Dispersion and deposition of droplets

  Dispersion and deposition is modelled within an additional conservation equation.

- Pollution modelling

  Dispersion of the ^{99m}Tc pollutant is based on atmospheric and thermal flow features.

3. CFD conservation equations

- The CFD computation is based on conservation equations for mass, momentum and energy.
- Turbulent motion is take into account with a k-ε turbulence model.
- Forest patches are considered with an extra sink term.
- A logarithmic boundary model with roughness height is applied to the ground.

CFD conservation equations	
$\rho(\nabla \cdot u_k) = 0$	Mass conservation equation
$\rho\left(\frac{\partial(u_k)}{\partial t} + \nabla \cdot (u_k u_l)\right) = -\nabla P + \nabla \cdot (\mu_{eff} \nabla u_k) + S_{u,k}$	Momentum conservation equation
$\mu_{eff} = \mu_l + \mu_t$	Turbulent viscosity
$S_{u,k} = -\rho C_d a_l U^2 = -\frac{1}{2}\rho C_n U^2$	Forest patches
$\frac{\partial \rho E}{\partial t} + \nabla \cdot \rho u_k E = -\nabla u_k P + \nabla \cdot (\Gamma_T \nabla T)$	Energy conservation equation

4. Dispersion modelling of ^{99m}Tc

- The activity from ^{99m}Tc is based on an additional conservation equation.
- Turbulent diffusion is based on the k-ε turbulence model.
- Brownian diffusion, terminal velocity and nuclear decay are considered.
- For each droplet diameter a separate conservation equation is required.
- Evaporation is not included.

Dispersion of ^{99m}Tc	
$\frac{\partial C_m}{\partial t} + \nabla \cdot [(u + v_{s,m}) C_i] = \nabla \cdot [(\Gamma_m + D_m) \nabla C_m] + S_{C,m}$	Droplet conservation equation
$\Gamma_m = \mu_{eff} / \rho$	Turbulent diffusion
$D = \frac{k_B\, T\, Cu}{3\pi\, \mu_l\, d_p}$	Brownian diffusion
$v_s = \frac{\rho_d g d_d^2}{18 \mu_a}$	Terminal velocity
$S_C = -\lambda C$	Nuclear decay

5. Modelling of droplet deposition

- Deposition is applied as an extra sink term to the elements adjacent to the ground.
- The sink term is a function of the deposition velocity and concentration ^{99m}Tc in the numerical element.
- Only dry deposition is considered.
- Dry deposition considers: gravitational settling, turbulent motion and Brownian diffusion.
- Deposition due to rainfall is not considered, but can be applied.

Deposition of ^{99m}Tc

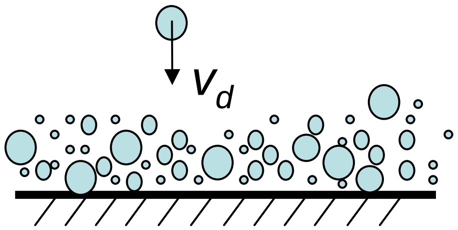
$$J_d = v_d \cdot C_b$$

Deposition flux

$$v_{dd} = \frac{v_s}{1 - \exp\left(-\frac{v_s I}{u^*}\right)}$$

Deposition velocity

Sketch of the droplet deposition



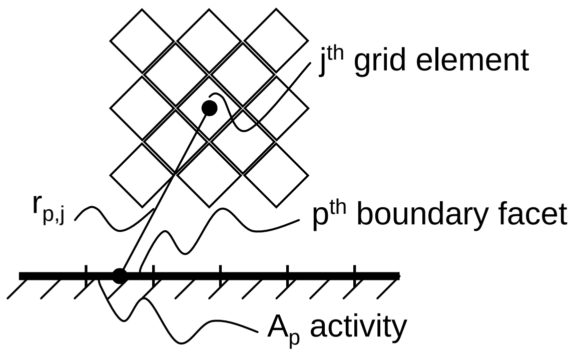
6. Radiation exposure from ^{99m}Tc

- The dose rate in each element is computed at the end of the time-step and is based on the accumulated droplet deposition.
- The activity at each boundary facet is considered a point source.
- The dose rate is based on the air Kerma rate constant for ^{99m}Tc in air.
- The air Kerma rate constant (Γ_a) is 0.018 μGy·m^{2}MBq^{-1}h^{-1}.

Calculation absorbed dose rate

$$\dot{K}_{a,j} = \Gamma_a \sum_{p=0}^{p=P_b} \frac{A_p}{r_{p,j}^2}$$

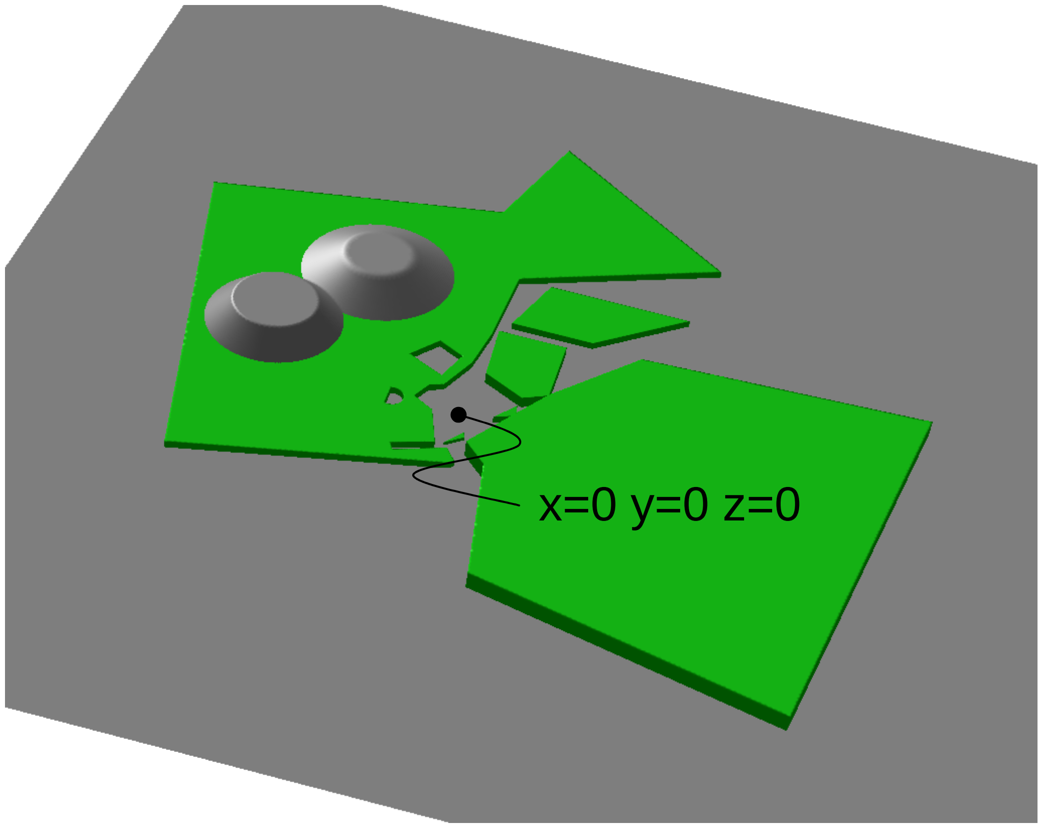
Sketch of the absorbed dose rate



7. Model setup and boundary conditions

- Dimensions CFD model:
  x=1000m / y=100m / z=950m.
- CFD Model:
  Transient simulation, with steady-state BCs.
- Simulation time:
  500s, with a 1s time-step size.
- CFD Mesh:
  Polyhedral mesh elements.
- Turbulence model:
  k-ε RNG model.
- Temperature:
  Energy calculation.
- Roughness length:
  y_0 is 0.03 m.
- Resistance coefficient forest:
  C_n is 0.1 m^{-1}.

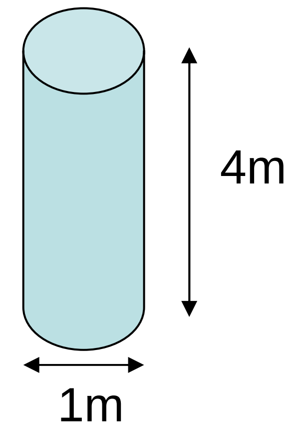
Geometry of the CFD model



8. Initial release of the droplets

- The starting point of the computation is a cylindrical formed cloud containing a uniform concentration of ^{99m}Tc.
- The explosion itself is not computed.
- The geometry of the cloud and its content are based on data provided by the NRPI.
- Possibilities for an explosion model are feasible and need to be discussed in a technical forum.
- The total activity in the cloud is 1,058MBq.

Shape of the initial cloud



Dia. versus activity in the cloud

Droplet diameter (m)	Volume activity (%)
$2 \cdot 10^{-5}$	10.0
$6 \cdot 10^{-6}$	46.6
$1 \cdot 10^{-6}$	15.0
$2 \cdot 10^{-7}$	28.4

9. Velocity boundary conditions

- Profiles for wind speed, kinetic energy and dissipation are based on a neutral atmospheric boundary layer.
- The wind speed is 4 m/s at 10m above ground.
- The turbulent kinetic energy is 0.27 m^2/s^2.
- The dissipation is inverse linear with the height from the ground.

Velocity boundary conditions
$U(y) = u^{*}_{ABL} \ln\left(\frac{y + y_0}{y_0}\right)$ Logarithmic velocity profile
$k(y) = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}}$ Turbulent kinetic energy profile
$\varepsilon(y) = \frac{u^{*3}_{ABL}}{\kappa(y + y_0)}$ Turbulent dissipation profile

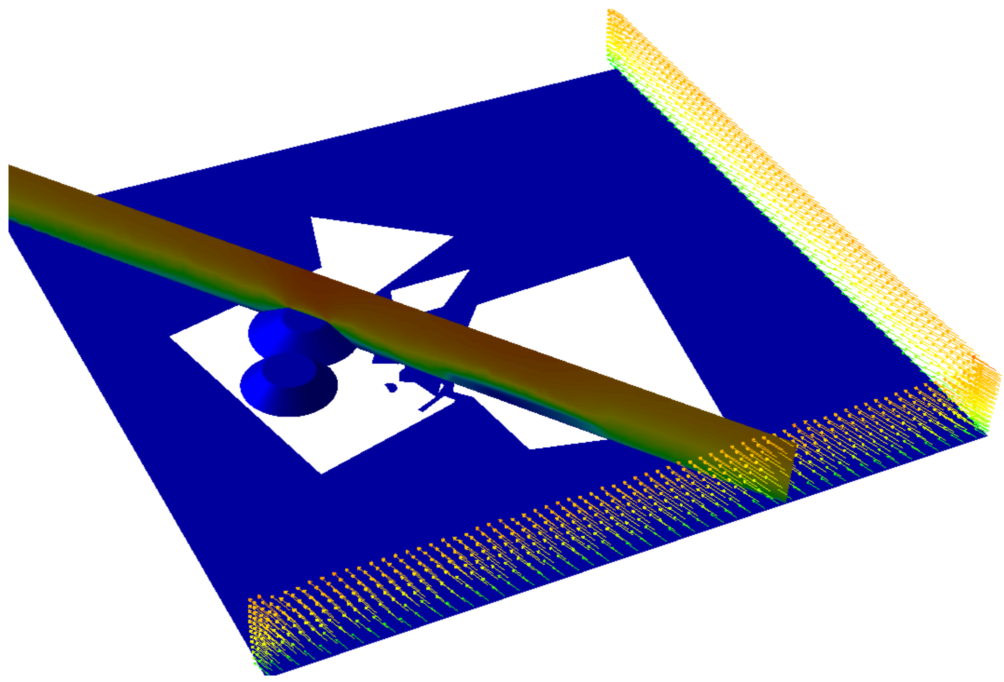
10. Simulation results

- Simulation process:
  - 1. Performed sensitivity simulations, 2. Fine-tune & calibrate simulation setup, 3. Performed final simulation
- Performed simulations include:
  - 1 final simulation with droplet spectrum
  - 10 simulations as part of the sensitivity analysis
- Simulations are benchmarked *only* against test 2 (15th May 2008) from the NRPI

11. Simulated atmospheric flow field

- Sustainable atmospheric flow
- Spatial variations in the grid resolution effect the sustainability of the flow field.
- Mesh sensitivity analysis was performed.
- Reduced wind speed in the forest patches
- Flow field is sensitive to wind speed, direction and forest settings
- Vortex formation in the wake area behind the forest

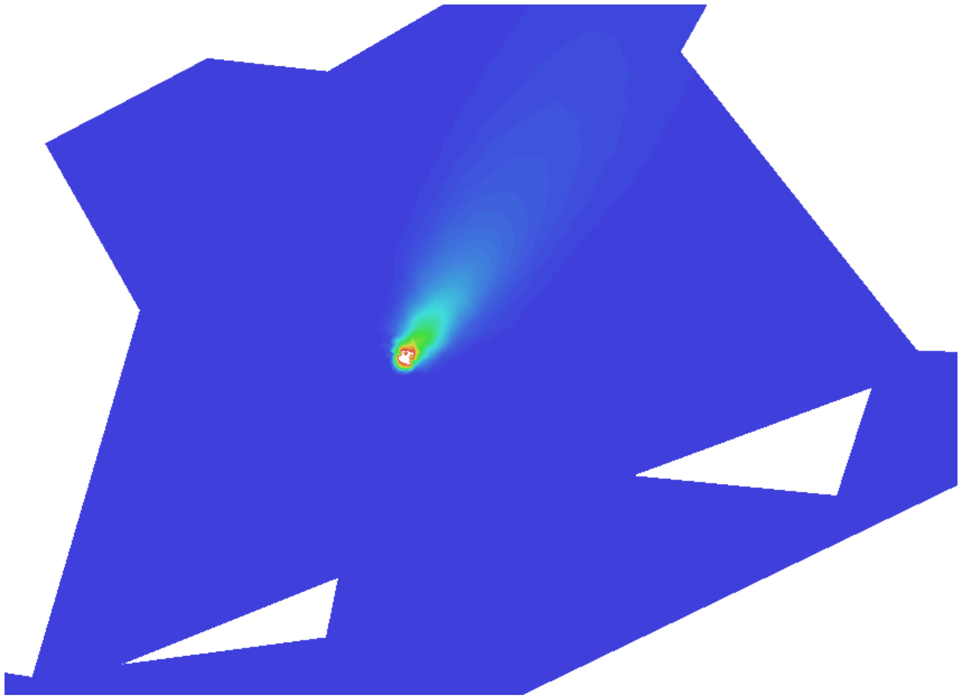
Prediction of the flow field



12. Deposition of ^{99m}Tc on the ground surface

^{99m}Tc deposition

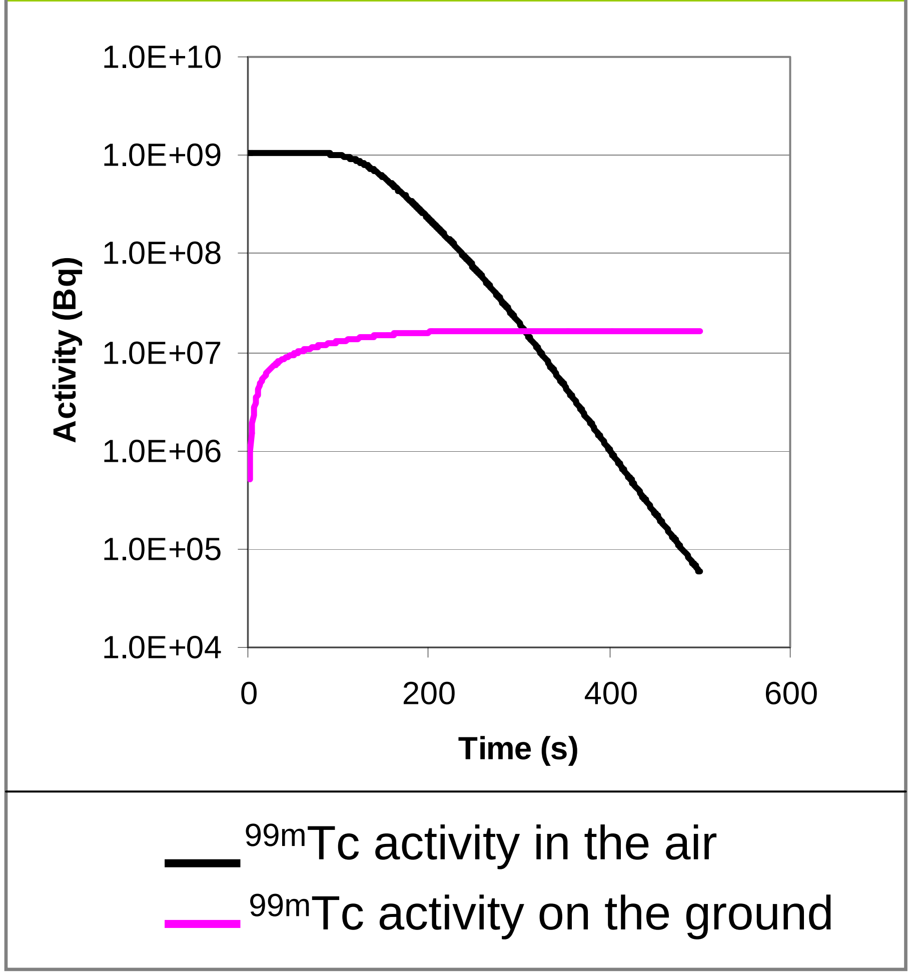
^{99m}Tc deposition zoom-in



13. ^{99m}Tc in the air and on the ground

- The total deposition of ^{99m}Tc on the ground 500s after the explosion is 1.6%.
- After 200s there is no further increase in ^{99m}Tc surface contamination.
- After 150-200s ^{99m}Tc reaches the outer edges of the computational domain.
- After 400s there is no significant concentration of ^{99m}Tc in the air.

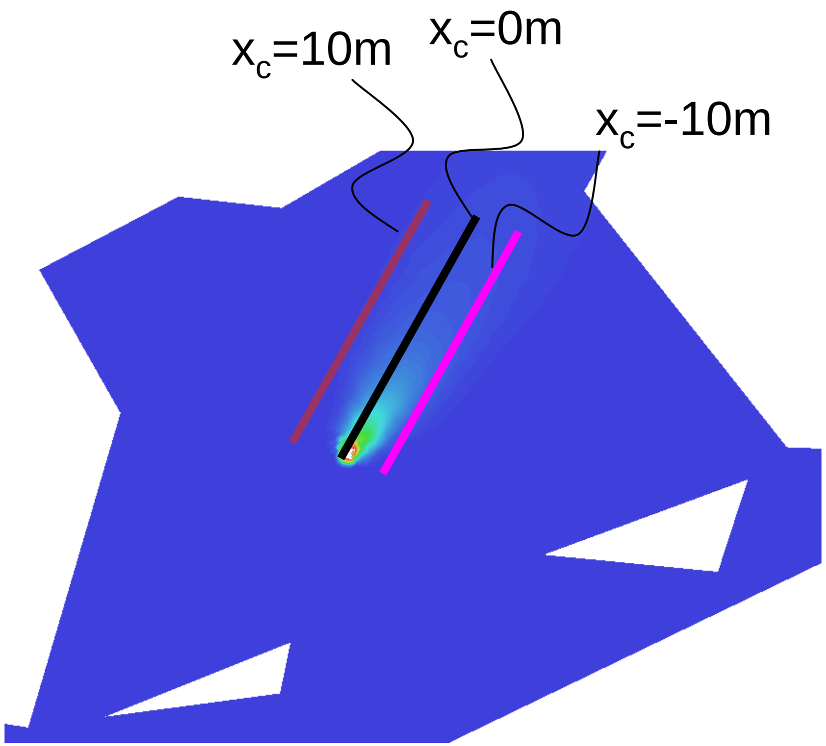
^{99m}Tc activity in the air and on the ground



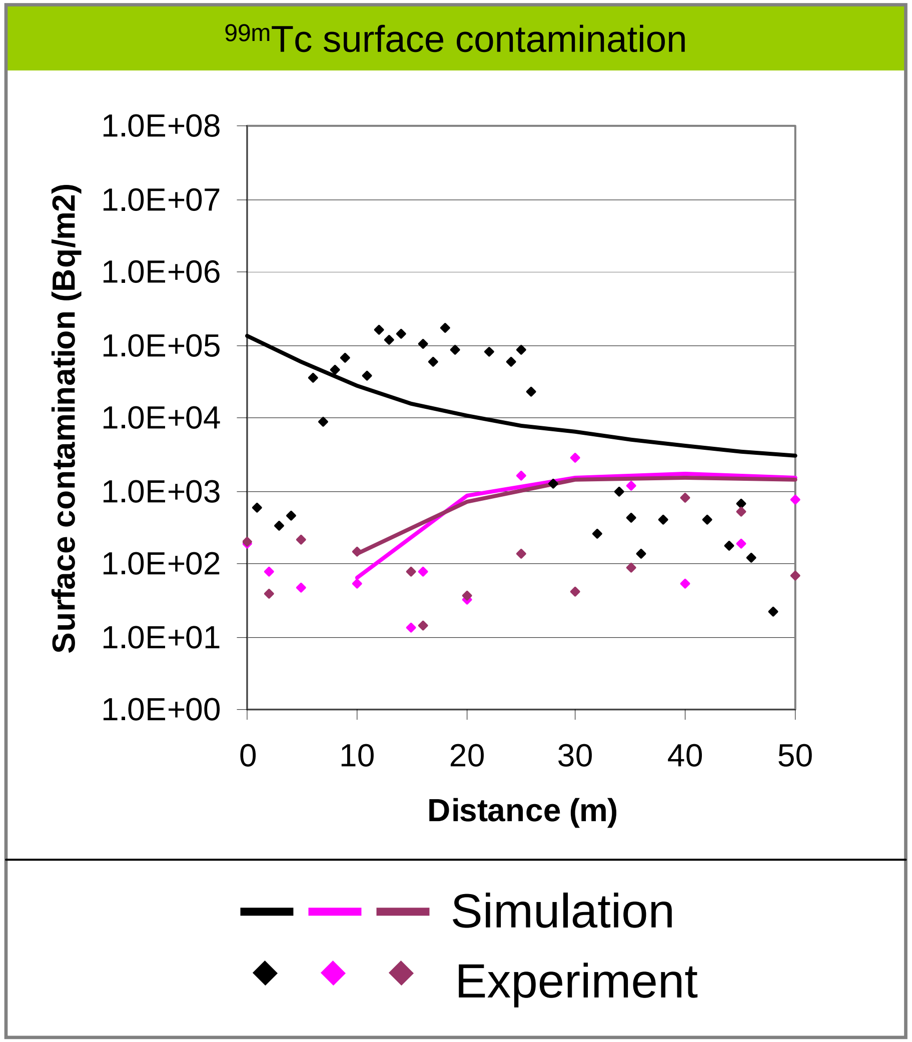
14. ^{99m}Tc in the air and on the ground

^{99m}Tc activity on the ground surface per diameter category			
Droplet diameter (m)	**Released activity (Bq)**	**Deposition (Bq)**	**Percentage deposition (%)**
$2 \cdot 10^{-5}$ / $2 \cdot 10^{-7}$	$1.06 \cdot 10^{9}$	$1.65 \cdot 10^{7}$	1.6

15. ^{99m}Tc surface contamination

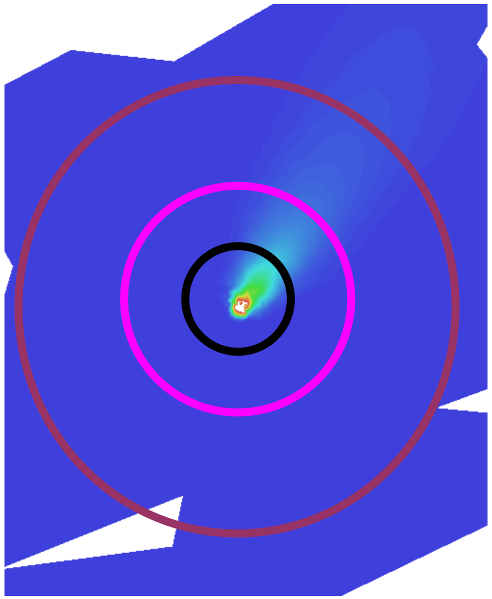


Position of the 3 lines in the graph relative to the explosion.



16. ^{99m}Tc in the air and on the ground

^{99m}Tc contamination zones

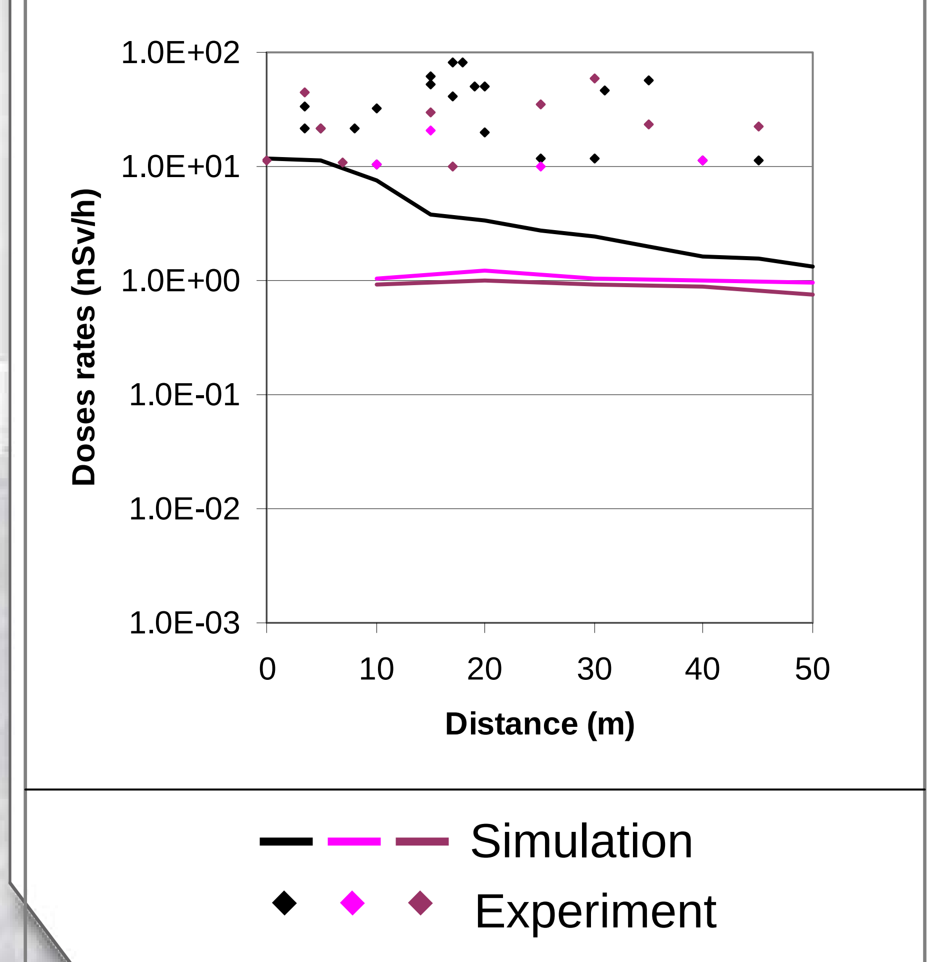


^{99m}Tc activity on the ground surface per diameter category

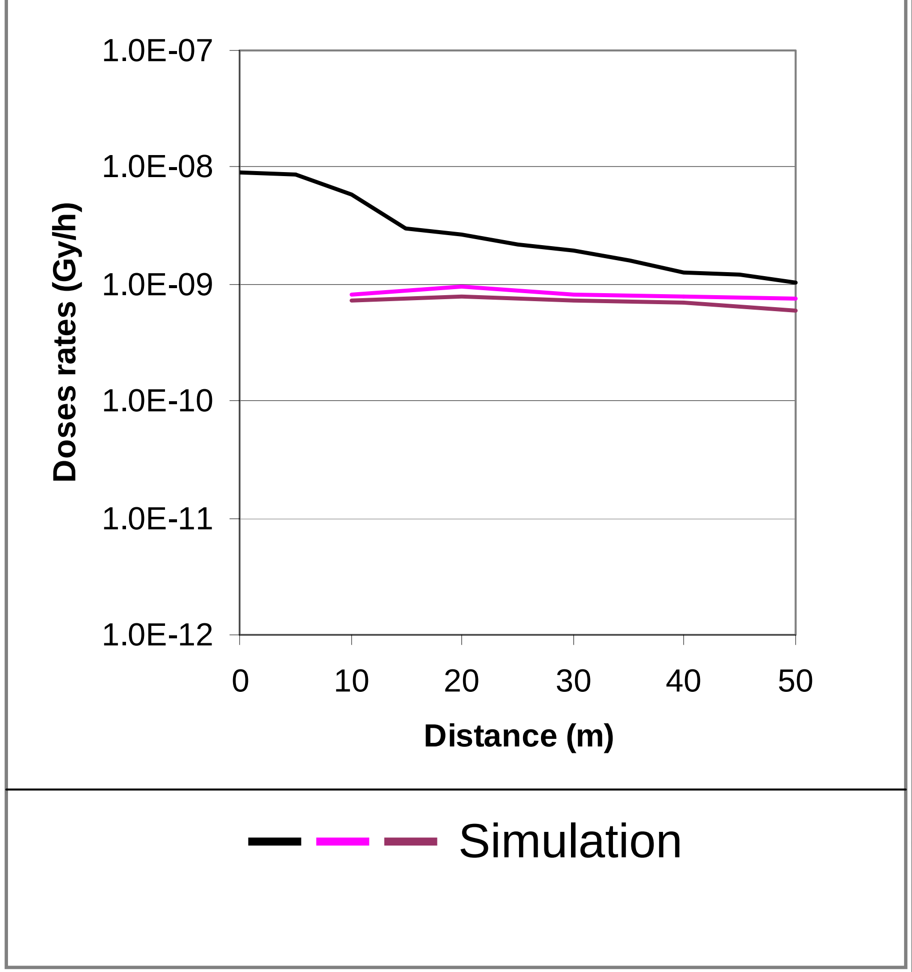
Droplet diameter (m)	R_{50} zone (m)	R_{75} zone (m)	R_{95} zone (m)
$2 \cdot 10^{-5}$ / $2 \cdot 10^{-7}$	7.4	16.6	42.1
$2 \cdot 10^{-5}$	7.2	16.3	41.9
$6 \cdot 10^{-6}$	7.8	17.2	42.5
$1 \cdot 10^{-6}$	7.8	17.3	43.9
$2 \cdot 10^{-7}$	6.1	15.8	46.1

17. ^{99m}Tc dose rates at 1m above ground

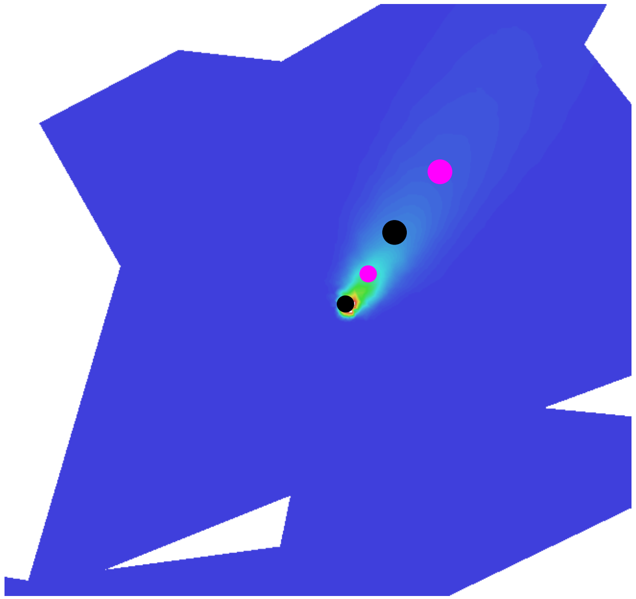
^{99m}Tc equivalent dose rates at 1m above ground

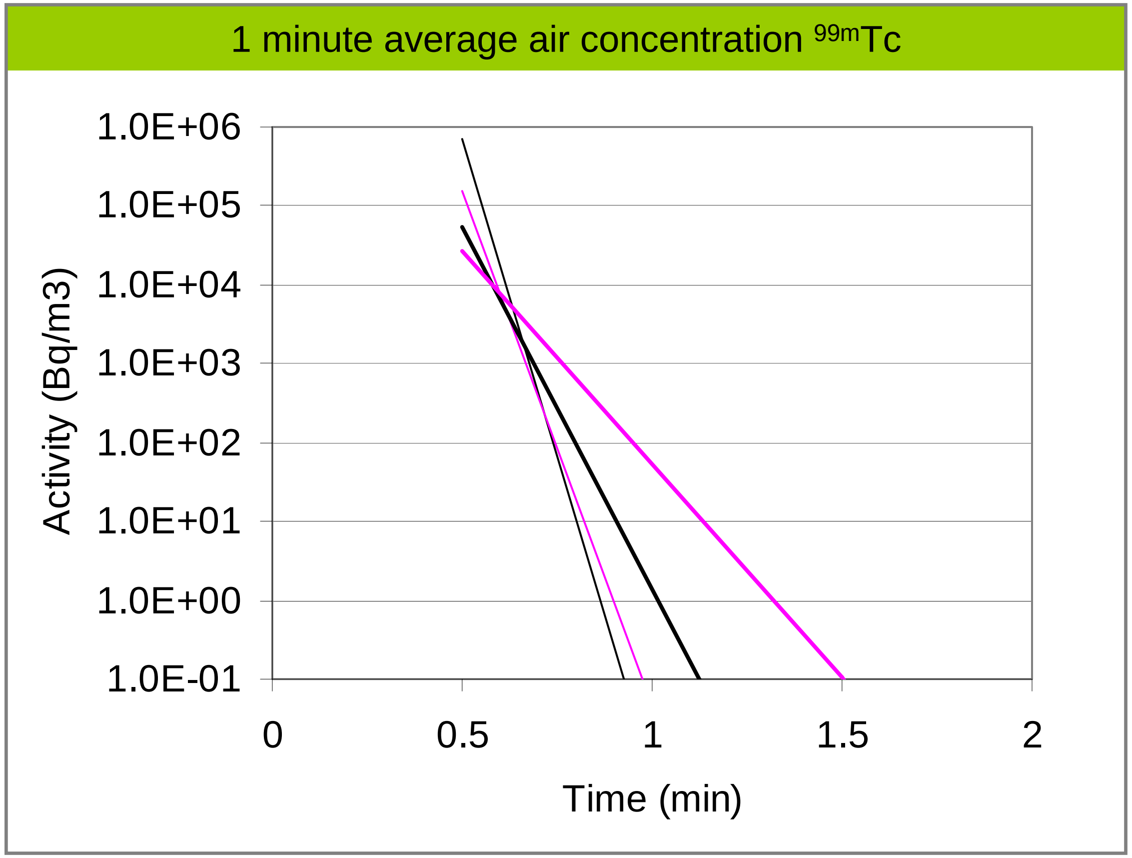


^{99m}Tc absorbed dose rate at 1m above ground



18. ^{99m}Tc concentrations in air





Graph with average concentrations as function of time for 4 positions.
The location of the 4 positions is shown in the adjacent picture.

19. Results from the sensitivity analysis

^{99m}Tc activity on the ground surface per diameter category					
Simulation	**Input parameter**	**Released activity (Bq)**	**Deposition (Bq)**	**Percentage deposition (%)**	**R_{95} zone (m)**
Default model input	**Default**	**$1.06 \cdot 10^{9}$**	**$9.16 \cdot 10^{6}$**	**0.9**	**38.4**

20. Conclusions

CONCLUSIONS

- CFD simulations give interesting qualitative results
- Effects from atmospheric conditions on the surface contamination are shown.
- CFD simulation results are very sensitive to atmospheric boundary conditions and initial cloud conditions.
- To reproduce the experimental results good climate data at the time of the experiment is required.

FURTHER WORK

- Incorporate a suitable algorithm to simulate the initial stages of the explosion
- Run a simulation for the final blind-test performed by the NRPI
- Other things that are of interest are: evaporation, wet-deposition & solar irradiation, LES calculation, automated topography

END