Simulation with Micro-SPRAY and SPRAYSHINE of the irradiation due to a radioactive plume and its deposition on all accessible surfaces in the urban environment

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INTRODUCTION

- Radioactive atmospheric releases can occur both in normal operation of e.g. NPPs or in case of an accident or a malevolent or terrorist action ("dirty bomb")
- Immediate exposure pathways are inhalation and irradiation by the plume when it disperses AND by the deposition on all surfaces (ground, façades and roofs)
  - ⇒ *Crucial assessment as precisely AND as quickly as possible of the exposure rate and health consequences on workers, population and / or rescue teams*
- As the radiation exposure is an effect from a distance AND there is a protective effect by the shading of the obstacles, the dose rate estimation is challenging in complex atmospheric environments with topography AND numerous buildings
- Past years, it was often considered a uniform atmospheric or surface activity concentration and the plume was supposed to extend infinitely over a flat terrain
  - ⇒ *A coefficient was calculated in advance taking into account a unit activity concentration, and factors to convert the activity flux into irradiation dose*
- Such a gross assumption being no more acceptable considering the 3D models, we proposed **in 2005** to compute the distribution of particles with Micro-SPRAY AND the dose field due the plume radiation with the CLOUDSHINE post-processor
- **Recently**, CLOUDSHINE has been turned into SPRAYSHINE able to calculate at receptors and along horizontal planes the gamma irradiation by airborne AND by deposited RN, consistently with the parallel version of Micro-SWIFT-SPRAY

DESCRIPTION OF CLOUDSHINE

Equation of the gamma photons flux Φ(E) (10 keV to 10 MeV) in the Lagrangian form

$$\Phi(E) = \sum_{\text{particles } i} \frac{f(E)\, B(E,\mu r_i)\, \exp(-\mu r_i)}{4\pi r_i^2} Q_i$$

with

$$B(E,\mu r) = 1 + a(E)\,\mu r \exp\big(b(E)\,\mu r\big)$$

f (E) disintegration fraction at the energy level E (in %)
B build-up factor representing the scattering of the flux (no unit)
Q_i radioactivity of particle i (in Bq)

μ linear attenuation coefficient in the air (in m^{-1})
r radial coordinate (origin where the flux is estimated) (in m)
a (E) and b (E) coefficients depending on the energy level

Equation of the gamma exposure rate D(E) at the energy level E and total exposure rate D

$$D(E) = C_b(E)\, E\, \mu_a(E)\, \Phi(E)$$

and

$$D = \sum_{\text{energy level } j} D(E_j)$$

μ_a (E) mass coefficient of energy absorption in the air (in $m^2.kg^{-1}$)
C_b (E) coefficient converting the dose absorbed in the air to the dose absorbed in the body tissues (in $Sv.Gy^{-1}$)
The coefficients depend on the gamma spectrum of each radionuclide and are interpolated from tabulated values

- **Particles in the shadow of topography or buildings do not contribute to the photon radiation**
  - *Interception if the height of the ray is less than the relief at one point at least of the meshing*
  - *For buildings, computation along the ray-triangle interception algorithm of Möller and Trumbore (1997) with an optimized screening of the obstacles to reduce the calculation time*
- **Handling of near or distant particles**
  - *Two methods have been tested to prevent the photon flux to tend to infinity when the distance between the numerical particle and the receptor goes to zero*
  - *Particles far from the point where the gamma flux is estimated are neglected using a threshold distance beyond that the calculated dose rate is less than ~10^{-19} or 10^{-20} $Sv.s^{-1}$*

DESCRIPTION OF DEPOSITIONSHINE (1/3)

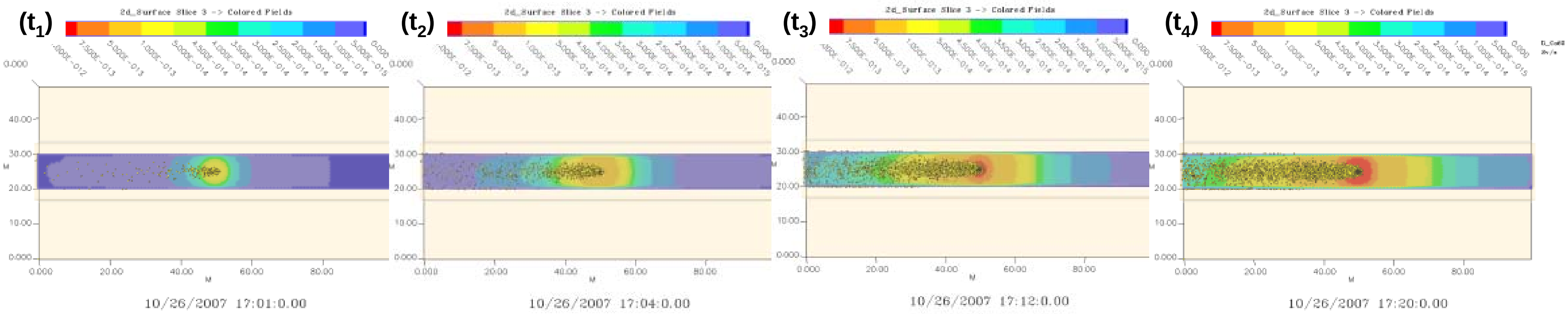
- Deposited numerical particles are considered as “frozen” (no displacement, nor rebound) and have a status depending on the deposition (ground or buildings façades, roofs or ceilings)

- Radiation evaluation distinct for airborne particles and particles on the different kind of surfaces

Test-case #1: the tunnel

- Release of ^{60}Co – 5.10^5 Bq in 1 hr – from a point source inside and in the middle of a tunnel
- Dimensions of the tunnel: 100 m long with 16 m x 5 m inner and 22 m x 7 m outer width and height
- Out of the tunnel, the wind module is equal to 2.3 $m.s^{-1}$ (at 10 m) – Mesh resolution = 1 m

- Due to high deposition velocity of 1 $m.s^{-1}$, efficient particles settling on the tunnel roof and internal walls
- From the particles positions and the gamma dose rate at 2 m AGL at four successive instants…
  - ⇒ *The irradiation is null out of the tunnel*
  - ⇒ *The highest dose is computed near the source where the maximum deposition occurs*

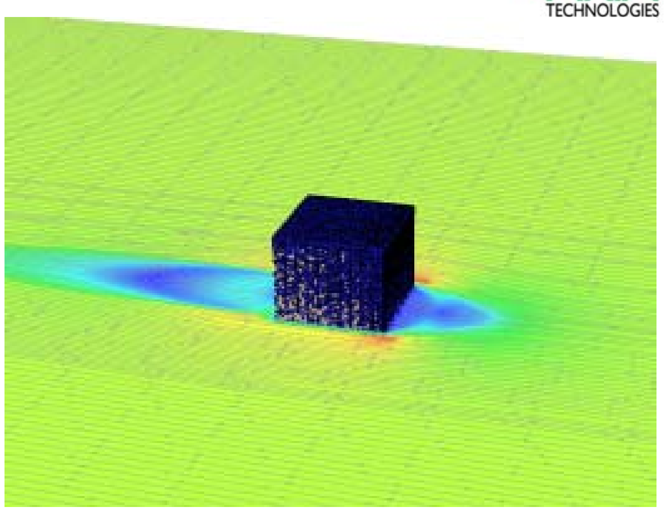


^{60}Co irradiation shape and value inside a tunnel at four successive times (t_1 to t_4)

DESCRIPTION OF DEPOSITIONSHINE (2/3)

Test-case #2: the cube

- 10 m edge cube – Mesh resolution = 1 m
- Stationary wind field (5 $m.s^{-1}$ far from the obstacle) & neutral atmosphere
- Release of ^{60}Co – 4.10^4 Bq in 5 min – at some distance of the cube
- Particles settle on the cube with a velocity of 5 $m.s^{-1}$ whatever the face
- SPRAYSHINE receptors in planes at 0 m, 10 m, 11 m and 20 m AGL



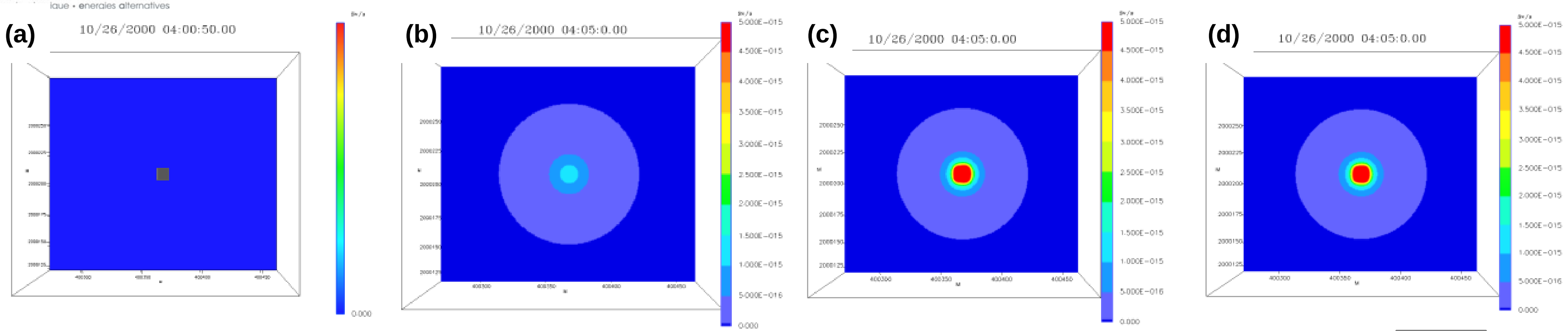
Wind module & streamlines at 2 m AGL – Particles stuck on the cube walls and roof

- Results at the four mentioned levels when deposition happens only on the roof
  - At 0 m, the dose rate is zero as can be expected (a)
  - At 20 m, iso-doses are concentric circles with the maximum located just above the roof (d)
  - At 10 or 11 m, iso-doses are more like squares as dose rate is evaluated on or very near the roof (b & c)

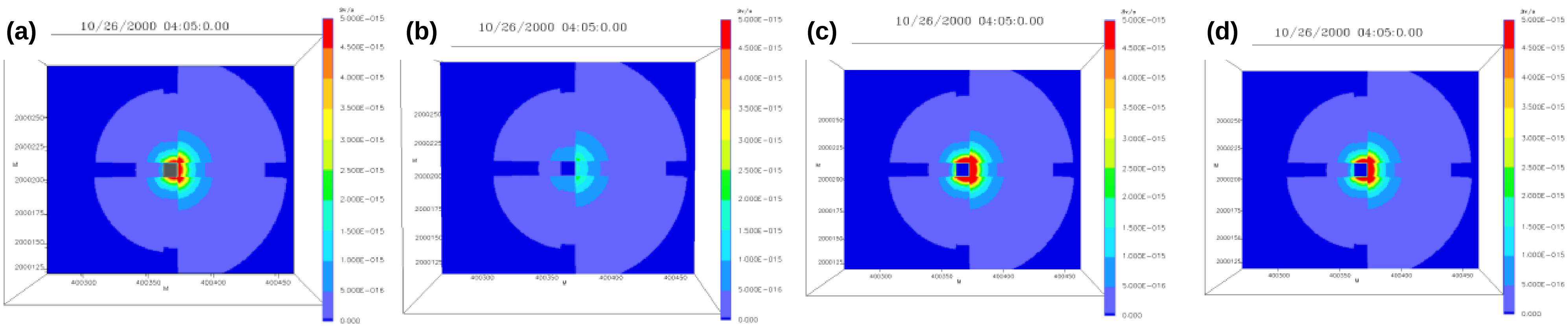
- Results at the four mentioned levels when deposition happens only on the cube walls
  - Plume coming from E, deposited particles and dose rate are greater on the cube E part than on W part
  - Receptors located just in front of each cube wall only see particles present on this face…
  - While SE (resp. NW, etc.) receptors see the particles on both S & E faces (resp. N & W, etc.)
  - ⇒ *Higher dose rates in the NE & SE quarters than in E, N or S areas*
  - ⇒ *Higher dose rates in the NW & SW quarters than in W region*

- Finally, shape and value of the exposure rate in case of deposition on all faces of the cube is the addition of the contributions of the deposition on roof and walls

DESCRIPTION OF DEPOSITIONSHINE (3/3)



*Gamma dose rates in planes at 0 m (a), 10 m (b), 11 m (c) and 20 m (d) AGL due to ^{60}Co particles deposited on the **cube roof***



*Gamma dose rates in planes at 0 m (a), 10 m (b), 11 m (c) and 20 m (d) AGL due to ^{60}Co particles deposited on the **cube walls***

PARALELL VERSION OF SPRAYSHINE (1/4)

- Dual objective
  - *Drastically reduce the execution time by splitting the particles among numerous cores*
  - *Cope with a huge domain by dividing it into “tiles” distributed to a shared memory and many processors*
- One-tile parallelization – Particles are distributed to available cores at each time of the computation
- Multiple tiles parallelization – The challenge is the optimization of the computational procedure!
  - *A particle in a given tile may contribute to the exposure rate in the other sub-domains*
  - *Interception of the gamma rays by topography or obstacles should be determined for each tile*
  - *As radiation vanishes with distance and tiles are chosen large enough, radiation in a tile depends only on the particles present in this tile and its eight neighbors (limited exchange of information)*
  - *With the time, SPRAYSHINE is active on different tiles and creates a varying neighborhood chronology*
  - *The necessary cores in a computation are at least the number of SPRAYSHINE active tiles*
  - *If there are many cores allocated to the same tile, the particles are distributed between them*

E.g. Consider a 100 tiles Micro-SWIFT computation, 50 tiles active during the Micro-SPRAY dispersion simulation and SPRAYSHINE launched with a pool of 200 cores ⇒ Two cores should be attributed to each SPRAYSHINE tile ; indeed, after neighborhood checking, four cores are given to each tile

PARALELL VERSION OF SPRAYSHINE (2/4)

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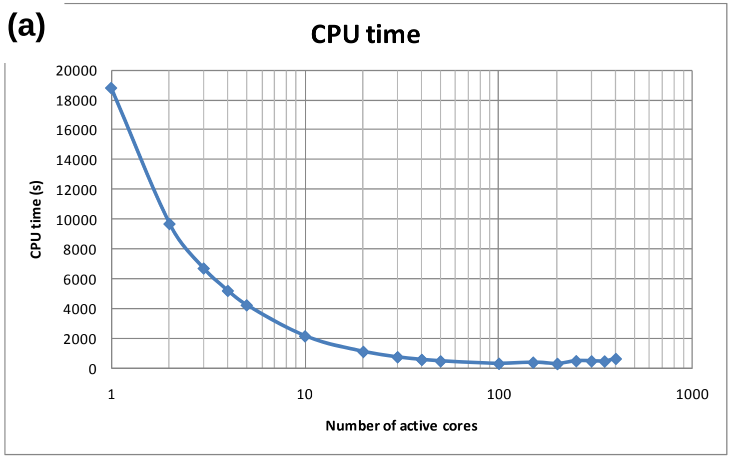
ARIA TECHNOLOGIES

Efficiency of the parallelization on one-tile

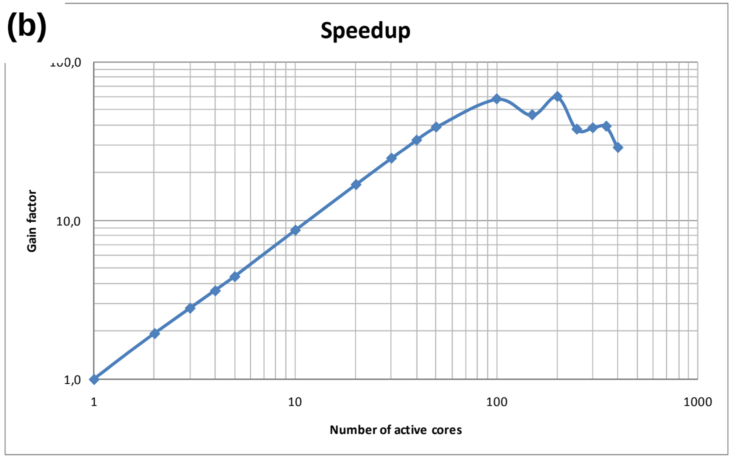
- Example of test-case in an urban district in the city of Lyons (France) (see the main features in the table)
- Calculations using 1 to 400 cores on a 47.7 Tflops Bull Itanium cluster with 932 nodes of 8 nodes (1.6 GHz)
  - *Up to 10 cores, the gain is quite-linear*
  - *Between 10 and 100 cores, the slope of the curve tends to decrease but maintains high performance*
  - *Between 100 and 400 cores, the gain oscillates around its maximum value before it goes down*

Total number of nodes in the horizontal grid	65,511 (= 261 x 251)		
Number of receptors (after clearing of the nodes in buildings)	38,492		
Number of obstacles (after grouping them together)	2,583		
Number of computed irradiating particles	Time frame #1	Time frame #2	Time frame #3
	6,431	7,883	7,883

(a)



(b)



Computational time (a) and speedup (b) according to the number of operated cores in the "Lyons simulation"

PARALELL VERSION OF SPRAYSHINE (3/4)

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Application of the parallelization on multiple tiles

- Example of test-case in the business district “La Défense” situated in the North-West part of Paris
- Hypothetical short release of ^{60}Co particles – 1 GBq in 1 min – done from a point source in the main “La Défense” avenue lined with high buildings
- Settling velocity is 0.1 $m.s^{-1}$ on the ground as on the façades, roofs and on the ceiling of the “Big Arch”
- Principal other features of the calculation are mentioned in the table below
- Following flow and dispersion computation with Parallel-Micro-SWIFT-SPRAY, the gamma dose rate is evaluated by SPRAYSHINE distinguishing the irradiation by the plume and the surface deposition
- Simulation is performed on **one tile**, then in a domain divided into **nine tiles** distributed to **nine cores**
- **Duration of this big size calculation gets down from around 3 hr to only 1 hr** (Windows 7 – 64 bits)

Total number of nodes in the horizontal grid	105,651 (= 351 x 301) – Mesh size = 3 m						
Number of obstacles (after grouping them)	6,486						
Number of time frames	30						
Meteorological data (in neutral atmosphere, along with observations recording)	Time	12:00	12:05	12:12	12:20	12:22	12:30
	Wind module (in $m.s^{-1}$)	2.00	1.69	1.69	1.69	2.81	2.25
	Wind direction (in °)	120	125	80	120	160	170

PARALELL VERSION OF SPRAYSHINE (4/4)

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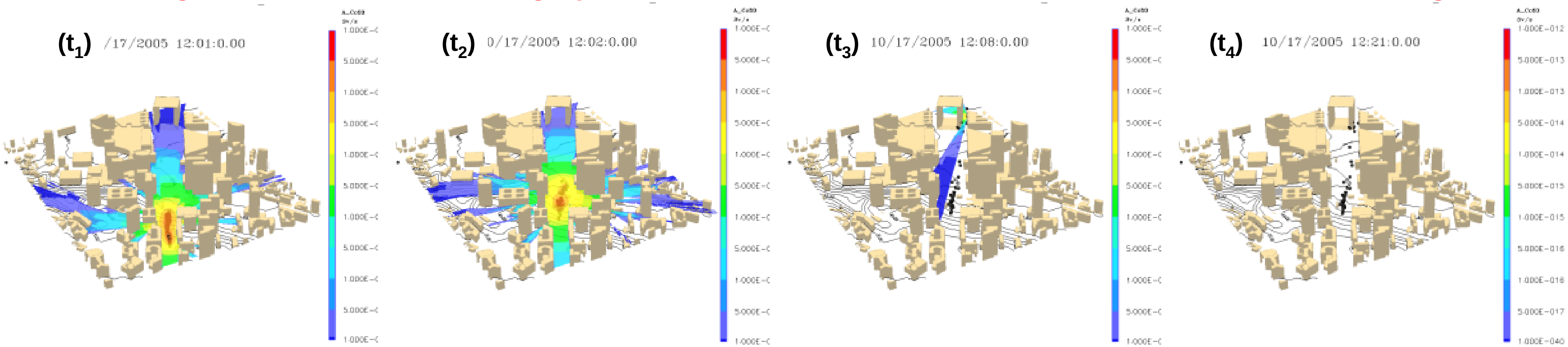
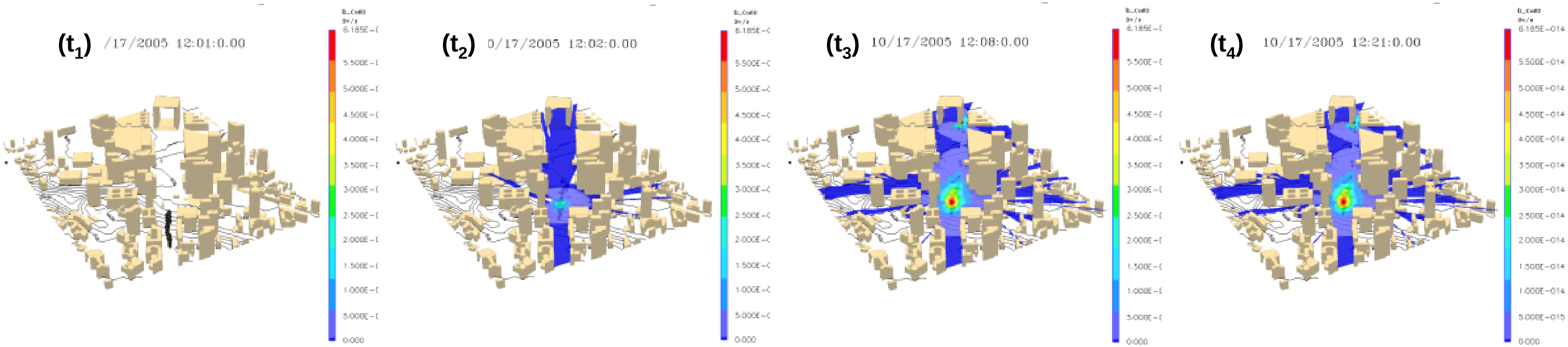
Topography outline, airborne and deposited particles positions and exposure rate in a horizontal plane at 20 m AGL at four instants

The images illustrate the shading by the obstacles and the non-zero dose rate "inside" the Big Arch



***CLOUDSHINE** computation in "La Défense" district a four instants (t_1 to t_4) with receptors at 20 m AGL*



***DEPOSITIONSHINE** computation in "La Défense" district at four instants (t_1 to t_4) with receptors at 20 m AGL* energie atomique • energies alternatives

CONCLUSION AND PERSPECTIVES (1/2)

ARIA TECHNOLOGIES

- Precise evaluation of 3D gamma exposure is an essential issue for impact assessment especially in case of accidental or malevolent radioactive releases

- As the irradiation is influenced by the shading of the topography AND obstacles, it is advisable to make use of modelling systems adapted to the built environment

  ⇒ *Micro-SWIFT-SPRAY is a compromise solution between the "full CFD" preciseness and computational times consistent with a crisis situation*

- **In 2005**, CLOUDSHINE post-processor working with the LPDM Micro-SPRAY was developed and validated to evaluate the dose rate by radioactive plumes

- **Recently**, CLOUDSHINE has been supplemented with DEPOSITIONSHINE dedicated to the exposure rate of RN deposited on all visible surfaces (ground, façades, roofs or ceilings) also taking account of the shading by the obstacles

- SPRAYSHINE post-processor handles with hollow geometries (arches, tunnels...) and gamma radiation estimates at receptors AND at any heights above the ground with a new algorithm for the interception between gamma rays and obstacles

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CONCLUSION AND PERSPECTIVES (2/2)

- Consistently with PMSS, a p-version of SPRAYSHINE has also been developed with a quite satisfactory speedup on domains consisting of one or multiple tiles

  ⇒ *This makes SPRAYSHINE performing both on a mono-processor laptop and on a super-computer dedicated to a high-resolution over a whole city*

- Progress are still necessary, especially in terms of ray tracing in order to reduce computational time for a huge simulation domain covering e.g. all Paris

- Our micro-scale modelling system is designed to predict the RN dispersion AND post-process the dose exposure at high resolution with moderate execution times

  ⇒ *Impact assessment near industrial buildings or in the urban context*
  ⇒ *Hopefully, a full and relevant answer in case of an emergency!*

- As the gamma exposure rate is directly measured in the field, the system could also be used with an inverse algorithm for a STE from available measurements

Thank you! Questions?