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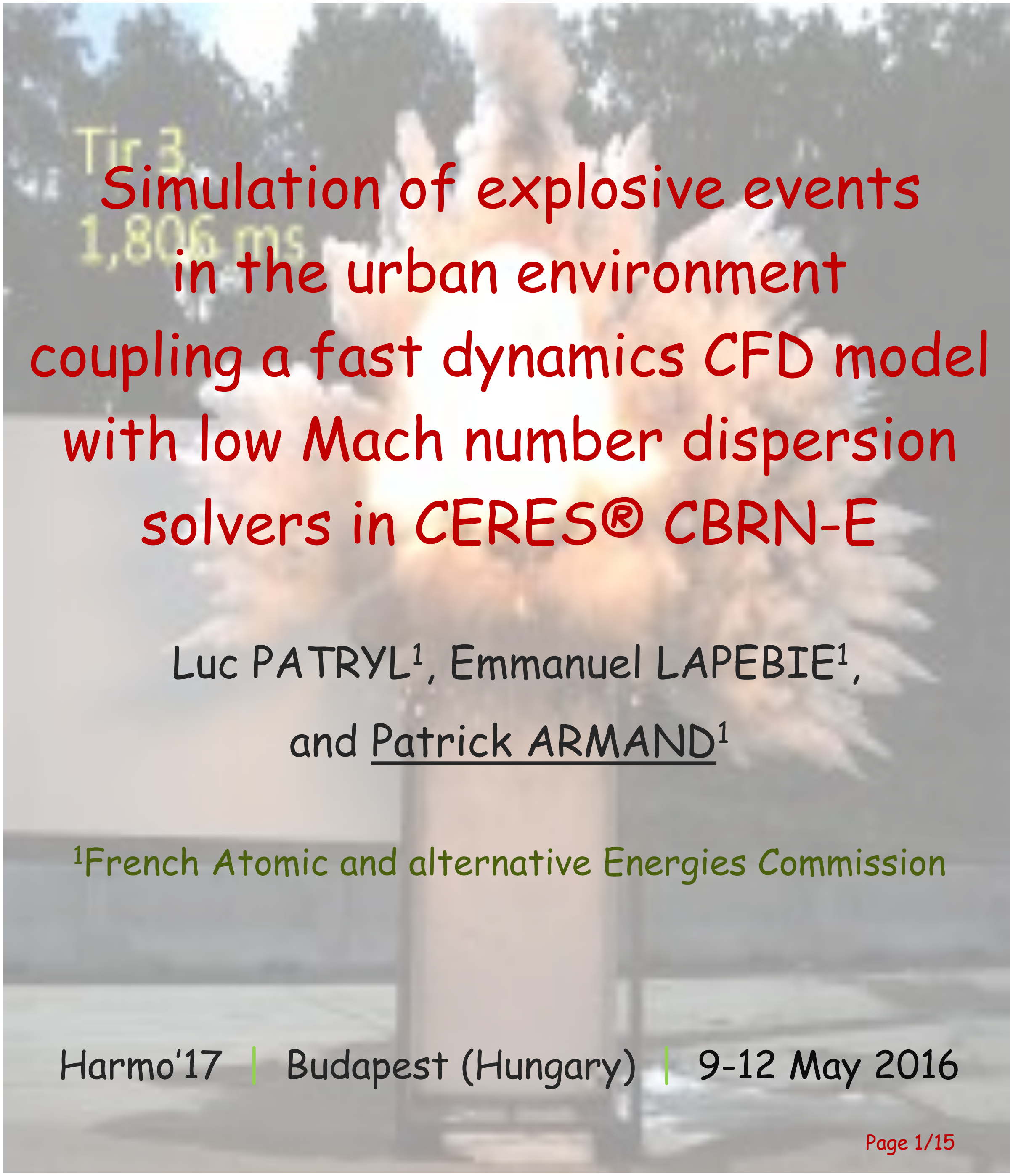

Simulation of explosive events in the urban environment coupling a fast dynamics CFD model with low Mach number dispersion solvers in CERES® CBRN-E

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Introduction, context and outline

- CBRN-E events may include deleterious atmospheric releases and / or explosions originating from industrial accidents or terror events

- A rapid assessment of the situation is of high-stake for rescue teams and stakeholders as it can be a strong element of differentiation between emergency handling strategies to efficiently control the situation and return to normal (cf. emergency exercises)

- Modelling may contribute to the cross feeding of topics relevant to the CBRN-E threats such as the prevention, detection, alert, intervention, and / or mitigation

- This is the motivation for the development of CERES® modelling and decision-support tool

- Outline of the presentation
  - Quick recall of the main development guidelines and features of CERES®
  - Brief insight on experiments and models related to the detonations in CERES®
  - Application to a coupled explosion and dispersion test-case in a large urban domain

CERES® CBRN-E modelling system in brief (1/2)

- CERES® is being developed in collaboration between divisions of the CEA in France
- It is designed to evaluate the short term and long term health consequences of chemicals, radionuclides or biological pathogenic agents, accidentally or maliciously emitted in the air
- It is committed to provide numerical results in a limited amount of time (less than 15 min. in most cases), thus to be applicable in the "hot phase" of an emergency
- It is able to deal with several types of threats and scenarios, to run flow and dispersion models adapted to complex built-up environments and to provide a mapping of danger zones or counter-measures zones directly useable by the civilian security
- Dispersion models implemented in CERES® have been rigorously validated using wind tunnel and in-field experimental data (see Duchenne et al., 2016)
- On-going developments include source term estimation and data assimilation
- The software motto is to be modular and flexible as versions can be instantly generated with the one and only components the user is interested in (e.g. chemical risk version)

CERES® CBRN-E modelling system in brief (2/2)

- The major features of CERES® are summarized hereafter (identity sheet)
  - 3D dispersion at local and regional scale in both natural and complex built-up environments
  - Various categories of threat agents (radionuclides, chemicals or biological pathogens) and endpoint health impact models specifically devoted to these kinds of releases
  - Large panel of scenarios (leakage from a tank or a pipe, evaporation from a pool, fire, explosion...) and associated simplified or more advanced "source term" models
  - Depending on the skill and computational resources of the user, choice between three dispersion models: Gaussian puff, sophisticated urbanized Gaussian and, more farsighted and R&D oriented, a Lagrangian Particle Dispersion Model (LPDM) using a 3D flow field
  - Range of meteorological data: measurements and / or meso-scale numerical weather forecast
  - Numerous data bases with the terrain elevation, land-use, building data, physicochemical properties of stable or radioactive elements, transfer coefficients in the soil and the biota, radiological dose conversion coefficients, toxicological reference values, etc.
  - Fate of the gases or particles released in the air considered according to their CBR nature
  - Tried and tested ergonomic graphical user interface with all kinds of maps exportable to GIS (e.g. ArcGIS®) as a support to the intervention and decision-making processes

High-Mach source terms in CERES® CBRN-E

- Attention has to be paid to transient source terms like those generated by energetic events as uncompressible flows are limited to Ma < 0.1 (velocity of 35 $m.s^{-1}$ or density increase of 11%)

- Several source terms begin with high-Mach flows, for instance in accidental releases from pressurized containers or in events involving high explosives (dirty bombs, B/C–IED), etc.

- To overcome this issue, simplified or full CFD strategies have been implemented in CERES®:
  - Source terms with no interaction with obstacles – Analytical description (e.g. D2R2 model for IED or TESATEX for stratified clouds models after explosive releases)
  - For more complex events – Description of mass, impulse and energy fluxes through a surface (e.g. indoor detonation and dissemination in a single- or multi-room building followed by an outdoor high-Mach flow through windows and doors computed as a boundary condition by the 3D compressible solver HI2LO, further computed by the LPDM solver in CERES®)
  - In the most complex cases – Use of 3D multiphase computations from the beginning (e.g. results remapped in HI2LO and, when reaching a low-Mach state, remapped in CERES® and its low-Mach dispersion solvers with a time coupling of the two models)

D2R2 – An analytical model for the IED (1/3)

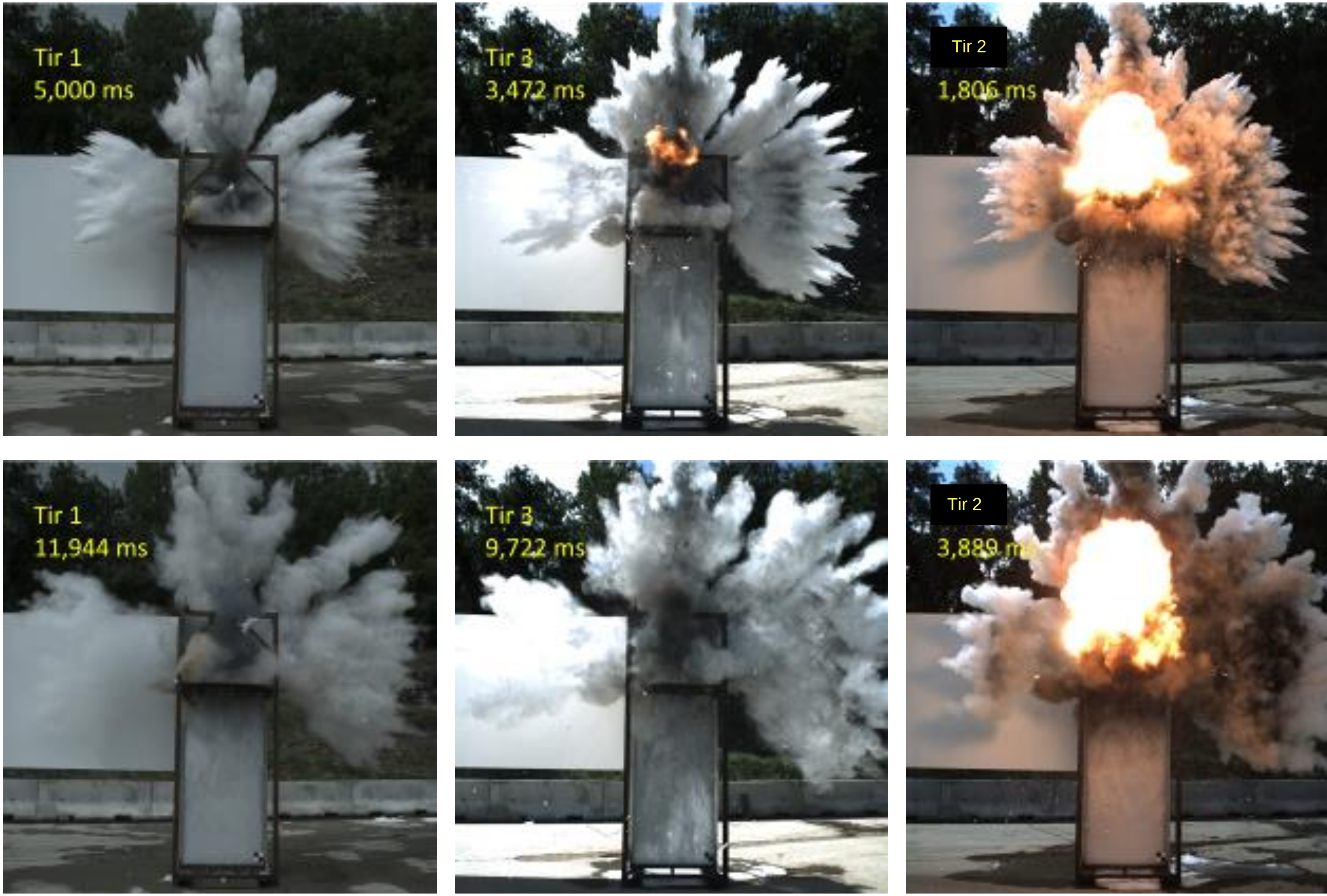
- Several explosive dissemination experiments conducted at CEA with liquids and powders
- Reference setup: cylindrical plastic shell (external diameter of around 10 cm) with an inner cylinder of high explosive of variable diameter; variable mass ratio between the explosive and the inert material ($1.6 < M_{inert} / M_{TNT} < 12.8$ in three experiments with water)
- From the analysis of experiments, two regimes can be identified:
  - Highly structured regime with the formation of characteristic "finger" instabilities
  - After a transitional break-up process, cloudy shapes followed by the expansion end
- D2R2 (Dynamical Dispersion Rapid Releases) model can describe correctly the two regimes as the predicted external cloud radius compares quite well with the experimental one
- D2R2 has been successfully applied to the CEA experiments and also to literature results such as Apparao and al. (2013) or Zabelka and al. (1969)

D2R2 – An analytical model for the IED (2/3)

Change of morphology for three M_{inert} / M_{TNT} ratios

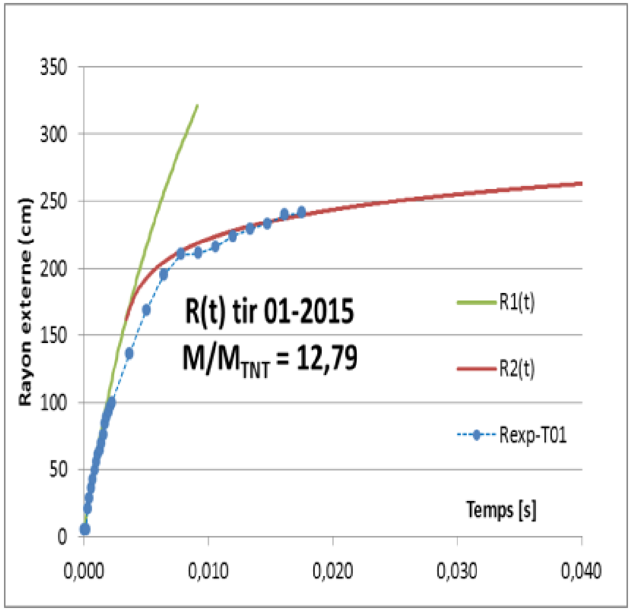
(from the left to the right: 12.8, 4.8 and 1.6)

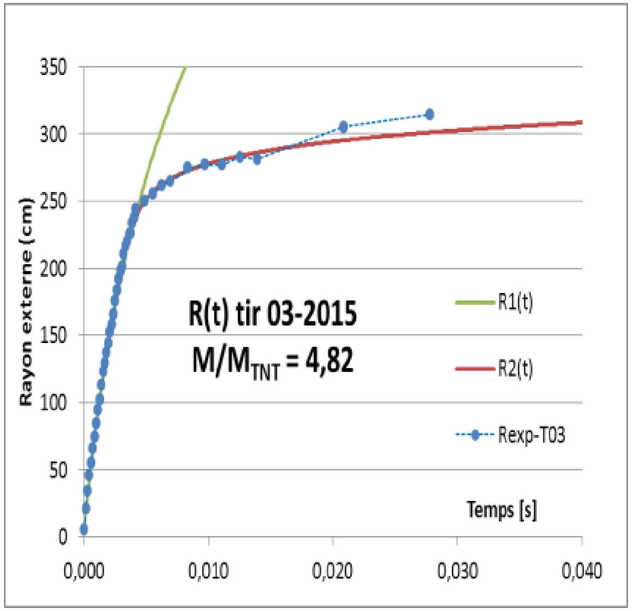
Top: fingers structures – Bottom: cloudy shapes

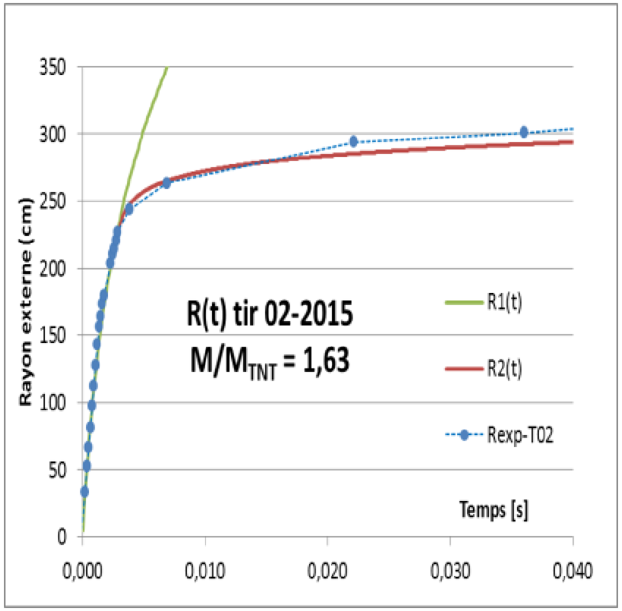


D2R2 – An analytical model for the IED (3/3)

D2R2 results compared to CEA experiments (time evolution of the external radius)
Blue: experiments – Green: D2R2 first regime – Red: D2R2 second regime







Note that the stabilization radius is very close for the three cases!

HI2LO – Source term as a boundary condition in a high-Mach 3D solver (1/2)

- HI2LO is the CEA reference model for 3D high-Mach to low-Mach transition computations (albeit not a fully multiphase model, HI2LO is able to remap results obtained with the models of the multiphase CHYMERE suite developed for CEA by the RS2N company)

- HI2LO is able to use complex boundary conditions and in-cell obstacles (which may serve as a source for boundary conditions) and it is also used to branch analytical source terms

- E.g. of "internal" source term – Subsonic, sonic or supersonic injection in a computational cell as if the cell was connected to a pressurized tank

>> A reservoir boundary condition (internal pressure 3.67 bar and temperature 991 K) is defined inside a computational cell and the release takes place during 0.02 second

>> The domain size is (3.2 x 0.8 x 0.8) (m) and the release is located at (3.1, 0.4, 0.4) (m)

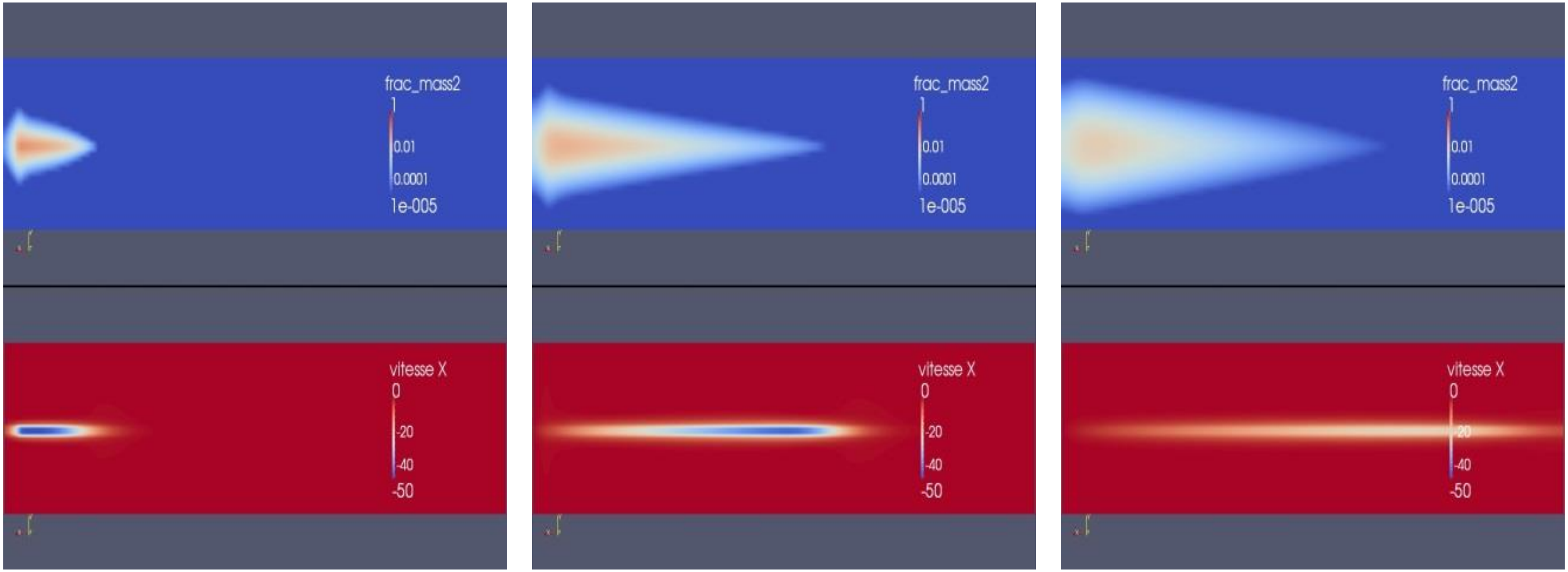
>> Strong turbulent mixing with ambient air is accounted for through a simple model

>> At the end of the simulation, the local Mach number is everywhere lower than 0.06

HI2LO - Source term as a boundary condition in a high-Mach 3D solver (2/2)

Pollutant mass fraction (top) and axial velocity (bottom)

Times from left to right: 5 ms, 25 ms and 45 ms (X axis flipped for clarity)



Coupling explosion and dispersion modelling in a real urban district (1/4)

- Strategies have been developed to take account of open air and semi-confined explosions with the coupled dispersion of noxious species >> HI2LO is coupled with PMSS in CERES®

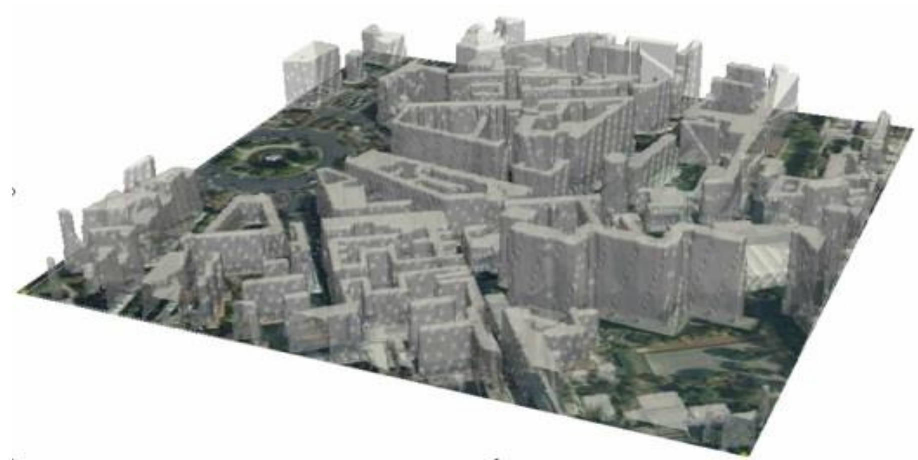
- HI2LO and CERES® share the ability to import topographies (Digital Elevation Maps) and the same urban geometries from GIS data (conversion of "shp" into 3D extruded obstacles)

- In built-up environments, high-Mach flow strongly interacts with the ground as the buildings

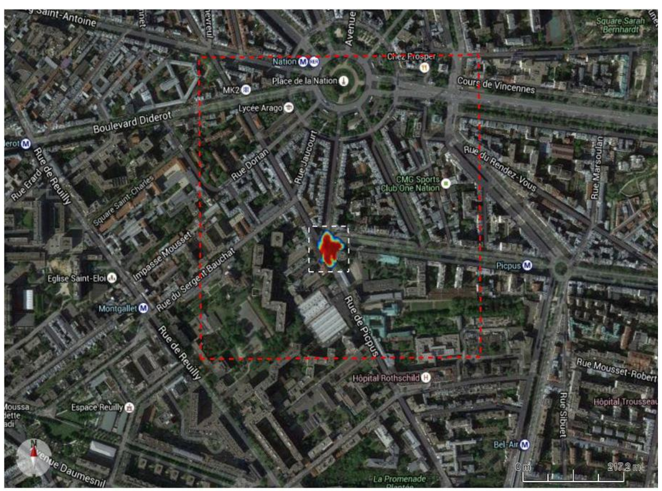
- The plume outer boundary and internal distribution of the species may be obtained when the maximum Mach number is under 0.1. giving the appropriate input state for PMSS where the HI2LO data are imported to continue the simulation for longer timescales

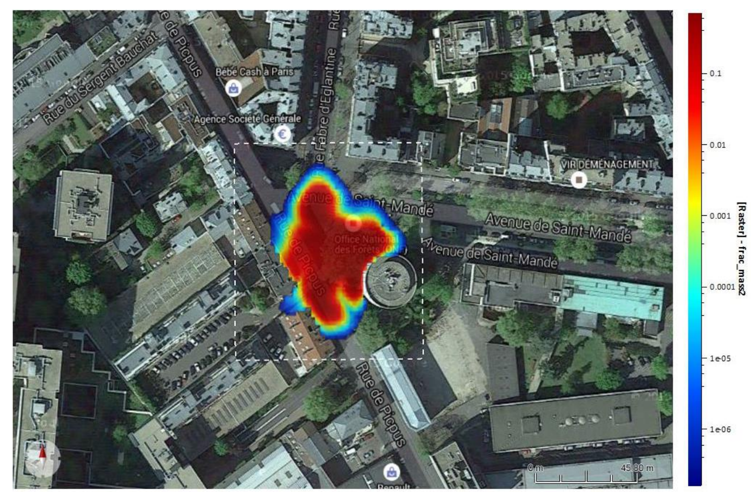
Coupling explosion and dispersion modelling in a real urban district (2/4)

Google Maps® view, BD TOPO shapefile, and HI2LO geometry after processing (from left to right)



Selection of a sub-domain from HI2LO and extraction of the source term for CERES®

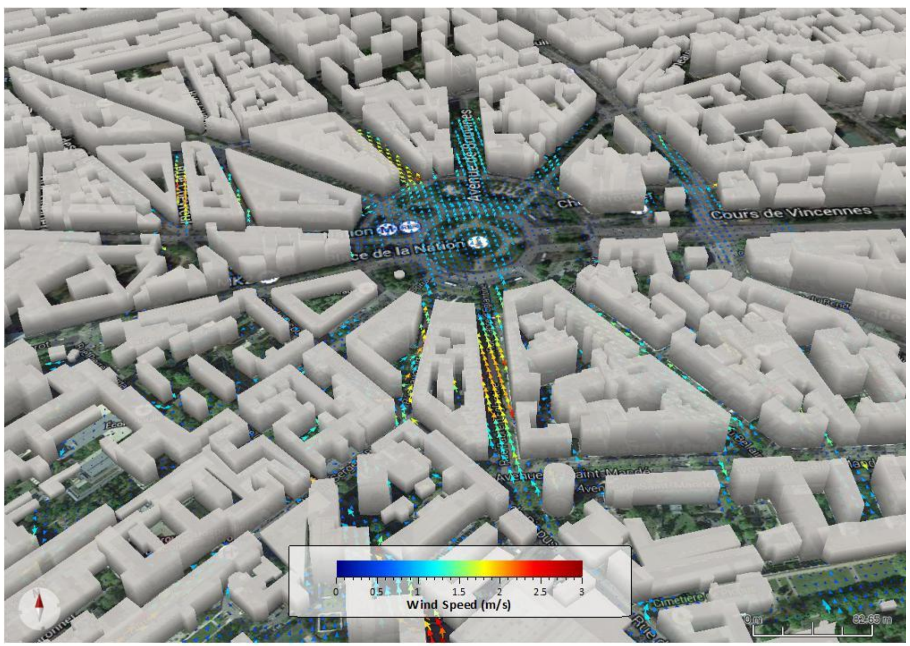


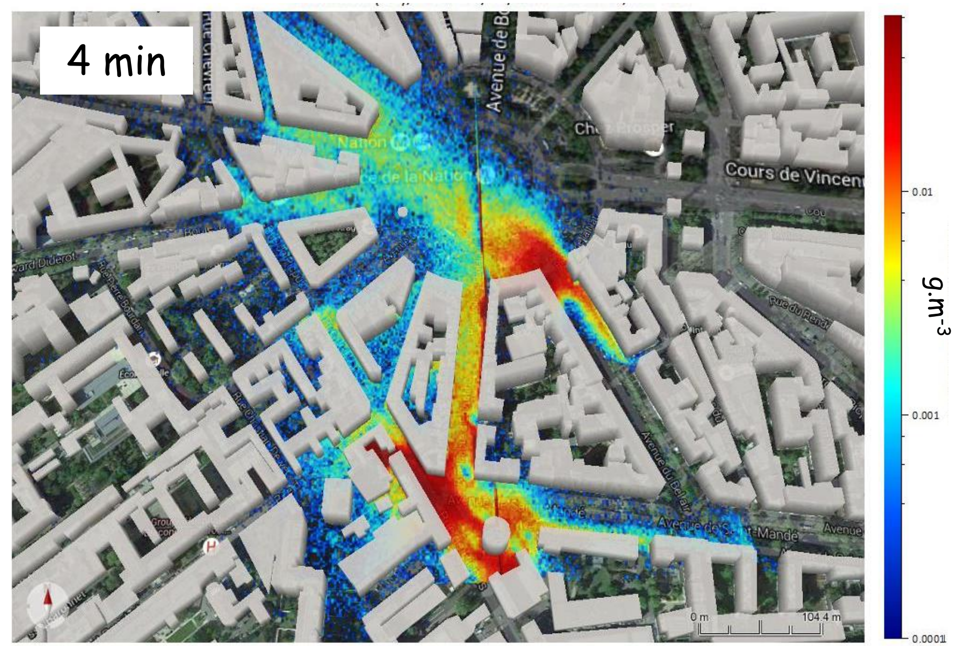


Coupling explosion and dispersion modelling in a real urban district (3/4)

- >> Fictitious explosion of a "dirty bomb" south of Nation place in Paris
- >> Wind from South to East (195° - 96°) – Wind speed : 2 – 8 m/s
- >> HI2LO grid – 640 x 600 x 100 m – Resolution 2 m
- >> CERES® source term – 72 x 76 x 20 m – Resolution 2 m
- >> PMSS grid – 3 x 2.5 x 2 km – Resolution 2 m
- >> HPC – Flow 1 hr 40 min (12 proc.) – Dispersion 5 min (30 proc.)

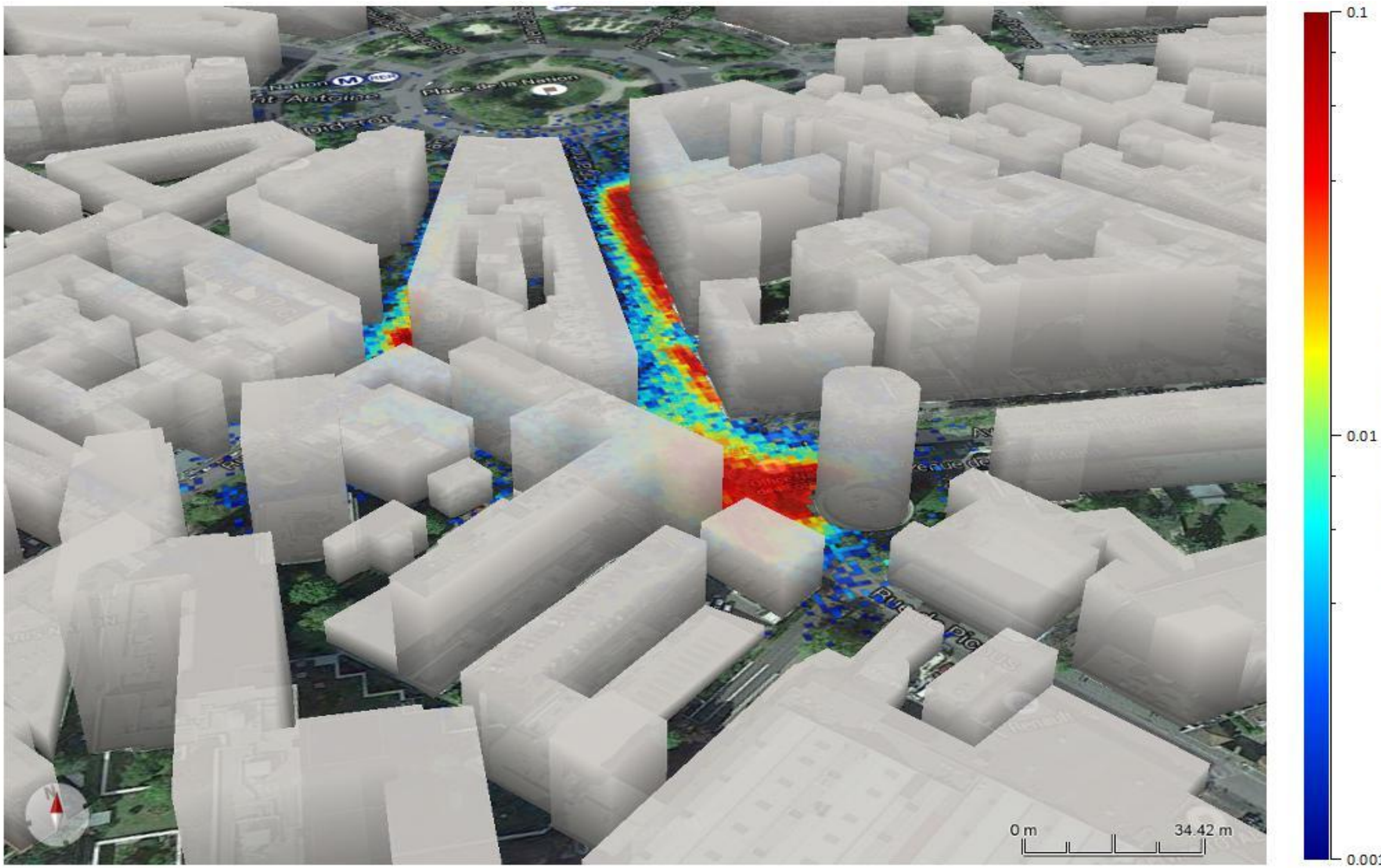
Wind field and concentration field at four times





Coupling explosion and dispersion modelling in a real urban district (4/4)

Total Effective Dose Equivalent (in Sv) (inhalation + cloud shine + ground shine)



Conclusions

- Explosions may originate from accidents or terror events, seriously affect the human health and the infrastructures, and generate the dissemination of hazardous species in open air, semi-confined industrial sites or urban districts, or initially confined infrastructures

- CERES® is equipped with both explosion and dispersion models adopting a graduated range of strategies to deal with more or less complicated environments and threat scenarios

- Our ambitious approach is the direct time-coupling between the transient results of the HI2LO Mach number CFD model with the PMSS Lagrangian dispersion solver in CERES® taking account of both the explosion characteristics and the obstacles influence

- This approach has been recently applied to districts in Paris in order to simulate the flow and dispersion pattern and assess the overpressure and the toxicity consequences in case of hypothetical explosive noxious releases

Questions?

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